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Analytical and numerical flexural properties of polymeric porous functionally graded (PFGM) sandwich beams

E.K. Njim [a], S.H. Bakhy [a], M. Al-Waily [b,*]

[a] Mechanical Engineering Department, University of Technology, Baghdad, Iraq

[b] Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Kufa, Iraq

* Corresponding e-mail address: muhanedl.alwaeli@uokufa.edu.iq

ORCID identifier: https://orcid.org/0000-0002-7630-1980 (M.A.-W.)

ABSTRACT

Purpose: Materials with porosity gradient functionally gradient properties reflect changes in the material's position spatially in response to changes in porosity. One porous metal comprised the FGM core and had not previously been considered in bending analyses.

Design/methodology/approach: Analytical formulations were derived based on the classical beam theory (CBT). According to the power-law scheme, the material properties of FG beams are supposed to vary along the thickness direction of the constituents.

Findings: The results show that the porosity and power gradient parameters significantly influence flexural bending characteristics. It is found that there is a fair agreement between the analytical and numerical results, with a maximum error percentage not exceeding 5%.

Research limitations/implications: The accuracy of analytical solutions is verified by employing the finite elements method (FEM) with commercial ANSYS 2021 R1 software.

Practical implications: FGM beams' elastic properties with an even porosity distribution through-beam core and bonded with two thin solid skins at the upper and lower surfaces were carried out.

Originality/value: This paper develops an analytical study to investigate the flexural problem of a functionally graded simply supported sandwich beam with porosities widely used in aircraft structures and biomedical engineering. The objective of the current work is to examine the effects of some key parameters, such as porous ratio, power-law index, and core metal type, on the flexural properties such as bending load, total deformation, and strain energy.

Keywords: Flexural analysis, PFGM, Sandwich beam, Polymer porous metal, Failure map, FEM

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ANALYSIS AND MODELLING

1. Introduction

Materials characterized by continuously varying properties are referred to as functionally graded materials (FGMs). As a result, they are used in the aerospace, defense, marine, and automotive sectors. Scientists in Japan developed FGMs originally for aerospace structures, and they are now being used for a wide range of different applications. Various fabricating methods are available to assemble FGMs from two or more materials [1]. Compared to conventional sandwich structures, using a functionally graded porous core material (FGPM) increases because these materials can reduce residual, thermal, and mechanical stresses generated between the core and the skin. It can become a more effective core material due to its excellent characteristics [2]. Because of their importance in biomaterial engineering is developed by functionally graded materials with porosity and microstructure gradients [3].

The production of porous functionally graded materials, FGPMs, is typically achieved by modulating pore volume or porosity concentration continuously or gradually [4,5]. In sandwich structures with composites, FGMs with modified chemical compositions, porosity, and microstructure gradients are developed to minimize collision damage [6]. The mechanical behavior of the FG porous sandwich structures has recently been studied by many scientists worldwide. Extensive research has been conducted on the flexural behavior of sandwich structures made of honeycomb, foam, and composite materials [7-9]. Using different types of core materials and mesh reinforcement, Shaaban et al. [10] studied the flexural behavior of lightweight ferro-cement beams. The study examined many issues, such as the first crack loading and deflection, the ultimate crack loading and deflection, the ductility index, strain characteristics, crack pattern, and failure mode.

The bending problem of functionally graded structures with important parameters, including volume fraction index, support and loading conditions, and beam configuration, has been studied and introduced in Refs. [11] and [12]. These sandwich beams are composed of two isotropic faces and a porous core with different gradients of internal pores. Bending experiments of FGM structures having an exponentially graded core with top and bottom face sheets composed of pure ceramic and pure metal have also been studied by Karakoti et al.[13] using the finite element method. Xavior et al. [14] contributed a more detailed experimental study utilizing the tensile, compressive, and 3-point bending flexural test methods to investigate the failure of segmented FG beams made of porous polymer materials. The bending behavior of sandwich composites using fiber-reinforced syntactic foam and syntactic foam core has also been studied [15-17]. Simultaneously, the flexural response was determined for the functionally graded polymeric composite beams by conducting a three-point bending test and a 3-D finite element simulation [18]. Hohe et al. [19] carried out a combination of gradient porous material experiments and numerical design for multifunctional aerospace applications with functionally gradient materials as sandwich cores, using combined numerical and experimental methods.

