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A Review Paper on Comparison of Numerical Techniques for Finding Approximate Solutions to Boundary Value Problems on Post-Buckling in Functionally Graded Materials

Elias Randjbaran[1,*], Rizal Zahari[1], Ramin Vaghei[2], Farrokh Karamizadeh[3]

[1]Aerospace Manufacturing Research Centre (AMRC), Level 7, Tower Block, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia
[2]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia
[3]Department of Civil Engineering, Science and Research branch, Islamic Azad University, Tehran, Iran
[*]Correspondence: Elias Randjbaran(Elias@gmx.co.uk)

Abstract The use of finite element models as research tools in biomechanics and orthopedics grew exponentially over the last two decades. However, the attention to mesh quality, model validation and appropriate energy balance methods and the reporting of these metrics has not kept pace with the general use of finite element modeling. Therefore, the purpose of this review was to develop the nonlinear filter and thermal buckling of an FGM panel under the combined effect of elevated temperature conditions and aerodynamic loading is investigated using a finite element model based on the thin plate theory and von Karman strain-displacement relations to account for moderately large deflection. It is found that the temperature increase has an adverse effect on the FGM panel flutter characteristics through decreasing the critical dynamic pressure. Decreasing the volume fraction enhances flutter characteristics, but this is limited by the structural integrity aspect. Structural finite element analysis has been employed to determine the FGM panel's adaptive response while under the influence of a uniaxial compressive load in excess of its critical buckling value. By increasing the applications of using composite materials inside aviation stages, it is visualized that the versatile FGM plate setup will broaden the operational execution over traditional materials and structures, especially when the structure is presented to a raised temperature. The vicinity of air motion facilitating stream brings about delaying the locking temperature and in stifling under loads, while the temperature build gives route for higher thermal-cycle abundance.

Keywords: Finite Element Methods; Functionally Graded Materials; Non-Linear Finite Element Formulation; Thermo-Mechanical Post-Buckling

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1. Introduction

The concept of Functionally graded materials was first considered in Japan in 1984 during a space plane project. Where a combination of materials used would serve the purpose of a thermal barrier capable of withstanding a surface temperature of 2000 K and a temperature gradient of 1000 k across a 10 mm section.[1] In recent years this concept has become more popular in Europe, particularly in Germany. A transregional collaborative research center (SFB Transregio) is funded since 2006 in order to exploit the potential of grading monomaterials, such as steel, aluminium and polypropylen, by using thermomechanically coupled manufacturing processes. In materials science functionally graded material (FGM) may be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material. The materials can be designed for specific function and applications. Various approaches based on the bulk (particulate processing), preform processing, layer processing and melt processing are used to fabricate the functionally graded materials. The FGMs are nonhomogeneous composites characterized by a smooth and continuous change of material properties from one surface to the other. This is achieved by gradually varying the volume fraction of the constituent materials. The FGMs are usually composed of two or more materials whose volume fractions are changing smoothly and continuously along desired direction(s). This continuous change in the compositions leads to a smooth change in the mechanical properties, which has many advantages over the laminated composites, where the delamination and cracks are more likely to initiate at the interfaces due to the abrupt variation in the mechanical properties between laminas. One of the advantages of using these materials is that they can survive environments with high temperature gradients, while maintaining structural integrity. Accordingly, one of the most important applications of functionally graded materials is in the skin panels of supersonic and Hypersonic flight vehicles, which have to survive the harsh thermal and mechanical loadings [1-3].

Numerical approaches to continuum micromechanics; Finite Element Analysis (FEA) based methods - Most such micromechanical methods use periodic homogenization, which approximates composites by periodic phase arrangements. A single repeating volume element is studied, appropriate boundary conditions being applied to extract the composite's macroscopic properties or responses. The FGMs are a new generation of composite materials wherein the material properties vary continuously to yield a predetermined composition profile. These materials have been introduced to benefit from the ideal performance of its constituents, e.g., high heat/corrosion resistance of ceramics on one side, and large mechanical strength and toughness of metals on the other side. FGMs have no interfaces and are hence advantageous over conventional laminated composites. FGMs also permit tailoring of material compositions to optimize a desired characteristic such as to minimize the maximum deflection for a given load and boundary conditions, or maximize the first frequency of free vibration, or minimize the maximum principal tensile stress. As a result, FGMs have gained potential applications in a wide variety of engineering components or systems, which include armor plating, heat engine components and human implants [13, 36]. The variations of material properties in an FGM are usually achieved by continuously varying volume fractions of the constituent materials. With the increased use of these materials, it is important to understand the nonlinear behavior of functionally graded plates under pressure load. Approximate solutions of complex engineering problems are usually obtained by a numerical method. In recent years, a new type of numerical method called mesh-free method (MFM) is being developed in the area of computational mechanics [4-8, 30]. A semi [9] considered post-buckling and non-linear bending analysis of functionally graded annular sector plates based on three dimensional theory of elasticity in conjunction with non-linear Green strain tensor as shown in Figure 1.

