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Review of Sandwich Beams with Functionally Graded Core

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Abstract:-

An elasticity solution is obtained for a sandwich beam with a functionally graded core subjected to transverse loads. The sandwich is subdivided into four elements, the top and bottom face-sheets, and top and bottom halves of the sandwich core. Euler-Bernoulli beam theory is used to model the face-sheets and plane elasticity equations are used to analyze the core. The Young's modulus of the core is varied exponentially through the thickness (from E_0 at mid-plane to E_h at the core/ face-sheet interface) and the Poisson's ratio is kept constant. The exponential variation of elastic stiffness coefficients allows exact elasticity solution for the problem. The equations of each element are expressed in terms of the surface tractions and displacements. By enforcing the compatibility of the tractions and displacement at the interfaces the complete solution for displacements and stresses in the beam are obtained. It is shown that the functionally graded core reduces the core/ face-sheet interface shear stress (τ_{xz}). The normal stress (σ_{zz}) varies linearly through the thickness and is independent of the variation in core properties.

Keywords- Functionally Graded Material, FGMs beam, Sandwich Beam, Reinforced FGCMs.

I. INTRODUCTION

Functionally graded material (FGMs):-

Functionally graded materials (FGMs) possess properties that vary gradually with location within the material. For example, a rocket motor casing can be made with a material system such that the inside is made of a refractory material, the outside is made of a strong metal, and the transition from the refractory material to the metal is gradual through the thickness. FGMs differ from composites: the volume fraction of the inclusion is uniform throughout the composite. The closest analogy of FGMs is laminated composites, but they possess distinct interfaces across which properties change abruptly. Although fabrication technology of FGMs is in its infancy, they offer many advantages. Suresh and Mortensen provide an excellent introduction to FGMs [1].

As the use of FGMs increases, in aerospace, automotive and biomedical applications for example, new methodologies have to be developed to characterize them, and to design and analyze structural components made with these materials [2]. The methods should be such that they can be incorporated into available methods with minimal modifications. One problem is that of response of FGMs to thermo-mechanical loads. Although FGMs are highly heterogeneous, it will be useful to idealize them as continua with properties that change smoothly with respect to spatial coordinates [3]. This will enable closed-form solutions to be obtained for some fundamental solid mechanics problems, and will aid the development of finite element models for structures made of FGMs [4].

Aboudi developed a higher order micro-mechanical theory for FGMs (HOTFGM) that explicitly couples local and global effects. Later the theory was extended to free-edge problems by Aboudi et [5]. Pindera and Dunn evaluated the higher order theory by performing a detailed finite element analysis of the FGM [6]. They found that the HOTFGM results agreed well with the FE results [7]. Marrey and Sankar studied the effects of stress gradients in textile composites consisting of unit cells large compared to the thickness of the composite [8]. Their method results in direct computation of plate stiffness coefficients from the micro-mechanical models rather than from use of homogeneous elastic constants of the composite and plate thickness. Other approximations can be used to model the variation of properties in a FGM. One such variation is the exponential variation, where the elastic constants vary according to formulas of the type $-c_{ij} = c_{ij}^{0}e^{\lambda z}$. Many researchers have found this functional form of property variation be convenient in solving elasticity problems. For example, Delale and Erdogan derive the crack-tip stress fields for an inhomogeneous cracked body with constant Poisson ratio and a shear modulus variation given [9]. Although elasticity equations are limited to simple geometries, specific boundary conditions and special types of loadings, they can provide exact solutions, which are valuable for understanding the physics and performing simple

Brief history of development

The current development of the finite element method started in 1940s in the field of structural engineering with the work in 1941 and in 1943,which used a frame of line (one dimensional) elements (bars and beams) for the solution of stresses in continuous solids. Courant proposed a variational form for the setting up of stresses [11]. Later he presented piecewise interpolation (or shape) functions over triangular sub regions making up the whole region as a method to obtain approximate numerical solutions. In 1947 Levy developed a new method namely force (or flexibility) method, and the same author in his another work suggested one more method the stiffness (or displacement) method [12].

