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EFFECT OF TITANIUM OXIDE TIO2 NANO PARTICLES ON MECHANICAL PERFORMANCE OF HYPRID COMPOSIT BEAMS

Zainab Talib Abid[1], Hussam Jawad Abdulsamad[2], Raghad Azeez Neamah[3], Abbas Ali Diwan[4], and Luay S. Al-Ansari[5]

[1] M.Sc., Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Najaf, 54001, Iraq, Email:zainabt.abid@uokufa.edu.iq.

[2] Ph.D., Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Najaf, 54001, Iraq, Email:husamj.alhamad@uokufa.edu.iq.

[3] Ph.D., Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Najaf, 54001, Iraq, Email:ragada.deibel@uokufa.edu.iq.

[4] Ph.D., Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Najaf, 54001, Iraq, Email:abbas.albosalih@uokufa.edu.iq.

[5] Ph.D., Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Najaf, 54001, Iraq, Email:luays.alansari@uokufa.edu.iq.

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ABSTRACT

In this work, wire mesh metallic fibers and the nanomaterial titanium oxide TiO_2 were used to reinforce the epoxy matrix to create the hybrid composite material specimens by the hand lay-up method. The effects of adding specific fractions of TiO_2 nano material on the dynamic characteristics of wire mesh hybrid composites were investigated. The vibrational characteristics (natural frequency and damping ratio) and mechanical characteristics (tensile and bending stresses) were examined. The numerical analysis for Bending and vibration cases was performed using ANSYS ABDL 2017 R2. Experimental results showed that the addition of TiO_2 nanoparticles significantly improved tensile strength and flexural strength in epoxy-steel wire-TiO_2 composites. However, increasing the nanoparticle ratio to the maximum values led to reduced performance. The composites showed a balance between stiffness and strength when optimized at 5 wt% TiO_2 and moderate layer counts. Natural frequencies and damping characteristics were affected by fiber volume, layering, and nanoparticle content.

KEYWORDS

Composite materials, Nano composites, Mechanical properties, Vibration, Titanium oxide.

1. INTRODUCTION

Composite materials are versatile, mechanical, and physical materials that combine multiple materials to enhance their properties. They consist of two phases: the matrix phase, which is continuous and produces polymeric materials like epoxy, polyester, and polyurethane, and the reinforcing phase, which is distributed and covered by the matrix phase (W. D. Callister Jr and D. G. Rethwisch, 2020). Polymers are utilized in many different industrial applications due to the fact that they have properties that are not found in other material types (i.e., ceramics and metal). These properties include strength and stiffness combined with lightness (Abbas, Z.A. and S.H. Aleabi, 2019). Researchers suggest that copolymerization can alter the mechanical properties of polymers by adding other monomers, which is increasingly used for economic or mechanical reasons (B. A. Korgel, 2006). Sometimes two different polymers are blended as a way to enhance the mechanical properties (B. A. Ibrahim and K. M. Kadum, 2010) that are also sensitive to the methods and variables used in the test, such as types of applied forces (tension, compression, biaxial, or shear) (M. J. Jerabek, 2009).

A brief overview of researchers' efforts to improve mechanical properties, such as tensile and flexural strength, and vibration, is provided, using various methods, including the use of different composite materials and nanomaterials of varying types and proportions

Moften et al. (2022) utilized a polymer blend of epoxy and polyester, mixed in different ratios, and reinforced with metal mesh. Results indicated 95% epoxy + 5% unsaturated polyester is optimal for ultimate tensile strength. Luay S. Alansari et al. (2023) improved epoxy's tensile properties by adding TiO_2 and SiO_2 nanoparticles in various ratios. Hybrid nanocomposites with 50% TiO_2 and 50% SiO_2 nanoparticles were created, and their tensile strength was examined using X-ray diffraction and SEM. Two new models were proposed. Yadeem, J.M et al. (2024) investigated the free vibration issue of simply supported axial- functionally graded beam (FGB) using the Rayleigh approach. The power law model is used to explain changes in physical mechanical properties. The computer program is used to verify the method's accuracy, with high accuracy found. According to the study, dimensionless deflection rises with the power-law index while the non-dimensional frequency parameter stays constant. Neamah RA et al. (2022) used the Hamiltonian principle to find motion equations, and the Navier method was used to analyze their impact on free vibration. The study found high agreement with previous research and suggested that the new FG beam model reduces dimensionless frequency. Al-Hajjar, A.M.H. et al. (2024) used the Rayleigh method to compute the static deflection under uniform load for non-prismatic axial functionally graded beams. The method's accuracy is good when compared to Finite Element Method and literature. For all material distribution parameters and at the same rate of variation, investigations show that maximum dimensionless static deflection decreases. Raghad Azeez Neamah et al. (2023) developed a new model of (FGB) using Euler and first and high-order shear deformation theories. The model is analyzed using the FORTRAN program and the ANSYS (17.2) APDL program. The model is based on ten layers and uses a power-law form to calculate material properties. The results show that shear significantly affects free vibration for short beams, and the model is reliable and capable of analyzing free vibration for other beams. Marwah Ghazi Kareem et al. (2025) introduced a novel displacement function for (FGM) plate free vibration analysis, using Hamilton's principle and ANSYS. The findings demonstrate that natural and dimensionless frequencies decline when length-to-thickness ratios and power-law indices rise, while increasing the power-law index increases non-dimensional frequencies. Ali, Muayad Abdulhasan, and Abbas Ali Diwan (2014) used the five epoxy composites made from dual reinforced particulate polymer blends. It uses Taguchi's parametric optimization and statistical modeling to optimize wear responses. The composites obtained optimal parameters using experimental tests on a DIN abrasion tester. The models showed high accuracy in predicting wear behavior, with correlation plots indicating their potential for improved wear properties. Kiran MD et al. (2018) evaluated the mechanical properties of epoxy polymer composites reinforced with glass fiber, alumina, titania, and silicon carbide as fillers. Results showed that adding 2% aluminum oxide and silicon carbide fillers to the glass fiber increased tensile strength by 22%, tensile strength by 14%, and impact strength by 84%. Z. T. Abid and H. J. Abdulsamad (2024) demonstrated that the addition of carbon fibers and glass fibers to a composite matrix with an epoxy matrix, containing AL_2O_3 nanoparticles, enhances the dynamic mechanical properties of the composites, achieving natural frequency at 0°and maximum impact strength at 45°. Majid Jasim, Zainab, and Husam Jawad Abdulsamad (2025) investigated the effects of adding steel woven fibers to polyethylene (LDPE) to improve the mechanical properties of fiber-matrix composites. The study found that adding metal woven fibers to the composite material slightly increased tensile strength and tensile modulus, but decreased ductility and flexural strength. The impact strength also decreased, with LLDPE and LOPE composites showing a decrease in impact strength and a decrease in flexural strength. Bakhtiar, N. S. A. A. et al. (2016) used epoxy resin and nano particles like carbon nanotubes and clay to create epoxy/ Clay and epoxy/Hybrid composites. They used methane as a carbon precursor and performed tensile and hardness tests using a Universal Testing Machine and a Shimadzu micro-hardness tester. Neamah, R. A. et al. (2018) created composite beam samples using epoxy and woven fiberglass. The impact of fiberglass layers on natural frequency was investigated experimentally and numerically. ANSYS software