Koutoati et al. [20] investigated a numerical model for static and free vibration analysis of an FGM sandwich beam with a porous material core using shear models and Abaqus software. Kaddari et al. [21] examined functionally graded porous structures' bending and free vibration behavior resting on elastic foundations using a new quasi-3D model. Seyedkanani et al. [22] conducted different flexural tests on 3D printed samples to examine designs of FGM practicality for improving the characteristics of lightweight structures. FEA verifies the experimental results.

The three-point bending test and impact behavior of carbon/epoxy composites modified with titanium dioxide nanoparticles were studied by [23]. Hanon et al. [24] studied the mechanical behavior of 3D printed FGM samples consisting of PLA and HT-PLA. Jing [25] conducted various experiments to examine the effect of low-speed impact on FG beam response under different energy values. The multi-objective design optimization of the sandwich beam was carried out. The simulation results show that the percentage of core absorbed energy decreases as the impact energy increases.

The ballistic limit velocity of sandwich panels with wired cores and aluminum face sheets in standard impact with cylindrical projectiles was studied numerically and experimentally by Avila et al. [26]. The main finding of this study was that the ballistic limit of sandwich panels is increased with the reduction of wire diameter, which leads to an increase in the number of rows and core thickness. In addition, A. Avila and M. Kamemi examined the ballistic resistance of sandwich constructions with aluminum face sheets and variable density polymer foam cores [27]. During the experiments, steel cylindrical projectiles with hemispherical noses were used. The results highlight that higher average densities of foams, along with an increase in core thickness, result in a better performance in increasing ballistic velocity limit and absorbing energy.

In a sandwich panel composite with aluminum face sheets, M. Kazimi [28] investigated the effect of changes in polyurethane foam core density on the quasi-static penetration process and energy absorption characteristics experimentally by keeping the core thick and mass constant. It is evident from the results that sandwich panels with a decreasing density foam core create more contact force. A shear plug failure in the front face sheet and a petalling loss in the back face sheet is also related to the indenter with decreasing and constant densities in the sandwich panels.

The present study investigates the influence of porosity and material gradation on the bending behavior of porous FG beams having a variation in stiffness through thickness using flexural analysis of a novel functionally graded porous polymer sandwich beam. A mathematical model to calculate the sandwich flexural stiffness, the maximum bending strength load, and the deflections tested on flat sandwich beams with porosities was developed using various parameters (core height, porosity parameter, and power-law index). The analytical results were validated by using a numerical method using finite elements. This paper is arranged as follows: section two introduces a theoretical investigation of the FG structure. FEA is described in section 3 as a means of verifying calculations. Section 4 presents the results, with helpful discussions, of the flexural test of the imperfect FG sandwich beam. Section 5 of the paper contains some crucial conclusions related to the flexural behavior of FG sandwich beams with an even distribution of porosities and practical suggestions for future work.

2. Mathematical formulation of FGM

A ceramic-metal beam made of FGM was commonly considered in most previous works found in the literature. As shown in Figure 1, for a beam with length (L) and thickness (*h*), 1, the top surface is assumed to be ceramic-rich (z = h/2) and gradually varies to the bottom surface (*z* = - *h*/2). Due to defects in the manufacture of the FGM beams, the porosity distribution would be even across the beam thickness. Thus, by introducing a power-law distribution scheme, the volume fraction of the upper constituent could then be assumed to be of the form [29].

$$V_1(z) = \left(\frac{z+\frac{h}{2}}{h}\right)^g \qquad (1)$$

The corresponding volume fraction of the mixture can be written as below:

$$V_1(z) + V_2(z) = 1 \qquad (2)$$

V_1 denotes the upper surface volume fraction, V_2 signifies the lower surface volume fraction, and g represents a power-law variation index (g = 0) describing material property variation in thickness. The effective material properties of the FG beam can be formulated as:

$$P(z) = (P_1 - P_2)\left(\frac{z+\frac{h}{2}}{h}\right)^g + P_2 \qquad (3)$$

In Equation (3), P_1 and P_2 are the corresponding material properties of the upper and lower constituents of the FG beam, respectively. The Poisson's ratio is assumed to be constant over the thickness for metallic and polymeric cores based on experimental results presented in Ref. [30].

