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Optimizing Vehicle Structures Using Functionally Graded Materials of Aluminum and Carbon Fiber Reinforced Polymer Composites

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Abstract

This article investigates the optimization of vehicle structures through application of functionally graded materials (FGMs), specifically aluminium and carbon fibre reinforced polymer (CFRP) composites. Such materials, known as FGMs, are characterized by spatial variations in composition and structure designed to improve so-called performance attributes. For the purposes of this research, the material properties of aluminium and CFRP composites are taken to be randomly distributed in thickness direction of a FGM according to sigmoid, power law and exponential distributions. We seek to capitalize on the high strength to weight ratio of CFRPs and the excellent ductility and thermal conductivity of aluminium, while successfully integrating these materials with graded transitions. Mechanical behaviour, stress distribution and potential failure mode of vehicle components fabricated from these FGMs were evaluated through computational simulations. Results indicate the use of graded transitions improves load bearing capacity, impact resistance, and overall durability over homogeneous materials. The contribution of this study is valuable in the design and manufacturing of next generation vehicle structures, where the use of FGMs is demonstrated to provide superior performance, safety, and efficiency.

Keywords: Functionally graded materials, aluminium, CFRP composites, vehicle structures, optimization

INTRODUCTION

The automotive sector is experiencing an escalating demand to enhance vehicle performance, safety, fuel efficiency, and environmental sustainability. The optimization of vehicle structures represents a critical domain of inquiry in this transformation. Historically, vehicle architectures have predominantly utilized homogeneous materials—such as steel or aluminum—thereby achieving a compromise among strength, weight, and economic considerations. Nevertheless, as the exigency for lighter and more efficient vehicles intensifies, traditional materials are increasingly being augmented or supplanted by advanced materials endowed with superior characteristics. Functionally graded materials (FGMs) have garnered considerable attention within this category of advanced materials due to their provision of multiple material advantages within a singular component [1].

Functionally graded materials are characterized by a spatially varying composition and structure throughout their volume, which engenders corresponding variations in material properties. This tailored approach can be employed to align with specific performance criteria, rendering FGMs

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a versatile alternative for various engineering applications [2]. Initially conceived for aerospace and defense sectors, where materials must withstand extreme thermal and mechanical conditions, FGMs have also found relevance within the automotive industry owing to their potential to enhance vehicle structural integrity [3].

The Significance of FGMs in Vehicle Structures

Functionally graded materials confer numerous benefits in vehicle structures, facilitating the seamless amalgamation of diverse materials, which in turn bolsters mechanical performance and longevity [4]. Combinations of metal-ceramic and polymer materials yield structures that are both lightweight and robust—an essential requirement for fuel efficiency and reductions in emissions. Furthermore, by permitting gradual transitions in material properties, FGMs enhance structural integrity and safety through optimized distribution of stress and strain.

Economical FGM Production Techniques

A variety of cost-effective methodologies for the fabrication of FGMs encompass additive manufacturing, centrifugal casting, and powder metallurgy [5]. Additive manufacturing affords precise control over material distribution, rendering it particularly suitable for intricate gradations. Centrifugal casting serves as an effective technique for FGMs exhibiting cylindrical symmetry, and is widely implemented in automotive applications. Powder metallurgy strikes a balance between economic viability and material quality, facilitating the production of FGMs with customized properties. These techniques can be fine-tuned to satisfy the automotive industry's requisites for lightweight, high-strength components at diminished costs.

LITERATURE REVIEW

Functionally graded materials (FGMs) represent a distinctive category of materials characterized by the spatial variation of properties derived from their constituent elements, which are systematically altered through modifications in composition and microstructure. The mechanical and thermal characteristics of these materials can be precisely engineered to optimize vehicular structures, thereby facilitating the application of FGMs across a broad spectrum from thermal barrier coatings in aerospace domains to automotive engineering [6]. Within the context of automotive design, FGMs fulfill critical performance standards pertinent to safety and efficiency, thereby rendering them an exemplary selection [7].

Recent advancements indicate a growing integration of FGMs within the realm of vehicle manufacturing. Their unparalleled performance characteristics—including diminished weight, augmented strength, and superior resistance to both impact and fatigue—render FGMs exceptionally advantageous in addressing contemporary demands for reduced fuel consumption and enhanced sustainability [8]. They play a pivotal role in meeting stringent environmental regulations while simultaneously catering to consumer preferences for more environmentally friendly vehicles [9]. The incorporation of FGMs into automotive design signifies a substantial technological advancement, facilitating the progression towards eco-conscious electric vehicles and autonomous driving systems [10]. This transformation holds the potential to significantly refine the driving experience, bolster crashworthiness, and integrate energy-absorbing mechanisms during collision events, thereby addressing critical safety and environmental imperatives [11].