17.2 was used to build a numerical model, revealing that crack depth significantly influences natural frequency and mode shape. M. Alsaadi et al. (2016) investigated the impact of silica nanoparticles (NS) on tensile, flexural, vibration, and properties of carbon/Kevlar/epoxy (CKFRE) hybrid composites. Results showed a 20% increase in tensile strength and 35.7% increase in flexural strength at a 3 wt.% NS content. NS particle interactions with epoxy and fibers significantly impacted dynamic parameters. M. Shukur, Z. (2024) used a 3D printer to create pre-twisted beams, which are measured and simulated using the finite element method. High agreement between finite element outputs and experimental results is demonstrated by the results, with no critical twisting angle for clamped-clamped beams. Raghad Azeez Neamah et al. (2020) used ANSYS APDL version 17.2 to model skew composite plates, examining their fundamental frequency. Results showed that skew angle and width-to-length ratio significantly influence the frequency, while fiber orientation, supporting type, and layer layouts slightly impact it. M. Al-Waily and T. J. Ntayeesh (2017) examined the impact of nanoparticles on a composite panel made of woven reinforcement fibers and polyester resin. The panel's natural frequency and mechanical properties were evaluated at different nanoparticle weight percentages. The findings demonstrated a high degree of agreement between the theoretical and experimental findings, suggesting that nanoparticles enhance the panel's properties by about 1%. Oluwaseyi A et al. (2021) The research investigates the impact of fiber type, volume ratio, and matrix type on the vibration properties of sandwich beams made of composite face sheet and core. The beams were tested using 22 composites and compared to ANSYS R1 2022 software. The hybrid fibers and polyester matrix achieved the highest natural frequency values for both clamped-clamped and simply supported boundary conditions, with the hybrid fiber and polyester matrix achieving the highest values. Ali A. Al-Saffar et al. (2020) investigated the impact of location, shape, and crack depth on the natural frequency of a cantilever circuler shaft. It found that increasing the depth of the crack lowers the shaft's frequency, while the first and second modes remain unaffected. J. T. Utomo et al. (2017) examined the impact of carbon layer number and position on the dynamic properties of carbon fiber-glass hybrid composite. Vibration data was collected using a dynamic signal analyzer system. Results showed that increasing carbon layer number increased composite natural frequency and decreased damping ratio. The outer carbon layer had the highest natural frequency and smallest damping ratio.

In this study, explores how the dynamic properties of wire mesh hybrid composite specimens with the addition of certain proportions of titanium oxide core material are affected. The mechanical properties such as strength of tensile and bending loads in addition to the vibrational properties (natural frequency and damping ratio) were studied. A numerical analysis was performed for bending and vibration cases and the numerical results were compared with experimental results for evaluation.

2. EXPERIMENTAL PART

The composite specimens were made from epoxy reinforced by Wire Mesh with different nombers of layers and with three volume fractions from nanoparticles (TiO_2) (2.5%, 5%, and 7.5%). as shown in Fig.1. All samples are listed in Table 1. Different composite material samples were manufactured by hand lay-up method because of their easy use and shapes.

