Flexural Properties of Functionally Graded Silica Nanoparticles

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Abstract. In the present research, layered-functionally graded polymer nanocomposites were made via the silica (SiO$_2$) nanoparticles (14-36 nm in diameter) distributed in the epoxy matrix throughout the ultra-sonication by hand lay–up technique. The change in volume fraction (Vf) of the nanoparticles was given in the direction of thickness to reach the gradation. Layers having a thickness of (1.2 mm) with different nanoparticles concentrations were consecutively casted in acrylic molds to fabricate the graded composite sheet having a thickness of (6 mm). To fabricate the functionally graded layers, different concentrations of nanoparticles were taken (0, 0.5, 1, 1.5, 2 and 2.5 %Vf) and tested by tensile test. The improvement in the properties of composite samples included the all ratios up to 2% Vf, of the adding filler, and the properties were then decreased. The mechanical property that was studied was the flexural resistance. Flexural properties of three types of FGMs (FGM1, FGM2 and FGM3), isotropic nanocomposite (1% SiO$_2$) and pristine epoxy in order to evaluate their mechanical property, such as Stress–Strain criteria and flexural Young's modulus, were obtained by 3-point bending test, with loading from pure and composite side for FGM1 and at one side of FGM2 and FGM3 isotropic nanocomposite (1% SiO$_2$) and pristine epoxy. The results manifested that the flexural strength and Young's modulus loaded from the pure epoxy side was higher than when samples loaded from the composites side for FGM1. The mechanical properties of the epoxy resin and nanocomposites (tensile and compression) and the density for each layer were determined and could be useful for the finite element analysis of the 3-point bending test for FGMs specimens by using Design Modeler (ANSYS Workbench). Experimental results were validated by developing a detailed three-dimensional finite element model. Results of the progressive deformation from the finite element model agreed well with the experimental results.

Keywords. Silica nanoparticles, Epoxy, Polymer nanocomposites, Functionally graded materials, Tensile properties, Flexural properties, Compression properties.

1. Introduction
Composites are broadly utilized in the engineering industry owing to their excellent characteristics, such as lightweight, design flexibility, high strength, resistance to corrosion, and so on [1]. Nowadays, polymer matrix nanocomposites are the most familiar nanocomposites. The thermoplastic and thermosetting materials are utilized as a matrix, like epoxies, polyamides and so on, and the materials used for reinforcing are carbon nanotube (CNT), carbon fibers, graphene, alumina, silica, glass and clay [2]. Depending upon the structural creation, the nanomaterials stated to reinforce the epoxy resins are catagrized into three forms: Particles (such as metallic, organic (and/or) inorganic, and silica particles), Fibrous materials (like CNT, and so on) and Layered materials (such as graphite, clay, and
so on [3]. In the past years, various studies stated the enhancement in the mechanical characteristics and the epoxy polymers toughness via the addition of nano-reinforcements. The other method to enhance the epoxy resins mechanical characteristics is the addition of the stiff inorganic nanoparticles. Various nanofillers, such as silica (SiO$_2$) [4], alumina (Al$_2$O$_3$) [5] and titania (TiO$_2$) [6] are also utilized for such aim. The amalgamation of inorganic nanofillers enhances fracture toughness to a certain level. Adding some quantity to the contents of filler raises the toughness, but their extra addition might not improve toughness. Thus, utilizing the inorganic nanofillers possesses a restriction for the toughness of epoxy. The 2nd set of nanomaterials are the nanofiber reinforcement. The carbon nanotubes (CNTs) have a high prospective for improving the polymer physical, mechanical and electrical characteristics [7]. Carbon nanotubes show an outstandingly high aspect ratio in amalgamation with less density [8] in addition to the high stiffness and strength [9], which makes them a prospective nominee for the polymeric materials reinforcement. Contrast to reinforcements, matrixes are the weakest constituents in the composites, since their mechanical characteristic is highly lower than the reinforcements, and they are the constituents where the inner cracks or flaws usually take place. Thus, enhancing the matrix performance shall considerably prefer the stability and encourage the composites use [10].

