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Manufacturing Functionally Graded Materials Using Centrifugal Force

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Abstract

In this work, functionally graded Materials (FGMs) were created by centrifugal force mixing polyester resin with silicon dioxide (SiO_2) to create five layers, each having a thickness of 1.2 mm. Tensile composite specimens with varying volume fractions (0, 10, 15, 20, 25, and 30)% are taken before the fabrication of the FGMs specimens, and their modulus of elasticity is subsequently computed. The fourth specimen was made using the exponential equation to describe the property distribution throughout the thickness of the three-points specimen, whereas the other three specimens were made using the power law equation when the power law index (β) was (0.5, 1, and 5). Flexural modulus of the functionally graded composite (FGMs) loaded from the neat polyester, raised by 37.1% for (β=0.5). When compared to pristine polyester, the flexural modulus improved by 33.3% for (β=1). The increase in (β=5)'s flexural modulus was (27.78%). The flexural modulus improved by 24.5% with exponential FGMs.Good correlations are observed, with the greatest absolute discrepancy between the numerical and experimental outcomes being 14.6% when the power law index (β) is at (0.5).The results of the experimental flexural test were verified using Design Modeler (ANSYS Workbench R2 2021).

Keywords: Functionally graded Materials (FGMs), Power law index, Flexural modulus, Exponential FGMs, Volume fraction, Polyester.

Notation

$E_{Fgm}(z)$	modulus of elasticity at any thickness
$E(V_f)$	modulus of elasticity for each volume fraction
$E(layer_i)$	modulus of elasticity for each layer
$E(i)$	modulus of elasticity at the lower surface of layer (i)
$E(i+1)$	modulus of elasticity at the upper surface of layer (i)
(V_m)	The volume fraction of Polyester
(V_f)	Volume fraction of (SiO_2) particles
β	power law index

1. Introduction

The need for new materials has gradually led to improvements in their qualities to meet the needs of new technical applications and get around the drawbacks of conventional materials, including metals, alloys, and conventional composite materials [1,2]. The old materials were often produced to provide the highest possible performance in technical applications [3].

To minimize the flaws in conventional materials and fulfil all the demands of industrial development, modern materials' properties (particularly their mechanical qualities) are progressively changed to improve their performance. Three types of these materials were considered according to the direction of the property variation: (a) 1-D functionally graded material (FGM), (b) 2-D functionally graded material, and (c) 3-D functionally graded material. The volume fraction of each component is always varied along one direction, or two directions, or three directions [4-6]. Those materials are considered as traditional composites but heterogeneous. Also, those materials have several important material properties, like high toughness, thermal resistance, and low density [7,8]. In 1D-FGM, the material properties change along one direction only and when this direction is "axial direction", the material is called "axial-FGM". If the mechanical and physical properties of functionally graded material are changed in a thickness direction, the material is called " Thickness – FGM" [9].

On the other side, several manufacturing processes were used to manufacture the traditional composite materials and these processes depend on the type, components, geometry, shape and arrangement of the composite materials. The most economical and visually appealing methods for metal-matrix-based FGMs are centrifugal casting and gravity. While centrifugal casting is used to attain a graded distribution of carbon fiber and graphite particles in an epoxy resin using polymer matrix-based FGMs [10].

A basic mechanical stirring mechanism and a vertical centrifugal casting process were used by Siddhartha et al. [11] to produce FGM and homogenous composites made of various materials with a polyester matrix and short glass fiber.

Siddhartha et al. [11] found that “adding short glass fiber to polyester-based (FGMs) composites significantly increase their tensile and flexural strengths compared to homogeneous composites”. Singh AK et al. [12] used Titania (TiO_2) particles and epoxy to manufacture FGM utilizing a vertical centrifugal casting technique after initially employing a basic mechanical stirring approach. They found that (TiO_2) filled FGMs have better mechanical properties than homogeneous composites, and unfilled polyester composites have the worst mechanical qualities.

Kumar MS et al. [13] manufactured a layered FGM using epoxy-alumina nanocomposites (FGPNC) by applying in-situ polymerization, when compared to pure layered epoxy, they observed that FGPNC had a greater flexural modulus and flexural strength under both types of loading circumstances when the weight percentage of nano-alumina was adjusted in the thickness direction.

Karakoti et al.[14] manufactured sandwich FGM using the exponential model studied the bending properties experimentally and compared the experimental results with the finite element simulation results. Xavior et al. [15] explained the experimental details of tensile, compressive and three-point bending tests and results for porous polymer FGM.

Seyedkanani et al. [16] carried out several flexural tests on 3D printed samples to assess the viability of FGM designs for enhancing the properties of lightweight structures. Additionally, they verified the experimental data using the finite element method.

Shareef, M. et al. [17] generated the five layers of artificial FGM made with epoxy and Al_2O_3 nanoparticles by hand lay-up. The results of the suggested FGM were compared with epoxy using a three-point bending test. They discovered that "the isotropic composite material and each type of FGM's flexural modulus and strength of the FGPNC are more than pristine epoxy.

