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EXPERIMENTAL STUDY OF NANO-COMPOSITE MATERIALS ON VIBRATION RESPONSES

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Abstract

This paper present of experimental and numerical study of nano Al_2O_3 cantilever beam for forced vibration, addressing an unexplored area in the existing literature. The proposed nano composite cantilever beam is modeled with hole and crack. The study is based on history loading calculation and composite morphology a global parameter, the transverse crack in nano composite cantilever beam was studied and analyzed experimentally using a four-channel dynamic signal acquisition (NI 9234) module for making high-accuracy measurements and its ideal for vibration applications. The relationship between the dispersion and interaction of the alumina nanoparticles within the cantilever beam and morphology of the solid, hole and crack composite has been identified. Furthermore, the influence of particles Al_2O_3 at different concentrations (0%, 1%, 3% and 4%) have been studied respectively. Supporting results proved that the crack and hole depth increases with increases of history loading. Nanoparticles dispersed within the specimen can increase energy dissipation during vibration, leading to improved damping characteristics. For future work, it is recommended to utilize statistical frequency domain input, such as Power Spectral Density (PSD), for assessing the structural response instead of employing time history loading.

Keywords: Nanocomposite, time domain, mechanical properties, cantilever beam, finite element method

1. INTRODUCTION

In the realm of engineering, conventional materials can be categorized into four main groups: metals, polymers, ceramics, and composites. Metals possess remarkable qualities including high rigidity, ductility, mechanical strength, and thermal stability. Additionally, they exhibit exceptional conductivity of both electricity and heat. Polymers have gained widespread popularity as one of the most extensively utilized engineering materials. This is attributed to their lower density, ease of machinability, and superior resistance to corrosion compared to other materials. Ceramics, characterized by strong covalent bonds, display distinct properties such as almost negligible thermal and electrical conductivities. Moreover, they exhibit exceptional thermal stability and hardness. Composite materials, on the other hand, are solid substances consisting of a minimum of two components that exist in separate phases. Wood serves as a natural composite, composed of cellulose fibers embedded in a lignin matrix. Another well-known example of a man-made composite material is reinforced concrete. Steel and concrete retain their unique characteristics within the composite structure. Through their synergistic collaboration, steel handles tension loads while concrete bears compression loads. Composite materials offer several key advantages, including exceptional strength-to-weight and stiffness-to-weight ratios. Additionally, they often exhibit excellent corrosion resistance. Fiber-reinforced composite (FRC) structures find application in various engineering fields such as aerospace, machinery, marine, and civil engineering projects. This is due to their superior strength-to-weight ratios, reduced weight, and enhanced ductile properties. Practical implementations of FRC structures include molded car panels, helicopter and wind turbine blades, tennis rackets, ski poles, and prostheses [Callister & Rethwisch, 2018].

Beams and beam-like elements play a vital role in various mechanical structures and find widespread usage in high-speed machinery, aircraft, and lightweight structures. Among structural members, fiber-reinforced laminated beams form a significant category, commonly employed as dynamic components in applications like robot arms, rotating machine parts, helicopter blades, and turbine blades. Just like other structural elements, beams are subject

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to dynamic excitations and vibrations. Engineers prioritize the reduction of vibrations in these structures as a fundamental requirement. One effective method to achieve this goal is by strategically adjusting the natural frequencies of the structure to diverge from the frequency of the excitation force [Tilahun & Lemu, 2021].

In recent decades, nano-composite plastics have gained widespread utilization in engineering applications, primarily due to their impressive strength-to-weight ratio, high stiffness, resistance to fatigue, and corrosion resistance. These materials offer a range of advantages, including ease of fabrication, design flexibility, and the ability to tailor material properties to suit diverse applications. Consequently, vibration techniques prove to be a viable non-destructive testing method for detecting cracks in components under examination [Madenci, 2021].

Therefore, understanding the vibration behavior of composite material structures is crucial for their design. Some works on the mechanical analysis of crack effect on composite material structures are reported below.

The analysis and study of the crack in cantilever beam was established by Altunışık et al. 2017. The natural frequency can be predicted experimentally and theoretically by the finite element method (FEM).

In a study conducted by Chatterjee et al. in 2019, the presence of cracks on the surface of E-glass/Epoxy composite cantilever beam-type structural elements was investigated using natural frequency detection. The experimental analysis involved conducting free vibration modal analysis to determine the mode shapes and corresponding frequencies of the cracked beam. The findings revealed that vibration analysis techniques can effectively detect cracks in cantilever beams, offering a faster, more accurate, and efficient approach to optimizing the performance of machinery and structures. The experimental setup employed in the study allowed for the identification of crack parameters, providing more precise information regarding the location and depth of the cracks. It was observed that cracks near the fixed end of the beam resulted in a greater reduction in natural frequencies, while cracks situated away from the fixed end exhibited higher frequency ranges. Additionally, deeper cracks had a more significant impact on reducing the natural frequency compared to shallower cracks.

The detection of cracks and their extent through vibration analysis techniques offers an efficient means of enhancing the lifespan of machinery and structures. By identifying and addressing cracks in a timely manner, the performance and longevity of machines and structures can be improved effectively. In Arabshahi and Zahrai's 2014 study, they proposed the use of the composite element method for both free and forced vibration analyses of beams with multiple steps. The composite beam element, being of a one-element-one-member configuration, eliminates the need to account for the discontinuity between different parts of the beam during modeling. Satisfactory comparisons have been made between the accuracy of this new composite element and existing results. One notable advantage of the proposed method is its easy extension to handle beams composed of any number of non-uniform segments. In the context of free and forced vibration analysis for cracked beams, using the composite element allows for the automatic inclusion of interaction effects between adjacent local damages in the finite element model. The accuracy of the present method has been satisfactory compared to both existing models and experimental results.

In a study conducted by Djidrov et al. in 2014, it was observed that the presence of cracks significantly impacts both the physical and dynamic characteristics of a structure. Detecting cracks in structures is therefore a crucial concern. Cracks in a structure have a noticeable effect on vibration parameters, including natural frequency, mode shape, and stiffness. The natural frequency and mode shape was analyzed by using finite element analysis as well as experimental. It is observed that specimens have different crack inclination, crack location and crack depth at varies natural frequency. The results obtained the crack near to fixed end it largely reduces natural frequency, while crack location and inclination was kept constant then crack depth increases natural frequencies were decreases. Also, if the crack location and the crack depth is kept constant then crack location increases natural frequencies increases. Sadettin Orhan in 2007 conducted a study on crack detection and classification in structures, focusing on free and forced vibration analysis of a cracked cantilever beam. The results indicate that free vibration analysis is effective for detecting both single and two-edge cracks, while forced vibration analysis better describes changes in crack depth and location, but is limited to detecting only single cracks. Kisa and Gurel introduce a novel numerical technique combining finite element and component mode synthesis methods to analyze the free vibration of uniform and stepped cracked beams with circular cross sections. The approach involves dividing the beam into substructures at the crack section and using flexibility matrices and fracture mechanics theory to account for the interaction forces. Numerical examples demonstrate the method's accuracy and effectiveness in assessing natural frequencies and mode shapes, making it suitable for vibration analysis of such cracked beams.

Banerjee in 2012 presents a dynamic stiffness method for conducting free vibration analysis of beams with attached spring-mass systems. It formulates an eigenvalue problem by combining dynamic stiffness matrices of the beam and spring-mass elements, and then uses the Wittrick-Williams algorithm to determine natural frequencies and mode shapes.