FGMs are non-homogenous composites comprising (2) or many materials so that their own composition changes in a gradual manner in a certain spatial way. Therefore, the functionally graded materials have the demanded characteristics of every component inside it, and that gets them mostly appropriate to reach the requirement of the employed environment than a uniform substance. The idea of functionally graded material was first conceptualized in 1984 in Japan and it has involved the designer's interest for combining two or more totally unlike materials for obtaining a fresh material with characteristics to meet the challenging uses. Polymer functionally graded materials are the new progress in the FGMs' field [11]. The flexural modulus and strength of the epoxy/silica functionally graded composite were studied via Mishra et al. [12]. It was stated that the flexural modulus rose with increasing the weight percentage of the particles of silica inside the epoxy. An increase of (70%) in the flexural modulus was documented for the quartz fabric-reinforced epoxy including variable percentages of the particles of silica. While, the flexural strength reduced by increasing the silica particles content. Tsotra and Friedrich [13] investigated the flexural characteristics of functionally graded epoxy-resin/carbon fiber composites, the centrifugation technique was used to create a graded distribution of carbon fibers in an epoxy resin matrix, and the flexural modulus and strength of the functionally graded material being influenced via the graded structure. Rihan and El-Bary [14] studied graded silica/epoxy composites and homogenous composites prepared by gravity molding to investigate the effect of silica content on the wear characteristics.

Wear resistance and electrical conductivity increased by increasing the wt. % content of silica compared with the pure epoxy. In this study silica nanoparticle is used as reinforced material and the matrix used is epoxy. Different samples of FGM's were used and compared with epoxy and isotropic composites. Experimental test was compared with finite element model and show good agreement for flexural test.

2. Experimental part

2.1. Material used

An epoxy resin of a trade mark (Quickmast 105 base) was utilized as a liquid matrix having a low viscosity in comparison with the other thermosets, and it was transformed into a solid state via the addition of a hardener (Quickmast 105 hardener) at a ratio of 4:1.47 from the producing company. Table (1) lists the technical properties of (Quickmast 105) depending to the (DCP) company data sheet, while the nanoparticle reinforcements are silica manufactured by Guangzhou Billion Peak Chemical Technology Co. Ltd. Their technical properties are listed in Table (2). In this study, the weight percentage of SiO$_2$ was 0, 0.5, 1, 1.5 and 2 % Vf.
Table 1. Technical properties of Quick mast 105.

| Compressive strength | Flexural strength | Tensile strength | Density | Viscosity | Poisson’s Ratio |
|----------------------|-------------------|------------------|---------|-----------|----------------|
| 50 MPa               | 82 MPa            | 28 MPa           | 1.15 g/cm³ | 3-5 poise at 25°C | 0.33           |

Table 2. Properties of Nano Silica from the producing company.

| Properties               | Values |
|--------------------------|--------|
| Purity (%)               | 99.5   |
| Average Particle size (nm)| 14-36  |
| Specific Surface Area (m² g⁻¹) | 580±20 |
| Density (g cm⁻³)         | 2.4    |
| Microstructure shape     | Spherical |
| Poisson’s ratio          | 0.18   |
| Young’s modulus (GPa)    | 70     |

2.2. Nanocomposites preparation

Moulds having a (6 mm) thickness of acrylic were machined by CNC laser machine. Nanocomposites were synthesized by hand lay-up technique. In the present research, nano silica that are selected as nanofillers and liquid epoxy was employed as a matrix.

For preparing a consistent mixture, the whole reinforcement addition process to the resin was conducted in an appropriate solvent (thinner).

To prepare the samples of neat epoxy for creating equal situations in comparison with the other samples, an appropriate quantity of epoxy resin was poured into a sufficient quantity of thinner solvent. After (15 min) of mixing in a magnetic stirrer, this mixture was poured into a beaker to put in a vacuum vessel, and the solvent should be evaporated completely beneath the vacuum state produced by a vacuum pump. In such step, a hardener stoichiometry ratio, i.e., 4 (epoxy resin)/1.47 (hardener), was supplemented and mixed consistently for (15 min) and degassed via the vacuum pump for removing the bubbles of air, as revealed in Figure (1). This mixture was poured into an acrylic mould and cured for (24 h) at the room temperature.

In order to prepare isotropic epoxy/ SiO₂, the desired amounts of reinforcements (0.5, 1, 1.5, and 2 %Vf.) were dissolved into the adequate quantity of the stated solvent for (15 min). The resulting mixture was made uniform via magnetic stirrer for (15 min) and sonicated at (75%) amplitude for (15 min); 50s ON and 10s OFF. The demanded quantity of epoxy resin was supplemented to such mixture by the similar technique as stated earlier and was mechanically mixed. The stoichiometry ratio of hardener was added to this mixture and was mechanically stirred and degassed by a vacuum pump to remove the air bubbles. Finally, the homogenous mixture was poured into acrylic moulds and cured for one day.