The bending behavior of the sandwich FG beam, considering the effects of volume fraction index, support and loading conditions, and beam configuration, was studied by Srikarun et. al. [18] and Yu et. al. [19]. Also, Atta et al. [20] studied the flexural problem of the polymeric FG beams by conducting a three-point bending test and a 3-D finite element simulation.

The novelty of this work is to propose a new procedure to manufacture two types of functionally graded composite (FGMs) (power law and exponential FGMs). Polyester and silica particles are used to manufacture composite materials with different elastic modulus, and these composites are used in the new procedure to produce FGMs. A three-point bending test is used to compare the experimental data and numerical results based on the Finite element method.

2. Materials and Methodology.

In this work, two types of materials are used to fabricate FGMs samples; polyester resin is used as matrix materials, while silica (SiO_2) is used as a reinforcement material, following a short description for each type.

2.1 Polyester Resin:

In this study, a trademark polyester resin (P-053) produced via iLKESTER company has been utilized as a matrix in the form of liquid (see Figure 1. a); it possesses less viscosity than other thermosets. And it has been converted into a solid condition by adding a ratio of (1:100) of a hardener from the supplied company [21]. The properties of polyester are illustrated in Table 1.

2.2 Silicon Dioxide (SiO_2)

One of the most complex and abundant material families, silicon dioxide, also known as silica (from the Latin Silex), is a chemical compound with the chemical formula SiO_2. It can be produced artificially or found naturally in a variety of minerals. SiO_2 particles have a high specific surface area, high strength, wear resistance, and fracture toughness, which makes them popular fillers in the preparation of polymer composite materials. [22]. The properties of SiO_2 are illustrated in Table 1.

SiO_2 is a great electrical insulator that is perfect for isolating integrated circuits and transistors. It is also a superb thermal insulator, making it appropriate for use in refractories and even in spaceship heat protection. SiO_2 is a necessary component in the production of glass. [23]. Fig.1. b illustrates the silica particles.

Table. 1 Mechanical and Physical Properties of Matrix and Particles Materials [21]

material	modulus of elasticity (G Pa)	Poisson ratio	density kg/m^3
Polyester Resin	2.5	0.3	1023
Silicon Dioxide (SiO_2)	66.3	0.15	2330

a. Polyester resin **b. The SiO_2 powder**

Figure. 1 Materials Used in This Study

3. Dies Preparation of mechanical test specimens

The acrylic dies were used to prepare the samples. Each die consists of three layers. The middle layer contains grooves of the sample shape required for a test, which are installed on the lower layer used as a base to prevent mixture leakage and the upper layer is used as a cover for the middle layer, with dimensions length 220 mm, width 60 mm, and thickness 10 mm, as shown in Fig.2. The die has been produced utilizing a CNC laser machine and ground for giving the final composite samples of the product following international standard specimens.

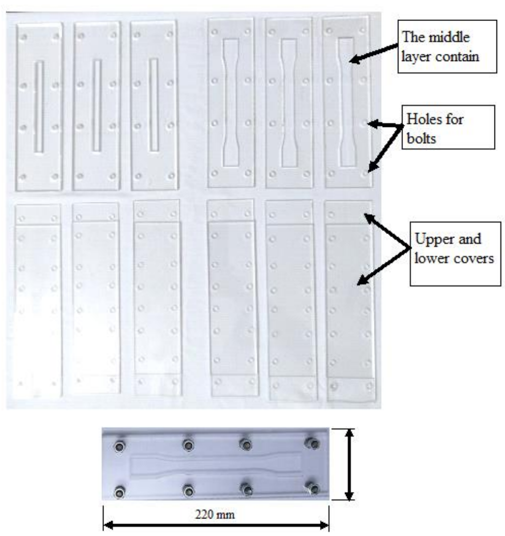


Figure 2. The acrylic dies

4. Experimental Procedure

4.1 Experimental Rig of the casting centrifugal force

One of the casting technologies utilizes centrifugal force without pressure to obtain specimens by employing centrifugal casting techniques. A centrifuge apparatus is manufactured in a new way that differs from the centrifugation methods in previous research in terms of the shape of the sample and the direction of the gradient by using variant dies. The centrifuge apparatus produces functionally graded composites manufactured under the same conditions during the die rotation process (in terms of temperature, rotation time, and die rotation speed). The centrifuge apparatus consists of several parts:

1. Disks: The centrifuge apparatus contains two disks perpendicular to the axis of rotation. These disks contain slots for the plate dies to be installed in between the two disks, as shown in Fig.3.
2. DC electric motor, as shown in Fig.4.
3. Bearings.
4. Coupling.
5. Sliding guide.
6. Steel frame.