Mishra and Sahu investigated the effects of cracks on the static, dynamic, and stability behavior of a transversely cracked beam using the Finite Element Method (FEM). The study focuses on free vibration, buckling, and parametric resonance characteristics. The analysis reveals that the location and depth of cracks significantly influence the frequencies of vibration and buckling load of the beam, with cracks near the free end having a greater impact on dynamic instability behavior. The results can be valuable for structural health monitoring, integrity testing, and ensuring structural safety and performance.

The investigation of Sahu and Das in 2019 focuses on the vibration characteristics of a laminated composite beam (LCB) with multiple transverse cracks, which are commonly used in aerospace, automobile, and other applications. Finite element method (FEM) and experimental tests using woven roving Glass/Epoxy laminated beam samples are employed to analyze the natural frequencies. The results reveal that crack location, depth, and fiber orientation significantly influence the natural frequencies, with cracks leading to decreased frequencies and higher fiber orientation causing a similar effect. Das and Sahu in 2020 examined the effects of transverse cracks on the natural frequencies of woven fiber Glass/Epoxy composite beams using numerical and experimental methods. The results demonstrate that crack location, depth, and fiber orientation significantly influence the natural frequencies, with higher fiber orientation leading to reduced natural frequencies in the laminated composite beam.

So, the main aim of this investigation is to study the influence of nano particles of (Al2O3) filled in polyester resin with volume fraction (vf = 0, 1, 3 and 4%) on vibration behavior experimentally. Therefore, it will focus on this study to determine the dispersion and interaction of the alumina nanoparticles within the cantilever beam and morphology of the composite of the cracked cantilever beam made from this composite material.

2. MATERIAL FABRICATION (METHODOLOGY)

2.1. Experimental Procedure; Sample preparation

The composite material plate was prepared in this study, by mixed the unsaturated polyester resin with nanoparticle of aluminum oxide, as well as, using a suitable mold within the measurements (length 190 mm, width 30 mm, thickness 3 mm) and a high precision scale.

Where the proportions were five different samples were made depending on the percentage of aluminum oxide (0%, 1%, 3%, 4%), as shown in table 1.

Table 1. The weight ratios of the composites

Weight fraction	0%	1%	2%	3%	4%
Al_2O_3	0	2.23	4.47	6.71	8.94
Hardener	8.94	8.86	10.96	10.85	10.74
Polyester	214.7	212.6	208.2	206.17	204.05

The specimens were classified into three groups, the first was flat plate without any fault, the second was cracked with crack dimension of (10mm), and the third group was notched plate with radius of notch was (5mm). Where each test was three similar specimens to determine the range of these specimen's result, fig. 1 shows the specimens of the above properties.

Fig. 1. The samples of the free vibration test

Where the installation is on one side, the installation area is 20mm2, and the test device is attached to the other end as in the picture.

These cracks and holes are made according to the dimensions shown in Table 2.

Table 2. Sample parameters

Parameters	Holes	Crack
The distance from the end	90 mm	90mm
Dimensions	10mm	(2×5) mm

Using the vibration test device in the laboratory shown in the image to obtain the results, where 15 three of them were tested with a percentage of 0%, the first with the presence of the hole, another with the presence of a crack and the other with solid and so on for the rest of the ratios prepared for the test [Kaybal et al. 2018] and [Khdair et al. 2019].

$$\text{Weight of } Al_2O_3\% = \frac{\text{Weight of } Al_2O_3\ {}_{Al_2O_3}}{\text{Weight of } Al_2O_3 + \text{Weight of Epoxy}} \times 100 \quad (1)$$

$$\text{Volume fraction } \% = \frac{Al_2O_3 \text{ Volume}}{\text{Composite volume}} \times 100 \quad (2)$$

2.2. Vibration test

The dynamic properties of the composites sample were evaluated using a free vibration test on a standardized cantilever beam, as seen in fig. 2 The following equipment's were utilized in the experiment: computer, Impact Hammer Instrument, Acceleration sensor: module kind (352C03-PCB piezotronics acceleration), Data Acquisition

Systems: module kind (NI cDAQ-9171) compatible with NI Compact DAQ NI 9234.

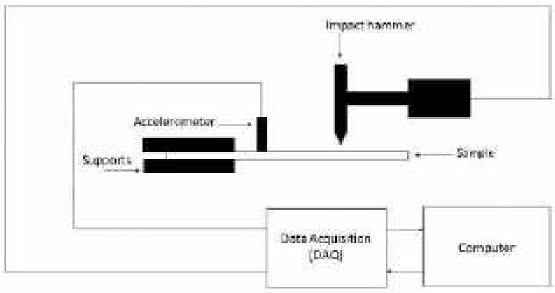


Fig. 2. The components and configuration of the vibration test

The data was post-processed using LabVIEW software. The acceleration time domain was converted to the amplitude frequency domain using the Fast Fourier Transform (FFT) algorithm that was built in LabVIEW software. The flow chart of the LabVIEW program is presented in fig. 3.

The difference between the two points on the response curve where the amplitude of these points is $\frac{1}{\sqrt{2}}$ times the highest peak amplitude is known as frequency bandwidth. The damping ratio is equal to the ratio between frequency bandwidth and the natural frequency, could be determined using equation below [De Silva, 2019]:

$$\zeta = \frac{\Delta\omega}{2\omega_n} \quad (3)$$

The quality factor (Q), which is the rate of energy loss for the stored energy, could be determined using following equation:

$$Q = \frac{1}{2\zeta} \quad (4)$$

3. RESULTS AND DISCUSSION

By conducting vibration tests, we concluded that the addition of nano-material improved the specifications of polyester. The results are studied on three cases for each sample (solid, hole and crack), where two readings were taken for each case from each sample and for each percentage of aluminum oxide added.

Table 3. Vibration properties of the samples

Specimens	Solid		hole		Crack	
	ζ	ωn	ζ	ωn	ζ	ωn
0%	0.039	15.3	0.046	13.9	0.0633	14.2
1%	0.04	14.6	0.060	15	0.034	14.6
3%	0.072	15.1	0.050	14.8	0.0335	14.9
4%	0.042	15.2	0.040	14.8	0.0539	13.9

The time history domain analysis is analyzing the data over a specific time interval. It is useful for understanding the time-varying behavior of the dynamic behavior of a vibrating system. The raw acceleration plot and further filtered acceleration and the amplitude and direction or displacement plots of cantilever are shown from fig. 3.1 to 3.24.

The acceleration response curve in the time domain for three distinct specimen shapes (solid, with a hole, and cracked) is presented herein. These specimens are composed of nano-alumina (Al_2O_3) at a concentration of 0%. The curves depict the acceleration in units of m/s².

