Research Article

Thermal Analysis of 2D FGM Beam Subjected to Thermal Loading Using Meshless Weighted Least-Square Method

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The paper analyzed the thermal problem of the 2D FGM beam using meshless weighted least-square (MWLS) method. The MWLS as a meshless method is fully independent of mesh, and an approximate function was used to construct a series of linear equations to solve the unknown field variable, which avoided the troublesome task of numerical integration. The effectiveness and accuracy of the approach were illustrated by a clamped-clamped FGM beam which was subjected with interior heat source. The volume fraction of FGM beam was assumed to be given by a simple power law distribution. The effective material properties of the FGM beam were assumed to be temperature independent and calculated by Mori-Tanaka method. The results showed that a good agreement was achieved between the proposed meshless method and commercial COMSOL Multiphysics.

1. Introduction

FGMs can resist high temperatures and are proficient in reducing the thermal stress and have received more attention from the researchers [1]. Most of these researches on FGMs have been restricted to heat conduction analyses, thermal stress analyses, thermal buckling analyses, thermal vibration, and optimization problem. Various numerical techniques, such as the finite difference method (FDM) [2, 3], finite element method (FEM) [4–7], boundary element method (BEM) [8], or more recently developed meshless methods [9–23], have been developed for analyzing thermal related problems and other problems. Because of the complexity of the relevant governing equation, analytical solutions are usually difficult to obtain for those arbitrary geometry and complex boundary conditions, and the exact solutions are usually obtained based on classical plate theory, first-order shear deformation theory, high-order shear deformation theory, and so on [24, 25]. Compared with FEM, FDM, and BEM, the meshless methods are associated with a class of numerical techniques that approximate a given differential equation or a set of differential equations using global interpolations on the discrete nodes or background mesh, exhibiting the advantages of avoiding mesh generation, simple data preparation, easy postprocessing, and so forth.

Liu and Gu [15] introduced meshless methods and their programming, such as the element-free Galerkin (EFG) method [12, 16], the hp-clouds method, the meshless local Petrov-Galerkin (MLPG) method [9, 10], meshless Galerkin method using radial basis functions [11, 14, 21], the least-square method [20], and meshless point interpolation method [19]. The main advantage of the MLPG method compared with regular Galerkin-based methods is that no background mesh is used to evaluate various integrals appearing in the local weak formulation of problem, but it requires a high-order quadrature rule to obtain converged results and thus needs much more computational effort in terms of CPU time than that for the FEM. Ching and Chen [9] proposed the thermoelastic analysis of a functionally graded composite considering temperature-dependent thermomechanical properties by the MLPG method. Andrew and Senthil [12] proposed a methodology for the two-dimensional simulation and optimization of material distribution of functionally graded materials for thermomechanical processes using a genetic algorithm. Katsikadelis [13] employed the meshless analog equation method to solve the 2D elastostatic problem for inhomogeneous anisotropic. A meshless algorithm of fundamental solution coupling with radial basis functions based on analog equation theory was proposed to simulate the static thermal stress distribution in 2D FGMs [14].
Mierzwiczak et al. [17] presented the singular boundary method for steady-state nonlinear heat conduction problems. Bhavani et al. [26] solved thermoelastic equilibrium equations for a functionally graded beam to obtain the axial stress distribution. Sohn and Kim [27] analyzed static and dynamic stabilities of FG panels which are subjected to thermal and aerodynamic loads. Hiroyuki [28] presented a two-dimensional (2D) higher-order deformation theory for the evaluation of displacements and stresses in functionally graded (FG) plates subjected to thermal and mechanical loading. Zhou et al. presented steady-state [29] and transient-state [30] heat conduction analysis of heterogeneous material using the meshless weighted least-square method. In this paper the pure meshless method (MWLS) was then extended to solve problems of thermoelastic analysis for the FGM beam with interior heat source. The volume fractions of constituent materials composing the FGM beam are assumed to be given with irregularly distributed data.

2. MWLS Analysis of the Thermal Problem

The solution of MWLS analysis to the thermal problem is described in this section. The shape functions in MWLS analysis is a moving least-squares approximation scheme which is originally developed for the smooth interpolation of irregularly distributed data.