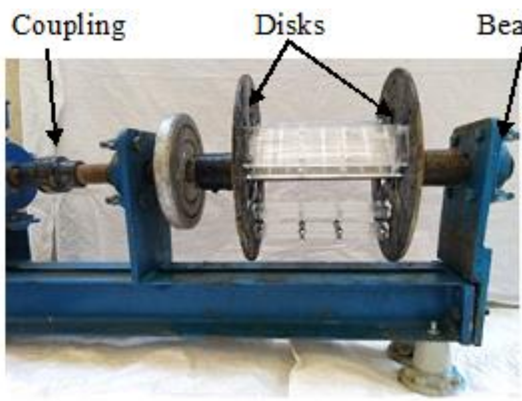


Figure 3. The slots in the disk

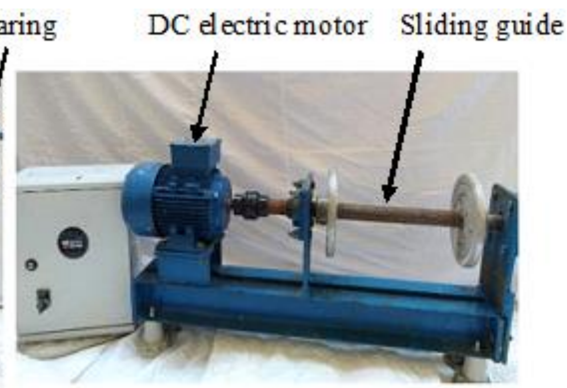


Figure 4. Electric motor

4.2 Fabrication of pure polyester and composite specimens

This type of specimen was fabricated for measuring and comparison purposes concerning the mechanical properties of the composite materials with different volume fractions of (SiO_2) particles from tensile tests. The fabrication process contains the following steps:

1. Wax was applied to the walls of the die to facilitate the sample's removal from the die after the solidification process.
2. The homogeneous composite was prepared and poured into the dies, then the dies were closed. The volume fractions of (SiO_2) particles used in this work were (0, 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3).
3. After the solidification of specimens, the dies are opened and the specimens take their final shape.

4.3 Fabrication of FGMs specimens:

In this section, the tensile and flexural specimens of FGMs (power law distribution) are prepared depending on the tensile test results of composite materials that were manufactured in the previous section. Table 2 shows the experimental modulus of elasticity of the composite materials with different volume fractions and these results can be drawn as shown in Fig.5 then the curve fitting method can be used to find the function described by the change in modulus of elasticity with the volume fraction (i.e. $E(V_f)$).

Table 2. Experimental Results of Elastic Modulus of Composite Materials Varying with The Volume Fraction of (SiO_2) particles.

No.	Volume fraction of Polyester (V_m)	Volume fraction of (SiO_2) particles (V_f)	Modulus of elasticity (GPa)
1	1	0	2.5
2	0.9	0.1	4.0485
3	0.85	0.15	5.1442
4	0.8	0.2	5.8663
5	0.75	0.25	6.2733
6	0.7	0.3	6.9588

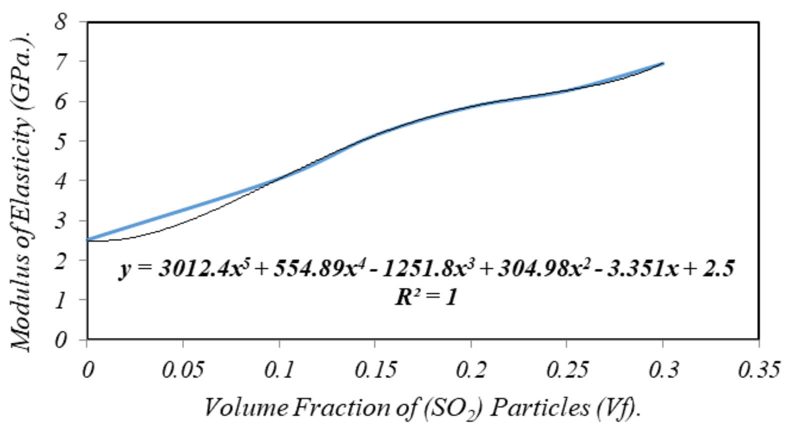


Figure 5. Experimental Results of Elastic Modulus of Composite Materials Varying with The Volume Fraction of (SiO_2) particles.

$$E(V_f) = 3012.4 * (V_f)^5 + 554.89 * (V_f)^4 - 1251.8 * (V_f)^3 + 304.98\,(V_f)^2 - 3.351 * V_f + 2.5 \qquad (1)$$

For power law distribution, the bottom material in tensile or flexural FGMs specimens (or inner material of cylinder FGMs specimens) is pure polyester, while the upper material in tensile or flexural FGMs specimens (or outer material of cylinder FGMs specimens) is a composite material with a (0.3) volume fraction of (SiO_2) particles. In the proposed experimental model of FGMs, the thickness of the specimen (h) is divided into five layers, each layer has constant mechanical and physical properties (i.e. has a constant volume fraction of (SiO_2) particles). To calculate the required volume fraction of (SiO_2) particles, the elastic modulus of each layer is calculated using the following equation [24]:

$$E(layer_i) = (E(i) + E(i+1))/2 \qquad (2)$$

Where: (i) is varying from 1-N (Number of Layers)

$E(i) = E\left(\frac{-h}{2} + \frac{h*(i-1)}{N}\right)$= modulus of elasticity at the lower surface of layer (i) and its value is calculated using Eq.(3) for power law distribution [25].

$$E_{Fgm}(z) = (E_2 - E_1)\left(\frac{z}{h} + 0.5\right)^{\beta} + E_1 \qquad (3)$$

$E(i+1) = E\left(\frac{-h}{2} + \frac{h*(i)}{N}\right)$= modulus of elasticity at the upper surface of layer (i) and its value calculated using Eq. (3) for power law distribution.