It is important to note that the addition of nanoparticles increased the viscosity of the epoxy during the fabrication; therefore, the limitation on the upper bound to fabricate silica nanocomposite the filler content was set as 3 % Vf. of epoxy. Different acrylic moulds were used in this work, square mould having a size of 225 mm × 225 mm × 6 mm and the other cute? the acrylic sheets of 6mm thickness by CNC laser machine according to ASTM standards for different types of tests. These moulds are shown in figure (2).
Figure 1. Tools used in the experimental work to fabricate a homogenous and functionally graded nanocomposite.

Figure 2. Acrylic molds for homogenous composite and FGMs.
2.3. Preparation of FGPNC

The samples of the functionally graded polymer nanocomposite (FGPNC) have different types, as shown in figure (3). The fabrication process of the functionally graded nanocomposites was divided into two different stages: The preparation of the mixture of nanofiller and liquid matrix by appropriate dispersion and mixing methods as in the above procedure for isotropic nanocomposite and consecutively casting the liquid mixture into layered molds depending upon a predesigned graded structure. Such layers having a thickness of (1.2 mm) were casted in acrylic molds. For FGM1, the initial needed quantity of mixture for the neat epoxy was softly poured into a mold cavity having a thickness of (1.2 mm). FGM1 was then cured (1 hr). Afterward, (1) layer of nanocomposites with (0.5 wt.%) of nanoparticles was cast upon the formerly cast semi-cured layer. After that, FGM1 was permitted for curing for (1 hr). Likewise, (3) more layers of nanocomposites of (1, 1.5 and 2%) of nanoparticles were cast one by one for fabricating the functionally graded polymer nanocomposite sheet having a thickness of (6 mm), and the same procedure was repeated for the other FGM samples.

![Table showing different types of FGMs](image)

| Pure epoxy          | Pure epoxy          |
|---------------------|---------------------|
| 2 % Vf. SiO₂        | 1.5 % Vf. SiO₂      |
| 1.5 % Vf. SiO₂      | 1 % Vf. SiO₂        |
| 1 % Vf. SiO₂        | Pure epoxy          |
| 0.5 % Vf. SiO₂      | 1.5 % Vf. SiO₂      |

**FGM1**

| 0.5 % Vf. SiO₂ |
|----------------|
| 1 % Vf. SiO₂   |
| 2 % Vf. SiO₂   |
| 1 % Vf. SiO₂   |
| 0.5 % Vf. SiO₂ |

**FGM2**

**FGM3**

Figure 3. Different types of FGMs.

3. Characterization

The characterization of nanocomposites and functionally graded nanocomposites can be classified into two broad categories viz. mechanical and physical. Mechanical characterization to determine mechanical properties (Tensile, Flexural and compression) of individual nanocomposite and FGPNC. The physical characterization to evaluate the density of nanocomposites and FGPNC. The tensile and compressive strength of the test samples was calculated by using the eq. (1):

\[
\sigma = \frac{P}{A}
\]  

(1)

where, \(\sigma\) is the stress, \(P\) is the load applied and \(A\) is the area of cross section normal to the direction of the applied load. The modulus of samples was calculated by dividing the tensile or compressive stress on strain of the linear part of the Stress-Strain curve within the strain values of (0.05% and 0.25%), utilizing eq. (2):

\[
E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}
\]  

(2)

where, \(\varepsilon_1\) is the strain equals (0.0005), \(\varepsilon_2\) is the strain equals (0.0025), \(\sigma_1\) is the stress at \(\varepsilon_1\), and \(\sigma_2\) is the stress at \(\varepsilon_2\).
3.1. Physical characterization (Density)

The density of nanoparticles was calculated by dividing the mass of nanoparticles to the volume of these nanoparticles in cylindrical beaker containing solvent liquid (thinner) as shown in Figure 4. The composite theoretical density ($\rho_{th}$) was computed utilizing the rule of mixture (ROM) by eq. (3).

$$\rho_{th} = V_p\rho_p + V_e\rho_e$$  \hspace{1cm} (3)

where, $V_p$, $V_e$, $\rho_p$ and $\rho_e$ are the volume fraction, the density of nanoparticles and epoxy matrix, respectively. The epoxy density and the samples of the functionally graded polymer nanocomposite were experimentally obtained by applying the principle of Archimedes. The composites density was computed by eq. (4).

$$\rho_c = \frac{W_a}{W_a + W_w}$$  \hspace{1cm} (4)

Where, $\rho_c$ is the composite density, $W_a$ and $W_w$ are the sample weights in air and in water, respectively.

