Influence of the Cohesive Zone Model Shape Parameter on Asphalt Concrete Fracture Behavior

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Abstract. A cohesive zone model (CZM) has been effective in exploring fracture behavior in various materials. In general, the cohesive parameters associated with material strength and cohesive fracture energy are considered more important than a CZM softening shape. However, the influence of the CZM softening shape becomes significant as the relative size of the fracture process zone compared to the structure size increases, which is relevant for asphalt concrete and other quasi-brittle materials. In this study, the power-law CZM is employed to investigate the influence of the CZM softening shape on asphalt concrete fracture. Three dimensional disk-shaped compact tension (DC(T)) test simulation is performed considering bulk (background) material viscoelasticity.

Keywords: Power-law CZM, fracture, asphalt concrete, viscoelasticity, disk-shaped compact tension (DC(T)) test simulation

INTRODUCTION

Asphalt concrete is considered as quasi-brittle material because the size of the fracture process zone compared to the structure size is considerable. For this type of material, linear elastic fracture mechanics (LEFM) is generally not applicable. Due to this reason, a cohesive zone model is considered as an attractive computational method to investigate fracture behavior in asphalt concrete. This is mainly because we can define a suitable constitutive model, which represents nonlinear softening behavior occurring along the fracture process zone in terms of displacement and corresponding traction.

Cohesive zone models have been used to investigate fracture behavior in various materials. Barenblatt [1] proposed a cohesive model to study brittle materials and Dugdale [2] adopted a process zone concept in conjunction with the cohesive model to investigate materials exhibiting plasticity. Xu and Needleman [3] presented a potential-based cohesive model, i.e. intrinsic model, where cohesive elements are inserted along either lines or regions, and implemented this model by means of the finite element method. An alternative cohesive law was proposed by Camacho and Ortiz [4]. They presented a stress-based cohesive law, extrinsic model, where a new

CP973, *Multiscale and Functionally Graded Materials 2006*
edited by G. H. Paulino, M.-J. Pindera, R. H. Dodds, Jr., F. A. Rochinha, E. V. Dave, and L. Chen

surface is adaptively created by duplicating nodes which were bounded previously. Detailed literature review can be found in the reference [5].

Unlike other materials, a relatively few number of studies using a CZM have been carried out for asphalt concrete [5,6]. This is mainly due to complicated features such as viscoelasticity and quasi-brittle behavior inherent in asphalt concrete. In this paper, the influence of CZM softening shapes on asphalt concrete fracture is examined in conjunction with a power-law CZM [5]. Viscoelastic bulk material is used.

POWER-LAW COHESIVE ZONE MODEL

A power-law CZM [5] is briefly explained. The effective displacement, δ_e, and the effective traction, t_e, for three-dimensional (3D) analysis become

$$\delta_e = \sqrt{\delta_n^2 + \delta_s^2} = \sqrt{\delta_n^2 + \delta_{s1}^2 + \delta_{s2}^2} \tag{1}$$

$$t_e = \sqrt{t_n^2 + t_s^2} = \sqrt{t_n^2 + t_{s1}^2 + t_{s2}^2}, \tag{2}$$

in which subscript n denotes normal component and subscripts s1 and s2 stand for shear components. The power-law CZM can be expressed as follows

$$t_e = \begin{cases} \sigma_c \delta_e / \delta_{cc} & \delta_e < \delta_{cc} \\ \sigma_c (1 - \delta_e / \delta_c)^{\alpha} \dfrac{1}{\left(1 - \delta_e / \delta_{cc}\right)^{\alpha}} & \delta_e > \delta_{cc} \end{cases} \tag{3}$$

where σ_c denotes material strength; δ_{cc} is displacement where traction becomes a maximum; δ_c is critical displacement in which a complete separation (i.e. zero traction) occurs; and α is an internal variable affecting the shape of the softening curve. Note that δ_{cc} and α are user- defined variables to control an initial slope and a softening shape, respectively. The δ_c is obtained by equating the area under the displacement and traction curve to the cohesive fracture energy which is given as

$$G_c = \frac{\delta_{cc}\sigma_c}{2} + \int_{\delta_{cc}}^{\delta_c} t_e \, d\delta_e \tag{4}$$

Figure 1 illustrates various shapes of the power-law CZM for different magnitudes of α. The ordinate is the normalized effective traction. The abscissa is the effective displacement which is normalized with respect to critical displacement evaluated when α=1. Notice that when α is equal to zero, the traction-displacement curve has a rectangular shape. As α increases, the shape of the power-law CZM softening curves changes from the linear to nonlinearly decaying shapes. Notice that when α=1, this model is equivalent to the bilinear model [5].