In 1954 it was developed matrix structural analysis methods using energy principles. This development illustrated the important role that energy principles would play in the finite element method [13]. The two dimensional elements are first treated in 1956. It was developed stiffness matrices for truss, beam elements and two-dimensional triangular and rectangular elements in plane stress [14]. The development of high speed digital computer in the early 1950s prompted further development of finite

History of Sandwich Beam

The theoretical model of sandwich structures was formulated in the middle of 20th century. It has been presented deflection of a sandwich rectangular plate. Some researchers described strength and stability problems of sandwich structures. It was also analysed properties of corrugated-core sandwich panels and discussed elastic behaviour of sandwich structures. Presented results of analytical analysis of the bending stiffness of a corrugated board and compared them

optimization studies. In this paper, we analyze a sandwich beam with a functionally graded core subjected to sinusoidal transverse loading. The plane elasticity equations are solved exactly to obtain displacement and stress fields. The face-sheets are modeled using the Euler-Bernoulli beam theory and elasticity equations are used to analyze the core. The displacement and stress fields in the functionally graded core are presented and compared to that in uniform core [10]. The results indicate that the use of functionally graded core results in reduced core/face-sheet interfacial shear stresses.

element stiffness equations expressed in matrix notation [15]. Extension of the finite element method to three dimensional problems with the development tetrahedral stiffness matrix was done in 1961. Up to early 1960s most of the finite element works are limited to small displacements and strains and static loadings. Later on in 1960 large deflection and thermal analysis and non linearities are considered by various authors. It was extended the finite element method to viscoelasticity problems in 1968. During the decades of the 1960s and 1970s, the finite element method was extended to applications in plate bending, shell bending, pressure vessels, and general three dimensional problems in elastic structural as well as to fluid flow and heat transfer. Further development of the method to applications large deflection and dynamic analysis also occurred in these periods. The finite element method is computationally intensive, owing to the required operations on very large matrices [16]. During 1960s the finite element software code NASTRAN was developed in conjunction with the space exploration program of the United States. NASTRAN was the first major finite element software package [17]. From the early 1950s to present, enormous advances have been made in the application of the finite element method to solve complicated engineering problems.

with expressions given by other authors used the finite element method to determine an expression for the equivalent stiffness of sandwich structures with various types of cores [18]. A more accurate expression for the stiffness of corrugated sheets was derived and analysed bending stiffness of a sandwich plate with a corrugated core for three-point and four-point bending tests. It was applied the finite element method to analyse bending and twisting of a corrugated board. Buannic et al. presented a homogenization method for a sandwich plate with a corrugated core and compared this method with results of finite element analysis. Analytical homogenization of a corrugated cardboard under torsion was described.An equivalent stiffness of a corrugated plate under bending and torsion treated as an orthotropic plate was discussed. There are comparison of dynamic behaviour of a clamped monolithic plate and a clamped sandwich plate with an Y-frame and corrugated core. Seong et al showed bending results of sandwich plates with bi-directionally corrugated cores. An application of a sandwich corrugated plate as a bridge structure was described. It determined rigidities of a double-layered cylindrical vessel in which the internal layer was corrugated. Stability of that structure was also investigated. Some researchers described behaviour of sandwich beams with corrugated cores [19]. The authors presented the comparison of results of the numerical analytical analysis and experimental investigation discussed.

II. DEFINITION

(General Engineering) a composite beam in which a viscoelastic layer is sandwiched between two elastic layers.A sandwich-structured composite is a special class of composite materials that is fabricated by attaching two thin but stiff skins to a lightweight but thick core. The core material is normally low strength material, but its higher thickness provides the sandwich composite with high bending stiffness with overall low density.Open- and closed-cell-structured foams like polyvinylchloride, polyurethane, polyethylene or polystyrene foams, balsa wood, syntactic foams, and honeycombs are commonly used core materials **[Figure1].**