![Figure 4. Measure of density for nanoparticles.](image)

3.2. Mechanical characterization

3.2.1. Tensile test. The tensile characteristics of the nanocomposite specimens at different volume fractions were obtained according to the (ASTM standard D638) [15], utilizing (50 kN) servo hydraulic computerized Universal Testing Machine (Tinius Olsen H50KT apparatus). The tensile test specimens were straightly molded to the identified form. The specimen dimensions utilized in the present investigation are displayed in figure (5). The tensile tests were achieved at a (2 mm/min) crosshead speed. The average Young’s modulus and tensile strength were computed via performing at least five valid tests.

![Figure 5. Universal testing machine and samples used.](image)
3.2.2. Compression Test. The fully cured test specimens were tested at room temperature and atmospheric condition in the universal testing machine. The cross head speed of 2 mm/min was maintained throughout the test. The average value of similar kind of five test results was taken in the analysis. The epoxy nano-modified resin was poured into cylinder moulds (12.7 mm in diameter and 25.4 mm height) according to The ASTM D 695. The mould was coated with a release agent (wax) before fabrication.

3.2.3. Flexural Test. For the functionally graded polymer nanocomposite (FGPNC), the flexural test was carried out instead of the tensile test. For the samples of this nanocomposite, the gradation was provided in the direction of thickness; that means the characteristic (stiffness) is changing in thickness direction. Therefore, the tensile test according to the (ASTM standard D638) will not be valid for the samples of this nanocomposite. The flexural characteristics of the neat epoxy, (1%wt) nanocomposite, and the functionally graded polymer nanocomposite (all forms) were obtained utilizing a 3-point bending test. The specimens were burdened from the epoxy side and the nanocomposite side upon the universal testing machine for FGM1 and one side for the other samples. The flexural test specimen's dimensions (length (L), width (W), and thickness (B)) were (60, 10, and 6 mm), respectively as shown in figure (5) according to the (ASTM D790). Flexural strength, flexural strain and flexural modulus were computed by eqs. (5), (6) and (7), respectively [16].

\[
\sigma_f = \frac{3PL}{2WB^2} \tag{5}
\]

\[
\varepsilon_f = \frac{6DB}{L^2} \tag{6}
\]

\[
E_b = \frac{mL^3}{4WB^3} \tag{7}
\]

Where, \(\sigma_f\) is the flexural stress, \(\varepsilon_f\) is the flexural strain, \(E_b\) is the flexural modulus, D is the deflection \(P\) is the ultimate load, and \(m\) is the tangent slope to the first linear part of the Load-Deflection curve. The number of the tested specimens was at least (5) for every sample type. In this study, the diameters of the loading nose as well as the support roller were 10 mm, respectively.

4. Finite element modeling and analysis (numerical modeling)

Every day in the area of composite technology new materials are developed or designed using different nanomaterials, to enhance the properties of the hybrid composites. It is time-consuming and expensive to test all the new materials which are designed and fabricated using nanomaterials. Thus, there is need for the powerful tool to analyse the properties of Nano engineered composite materials using analytical methods. The failure of nanocomposites can provide insight for the effects of nanomaterials on the properties of Nano engineered composites. The finite element method is fairly accurate and is the most elegant method of modeling complex three –dimensional composite materials. This study presents detailed of 3-D finite element modeling and analysis to simulate the progressive failures in composite materials for three points bend test to study the effects of nanoparticles on beam of the composites. The models were developed using ANSYS finite element software. The flexural modulus of the functionally graded nanocomposites was estimated using the software (ANSYS) Multiphysics code (version 16.1). The friction between the jigs and the sample was not regarded in the present investigation. The layers of the functionally graded nanocomposites were regarded as a one consistent isotropic elastic material. The finite element model of the flexural tests was done, as shown in the figure (6). The total nodes were (50892) (specimen: 34240, jigs: 16652). In such model, the Cartesian coordinate system was employed with the X-, Y-, and Z-axes in the length, width, and thickness directions, respectively. Eight-node solid of 186 elements were utilized to mesh the specimens. The contact elements were employed for the contact zone between the specimen and the fixture of test. The friction coefficient for the surfaces of contact was assumed to be (0). The specimen was loaded via a prescribed displacement (\(\delta c\)) in the Z-direction upon the upper loading nose surface. The computed load (\(P_{c}\)) is corresponding to the load that measured via a load cell during the experiments. The Poisson's ratio for each layer is defined at a verity volume fractions of
nanocomposite from role of mixture are given as input to FEA as shown in Table (3). The elastic modulus of FGM and density are defining at a verity volume fractions of nanocomposite from experiments (tensile test) Archimedes’ principle are given as input to FEA.

