



A new refined simple TSDDT-based effective meshfree method for analysis of through-thickness FG plates

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ABSTRACT

In this paper a novel numerical method based on the Moving Kriging (MK) interpolation meshfree method, integrated with a simple higher-order shear deformation plate theory for analysis of static bending, free vibration and buckling of functionally graded (FG) plates is presented. In the proposed technique, the shape functions are built by the Kriging technique which possesses the property of Kronecker delta function which makes it easy to enforce essential boundary conditions. The present formulation is based on a refined simple third-order shear deformation theory (R-TSDDT), which is based on four variables and it still accounts for parabolic distribution of the transverse shearing strains and stresses through the thickness of the plate present in the original simple third-order shear deformation theory (TSDDT). In this theory, instead of assuming a specific distribution for the displacement field, the theory of elasticity is used for obtaining the kinematics of the plate deformation. We first propose the formulation, and then several numerical examples are provided to show the merits of the proposed approach.

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1. Introduction

Development of recent technologies requires introduction and use of new materials to meet the specific needs of such technologies. For instance, in the aerospace applications where mechanical strength and thermal shielding is needed at the same time, new materials are required. Also, in bioengineering applications new materials which are bio-compatible and at the same time meet specific strength and stiffness requirements are desired. A classical way of making new materials has been to use two or more different constituents in a single body. Laminated composite materials are excellent examples of such remedies. However, the inherent tendency of composites for delamination in the presence of high shearing stresses, suggested the introduction of functionally graded materials (FGMs). The FGMs are usually made from ceramic and metal constituents with gradual variation of volume fractions. As the results, material properties of the FGMs vary gradually in one or more directions in order to meet specific requirements. The FG structures are most useful in aerospace applications where simultaneous resistance to thermal shocks and high mechanical strength and ductility are required. In such applications,

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plates are a main part of the structures. Therefore, a thorough understanding of the behavior of FG plates in various contexts, such as static deflection, free and forced vibration, and also buckling is a crucial task in design of modern structures.

In order to predict the behavior of plates, different models have been introduced and developed in the past decades. The classical plate theory (CPT) is the first one which neglects the effect of shearing stresses in the transverse deformation of plates. This theory is based on the Kirchhoff–Love assumptions for the displacement field of a plate. The CPT is suitable for the analysis of thin plates. However, for accurate analysis of thick plates the effect of shearing stresses should be taken into account. The first order shear deformation theory (FSDT) was introduced by Reissner [1] and Mindlin [2] to account for the effect of transverse shear deformation on the flexural behavior of plates. In the FSDT the shearing strains and stresses are constant through the plate thickness and therefore the free boundary conditions in the top and bottom layers of the plate cannot be modeled. To overcome this drawback, and also for calculation of the shear forces, the so called shear correction factor is introduced in this theory. However, accurate value of this factor which is different for different problems plays an important role in the accuracy of the results. To overcome this shortcoming, various higher order shear deformation theories have been developed. To name a few, the works of Ambartsumian [3], Reissner [4], Levinson [5], Reddy [6,7], and Soldatos [8] can be mentioned. In the third order shear deformation theory (TSDT), the shearing strains and stresses have a quadratic variation in the thickness direction and therefore there is no need for a shear correction factor. In addition to the TSDTs, there is a so called simple third order shear deformation theory (STSDT) in which the in-plane displacement field has a higher order variation, while the transverse deflection is constant through the plate thickness. In the STSDT the number of unknown functions in the displacement field is equivalent to that of the FSDT, while the shearing strains vary quadratically in the thickness direction [9].

The STSDT can be further facilitated by integrating the theory of elasticity in the process of selection of the displacement field. The resulting theories are usually called refined simple third order shear deformation theory (R-STSDT). In the R-STSDT, which was first proposed by Shi [10], instead of assuming a specific distribution for the displacement field, the theory of elasticity is used for obtaining the kinematics of the plate deformation. In the present work, the formulation of the R-STSDT is integrated with an MK interpolation-based meshfree method for the first time for static, free vibration, and buckling analysis of FG plates.

It is almost impossible to obtain analytical solutions for FG plates of arbitrary shape, under various types of loading and boundary conditions. Therefore, analysis of such problems lends itself completely to the numerical techniques. Because of the emergence of new strategies for accurate modeling of the behavior of plates, numerical methods are still an active research area in this field [11–14]. Different types of numerical methods have been successfully utilized for performing various analyses on the FG plates. Since in this study, our focus is on the meshfree methods, a brief review of the meshfree analysis of plates will be given.

Dai et al. [15] analyzed FG plates by the radial point interpolation method (RPIM). Their method was used for static deflections, natural frequencies and dynamic responses of plates with different boundary conditions and volume fraction exponents. Later, they made use of the element free Galerkin (EFG) method for thermo-mechanical analysis of FG plates [16]. Their method was used for active shape control of FG plates with the utilization of distributed piezoelectric actuators. Ferreira et al. [17] proposed the use of the collocation multiquadric radial basis function for the static analysis of functionally graded plates based on the third-order shear deformation theory. They later extended their previous work for the free vibration analysis of FG plates [18]. Both the first and third order shear deformation theories were adapted in that work. The local Kriging meshless method was used by Zhu and Liew [19] for the modal analysis of FG plates. The Eigen values of the discretized system were obtained by considering the FSDT of plates. Bui et al. [20] proposed a truly meshfree technique for the static and dynamic analysis of sandwich structures with FG cores. In their work, a meshless integration technique [21–23] was utilized for accurate evaluation of domain integrals. The FSDT along with the local Kriging meshless method was used by Zhang et al. [24] for investigation of mechanical and thermal buckling of FG plates. Lei et al. [25] presented the element free kp-Ritz method for the analysis of laminated carbon reinforced FG composite plates. The flexural behavior of the plate was accounted for by the FSDT. An improved meshfree method based on the moving Kriging technique was presented for mechanical analysis of FG plates [26]. Moradi-Dastjerdi and Malek-Mohammadi [27–30] have performed extensive research on the mechanical behavior of different types of plates reinforced by carbon nanotubes using higher order plate theories.

It should be stated that the authors have studied the mechanical response of FG plates based on the FSDT theory, previously [26]. Apart from the discretization technique, i.e., the moving Kriging method, the present study and the former are significantly different. The main distinctions between these two works can be addressed as follows:

- The simple approach presented in [26] is based on the FSDT theory, while the present work makes use of a higher order theory, i.e., the R-STSDT, and those theories are quite different between each other. The main advantage of the present work is that in the TSDT theory the kinematics of the displacement field is derived from the theory of elasticity, rather than the hypothesis of displacement.
- In [26], the shear correction factor, which plays an important role in the accuracy of the results, is required. In the present formulation, no shear correction factor is needed, and the shearing stresses are computed directly with high accuracy.
- In the FSDT-based approaches [26], the shearing strains and stresses are *constant* through the plate thickness, which is not quite realistic especially for describing the free boundary conditions in the bottom and top layers of the plate. This

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