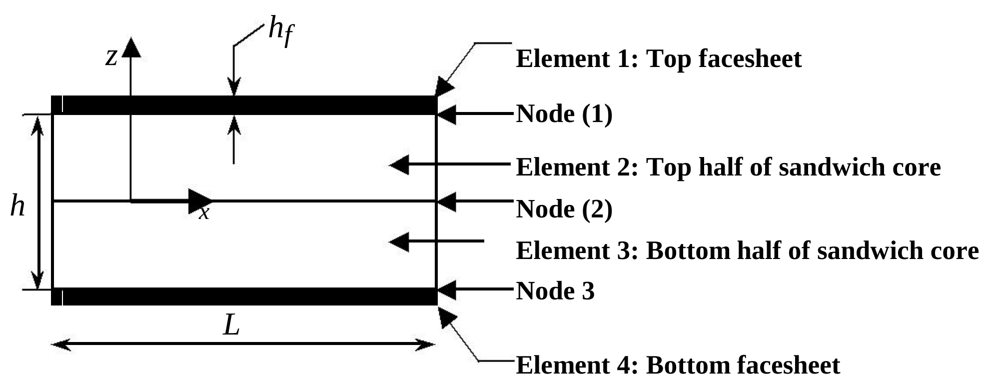

Figure 1: Sandwich beam with functionally graded core with schematic of the analysis elements.

Open- and closed-cell metal foam can also be used as core materials [24]. Laminates of glass or carbon fiber-reinforced thermoplastics or mainly thermoset polymers (unsaturated polyesters, epoxies) are widely used as skin materials. Sheet metal is also used as skin material in some cases. The core is bonded to the skins with an adhesive or with metal components by brazing together. Sandwich constructions have two thin, elastic outer layers and a middle layer - core made of material with relatively small stiffness comparing to stiffness of the the outer layers. Calculation of these constructions is based on the supposition that all three layers deform simultaneously, and as the result a unique neutral line is formed between the outer layers. With this approach to the calculation it is possible to describe, with high accuracy, the stress and the strain state of a construction as well as the local influence in each layer.A sandwich structure consists of two external thin, strong, facings bonded to a thick light-weight and weaker core. The core carries the through-the-thickness shear loads, while the facings resist in-plane and bending loads. The high specific strength and specific stiffness of sandwich construction coupled with outstanding thermal and acoustic insulation make it ideal in structural design. Sandwich beams subjected to bending and shear loads may fail in several ways including tension or compression failure of the facings, shear failure of the core, wrinkling failure of the compression facing, local indentation, debonding of the core/facing interface and global buckling [26]. The initiation of each failure mode should be studied separately and is described by a different failure equation. The critical load for failure initiation is the lowest load of all potential failure modes. Following initiation of failure by a specific failure mode, interaction of

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failure modes may occur and failure could progress by another failure mode.

Sandwich Theory

Sandwich theory describes the behaviour of a beam, plate, or shell which consists of three layers - two facesheets and one core. The most commonly used sandwich theory is linear and is an extension of first order beam theory. Linear sandwich theory is of importance for the design and analysis of sandwich panels, which are of use in building construction, vehicle construction, airplane construction and refrigeration engineering [27].

Sandwich Materials and specimens

Composite sandwich structure panel used for testing at NASA

Figure 2.4(a)

Application of Sandwich Beam

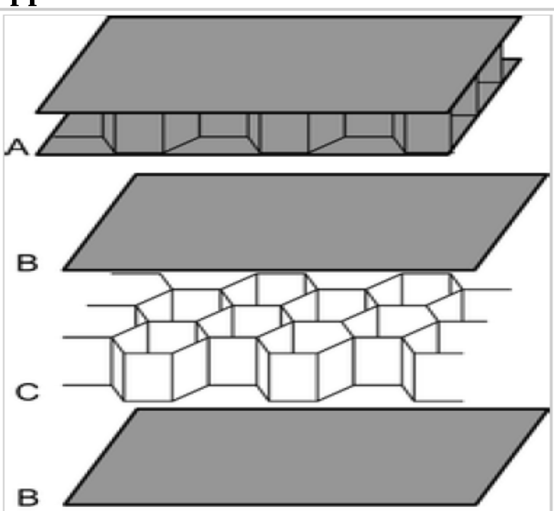

Diagram of an assembled composite sandwich (A), and its constituent face sheets or skins (B) and honeycomb core (C) (alternately: foam core)

Figure2.5 (a)

The composite honeycomb structure of a helicopter nozzle

Figure2.5 (b)

Sandwich structures, widely used in aerospace and naval applications, tend to be limited to a small range of material combinations. For example, a metallic foam core is generally combined with a metal face sheet; a composite face is usually coupled with a polymeric foam core or a resin-impregnated paper honeycomb **[Figure2.5 (a)].** Ashby and Brechet demonstrate that better performance may be achieved by using hybrid sandwich beams comprising non-traditional pairs of materials.