In light of the rapid evolution within the automotive sector, FGMs possess considerable promise for the engineering of innovative applications that will redefine vehicle performance and sustainability paradigms [12]. These advancements are poised to enable vehicle designs to leverage lighter and stronger materials while aligning with global initiatives aimed at minimizing carbon emissions and advancing green technologies for enhanced transportation efficiency [13]. Collaborative efforts between researchers and industry practitioners continue to adapt FGMs to specific engineering challenges, resulting in significant innovations in components characterized by increased wear resistance, reduced material wastage, and enhanced energy efficiency [14].

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The integration of smart materials within FGMs is also feasible, facilitating real-time monitoring and self-repairing capabilities that extend the operational lifespan of products [15]. For instance, aluminum and carbon fiber reinforced polymer (CFRP) composites amalgamate high structural integrity with lightweight characteristics [16]. Empirical studies have substantiated that these materials mitigate stress and deformation under loading conditions while improving performance and maintenance efficacy in both aerospace and automotive sectors [17]. Additional research has underscored the critical role of FGMs in aerospace applications, optimizing both strength-to-weight ratios and structural efficiency [18].

The gradation of properties plays a crucial role in augmenting bending resistance and stress distribution under dynamic loading conditions within transportation vehicles [19]. Functionally graded aluminum-based composite foams have demonstrated stable load-bearing capabilities and impact resistance [20]. Likewise, FG aluminum/ceramic composites exhibit exceptional mechanical properties and wear resistance, positioning them as viable candidates for automotive implementations. Furthermore, investigations into aluminum-CFRP composites validate their compatibility for adhesive bonding, ensuring structural integrity under various operational conditions [6].

To effectively incorporate FGMs into vehicular structures, further investigation is warranted regarding cost-effective manufacturing methodologies, the validation of experimental outcomes, and the exploration of novel material combinations [7]. Such endeavors will enhance performance and sustainability, ultimately guiding automotive engineering towards a transformative paradigm. With these advancements, the industry is poised to enter a new epoch of smart mobility solutions that foster continuous, safe, efficient, and environmentally responsible growth [8].

MATERIALS AND METHODS

Material Properties

For this study, two materials were selected for creating functionally graded materials (FGMs): aluminium and carbon fibre reinforced polymer (CFRP) composites. The choice of these materials was based on their mechanical properties and their common usage in vehicle structures.

- **Aluminium (Al):**
  - *Density*: 2,700 kg/m³
  - *Young's modulus*: 70 GPa
  - *Poisson's ratio*: 0.33
  - *Yield strength*: 250 MPa
- **Carbon Fiber Reinforced Polymer (CFRP):**
  - *Density*: 1,600 kg/m³
  - *Young's modulus*: 80-150 GPa (depending on fibre orientation)
  - *Poisson's ratio*: 0.2
  - *Tensile strength*: 600-1,000 MPa (depending on fibre orientation)

These materials were chosen for their complementary properties. Aluminium offers good ductility and corrosion resistance, while CFRP provides high strength-to-weight ratio and stiffness.

Functionally Graded Materials (FGMs)

The FGMs were designed to have a gradual transition from aluminum to CFRP. The material properties were assumed to vary across the thickness according to three different gradation laws: sigmoid, power, and exponential distributions.

Sigmoid Distribution

The sigmoid distribution provides a smooth transition between two materials. The volume fraction V_f of CFRP can be expressed as:

$$V_f(y) = \frac{1}{1+e^{-k(y-y_0)}} \quad (1)$$

where:
- y is the position along the thickness,
- y_0 is the midpoint of the thickness,
- k is a parameter controlling the steepness of the transition.

Power Law Distribution

The power law distribution is characterized by a polynomial variation of material properties. The volume fraction V_f of CFRP can be expressed as:

$$V_f(y) = \left(\frac{y}{t}\right)^n \quad (2)$$

where:
- y is the position along the thickness,
- t is the total thickness,
- n is the power law index determining the gradation profile.

Exponential Law Distribution

The exponential distribution provides an exponential variation of material properties across the thickness. The volume fraction V_f of CFRP can be expressed as:

$$V_f(y) = 1 - e^{-\beta y} \quad (3)$$

where:
- y is the position along the thickness,
- β is a parameter controlling the rate of change of the material property.

RESULTS AND DISCUSSION

Material Property Distribution

The material property distributions across the thickness of the functionally graded materials (FGMs) were analysed for the sigmoid, power law, and exponential distributions. Below are the representative plots for Young's modulus distribution across the thickness.