In the current investigation, it is assumed that the beam is made up of only one metal with a porosity volume fraction of ($\alpha << 1$) that is distributed evenly in the FG core, and the suggested volume fraction rule can be expressed as [30]:

$$V_p(z) = V_m - \alpha . V_m\left(\frac{z}{h}+\frac{1}{2}\right)^g \qquad (4)$$

For example, $g = 0$, $V_p(z) = V_m - \alpha V_m$, while $g = V_p = V_m = 1$, where V_p is the total volume of porous metal, V_m is the volume of core metal, and α is the porosity parameter. Consequently, the proposed mechanical properties of the FGM porous metal can be represented as:

$$P(z) = P_m - \alpha . P_m\left(\frac{z}{h}+\frac{1}{2}\right)^g \qquad (5)$$

Here, P_m is the value of the material properties of the core metal of the FG beam. Thus, for the homogenous beam ($\alpha = 0$), while for the imperfect FG beam, the material properties can be expressed as:

$$E(z) = E_m - E_m . \alpha\left(\frac{z}{h}+\frac{1}{2}\right)^g \qquad (6)$$

$$\rho(z) = \rho_m - \rho_m . \alpha\left(\frac{z}{h}+\frac{1}{2}\right)^g \qquad (7)$$

a) b)

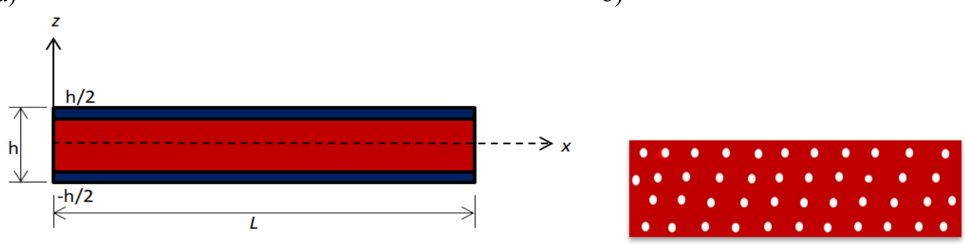

Fig. 1. a) Geometry of FGM beam, b) Porous distribution through-beam thickness

3. Suggested mathematical modeling for bending characteristics of PFGM sandwich beams

According to the failure map shown in Figure 2, the failure modes and their critical loads of FG sandwich beams can be represented in five failure categories in flexure, including [31]:

1) skin yielding;
2) skin wrinkling;
3) failure by core shear; and in limited applications, failure may occur by
4) indentation of the core; and
5) adhesive bond failure.

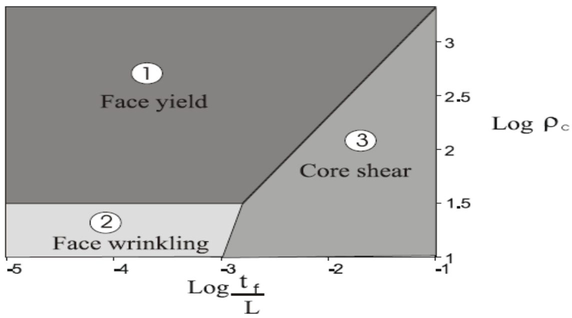

Fig. 2. Three-point bending failure mode map for a beam having aluminum skins and an FG core [32]

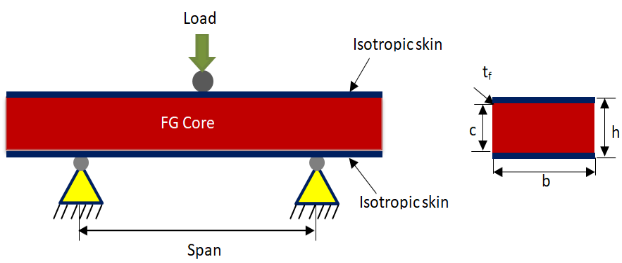

Fig. 3. Three-point bending modeling for FGM porous sandwich beams

In a 3-point bending test, the total deformation (δ) due to bending and shear at the beam midspan may be obtained by using the following Equation [31]:

$$\delta = \delta_b + \delta_s = \frac{Fl^3}{48(EI)_{eq}} + \frac{Fl}{4(AG)_{eq}} \quad (8)$$

where F is the bending load, l is the span, A: area of the core, as shown in Figure 3, and G: modulus of shear. So, the overall stiffness of these components can be represented in the following forms:

$$(EI)_{eq} = \left(\left(\begin{array}{c} E_f\left(\frac{bt^3}{12} + (bt)\, d_u{}^2\right) + \\ E_f\left(\frac{bt^3}{12} + (bt)\, d_1{}^2\right) \end{array} \right) + \atop \sum E_i\left(\frac{b\, c_i{}^3}{12} + (bc_i)\, d_i{}^2\right) \right) \quad (9)$$