2.1. The Moving Least-Square (MLS) Approximation Scheme. Construct the local approximate function \( f^h(x) \) of an unknown field variable function \( f(x) \) expressed as

\[
f(x) \approx f^h(x) = p^T(x)a(x)
\]

where \( p^T(x) \) is the basis function and the quadratic basis \( p^T(x) = \{1, x, y, x^2, xy, y^2\} \) is used in this paper. In 2D space, the number of basis function \( m=6; a(x) \) are unknown coefficients, which are solved by minimizing a weighted discrete residual given as

\[
\frac{\partial J}{\partial a_j(x)} = \frac{\partial}{\partial a_j(x)} \left( \sum_{i=1}^{N} \omega_i(x) \left[ f^h(x, x_i) - f(x_i) \right] \right) = 0 \quad j = 1, 2, \ldots, m
\]

The minimum value of \( J \) may be achieved through differentiating with respect to \( a(x) \)

\[
\frac{\partial J}{\partial a(x)} = 2 \sum_{i=1}^{N} \omega_i(x) \left[ \sum_{j=1}^{m} p_j(x_i) a_j(x_i) - f_i \right] p_j(x_i) = 0 \quad j = 1, 2, \ldots, m
\]

in which \( x_i \) are the positions of the \( N \) nodes, \( f_i \) refers to the nodal parameter of the field variable at node \( i \), \( a_j(x) \) is the weighting function and usually a compactly supported function that is only nonzero in a small neighborhood called the "support domain" of node \( x_i \). The exponential function is used in this study.

\[
\omega(r) = \begin{cases} 
\exp\left(-r^2\beta^2\right) & r \leq 1 \\
1 - \exp\left(-\beta^2\right) & r > 1 
\end{cases}
\]

where \( r = \|x - x_i\|/d_{ml} = \sqrt{(x - x_i)^2 + (y - y_i)^2}/d_{ml} \) for circular support domain and \( \beta \) is a constant. \( d_{ml} \) denotes the radius of the circular support domain.

To obtain \( a(x) \), (3) can be rewritten in the matrix form

\[
A(x) a(x) = B(x) f
\]

where

\[
A(x) = \sum_{i=1}^{N} \omega_i(x) p(x_i) p^T(x_i), \quad B(x) = \left[ \omega_1(x) p(x_1) \omega_2(x) p(x_2) \ldots \omega_N(x) p(x_N) \right], \quad f = [f(x_1), f(x_2), \ldots, f(x_N)]^T.
\]

\( d_{ml} \) is chosen to make \( A(x) \) be the nonsingular matrix everywhere in the whole domain; however, the circular support domain must have enough neighborhood nodes. Through finding out the \( k \)th nearest points of the evaluation point \( x \), the smallest support domain radius including these points can be obtained. The value of \( kk \) is gained by comparing some numerical examples with their analytical solutions in Zhou et al. [29, 30].

Solving \( a(x) \) from (5), coefficients \( a(x) \) can be obtained

\[
a(x) = A^{-1}(x) B(x) f
\]

Substituting (6) back into (1) and removing unknown \( a(x) \), we have

\[
f^h(x) = p^T(x) A^{-1}(x) B(x) f = S(x) f
\]

Set \( p^T(x) A^{-1}(x) B(x) = S(x) \), where \( S(x) \) is the shape function.

2.2. Heat Conduction Analysis of FGM Object. The steady-state heat conduction equation and the thermal boundary conditions of FGM objects are as follows, respectively,

\[
k(x) \nabla^2 T(x) + \nabla k(x) \cdot \nabla T(x) + Q = 0
\]

Dirichlet boundary: \( T(x) = T_\Gamma \quad x \in \Gamma_1 \)

Neumann boundary: \( n \cdot k(x) \nabla T(x) = \vec{n} \quad x \in \Gamma_2 \)

Mixed boundary: \( n \cdot k(x) \nabla T(x) = h (T_{\infty} - T(x)) \quad x \in \Gamma_3 \)

where \( T(x) \) is the temperature field on a fixed domain \( \Omega \) surrounded by a closed boundary \( \Gamma = \Gamma_1 + \Gamma_2 + \Gamma_3 \). The variable \( x \) denotes the physical dimensions expressed in Cartesian coordinates, \( x: (x, y) \). \( n \) is the outward surface normal. The
parameters $k, T_{co}, h$ and $Q$ are the thermal conductivity, ambient temperature, the heat transfer coefficient, and the heat resource, respectively.