For power law distribution, the value of $E(layer_i)$ will change when the position of the layer (i.e. the value of i) changes. While the value of $E(layer_i)$ will change when the position of the layer (i.e. the value of i) changes in the exponential distribution case.

After calculating the elastic modulus of each the five layers, the volume fraction of (SiO_2) particles can be calculated using Eq. (1). Table 3 shows the required volume fraction of (SiO_2) particles for the five layers when the power law distribution is used and the power law index (β) is (1). Also, Tables 4 and 5 lists the required volume fraction of (SiO_2) particles for the five layers when the power law index (β) is (0.5) and (5) respectively, and the block diagram in Fig.(6) shows the fabrication steps of FGM.

Table 3. The Calculating Volume Fraction of (SiO_2) particles and Elastic Modulus for the Five Layers When the power law index (β) is (1).

No. Layer	$Ec=E_{top}$	$Em=E_{bottom}$	Calculating V_f%	E layer	
				Eq.(1)	Eq.(3)
1	6.9588	2.5	5	2.9428	2.9459
2	6.9588	2.5	9.2	3.8579	3.8376
3	6.9588	2.5	13	4.7387	4.7294
4	6.9588	2.5	18	5.6294	5.6212
5	6.9588	2.5	27.5	6.5203	6.5129

Table 4 The Calculating Volume Fraction of (SiO_2) particles and Elastic Modulus for the Five Layers When the power law index (β) is (0.5).

No. Layer	$Ec=E_{top}$	$Em=E_{bottom}$	Calculating V_f%	E layer	
				Eq.(1)	Eq.(3)
1	6.9588	2.5	7	3.3489	3.3434
2	6.9588	2.5	12	4.5165	4.53696
3	6.9588	2.5	15	5.1442	5.1546
4	6.9588	2.5	18	5.6294	5.6489
5	6.9588	2.5	22	6.047	6.0741

Table 5. The Calculating Volume Fraction of (SiO_2) particles and Elastic Modulus for the Five Layers When the power law index (β) is (5).

No. Layer	$Ec=E_{top}$	$Em=E_{bottom}$	Calculating V_f%	E layer	
				Eq.(1)	Eq.(3)
1	6.9588	2.5	0	2.5	2.5006
2	6.9588	2.5	0.1	2.51	2.52
3	6.9588	2.5	3	2.6407	2.666
4	6.9588	2.5	6.5	3.2404	3.2649
5	6.9588	2.5	14.5	5.0484	5.0049

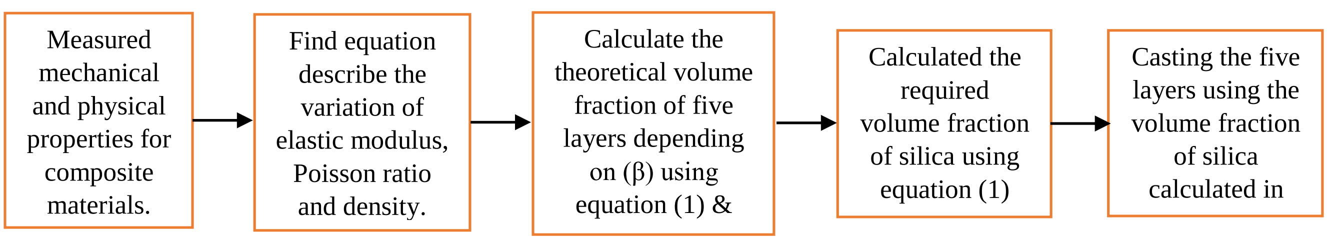


Figure 6. The steps of the numerical solution

8. Mechanical Properties

a. Tensile test experiments

According to ASTM D638 as shown in Fig.7 with 3mm thickness [26]. Twenty-four homogenous tensile samples are produced by mixing polyester with (0, 5, 10, 15, 20, 25, 30, and 35) % of SiO_2 (three samples for each percent) depending on volume fraction (V_f) percentage. The first three samples are produced from pure polyester mixed manually with hardener. The other samples are produced from SiO_2 with different percentages and mixed with polyester by using an electric mixer for several minutes for each mixing. After completing the mixing process, the hardener is added and then poured into the tensile molds. During tensile testing, the samples' ends are clamped at both the upper and lower places using the tensile testing machine. The instrument's PC screen shows the applied stress and degree of extension. [27].

The process for conducting uniaxial tensile tests using electronic universal testing equipment with microcomputer control is shown in Fig.8.