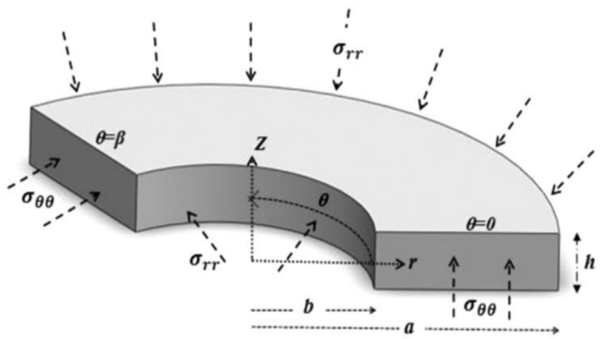

Figure 1. Geometry of the plate [9].

2. Materials and Methods

Given the (linear and/or nonlinear) material properties of the constituents, one important goal of micromechanics of materials consists of predicting the response of the heterogeneous material on the basis of the geometries and properties of the individual phases, a task known as homogenization. The benefit of homogenization is that the behavior of a heterogeneous material can be determined without resorting to testing it. Such tests may be expensive and involve a large number of permutations (e.g., in the case of composites: constituent material combinations; fiber and particle volume fractions; fiber and particle arrangements; and processing histories). Furthermore, continuum micromechanics can predict the full multi-axial properties and responses of inhomogeneous materials, which are often anisotropic. Such properties are often difficult to measure experimentally, but knowing what they are is a requirement, e.g., for structural analysis involving composites. To rely on micromechanics, the particular micromechanics theory must be validated through comparison to experimental data. The second main task of micromechanics of materials is localization, which aims at evaluating the local (stress and strain) fields in the phases for given macroscopic load states, phase properties, and phase geometries. Such knowledge is especially important in understanding and describing material damage and failure. Conventional aerospace composites have been composed of high-stiffness carbon fibers to maintain dimensional stability under high-performance application. The stiffness property is often associated with a particular susceptibility to impact damage and a corresponding reduction of mechanical properties. However, such structures are expected to only encounter few unintentional impacts. Composite structures for military ground vehicles, on the other hand, are designed to absorb multiple high-energy impacts but have much less dimensional restrictions. Since softer materials tend to dissipate more energy during impact, a low modulus/high strength alternative would be well suited for backing panel composites [8-24].

Effective Material Properties of Functionally Graded Materials Consider an FGM layer that is made from a mixture of ceramics and metals. Assume that the composition is varied from the outer to the inner surface, i.e., the outer surface (Z=-h/2) of the panel is metal rich, whereas the inner surface (Z=+h/2) is ceramic rich, where Z is in the direction of the downward normal to the middle surface, and h is the thickness of the layer. The thermal postbuckling behavior of FGM cylindrical shells surrounded by an elastic medium was presented on the basis of two micromechanical models and multi-scale approach. The surrounding elastic medium is modeled as a Pasternak foundation. The material properties of FGMs are assumed to be temperature dependent. Numerical results demonstrate that both buckling temperature and thermal postbuckling strength of the FGM shells increase with increase in foundation stiffness, Figure 2 shows the details [10-16]. Duc and

Cong [17,23] proposed an analytical investigation on the postbuckling behaviors of thick symmetric functionally graded plates resting on elastic foundations and subjected to thermomechanical loads in thermal environments as shown in Figure 3. The formulations presented by Duc and Cong are based on third order shear deformation plate theory and stress function consider Von Karman nonlinearity [29-39].

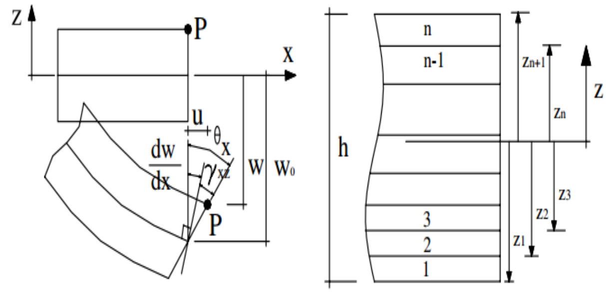

Figure 2. (a) Displacement in point P on plane Oxz; (b) layer order and coordinate system [10].

