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Buckling failure analysis of cracked functionally graded plates by a stabilized discrete shear gap extended 3-node triangular plate element

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ABSTRACT

We present new numerical results in buckling failure analysis of cracked composite functionally graded plates subjected to uniaxial and biaxial compression loads. An accurate extended 3-node triangular plate element in the context of the extended finite element method (XFEM) is developed, integrating the discrete shear gap method (DSG) to eliminate shear-locking. The plate kinematics is based on the Reissner–Mindlin theory, and material properties are assumed to vary through thickness direction, obeying a power law distribution. The developed DSG-XFEM is found to be effective and accurate as it owns many desirable advantages: conveniently representing crack geometry which is independent of the mesh; shear-locking effect is no longer valid; mesh distortion is insensitive and controllable; thin plates is possible; triangular elements are easily generated for problems even with complex geometries; and high accuracy. All these arisen features are demonstrated through numerical examples and the effects of crack-length, material gradation, mesh distortion, inclined angles of cracks, boundary conditions, width-to-thickness ratio, length ratio, etc. on the critical buckling coefficient (CBC) are analyzed. Numerical results reveal that the material gradation, crack-length, thickness, length ratios, etc. have a strong effect on the behavior of CBC. This phenomenon is mainly attributed to the plate stiffness degradation due to the presence of local defects and material composition. Also, the boundary conditions greatly alter the CBC whereas the inclination of cracked angle is found to be insignificant.

1. Introduction

Functionally graded materials (FGMs) are a specific class of composite materials that have a smooth and continuous variation of material properties from one surface to another, resulting in a non-uniform microscopically inhomogeneous structure with continuously graded macro-properties as illustrated in Fig. 1 [1]. The material properties of FGMs are derived from a function of position in the through-thickness direction. The preceding studies have shown that the FGMs are capable of alleviating and reducing the stress concentration, thermal stresses, and residual stresses, etc. Consequently, they have been widely used as engineered materials in many engineering applications including thermal barrier coatings [2], biomedical materials [3], impact and wear resistance [4] and piezoelectric devices [5].

Thin-walled structures in general or plate-like structures in particular are one of the major parts in many engineering applications. The use of plates in civil, power, aeronautical, mechanical, marine, and many other fields is very common in our modern life. Under different loading conditions, the plates are often prone to different failure modes including buckling which is studied in the present work. In fact, the failure phenomena induced by buckling are a quite common occurrence in engineering structures, especially in plates and shells structures. More importantly, the buckling can often occur when defects (e.g., cracks, void) are present in the plates, and as a consequence that can cause a local phenomenon characterized by complex wrinkling deflection patterns in the region around cracks [6].

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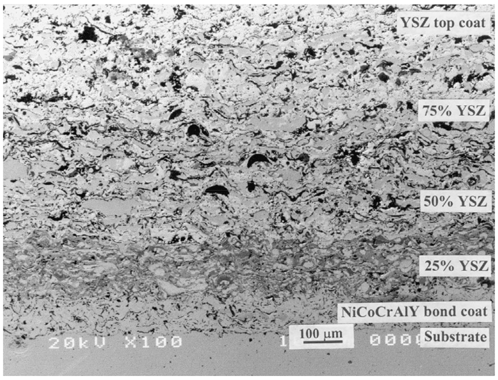

Fig. 1. NiCoCrAlY-YSZ composite five layered functionally graded material.

1.1. Background

The desirable advantages of FGMs and the widely used plate structures have attracted many scientists and researchers to gain a better understanding of their mechanical behaviors. Chang and Batra [7] presented a three-dimensional thermoelastic deformation analysis of FGM plates. Neves et al. [8] developed a meshless method utilizing a third-order shear deformation theory for static, free vibration and buckling of FGM plates while Lee et al. [9] analyzed thermoelastic behavior using the element-free kp-Ritz method. Huang and his co-workers investigated the natural frequencies of cracked FGM plates in two and three-dimensions [10–12]. In recent years, several works devoted to the FGMs are studied by the authors, e.g., see Refs. [13–22].