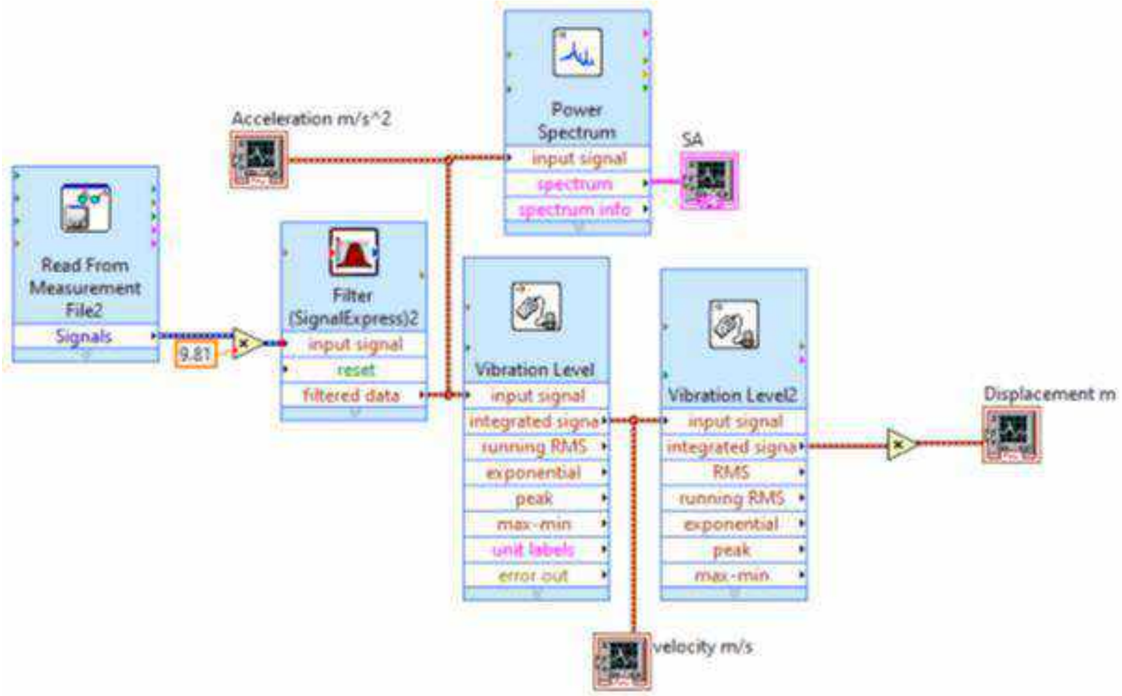


Fig. 3 The flow chart of the LabVIEW program

In evaluating the vibration responses from the figures (4, 5 and 6), it can be inferred that the solid specimen demonstrated the most robust initial response, with the highest acceleration range. However, the optimal vibration response would depend on the specific application. For instance, if high initial acceleration is desirable, the solid specimen might be preferred. On the other hand, if a more controlled and moderate acceleration response is needed, the specimens with a hole or cracks could be more suitable.

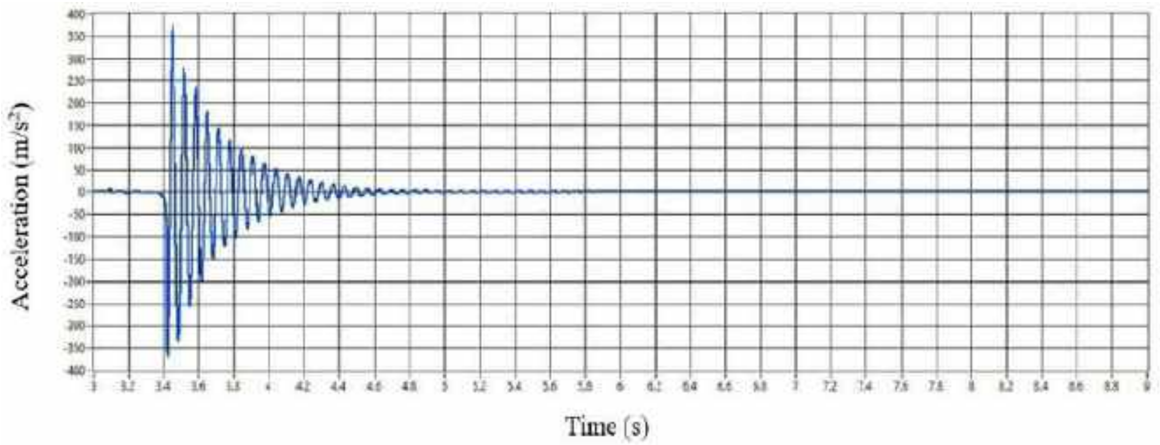


Fig. 4. Acceleration responses nanoparticle 0% of nano-alumina (Al_2O_3) for solid specimen

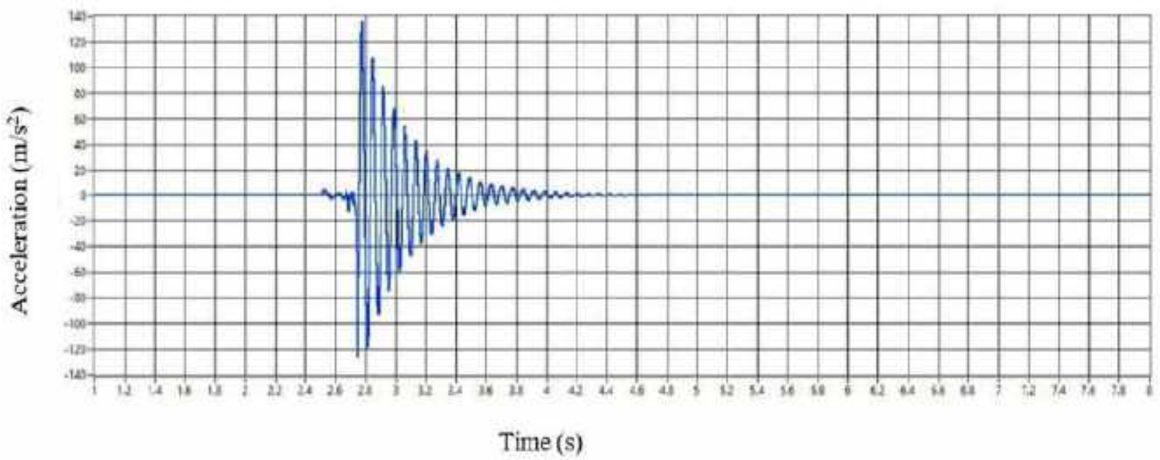


Fig. 5. Acceleration responses nanoparticle 0% of nano-alumina (Al_2O_3) for hole specimen

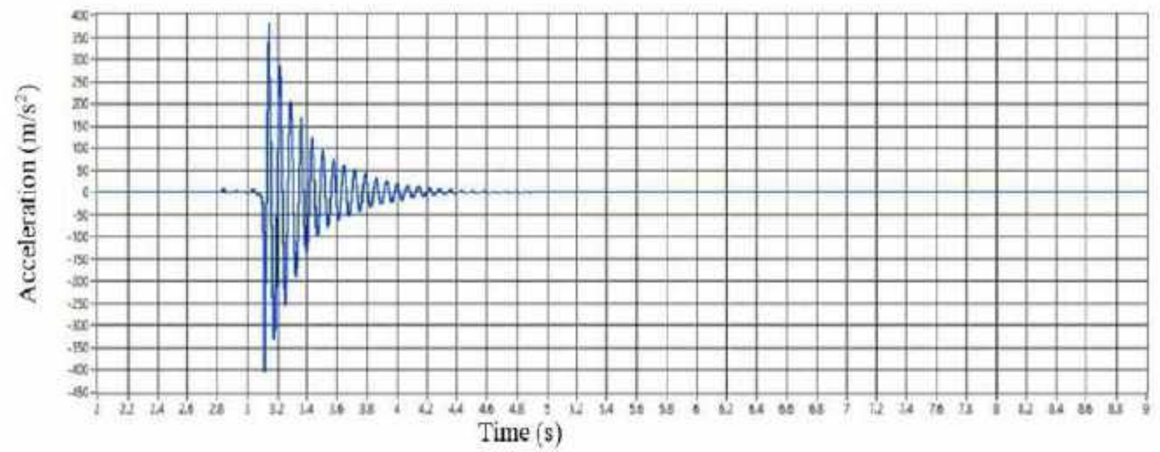


Fig. 6. Acceleration responses nanoparticle 0% of nano-alumina (Al_2O_3) for crack specimen

Upon evaluation of figures (7, 8 and 8) for these specimens composed of nano-alumina (Al_2O_3) at a concentration of 1%, the solid specimen displayed the most substantial initial response, characterized by its wider acceleration range. The determination of the optimal vibration response is contingent on the specific application requirements. Should a vigorous and pronounced initial acceleration be paramount, the solid specimen may be deemed preferable. Conversely, for scenarios demanding a more

controlled and moderate acceleration profile, the perforated or fractured specimens might offer more suitability.
Upon comprehensive assessment of figures (10, 11 and 12) for these specimens composed of nano-alumina (Al_2O_3) at a concentration of 3%, the solid specimen demonstrated the most pronounced initial response, characterized by its notably broader acceleration range.