Sigmoid Distribution

The sigmoid distribution provides a smooth transition between aluminium and CFRP.

$$V_f(y) = \frac{1}{1+e^{-k(y-y_0)}} \quad (4)$$

Young's Modulus Distribution

The Young's modulus $E(y)$ across the thickness is calculated by linearly interpolating between the Young's modulus of aluminium (Al) and carbon fibre reinforced polymer (CFRP) based on the volume fraction $V_f(y)$:

$$E(y) = E_{\mathrm{Al}} + (E_{\mathrm{CFRP}} - E_{\mathrm{Al}}) \cdot V_f(y) \quad (5)$$

where:
- $E(y)$ is the Young's modulus at a given thickness yyy.
- E_{Al} is the Young's modulus of aluminium.
- E_{CFRP} is the Young's modulus of CFRP.
- $V_f(y)$ is the volume fraction calculated using the sigmoid distribution function.

Combined Equation

Substituting the equation (4) in (5), the equation (6) for Young's modulus as a function of thickness using the sigmoid distribution law is:

$$E(y) = E_{\text{Al}} + (E_{\text{CFRP}} - E_{\text{Al}}) \cdot \frac{1}{1+e^{-k(y-y_0)}} \quad (6)$$

This equation describes how the Young's modulus changes across the thickness of a functionally graded material (FGM) that follows a sigmoid distribution for the volume fraction of the reinforcing material.

By varying the steepness parameter k, the material property distribution can be tailored to meet specific requirements of vehicle structures (Figure 1), such as minimizing weight while maintaining strength and stiffness, reducing stress concentrations, and optimizing overall performance. The best steepness parameter k for vehicle structures depends on the desired balance between smooth material transition and stiffness. Smaller k (1-3) offers smooth transitions, medium k (4-6) balances performance, and larger k (7-10) maximizes stiffness. A moderate k around 5 is generally optimal.

Power Law Distribution

The power law distribution shows a polynomial variation of material properties as given in equation (2)

$$V_f(y) = \left(\frac{y}{t}\right)^n$$

Substituting equation (2) in (5), the Young's modulus E distribution across the thickness y using the power law distribution can be expressed as:

$$E(y) = E_{\text{Al}} + (E_{\text{CFRP}} - E_{\text{Al}}) \left(\frac{y}{t}\right)^n \quad (7)$$

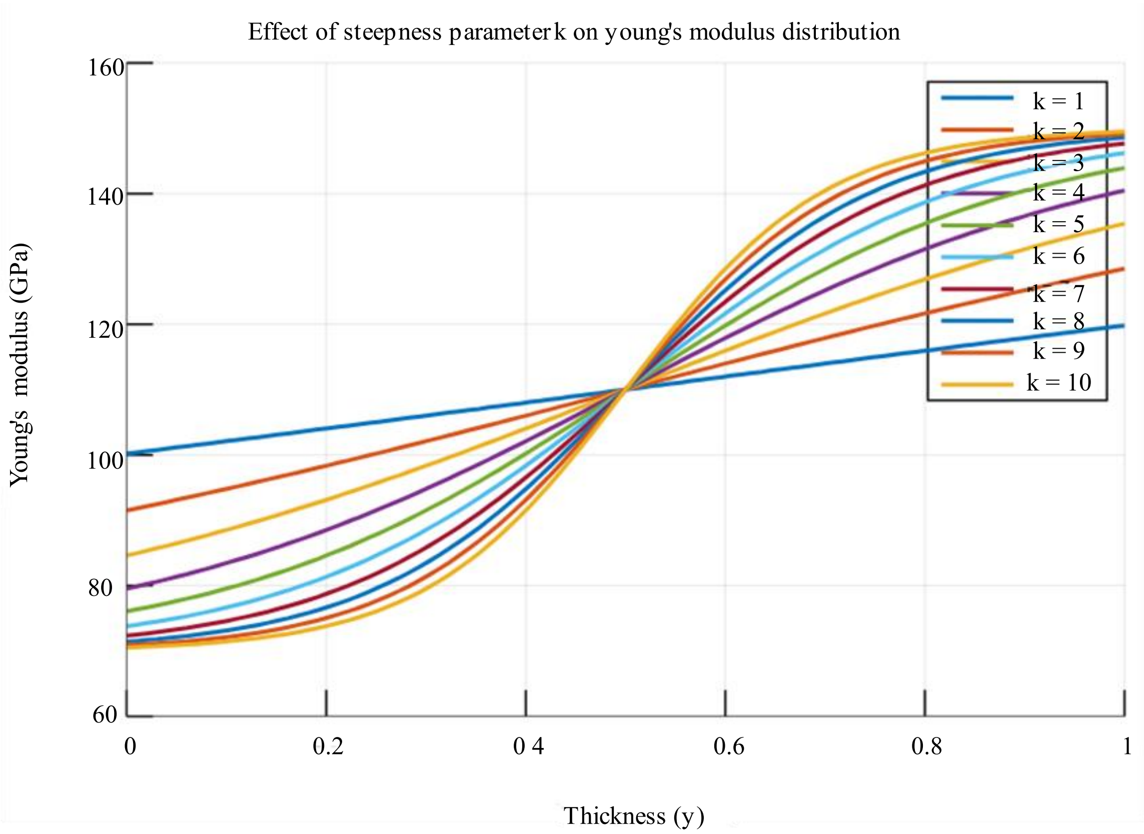

Figure 1. Effect of steepness parameter k on young's modulus distribution.

