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Static Behavioral Studies of a 2D Taper Beam using Finite Elements Comprised of Functionally Graded Materials

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Abstract. The study examines the thermal and structural properties of beams made of functionally graded materials (FGMs) using the Finite Element Analysis (FEA) method and Reddy's beam theory. The distribution of material qualities in thickness and length directions is influenced by mechanical and thermal loads. We calculate the stress and deflection of FG beams with a uniform load distribution. Quantitative results demonstrating the effects of multiple factors are provided by the Fusion 360 software. These include the change from alumina (ceramic) to aluminum (metal), boundary conditions, volume fraction distribution, and geometric features.

1 Introduction

FGMs are composite materials that seamlessly transition the material properties between adjacent layers because they are made of a blend of metal (p2) and ceramic (p1). FGMs can enhance fracture resistance qualities and lessen residual, heat, and stress concentration at the layer interface [1]. These materials are mostly used in high-temperature situations such as gas turbine blades, aerospace structures, energy systems, and solid-oxide fuel cells. FGMs are useful in many technical domains, such as high temperature technologies, biomechanics, nanotechnology, tribology, and optoelectronics, because they can tolerate temperatures as high as 1600 °C [2]. Although ceramic materials are incredibly heat resistant, traditional composite materials are frequently inappropriate for usage in high-temperature scenarios due to their intrinsic lack of hardness. Ceramics have been employed in the aircraft industry due of their high strength-to-stiffness ratio; nevertheless, their strength is diminished by high temperatures [3]. Functionally graded material (FGM) is a composite material composed of several stages of materials, typically metals and ceramics. The significant bending-stretching coupling effect of FGMs is well-known. The chemical reaction is shown in Figure 1 [4].

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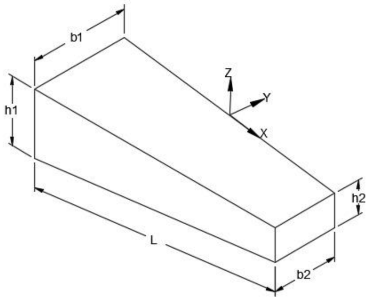


Fig. 1. Configurations taper beam with dimensions and coordinate axes

2 Theory and methodology

With an emphasis on metal-ceramic FGMs with useful applications in aerospace, this work investigates the gradient in FGM beams along length, thickness, and x and z axes [5, 6]. It describes material compositional profiles along gradient directions using mathematical models of exponential and power law distributions. The volume fraction of metal (V_f) is expressed in two directions as a function of continuous power law variation [7, 8].

$$V_f(x,z) = \left(\frac{x}{L}\right)^{k_x}\left(\frac{z}{h(x)}+\frac{1}{2}\right)^{k_z} \tag{1}$$

The length and thickness variation of the material is represented by the "k" value, and the power law indices for the length and thickness of the beam are k_x and k_z. With zero denoting pure ceramic and infinitely large values denoting pure metallic, varying the "k" value represents infinite compositional distributions [9].

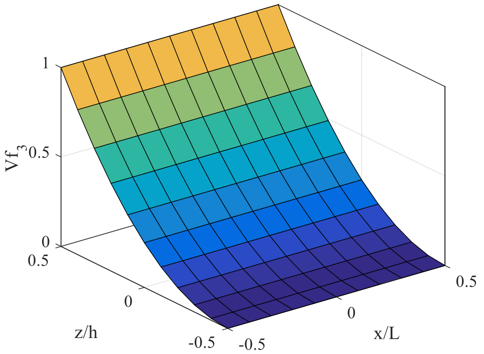


Fig. 2. Metal volume fractions in the thickness (z/h) and length (x/L) directions

The material characteristics of a taper beam made of functionally graded (FG) material, which has an even distribution of qualities, are as follows:

$$P(x,z) = (P_1 - P_2)\left(\frac{x}{L}\right)^{k_x}\left(\frac{z}{h(x)}+\frac{1}{2}\right)^{k_z} + P_2 \tag{2}$$