After a thorough assessment of figures (13, 14 and 15) for these specimens composed of nano-alumina (Al_2O_3) at a concentration of 4%, it becomes evident that the solid specimen displays a distinctly prominent initial reaction, marked by an appreciably broader range of acceleration. Acceleration response is important in assessing the dynamic forces acting on a system, as it relates to the inertial forces generated by the mass of the vibrating specimen. However, it decreases with increases of nanomaterial addition.

The structures may experience sudden loads that can cause a failure, and time history domain analysis is necessary to understand the dynamics of the impact or to capture the behavior of the structure over time.

These specimens are formulated with a composition of nano-alumina (Al_2O_3) at a concentration of 0%. The curves (16, 17, 18) depict displacement, measured in meters, over a temporal span. In assessing the displacement responses, it is apparent that the solid specimen manifests the most pronounced initial reaction, with a notably wider displacement range.

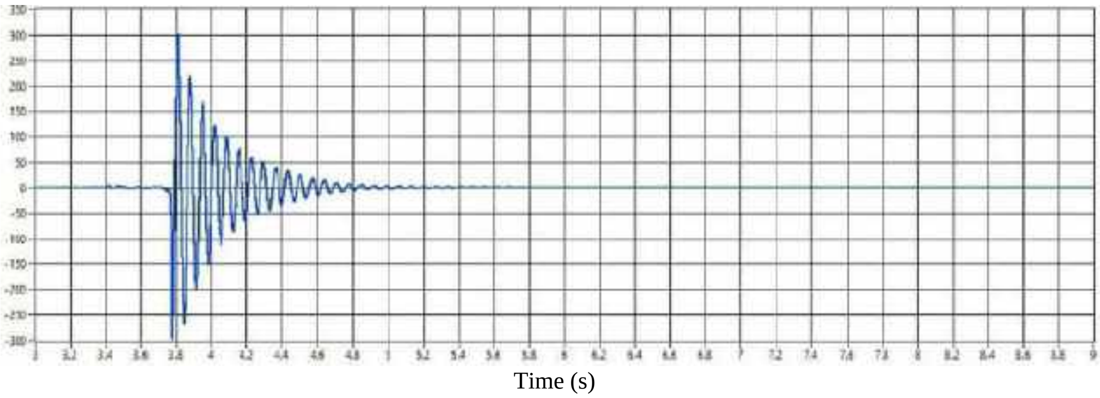


Fig. 7. Acceleration responses nanoparticle 1% of nano-alumina (Al_2O_3) for solid specimen

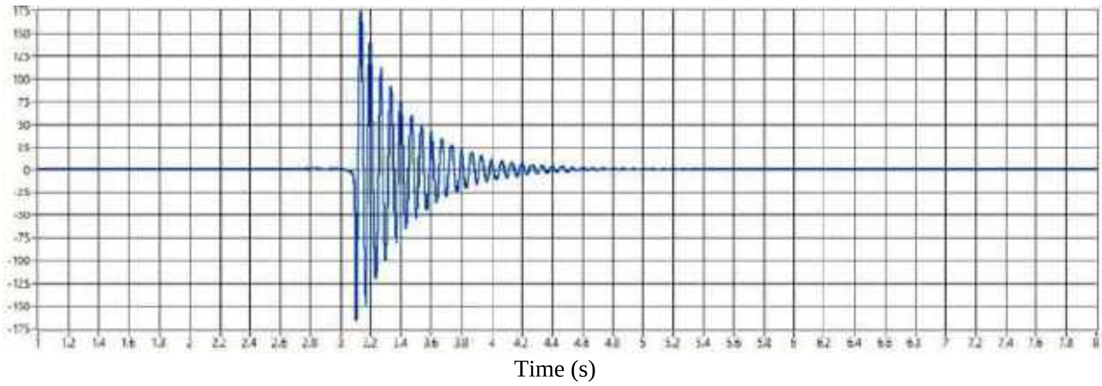


Fig. 8. Acceleration responses nanoparticle 1% of nano-alumina (AL_2O_3) for hole specimen

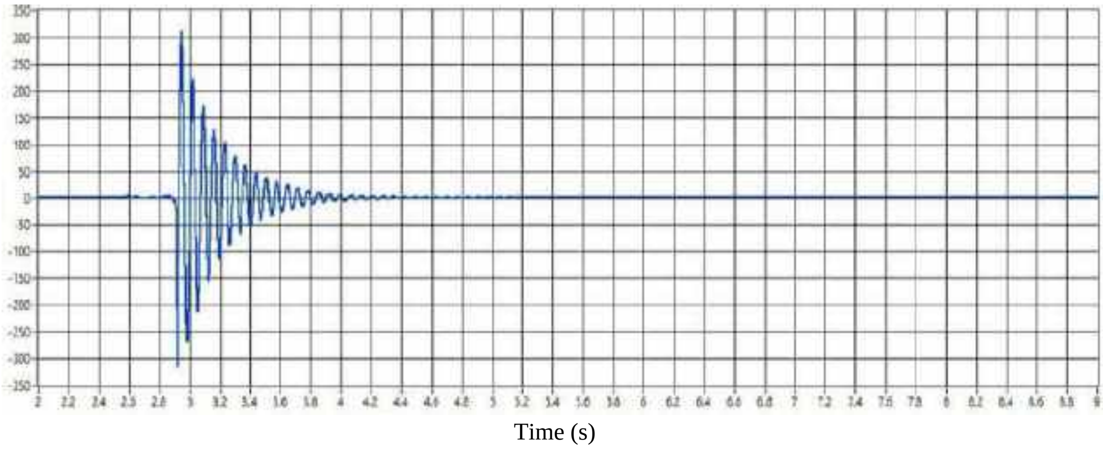
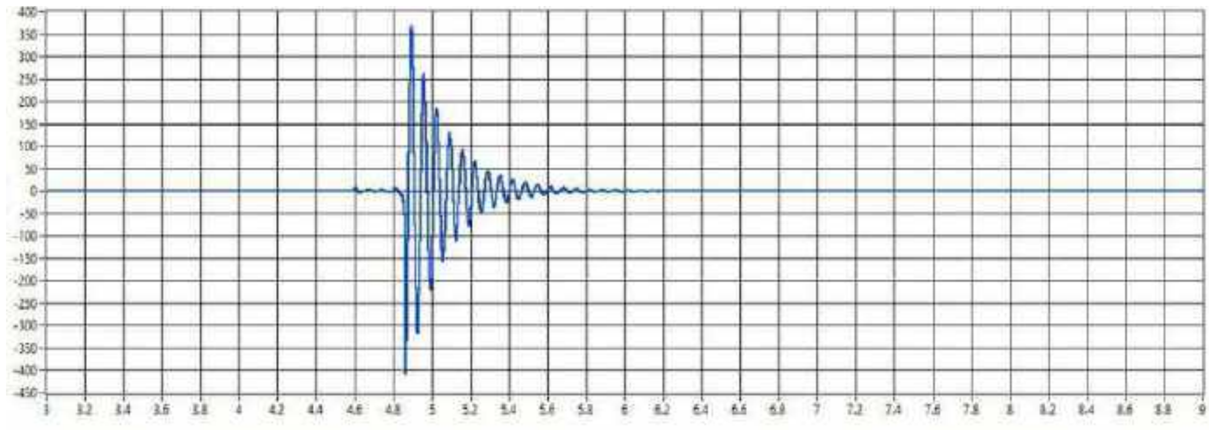
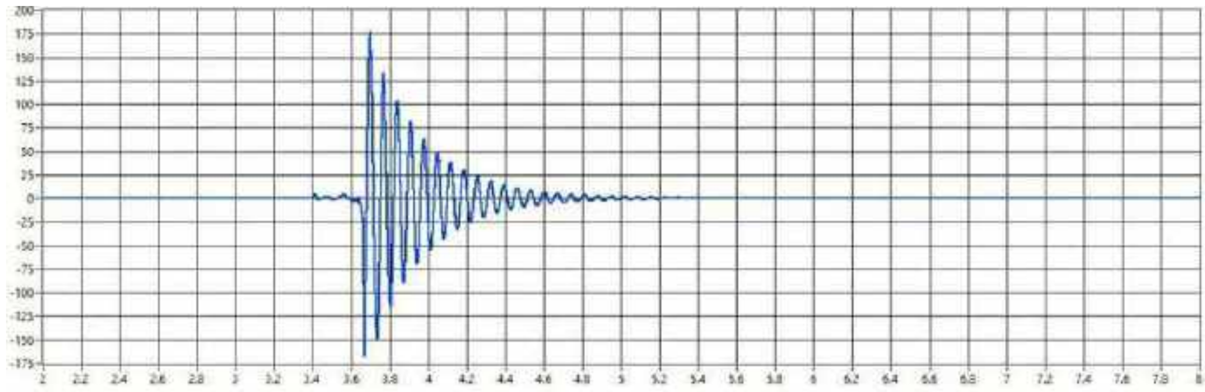