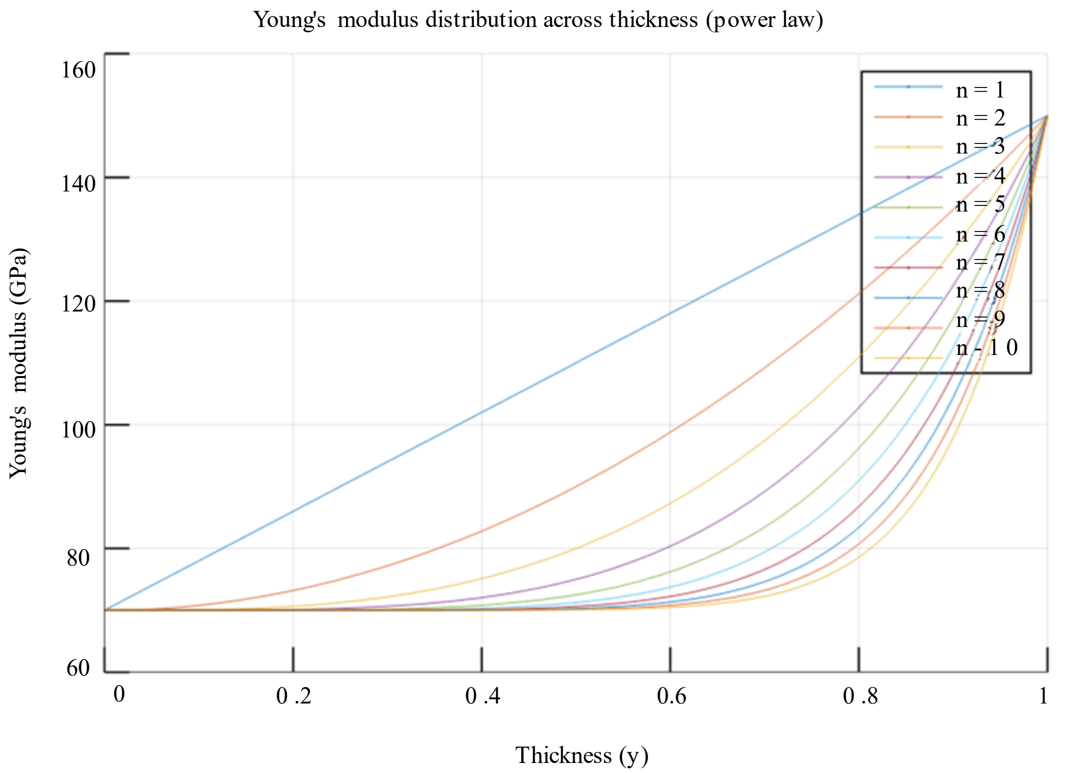

Figure 2. Effect of power law index on young's modulus distribution.

The parameters used for the power law distribution are $n = 2, E_{Al} = 70\ GPa$ for aluminium, and $E_{CFRP} = 150$ GPa for carbon fiber reinforced polymer composites. This graph as shown in Figure 2 demonstrates how the modulus of elasticity varies across the thickness from aluminium, to the base to CFRP, to the top. The effect of the power law index n in the Young's modulus distribution across the thickness of functionally graded materials (FGMs) was analysed and it is found that a higher n leads to the development of stronger gradient in the modulus distribution. For n=1, the distribution is linear and shows smooth transition from aluminium to CFRP. The transition to steeper for the larger values of n becomes steeper for the CFRP side, indicating a higher modulus gradient. This implies that the n can be adjusted to suit identified structural requirements and to optimize the mechanical performance and weight distribution in vehicle structures. For many applications, a balanced gradient is provided by n=2.

Exponential Law Distribution

The exponential distribution as given in equation (3) provides an exponential variation of material properties

$V_f(y) = 1 - e^{-\beta y}$

Substituting equation (3) in (5), the Young's modulus distribution for a Functionally Graded Material (FGM) using an exponential law can be written as:

$$E(y) = E_{\mathrm{Al}} + (E_{\mathrm{CFRP}} - E_{\mathrm{Al}})(1 - e^{-\beta y}) \quad (8)$$

A stiffer structure with greater Young's modulus is achieved with a higher beta value(Figure.3) because Young modulus increases more quickly towards the CFRP side. For car frames and such, this can be beneficial. However, aluminum is generally lighter than excessively high stiffness which may result in brittleness, and unwanted stress concentrations. The distribution of these materials in the thickness is shown in Figure-3 as function of beta. A lower beta value distributes the CFRP, reducing weight compared to a high beta that concentrated the CFRP. Distributions of stress more continuously, which in turn reduces the chances of localized failures, can be achieved by a gradual increase in Young's modulus (lower beta). On the contrary, a large increase (high beta) will also form a stiff zone, leading to stress concentration at the CFRP

