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Cohesive Zone Model to Predict Fracture in Bituminous Materials and Asphaltic Pavements: State-of-the-Art Review

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Abstract

Cohesive zone (CZ) modeling has been receiving increasing attention from the asphaltic materials and pavement mechanics community as a mechanistic approach to model crack initiation and propagation in materials and structures. The CZ model provides a powerful and efficient tool that can be easily implemented in existing computational methods for brittle, quasi-brittle, and ductile failure as well as interfacial fracture, all of which are frequently observed in asphaltic materials. Accordingly, this paper introduces the CZ modeling approach in the form of a state-of-the-art review addressing the concept of CZ modeling, CZ constitutive relations, their implementation into computational methods, and up-to-date applications of CZ modeling to bituminous mixtures and pavement structures. This paper also includes a brief discussion on the current challenges that researchers face and the future directions to the modeling of fracture in bituminous materials and pavements. CZ modeling is not a topic that can be possibly discussed in a single article; therefore, it should be clearly noted that this review primarily attempts to deliver some of the core aspects of CZ modeling in the area of bituminous composites.

Keywords: cohesive zone model, fracture, bituminous mixtures, asphalt pavement

Introduction

As shown in figure 1, various asphalt pavement distresses are related to fracture, including fatigue cracking (both top-down and bottom-up), thermal (transverse) cracking, and reflective cracking, of the asphalt layer. The fracture resistance of asphalt materials significantly influences the service life of asphalt pavements and consequently the maintenance and management of the pavement network.

Figure 1. Asphalt pavement distresses related to cracking.

Probably, the most developed and successful approach for modeling damage evolution in bituminous materials is the continuum damage mechanics (CDM) approach, as many researchers (Kim and Little 1990, Park et al. 1996, Lee et al. 2000, 2003, Chehab et al. 2002, 2003, Daniel and Kim 2002, Gibson et al. 2003, Tashman et al. 2004, Chehab and Kim 2005, Masad et al. 2005, Darabi et al. 2011) have studied. More specifically, researchers (Chehab et al. 2002, 2003, Darabi et al. 2011) took into account the major components of asphalt mixture behavior (elastic, viscoelastic, plastic, and viscoplastic) based on a work potential theory, the elastic-viscoelastic correspondence principle, time-temperature superposition with growing damage and a strain-hardening model for viscoplastic behavior to demonstrate good agreement between model predictions and asphalt mixture performance testing results. The CDM approach is relatively simple to apply because it treats the heterogeneous mixtures as macroscopically homogeneous continua.

In spite of significant versatility and simplicity in characterizing structural degradation and damage evolution of bituminous materials, the CDM approach is somewhat limited as it does not account for individual and interrelating effects of mixture constituents and directly measured or measurable physical damage phenomena such as micro- and macrocracks. Various types of damage, including cracks in the asphalt sample, are spatially averaged and represented by stiffness reduction in the asphalt sample as a function of damage parameters. The damage parameters are determined by fitting the model to experimental macroscopic behavior of the sample. Therefore, the CDM approach is limited in capturing and predicting the formation and propagation of a few dominant cracks leading to structural failure. Furthermore, it is limited to address damage behavior related to interactions of small-scale mixture constituents.

One of the most powerful tools for studying fracture processes and damage evolutions of engineering materials is fracture mechanics. Fracture mechanics is the study of the re-

sponse and failure of structures as a consequence of crack initiation and propagation. Fracture mechanics approaches directly deal with discrete internal boundaries (cracks) in a body, and damage evolution is characterized by employing certain fracture criteria governing the prediction of internal boundaries.

Since Majidzadeh et al. (1971) introduced the fracture mechanics concepts to the field of pavements, the fracture mechanics approach has been widely used in characterizing and predicting pavement cracking analysis. Different from CDM approaches, the fracture mechanics approach can account for the initiation of microcracks and their coalescence to macrocracks, followed by a complete failure of the structures. Therefore, the fracture mechanics approach reflects detailed damage evolution characteristics that are based on the underlying physics of the damage.