Fig. 9. Acceleration responses nanoparticle 1% of nano-alumina (AL2O3) for crack specimen



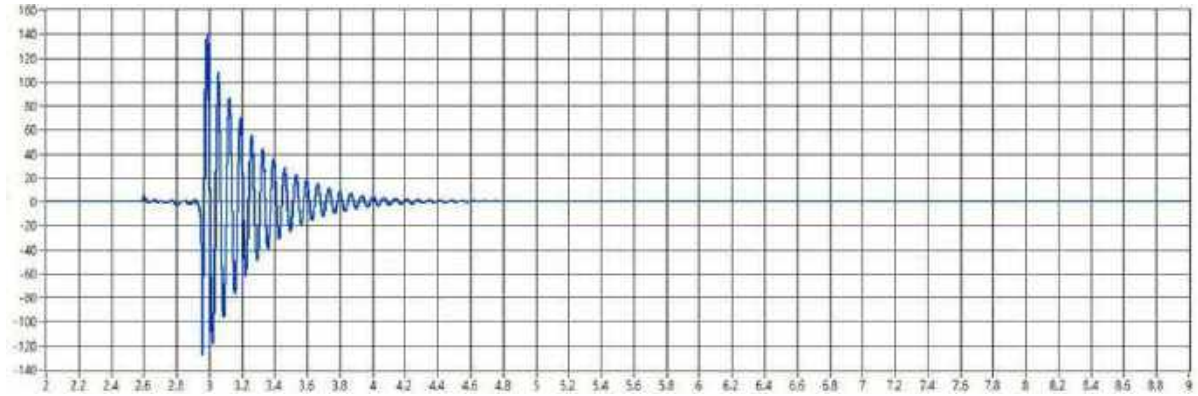
Time (s)

Fig. 10. Acceleration responses nanoparticle 3% of nano-alumina (AL_2O_3) for solid specimen



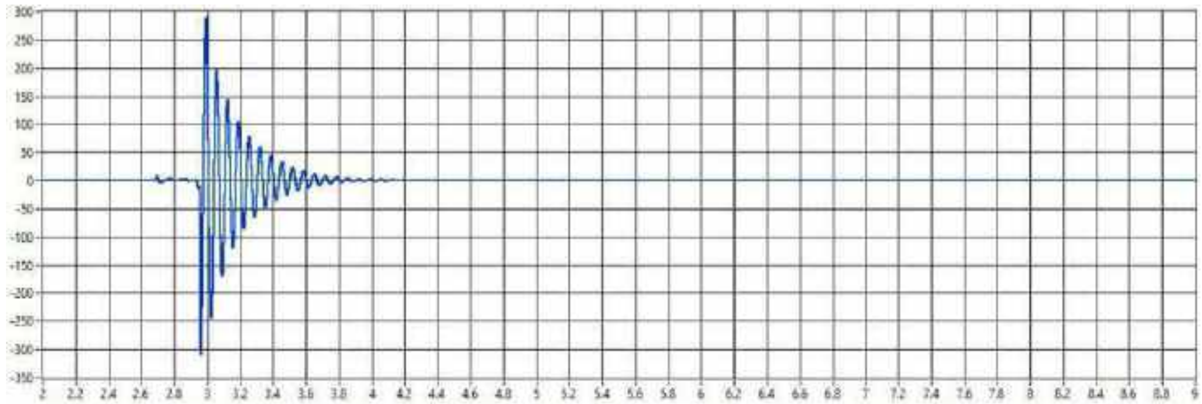
Time (s)

Fig. 11. Acceleration responses nanoparticle 3% of nano-alumina (AL_2O_3) for hole specimen



Time (s)

Fig. 12. Acceleration responses nanoparticle 3% of nano-alumina (AL_2O_3) for crack specimen



Time (s)

Fig. 13. Acceleration responses nanoparticle 4% of nano-alumina (AL_2O_3) for solid

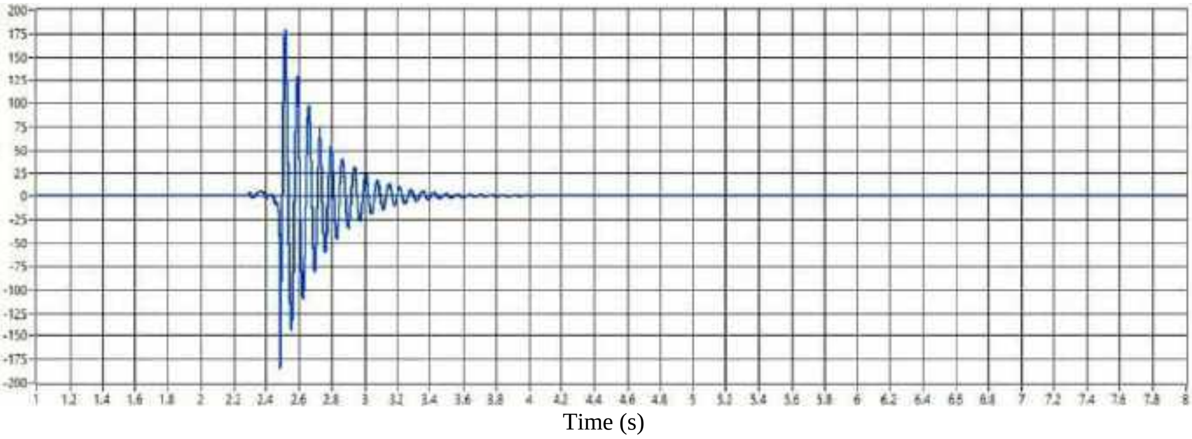


Fig. 14. Acceleration responses nanoparticle 4% of nano-alumina (AL_2O_3) for hole specimen