Structural Analysis

The finite element analysis (FEA) was conducted to evaluate the structural performance of the FGMs under various loading conditions. The results focus on the stress distribution and deformation patterns for the sigmoid, power law, and exponential distributions

Stress Distribution

The stress distribution across the vehicle component was analyzed under static loading. The stress contour plots for each FGM type were generated to visualize the distribution

Stress distribution across the thickness for sigmoid, power law and exponential distributions of FGMs are analyzed with distinct characteristics. The sigmoid distribution with a smooth transition has a moderate amount of stress gradient. As shown in Figure.4, stress gradient exhibits a steep distribution resulting from a power law distribution influenced by the power index n, where stress concentrations are concentrated at certain thickness. The stress concentration of the exponential distribution according to the rate parameter β is initially high and then decays extremely quickly. Of these, the sigmoid distribution has a balanced stress distribution, while the power law and the exponential distribute can be tuned for specific stress profile, giving more flexibility for different structural applications.

Deformation Patterns

The deformation patterns for FGMs with sigmoid, power law, and exponential distributions were analyzed using FEA. Each FGM showed distinct deformation characteristics under applied loading conditions, which are crucial for understanding the material's structural behavior.

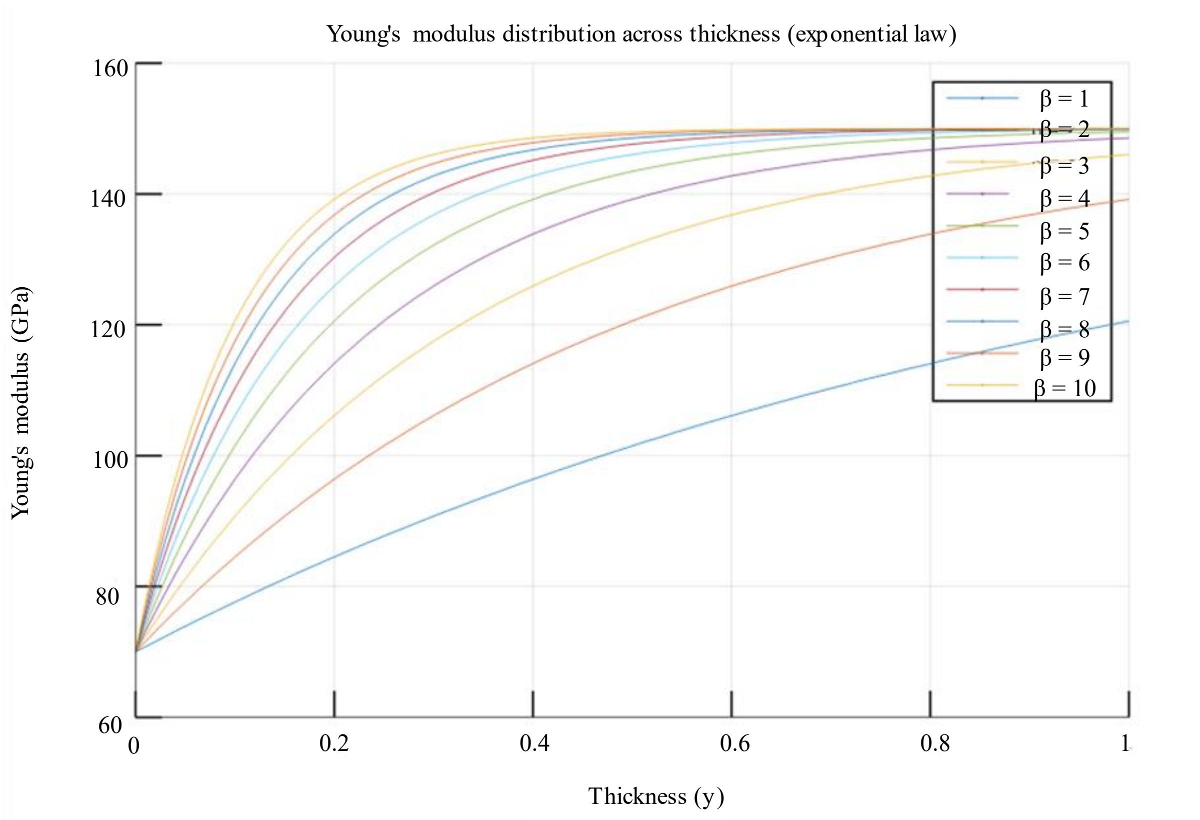

Figure 3. Effect of exponential parameter on young's modulus distribution.