Imperfection like cracks can appear in FGM plates because of many reasons such as fatigue, corrosion, high unexpected loads, and high temperature environments. The presence of the defects (e.g., cracks) in FGM plates can greatly affect the performance of structures. Therefore, many previous efforts have devoted to the study of FGM plates including the buckling phenomena, e.g., see Refs. [23–28]. They are expected to gain basic knowledge and provide useful information for designers [23]. It is obvious that the investigation of buckling phenomena of FGM plates without cracks is fairly well covered in the literature. However, buckling failure studies of FGM plates with cracks are rather rare. Very recently, Panahandeh-Shahraki and Rad [23,24] developed a finite element model using classical plate theory for buckling analysis of cracked FGM plates supported by Pasternak foundation and in tension. Natarajan et al. [25] used the field redistributed shape functions to alleviate the shear-locking on the buckling of FGM plates with internal discontinuities. Shariat et al. [26] presented a closed-form solution for buckling of imperfect FGM plates using classical plate theory. The analytical approach developed for the buckling analysis of cracked FGM plates, however, in general may be very limited to problems with simple geometries and boundary conditions, and numerical methods e.g., boundary element method, meshfree method, extended finite element method, are preferable in practice.

The finite element method (FEM) has shown to be a powerful numerical tool in modeling many engineering problems including buckling of cracked FGM plates [23,24]. However, the FEM is not well suited for modeling problems with non-smoothed solutions like crack. The extended finite element method (XFEM) using enrichment technique emerged recently (e.g., see Refs. [20–22,25]) has shown to be a more effective and accurate technique than the conventional FEM in modeling crack problems as crack geometry is independent of the mesh.

In modeling buckling of plates, shear-locking phenomenon often appears once the plate thickness becomes small (as a thin plate) where the pure bending dominates the plate deformation. The preceding efforts have found that the shear-locking may be caused by the fact that the transverse shear strains are not eliminated under pure bending conditions. Different existing techniques have proposed to overcome the drawbacks of bending and shear strain fields under thin plate situation. Among those by which the locking phenomenon can be suppressed include: the mixed interpolation method [29], the field redistributed substitute shape functions [30], the stabilized conforming nodal integration [31], the *p*-adaptivity, for example the moving Kriging interpolation [32,33], the high-order NURBS functions [13,14,34,35], the simple first-order shear deformation plate theory [14], the discrete shear gap method (DSG) [36], the assumed strain method [37], and the discrete Kirchoof element (DKT) [38].

1.2. Approach and objective

Our main goal is to investigate mechanical buckling behaviors of cracked non-homogenous functionally graded plates using a novel stabilized discrete shear gap extended 3-node triangular plate element (named as DSG-XFEM). The DSG-XFEM is originally developed by the authors for frequency analysis of cracked isotropic homogeneous plates [39], and that is extended here to buckling analysis of cracked FGM plates under uniaxial and biaxial compression loads. We investigate the effect of cracks and other aspect ratios on the critical buckling parameter through numerical examples. Also, we address numerical properties of the developed method affecting the critical buckling factor of cracked FGM plates.

By employing the DSG technique [36], the present formulation does not suffer any shear-locking effect and can deal with thin plates without any difficulty. It hence makes the proposed approach different and more effective than the one developed by Bachene et al. [40]. Although many previous works have successfully shown in treating the shear-locking, see e.g. [29,37,38], however they do not take into account the mesh distortion comprehensively, which often encounter in practical problems using commercial software for mesh generation. Naturally it motivates us to integrate the DSG technique into the versatile XFEM to form a new method for accurately and effectively modeling the buckling behaviors of cracked plates. One should be noted that, due to the simplicity, the contact condition at the crack-faces is not taken into account in the present work. The applicability of the present method is high as it inherently owns several desirable features of an effective numerical method: (a) the discontinuity induced by cracks is treated by enrichment method, by which the cracks are mesh-independent; (b) unlike the traditional FEM, the crack can be defined arbitrarily and straightforwardly, see e.g., [20–22]; (c) with the aid of the DSG, neither shear-locking effect is valid nor mesh distortion is sensitive. (d) the mesh distortion can be controllable; (e) the method is applicable to both thin and moderately thick plates; (f) triangular elements can easily and automatically be generated for problems even with complex geometries; (g) the approach offers high accuracy on the solution of critical buckling factor.

1.3. Outline

The rest of the paper is organized as follows. Theoretical formulation is presented in Section 2 involving governing equation, functionally graded Reissner–Mindlin plate theory, and discrete shear gap method. Formulation of XFEM for buckling analysis of cracked FGMs plates is presented in Section 3. Validation or accuracy study of the developed method is analyzed and presented in