Moreover, that the equivalent shear rigidity is represented as:

$$(AG)_{eq} = \frac{bd^2G_c}{c} \quad (10)$$

The subscripts c and b refer to the core thickness and the beam's width, respectively. Furthermore, the subscript d is the distance of the centroid between the upper and lower skins; when $d \approx t_c$, Equation (10) is reduced to:

$$(AG)_{eq} = bdG_c \quad (11)$$

$$G_c = \frac{E_c}{2(1+\nu)} \quad (12)$$

$$E_c = E(z) = E_m - E_m\alpha\left(\frac{z}{h} + \frac{1}{2}\right)^g \quad (13)$$

The bond failure type represented by the lower limit force is given as:

$$F_{bf} = 4bc_i\left(\frac{t}{l}\right)\sqrt{\frac{SE_f}{t}} \quad (14)$$

where c_i is the thickness of each core layer i, t is the thickness of the skin, E_f is the face-sheet elastic moduli, and S is the rate of released strain energy, which is given by:

$$S = \frac{M^2}{2b(EI)_{eq}} \quad (15)$$

The maximum bending moment M is calculated as:

$$M = \frac{Fl}{4} \quad (16)$$

Failure maps reveal that face yielding is the most common type of failure. Typically, it occurs when the normal stress on the face sheet is close to its strength (σ_{yf}). So, for an FGM-core sandwich beam, the yielding stress for the face-sheet can be expressed as follows:

$$\sigma_f = \left.\frac{Fly_iE_f}{4(EI)_{eq}}\right|_{max} = \sigma_{yf} \quad (17)$$

Each layer centroid is measured in terms of its distance from the neutral axis, y_i.

4. Finite element modeling

Modeling complex three-dimensional composite materials is easier with finite element methods (FEM) because it is more accurate [33-37]. An analysis of the effects of porosities on a 3-point bending beam of FG material was performed utilizing 3D finite element modeling and analysis.

ANSYS finite element software was used to develop the models. Numerical simulations relying on the FE technique were provided in the ANSYS 2021 R1 release software to measure numerical findings with those obtained during the tests. A flexural test measures a part's overall strength and stiffness and checks that the proportions are correct. Furthermore, FEA techniques simulate similar loading conditions to validate experimental results [38-40].

As shown in Figure 3, numerical analyses of 3-point bending were performed for beams with a core made of FGM (polymer) and a face sheet made of isotropic material (Al). The FG core was modeled as a shell structure, whereas the face sheets were solid blocks. In FE simulations, the mechanical characteristics of the FG core were estimated via equations (6) and (7), as and Layers of metal skin with a thickness of 0.5 mm are regarded as isotropic materials whose properties have already been characterized, as given in Table 1.

Table 1.
Material properties employed in the FG sandwich beam [41]

Property	FG core (PLA)	Face Sheets (Aluminum)
E, GPa	2.4	70
ρ, kg/m^3	1360	2702
ν	0.38	0.33

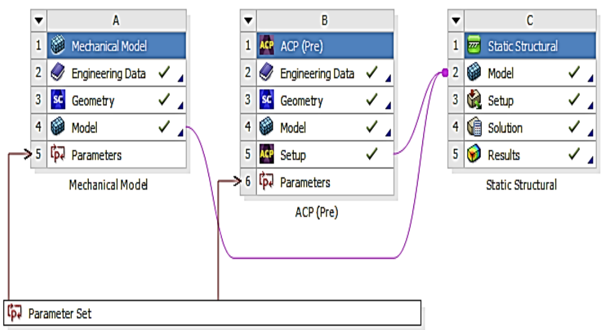

Fig. 4. View of analysis stages via ANSYS tool

Figure 4 show the simulation steps of the three-point bending test as ANSYS generated it. According to the symmetry of the geometry and loads of the examined surfaces, only half of the model was constructed. A composite shell element is used as the skin of the beams (SHELL99), and brick elements are used as the FG core (SOLID45) [ANSYS HELP].