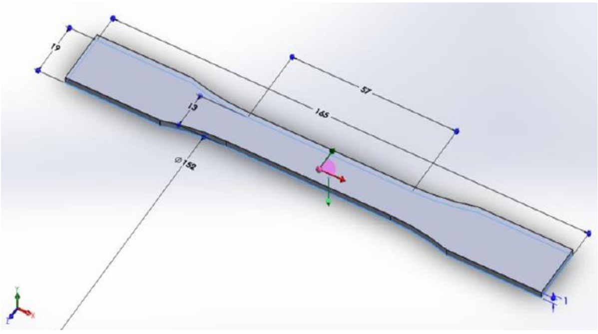


Figure 7. A schematic diagram of the tensile specimen (mm) according to ASTM standard D638

Figure 8. Tensile Test Setup

b. The Flexural test

(i) **The material used and the specimen's Preparation**

It is necessary to conduct 3-point bending experiments on functionally graded beams with uniform porosities distributed throughout the thickness direction to determine the beams' flexural properties and strength. A tensile test sample was manufactured by inserting molds into the flexural test sample, with dimensions of, the length (L), width (w), and thickness (h) of the flexural test sample are 120 mm, 10 mm, and 6 mm, following ASTM standard D790, as shown in Figure 9 [28], using the same procedure as for the tensile sample. Table 6 provides a list of the geometrical characteristics of the FGMS specimens utilized in the studies.

Table 6. The dimensions of FGMs specimens (mm).

Specimen No.	Details of specimens	Dimensions (mm)	Total thickness (mm)
FGMs1	β=0.5	120 x 10	6
FGMs2	β=1	120 x 10	6
FGMs3	β=5	120 x 10	6
FGMsE	exponential FGMS	120 x 10	6

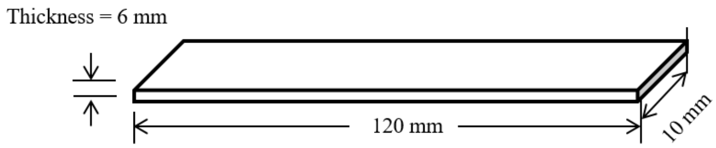


Figure 9. The specimen's dimensions as per ASTM standard D790.

(ii) Experimental setup

Three-point bending tests are usually conducted to evaluate resin matrix (polyester) flexural properties, in the various FGMS models [29]. Following ASTM standards, the load is applied by a roller with a diameter of 5mm. A simply supported rig maintains the cross-head speed at (4mm/sec). The midspan deflection is measured with a transducer, deflectometer, or dial gauge. The sandwich's displacement was evaluated by applying the load at the specimen's centre on the PC. This produced load-deflection curves that could be used to calculate the sandwich stiffness and core shear modulus. A three-point bending device (universal device) was used to test three samples for each sample type. The failure mode map indicates that the upper facing has a local yield failure. Fig.10 depicts the FGMS beams arranged experimentally.

(a) **(b)**

Figure 10. Three-Point bending test using UTM and FGMs beam samples used, (a) before and (b) after.

9. Simulation Three-Point Bending Test Modeling

An analysis of advanced failures in FGMs is introduced in the current investigation, which explores the beams for a 3-point bend test. The functionally graded flexural modulus was calculated using the ANSYS Multiphasic Code Version 2021 R1.

For this study, we assumed that the friction coefficient between the surface of the sample and the jig could be zero (friction between the sample and the jig was not considered). A homogeneous isotropic elastic material was considered to consist of the FGMs layers [30].

Fig.11 shows that FE models were conducted for flexural tests. It comprised (50892) nodes (Easy: 34240, Jigs: 16652). Cartesian coordinates are utilized for measuring thickness, width, and length using the x, y, and z axes. Meshing the samples was done using solid 186 elements with eight nodes. A predetermined displacement (δ_o) in the y-direction on the top-loading nose surface encumbered the sample. The procedures used in this investigation are shown in Fig.12.

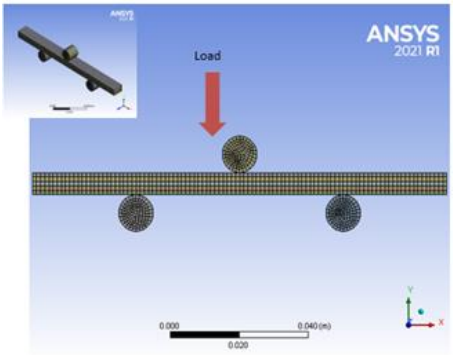


Figure 11. The FE model with mesh for flexural test

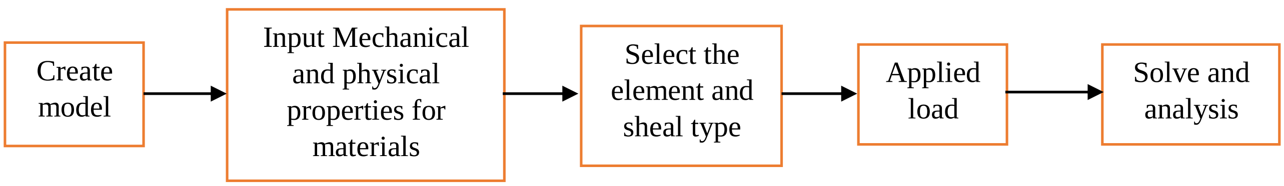


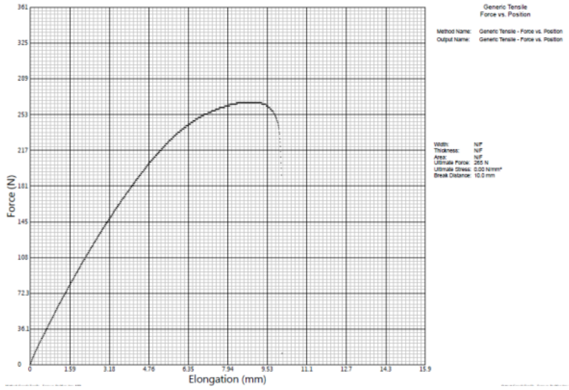
Figure 12. The steps of the numerical solution