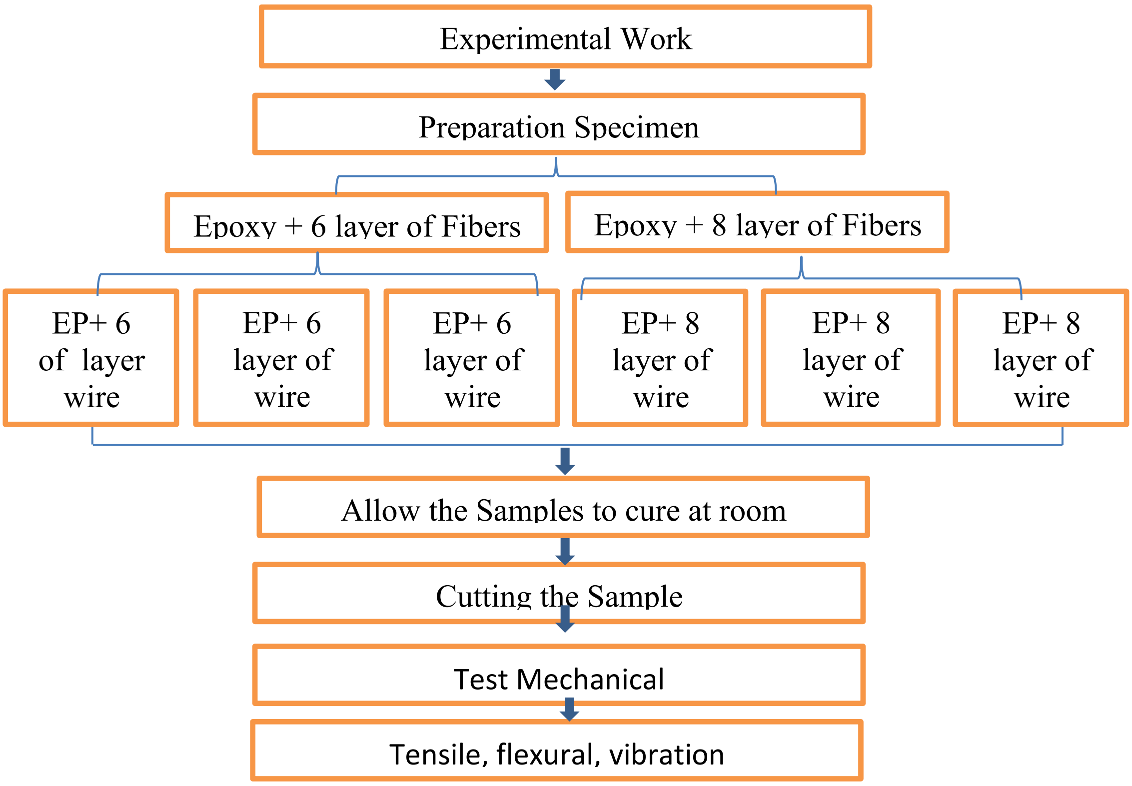


Fig.1. Diagram of the experimental process.

The following steps were followed to prepare the required samples:

1. Glass molds were prepared as follows: a base with dimensions of 330 mm × 220 mm and spacer bars on three edges of the base with a thickness of 4 mm.
2. The mold was lubricated with a layer of wax to prevent sticking, as shown in Fig. 2.
3. The layers of wire mesh were cut to the required dimensions, and then their volume ratio was calculated.
4. The weight of the wire mesh fibers and resin was calculated according to the volume ratio.
5. The total weight was then added and multiplied by the specified percentage of the nanomaterial (100 – V_f for layers) × volume of the mold.
6. We have the weight of the nanomaterial to be added to the epoxy, and it is mixed for 10 minutes by a mechanical mixer.

7. A 1200 W ultrasonic processor of the type MSK-USP-12N/MTI Corporation was used for mixing, dispersing, and homogenizing for 30 minutes.
8. Then the hardener was added and mechanically mixed for 10 minutes to insure homogeneous mixing.
9. The mixture is left for 15 minutes in the vacuum oven under a temperature of 40°C and pressure (-80 kPa) (N. S. A. A. Bakhtiar et al., 2016).
10. A syringe tube is inserted into the mold to the bottom and used to inject the epoxy from the bottom to the top to remove air and fill all parts of the mold.
11. Another waxed glass plate is then installed over the mentioned parts of the mold to obtain an open-ended mold.
12. The mold is fixed with clamps from three sides as shown in Fig. 3.
13. The epoxy is injected by the tube into the mold until it fills the entire volume.
14. The initial sample is leaved in the mold at room temperature (24°) for 24 hours to ensure solidification.
15. The samples are then extracted and prepared for each required test by cutting the sheets according to the standard dimensions.

Fig. 2. waxed mold

Fig. 3. Fixing the mold with clamps

Table 1. Composites Samples

Sample	Number of Wire mesh layers	Nano particles %
A1	6	2.5
A2	6	5
A3	6	7
B1	8	2.5
B2	8	5
B3	8	7.5

3. MECHANICAL TESTS

3.1. Tensile test

Tensile strength is the material's capacity to withstand breaking when tensile forces are applied to samples' two ends (Z. S. Radeef et al.,2024). The tensile test was done to obtain the tensile properties of composite samples, according to the ASTM D3039 standard for composites with wire mesh fiber (A. Abdelhussein et al., 2024), as shown in Fig. 4. Tensile testing apparatus (WDW-100KN) was used for the test, which was conducted at lab temperature 25ºC, as shown in Fig. 5. The stress was constantly applied at a steady rate of 2 mm/min. This machine's computer software was used to calculate the composite materials' tensile strength, modulus, and tensile stress-strain relationships. Three tests were conducted on each type of model, and the average result was considered. The fabricated samples for the tensile test can be shown in Fig.6.

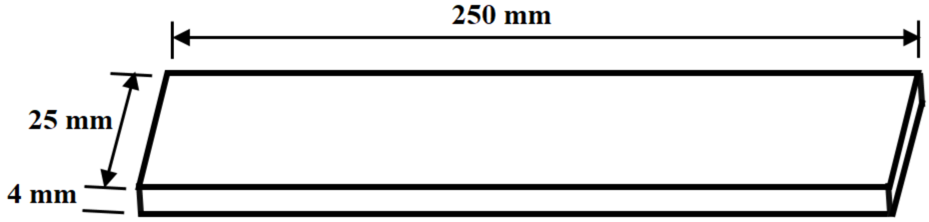


Fig. 4. The standard sample for the tensile test.

Fig. 5. Tensile test machine.

