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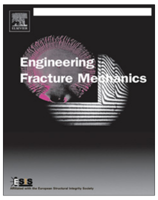

An extended state-based peridynamic model for damage growth prediction of bimaterial structures under thermomechanical loading

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ABSTRACT

An extended ordinary state-based peridynamic model considering thermomechanical loading is presented to predict damage growth of bimaterial structures, such as cermet. In this new model, the three-dimensional (3D) and two-dimensional (2D) (both plane stress and strain) cases are all considered. As examples, 2D bimaterial beams and 3D thick plates are analyzed under thermal loading and three-point bending. m-convergence and δ-convergence are discussed in the cases of 2D verification, and comparison of displacement with finite element model shows great accuracy of the extended model. Damage growth (in term of crack propagation) of bimaterial beams due to incremental thermal loading and three-point bending is investigated. The new model successfully captures interface crack propagation in bimaterial beams under thermal loading as well as crack growth within substrate material and at bimaterial interface under quasi-static and impact loading. Distribution of elastic strain energy density is analyzed during dynamic crack propagation under impact loading.

1. Introduction

Bimaterials, such as cermet, have been widely used because of their two different phase properties, coupling high hardness, and deforming capacity. Analysis, especially failure prediction, of cermet due to thermal and mechanical loading is necessary, and it has attracted much attention.

Analytical solutions [1,2] for thermomechanical crack problems of bimaterials are available only for a few cases. The numerical methods, such as finite element method [3,4], extended finite element method [5], and boundary element method [6], were used to analyze behaviors of interfacial fracture in bimaterials under effect of thermomechanical loads. However, these available methods, which are based on classical local theory with assumption of displacement continuity, are naturally unsuitable to failure analysis of cermet. To ease inadequacies of classical local theory, theory of peridynamics [7] was formulated to handle problems involving discontinuities. Essentially, the theory of peridynamics is a reformulation of continuum mechanics, in which the integral-differential equations are established to replace the partial differential equations. This

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Nomenclature

$\boldsymbol{b}$	applied body force density
$\underline{d}$	damage history scalar state
$\underline{e}^d$	deviatoric extension state
$\underline{e}[t']\langle\xi\rangle$	extension value of bond ξ at time t'
E	Young's modulus
G_0	critical fracture energy release rate
$\mathrm{H}_{\boldsymbol{x}}$	neighborhood of point $\boldsymbol{x}$
K_{IC}	critical stress intensity factor
m	ratio between the horizon size and the grid spacing
s_0	critical stretch value
$\underline{\mathbf{T}}$	force vector state
$\underline{t}$	scalar force state as the magnitude of $\underline{\mathbf{T}}$
$\boldsymbol{u}$	displacement of material point $\boldsymbol{x}$
v	Poisson's ratio
W	peridynamic strain energy density
ρ	mass density
μ	shear moduli
Ω	classical elastic strain energy density
dV/V	volume dilatation
ε_{ij}^d	deviatoric strain tensor
β	coefficient of thermal expansion
Θ	temperature variation
$f(\Theta)$	energy variation due to temperature change
θ	peridynamic volume dilatation
φ	volume weight of broken bonds
$\underline{\omega}$	influence function
δ	horizon value
Δx	uniform grid spacing
k', α, β'	positive peridynamic constants

means that compared to displacement derivatives used in classical mechanics equations, which are not defined at discontinuities, the peridynamics-based formulation is applicable for fracture and discontinuity analysis. Thus, initiation and propagation of crack can be modeled by peridynamics without any special techniques.

The original formulation of peridynamics, so called "bond-based", assumes that points are connected with bonds through spring-like interactions and response in a bond is independent of other bonds. However, this formulation has a restriction on material properties, i.e., the Poisson's ratio requires to be 1/3 for the 2D plane stress case and 1/4 for both cases of plane strain and 3D [7,8]. Even the proven model [9] and computational techniques [10] were proposed to overcome the constraint limitation of Poisson's ratio, the bond-based model still cannot capture general characteristics of materials. To reduce the constraint, a more general framework, called "state-based" peridynamics [11], was proposed, and the bond force density between points depends on deformations of points of the whole family.

The state-based peridynamic model can be classified into "ordinary state-based peridynamics" and "non-ordinary state-based peridynamics" [11]. The ordinary state-based model employs explicit dependence of volumetric and distortional deformations for material response, and it can reproduce material behaviors in conventional theory of solid mechanics, for not only linear elastic material state of 3D [12] and 2D cases [13,14], but also plastic [15,16], viscoelastic [17], and viscoplastic [18] cases. Unlike the ordinary one, the non-ordinary state-based model does not necessarily require force state parallel to deformed position of connected bond, and it was used to model peridynamic beam [19], plates and flat shells [20].

With the capability of handling discontinuities, the peridynamic theory has been successfully applied to damage growth prediction of various problems. Silling [21] presented numerical analysis of Kailthoff-Winkler experiments by peridynamics. Gerstle [9] analyzed plain and reinforced concrete structures through "micropolar peridynamics model". Askari et al. [22] investigated failure modes of laminated composites with a large center notch under tension or shear-tension loads. Xu et al. [23] performed simulation of cruciform composite specimens under biaxial loads. Colavito et al. [24] studied nanoclay-epoxy nanocomposites subjected to lower-velocity impact. Ha et al. [25,26] evaluated dynamics crack propagation and crack branching with peridynamics. Oterkus et al. [27] analyzed fracture properties of stiffened composite curved panels with a pre-crack under combined axial tension and internal pressure. Agwai et al. [28] presented crack propagation in multilayer thin-film structures of electronic packages by peridynamics. Zhou et al. [29,30] investigated crack propagation in rock materials by extended non-ordinary state-based peridynamic model.

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