10. Results and discussions

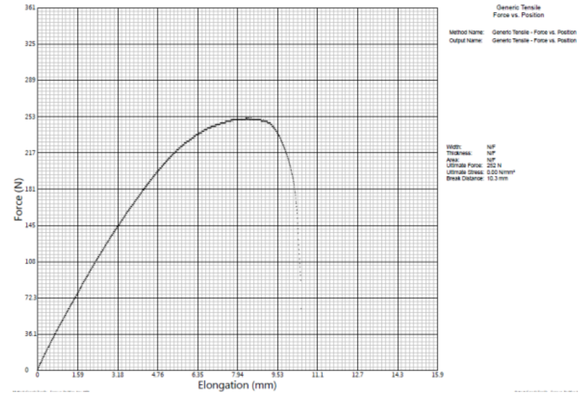
This section is divided into two parts: the first one deals with the experimental results of the three-point bending of FGMs specimens and the second one deals with the comparison between the experimental and numerical results of the three-point bending of FGMs specimens.

(i) Experimental Results of Three Point Banding Test

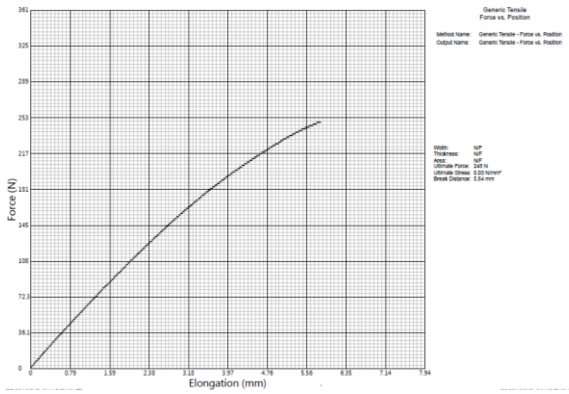
Three types of FGMs are used in this paper, depending on the value of the power law index (β). Fig.13 shows the force-elongation experimental results of the three-point bending test for power law index (β) is (0.5, 1, and 5) in addition to exponential FGMs. From Fig.13, the specimen tends to be brittle, when the power law index increases due to increasing the content of silica particles in FGMs. On the other side, the exponential FGMs tend to appear as brittle as illustrated in Fig.13-d. By comparing Fig.13-c and 13-d, the behavior of power-law FGMs when (β=5) is approximately similar to that of exponential FGMs.



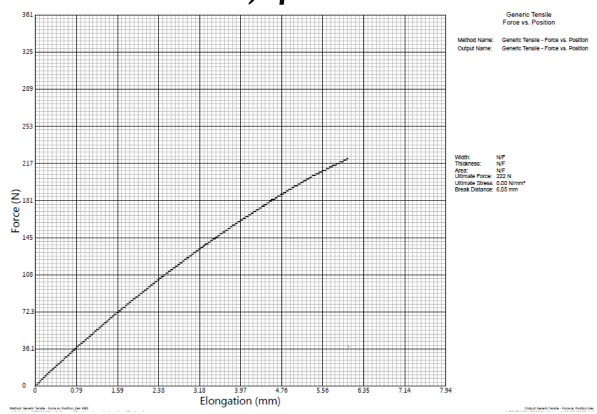
a) β=0.5



b) β=1



c) β=5



d) Exponential FGMs

Figure 13. Force-Elongation Experimental Results of FGMs When (a) β =0.5, (b) β =1, (c) β =5 and (d) Exponential FGMs.

The results obtained from the experimental tests by finding the magnitude of the slope of the curve’s path and with the help of the equations in references [28] it is possible to find the magnitude of the modulus of elasticity in bending for each type of FGMs specimens, which are illustrated in Table 7. The flexural modulus of the functionally graded composite (FGMs) enhanced by (37.1%) for (β=0.5) loaded from the neat polyester. For (β=1), the improvement in the flexural modulus was (33.3%) as compared with pristine polyester. The enhancement in the flexural modulus of (β=5) was (27.78%). For exponential FGMs, the improvement in the flexural modulus was (24.5%). The results give the ability to choose the appropriate value for the material distribution (β) to obtain the required response to the threshold, and this leads to reducing internal stresses as well as reducing delamination.