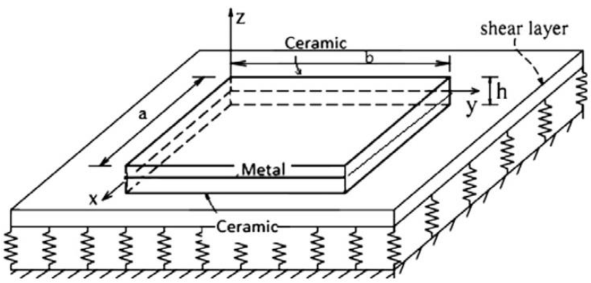

Figure 3. Symmetrical S-FGM plate on elastic foundation. [17].

2.1 Voigt and Mori-Tanaka models

Voigt in 1887; Strains constant in composite, rule of mixtures for stiffness components and Mori-Tanaka Method is typical for mean field micromechanics models, fourth-order concentration tensors relate the average stress or average strain tensors in inhomogeneities and matrix to the average macroscopic stress or strain tensor, respectively; inhomogeneity "feels" effective matrix fields, accounting for phase interaction effects in a collective, approximate way. Thermal Post buckling of Shear Deformable FGM Cylindrical Shells Surrounded by an Elastic Medium presents a study of the thermal postbuckling response of a shear deformable functionally graded cylindrical shell of finite length embedded in a large outer elastic medium by Shen in 2013. The surrounding elastic medium is modeled as a Pasternak foundation. Two kinds of Micromechanics models, namely the Voigt model and Mori-Tanaka model, are considered. The governing equations are based on a higher-order shear deformation shell theory that includes shell-foundation interaction. The thermal effects are also included and the material properties of functionally graded materials (FGMs) are assumed to be temperature dependent. The governing equations are solved by a singular perturbation technique. The numerical results show that in some cases the FGM cylindrical shell with intermediate volume fraction index does not have an intermediate buckling temperature and thermal postbuckling strength. The results reveal that Voigt model and Mori-Tanaka model have the same accuracy in predicting the thermal buckling and postbuckling behavior of FGM shells. The results confirm that in the case of heat conduction, the postbuckling equilibrium path for geometrically perfect FGM cylindrical shells with simply supported boundary conditions is no longer of the bifurcation type. Thermal Postbuckling of Functionally Graded Materials Shells Consider a circular cylindrical shell that is made of the combined ceramic and metallic materials with continuously varying mix ratios comprising ceramic and metal. The length, mean radius, and total thickness of the shell are L, R, and h, respectively. The shell is referred to a coordinate system (X, Y, Z) in which X and Y are in the axial and Figure 4 shows the circumferential directions of the shell and Z is in the direction of the inward normal to the middle surface [18-19]. Shen and Wang [20] performed two step perturbation technique to determine the load–deflection and load–bending moment curves for FGM plates as presented in Figure 5 and they concluded that the characteristics of nonlinear bending are significantly influenced by foundation stiffness, temperature rise, transverse shear deformation, the character of inplane boundary conditions and the amount of initial compressive load [40-54].

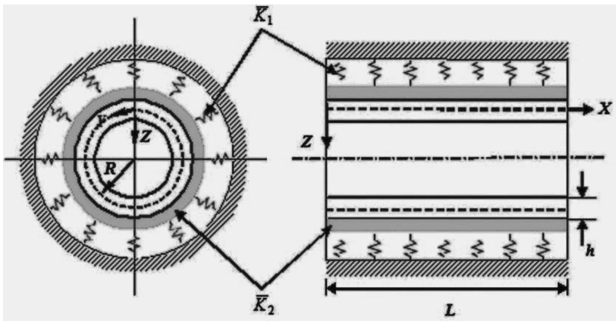

Figure 4. Geometry and coordinate system of a cylindrical shell surrounded by an elastic medium [18].

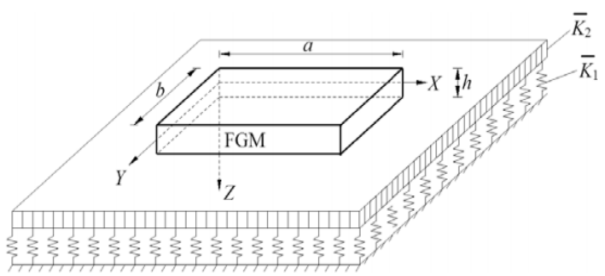

Figure 5. An FGM rectangular plate resting on a Pasternak elastic foundation [20].

