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Numerical simulation of functionally graded cracked plates using NURBS based XIGA under different loads and boundary conditions

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ABSTRACT

In this paper, extended isogeometric analysis (XIGA) is performed to simulate the cracked functionally graded material (FGM) plates using first order shear deformation theory (FSDT) under different types of loading and boundary conditions. The gradation in material properties of the plate vary exponentially along thickness direction. The top and bottom surfaces of the plate are composed of ceramic and metal respectively. The properties of the equivalent composite are evaluated by rule of mixtures. The crack faces are modeled using Heaviside function, whereas the singularity in the stress field at the crack tip is modeled by employing crack tip enrichment functions. The domain integral approach is used for evaluating the stress intensity factor. The results obtained by XIGA for FGM plate are compared with equivalent composite plate.

1. Introduction

In order to meet the demand of new technologies for aerospace and high temperature applications, the material science and engineering community is continuously engaged in the development of new materials with enhanced properties. Generally, all the metals and their alloys are susceptible to creep, oxidation and loss of structural integrity. The coatings of ceramic have several drawbacks such as low strength, low toughness, poor interfacial bonding and consequently tendency towards cracking and spallation. Therefore, a variety of metal/ceramic composite materials including functionally graded materials (FGMs) have been developed to exploit the advantage of metals and ceramics. The FGMs are special type of composite structures having continuously varying material properties between top and bottom surfaces. The FGMs are characterized by a smooth transition from one material to another, thus avoiding high inter-laminar shear stresses and de-lamination that persists in laminated composites. Due to the improved mechanical behavior, FGM plates are increasingly used in a variety of engineering applications [25]. A significant number of studies have been conducted to examine the mechanical behavior of FGM plates [28].

In general, thin-walled plate structures are subjected to cyclic loading, which leads to the development of surface cracks or growth and merging of existing cracks. It has been noticed that the presence of cracks considerably affects the structural integrity, lowers the material strength and shortens the service life. Hence, the study of fracture behavior of these structures is an area of great practical and theoretical importance.

The performance of these structures is evaluated by conducting various tests in presence of crack, but there are various unresolved issues with these experiments. Thus, most of the studies on the fracture of plates are concentrated on in-plane tensile loading [30] using analytical approaches. Some efforts are also made to resolve these issues using numerical methods. A limited work has been done on the simulation of crack growth using Reissner–Mindlin plate theory. In Reissner–Mindlin plate theory [42,28], the near tip-fields are defined in terms of moment and shear force intensity factors. The values of stress intensity factor for mode-II and mode-III is evaluated by Joseph and Erdogan [26] under antisymmetric loading. Sosa and Eischen [45] employed the path independent integral for the computation of stress intensity factor for the plate bending. Dolbow et al. [18] derived the domain based interaction integral for computing the mixed mode intensity factors in context of Reissner–Mindlin plate theory. Potyondy et al. [34] performed the crack growth in thin shells by finite elements and continuous remeshing. The crack growth direction was evaluated from the fracture analysis of thin plates [24]. In finite element analysis, the crack growth is burdened by the necessity to remesh at each stage of crack evolution. In order to overcome this problem, a number of numerical methods has been developed such as element free Galerkin method [6], boundary element methods [48,49], reproducing kernel particle method [29], meshless local

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Petrov Galerkin method [2], extended finite element method [5], cracking particles method [37], meshfree particle method [38] and immersed particle method [40].

In recent years, some work has been reported in literature on thin structures. In 2000, Dolbow et al. [18] solved few plate crack problems using extended finite element method (XFEM) using Reissner–Mindlin plate theory. Yang and Shen [50,51] performed the dynamic analysis of FGM plates subjected to impulsive loads using a Galerkin procedure coupled with modal superposition methods. Qian et al. [35] employed the higher order shear deformation theory to perform the deformation and vibration analysis of FGM plates. Rabczuk and Areias [36] proposed a meshfree method for arbitrary evolving cracks in thin shells. They used extrinsic basis with third degree completeness for removing the membrane locking. Rabczuk et al. [39] employed the meshfree thin shell method for the dynamic fracture analysis of shells using Kirchhoff–Love theory. Bui and Nguyen [12] performed the vibration and buckling analysis of orthotropic plates using meshfree methods. Bui et al. [13] conducted the free vibration analysis of plates using meshfree method without shear locking. They [14] also performed the buckling analysis of plates using first order shear deformation theory under uniaxial in-plane compression and pure shear loads. Lasry et al. [27] computed the stress intensity factor for the plates using XFEM. [32,31] studied the influence of crack length on the linear flexural and free vibration of FGM plates using XFEM. Baiz et al. [3] performed the buckling analysis of cracked plates by smoothened FEM and XFEM. Chau-Dinh et al. [15] developed phantom-node method for the analysis of shells with through-thickness cracks. Amiri et al. [1] described a phase field model for the fracture in Kirchoff–Love thin shells using local maximum entropy meshfree method.