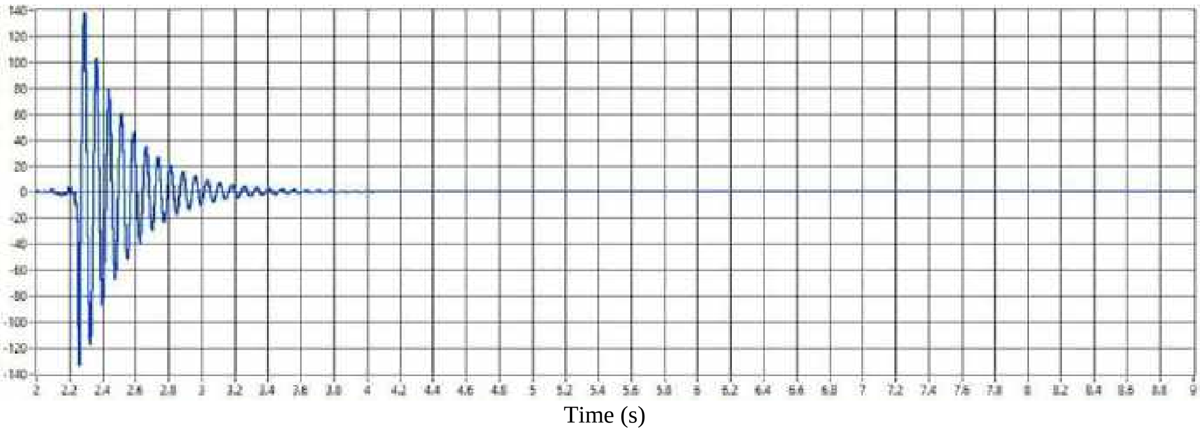


Fig. 15. Acceleration responses nanoparticle 4% of nano-alumina (AL_2O_3) for crack specimen

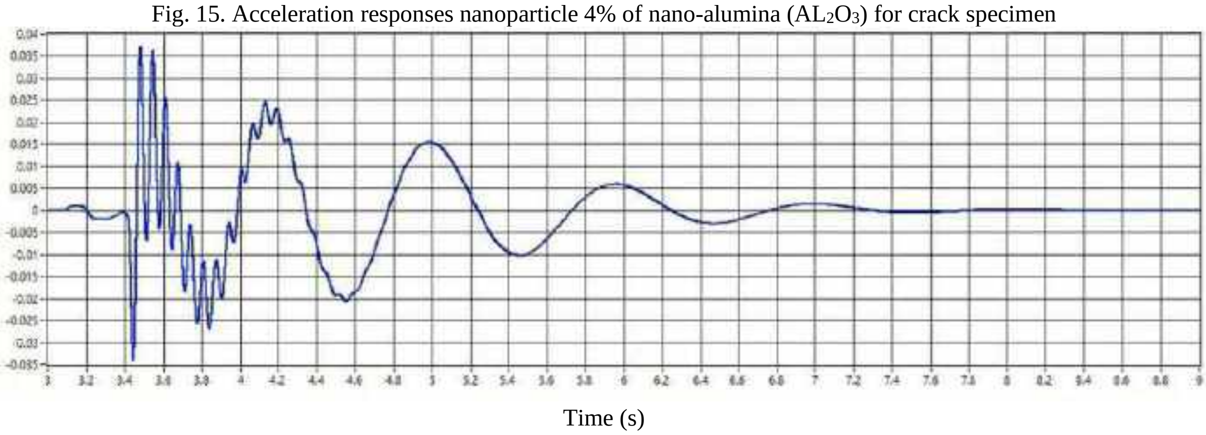


Fig. 16. Displacement responses nanoparticle 0% of nano-alumina (AL_2O_3) for solid

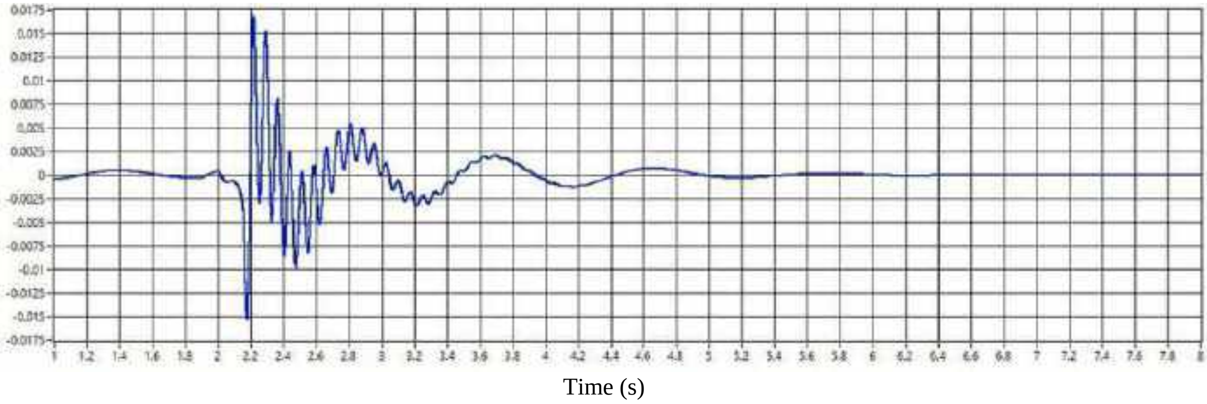


Fig. 17. Displacement responses nanoparticle 0% of nano-alumina (AL_2O_3) for hole

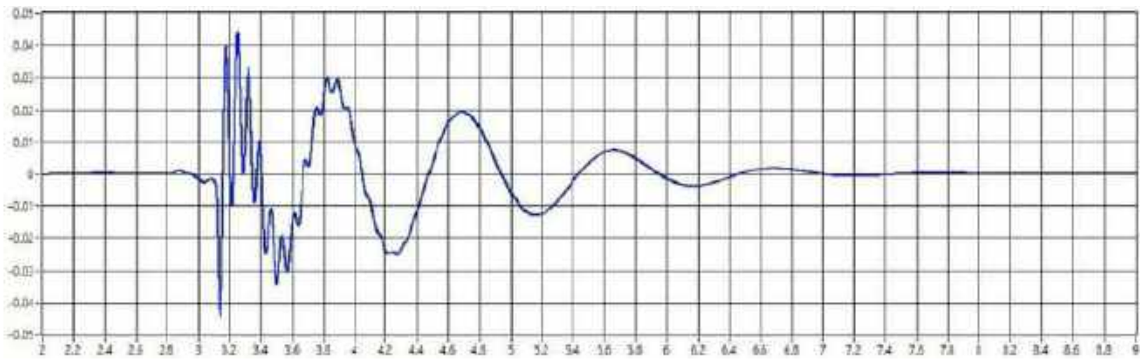


Fig. 18. Displacement responses nanoparticle 0% of nano-alumina (AL_2O_3) for crack specimen

Random vibration analysis was used to analyze structures under non-deterministic loading conditions. The loads are not deterministic because the time history of the load is unique every time. Upon meticulous evaluation for the figures (19, 20, 21), the solid specimen showcases the most pronounced initial displacement response, characterized by its notably broader displacement range. So, the maximum displacement value for solid specimen decreased slightly by adding 1% of