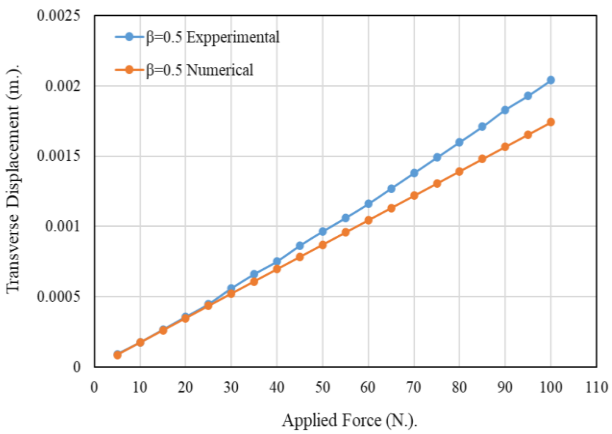
Table 7. The modulus of elasticity in bending for each type of FGMs

No.	FGMs type	modulus of elasticity in bending (GPa)
1	β = 0.5	3.9732
2	β = 1	3.7487
3	β = 5	3.4619
4	Exponential	3.3116

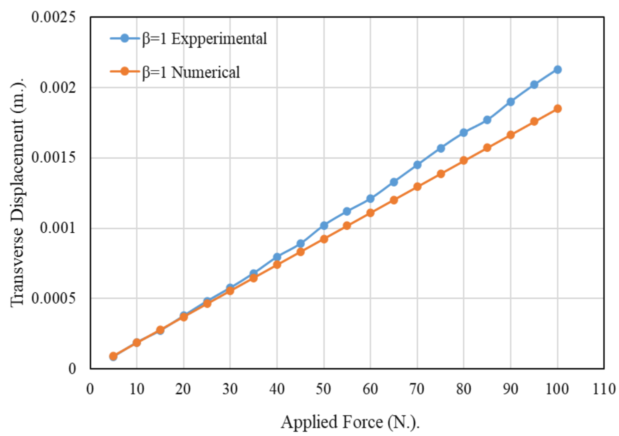
(ii) Comparison Between Experimental and Numerical Results of Three-Point Bending Test

The comparison between the experimental and numerical results is displayed. Four FGMs specimens with three points were tested experimentally. The power law equation was used to manufacture three specimens when the power law index is (0.5, 1 and 5), while the fourth specimen was manufactured using the exponential equation to describe the property distribution along the thickness of the three-point specimen. The transverse displacements of power law FGMs are shown in Fig.14. The good agreements between them are found and the maximum absolute error between them is (14.6 %) when the power law index is (0.5) as illustrated in Fig.15. For exponential FGMs, the comparison between the transverse displacement of the experimental test and numerical simulation is displayed in Fig.16 and the maximum absolute error percentage between them is (9.872%) as shown in Fig.17.

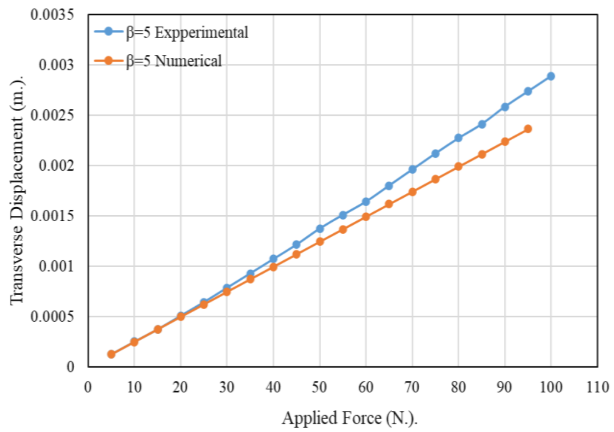
These good agreements between the experimental and numerical results prove that the numerical model is suitable to simulate the three-point bending test for two types of FGMs (power law and exponential FGMs).



(i) β=0.5



(ii) β=1.



(iii)β=5

Figure 14. The comparisons between the three-point banding of the experimental test and numerical simulation for different power law indexes.

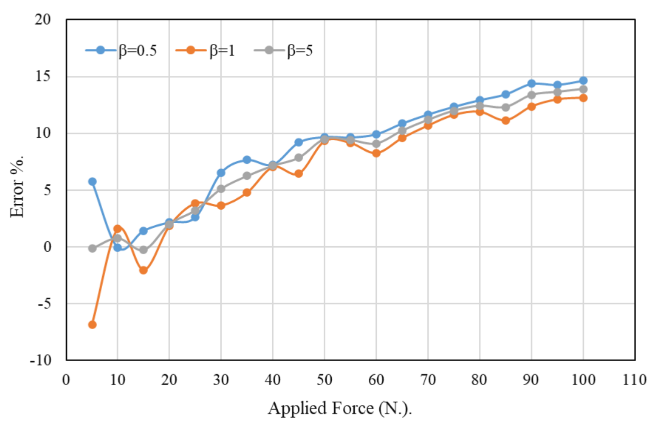


Figure 15. The error percentage between the three-point banding results of the experimental test and numerical simulation for different power law index.