Fig. 6. Tensile Samples Prepared for Test

3.2. Flexural Test

All the composite specimens were machined according to the ASTM D790 standard (W. astm. org. ASTM D790-17 ,2019). The composite specimens' flexural properties were assessed using a three-point bending test by the same instrument used for the tensile test, which can be used for tensile and bending tests. Fig.7 illustrates the dimensions of the composite specimen, which were 128 x 12.7 x 4 mm^3. The samples of this test can be shown in Fig. 8. Increasing the span-to-depth ratio of the specimen can be utilized to reduce or eliminate the effect of shear deformation, as a result, the modulus of elasticity data can be calculated more accurately. A uniform velocity of (5mm/min) was used to exert the load continuously to fail the samples using a bending test head as displayed in Fig.9. Eq.1 and 2 have been used to calculate bending stress, flexural bending strain, and elastic modulus (E. N. Abbas et al.,2020; R. Yahaya et al.,2015):

$$\text{Flexural Strength } (F_S) = 3FL / (2bh^2) \quad (1)$$

$$\text{Flexural Modulus } (F_b) = (L^3m) / (4bh^3) \quad (2)$$

Where F is the maximum load (N), b is the specimen's width (mm), h is the specimen's height or thickness (mm), L is the support span's breadth (mm), and (m) the tangents slope to the load-deflection curves beginning with a straight-line segment.

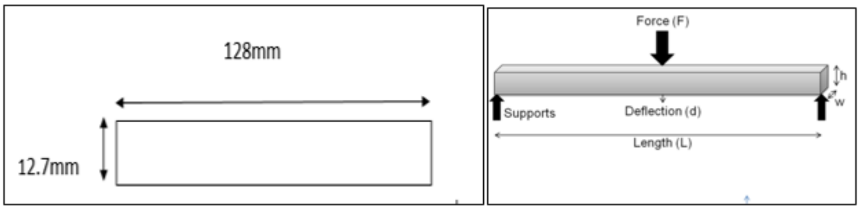


Fig. 7. The standard sample for the flexural test.

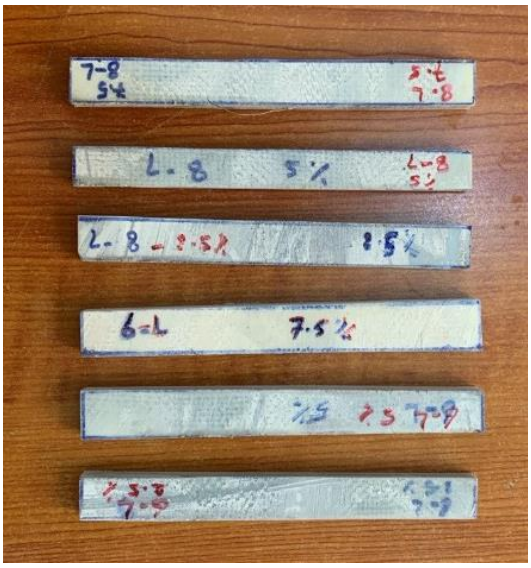


Fig. 8. Specimens before the test

Fig. 9. Three-point flexural test machine

3.3. Vibration Test

To perform the vibration test, a work clamping device firmly fixes one end of the specimen, leaving the other end free to produce a fixed-free boundary condition. The beam's suspended length for impulse testing was 180 mm. An impulse hammer is used to stimulate the flexural vibrations of the beam. A standardized cantilever beam was used for a free vibration test to assess the composite beams dynamic properties. The composite beams' vibration characteristics were tested using an impulse stimulation technique (Z. T. Abid and H. J. Abdulsamad , 2024). Fig. 10 displays the setup and tools. An accelerometer is used to find responses. A computer-controlled data-gathering system was used to record and analyze the transducer's vibration signals. The specimens' FRF plots were recorded for later processing. The following devices were employed in the experiment:

1. Fixing stand and sample.
2. Accelerometer Part model (SN 151779).
3. Digital storage oscilloscope, model ADS 1202CL+ and the serial No. 01020200300012.
4. During the transient test, the PCB Piezotronics vibration division's Impact Hammer Instrument, model (086C03), was utilized to apply impulse force to the cantilever beam.
5. Amplifiers, model 480E09, the amplifier measures the response signal from the accelerometer and gives output signal to the digital storage oscilloscope

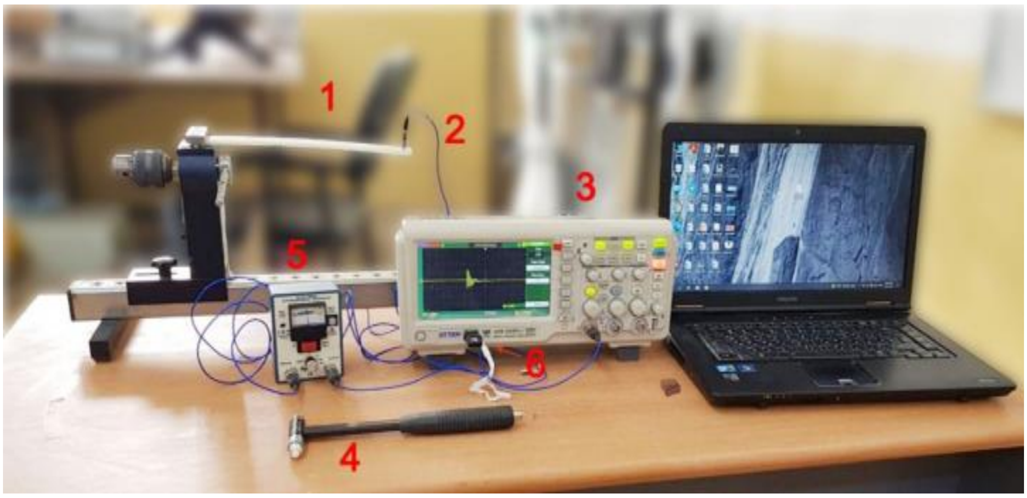


Fig. 10. Vibration Test Machine

As illustrated in Fig. 11, the output signal of the vibration test was analyzed using the sig-view program to determine the composite beam's natural frequency using the fast Fourier transformation (FFT) approach (A. A. Alhumdany et al., 2015). The natural frequency values of the composite beam are represented by the frequency with the maximum amplitude in the frequency-response domain. This occurs because the frequency-response domain is created by converting the time-response domain using the FFT. Since the FFT transforms the time-response domain into the frequency-response domain, the frequency is assigned the maximum amplitude in the frequency-response domain, which represents the intrinsic frequency value of the composite beam.

