COHESIVE ZONE MODELING OF FRACTURE IN ASPHALT CONCRETE

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Abstract
This paper describes the development of a cohesive zone fracture model to simulate crack initiation and propagation in asphalt concrete. The cohesive zone modeling approach involves the use of intrinsic constitutive laws to connect traditional finite elements to simulate localized damage and softening behavior. The model presented has the ability to simulate complex fracture behavior, such as crack nucleation, crack initiation, and non-prescribed mixed-mode crack propagation, and can capture complex fracture process zone phenomena. The present model allows physical modeling of fracture, where both finite material strength and fracture energy are considered in an intrinsic separation law. This paper also describes the simulation of laboratory test specimens to calibrate the cohesive zone model parameters. The calibrated model is shown to compare favorably to single-edge notched beam fracture tests. The calibrated parameters were then used to simulate crack propagation in the indirect tension test (IDT) with reasonable success. Ongoing work to implement viscoelastic, rate-dependent and mixed-mode fracture capabilities should lead to even better simulation results in the near future.

1. Introduction

In order to better understand cracking in pavement systems, many experimental investigations have been conducted. Majidzadeh [1] first attempted to study crack propagation using fracture testing. Since then, several researchers [2, 3, 4] have developed fracture testing programs, with varying degrees of success, to measure and describe crack initiation and propagation in asphalt concrete. Cohesive zone models (CZMs) have been used in the analysis and simulation of crack propagation for both homogeneous and nonhomogeneous material systems. Dugdale [5] and Barenblatt [6] proposed cohesive models to investigate ductile and brittle material fracture behavior, respectively. Xu and Needleman [7] and Camacho and Ortiz [8] presented a potential based cohesive model and stress-based cohesive model, respectively, with a corresponding implementation by means of the finite element method. These models have been extended to explore crack propagation in concrete [9], ductile metals [10] and functionally graded materials (FGMs) [11]. Cohesive zone modeling involves the placement of interface elements in a finite element model, where the separation law used at the interface describes a typical softening curve. Cohesive zone models are particularly useful for computational modeling of fracture processes for a number of reasons, including: 1) computational efficiency; 2) ability to simulate complex global fracture behavior with a relative simple, local (intrinsic) damage function; 3) ability to simulate crack nucleation, crack initiation, and non-prescribed, mixed-mode crack propagation. For asphalt concrete, Soares et al. [12] used a cohesive zone modeling approach to investigate crack propagation in indirect tension specimens using the cohesive law proposed by Tvergaard [13].
For this work, an effective cohesive model is implemented using a user-defined element subroutine in ABAQUS, or UEL [14].

2. Cohesive zone model

The cohesive zone modeling approach, which incorporates cohesive strength, and fracture energy, models the damage occurring in a cohesive zone located ahead of a crack tip. Figure 1 illustrates the cohesive zone concept in the opening mode (pure mode I). The cohesive surfaces are held together by a cohesive traction dependent on the displacement jump across the crack faces. Some of the cohesive parameters are the tensile strength ($\sigma_c$), critical displacement ($\delta_c$) and fracture energy ($\Gamma_c$).

![Diagram of cohesive zone concept](image)

Figure 1: Schematic representation of (a) the cohesive zone concept and (b) the displacement jump ($\delta$) and corresponding traction ($t_n$) along a cohesive surface.

For this work, an exponential form for the free energy potential, which is computationally convenient, was adopted [15]:

$$\phi = e\sigma_c\delta_c \left[1 - \left(1 + \frac{\delta}{\delta_c}\right) \exp\left(-\frac{\delta}{\delta_c}\right)\right],$$  \hspace{1cm} (1)

where $e$ is $\exp(1)$, $\sigma_c$ is the material’s tensile strength, and $\delta_c$ is critical displacement. An effective opening displacement ($\delta$) is defined as:

$$\delta = \sqrt{\delta_n^2 + \beta^2\delta_t^2}. \hspace{1cm} (2)$$

Where $\delta_n$ is the normal displacement jump, $\delta_t$ is the shear sliding and $\beta$ is the ratio between maximum normal traction and shear traction. As illustrated in Figure 2, the unloading path is toward the origin of the load-displacement curve. For the loading, the relationship between the traction and displacement jump follows the form:

$$t = \frac{\partial \phi}{\partial \delta} = e\sigma_c\left(\frac{\delta}{\delta_c}\right) \exp\left(-\frac{\delta}{\delta_c}\right). \hspace{1cm} (3)$$