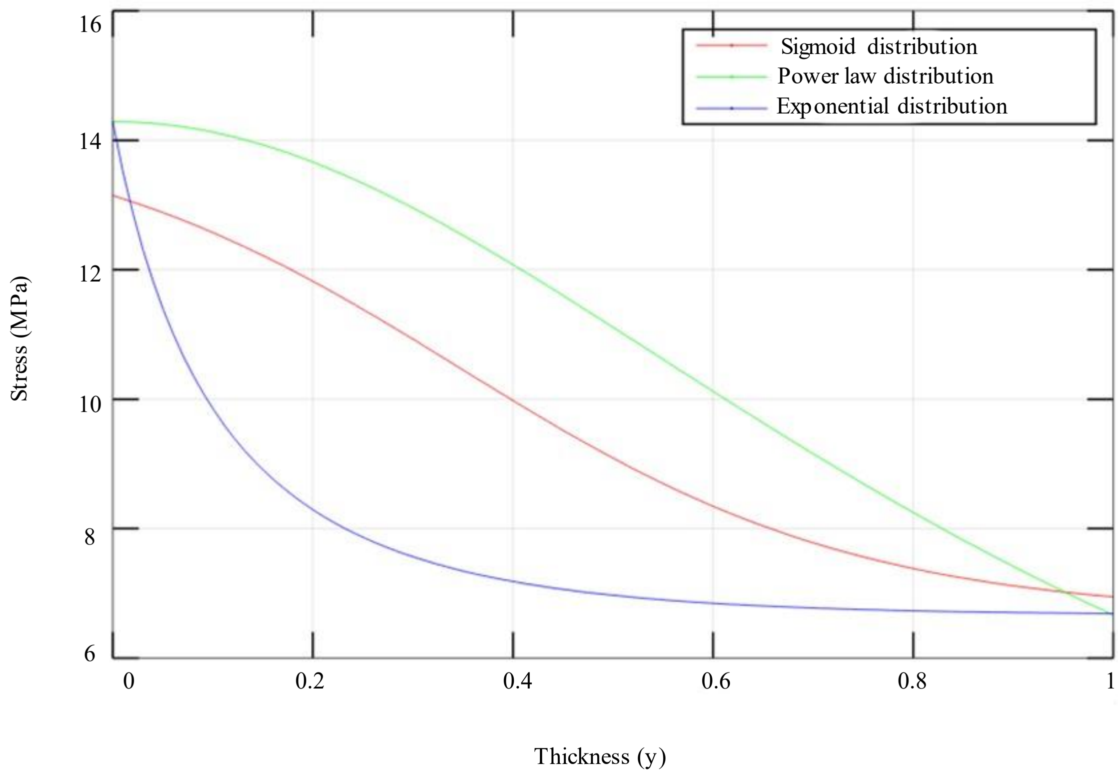

Figure 4. Stress distribution across thickness for the fgm with different laws.