All samples were machined in accordance with ASTM-E756 (M. Martinez Agirre and M. J.

Elejabarrieta, 2011) as shown in Fig. 12 specimens with dimensions of 250 mm × 25 mm × 4 mm. The test was replicated three times for every type of specimen, and the mean value was taken into consideration.

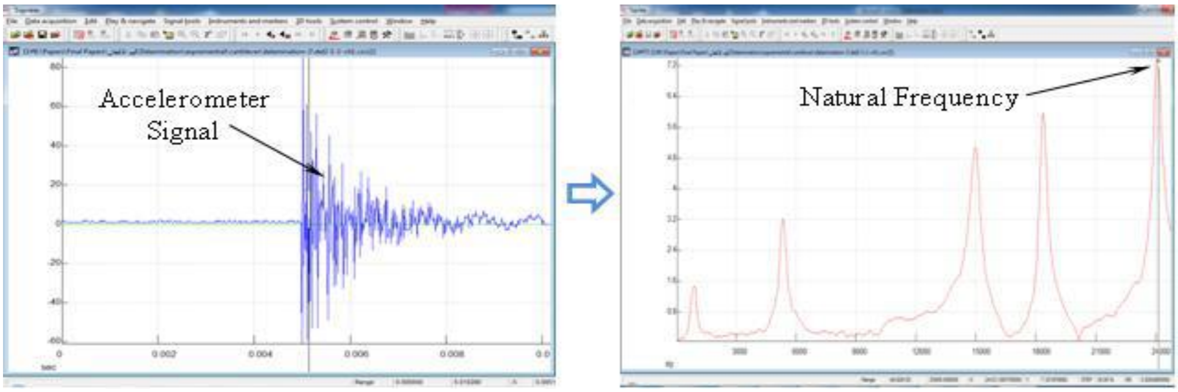


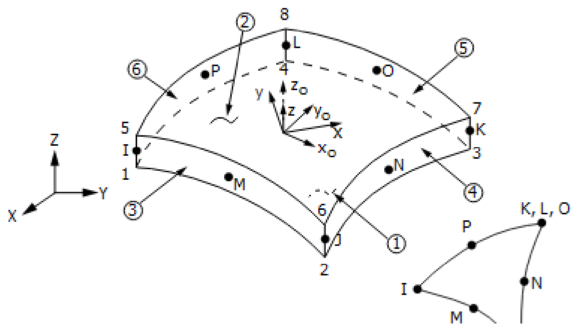
Fig. 11. Analysis of Digital Storage Oscilloscope Signal by FFT Function with Sig-View Program

Fig. 12. Vibration specimen.

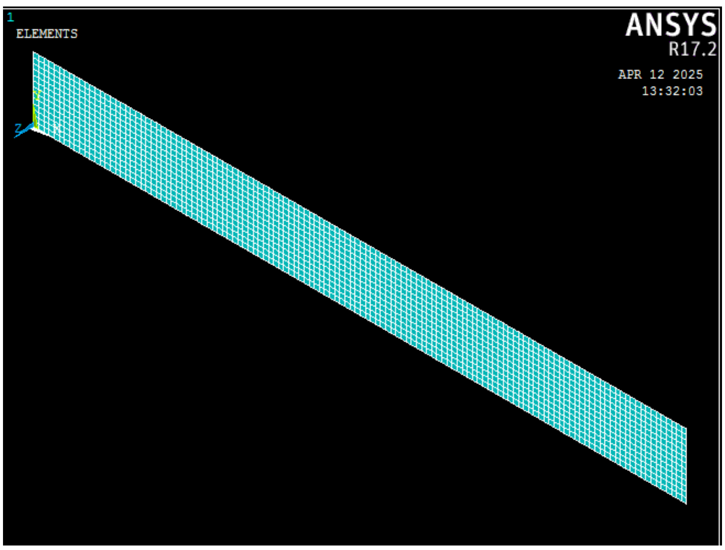
4. NUMERICAL ANALYSIS

4.1. Bending Numerical Analysis

In this section, a 2D model of the composite beam is built in ANSYS (17.2) APDL software. The composite beam with dimensions length*width* thickness (128 x 12.7 x 4 mm^3) is modeled by drawing rectangular with dimension length * width of the composite beam (128 mm x 12.7 mm) (i.e. top view of composite beam). In this section, the composite beam is consisted from 13 layers (6 layers of wire mesh and 7 layers of epoxy- TiO_2 nano mixture) and 17 layers (8 layers of wire mesh and 9 layers of epoxy- TiO_2 nano mixture) through the thickness direction. The mechanical properties of the composite beam are varied along thickness direction according to wire mesh and epoxy nano mixture. After completing the two-dimensional drawing, the material properties (modulus of elasticity, density, and poisons ratio) of wire mesh layers are completely different from the epoxy nano mixture. The mechanical properties of epoxy nano mixture are calculated by mixing rule form and calculated according to nano percentage then entered manually to ANSYS software. In the meshing stage, shell element (SHELL281) is used for meshing and each layer of this beam is meshed according to its material properties and dimensions as shown in Fig. 13. To analyze the static deflection of this beam, the concentrated load is applied at the mid span. The 281 shell element is used because: "SHELL281 is suitable for analyzing thin to moderately-thick shell structures. It has 8 nodes with six degrees of freedom at each node: translations in the directions of x, y, and z, and rotations about the axes of x, y, and z. If the membrane option is used, the element has translational degrees of freedom only. SHELL281 is well for linear, huge rotation, and/or huge strain nonlinear applications. Change in shell thickness is accounted by nonlinear analyses. SHELL281 accounts for the follower (load stiffness) effects of distributed pressures. SHELL281 can be used for applications for modeling composite shells or sandwich construction (M. K. Thompson and J. M. Thompson, (2017). The number of elements and nodes are (1664 and 5275) respectively.