2.2 Euler–Bernoulli Beam Theory and von-Karman Geometric Nonlinearity

The Föppl–von Kármán equations, named after August Föppl and Theodore von Kármán, are a set of nonlinear partial differential equations describing the large deflections of thin flat plates. With applications ranging from the design of submarine hulls to the mechanical properties of cell wall. While the Föppl–von Kármán equations are of interest from a purely mathematical point of view, the physical validity of these equations is questionable. Euler–Bernoulli beam theory is a simplification of the linear theory of elasticity which provides a means of calculating the load-carrying and deflection characteristics of beams. Additional analysis tools have been developed such as plate theory and finite element analysis, but the simplicity of beam theory makes it an important tool in the sciences, especially structural and mechanical engineering. Yaghoobi and Torabi in 2013 investigated that beams made of functionally graded materials (FGMs) resting on a nonlinear elastic foundation subjected to axial force are studied as illustrated in Figure 6, Figure 7. The material properties of FGMs are assumed to be graded in the thickness direction according to a simple power law distribution in terms of the volume fractions of the constituents. The assumptions of a small strain and moderate deformation are used. Based on Euler–Bernoulli beam theory and von-Karman geometric nonlinearity, the integral partial differential equation of motion is derived. Then this partial differential equation (PDE) problem, which has quadratic and cubic nonlinearities, is simplified into an ordinary differential equation (ODE) problem by using the Galerkin method. Finally, the governing equation is solved analytically using the variational iteration method (VIM) [21-45].

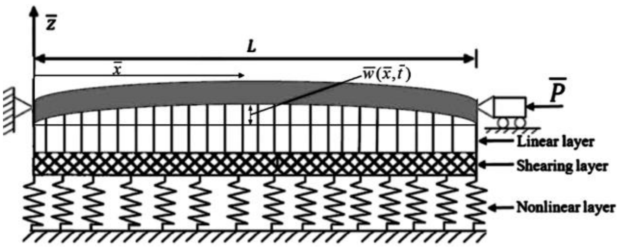

Figure 6. Schematic of the imperfect FG beam with nonlinear foundation [21].

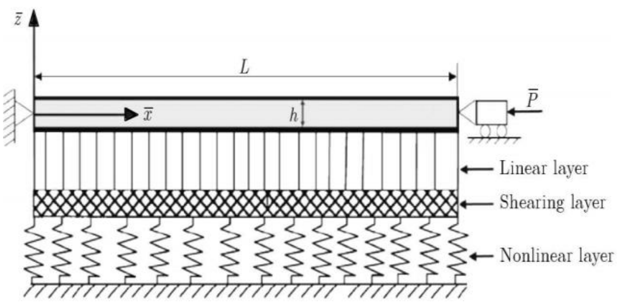

Figure 7. Schematic of the FG beam with a non-linear foundation [22].

3. Results and Discussions

The aforementioned literature review demonstrates that the buckling and post buckling analysis of FGM plates have mostly been carried out based on the plate theories. Very rare stability analyses have been shown in FGM rectangular plates based on the three-dimensional theory of elasticity.

It is shown that, utilizing the considerable control authority generated, even for a small actuator volume fraction, the out-of-plane displacement of the post-buckled FGM panel's can be significantly reduced. Such displacement alleviation allows for load redistribution away from the FGM panel's unloaded edges.

The results show that in some cases the FGM cylindrical shell with intermediate volume fraction index does not necessarily have intermediate buckling temperature and thermal postbuckling strength. The results reveal that the difference of the buckling temperatures between Mori-Tanaka Model and Voigt Model solutions is very small, and the difference in the thermal postbuckling strength between Voigt Model solutions may be negligible. The results confirm that in the case of heat conduction, the postbuckling equilibrium path for geometrically perfect FGM cylindrical shells with simply supported boundary conditions is no longer of the bifurcation type.

4. Conclusion

Structural finite element analysis has been employed to determine the FGM panel's adaptive response while under the influence of a uniaxial compressive load in excess of its critical buckling value. In this review paper, two methods based on the two theories used to analyze the FGM.

Results of the two Mori-Tanaka and Voigt models for buckling temperatures and also thermal post buckling strength are almost the same and the differences are negligible. Reducing out of plane displacement of FGM panel can allow redistributing the loads away from unloaded edge of panel. The results show that in some cases the FGM cylindrical shell with intermediate volume fraction index does not necessarily have intermediate buckling temperature and thermal post-buckling strength.

These results are based on this conclusion that the characteristics of nonlinear bending are significantly influenced by foundation stiffness, temperature rise, transverse shear deformation, the character of in-plane boundary conditions and the amount of initial compressive load. It is shown that the Pasternak elastic foundation may

Enhance the buckling resistance of the shell. Furthermore, the influence of the Winkler constant of the elastic foundation is almost negligible, however, the shear layer may effectively delay the circumferential bifurcation. Both Winkler and shear layers of the elastic foundation may change the critical mode number. Furthermore, for both heat conduction and uniform temperatureloadings, the regarding of the temperature dependency results in lower values of the critical buckling temperature difference.

As a result, the influence of linear and shear layers of the foundation is to weaken the nonlinear behavior of the FGM beam, whereas the effect of the non-linear foundation stiffness is to harden the beam response.

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