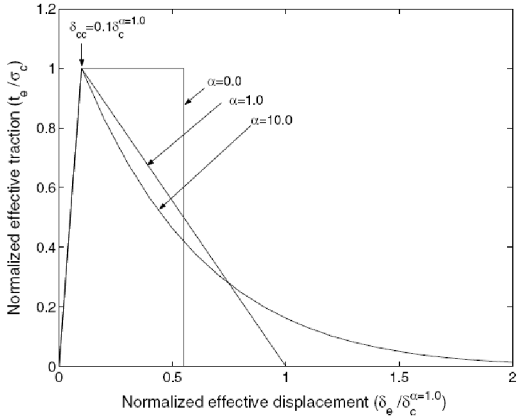


FIGURE 1. Power-law CZM for different magnitudes of α

COMPUTATIONAL RESULTS

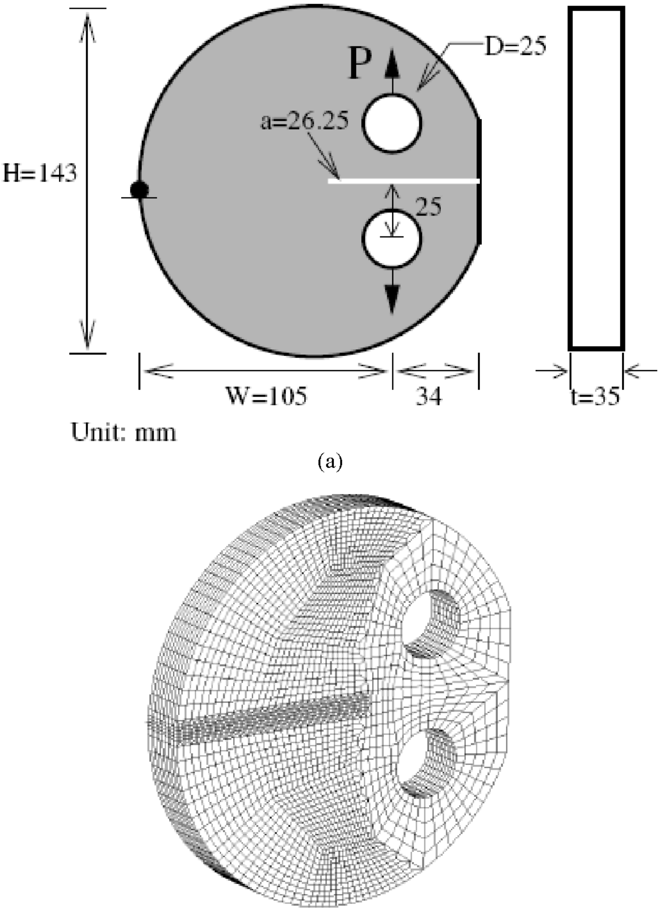
In this section, three-dimensional DC(T) test simulation is performed considering bulk (background) material viscoelasticity. Figure 2 (a) illustrates a DC(T) specimen which is 143 mm high, 139 mm long and 35mm thick. The length of the mechanical notch, say a, is 26.5mm, leading to a/w=0.25. Displacement control inducing a constant crack mouth opening displacement (CMOD) rate of 1.0mm/min. is adopted. Figure 2 (b) shows three dimensional mesh discretizations for the whole geometry. The DC(T) test specimen is constructed using 28094 8-node brick elements for the bulk material and 840 8-node elements for the cohesive material. The cohesive elements are inserted along the middle of specimen to enable the simulation of pure mode-I crack propagation. Symmetry condition along the thickness direction is employed to reduce the computational cost. A constant Poisson's ratio is used: ν=0.35. The fracture energy obtained at -20°C and 1mm/min. CMOD rate is 120 J/m^2 and the material strength measured at -20°C is 2.90Mpa [5,7]. The parameter δ_{cc} is defined as 0.01δ_c to reduce artificial compliance due to the pre-peak slope of the CZM [5]. Model parameters (see Table 1) and shift factors (see Table 2) evaluated from experiment of IDT test are adopted for viscoelastic analysis of bulk materials. The geometry, material properties and cohesive parameters are based on the cored pavement material located in northeast Iowa, in which PG64-22 binder is used.