a- Element Geometry

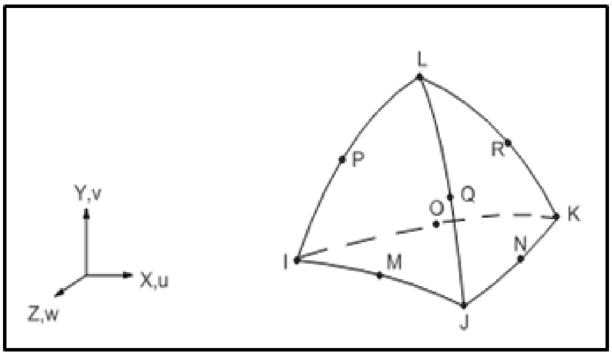


b- Beam Meshing

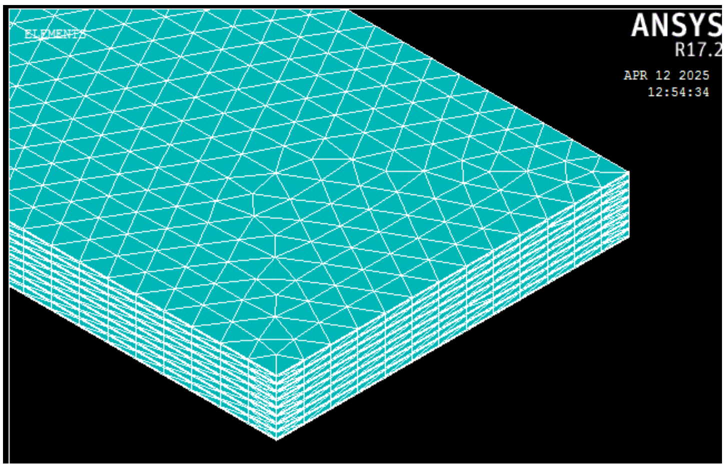
Fig. 13. Shell element Geometry and Beam Meshing for bending numerical analysis.

4.2. Vibration Numerical Analysis

In ANSYS APDL (17.2) software, a 3D model for this type of composite beam was built to simulate and analyze the free vibration and calculate its natural frequency. In this section, the composite beam has consisted of 13 layers (6 layers of wire mesh and 7 layers of epoxy- TiO_2 nano mixture) and 17 layers (8 layers of wire mesh and 9 layers of epoxy- TiO_2 nano mixture) through the thickness direction. The mechanical properties of epoxy nano mixture are calculated by the same method as in the bending analysis. In the meshing stage, the solid Tetrahedral 10 nod 187 element is used for meshing and each layer of this beam is meshed according to its material properties and dimensions as shown in Fig.14. This beam was modeled by drawing the length and width while the thickness was represented from different layers, each layer of wire mesh has 0.4 mm thickness while the thickness of the epoxy- TiO_2 nano mixture layers is calculated by subtracting the wire mesh thickness from the total beam thickness and inserted between wire mesh layers. The number of elements and nodes depends on the convergence criteria of numerical solutions and composite beam thickness is (6643 – 145820) elements and (11754-210224) nodes.



a- Element geometry



b- Layers in meshing stage

Fig. 14. Element geometry and meshing of thirteen and seventeen layers for three-dimensional model.

5. RESULTS

This section explains and discus the experimental and numerical results with comparison between it for evaluation of analysis.

5.1. Tensile Strength Results

The strength of fiber reinforced polymer composites depends on weaving style and bonding between fiber and matrix (S. Shibata et al., 2005). Fig. 15 shows the stress curves and titanium oxide ratio for the epoxy matrix reinforced with titanium oxide and wire mish fibers. It is noted here that the stress values of the composites increased when the nano ratio was 5%. Another reason for this increase is the low viscosity of the epoxy resin, which gives it an excellent ability to spread through the titanium oxide and fibers, ensuring sufficient permeability of the liquid resin through the fiber bundles. The resulting composite requires a higher load to break the physical bond, but the onset of the stress curve decreases when the nano ratio exceeds 5%. There are reasons related to the properties of the composite materials and their interactions, including poor homogeneous distribution or reduced cohesion between the components, which makes the material brittle and thus less able to withstand stresses.

In Fig. 15, when the number of layers was increased, the tensile strength decreased. The reason is that the load may not be distributed evenly on all layers. This leads to stress concentration on some layers, which reduces the overall efficiency of the structure. As the number of layers increases, the mechanical properties of the material may change due to internal stresses or changes in the crystal structure. The current study results are consistent with the findings of (Huang, K. S. et al., 2006).

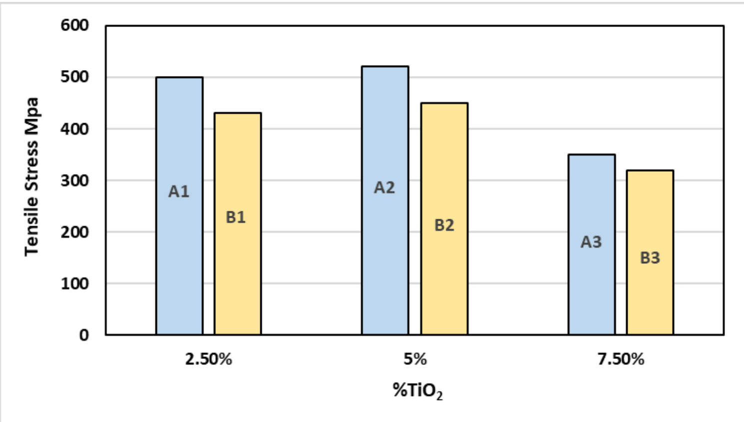


Fig. 15. Tensile stresses of epoxy matrix reinforced by wire mesh fibers and 2.5 %, 5 % and 7.5 % of TiO2 Nano material

5.2. Flexural Results

5.2.1. Experimental Flexural Results

The effect of rigid fillers on the stress-strain behavior of polymer matrices has been long known, especially for micro-scale fillers or larger. These fillers commonly tend to increase the stiffness of the material but they may decrease its strength and strain at break. The three-point bending test was performed to calculate the flexural characteristics of composite specimens. The flexural strength is the ultimate stress at the failure of the composite samples. The flexural characteristics of the composite specimens are calculated from Eq.1 and 2.