In FEM, XFEM and meshfree methods, the approximation of the geometry introduces some error in the solution since different basis functions are employed for defining the geometry and solution. In order to overcome this issue, Hughes et al. [23] developed a powerful numerical tool, known as isogeometric analysis (IGA). Shojaee et al. [43] and Valizadeh et al. [46] used IGA for vibration and buckling analysis of laminated composite plate and orthotropic plates respectively. Valizadeh et al. [47] used the NURBS based finite element method to conduct the bending, vibration and buckling analysis of FGM plates using FSDT. Yin et al. [52] proposed locking free plate formulation to analyze the static, bending, buckling and free vibration of homogeneous and FGM plates. Nguyen-Thanh et al. [33] employed IGA for thin shell analysis using polynomial splines over hierarchical T-meshes. In order to analyze the problems in the presence of flaws, IGA combined with extrinsic PU enrichment, is known as extended isogeometric analysis (XIGA). Benson et al. [7] analyzed few plane crack fracture mechanics problems using XIGA. Haasemann et al. [21] performed the analysis of bi-material body with curved interfaces using XIGA. The greater accuracy and higher convergence rate is achieved using XIGA in fracture mechanics problems as described in De Luycker et al. [17]. They employed blending technique for the tip enrichment to ensure compatibility of two enrichment functions with the un-enriched domain. The compatibility at the boundaries of the enriched domains has been enforced by multiplying the enrichment function with a bubble function. C^0 lines are added to overcome the incompatibility of the degree of continuity between basis functions and blending functions for the NURBS. Ghorashi et al. [19] conducted the fracture analysis of structures using XIGA. They [20] also performed the fracture analysis of orthotropic cracked media by XIGA using T-spline basis functions. Bhardwaj and Singh [8] carried out the analysis of plane problems in the presence of flaws using XIGA. They [9] solved few cracked plate problems of homogeneous materials by XIGA under different loads and boundary conditions. They also performed the stochastic fatigue crack growth analysis of bi-layered FGM plate [10]. Nguyen-Thanh et al. [33] performed the analysis of through-thickness cracks in thin shell using Kirchhoff–Love theory by XIGA. So far, no work has been reported in literature on the fracture analysis of cracked FGM plates using XIGA. Therefore, the objectives of the present study are,

- To extend the XI GA for the analysis of FGM and composite plate with through-thickness cracks.
- To study the behavior of cracked FGM and equivalent composite plate under different types of load and boundary conditions.
- To compare the FGM plate with equivalent composite plate under different types of load and boundary conditions.
- To highlight the advantages of XIGA in modeling cracked FGM plates.

This paper is organized as follows: the material properties of the functionally graded materials are presented in Section 2. A brief overview of first order shear deformation (Reissner–Mindlin) plate theory is presented in Section 3. XIGA formulation for cracked plate is presented in Section 4. The stress intensity factor computation for cracked plates is described in Section 5. The numerical results and parametric studies are presented in Section 6 followed by concluding remarks (Section 7).

2. Material properties

A square plate made of ceramic (alumina) and metal (aluminum alloy) is taken having x, y coordinates in the plane of the plate and z along the thickness direction (see Fig. 1). The top surface of the plate is having 100% ceramic, and is graded to 100% metal at the bottom by the following exponential law,

$$E(z) = E m e^{\alpha z} \quad (1)$$

where, α is given as,

$$\alpha = \frac{1}{h} \ln\left(\frac{E_c}{E_m}\right) \quad (2)$$

E_c and E_m are the elastic modulus for the ceramic (alumina) and metal (aluminum alloy) respectively. The elastic modulus of the FGM is obtained by applying the rule of mixture. The volume fractions of ceramic (V_c^{FGM}) and metal (V_m^{FGM}) in FGM [11] are obtained as,

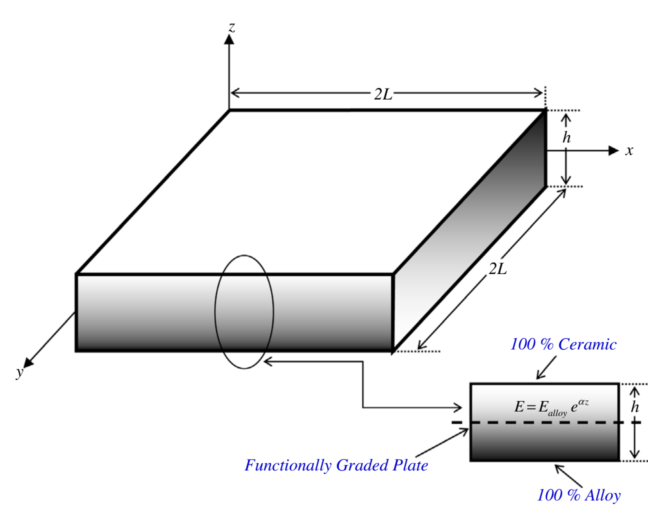

Fig. 1. Schematic representation of functionally graded plate.