Figures 5 and 6 show the mesh generated and boundary conditions employed in conducting this test. The solid support was provided, while forced displacement was used to control the indenter. As a result, the reaction forces at the support may be used to evaluate the bending forces. The example of strain energy results is illustrated in Figure 7.

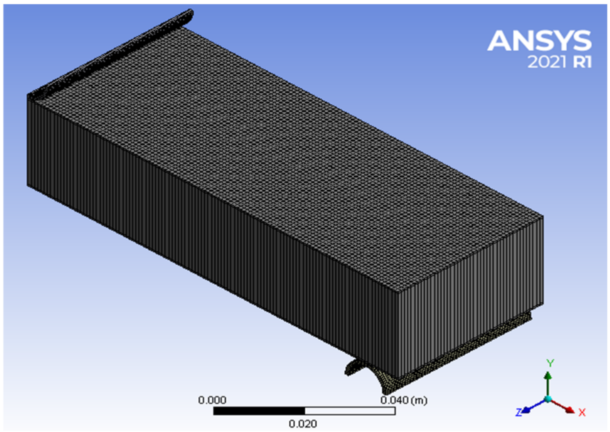

Fig. 5. Beam mesh generating

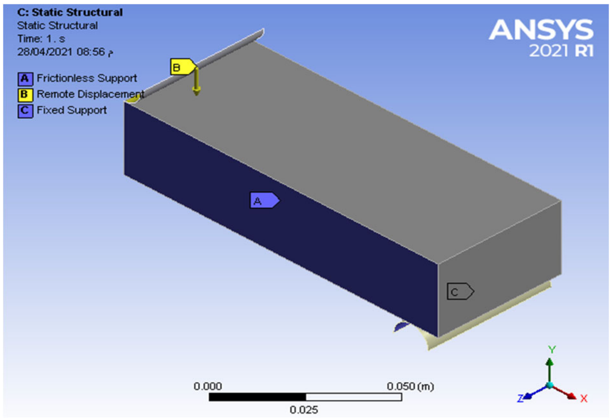

Fig. 6. Beam modeling of 3-point bending

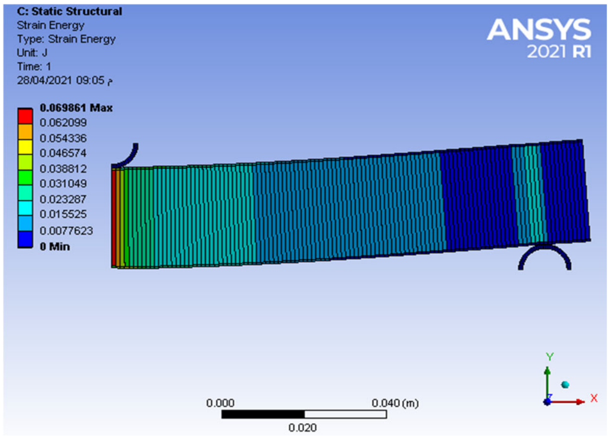

Fig. 7. Strain energy results example

5. Results and discussion

This work carried out an analytical investigation to analyze the FGM sandwich beams flexural problem with porous metal. The materials are assumed to be homogenous in the upper and lower beam parts, while the FGM part consists of one metal with a porosity gradient through-thickness direction. A numerical investigation using ANSYS 2021 R1 software for verification purposes was also employed. The results calculated include the maximum bending load, total deflection, and strain energy of the simply supported FGM sandwich beam with various parameters, including porosity coefficient, core height, and gradient index.

The sandwich beam dimensions were made according to the ASTM C393 standard [42] (i.e., L = 230 mm, W = 45 mm), while various core heights were used (C = 10, 15, 20, 25, and 25 mm). Various porosity parameters were employed (α = 0 to 0.3), while power-law indices changed from (*g* = 0 to 10). The following dimensionless relation is used to estimate the deflection parameter $\overline{w}$ [43]:

$$\overline{w} = \frac{100E_m bh^3}{Fl^3}.w\,(x,z) \tag{18}$$

where the subscript *m* represents metal used. Table 2 gives a comparison of analytical and numerical solutions for and maximum bending load with two porosity parameters (α = 0.1 and 0.3) and the gradient index (*g* = 1) for various core heights (10), 15, 20, and 25 mm). Equation 17 was used in analytical solutions, while ANSYS tools were used in numerical solutions. It can be concluded that the maximum bending load decreases with increasing porosity factor due to the decrease in material rigidity. The results show an acceptable error between the analytical and numerical solutions, with a maximum discrepancy of no more than 5%. This percentage is affected by the power-law index and porous factor for the same FG beam geometrical properties.