Sandwich structures can be also widely used in sandwich panels, this kinds of panels can be in different types such as FRP sandwich panel, aluminum composite panel etc **[Figure2.4 (a)].** FRP polyester reinforced composite honeycomb panel (sandwich panel) is made of polyester reinforced plastic, multi-axial high-strength glass fiber and PP honeycomb panel in special antiskid tread pattern mold through the process of constant temperature vacuum adsorption & agglutination and solidification [28].Weight savings offered by sandwich constructions for structures that require high bending stiffness are significant. However, sandwich constructions have not been fully exploited in structural applications due to damage tolerance concerns **[Figure2.5 (b)].** The core/ face sheet delamination is a major concern in sandwich construction. The stiffness discontinuity at the face sheet and core interface results in a large increase in shear stresses. While the core material itself can withstand very high shear stresses, the bond (or adhesive layer) at the interface is relatively weaker. It is believed that the stress concentration can be controlled by varying (functionally grading) the core properties through the thickness.

Types of sandwich structures

Metal composite material (MCM) is a type of sandwich formed from two thin skins of metal bonded to a plastic core in a continuous process under controlled pressure, heat, and tension.Recycled paper is also now being used over a closed-cell recycled kraft honeycomb core, creating a lightweight, strong, and fully repulpable composite board. This material is being used for applications including point-of-purchase displays, bulkheads, recyclable office furniture, exhibition stands, and wall dividers.To fix different panels, among other solutions, a transition zone is normally used, which is a gradual reduction of the core height,until the two fiber skins are in touch. In this place, the fixation can be made by means of bolts, rivets, or adhesive [29].

Properties of sandwich structures

The strength of the composite material is dependent largely on two factors:

1. The outer skins: If the sandwich is supported on both sides, and then stressed by means of a force in the middle of the beam, then the bending moment will introduce shear forces in the material. The shear forces result in the bottom skin in tension and the top skin in compression. The core material spaces these two skins apart. The thicker the core material the stronger the composite. This principle works in much the same way as an I-beam does.

2. The interface between the core and the skin: Because the shear stresses in the composite material change rapidly between the core and the skin, the adhesive layer also sees some degree of shear force. If the adhesive bond between the two layers is too weak, the most probable result will be delamination.

III. RESULTS AND DISCUSSION

The inplane displacement $U(z)$ and transverse $W(z)$ deflections through the thickness of the sandwich core calculated using the elasticity analysis described in the previous section are plotted in **Figures 4 and 5,** respectively. The inplane displacements exhibit highly non-linear variation through the thickness of the core for the functionally graded core sandwich in comparison to the uniform core sandwich. A very attractive feature of the elasticity solutions is that it can provide the through the thickness compressions of the beam which is often neglected or ignored in beam models. The through the thickness variations of the transverse deflection **[Fig. 5]** indicates that maximum core compression occurs at the mid-plane of the core where the elastic modulus is least.

