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Effects of variable thickness and imperfection on nonlinear buckling of sigmoid-functionally graded cylindrical panels

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ABSTRACT

The use of variable thickness can help the designers and researches reduce the weight of the functionally graded (FG) panel structures. For cases where reduction of weight is of high importance, such as space structures, ocean engineering, this type of panel is the best choice. Hence, this paper analyzes the effect of the variable thickness on nonlinear buckling of imperfect cylindrical panels made of sigmoid-functionally graded material (S-FGM) under combined axial compression and external pressure. The governing equations are in nonlinear form based on the classical shell theory with the von Karman assumption. By applying Galerkin procedure and the Airy stress function, the resulting equations are solved to obtain closed form expressions for critical buckling load and load–deflection curves. In numerical results, effect of variable thickness, the volume fraction index, imperfection size, loading as well as the geometric parameters on the load–dimensionless deflection curves are discussed in details.

1. Introduction

Panel structures with variable thickness are a special class of modern structures, frequently used in the industries like aerospace, aircraft, space vehicles, ocean engineering and in other important engineering structures. The consideration of buckling behavior for such these structures is essential to have an efficient and reliable design. Moreover, the use of the variable thickness helps to reduce the weight of structures and improve the utilization of the material. Recently, because of strong potential applications of this type of structure, there have been increasing research and development activities in the field of buckling behavior, dynamic and vibration analyses.

The buckling and vibration analyses of variable thickness panels and shells have been discussed by several authors. For example, Sakiyama et al. [1] studied the vibration of twisted and curved cylindrical panel with variable thickness using the principle of virtual work and the Rayleigh Ritz method. The static and vibration analyses of orthotropic toroidal shells with variable thickness were presented by Jiang and Redekop [2]. Duan and Koh [3] analyzed the axisymmetric transverse vibration of cylindrical shells with thickness varying monotonically. The buckling behavior of cylindrical shell under the external pressure with variable thickness was investigated by Nguyen et al. [4]. Calculation of natural frequencies and vibration modes of variable thickness cylindrical shells using the Wittrick Williams algorithm is also presented by El-Kaabazi and Kennedy [5]. Based on a three-dimensional (3-D) method, Kang [6] investigated the free vibration frequencies of joined thick conical-cylindrical shells of revolution with variable thickness. Awrejcewicz et al. [7] proposed a novel numerical/analytical approach to study geometrically nonlinear vibrations of shells with variable thickness of layers. By using the Generalized Differential Quadrature method, Bacciocchi et al. [8] presented the vibration analysis of variable thickness shells. Recently, Groh and Weaver [9] investigated the buckling analysis of variable angle tow, variable thickness panels with transverse shear effects.

In the past few years, the use of functionally graded materials (FGMs) has gained intensive attention in many engineering applications [10–12]. FGMs are made from a ceramic and metal. A metal exhibits better mechanical, but cannot withstand exposure to high temperatures. In other hand, a ceramic is useful in high strength and temperature applications, however, suffers from low toughness. Due to these advantages, FGMs have been applied in many engineering applications. FGMs were initially designed as thermal barrier materials for aerospace structures and fusion reactors [13].

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Instead of using a single-property yttria-stabilized zirconia (YSZ) coating to achieve the thermal barrier for the piston crown, a varying-properties FGM was used by Chan [14]. An example is FGM thin-walled rotating blades was presented by Librescu and Song [15]. Applications of FGMs have recently been reported in the open literature, e.g.. FGM sensors [16] and actuators [17], FGM metal/ceramic armor [18], FGM photodetectors [19] and FGM dental implant [20].

Many researches have been presented to investigate the dynamic and vibration analyses of FG cylindrical panels with the constant thickness as [21–42].

The buckling behavior of panel structures depends on interactions, which may exist between the different applied loads. In the following, attention will be focused on the buckling behavior of FG panels with the constant thickness under various loadings. For instant, [43–55].

Up to now, there is very little publishes to investigate behavior analysis of FG plates and shell with the variable thickness. Nejad et al. [56] presented the elastic analysis of axially functionally graded rotating thick cylinder with variable thickness under non-uniform arbitrarily pressure loading. Efraim and Eisenberger [57] proposed the exact vibration analysis of variable thickness thick annular isotropic and FGM plates. Xu and Zhou [58] studied the stress and displacement distributions of continuously varying thickness functionally graded rectangular plates. Hosseini-Hashemi et al. [59] presented the vibration analysis of radially FGM sectorial plates of variable thickness on elastic foundations. Tajeddini et al. [60] described a study of three-dimensional free vibration analysis of thick circular and annular isotropic and FG plates with variable thickness along the radial direction, resting on Pasternak foundation. By using the first-order shear deformation theory (FSDT), Ghannad et al. [61] proposed the elastic analysis of pressurized thick cylindrical shells with variable thickness made of functionally graded materials. The magneto-thermo-mechanical response of a functionally graded magneto-elastic material annular variable-thickness rotating disk was investigated by Bayat et al. [62]. Recently, Dai et al. [63] presented the thermo-elastic analysis of a functionally graded rotating hollow circular disk with variable thickness and angular speed.

