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Implementation and verification of the Park–Paulino–Roesler cohesive zone model in 3D

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ABSTRACT

The Park–Paulino–Roesler (PPR) potential-based model is a cohesive constitutive model formulated to be consistent under a high degree of mode-mixity. Herein, the PPR's generalization to three-dimensions is detailed, its implementation in a finite element framework is discussed, and its use in single-core and high performance computing (HPC) applications is demonstrated. The PPR model is shown to be an effective constitutive model to account for crack nucleation and propagation in a variety of applications including adhesives, composites, linepipe steel, and microstructures.

1. Introduction and motivation

Cohesive zone modeling of fracture processes dates to Dugdale's strip yield model [1]. In this model, yield magnitude closure stresses are applied between the actual crack tip and a notional crack tip, the length of the total plastic zone, to circumvent the unrealistic prediction of infinite stresses at the crack tip. Barenblatt [2] placed material-specific stresses according to a prescribed distribution in the aforementioned inelastic zone, leading to the many cohesive zone models (CZMs) available today. Applications of CZMs abound in the literature. Hillerborg et al. [3] were the first to model failure in a material by adapting a CZM into a finite element analysis. The cohesive finite element method (CFEM) has been used to conduct studies across a wide range of material systems: rock (e.g. Boone et al. [4]), ductile materials at the microscale (e.g. Needleman [5] and Iesulauro [6]), ductile materials at the macroscale (e.g. Tvergaard and Hutchinson [7] and Scheider and Brocks [8]), concrete (e.g. Ingraffea et al. [9]; Elices et al. [10]; Park et al. [11]), bone (e.g. Tomar [12] and Ural and Vashishth [13]), functionally graded materials (Zhang and Paulino [14]), and asphalt pavements (Song et al. [15]). Hui et al. [16] and Park and Paulino [17] have presented a review of the literature in the field and thus the reader is referred to these articles and the references therein.

The fracture behavior in potential-based cohesive zone models is characterized by a potential function, from which traction–separation behavior proceeds. Taking the first derivative of this potential function with respect to the displacement separation, results in the cohesive tractions. The second derivative, in turn, provides the material tangent modulus. A cursory search of potential-based CZMs in the literature will undoubtedly return hundreds of models. Needleman's potential from

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Nomenclature

$\mathbf{B}$	strain-displacement matrix
E	Young's modulus
$\mathbf{D}$	material tangent stiffness matrix
D	coupled damage parameter
$\mathbf{f}$	internal force vector
$\mathbf{J}$	Jacobian
$\mathbf{K}$	stiffness matrix
K	strength coefficient
m, n	non-dimensional exponents
N_1, N_2, N_3, N_4	shape functions for 8-noded cohesive element
n, $t1$, $t2$	opening and sliding directions
$\mathbf{t}$	traction vector
T_n	normal cohesive traction
T_t	effective tangential cohesive traction
$T_{\mathrm{t}1}$, $T_{\mathrm{t}2}$	tangential cohesive tractions in sliding directions
$T_{max\ coupled}$	coupled cohesive strength
α, β	shape parameters
Γ_n, Γ_t	energy constants
Δ_n	normal separation
Δ_t	effective sliding displacement
$\Delta_{\mathrm{t}1}$, $\Delta_{\mathrm{t}2}$	sliding displacements
$\Delta_\mathrm{n}^{\max}, \Delta_\mathrm{t}^{\max}$	max normal and tangential separations reached during loading/unloading
δ_n, δ_t	normal and tangential final crack opening widths
δ_nc, δ_tc	normal and tangential critical opening displacements at which T_n and T_t equal $\sigma_{\max}$ and $\tau_{\max}$, respectively
$\bar{\delta}_\mathrm{n}, \bar{\delta}_\mathrm{t}$	normal and tangential conjugate final crack opening widths
ε_p	plastic strain
λ_n, λ_t	initial slope indicators
ν	Poisson's ratio
ξ, η	natural coordinate system axes
$\sigma_{\max}$, $\tau_{\max}$	normal and tangential cohesive strengths
ϕ_n, ϕ_t	fracture energies
Ψ	PPR model's potential function
$\langle\cdot\rangle$	Macaulay bracket $\langle x\rangle = \begin{cases} 0, x < 0 \\ x, x \geq 0 \end{cases}$

1987 [5], often cited in the literature, describes the normal, Mode I, interaction with a polynomial potential; however, it is limited because it only considers decohesion by normal separation. Tvergaard extended Needleman's potential to better account for mode-mixity with the use of an interaction formula defining an effective displacement [18]. Needleman later developed a potential accounting for debonding by tangential separation [19] whereby the normal and tangential interactions are described by exponential and periodic functions, respectively. Alternatively, Xu and Needleman developed a potential where the normal and tangential separations are both described by exponential functions [20].

Park et al. published a unified potential-based CZM, the PPR (Park–Paulino–Roesler) CZM [21], that addresses the shortcomings of the prevailing potential-based CZMs in the literature, particularly with respect to mode-mixity, user flexibility, and consistency. First, it characterizes different fracture energies and cohesive strengths in each fracture mode, an accommodation not made by most CZMs. Moreover, it provides for several material failure behaviors by allowing the modeler to define the shape of the softening curve in both the normal and shear traction–separation relations; in most CZMs, softening behavior is hard-coded and cannot be changed. Finally, and perhaps most important, it is consistent in anisotropic fracture energy conditions; it demonstrates a monotonic change of the work-of-separation for both proportional and non-proportional paths of separation, a quality not seen in most CZMs.

This paper describes the generalization of the PPR model to three dimensions, details its implementation in a finite element framework, and presents its use in single-core and high performance computing (HPC) applications. We identify a variety of examples which assess the various features of the PPR model considering different loading conditions (e.g. quasi-static and dynamic), mode-mixity, bulk material behavior, and interfacial behavior (investigating the parameter space that defines the traction–separation relationship). The examples include a mode I T-peel specimen, a mixed-mode (I and II) bending specimen, an edge crack torsion (ECT) specimen (modes II and III), the Battelle Drop-Weight Tear (BDWT) test, and intergranular fracture (grain-boundary decohesion) at the microstructural scale.