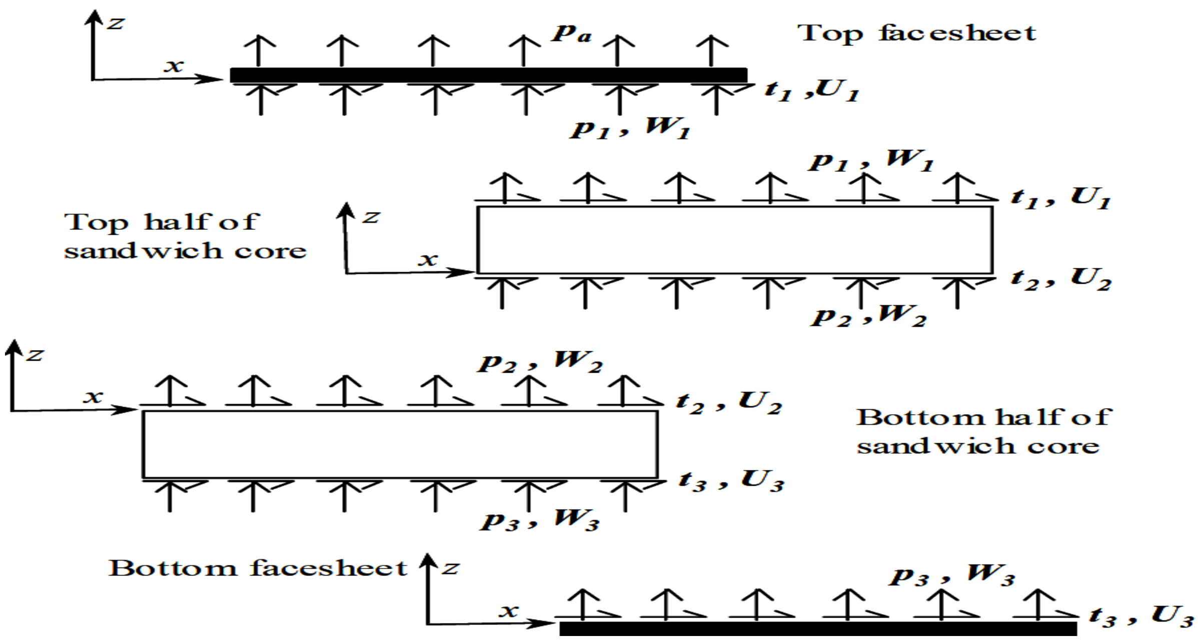

Figure show Traction forces and displacements at the interfaces of each element in the FGM Sandwich Beam

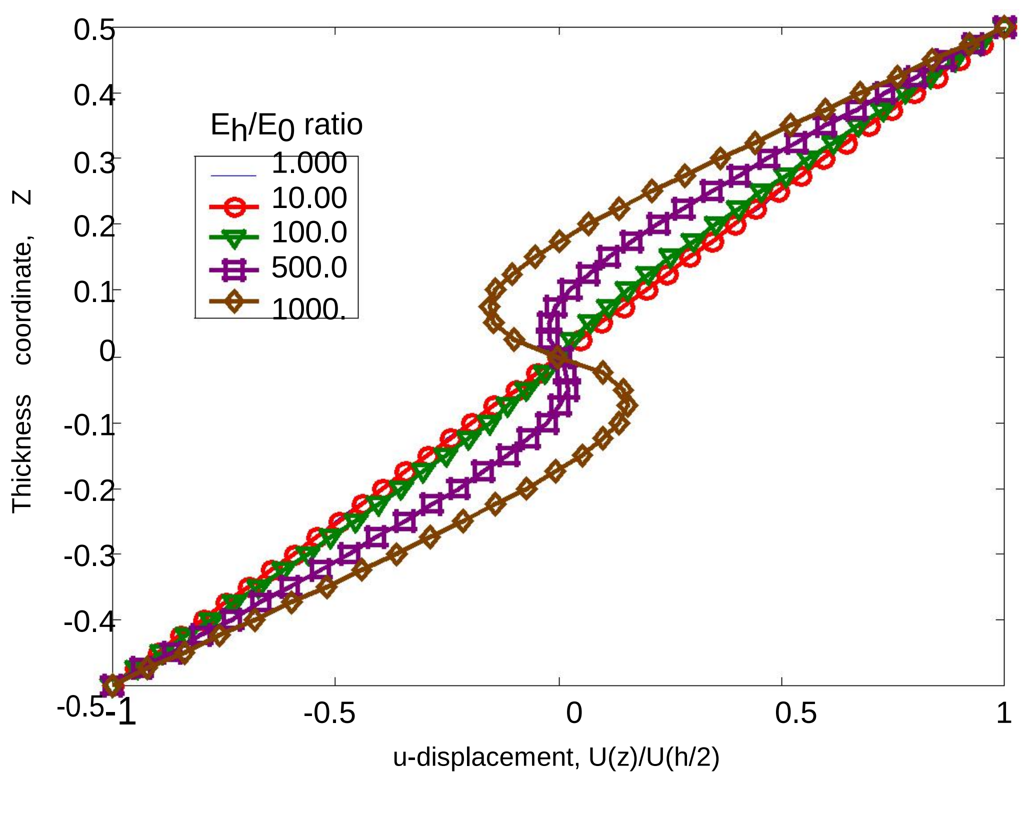

Figure 4: Variation of inplane displacement (U) through the thickness of the FGM beam for different ratios (E_h/ E_0) at E_f/E_0 = 1000. (E_f, face sheet modulus, E_h Sandwich core modulus at face sheet interface, E_0 sandwich core modulus at center)