Surveying the open literature shows that the effect of variable thickness on nonlinear buckling behavior of the imperfect cylindrical panel made of sigmoid-FGM has not been yet considered. Hence, this paper will focus on analyzing the research gap. Furthermore, the cylindrical panel is subjected to combined the axial compression and the external pressure. The governing equations are in nonlinear form based on the classical shell theory (CST) with the von Karman assumption. Initial geometrical imperfections are also accounted. By applying Galerkin procedure and the Airy stress function, the resulting equations are solved to obtain closed form expressions for load–deflection curves. In numerical results, the effect of the variable thickness, the volume fraction, imperfection parameter, loading as well as the geometric parameters of the panel on critical buckling load and nonlinear load–dimensionless deflection curves are discussed. According to the present results, it is revealed that the variable thickness has significant impact on the buckling behavior of the S-FG cylindrical panels.

2. Cylindrical panel model with the variable thickness

2.1. Geometry of the S-FG cylindrical panel with variable thickness

Consider a cylindrical panel with axial length a, arc length b, radius of curvature R and thickness h is shown in Fig. 1. Assume that the thickness of the cylindrical panel to vary in the x and y directions as follows [64]

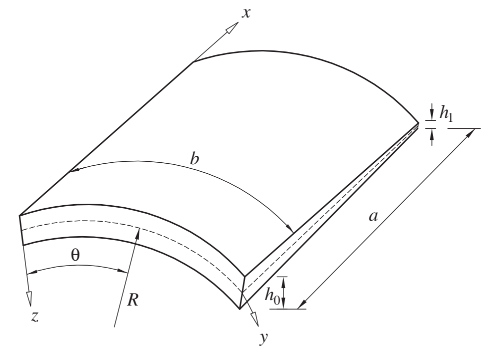

Fig. 1. Geometry of the S-FG cylindrical panel with the variable thickness.

$$h = h_0\varphi(x,y), \quad (1)$$

where h_0 is a constant.

Eq. (1) can be applied for both directions x and x, but in this study we assume that the cylindrical panel rigidities only varies in x direction. Therefore, the function $\varphi(x,y)$ can be written in the following form

$$\varphi(x,y) = \varphi(x) = 1 + cx^d, \quad (2)$$

in which, d represents a non-uniform parameter for the variable thickness S-FG cylindrical panel. For example, if $d = 0$, the thickness of the cylindrical panel is constant in both x and y directions. By taking $d = 1$, the thickness varies linearly from h_0 at $x = 0$. When the non-uniform parameter is equal to two ($d = 2$), the variation of the thickness (h) in the x direction is parabolic. To illustrate, in the Fig. 1, we assume that a S-FG cylindrical panel with linearly variable thickness in the x direction ($d = 1$).

The term c can be easily determined as follows

$$c = \frac{h_1 - h_0}{h_0}, \quad (3)$$

where h_1 denotes the thickness at the right end of the cylindrical panel.

2.2. The cylindrical panels made of sigmoid-functionally graded materials

Assume that the composition is varied from the outer surface to the inner surface, i.e. the outer surface ($z = h/2$) and inner surface ($z = -h/2$) of the panel are metal-rich, whereas the middle surface ($z = 0$) is ceramic-rich (see Fig. 2). In such a way, the effective material properties Pr_{eff} can be expressed as

$$Pr_{eff}(z) = Pr_m V_m(z) + Pr_c V_c(z), \quad (4)$$

in which, $V_m(z) + V_c(z) = 1, V_c(z)$ and $V_m(z)$ are the volume fractions of ceramic and metal, respectively; subscripts m and c stand for the metal and ceramic constituents.

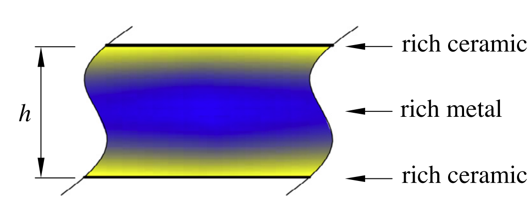

Fig. 2. Sigmoid-functionally graded materials.