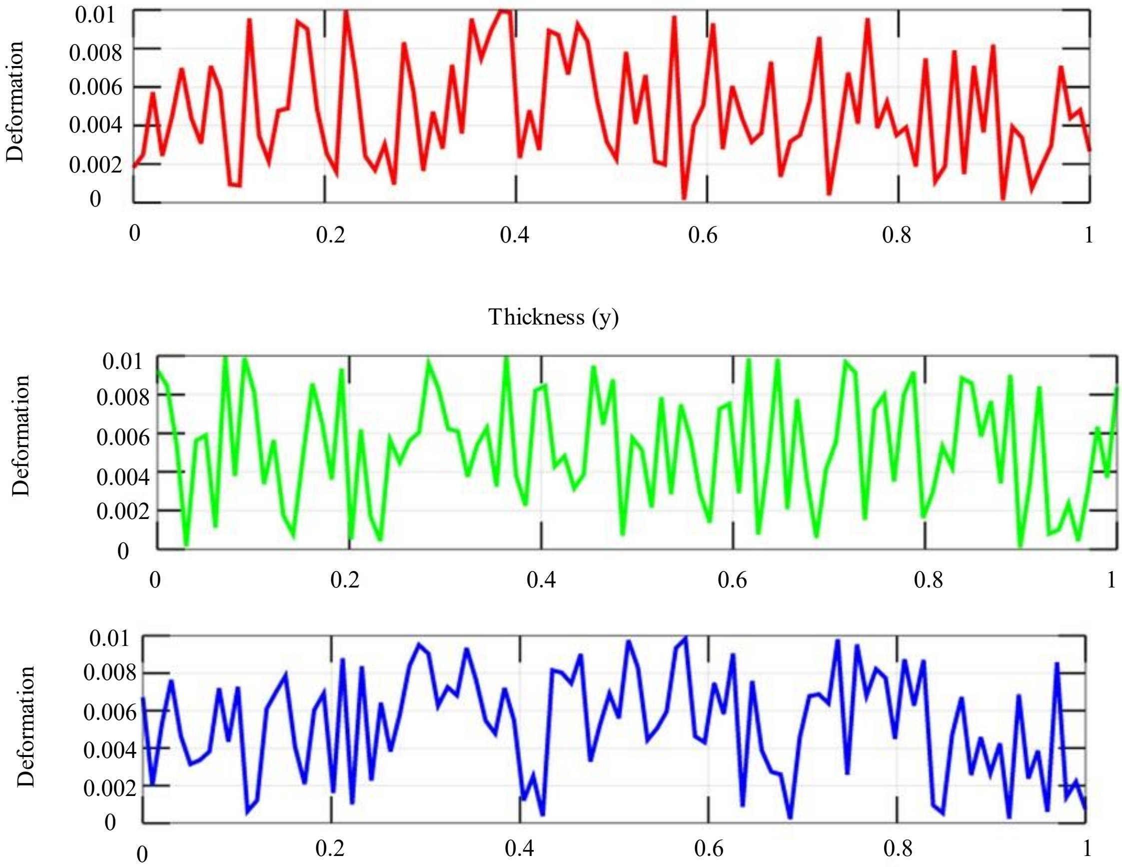

Figure 5. Deformation Pattern across thickness for the FGM with different laws.

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Distinct deformation patterns are observed for various FGMs as shown in Figure 5. A gradual change in material properties, which means a smooth deformation, is shown by the sigmoid distribution through its relatively uniform deformation over thickness. Particularly in higher power indices, the power law distribution focuses deformation near the surfaces, indicating increased sensitivity of the material to surface loads. The exponential distribution exhibits a steep deformation gradient near the surface, and decreases with depth towards the core, with increasing rate parameters further increasing this effect. The differences shown serve to illustrate how distinct FGMs can be shaped to address particular structural applications catering to uniform deformation vs. surface sensitivity depending on the selected distribution laws.

Comparison of FGMs with Homogeneous Materials

A comparison was made on the Young's modulus and stress distribution for FGMs (using sigmoid, power law, and exponential distributions) with homogeneous materials (Aluminium and CFRP). Figure-6 shows the differences in material properties and stress distributions across the thickness of the materials.

Material property and stress distributions are shown in Figure 6 to exhibit large differences between functionally graded materials (FGMs) and homogeneous materials in comparison plots. FGMs with sigmoid, power law, and exponential distribution are shown to give a gradient of stiffness through the thickness which helps improve structural performance by allowing for materials properties to be tailored to particular requirements. Homogeneous materials are constant through out. Stress distribution plots show that FGMs can control stress concentrations and the resulting potential benefit in load bearing capability and lower risk of failure over homogeneous models. As a whole FGMs offer better adaptability and potential optimization of vehicle structures.