Material properties of beam, ‘E’, ‘μ’ and ‘ρ’ of FGM is given below.

$$E(x,z) = (E_1 - E_2)\left(\frac{x}{L}\right)^{k_x}\left(\frac{z}{h(x)} + \frac{1}{2}\right)^{k_z} + E_2 \qquad (3)$$

$$\rho(x,z) = (\rho_1 - \rho_2)\left(\frac{x}{L}\right)^{k_x}\left(\frac{z}{h(x)} + \frac{1}{2}\right)^{k_z} + \rho_2 \qquad (4)$$

2.1 Displacement equations of bending

The displacement equations employing HSDT with the unique shear strain function are presented via shear deformation theory.

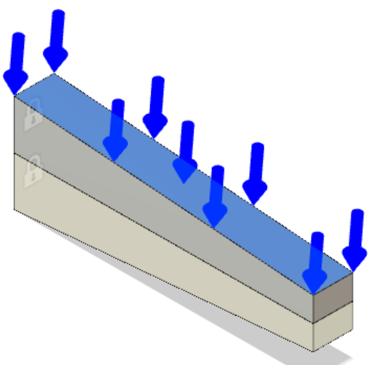
$$U(x,z,t) = u(x,t) - z\frac{\partial w}{\partial x}(x,t) + f(z)\emptyset(x,t) \qquad (5)$$

$$W(x,z,t) = w(x,t) \qquad (6)$$

3 Result analysis

Figure 2 shows how numerical studies employing HSDT under various boundary conditions are used to anticipate the static analysis of the FG beam. The FG beam is made up of two different materials: aluminum metal, which has an elasticity modulus of 70 GPa and a Poisson's ratio of 0.3, and alumina ceramic, which has a modulus of 380 GPa and variations in thickness and length of 0.3.

(a)



(b)

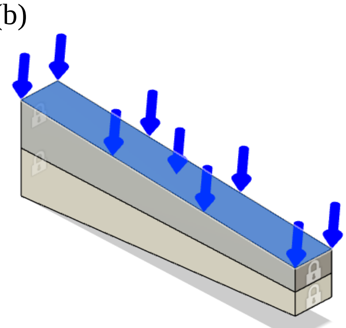


Fig. 3. A functionally graded (a) CF (b) CC beam subjected to a UDL

3.1 Simulation model

To use Fusion 360 software to analyze the properties of functionally graded materials. Engineers can create simulations or import CAD models, constructions, etc. with this software. They can then conduct prototype testing in locations that would not be feasible for them to access, apply operating stresses, evaluate physical reactions, and optimize designs early on. The behavior of multi-layered FGM beams under mechanical and thermal loads can be simulated using this model. A finite element model of a cantilever that is clamped-clamped under UDL conditions is shown in Figure 3 of the accompanying illustration.

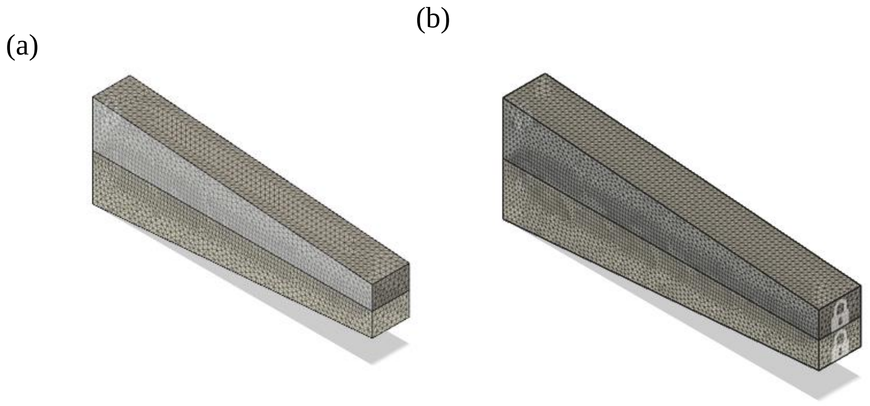


Fig. 4. Model of FGM beam with a) CF and b) CC end conditions in a finite element simulation