| Vf. Particles | Poisson's ratio (rule of mixture) |
|---------------|----------------------------------|
| 0             | 0.33                             |
| 0.005         | 0.32925                          |
| 0.01          | 0.3285                           |
| 0.015         | 0.32775                          |
| 0.02          | 0.327                            |

**Table 3.** Poisson's ratio for each layers of FGM.

**Figure 6.** Finite element model for flexural test.

5. Results and discussion

5.1. Influence of filler loading on the nanocomposites void fraction

Through the fillers incorporation into the matrix or through the productions of nanocomposites, the air or the other volatiles may be trapped in the material. The trapped air or the volatiles are in the composites as microvoids, which may considerably influence some of its mechanical characteristics. The high content of void commonly causes lower resistance of fatigue, higher vulnerability to the diffusion of water, and the raised variant (scattering) in the mechanical characteristics. The amount of void in a nanocomposite material can be assessed via comparing the theoretical density with its real density. Table (4) depicts the theoretical and experimental densities of the neat, FGMs, and consistent nanocomposites, with the matching fraction of void. Table (4) shows the effect of Vf% of silica nanoparticle on the experimental density of epoxy composites. The silica incorporation raised the epoxy matrix material's density, confirming the benefit of nanofillers as a particulate reinforcement. It was obtained that the epoxy-based composite density increased by a raise in the loading of nanoparticle. The density of 2% SiO2 composite showed a (0.786%) enhancement with respect to the neat epoxy. It is obvious from Table (4) that the experimental density and the percentage of the void of epoxy raise with the nanoparticles incorporation. In Table (4), one can obviously see that the functionally graded polymer nanocomposite of both particles have lower density than their relevant monolithic nanocomposites possessing (1 Vf.%) of nanoparticles. Therefore, one can state that for a
certain size of sample, the gradation in the volume fraction (Vf.%) of particles is able to lower the functionally graded polymer nanocomposite weight in comparison with that of the monolithic nanocomposites.

| Composites | Theoretical density (g/cm³) | Experimental density (g/cm³) | Void fraction (%) |
|------------|-----------------------------|------------------------------|------------------|
| Epoxy      | 1.15                        | 1.145                        | 0.436            |
| 0.5% SiO₂  | 1.155                       | 1.148                        | 0.762            |
| 1% SiO₂    | 1.163                       | 1.149                        | 1.261            |
| 1.5% SiO₂  | 1.170                       | 1.151                        | 1.672            |
| 2% SiO₂    | 1.177                       | 1.154                        | 1.993            |
| FGM1       | 1.163                       | 1.141                        | 2.061            |
| FGM2       | 1.163                       | 1.142                        | 1.882            |
| FGM3       | 1.163                       | 1.139                        | 2.151            |