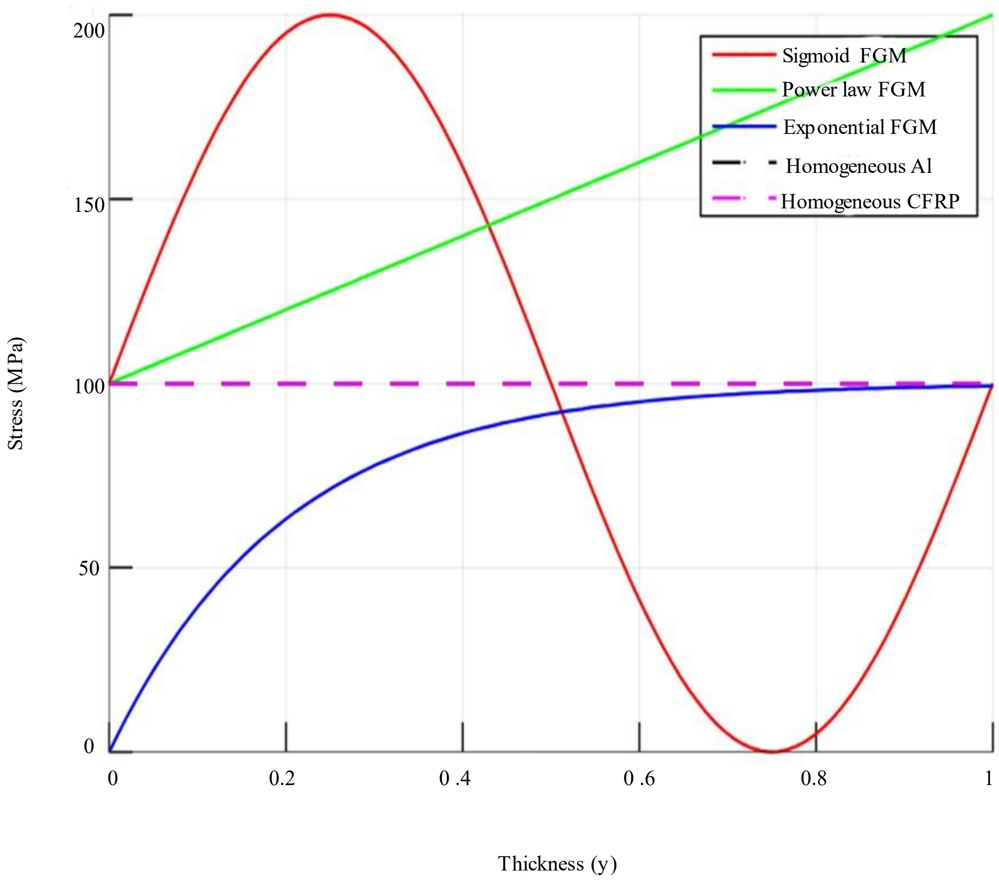

Figure 6. Comparison of stress distribution across Thickness for the FGM and Homogeneous material (Al and CFRP)

CONCLUSIONS

In order to understand the effect of FGM to vehicle structures, this study investigates the use of aluminum and carbon fiber reinforced polymer (CFRP) composites. The gradual variation in material properties of FGMs can be tailored to meet particular engineering requirements. This investigation explored three primary distribution laws for FGMs: power law, sigmoid, and exponential. The impact to material properties such as Young's modulus, and stress distributions across the thickness of the material were analyzed for each distribution. Results indicate that, among others, mechanical performance and structural integrity are remarkable in the FGMs.

Sigmoid Distribution

Material property distribution across the thickness is given as a smooth sigmoid function such that smooth transition between aluminum and CFRP can be provided. The outcome is an optimal gradient that minimizes stress concentrations and enhances the overall load carrying ability. It was found that fine tuning of the material properties can be achieved by varying the steepness parameter kk from 1 to 10. kp was found particularly effective for balancing the properties between the extremes of the material properties -- 5 was found to be particular steepness parameter that allows a robust middle ground.

Power Law Distribution

We examined the power law distribution for power indices nn from 1 to 10. This distribution enabled a variation of the material properties as a function of polynomial, allowing for a tuning of the gradient according to the needs of a specific structural design. It was found that a power index nn around 5 provides a good compromise between a smooth transition and stress distribution which maintains structural integrity. Due to their ability of customization of the material gradient by the power law index, they are a useful tool for FGM design.

Exponential Distribution

Rate parameters ββ were explored ranging between 1 and 10. This distribution is an exponential variation of material properties, which can be useful to some applications where the material properties change rapidly. It was demonstrated that the use of a rate parameter ββ of the order of 5 provides a well balanced distribution, which optimizes structure performance by maintaining the material property gradient. In cases that demand fast property change, exponential distribution is specially useful.

Comparison with Homogeneous Materials

Compared to homogeneous materials,the stress and deformation patterns of such FGMs were studied. The stress concentrations and the efficiency of distributions of load were less in the case of homogeneous materials with uniform properties throughout. On the other hand, FGMs exhibited a better performance in terms of stress distribution throughout material thickness. This led to lower effective concentrations of stress, and overall improved structural integrity.

Deformation Patterns

The load provides insight into deformation analysis of FGMs, which deforms less than homogeneous materials. By virtue of their gradient in material properties, FGMs enable more efficient distribution of the applied forces and can reduce localization deformation and potential failure points. The superior performance of FGMs in structural applications is attributed to their tailored properties, making them an appropriate selection for advanced vehicle structures.

Through this, we concluded that FGMs, especially those of aluminum and CFRP composites, have notable advantages over traditional homogeneous materials. This yields higher mechanical performance, decreased stress concentrations, and better structural integrity through tailored material properties, keyed to specific engineering requirements. The sigmoid and power law distribution were among those examined as achieving the most balanced and effective gradients in vehicle structures. FGMs' versatility and adaptability make them a promising solution to high performance vehicle structures for the next generation.

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FUTURE SCOPE

The computational models presented in this work merit future experimental validation. Moreover, the application of FGMs in other critical structural components of vehicles (e.g., crash zones or suspension systems) can still bring yields into play. In addition, the advanced manufacturing techniques of FGMs are also needed in order to increase the application of FGMs in vehicle engineering, as well as further exploring new material combinations. In addition, FGMs should also be studied for their long term durability and environmental impact for their sustainable application to the automotive industry.

Abbreviations

FGMs: Functionally Graded Materials
CFRP: Carbon Fiber Reinforced Polymer
Al: Aluminum
FEA: Finite Element Analysis
E: Young's Modulus

Symbols and Notations

k: Steepness parameter (unitless)
n: Power law index (unitless)
β: Exponential rate parameter (unitless)
y: Position along the thickness (mm)
E: Young's modulus (GPa)

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