4 Results of Numerical Simulation under Mechanical Load and Discussion.

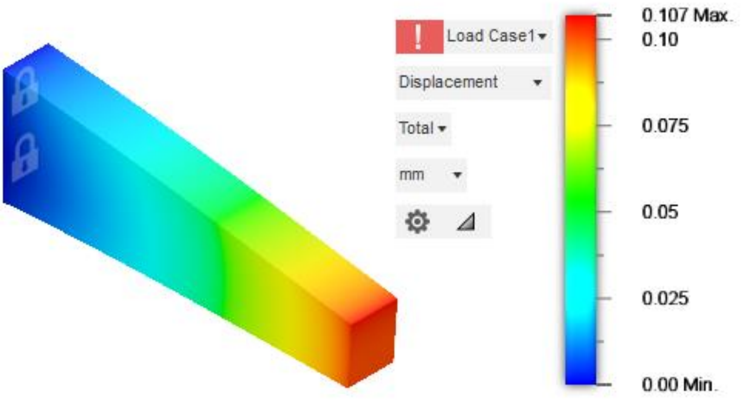


Fig. 5. Plot showing the displacements of the cantilever FGM beam under mechanical stress at (k=0)

The beam's breadth (b = 0.1 m) and thickness (h = 0.1 m) are maintained constant. The length of the beam, L = 0.4 m, is calculated using the slenderness ratio, L/h = 4. Engineers examine functionally graded material properties using Fusion 360 software. Engineers can use it to upload CAD models or construct simulations shown in figure 4 apply operational loads, examine physical reactions, refine designs early, and test prototypes in difficult conditions. "The program can simulate mechanical and thermal loads on multi-layered FGM beams, and it can also create a finite element model with cantilever and clamped-clamped end conditions.

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Table1. Maximum transverse deflection of a cantilever beam under a mechanical load for a variable power-law exponents.

Power-law exponent	Deflection (mm)
K =0	0.107
K=0.2	0.091
K=0.5	0.083
K=1	0.075
K=2	0.069
K =5	0.054
K =10	0.039

A numerical analysis of a clamped free and clamped-clamped functionally graded material (FGM) beam subjected to mechanical deformation as shown in Figures 5 and 6, and stress as shown in Figures 7 and 8, revealed that transitioning the material composition from metal to ceramics reduces the beam's deflection, as illustrated in Table 2.

Fig. 6. Clamped-Clamped FGM beams with a displacement map under mechanical load at (k=0)

Table 2. Maximum clamped-clamped beam deflection for different power-law values Exponent when subjected to a force

Power-law exponent	Deflection (mm)
K=0	0.00600
K=0.2	0.00485
K=0.5	0.00410
K=1	0.00319
K=2	0.00126
K=5	0.00101
K=10	0.00082

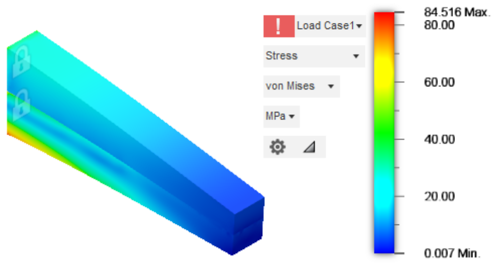

Fig. 7. Stress curve of cantilever beam under mechanical load.