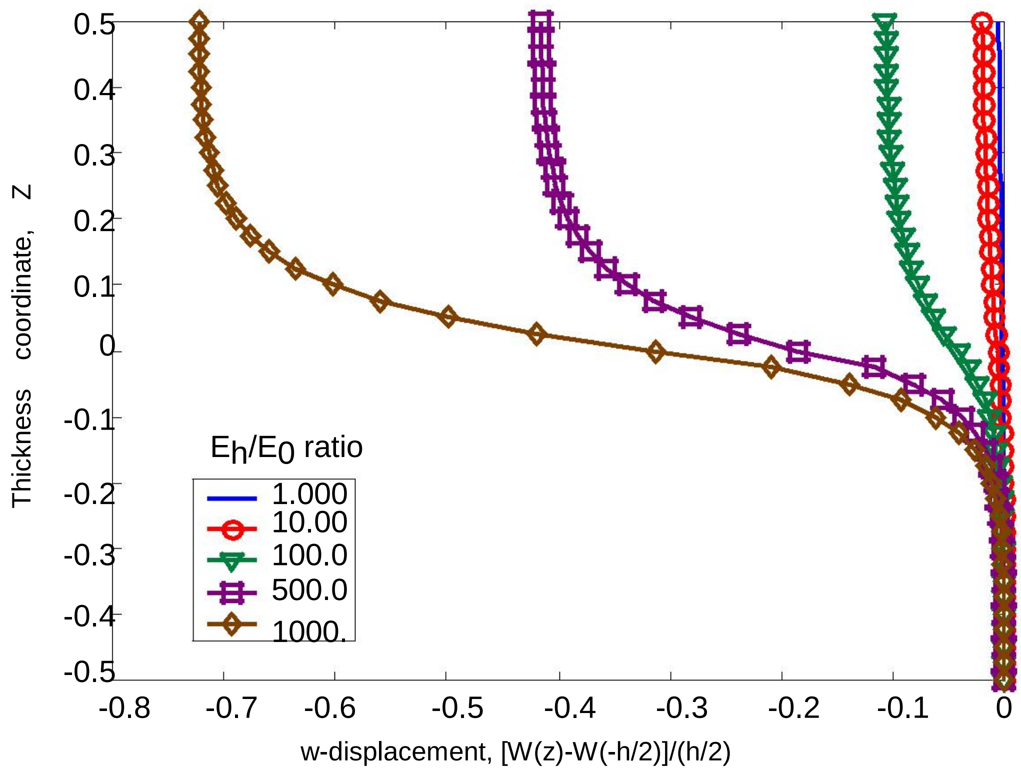

Figure 5: Variation of transverse displacement (W) through the thickness of the FGM beam for different ratios (E_h/ E_0) at E_f/E_0 = 1000. ($E_{f,}$ face sheet modulus, E_h Sandwich core modulus at face sheet interface, E_0 sandwich core modulus at center)

IV.ACKNOWLEDGEMENT

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V.CONCLUSIONS

An elasticity solution was derived for a sandwich beam with a functionally graded core. Exponential variations of the elastic coefficients in the sandwich core simplify the calculations **[Figure 3]**. Solutions are presented for displacements and stresses in the core. The elasticity solution was verified using a finite element analysis. Varying core properties through the thickness shows promise for reducing core/face-sheet interface shear stresses. The developed method can be extended to any general variation of elastic modulus by using multiple elements of the core to approximate the required elastic modulus.