TABLE 1. Prony Series Parameters For The Master Relaxation Modulus Using The Generalized Maxwell Model [6].

i	Relaxation Modulus	
	E_i(GPa)	τ_i(sec)
1	3.54	15
2	3.43	249
3	1.75	4817
4	7.21	57378
5	11.92	2605452

TABLE 2. Shift Factors

Temperatures	log (1/a_T)
-30°C	0
-20°C	1.95
-10°C	3.2



(a)

(b)

FIGURE 2. DC(T) test simulation: (a) geometry and boundary conditions; (b) mesh configurations for the whole geometry.

Figure 3 shows comparison of present numerical results with experimental results. Two thick solid lines denote experimental results, while thin solid line with square and circle markers indicate numerical results using a power-law CZM with α=1 and α=10, respectively. When the power-law cohesive zone model with α=1 is used, the numerical results over-predict the peak load and show quite different softening trend compared to experimental results. However, when the power-law CZM with α=10 is employed, we can clearly see that the peak load and the softening trend of the present numerical results are quite similar with those of experiments. It can be inferred from the comparison that the linear softening curve does not represent fracture phenomena of asphalt concrete well. It may be attributed to the CZM softening shape in which it has the constant reduction of traction with respect to displacement. In fact, it is observed in asphalt concrete that first, the capacity to resist crack opening drops suddenly due to cracks along interfaces between aggregates and asphalt mastics, and then the cohesion occurs because of asphalt mastics. So, it can be concluded that the softening curve of the power-law CZM with α=10 predicts asphalt concrete fracture behavior reasonably well.

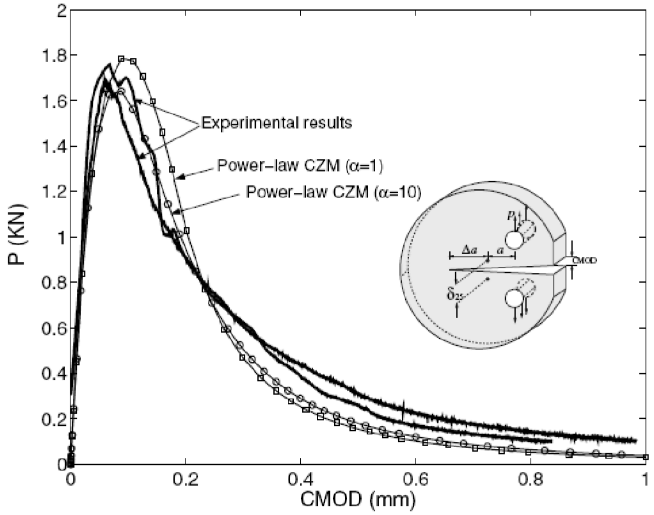


FIGURE 3. Comparison of P versus CMOD curves between experimental and numerical results

CONCLUSIONS

A power-law cohesive zone model is employed to investigate the influence of CZM softening shapes on asphalt concrete fracture. Three-dimensional disk-shaped compact tension (DC(T)) test simulation is performed considering bulk (background) viscoelasticity. Material properties and cohesive parameters are obtained from experimental tests. In this study, it is demonstrated that a CZM softening shape influences numerical results considerably. Moreover, the softening shape of the power-law CZM with α=10 is considered more appropriate for asphalt concrete fracture modeling.

ACKNOWLEDGMENTS

We are grateful to the support from SemMaterials (previously Koch Materials) and the National Science Foundation (NSF) through the GOALI project CMS 0219566 (Program Manager, P.N. Balaguru). Any opinion expressed herein are those of the writers and do not necessarily reflect the views of the sponsors.

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