Table 3. Maximum cantilever taper beam stress value under mechanical load for different power-law exponent values

Power-law exponent	Stress-σ_x (N/mm^2)
K=0	84.516
K=0.2	94.327
K=0.5	112.721
K=1	110.846
K=2	86.079
K=5	70.976
K=10	63.036

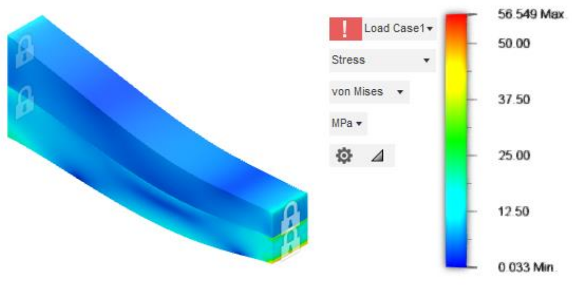

Fig. 8. Clamped-clamped FGM beams under mechanical load: stress map along x direction

Table 4. Maximum stress value for various power-law exponent values in a clamped-clamped taper beam subjected to mechanical load

Power-law exponent	Stress-σ_x (N/mm^2)
K=0	56.549
K=0.2	65.207
K=0.5	79.624
K=1	72.006
K=2	56.335
K=5	51.805
K=10	43.686

5 Results of numerical simulation subjected to thermal load

This computational study examines the static characteristics of a functionally graded clamped-clamped beam subjected to thermal stress. The FGM beam is subjected to a constant temperature. The coefficient of thermal conductivity the thermal expansion of ceramics is lower than the coefficient of thermal expansion. The metal is undergoing expansion. Figure 11 illustrates the occurrence of distortion. Graph the isotropic cantilever beam for k = 0 subjected to thermal stress. The displacement of the isotropic substance (k=0) occurs solely in the axial direction. When the thickness degree modifies the coefficient of thermal expansion, k=1.0. As a result, the most significant deviation occurred at y, in a lateral direction. Figure 11 provides a comprehensive summary of the subject. The maximum deflection of the cantilever beam and the simply supported beam subjected to various thermal loads the indexed power law values are presented in Table 5. Refer to Table 6 in that order.

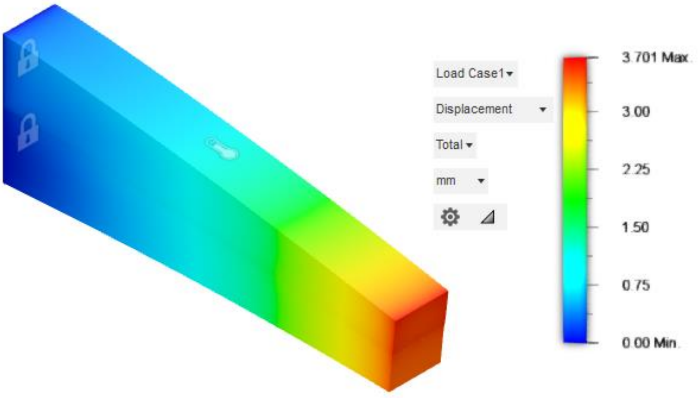

Fig. 9. The x-axis displacement plot of a cantilever FGM taper beam subjected to a thermal load at k=0

Table 5. Maximum transverse deflection of a cantilever beam subject to a thermal load at a uniform temperature of 500 ^{0}C for different power-law exponent values.

Power-law exponent	Deflection(mm)
K=0	3.701
K=0.2	6.240
K=0.5	13.541
K=1	12.421
K=2	9.068
K=5	7.534
K=10	6.392

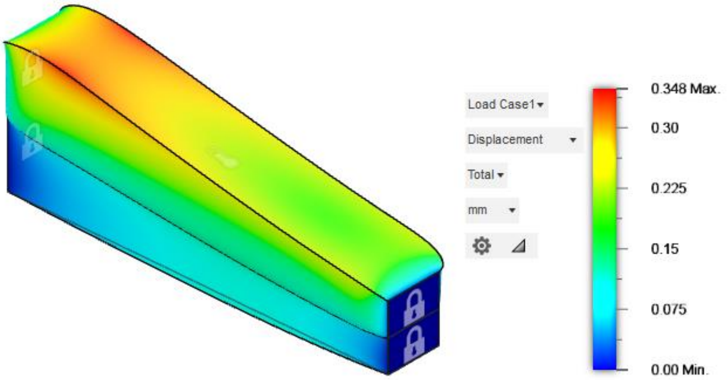

Fig. 10. Displacement figure for clamped-clamped FGM beams under thermal load at k=0, along x direction

Table 6. Maximum transverse deflection of a clamped beam under thermal load (uniform temperature = 5000 °C) for different values of power-law exponents

Power-law exponent	Deflection (mm)
K=0	0.348
K=0.2	0.592
K=0.5	0.928
K=1	0.720
K=2	0.451
K=5	0.393
K=10	0.218

The thermal displacements are also identified in this numerical study and are summarized in tables 5 and 6. It is implied by Figures 9 and 10 that thermal displacement is dispersed at k=0.