Substituting the unknown temperature field variable $T(x)$ of (8) with the approximate function of (7), the residuals are minimized in a least-squares manner,

$$
\nabla \delta T = \frac{\partial T}{\partial x} \delta x + \frac{\partial T}{\partial y} \delta y + \frac{\partial T}{\partial z} \delta z
$$

$$
P = -\sum_{j=1}^{N} k_j \nabla^2 S_j (x_j) + \nabla k_j \nabla S_j (x_j) Q + \sum_{j=1}^{N} n_j \cdot \nabla S_j (x_j) \vec{q}
$$

(14)

where $I$ and $J$ refer to node indices, $N_1$, $N_2$ and $N_3$ is the number of interior nodes in the boundary $\Gamma_1, \Gamma_2,$ and $\Gamma_3$, respectively.

2.3. Thermoelastic Analysis of FGM Object. Consider the 2D FGM anisotropic linear elastic body defined in the domain $\Omega$ bounded by $\Gamma$. The governing equation and boundary condition can be written in the following form disregarding the body forces

$$
\sigma_{ij,j} = 0 \quad \text{in } \Omega
$$

(15)

stress boundary condition: $\sigma_{ij} n_j - \overline{T}_j = 0$ on $\Gamma_i$

(16)

displacement boundary condition: $u_i = \overline{u}_i$ on $\Gamma_u$

in which $\sigma_{ij}$ is the components of the Cauchy stress tensor. A comma followed by index $j$ denotes the partial differentiation with respect to coordinate $x_j$ of a material point. $n_j$ is the unit outward normal to $\Gamma$. $\overline{u}_i$ are the displacement components, and $\overline{n}_i$ are the prescribed displacements on $\Gamma_u$. $\overline{T}_j$ are the prescribed traction on $\Gamma_i$. $\overline{T}_j$ and $\overline{u}_i$ are the complementary parts of the boundary $\Gamma$. MWLS analysis requires a discretization of the domain $\Omega$; (15)-(16) becomes

$$
\sigma_{ij}(x_k) = 0 \quad x_k \in \Omega, \ i, j = 1, 2; \ k = 1, 2, \ldots, N_\Omega
$$

(17)

$$
\sigma_{ij}(x_k) n_j = \overline{T}_j (x_k)
$$

(18)

$$
u_i (x_k) = \overline{u}_i (x_k)
$$

(19)

where $N_\Omega, N_i$, and $N_u$ is the number of interior nodes in the domain $\Omega$, in the boundary $\Gamma$, and $\Gamma_u$, respectively.

Substituting $\sigma_{ij}, u_i$ of (17)-(19) with the approximate function of (7),

$$
\sum_{i=1}^{N} \mathbf{H}_i (x_k) f_i = 0 \quad x_k \in \Omega, \ k = 1, 2, \ldots, N_\Omega
$$

(20)

$$
\sum_{i=1}^{N} \mathbf{Q}_i (x_k) f_i = \overline{T}_k \quad x_k \in \Gamma_i, \ k = 1, 2, \ldots, N_i
$$

(21)

$$
\sum_{i=1}^{N} \mathbf{N}_i (x_k) f_i = \overline{u}_k \quad x_k \in \Gamma_u, \ k = 1, 2, \ldots, N_u
$$