Perhaps, the first great development in understanding the mechanics of fracture is by Griffith (1920) who postulated that crack extension will occur in an object when the energy released to produce unit area of crack is equal to or greater than the critical energy release rate of the object, namely $G \geq G_c$. The critical energy release rate is considered a material constant, which is quite true for some solids including many linear elastic materials. However, traditional linear elastic fracture studies are not valid when the crack tip is subjected to certain level of plastic yielding, which in turn in a case where fracture process zones are large, and the interaction between the process zone and free boundaries can influence the behavior. Consequently, G_c is not a material constant, but can depend on specimen size, as intensively discussed in a book (Bazant and Planas 1998). Furthermore, for various viscoelastic media such as bituminous paving mixtures, numerous observations suggest that the critical energy release rate is perhaps better represented as a material parameter not a material constant, because it depends on the loading rate or even the loading history (Knauss 1970, Christensen 1979, Costanzo and Allen 1993, Yoon and Allen 1999). Most traditional fracture mechanics approaches assume the existence of infinitely sharp crack tips leading to stress singularities preceding the crack tips. However, in actual materials (rather than in the conceptual situations), neither the sharpness of the crack nor the stress singularity of the crack tip is often observed; therefore, an alternative approach is necessary for a more appropriate fracture characterization.

As an alternative, the cohesive zone (CZ) modeling approach has received increased attention from the asphaltic materials and pavement mechanics community. It is a well-established way to model crack development in monolithic and composite materials not only because it removes the stress singularity at the crack tip but also because it provides a powerful and efficient tool that can be easily implemented in various computational methods, such as finite element and discrete element methods (FEM and DEM). Moreover, the CZ approach can model both brittle failure and ductile failure, which are frequently observed in asphaltic materials due to the wide range of service temperatures and loading rates. In addition, the CZ approach can model cracks along bimaterial interfaces (such as aggregate-asphalt interfaces), which are often considered weak zones susceptible to cracking. In comparison, the typical elastic fracture mechanics theories are limited to modeling damage evolution because of crack growth along the bimaterial interfaces.

To that end, this paper introduces the CZ approach as a useful tool to model crack development in asphaltic materials and pavements. This paper is in the form of a state-of-

the-art review addressing the concept of CZ modeling, CZ constitutive relations and their implementation into computational methods, and offers up-to-date applications of CZ modeling to bituminous materials and structures. CZ modeling is not a topic that can be possibly discussed in a single article; therefore, it should be clearly noted that this paper primarily attempts to deliver some of the core aspects of CZ modeling, and applications mostly targeting bituminous composites. This paper also includes a brief discussion on the current challenges that researchers face and future directions to the modeling of fracture in bituminous materials and pavements. It is the author's hope, through this paper, to have readers capture any insights into the CZ modeling concept, its usefulness and pros and cons in the modeling of fracture-related behavior of bituminous materials and structures, so that a better use of it can be achieved.

Fracture process behavior and cohesive zone modeling

The fracture process zone is a nonlinear zone characterized by progressive softening, for which the stress decreases at increasing deformation. The nonlinear softening zone is surrounded by a nonsoftening nonlinear zone, which represents material inelasticity. Bazant and Planas (1998) skillfully classified the fracture process behavior in certain materials into three types: brittle, ductile and quasi-brittle. As shown in figure 2 (reproduced from Bazant and Planas 1998), each type presents different relative sizes of those two nonlinear zones (i.e., softening and nonsoftening nonlinear zones) and of the structure.

Figure 2. Types of fracture process zone (reproduced from Bazant and Planas 1998).