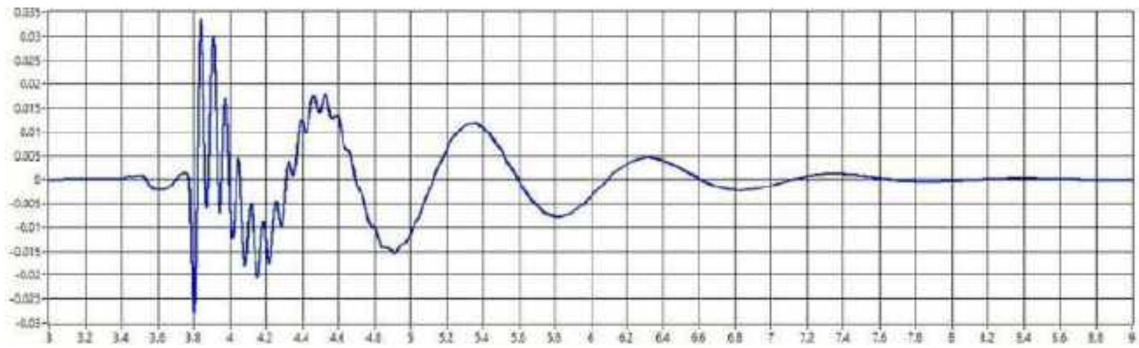


Fig. 19. Displacement responses nanoparticle 1% of nano-alumina (AL_2O_3) for solid specimen

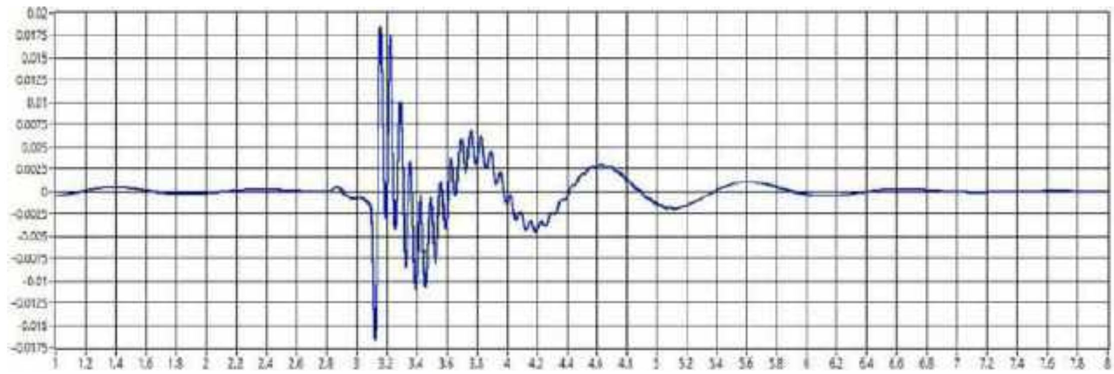


Fig. 20. Displacement responses nanoparticle 1% of nano-alumina (AL_2O_3) for hole specimen

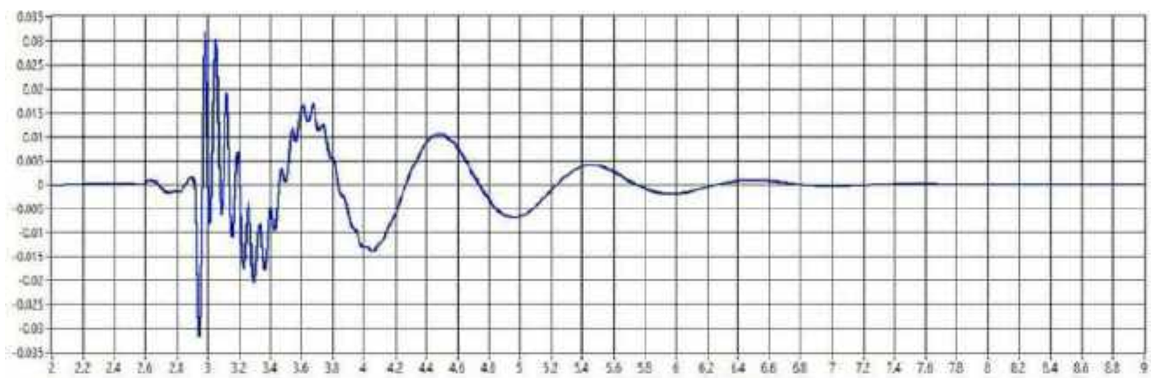


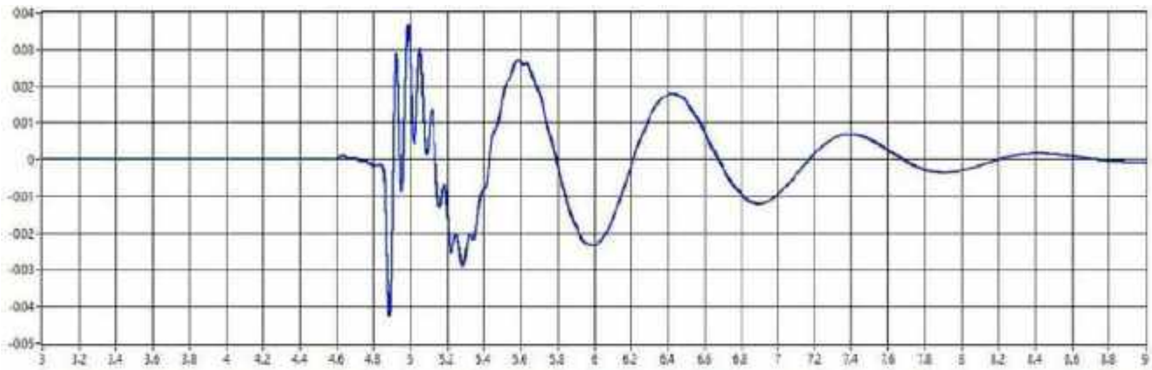
Fig. 21. Displacement responses nanoparticle 1% of nano-alumina (AL_2O_3) for crack specimen

nano-alumina (Al_2O_3) and estimate damping increased as well as for hole specimen and vice versa for crack specimen with adding 1% of nano-alumina (Al_2O_3).

For the case of specimens formulated with a composition of nano-alumina (Al_2O_3) at a concentration of 3% and upon the figures (22, 23, 24) the solid specimen emerges as the frontrunner in displaying the most pronounced initial displacement response and an identical response was observed in relation to the content featuring a 4% concentration of nano-alumina (Al_2O_3) as seen in figures (25, 26, 37).