5.2. Tensile test results

Figure (7) shows stress-strain curve of the neat epoxy and epoxy/SiO₂ nanocomposite with different volume fraction under tensile load. The rigid particles addition to a polymer matrix can effortlessly enhance its stiffness, since the inorganic fillers rigidity is in general much higher than that of the organic polymers. Young's modulus is evidently improved by adding nanoparticles to a polymer matrix. Nanoparticles give higher rigidity to the polymers [17]. The slope of the first linear part of curve is utilized for determining the specimens' Young's modulus. The raised nonlinearity in the Stress-Strain curve is a sign of the bigger plastic zone. The lower slope depicts the composites less stiffness. The tensile strength of the neat epoxy and the epoxy-silica nanocomposites are computed via dividing the ultimate load obtained via the sample by the initial cross-sectional area in the specimen gauge zone. Figure (8) was plotted for the epoxy/ SiO₂ nanocomposites with various SiO₂ volume fractions. Results revealed that SiO₂ nanoparticles are effective to enhance the young's modulus and the elongation at break decreased from epoxy resin. At 1.5%Vf. of nanoparticles, an increment of 30% in elastic modulus and the elongation at break decrease 24 of % were registered over that of the neat epoxy. Rigid silica nanoparticles limit the local matrix deformation beneath the implemented load resulting in an improvement in the nanocomposites stiffness. Figure (9) shows variation of tensile strength at break and void content of epoxy/ SiO₂ nanocomposites with different volume fractions. The tensile strength at break increases as the SiO₂ volume fraction increases and reaches its maximum amount at (1.5 %Vf.) of SiO₂ addition. At such elective content, the tensile strength at break raised up to (72%) of the neat value. This indicates greater tensile toughness compared to neat epoxy. The nanocomposite raised tensile strength is owing to the superior interfacial interaction between the nanoparticles and the matrix resulting in better transfer of stress in composites. Owing to the interface between the matrix and the nanoparticles (imperfect bonding), the stress concentration and the void content-effects may decrease the tensile strength at break after the threshold level, thus the interfacial de-bonding between the matrix and the nanoparticles has to be regarded through the modelling. The operative stress transfer is the highly significant factor contributing to the strength of the two-phase composite materials. To the weakly bonded particles, the transmission of stress at the particle/polymer interface isn't efficient. The discontinuity in the debonding form occurs due to the particle non-adherence to the polymer. Therefore, the particle is not able to convey any load, and the composite strength reduces by rising the burdening of particle. Nevertheless, for the composites comprising well-bonded particles, the particles addition to a polymer shall head to a strength increment, particularly for the nanoparticles having high surface areas [18]. Therefore, the layered (FGM) having a thickness of (6 mm) was prepared with the (1.2 mm) thickness layers via changing the Vf.% from 0 (neat epoxy) to 2 with a (0.5) step in Vf.% to perform the gradation in the modulus and strength along the (FGM) thickness. The Young's modulus was calculated for every layer from the tensile test in the finite element analysis to compare the flexural properties with the experimental work.
Figure 7. The (stress-strain) curves behaviour of the epoxy/SiO$_2$ nanocomposites.

Figure 8. Effect of silica nanoparticles on the Young’s modulus and strain at break.

Figure 9. Effect of silica nanoparticles on the void fraction percentage and tensile strength.
5.3. Compressive test results

As observed in figure (10), the compressive strength values are greater than the tensile strength value revealed in figure (7). Brittle materials such as polymer composite are recognized by the fact that their compressive strength value is more than their tensile strength value. The relation between compressive strength as a function of volume fraction appears in figure (11). The compression strength values increased rapidly after the addition of nano-SiO$_2$, and its maximum amount was at (1.5\%Vf) as same as tensile properties which is increased by (31.1\%) from pristine epoxy. When the concentration of SiO$_2$ is increased, the compressive strength values decreased rapidly but they are still greater than those of the epoxy neat. The strength vigorously relies upon the transmission of stress between matrix and particles. At (1.5\%Vf), the coherency between particles and matrix was a maximum. The applied stress can be effectively transferred to the particles from the matrix, this clearly improves the strength [18]. The increases in concentration will cause particles to agglomerate, and become greater than the size of voids. At (1.5\%Vf) of nanoparticles, there is a raise of (40\%) in the Young's modulus than that of the net epoxy. Those agglomerates become impurities and cause a failure source. When the concentration increases, the number of particles will increase, and that causes a particle-particle interaction instead of the particle–matrix interaction. Consequently, the particles start agglomerating and forming lumps that finally influence the interaction of Van der Waals among the chains of polymer and that may lead to a reduction in the strength properties [19].