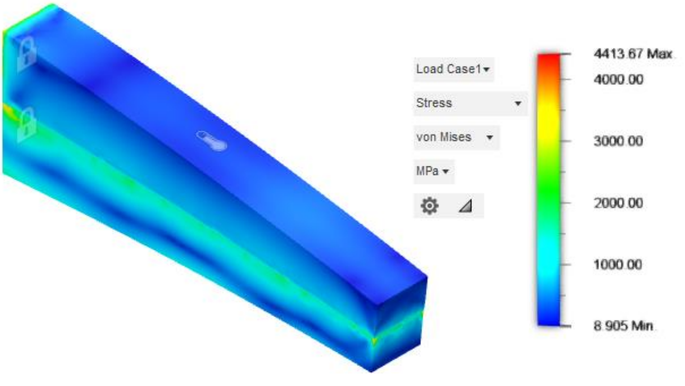

Fig. 11. Stress map for clamped free FGM beam under thermal load at k=0 in the x direction.

Table 7. Maximum clamped-free beam stresses under thermal load at different power-law exponent values (uniform temperature=500^{0}c)

Power-law exponent	**Stress-σ_x (N/mm^2)**
K=0	4413.67
K=0.2	4820.20
K=0.5	5130.66
K=1	3820.89
K=2	3692.12
K=5	3172.481
K=10	2998.274

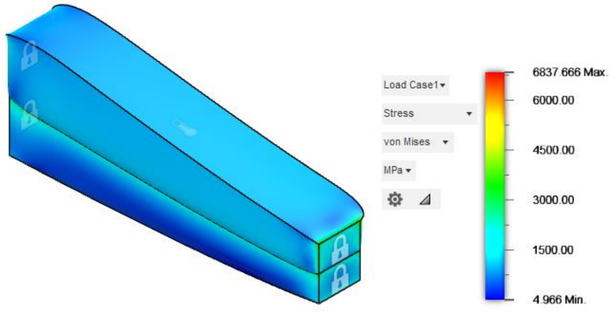

Fig. 12. Stress diagram for clamped-clamped FGM beam under thermal load at k=0 along x direction

Table 8. Maximum clamped-clamped beam stresses under thermal load at different power-law exponent values (uniform temperature=500^{0}c)

Power-law exponent	**Stress-σ_x (N/mm^2)**
K=0	66837.666
K=0.2	6962.150
K=0.5	6108.542
K=1	5823.254
K=2	5495.152
K=5	5089.527
K=10	4825.781

Tables 7 and 8 of this numerical study also include the thermal stresses. When k=0, it is implied by Figures 11 and 12 that thermal stresses are dispersed.

This work investigates the stress components under mechanical and thermal loads in a clamped-clamped beam and a cantilever beam along the x direction. We determine the maximum stress values for both beams; the clamped-clamped beam shows an increase to the first value, while the cantilever beam shows a reduction with metal grading to ceramic.

6 Conclusions

Using Fusion 360, examine the static behavior of a FG clamped-clamped and clamped free beam under a load that is distributed equally. We reconcile the numerical data with the references and theoretical value. This study suggests determining the thickness and length of the FGM beam. The static behavior (deflection and stress) of the FGM beam is further affected by the mechanical load, boundary conditions, and material grading. To achieve the intended goals of minimizing displacements and stresses in a beam-type construction, designers might further modify the material properties of the FG beam by choosing a suitable power-law exponent.

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