For the unloading and reloading, the traction can be obtained with the following expression,

$$t = \sigma_{\text{max}} / \delta_{\text{max}}. \hspace{1cm} (4)$$

The cohesive fracture energy, which is the area under the load-displacement curve, is defined by:

$$\Gamma_c = \int_0^{\infty} t\, d\delta = e\sigma_c\delta_c. \hspace{1cm} (5)$$
3. Verification of cohesive model

A double cantilever beam (DCB) simulation was used to validate the implementation of cohesive model in UEL (Figure 3). Two-dimensional plane strain elements were used for the bulk material and linear, four-noded cohesive elements were used for the cohesive material. The length (L) and thickness (H) used were 100.0 mm and 1.0 mm, respectively. A uniform mesh size having 0.125 mm by 0.125 mm elements was used [16]. External displacement was applied to the node located at x=0 and y=0.

Young’s modulus was taken as 100 GPa and Poisson’s ratio was set at 0.25. The critical displacement used was 0.01 mm and the fracture energy was set at 1.0*10^6 J/m^2. For this analysis, 0.1δ_c was defined as the crack tip location. A plot of the normalized crack length, a/H, versus the normalized crack opening displacement, δ/δ_c, along with the analytical solution is illustrated in Figure 3. The numerical results show excellent agreement with the analytical solution.
4. Calibration of cohesive parameters

Once the initial validation of the cohesive zone modeling approach and implementation into ABAQUS was complete, the next step taken was to calibrate the model using asphalt mixture fracture test results. As illustrated in Figure 4, a simply supported, single-ended notched beam (SENB) was employed, with length, height, and thickness dimensions of: 376 mm, 100 mm, and 75 mm, respectively. Testing in triplicate replication was conducted at -10°C with a controlled crack-mouth opening displacement of 0.7 mm/min. A notch depth of 19 mm was used. For purposes of initial model validation, testing of a single asphalt mixture was conducted. A 9.5-mm nominal maximum sized aggregate surface mixture was selected, which was used at the Greater Peoria Regional Airport. The fracture energy for this mixture ($\Gamma_{\text{meas}}$) was determined to be 344 N/m, and the load-crack mouth opening displacement (CMOD) relationship can be seen in Figure 5. A mixture tensile strength of 3.56 MPa ($\sigma_{\text{meas}}$) was obtained from the Superpave indirect tension test (IDT), using AASHTO TP-9 testing and analysis protocols (12.5-mm/min loading head rate).

![Figure 4: Typical mesh for analysis of SENB specimen (L=376 mm, H=100 mm, pre-crack=19 mm) and close up of top region where cohesive elements were inserted.](image)

To simulate the SENB test, displacement boundary conditions were imposed at the center of the top edge of the model. For this preliminary investigation, several simplifying assumptions about the bulk material were made. The bulk material was modeled as elastic, homogeneous, isotropic, and rate-independent. Young’s modulus was taken as 14.2 GPa (based upon complex modulus testing of the mixture at -10°C and 1 Hz), and a Poisson’s ratio value of 0.35 was assumed. Two-dimensional, four-noded cohesive elements were inserted along the center of the specimen, and plane-strain elements were used for the bulk material. A first order calibration of critical stress and fracture energy was accomplished by trial-and-error matching of numerical results with 3-point bending test results. The calibrated model parameters were determined as $\Gamma_c = 241$ J/m$^2$ and $\sigma_c = 3.92$ MPa. Relatively small calibration shifts of intrinsic damage model parameters ($\Gamma_c = 0.7\Gamma_{\text{meas}}, \sigma_c = 1.1\sigma_{\text{meas}}$) were required to bring simulated results into reasonable comparison with measured results as shown in Figure 5. Ongoing work to implement viscoelastic bulk material properties and rate-dependent, mixed-mode fracture capabilities into the cohesive model should lead to a more versatile and accurate model in the near future. The mixed mode capability is
particularly important for the study of reflective cracking, thermal cracking, and even top-down fatigue cracking, since asphalt pavements and overlays are subjected to combined thermal and traffic loading.

![Figure 5: Comparison between experimental result and numerical result with calibrated parameters.](image)

5. Model validation – prediction of indirect tension test (IDT) results

In order to evaluate the validity of the calibrated cohesive zone model approach, a second testing mode was employed. As illustrated in Figure 6, tensile failure in an indirect tension test (as described earlier) was simulated. The IDT specimens tested were approximately 150 mm in diameter (D) and 50 mm in thickness (T). Following AASHTO TP-9 protocols, horizontal and vertical displacement measurement gages were mounted on the centers of flat faces of the specimen, with gage lengths of 38.1 mm.