The Fig. 16 shows the flexural properties of the hybrid composite. The flexural strength of the composite specimens in the direction is the highest because they are subjected to both tensile and compressive stresses during bending. The maximum flexural strength of the outer fibers of the beam specimens was measured in the three-point bending test configuration, and it was also observed that the maximum flexural strength depends on the fiber volume fraction and fiber length in the beam specimens.

The tensile strength of the wire mesh fibers is very high, and its compressive strength is very low, and also when the fiber layers' increase, the flexural value increases. The Fig.16 also shows the increase in the hybrid composite when (5 wt %) of (TiO_2) is added. The large interface areas of titanium nanoparticles in contact with the epoxy matrix are responsible for better load transfer from the matrix to the particles. With the increase of the surface area of titanium nanoparticles, the effective interface area for energy absorption increases, resulting in a strong interlocking mechanism between the fiber surfaces and the polymer matrix.

In this Fig.16, the bending strength starts to decrease as the number of layers of steel wire increases due to the uneven distribution of stresses between layers. As the number of layers increases, the outer layers are subjected to greater stress than the inner layers, resulting in a decrease in the overall bending strength. In addition, slippage may occur between layers due to friction, which reduces the effective force tolerance. These factors combined lead to a decrease in the bending strength as the number of layers increases. The current study results are consistent with the findings of (Prasad, V. et al., 2018).

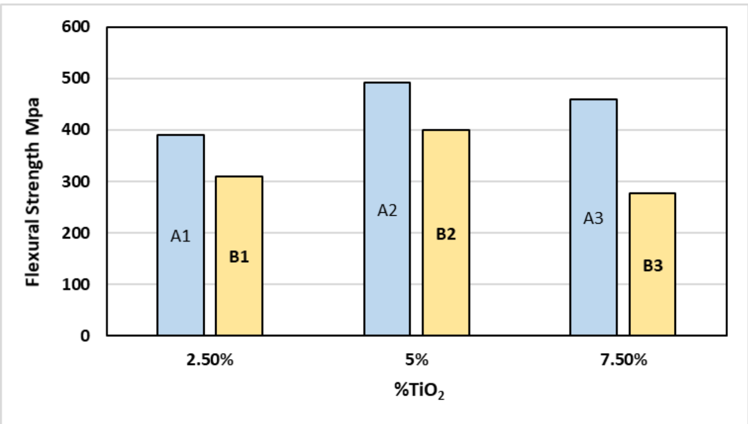


Fig. 16. The flexural strength of the epoxy matrix reinforced by wire mesh fibers and 2.5 %, 5 % and 7.5 % of TiO2 Nano material

5.2.2. Numerical Flexural Results

The comparison between the numerical and experimental findings of the flexural strength is showed with an error not exceed 5.5 %, as shown in Table 2. This difference in results is due to several reasons, including the composite manufacturing method, the fixing process effect of the sample and device's calibration.

Table 2 Experimental and Numerical results of the flexural test

Sample	Flexural Strength (Mpa)		
	Experimental result	Numerical result	Error %
A1	390	406	4
A2	492	503	2.2
A3	460	471	2.3
B1	310	325	4.8
B2	400	422	5.5
B3	277	292	5.4

5.3. Vibration Results

5.3.1. Experimental Vibration Results

The vibration characteristics for all composite material types were obtained experimentally using the half-power bandwidth method. Fig. 17 shows the amplitude-frequency response curve as an example, for sample contains epoxy matrix reinforced by 6-layers of wire mish fibers. For the first mode, the peak amplitude (A) equal to (0.35) corresponds to (Wn=46 Hz), which represents the natural frequency for the first mode. Dividing the peak amplitude by √2 to obtain the half-power points (f1 = 44 Hz, f2 = 52 Hz). Then damping ratio can be calculated using Eq.3 as follow:

$$\zeta = \frac{70.4-65}{2\times 67} = 0.0402 \qquad (3)$$

In polymers, damping is the most sensitive measure of molecular transformations and structural heterogeneity. The vibration will produce unwanted noise, reducing the lifetime of a composite structure by introducing fatigue crack. In Table 3, Natural frequencies and damping ratios are shown.

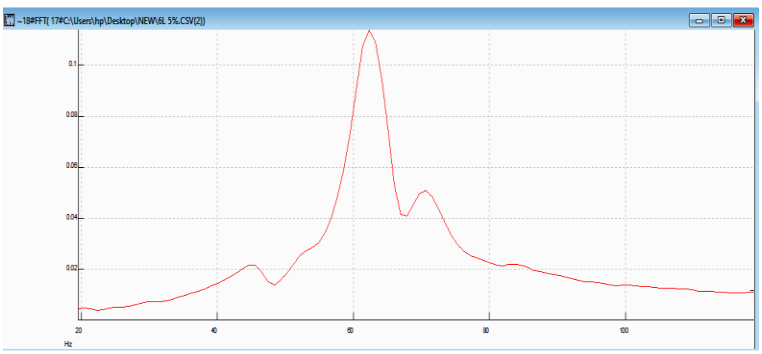


Fig. 17. Amplitude-Frequency response curve for (EP + 6-layer of wire mesh) and 7.5 % of TiO2 nano.