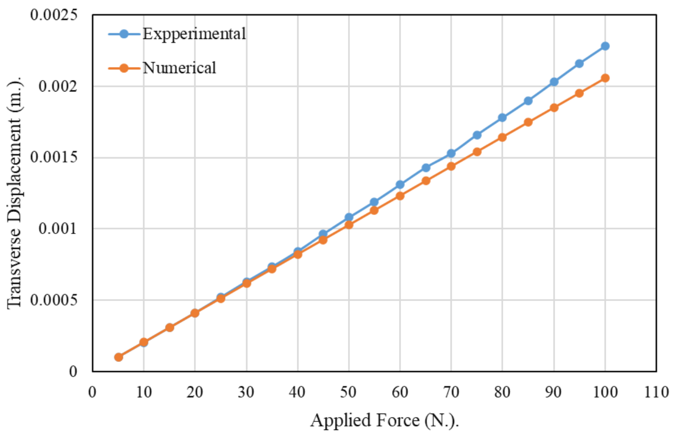


Figure 16. The Comparisons Between the Three-Points Banding of Experimental Test and Numerical Simulation for Exponential FGCO.

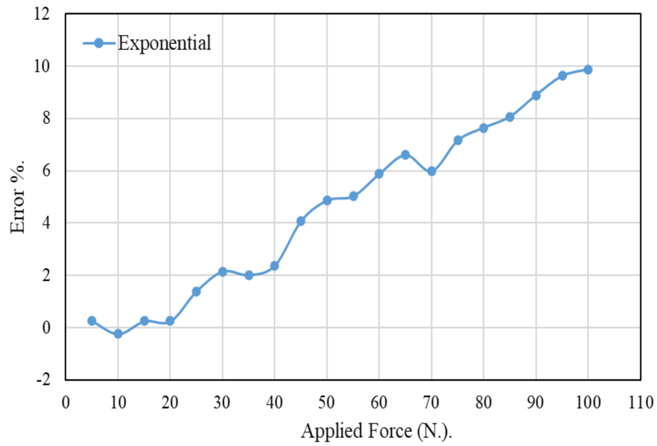


Figure 17. The error percentage between the three-point banding results of the experimental test and numerical simulation for exponential FGCO.

11. Conclusion and Future Work

In this work, the experimental procedure to manufacture the power law and exponential FGMs was described and used to produce specimens of the three-point bending test. The manufacturing process of these FGMS specimens is based on the experimental modulus of elasticity of composite material consisting of polyester and silica partials. The comparison between the experimental and numerical results of the three-point bending of FGMs was made to check the convergence between the two models. From this study, the following points can be concluded:

1- The increase in Silica volume fraction leads to an increase in the modulus of elasticity of the composite material.

2- The proposed experimental procedure is a good method to manufacture the power law and exponential FG beam when the base material is a polymer.

3- The flexural modulus of the functionally graded composite (FGMs) enhanced by (37.1%) for (β=0.5) loaded from the neat polyester. For (β=1), the improvement in the flexural modulus was (33.3%) as compared with pristine polyester. The enhancement in the flexural modulus of (β=5) was (27.78%). For exponential FGMs, the improvement in the flexural modulus was (24.5%).

4- In three-point bending, there is an excellent agreement between the experimental and numerical models of power law and exponential FGMs. The maximum absolute error between them is (14.6 %) and (9.872%) for the power law FGMS (β=0.5) and exponential FGMs respectively.

5- When the power law index increases, the FGMs tend to be brittle material due to the increase in the volume fraction of Silica particles.

In future works, the proposed procedure will be used to manufacture FGMs tensile test specimens with appropriate ASTM to study the equivalent tensile properties of FGMs and try to simulate it.

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تصنيع مواد متدرجة وظيفيا باستخدام قوة الطرد المركزي

الخلاصة *في هذا العمل، تم إنشاء مواد متدرجة وظيفيًا (FGMs) عن طريق خلط راتنجات البوليستر مع ثاني أكسيد السيليكون (SiO_2) بقوة الطرد المركزي لإنشاء خمس طبقات، يبلغ سمك كل منها 1.2 mm . يتم أخذ عينات مركبة الشد ذات أجزاء حجمية متفاوتة (0، 10، 15، 20، 25، و30)٪ قبل تصنيع عينات (FGMs) ، ويتم حساب معامل المرونة الخاصة بها لاحقًا. تم صنع العينة الرابعة باستخدام المعادلة الأسية لوصف توزيع الخواص على طول سماكة العينة ثلاثية النقاط، بينما تم صنع العينات الثلاثة الأخرى باستخدام معادلة قانون القوة عندما كان مؤشر قانون القوة (β) (0.5، 1 و 5). معامل الانحناء للمركب المتدرج وظيفيا (FGMs) المحمل من البوليستر مرتفع بنسبة 37.1% لـ (β=0.5) بالمقارنة مع البوليستر الأصلي، يوجد تحسن معامل الانحناء بنسبة 33.3% لـ (β=1) وكانت الزيادة في معامل الانحناء (β=5) بنسبة (27.78%).وكذلك حصل تحسن في معامل الانحناء بنسبة 24.5% مع (FGMs) الأسي.وقد لوحظت ارتباطات جيدة، حيث بلغ أكبر تباين مطلق بين النتائج العددية والتجريبية 14.6% عندما يكون مؤشر قانون القوة (β) عند (0.5).تم مقارنة نتائج اختبار الانحناء التجريبي مع النتائج العددية باستخدام (ANSYS Workbench) Design Modeler.*

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