In the first type of fracture behavior (fig. 2(a)), the whole nonlinear zone is small compared to the structure size, and both the softening zone and nonlinear hardening zone are very small. Then, the entire fracture process takes place almost at the crack tip, and linear elastic fracture mechanics (LEFM) can be successfully used. Brittle materials such as glass,

brittle ceramics and brittle metals show this type of fracture process behavior. In the second (fig. 2(b)) and third (fig. 2(c)) types of behavior, the ratio of the nonlinear zone size to the structure size is not small; hence, LEFM is inappropriate. In the second type of fracture behavior, as can be seen in the figure, most of the nonlinear zone consists of the inelastic hardening zone (plastic yielding), and the size of actual fracture process (softening) is still small. Many ductile materials (e.g., ductile metals and tough alloys) fall into the second behavior type, and the elasto-plastic fracture mechanics (EPFM) is typically used for this type of fracture behavior. The third type of behavior includes situations in which a major part of the nonlinear zone undergoes progressive damage with material softening due to microcracking, void formation, interface breakages, frictional slips, and others. The softening zone is then surrounded by the inelastic material yielding zone, which is much smaller than the softening zone; therefore, it is often negligible in the analysis. This behavior we call quasi-brittle fracture includes a large fracture process zone that should be taken into account in calculations. Various civil engineering materials such as concrete, rock, coal, cemented sands, stiff clays, woods, and various toughening ceramics present the quasi-brittle fracture behavior.

The nonlinear fracture process can be modeled by the CZ or cohesive crack (Bazant and Planas 1998) model. CZ models regard fracture as a gradual phenomenon in which separation takes place across an extended crack tip, or CZ (fracture process zone), and where fracture is resisted by cohesive tractions. Conceptually, a cohesive crack is a fictitious crack that is able to transfer stress from one face to the other. This model was introduced in the early 1960s by Dugdale (1960) and Barenblatt (1962). Cohesive cracks have since been used by a number of researchers to describe the near-tip nonlinear zone for cracks in most engineering materials: metals, polymers, ceramics, and geomaterials. As one of the noteworthy studies in the area of cementitious materials, Hillerborg et al. (1976) extended the concept of cohesive crack for concrete by proposing that the cohesive crack can develop anywhere in a structure, although there is no preexisting crack. They called this extension the fictitious crack model (Hillerborg et al. 1976, Gustafsson 1985, Hillerborg 1985). The fictitious crack model is mathematically identical to the classical cohesive crack model when the fictitious crack model is used to describe the behavior of a preexisting crack (Bazant and Planas 1998).

Park (2009) skillfully introduced the nonlinear fracture process of the CZ model with four stages as shown in figure 3. The first stage (Stage I) represents general material behavior without damage. The next stage (Stage II) is the initiation of a crack when a certain criterion such as a maximum stress ($\sigma_{\max}$) shown in the figure is met. The third stage (Stage III) describes the nonlinear material softening that characterizes damage evolution, and the final stage (Stage IV) defines failure with a critical crack opening width (δ) representing the new surfaces created by the fracture process, which have no traction (no loadbearing capacity). Simply put, with increasing separation (Δ) the traction (T) increases, reaches a maximum (cohesive strength $\sigma_{\max}$), and then, governed by the softening curve (T as a function of Δ), decreases and eventually vanishes at the critical separation (δ) creating traction-free crack surfaces. The CZ surface sustains a distribution of tractions that are a function of the displacement jump across the surface. The relationship between the CZ tractions

and the separation displacements (or equivalently crack opening widths) identifies the shape of the softening curve (Stage III) and defines the constitutive law for the CZ.

Figure 3. Schematic illustration of the cohesive zone model.

Cohesive zone constitutive relations

An important issue on the use of CZ model is the determination of the relationship between the CZ tractions and the separation displacements. In particular, the relevant fracture parameters such as cohesive strength (σ_{max}), critical separation (δ), and fracture energy (ϕ) as represented in figure 3, as well as the shape of the softening curve (traction-separation curve), must be identified. A number of different CZ models have been developed and proposed by researchers as presented in many literatures (Dugdale 1960, Barenblatt 1962, Needleman 1987, 1990, Rice and Wang 1989, Tvergaard 1990, Tvergaard and Hutchinson 1992, 1993, Xu and Needleman 1993, Allen et al. 1994, Camacho and Ortiz 1996, Geubelle and Baylor 1998, Ortiz and Pandolfi 1999, Yoon and Allen 1999, Allen and Searcy 2001, Yang and Thouless 2001, Espinosa and Zavattieri 2003, Zhang and Paulino 2005, Shim et al. 2006, Park et al. 2009). Depending on the prefraction response of the cohesive surfaces, each model can be classified by either intrinsic or extrinsic. The prefraction response is characterized by the existence of an artificial initial stiffness in the CZ model. Models for which the artificial initial stiffness is considered are called intrinsic models, whereas models assuming initial rigidity for the CZs are called extrinsic models.

