Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 54(10) (2023) 479-482
DOI: 10.22060/mej.2022.20998.7356

Investigation of the Effect of Porosity on Thermo-Elastoplastic Bending of Functionally Graded Plates Using 3D Meshless Radial Basis Reproducing Kernel Particle Method

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ABSTRACT: In this paper, the effect of porosity on the thermo-elastoplastic bending response of temperature-dependent functionally graded plates exposed to a combination of thermal and mechanical loads is studied using a three-dimensional meshless model based on the radial basis reproducing kernel particle method. To describe the plastic behavior of the plate, the von Mises yield criterion, isotropic strain hardening, and the Prandtl-Reuss flow rule are adopted. The material properties are continuously varying in the thickness direction according to a power-law function in terms of the ceramic and metal volume fractions. The modified rule of mixtures is employed to locally evaluate the effective thermomechanical parameters of the functionally graded material. A 3D meshless model based on the radial basis reproducing kernel particle method is developed and used in all analyses. To show the accuracy and efficiency of the present method, the obtained results are compared with the existing analytical and numerical results and very good agreements have been observed. Several numerical examples for temperature, deflection, and stress analysis of porous functionally graded plates are presented, and the effect of significant parameters such as porosity coefficient, material gradient index, thickness ratio, and boundary conditions on the bending response of plates has been investigated.

Review History:

Received: Feb. 02, 2022
Revised: Aug. 14, 2022
Accepted: Sep. 10, 2022
Available Online: Sep. 23, 2022

Keywords:

Thermo-elastoplastic analysis
Functionally graded plate
Porosity
Reproducing kernel particle method
Radial basis function

1- Introduction

Functionally Graded (FG) materials are advanced composites that are purposefully made through the heterogeneous distribution of different constituents. Continuous changes of properties in FG materials cause different thermo-mechanical behavior in them and this can help to improve physical characteristics including stress concentration, thermal stresses, and residual stresses. The high practical capabilities of FG materials, including high strength, high-temperature resistance, and impact resistance, have made it possible for designers to use them widely in various fields of mechanics, aerospace, electronics, nuclear, biomedicine, etc. The wide use of plates in most modern and practical engineering structures, as well as the unique properties of FG materials, has become the study of the thermo-mechanical behavior of FG plates into an attractive research field. Among the different methods of producing FG materials, the sintering process is known as one of the suitable methods for manufacturing these materials. In this method, due to the large difference in coagulation temperature between the components, the occurrence of porosity in the material is inevitable [1]. For this reason, investigating the effect of porosity in the analysis of functionally graded structures is of particular importance. Zenkour [2] presented the bending responses of porous FG single-layered and sandwich thick rectangular plates using a quasi-3D shear deformation theory. Thermo-elastic analysis of FG porous materials with temperature-dependent properties using a staggered finite volume method was developed by Gong et al. [3]. The staggered grid technique is employed to incorporate property variation into the discretization of governing equations. Liang and Wang [4] proposed a quasi-3D trigonometric shear deformation theory for wave propagation analysis of FG sandwich plates with porosities resting on a viscoelastic foundation. By dividing the transverse displacement into bending, shear, and stretching components, they calculated the transverse shear and normal deformations. Mashat et al. [5] presented a quasi-3D higher-order plate theory for bending analysis of FG plates resting on elastic foundations under hygro-thermo-mechanical loads with porosity. They considered the impacts of transverse shear deformation as well as the transverse normal strain. The influence of porosity distribution on free vibration and buckling analysis of multi-directional FG sandwich plates was investigated by Sah and Ghosh [6]. To incorporate the porosity in the FG face sheet, they considered even, uneven, logarithmic uneven, linear uneven, and sinusoidal uneven porosity distribution models. In recent years, meshless methods have been developed as one of the most powerful computational methods and have been successfully used to solve many practical problems.

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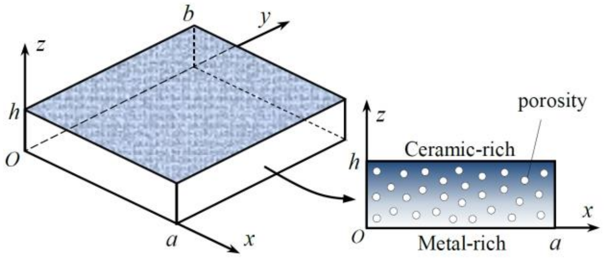

Fig. 1. Porous FG plate in the 3D coordinate system

One of the most common and widely used meshless methods, which is well-developed based on the smooth particle hydrodynamics method, is the Reproducing Kernel Particle Method (RKPM). Although the shape functions created by the RKPM method have excellent smoothness, this method has some shortcomings in the numerical simulation process so the accuracy and stability of the results are affected by different kernel functions [7]. To reduce the negative effects of different kernel functions as well as improve the accuracy and stability of calculations, the Radial Basis Function (RBF) has been integrated with the RKPM method and a new method called the Radial Basis Reproducing Kernel Particle Method (RRKPM) has been introduced. One of the most important advantages of the RRKPM is to increase the convergence and accuracy of the results by reducing the dependence of its approximation function on the kernel function [8]. In the present study, a 3D radial basis reproducing kernel particle model is presented for nonlinear thermo-elastoplastic bending analysis of temperature-dependent porous FG plates exposed to a combination of mechanical and thermal loads.