Table 2.
The analytical and numerical maximum bending load (N)

Porosity, Beta	Power-law index, k	FG core height, mm	Ana.	Num.	Error, %
0.1	1	10	573	558.7	2.50
0.1	1	15	1140	1109	2.72
0.1	1	20	2200	2160	1.80
0.1	1	25	3830	3678	3.73
0.3	1	10	485	470	3.09
0.3	1	15	967	935	3.31
0.3	1	20	1850	1795	2.97
0.3	1	25	3425	3380	1.31

On the other hand, Table 3 presents the analytical and numerical maximum bending deflection at two different porosity parameters (α = 0.1 and 0.3). In addition, as seen from Table 3, the maximum difference was 4.24 %, which occurred at a core height of 25 mm and a porosity of 0.3. As can be seen, there is suitable consistency between the proposed analytical solution and that obtained by FEA.

Table 3.
The analytical and numerical maximum bending deflection, mm

Porosity	Power-law index, k	FG core height, mm	Ana.	Num.	Error, %
0.1	1	10	13.8	13.33	3.526
0.1	1	15	11.8	11.48	2.787
0.1	1	20	9.56	9.36	2.137
0.1	1	25	7.96	7.79	2.182
0.3	1	10	13.2	12.87	2.5
0.3	1	15	11	10.79	1.19
0.3	1	20	8.65	8.39	3.099
0.3	1	25	5.9	5.66	4.240

Table 4
Material characteristics of various FG core types used in numerical simulation [44]

FG core type	E, MPa	ρ, kg/m^3	ν
Polyethylene	1100	950	0.42
PEEK – 30 % CF	7700	1410	0.44
PETG	2100	1290	0.36
ABS	3250	1425	0.4
TPU	2400	1450	0.36

Table 4 reports details of material properties employed in the simulation. The porous metals used include polyethylene, PEEK 30% CF, Acrylonitrile Butadiene Styrene (ABS), Polytropic acid (PLA), Thermoplastic polyurethane (TPU), and Polyethylene terephthalate with glycol (PETG). Figure 8 shows the numerical results of the maximum bending load of a simply-supported sandwich beam using five types of porous polymer cores. The maximum bending load variations are given for porosity (α = 0.1, 0.2, and 0.3) at power-law index (*g* = 0.5), a face sheet thickness of 0.5 mm, and a core height of 10 mm. From the results depicted, it is found that the porosity ratio plays an important role in identifying flexural properties. Furthermore, we can also note that the PEEK 30% CF material has higher stiffness than all other types due to the high mechanical properties values utilized. This explains why this type is used in wide applications in the construction of aircraft. For the sake of displaying the changing the total deformation of materials, Figure 9 presents the results of the simply supported beam at a porosity ratio (α = 10%) for various porous metals and a face thickness of 0.5 mm. Different gradient indices (g = 0, 0.5, 1, 2, 5, and 10) were used. The results showed that the total deformation increased with the gradient index, and the differences at high values (i.e., g = 5, 10) are disappeared.

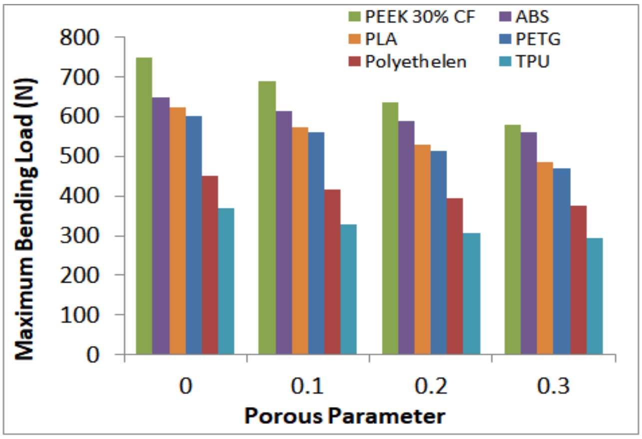

Fig. 8. Maximum bending load for various core metal types at g = 0.5, core height of 15 mm

