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Mixed mode fracture analysis of adiabatic cracks in homogeneous and non-homogeneous materials in the framework of partition of unity and the path-independent interaction integral

E. Goli [a], H. Bayesteh [b], S. Mohammadi [b,*]

[a] Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

[b] High Performance Computing Lab, School of Civil Engineering, University of College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

In this paper, the path independent interaction integral has been implemented in the framework of the extended finite element method for mixed mode adiabatic cracks under thermo-mechanical loadings particularly in orthotropic non-homogenous materials. The mesh insensitivity and increased accuracy due to the thermal and displacement asymptotic analytical solutions are discussed and the contour independency of the interaction integral is investigated in different examples. Finally, the problem of crack propagation in orthotropic FGM materials under the thermal loading is investigated to assess the accuracy and robustness of proposed approach.

1. Introduction

New engineering demands have led to the outburst of novel and advanced tailored materials, covering a wide range of layered composites and inhomogeneous materials. Generally, homogenous materials do not properly perform under high thermal gradient or certain mechanical loadings. On the other hand, composite materials have shown severe disadvantages mainly in the form of stress concentration and delamination at the interfaces. Alternatively, functionally graded materials (FGMs) have been designed with continuous variation of material properties to remove the deficiencies related to the existence of interfaces and the inefficient response of homogeneous materials to general thermo-mechanical loadings. In recent years, FGMs have been widely used in high-tech engineering applications such as thermal barrier coating for space applications [1], piezoelectric and thermoelectric devices [2–6], thermionic converters [7], wear and impact resistant components [8] and biomedical and eco-materials [9,10]. FGMs are produced in both isotropic and orthotropic forms, using some of the fabrication techniques such as the plasma sprayed coating [11].

Bending of orthotropic FGMs beams [12], bimaterial FGMs [13], fracture mechanics of thermal barrier FGM coatings [14], crack propagations in FGMs [15,16] and finally FGMs under the impact loading [17,18] are among the main research topics on the subject. Applications of FGMs to withstand high mechanical and thermal loadings simultaneously are probably the most important issue of FGMs, as they may become extremely vulnerable to crack initiation and propagation. As a result,

* Corresponding author. Tel.: +98 21 61112258; fax: +98 21 6640 3808.
E-mail address: smoham@ut.ac.ir (S. Mohammadi).

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Nomenclature

A	surface of the domain surface integral
b^T	vector of additional degrees of freedom corresponding to the crack tip enrichments
a_{ij}	contracted notation of the compliance matrix
B	matrix of shape function derivatives
B_{th}	matrix of thermal shape functions derivatives
b^H	additional degrees of freedom corresponding to the Heaviside enrichment
C_{ijkl}	constitutive tensor
E_1, E_2	Young's modules with respect to the principal axes of orthotropy
$F, (F_T)$	set of crack tip enrichment functions for mechanical field (for thermal field)
f	total force vector
$f^{mech.}$	vector of mechanical force
f^{th}	thermal force vector
G_{12}	shear modulus
H	heaviside function
Im	imaginary part
J	path-independent J integral
J^{act}	J integral for the actual field
J^{aux}	J integral for the auxiliary field
K_{11} and K_{22}	heat conductivity coefficients along the global directions 1 and 2, respectively
K	diagonal matrix of heat conductivity coefficients
K_I, K_{II}	mode I and II stress intensity factors
K_{In}, K_{IIn}	normalized stress intensity factors
K_{IC}^x, K_{IC}^y	mode I toughness with respect to local coordinates at the crack tip
$K_{\theta\theta}$	stress intensity factor in θ direction
$K_{\theta\theta C}$	critical stress intensity factor in θ direction
M	interaction integral
N	shape function
n_j	unit outward normal vector to the Γ_s
Q	thermal stiffness matrix
q	continuous weight function
$\bar{q}$	prescribed value of heat flux
Re	real part
r	radial direction in polar coordinates
S_{ijmn}	compliance tensor
T	temperature field
$\bar{T}$	prescribed value of temperature
u	displacement field
w	strain energy density
$\alpha_1, \alpha_2, \alpha_3$	coefficients of thermal expansion in principal orthotropy directions
Γ_T	boundary related to the thermal loading
Γ_q	boundary related to the prescribed heat flux
ΔT	temperature difference from the reference temperature
δ_{ij}	Kronecker delta
ε_{ij}	components of strain
ε_{ij}^m	mechanical part of strain
ε_{ij}^t	total strain
ε_{ij}^{th}	thermal part of strain
$\varepsilon_{ij}^{act\_m}$	mechanical part of strain in actual field
$\varepsilon_{ij}^{act\_th}$	thermal part of strain in actual field
$\varepsilon_{ij}^{act\_t}$	total strain in actual field
θ	angular direction in polar coordinates
θ_0	angle of crack propagation
μ_1^{tip}, μ_2^{tip}	roots of the characteristic equation at the crack tip location
υ	Poisson's ratio
σ_{ij}	stress components
σ_{ij}^{aux}	auxiliary stress field
σ_θ	hoop stress

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