(22)

where $\mathbf{H}, \mathbf{Q},$ and $\mathbf{N}$ denote shape function similar to $S$ of (7).
\[ H_l(x_k) = \frac{E}{1 - \nu^2} \begin{bmatrix} \frac{\partial^2 N_l(x_k)}{\partial x^2} + \frac{1 - \nu}{2} \frac{\partial^2 N_l(x_k)}{\partial y^2} & 1 + \nu \frac{\partial^2 N_l(x_k)}{\partial x \partial y} \\ \frac{1 - \nu}{2} \frac{\partial^2 N_l(x_k)}{\partial x \partial y} & \frac{1 + \nu}{2} \frac{\partial^2 N_l(x_k)}{\partial x^2} \end{bmatrix} \] (23)

\[ Q_l(x_k) = \frac{E}{1 - \nu^2} \begin{bmatrix} \frac{1}{m} \frac{\partial N_l(x_k)}{\partial x} + m \frac{1 - \nu}{2} \frac{\partial N_l(x_k)}{\partial y} & \frac{1 - \nu}{2} \frac{nu}{mv} \frac{\partial N_l(x_k)}{\partial y} + m \frac{1 - \nu}{2} \frac{\partial N_l(x_k)}{\partial x} \\ \frac{1}{m} \frac{nu}{mv} \frac{\partial N_l(x_k)}{\partial y} + m \frac{1 - \nu}{2} \frac{\partial N_l(x_k)}{\partial x} & \frac{1}{m} \frac{\partial N_l(x_k)}{\partial x} + m \frac{1 - \nu}{2} \frac{\partial N_l(x_k)}{\partial y} \end{bmatrix} \] (24)

\[ N_l = \begin{bmatrix} N_l(x_k) & 0 \\ 0 & N_l(x_k) \end{bmatrix}, \]

\[ f_l = \begin{bmatrix} f_{1l} \\ f_{2l} \end{bmatrix}, \]

\[ \bar{t}_k = \begin{bmatrix} \bar{t}_1(x_k) \\ \bar{t}_2(x_k) \end{bmatrix}, \]

\[ \bar{w}_k = \begin{bmatrix} \bar{w}_1(x_k) \\ \bar{w}_2(x_k) \end{bmatrix}, \]

where \( l = \cos(\theta, x) \), \( m = \cos(\theta, y) \); \( \theta \) is the normal vector of any point.

Substituting the unknown field variable \( \sigma_{ij} \) of (15)–(16) into (1), the residuals are minimized in a least-squares manner,

\[
\Pi = \int_N \sigma_{ij} \sigma_{ik} \, d\Omega + \int_{\Gamma_u} (u_i - \bar{u}_i) (u_j - \bar{u}_j) \, d\Gamma_u + \int_{\Gamma_t} (\sigma_{ij} \eta_j - \bar{t}_i_j) (\sigma_{ij} \eta_j - \bar{t}_i_j) \, d\Gamma_t
\]

Similar to (12) the system equations of the MWLS method for solving thermoelastic problem is written in the following matrix form

\[ Kd = P \] (27)

where

\[ K = \sum_{s=1}^{N_n} H^T(x_s) H(x_s) + \sum_{s=1}^{N_u} N^T(x_s) N(x_s) + \sum_{s=1}^{N_t} Q^T(x_s) Q(x_s) \]

\[ P = \sum_{s=1}^{N_n} N^T(x_s) \bar{u}_s + \sum_{s=1}^{N_t} Q^T(x_s) \bar{t}_s \] (29)

where \( H, Q, \) and \( N \) are obtained by (23)–(25) and \( d \) denotes the displacement of \( x, y, [u_1, u_2] \).

The thermal stresses is written in the matrix form

\[ \sigma = D\varepsilon - \beta^T \] (30)

where \( D \) is the stiffness matrix for a linearly elastic, isotropic 2-D solid. \( \varepsilon \) is the infinitesimal strain vector.

\[ \varepsilon = \begin{bmatrix} \frac{\partial u_1}{\partial x_1} & \frac{1}{2} \frac{\partial u_2}{\partial x_1} & \frac{1}{2} \frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \end{bmatrix}^T, \]

\[ D = \frac{T}{1 - \nu (x)} \begin{bmatrix} 1 & \bar{v}(x) & 0 \\ \bar{v}(x) & 1 & 0 \\ 0 & 0 & \frac{1 - \bar{v}(x)}{2} \end{bmatrix} \] (31)

in which \( T = E/(1 - \nu^2) \), \( \bar{v} = \nu/(1 - \nu) \), \( \beta = (\alpha E/(1 - \nu)) \) for plane stress with \( E, \nu \) and \( \alpha \) denoting the Young’s modulus, Poisson’s ratio, and coefficient of thermal expansion, respectively, and \( T = E/(1 - \nu^2) \), \( \bar{v} = \nu/(1 - \nu) \), \( \beta = (\alpha E/(1 - 2\nu)) \) for plane strain.