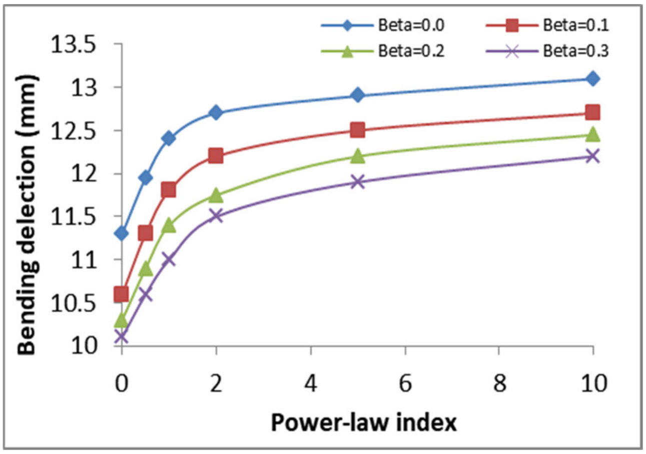

Fig. 9. Bending deflection for power-law indices at the core height of 10 mm

Figure 10 displays the variations of the strain energy of a simply-supported sandwich beam with a porous PLA core, with various porosity factors (α= 0.1, 0.2, and 0.3), volume fraction index (g = 1), and by using four values of core heights (c = 10, 15, 20, and 25mm). Because of the decrease in material toughness, the strain energy decreases with increasing porosity parameters and core height.

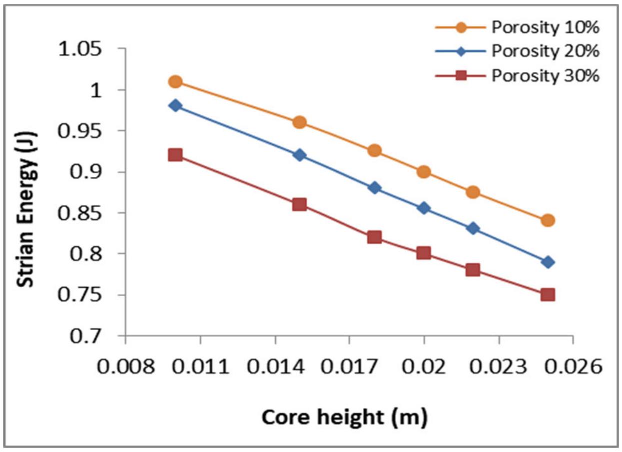

Fig. 10. The strain energy of a simply-supported sandwich beam at power-law index g = 1

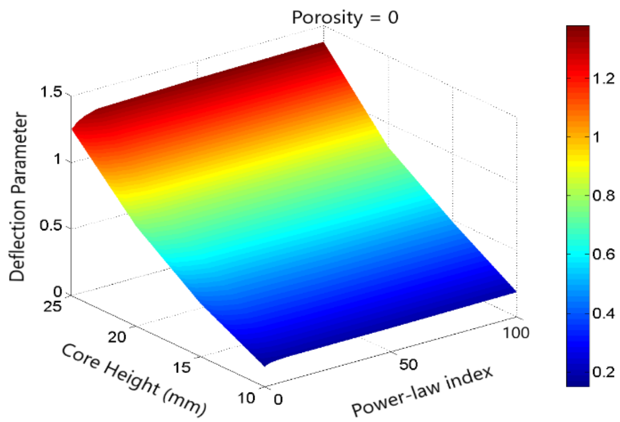

Fig. 11. 3D surface plot of the simply-supported sandwich beam at porosity (α = 0)