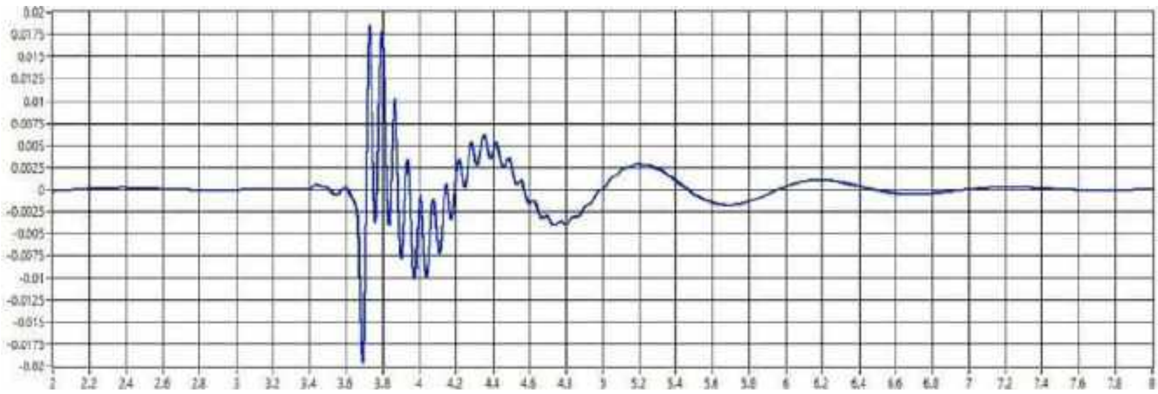
In terms of energy dissipation, the acceleration and displacement responses of the three specimen types (solid, perforated with a hole, and cracked) exhibit notable variations. The solid specimen, with its pronounced initial acceleration and displacement profiles, tends to exhibit higher energy dissipation due to its broader range of motion. On the other hand, the perforated and cracked specimens, with their controlled acceleration and displacement behaviors, are expected to have comparatively lower energy dissipation.

From an engineering standpoint, selecting a specimen for applications involving energy dissipation should align with the desired outcome. If effective energy absorption and dissipation are crucial, the solid specimen might be favored. For applications where controlled energy release is



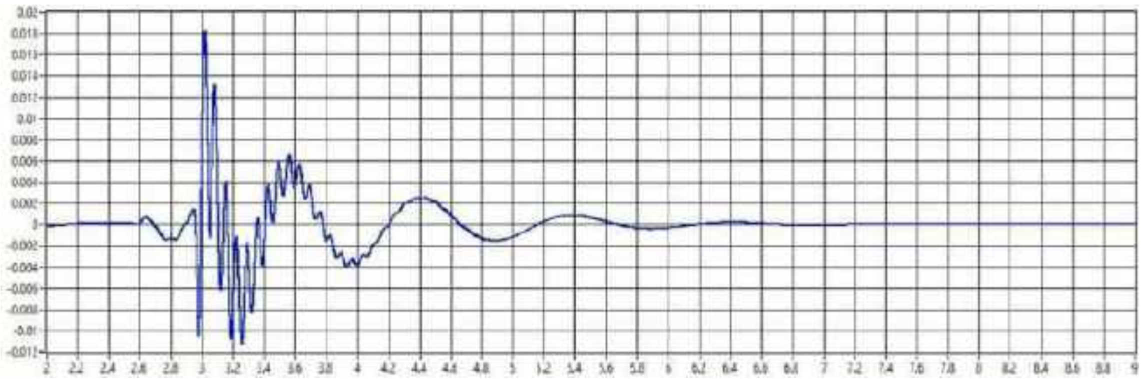
Time (s)

Fig. 22. Displacement responses nanoparticle 3% of nano-alumina (AL_2O_3) for solid specimen



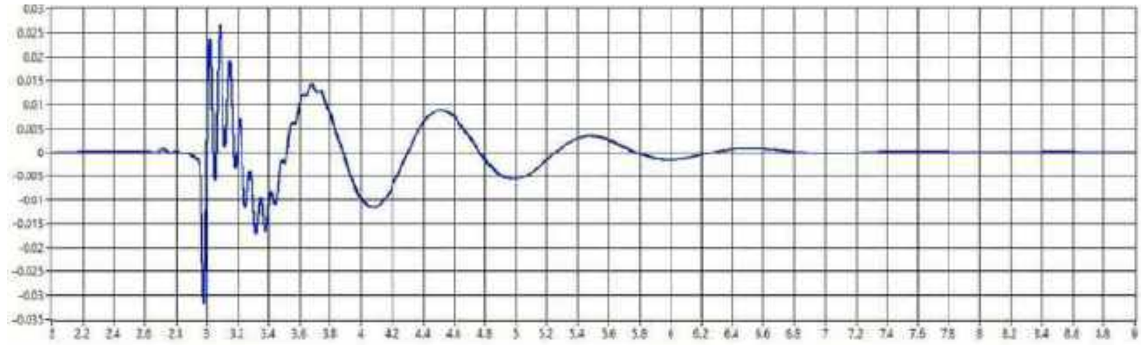
Time (s)

Fig. 23. Displacement responses nanoparticle 3% of nano-alumina (AL_2O_3) for hole specimen



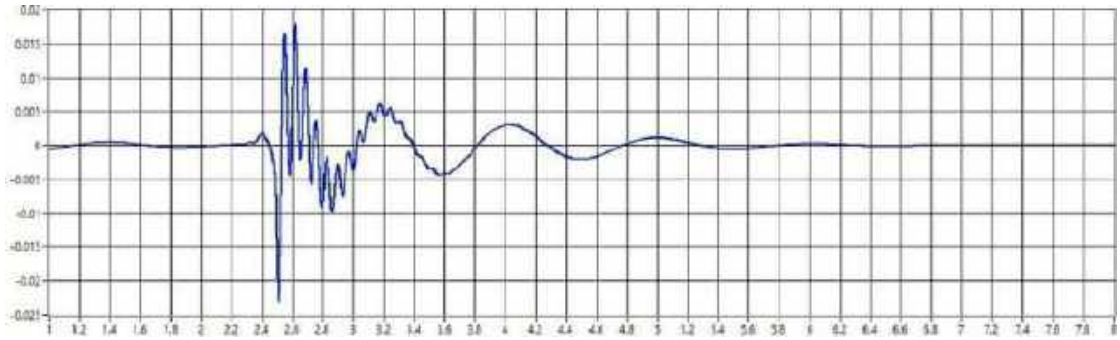
Time (s)

Fig. (24. Displacement responses nanoparticle 3% of nano-alumina (AL_2O_3) for crack specimen



Time (s)

Fig. 25. displacement responses nanoparticle 4% of nano-alumina (AL_2O_3) for solid specimen



Time (s)

Fig. 26. Displacement responses nanoparticle 4% of nano-alumina (AL_2O_3) for solid specimen

Time (s)

Fig. 27. Displacement responses nanoparticle 4% of nano-alumina (AL2O3) for crack specimen

required, the perforated or cracked specimens could offer more suitable options, given their moderate displacement responses and thus potentially more controlled energy dissipation characteristics.

4. CONCLUSIONS

In the current study, vibration characteristics of alumina nanoparticles (Al_2O_3) filled polyester composites were studied. Various loading percentages of (Al_2O_3) nanofillers related to hardener resin were added to assess the effect of using such nanofillers on bulk polyester. The experimental modal analysis was implemented using FFT analyzer (Dewsoft brand). The displacement response and acceleration response were considered. The crack was near to fixed end it imparts more reduction in history loading. It was found that if crack depth increases then history loading increases. The induced crack causes a reduction in loading interaction. The fabricated nanocomposite material properties are directly affected by the addition of alumina nanoparticles (Al_2O_3); increasing the weight fraction of alumina nanoparticle (Al_2O_3) will increase in the time domain until (3 %) are reached, and also a decrease in the same properties for higher weight fraction of alumina nanoparticles (4%). The novelty of this study lies in utilizing nano-composite materials (nanoparticles of aluminum oxide) for dynamic analysis of the composite beam, addressing a critical challenge in laminated machine element structures. Despite the practical significance of composite structures with cracks, the subject remains scarcely explored, primarily due to the intricate nature resulting from stretching bending coupling, orthotropy, and ply-orientations, compounded by the presence of cracks. For future research, an alternative approach to employing time history loading involves utilizing statistical frequency domain input, such as Power Spectral Density (PSD), to assess the structural response.

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