2.4. Material Properties. Two homogenization methods are often used to evaluate the effective material properties for FGs. One is the rule of mixtures, and the other is the micromechanical model. The former is simply a linear rule of mixtures and the effective value can be determined by

\[ P = P_1 V_1 + P_2 V_2 \] (32)

where the volume fractions satisfy \( V_1 + V_2 = 1 \), and \( P \) may be elastic modulus \( E \), bulk modulus \( \mu \), Poisson’s ratio \( \nu \), coefficient of thermal expansion \( \alpha \), thermal conductivity \( k \), and shear modulus \( \mu \).

The most widely used micromechanical model is Mori-Tanaka model [9, 31]. It is the modified rule of mixtures and
The effective material properties can be defined using the following relation,

\[ k = k_1 + \frac{3k_1V_2(k_2 - k_1)}{3k_1 + V_1(k_2 - k_1)} \tag{33} \]

\[ E = E_1 + \frac{V_2(3E_1 + 4\mu_1)(E_2 - E_1)}{3(1 - V_2)(E_2 - E_1) + 3E_1 + 4\mu_1} \tag{34} \]

\[ \mu = \mu_1 + \frac{V_2(\mu_1 + f\alpha_1)(\mu_2 - \mu_1)}{(1 - V_2)(\mu_2 - \mu_1) + \mu_1 + f\alpha_1} \tag{35} \]

\[ \alpha = \alpha_1 + \frac{E_2(E_1 - E)(\alpha_2 - \alpha_1)}{E(1 - E_2)} \tag{36} \]

where \( G_1 = E_1/(1-2v_1); \ G_2 = E_2/(1-2v_2); \ \mu_1 = E_1/2(1+v_1); \ \mu_2 = E_2/2(1+v_2); \ f\alpha_1 = \mu_1(9E_1 + 8\mu_1)/6(E_1 + 2\mu_1). \)

### 3. Numerical Results and Discussions

In order to demonstrate the efficiency and accuracy of the presented method, firstly, we choose a isotropic square region (Case 1) with defined boundary conditions; through heat conduction analysis the results are compared with the analytical solutions and FDM. Then a clamped-clamped FGM beam (Case 2) which was subjected with interior heat source is analyzed using MWLS method.

#### 3.1. Case 1

A 100×100m isotropic square region is shown in Figure 1. The top and bottom boundaries are insulated. The left and right boundaries are assigned a temperature of 200°C and 100°C, respectively. The spatial variation of the thermal conductivity is taken to be cubic in the x-direction as \( k(x, y) = (1 + x/100)^3 \).

An analytical solution is given as

\[ T(x, y) = \frac{800}{6} \left[ \frac{1}{(1 + x/100)^2} + \frac{1}{2} \right] \tag{37} \]

### Table 1: Maximum of relative error.

<table>
<thead>
<tr>
<th>Grid</th>
<th>MWLS</th>
<th>FDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>10×10</td>
<td>0.15%</td>
<td>0.35%</td>
</tr>
<tr>
<td>20×20</td>
<td>0.05%</td>
<td>0.077%</td>
</tr>
<tr>
<td>30×30</td>
<td>0.024%</td>
<td>0.033%</td>
</tr>
</tbody>
</table>

#### 3.2. Case 2

A clamped-clamped FGM beam is shown in Figure 3, length L=1m, width D=0.5m, and thickness H=0.1m; material property is shown in Table 2, interior heat source \( Q=5e5W/m^3 \); the spatial variation of the volume fraction of Al is taken to be a power law distribution in the y-direction as \( V = (y/D)^a \).

The beam is assumed to be in a state of plane strain normal to the xy plane, and the design region is discretized as 31×15 and 61×30. The effective material properties are determined by the Mori-Tanaka model (Eq. (33)–(36)). In order to verify the proposed computational method, we do some comparisons between the MWLS and the commercial COMSOL Multiphysics for a homogeneous material \( a=0 \), relevant results are shown in Figure 4 and listed in Table 3. The results obtained with the two methods are in good agreement in temperature field aspect; however, the x-displacements and y-displacement have a little difference in 31×15 grid and in 61×30 the results are in good agreement in Table 3. From Figure 4 we also can know that our method and COMSOL Multiphysics have the same distribution trend. The maximum temperature 361.3K is in the center (0.5, 0.25) of the beam.