In the intrinsic models, as illustrated in figure 4(a), the traction-separation relation is such that with increasing separation, the traction across the CZ reaches a maximum, then decreases and eventually vanishes, indicating a complete decohesion (separation). In contrast, the extrinsic CZ model, as shown in figure 4(b), does not display the initial ascending trend in the traction-separation curve. It is assumed that separation occurs when CZ traction reaches the cohesive strength of the material, and once the separation occurs, the CZ traction decreases as separation continues.

Figure 4. CZ traction–separation relations: (a) intrinsic model and (b) extrinsic model.

Intrinsic formulations are easier to implement but may become very computationally expensive because many cohesive elements, some of which are not really necessary, need to be inserted a priori within the finite element meshes. On the other hand, the extrinsic models are probably more realistic than the intrinsic approach, because they do not assume the preexistence of CZ elements within the finite element meshes. This characteristic is generally referred to as “initial rigidity,” as illustrated in figure 4(b).

Shet and Chandra (2002) summarize some of the popular CZ models developed by researchers with specific purposes regarding the shape of the CZ traction-separation curve and the model parameters involved. Representative problems attempted and solved using each CZ model are also presented in the study. The work of separation, cohesive strength and critical displacement is typically the key parameters that characterize individual CZ models. As presented in the study, the CZ model has been used in various applications and materials (ductile, quasi-brittle, and brittle) with and without rate-dependent mechanical behavior, which infers that it can provide an ideal framework to model strength, stiffness, and failure in an integrated manner.

Computational implementation of cohesive zone models

Perhaps, the success and popularity of the CZ modeling of fracture are because it provides a powerful and efficient tool that can be easily implemented in various computational methods such as FEM and DEM. Regardless of the origin in developing the CZ model (i.e., potential-based or non-potential-based), equations relating normal and tangential displacement jumps across the cohesive surfaces with proper tractions define a CZ model, and the CZ model is implemented numerically via interface elements.

A CZ element in the finite element mesh consists of two line elements (i.e., cohesive surfaces) that connect the faces of adjacent elements during the fracture process. The two lines (surfaces) initially lie together as the intact state but are progressively separated as the level of damage at the CZ increases. The damage evolution followed by a complete separation is controlled by the corresponding traction-separation relationship.

In an attempt to illustrate differences between the two CZ implementation techniques (i.e., intrinsic and extrinsic), figure 5 is introduced herein. Figure 5 represents a typical two-

phase composite in which black rigid particles are embedded in white matrix. As shown in figure 5(a), the two-phase composite is subjected to uniaxial tensile loading condition by imposing the following boundary conditions: vertical and horizontal displacements at the bottom face are constrained, and uniaxial tensile displacements are applied to the top face at a constant rate (U_0).

Figure 5. Finite element mesh of a two-phase composite and its CZ developments simulated by two different implementation techniques: intrinsic vs. extrinsic.

Assuming CZ elements signifying damage evolution due to crack growth are only placed within the white matrix phase and are not developed within rigid black particles, finite element simulation results from the two different modeling approaches (intrinsic vs. extrinsic) are shown in figure 5(b), (c), respectively, in the form of snapshots taken at the same loading level. Dark black lines within the white matrix phase represent CZ elements involved in the damage process.

As shown in figure 5(b), in the case of intrinsic modeling, the possible cracked configurations of the bodies are governed by the topology of the finite element discretization, which implies mesh-dependent simulation results. Finite element simulation results are affected by the size and orientations of CZ elements, which is due to the fact that the CZ is represented by a highly nonlinear relation between the traction and displacement jump. In order to capture the temporal- and spatial-dependent development of cracks properly, enough number of CZ elements needs to be placed in an optimized manner, otherwise considerable accuracy can be lost. This mesh dependence has been reported by many researchers (Xu and Needleman 1994, Miller et al. 1999, Klein et al. 2001, Scheider and Brocks 2003).