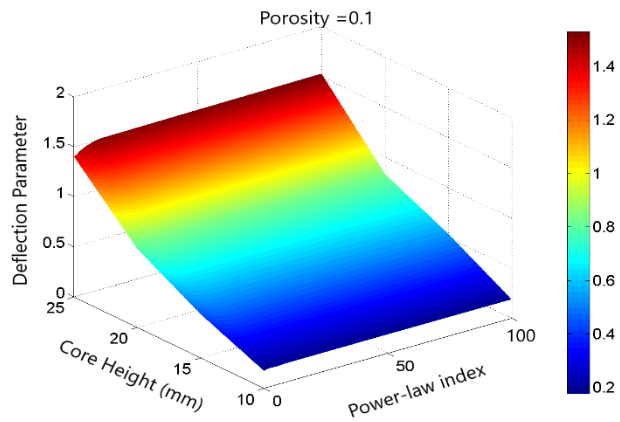

Fig. 12. 3D surface plot of the simply supported sandwich beam at porosity (α = 0.1)

Figures 11-14 indicate the 3D surface generated by MATLAB software in terms of non-dimensional deflection parameters as a function of gradient indices and the core thickness of a simply-supported sandwich beam with a PLA core and aluminum skins. The results show that the deflection parameter increases with both the porosity ratio and the power-law index. The variation in results increases positively with the increase of the volume fraction exponent. It indicates that the beam exhibits more ductility.

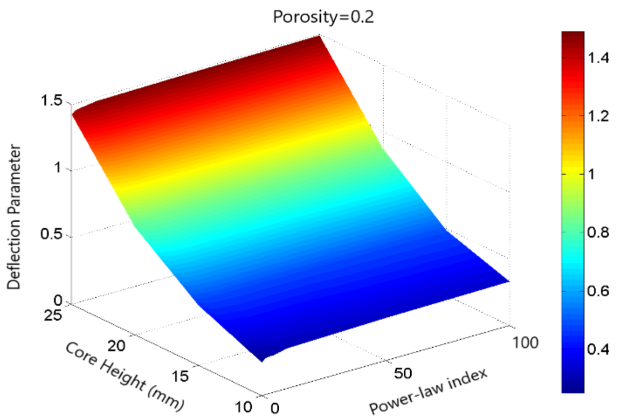

Fig. 13. 3D surface plot of the simply-supported sandwich beam at porosity (α = 0.2)

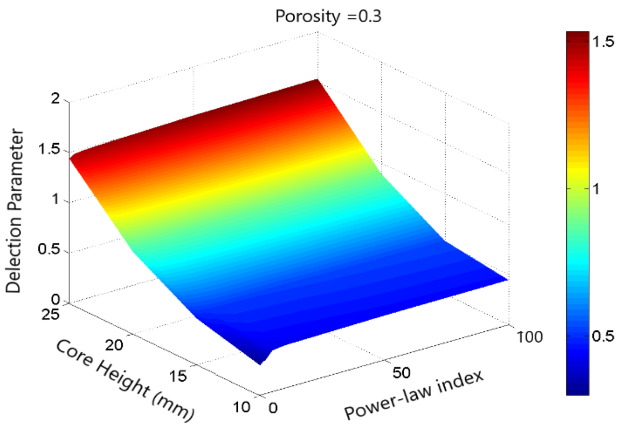

Fig. 14. 3D surface plot of the simply supported sandwich beam at porosity (α = 0.3)

6. Conclusions

The bending analysis of sandwich beams composed of two isotropic faces and a porous core with different gradients of internal pores is studied. The bending Equation for each type of failure is derived using the linear constitutive relationship of the beam based on CBT. The material properties are calculated according to the suggested mixing rules. A comprehensive comparative study was carried out with numerical techniques to verify the accuracy of the analytical solution. The complete numerical results are introduced, including bending, deflection, and strain energy expressed in essential parameters such as power-law index and porosity coefficient. The current work's main conclusions are described as,

1. Based on numerous criteria, this proposed analytical method effectively describes the flexural properties of sandwich beams with porous FG cores.
2. This paper presents the analysis and results of a thorough study of the porous FGM material that would be beneficial in engineering applications.
3. The results show that bending loads decrease with increasing porosity factors and increase with increasing gradient indices. While for both the perfect and imperfect sandwich plate FGM, the dimensionless deflection parameter increases with the power-law index value.
4. Changing the porosity parameter from (α = 0.1 to 0.3) reduces the maximum bending load by 15.3% at a core thickness of 10 mm and a gradient index of 1, while the same variations reduce deflection by 4.3% variations yield a 4.3% reduction.
5. It is desirable to conduct experimental studies and the above proposed analytical solution to gain more valuable knowledge.

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