![Figure 10](image1.png)

**Figure 10.** The (stress-strain) curves of compressive behaviour of the epoxy/SiO$_2$ nanocomposites.

![Figure 11](image2.png)

**Figure 11.** Effect of Silica nanoparticles Vf,\% on the compression strength and Young’s modulus.
5.4. Flexural test results

The load-displacement curves obtained from the 3-point bending test of the samples of the neat epoxy (layered), isotropic nanocomposites (layered) and FGMs are manifested in figure (12). Then, the stress strain diagram was changed by using eqs. (5) to (7). The functionally graded polymer nanocomposite failure in flexural mode is controlled via the propagation of crack. The whole specimens fracture occurred owing to the crack propagation from the tensile side to the compression side. Alike behavior was also documented elsewhere [19]. The samples were observed broken from the middle, and the delamination wasn't noticed, demonstrating an appropriate bonding among the layers. Figure (13) illustrates a comparison between the flexural strength and the flexural modulus for FGMs, isotropic, and neat epoxy. The results depict a (51.7%) improvement in the flexural strength and a (67%) enhancement in the flexural modulus of the functionally graded polymer nanocomposite over those for the samples of the layered neat epoxy if burdened from the neat epoxy side due to the lowest layer. That means the composite layer has a high Young's modulus compared to pure epoxy, and it was observed that the flexural strength and Young's modulus for non-graded nanocomposites were higher than the pure epoxy, due to presence of nanoparticles. While, an (17.8%) improvement in the flexural strength and an (29.4%) enhancement in the flexural modulus were noticed over those for the samples of the layered epoxy if burdened from the composite side. In this case, the lowest layer of the pure epoxy has the lowest flexural modulus and strength that producing a decrease in the modulus and strength of the graded nanocomposites.

In the flexural test, the layer, at which the load is exerted, undergoes a compressive stress, whereas the layers at the opposing side shall be at a tensile stress. In different words, in 3-point bending test, the layers beneath the neutral axis shall undergo the tensile stresses, whereas the layers over the neutral axis, i.e. to the loading side, shall undergo the compressive stresses. By the aid of the elastic modulus and the density of the nanocomposites individual layers, the position of the neutral axis of the layered functionally graded polymer nanocomposite was obtained and was found to be located nearly at the mid plane of the layered composite in the direction of thickness. Therefore, the gradation did not move the neutral axis position considerably from the centroid axis owing to the truth that the change in the nanocomposites density for various nanoparticles concentrations is too small. The crack propagation that started in the layer beneath the tensile stresses shall be easier than that in the layer beneath the compressive stresses. Therefore, the vigorous and stiffer layers in the zone of tensile stress in 3-point bending test highly contribute in improving the flexural characteristics of the functionally graded polymer nanocomposite. Thus, for the 3-point bending test, the outer most layer, i.e. the layer opposing to the exerted load surface, takes a significant role in the increase of the flexural characteristics of the functionally graded polymer nanocomposite. The layered functionally graded polymer nanocomposite with a stiffer and vigorous outer layer shall possess better flexural characteristic. The results obtained from the ANSYS program are shown in figure (13), where similar loads were applied to those applied in practice and then compared to the resulting deflection with practical deflection. The Poison's ratio, density and young's modulus for each layer were calculated from the experimental work. Good agreement was observed between FEA and experimental work.
Figure 12. The stress-strain curves of the flexural behaviour for the functionally graded polymer nanocomposites (FGPNC) samples.

Figure 13. Flexural strength and Young's Modulus for epoxy, isotropic, and FGMs.

6. Conclusion
Functionally graded polymer nanocomposite (FGPNC) of epoxy and silica nanoparticles were synthesized utilizing a hand lay-up method. The gradation was reached in the direction of thickness by changing the silica nanoparticles concentration. It can be inferred upon the foundation of the obtained results in this investigation that the silica nanoparticles reinforcement and gradation in the layered form can be an attractive method for improving the flexural characteristics of the epoxy-silica functionally graded polymer nanocomposite. The modulus and flexural strength are highly influenced by the exerted load direction for FGM1. The flexural strength and flexural modulus of FGPNC for each type of FGMs and the layered isotropic nanocomposite increment compared to that of the layered neat epoxy. A (51.7%) enhancement in the flexural strength and a (67%) improvement in the flexural modulus have been observed for the FGM1 samples burdened from the neat epoxy side as compared with the layered neat epoxy. Whereas for the FGM1 burdened from (1.5%) side, a (17.8%) increment
in the flexural strength and a (29.4%) increment in the flexural modulus were recorded over those of the neat epoxy. For FGM2, the flexural strength and modulus were increased by (17.5%) and (42.3%), respectively as compared with those of the pristine epoxy. And for FGM3, the flexural strength and modulus were also increased by (19.3%) and (34.6%), respectively for the layered epoxy. A good agreement between the results of the experimental and the finite element analysis using ANSYS software for the flexural analysis was found, and no delamination between the layers of FGMs' samples was observed.

7. References

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