For \( a=2 \), we analyzed the heat conduction and thermoelastic problem using MWLS method. Temperature field distribution, x-displacement, and y-displacement are plotted in Figures 5, 6, and 7, respectively. Figure 5 indicates that the maximum temperature 425.6K is higher than the homogeneous material of Figure 2(a), in the Cartesian coordinates (0.5, 0.179) of the beam. Figures 6 and 7 show that when subjected to temperature rise, the beam expands and the maximum y-displacement is located at the top middle of the beam. Then we do heat conduction analysis in different...
material distribution in different heat source; the result is listed in Table 4. From Table 4, we can know that the maximum temperature of FGM model is higher than that of the fully metal model. Moreover, as the volume fraction index is increased, the maximum temperature increases. This is because for FGMs, when the volume fraction index is increased, the contained quantity of ceramic increases. Finally, to make a comparison, we do thermoelastic analysis and obtain thermal stresses in the neutral axis of the beam among \( a = 0 \), \( a = 2 \), and \( a = 3 \), as shown in Figure 8. In Figures 8(a) and 8(c), the volume fraction of Al is gradually decreased from \( a = 0 \) to \( a = 3 \), the \( \sigma_x \) and \( \sigma_y \) stresses are in an upward trend. The maximum thermal stress always occurred in the vicinity of neutral axis of the beam from Figures 8(a), 8(c), and 8(d). The results also agreed well with the presented elasticity solutions of [26].

4. Conclusion

In this paper, a novel thermoelastic analysis of FGM beam based on MWLS method was presented. We do thermoelastic and heat conduction analysis aimed at a clamped-clamped thick beam which is subjected with interior heat source. The FGM beam is assumed to be given by a simple power law distribution. Material properties of the FGM beam are obtained by Mori-Tanaka method. Through being compared with analytical solution and the commercial software of COMSOL Multiphysics, the effectiveness and accuracy are verified. We also listed the comparison of thermal stresses with the variation of power law index. The present method of analysis will be also useful in the design and optimization of FGM objects.

Nomenclature

\( a(x) \): Coefficient
\( A(x), B(x) \): Matrices of computation
\( d_{m l} \): Radius of the circular support domain
\( f_i \): The nodal parameter of the field variable at node \( I \)
\( I, J \): Node indices
\( k \): Thermal conductivity
Figure 4: Comparison of our method with COMOSOL of $a=0$.

Table 3: Comparison of MWLS method and COMSOL Multiphysics.

<table>
<thead>
<tr>
<th>method</th>
<th>Temperature/K</th>
<th>X displacement /mm</th>
<th>Y displacement/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWLS (31×15)</td>
<td>361.8</td>
<td>0.596</td>
<td>2.95</td>
</tr>
<tr>
<td>MWLS (61×30)</td>
<td>361.3</td>
<td>0.71</td>
<td>3.88</td>
</tr>
<tr>
<td>COMSOL (948 triangle mesh)</td>
<td>361.1</td>
<td>0.639</td>
<td>3.81</td>
</tr>
</tbody>
</table>
Table 4: Comparison of different material distribution in different heat source.

<table>
<thead>
<tr>
<th>MWLS (31x15) Q=5e5W/m³</th>
<th>Temperature/K maximum</th>
<th>Temperature/K minimum</th>
<th>Temperature/K maximum</th>
<th>Temperature/K minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=0</td>
<td>361.8</td>
<td>300</td>
<td>910.8</td>
<td>300</td>
</tr>
<tr>
<td>a=2</td>
<td>425.6</td>
<td>300</td>
<td>1558.2</td>
<td>300</td>
</tr>
<tr>
<td>a=3</td>
<td>436.1</td>
<td>300</td>
<td>1660.9</td>
<td>300</td>
</tr>
</tbody>
</table>

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Acknowledgments

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