![Figure 6: Schematic drawing of Indirect Tension Test (IDT).](image)
Using the calibrated cohesive parameters, $\Gamma_c = 241$ J/m$^2$ and $\sigma_c = 3.92$ MPa, crack propagation in the IDT test was simulated. Based upon the relatively fast loading rate in the IDT test, a Young’s modulus of 18.7 GPa (complex modulus testing at 10 Hz) was used. Poisson’s ratio was taken as 0.20. In this analysis, 2D plane strain elements were used for the bulk elements, and linear 2D, 4-node elements were used for the cohesive elements, which were inserted along the vertical axis of the specimen. Strip displacement boundary conditions (Case 1) were applied over a span of 19 mm at the top and bottom of the specimen, where top and bottom nodes along the cohesive elements were constrained from movement along x direction. The specimen was assumed to fail when the horizontal opening displacement of center nodes along the cohesive elements reached a computed critical displacement of 0.02262 mm, as determined from Eq. (5) using calibrated parameters.

Figure 7: Comparison between numerical and experimental results of 3 samples tested in indirect tension (using SENB calibration parameters)

Figure 7 shows the comparison between numerical result and experimental results of three replicate samples. The model predicted cracks initiating at the middle of the specimen and propagating to top and bottom regions. Since compression was present in the vicinity of the applied strip loads at the top and bottom of the specimen, the crack had not yet extended into those regions at the step when the tensile failure criterion was reached in the center of the specimen. Although the prediction deviates from the experimental results, the findings are logical. Since the simulation does not currently account for the localized damage under the loading heads, an over prediction of failure load is a reasonable consequence. However, there is room for further extension and improvement, as explained below.

Another numerical simulation was performed with a point displacement boundary condition (Case 2). For case 2, a crack developed across the entire diameter of the specimen. As illustrated in Figure 7, the model predicted a lower peak load level for the specimen, compared to strip loading simulation. This was expected, since a distributed load on an indirect tension specimen induces less tension than a point load of equal magnitude. Figure 8 shows a deformed shape comparison for cases 1 and 2.
By observing the simulated load deflection behavior of the beam and IDT specimens before the peak load is reached (Figures 5 and 7), it appears that the present cohesive zone application tends to over predict the compliance of the specimen across the impending failure plane. More work is needed to determine what portion of this discrepancy is due to the inherent compliance of the pre-peak region of the intrinsic cohesive zone model used (evidenced by the rising portion of the curve in Figure 2). An extrinsic cohesive zone model [8] is under development, which eliminates the loading portion of the softening curve and thus the associated compliance; although it is not yet known what degree of predictive accuracy would be gained. Other model extensions, such as viscoelastic material modeling, rate-dependency, damage in the bulk material elements, and 3D modeling are also expected to close the gap between measured and predicted results.

6. Summary and conclusion

An effective cohesive zone model was developed for the commercially available finite element code ABAQUS and implemented through a user subroutine in order to simulate crack propagation in bench-scale asphalt mixture fracture tests. An exponential form for the free energy potential was used in the present cohesive zone formulation. In order to verify the correct implementation of the cohesive zone model, a double cantilever beam was analyzed. The numerical result from this simulation matched the analytical solution remarkably well even for small crack extensions, which included boundary effects.

As a first-order validation step, crack propagation in an indirect tension test was simulated using parameters calibrated from the SENB test. Given the relatively simple modeling approach used, reasonably good results were obtained without further model calibration. Ongoing work to implement viscoelastic, rate-dependent and damage in the bulk material elements should lead to even better simulation results in the near future. Also under development is extension of this work to three dimensions, and an extrinsic cohesive zone model, which eliminates interface compliance prior to reaching the point of critical traction.

Mixed mode fracture testing and cohesive zone modeling are also under development. The calibrated models will then be used to predict fracture behavior of various pavement structures under environmental and vehicular loads. These models will have the potential
advantage of being capable of capturing nucleation, initiation, and propagation of multiple cracks with computational efficiency and without the need for predefined crack paths.

7. Acknowledgements
We are grateful for the support provided through the National Science Foundation (NSF) through the GOALI program, award #0219566. Any opinions expressed herein are those of the writers and do not necessarily reflect the views of the sponsor.

8. References