Table 3 Vibration properties of composite samples with different materials

Sample	Characteristics	
	Natural frequency (Hz)	Damping ratio
A1	65.8	0.0431
A2	75.6	0.0308
A3	67.3	0.0402
B1	69.5	0.0318
B2	70.6	0.0362
B3	71.4	0.0339

The results show that the vibration characteristics of the hybrid composite are greatly affected by the fiber properties, the number of layers, and the proportion of nanomaterials. The proportion of steel wire fibers increases the natural frequency with the decrease of the damping ratio. The natural frequency of steel wire fibers according to model A was when the layers were 6 and the proportion of the nuclear material was 5%. Increasing the nuclear material increases the damping ratio with the decrease of the natural frequency. In model B, the result of the natural frequency and damping ratio is in the opposite direction, where the higher the value is the natural value. The lower the frequency, the lower the value of the damping ratio. The reason is that the more layers, the greater the deformation during vibration, which leads to higher friction between the surfaces, which leads to higher energy consumption, thus improving the damping performance of the system as a whole. In general, natural frequencies come in a variety of forms. Not all of them are equally important. The importance of each is determined by the nature of the situation.

5.3.2. Numerical Vibration Results

The numerical analysis (modal analysis) of the dynamic properties of the composites materials prepared in the present study was performed free vibration modeling and comparison with the experimental results to verify the model reliability. First mode c-f 6 wire mesh layers and 7.5% nano is indicated in Fig. 18. The comparison between the numerical and experimental findings of the natural frequency showed almost acceptable with an error not exceed 6.4 %, as shown in Table 4. This difference in results is due to several reasons, including the composite manufacturing method, the fixing process effect of the sample and the sensor, and the influence of surrounding noise during the test. No significant variation in the natural frequency was observed between the samples, but it increased or decreased significantly with changes in the volume fraction of the steel wire fibers. This indicates a direct influence of the composite's modulus of elasticity on the natural frequency of the composite beam, which is consistent with the experimental results.

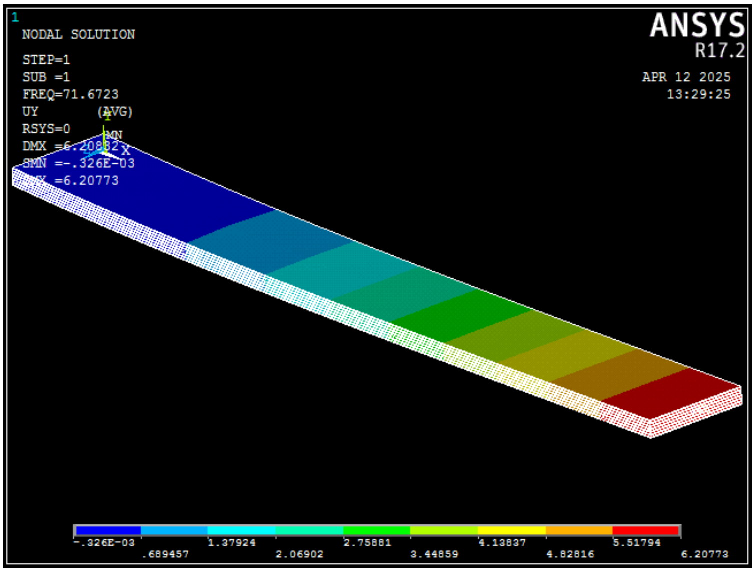


Fig. 18. First mode c-f 6 wire mesh layers 7.5% nano

Table 4 Experimental and numerical results of the free vibration test

Sample	Fundamental Natural Frequency (Hz)		
	Experimental result	Numerical result	Error %
A1	65.8	70	6.3
A2	75.6	80	5.8
A3	67.3	71.5	6.2
B1	69.5	74	6.4
B2	70.6	74.5	5.5
B3	71.4	75	5

6. CONCLUSION AND FUTURE WORK

This study investigated the mechanical and dynamic behavior of epoxy matrix composites reinforced with steel wire mesh fibers and titanium dioxide (TiO_2) nanoparticles at various weight percentages and layering configurations. The following conclusions can be drawn:

1. The tensile strength improved significantly with the addition of TiO_2 nanoparticles up to 5 wt%, due to improved resin infiltration and better bonding between matrix and reinforcement. And increasing the nanoparticle ratio beyond 7.5% led to reduced tensile performance, likely due to poor nanoparticle dispersion and increased brittleness.
2. Flexural strength increased with the addition of TiO_2 up to 5 wt%, due to enhanced load transfer and interfacial bonding, supported by the high surface area of the nanoparticles. The epoxy-steel wire-TiO_2 composites showed a balance between stiffness and strength when optimized at 5 wt% TiO_2 and moderate layer counts.
3. Natural frequencies and damping characteristics were significantly affected by fiber volume, layering, and nanoparticle content. Increasing the steel wire layers generally raised the natural frequency but reduced the damping ratio.

4. Higher TiO_2 content improved damping due to increased internal friction and energy dissipation during vibration, though it could slightly lower the natural frequency.
5. Sample A2 (6 layers and 5% TiO_2) exhibited optimal dynamic performance, indicating a good balance of stiffness and damping
6. Numerical models of both static and dynamic tests showed good agreement with experimental results, with errors not exceeding 5.5 % for flexural strength and 6.4% for natural frequency.
7. The consistency between numerical and experimental results confirms the reliability of the modeling approach and supports its use for future composite design optimization.

According to the mentioned finding, the following suggestions can be considered for future work:

1. Investigate the effects of combining TiO_2 with other nanoparticles such as graphene, carbon nanotubes, and silica to enhance multifunctional mechanical properties.
2. Extend the mechanical and dynamic testing to include fatigue life, impact resistance, and fracture toughness to get comperehensive understanding of failure mechanisms in the composite system.

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