2- Methodology

A rectangular porous FG plate with dimensions $a \times b \times h$ is considered. A schematic view of the plate in the Cartesian coordinate system *xyz* is shown in Fig. 1. The *z*-axis is positioned across the thickness and the *xy* plane ($z=0$) coincides with the bottom surface of the plate. It is assumed that the bottom surface of the plate varies from metal-rich to ceramic-rich at the top surface.

It is assumed that the plate is initially at a uniform temperature $T_0 = 300\,\mathrm{K}$ and is completely stress-free. Subsequently, the top surface of the plate is exposed to a combination of thermal and mechanical loads. The ceramic constituent is completely brittle and always retains its elastic deformation. While yield in FGMs occurs in their metal constituent when the equivalent stresses are greater than the yield limit. So far, various homogenization methods have been proposed to estimate the effective mechanical properties of metal-ceramic composite materials. One of the simplest and most convenient homogenization techniques is the modified rule of mixtures, which predicts the effective material properties of a metal-ceramic composite using the volume fraction of its constituents.

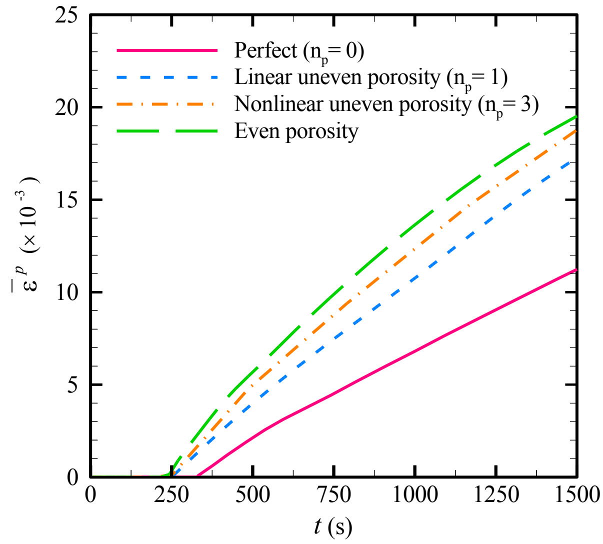

Fig. 2. Variations of equivalent plastic strain with respect to time for SSSS porous FG square plate for different values of porosity gradient index, ($h/a = 0.1, n = 1, p_0 = 0.2$)

3- Results and Discussion

A parametric study has been performed to investigate the effect of important parameters including shape parameter and nodal density on computational accuracy, and their optimal values have been extracted. Then, to prove the efficiency and accuracy of the present method, several numerical examples are analyzed and the results are compared with those obtained from analytical and numerical methods. In Fig. 2, the variations of the equivalent plastic strain with respect to time, $(\bar{\varepsilon}^p - t)(\frac{a}{2},\frac{b}{2},h)$, through the thickness of SSSS porous FG plate are shown for different values of the porosity gradient index n_p . It can be seen that with the increase of n_p , $\bar{\varepsilon}^p$ increases significantly. According to the figure, it can be concluded that the effect of increasing the porosity coefficient in increasing plastic strain is significant.

4- Conclusions

In this paper, a 3D thermo-elastoplastic formulation based on the radial basis reproducing kernel particle approach was developed to explore the nonlinear bending behavior of temperature-dependent porous FG plates under a combination of mechanical and thermal loads. In this regard, the following results were obtained

- By increasing the porosity coefficient *p*, the deflection of the plate increased and the stress σ_{xx} on the upper surface of the plate decreased.

- The increase in the porosity coefficient led to a decrease in the equivalent stress level and an increase in the amount of equivalent strain and plastic strain.

- With the increase of the material gradient index *n*, the deflection of the plate increased and its plastic strain decreased.

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HOW TO CITE THIS ARTICLE

R. Vaghefi, Investigation of the Effect of Porosity on Thermo-Elastoplastic Bending of Functionally Graded Plates Using 3D Meshless Radial Basis Reproducing Kernel Particle Method, Amirkabir J. Mech Eng., 54(10) (2023) 479-482.

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