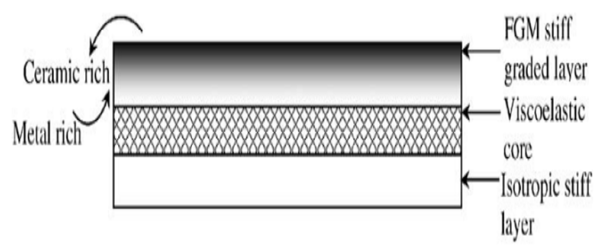

Figure show Sandwich beam with FGM layer

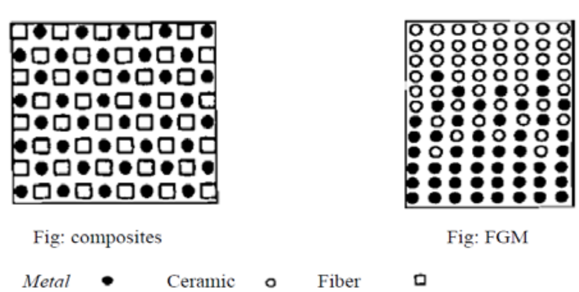

Figure show configuration of composites and FGM

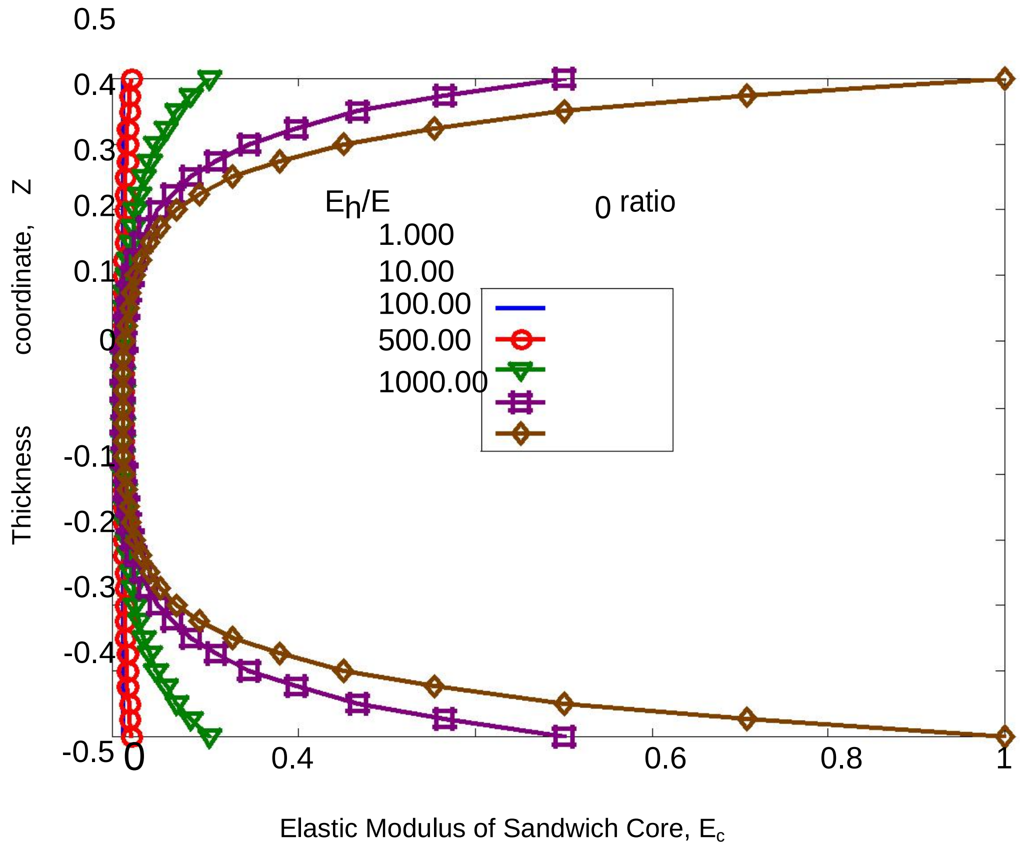

Figure 3: Through the thickness variations of core modulus considered for the functionally graded sandwich beam, (E_h is the sandwich core modulus at face sheet interface and, E_0 the sandwich core modulus at center)

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