Several researchers have also reported numerical issues associated with artificial compliance in the response of the bodies of interest to externally applied loads due to the assumption of the initial artificial stiffness in the traction-separation relations of intrinsic CZ

models. This phenomenon is related to the assumption made in intrinsic CZ models that discontinuities in the displacement fields happen in the uncracked body. As a result, an artificial elasticity rises at the inter-element boundaries and the corresponding stiffness of that imaginary spring introduced between bulk elements depends on the initial stiffness of the intrinsic CZ model. The artificial compliance effect can be significant and results in an adverse numerical impact when CZ elements are embedded in a large area in the object and/or when the initial ascending slope is not sufficiently steep. This problem may be effectively controlled by specifying very high values of initial stiffness in the CZ model (Geubelle and Baylor 1998, Espinosa et al. 2000, Alfano and Crisfield 2001, Klein et al. 2001, Zavattieri and Espinosa 2001, Espinosa and Zavattieri 2003, Song et al. 2006a). However, the use of "too stiff" initial cohesive stiffness can generate problems with stability and severely restrict the simulation time steps. Espinosa and Zavattieri (2003) suggested a scheme in which two time steps, the standard time step related to the properties of the bulk material and the second time step named by the authors as the cohesive time step, are calculated and the smallest between the two is taken as the overall time step.

In the case of extrinsic modeling, as clearly demonstrated in figure 5(c), cohesive elements are inserted as needed by node duplication (the process generally referred to as dynamic or adaptive insertion) in the mesh whenever a damage initiation criterion is reached. This initial rigid response lets the adjacent continuum elements remain concurrent before initiation of the fracture process, eliminating the problem of artificial compliance prior to fracture. The node duplication process is followed by gradual reduction in the load-bearing capacity of the cohesive element and the eventual complete failure of that element after the characteristic interfacial separation is reached. However, this adaptive insertion scheme requires extra implementation efforts because it requires the continuous update of the node numbering within the mesh as edges of continuum elements are duplicated to simulate the propagation of cracks. This topic has been investigated by several researchers (Pandolfi and Ortiz 1998, 2002, Mota et al. 2008, Paulino et al. 2008). Challenges associated with the use of extrinsic CZ models include the difficulties related to the continuous update of the node numbering as cohesive elements are inserted in the meshes and mesh dependency (Ruiz et al. 2001, Papoulia et al. 2003, Zhou and Molinari 2004). Other researchers have reported problems with what they called time discontinuity of the inter-element tractions (Papoulia et al. 2003, Sam et al. 2005).

In addition, as similar to the intrinsic case, the possible crack development in the body is also affected by the initial configuration of volume elements in the finite element mesh. Therefore, simulation results are dependent on the finite element discretization. For an appropriate level of model accuracy, the mesh needs to be fine enough so as to properly capture the highly nonlinear traction-displacement relation.

Application of cohesive zone model to asphalt mixtures and pavements

The CZ modeling approach in asphalt materials and flexible pavements was probably first employed by Jeng and his colleagues (Jeng and Perng 1991, Jeng et al. 1993) to model crack resistance and propagation in asphalt pavement overlays. Over the past several decades, two primary attempts have been made by various researchers for the use of the CZ concept

to the analysis and modeling of fracture process in asphaltic materials and pavements. One of the primary efforts has been pursued to estimate fracture properties (i.e., CZ parameters) of the materials so that the properties can be used to predict fracture-related damage evolution in the mixtures and structures. For a more appropriate estimation, researchers have sometimes modified preexisting fracture test methods or even newly designed their own testing protocols because preexisting fracture test methods could not properly capture fracture processes of highly nonlinear, inelastic, and heterogeneous materials such as asphaltic materials. Another challenge that researchers have faced is the use of CZ models that are tailored for a more accurate estimation of fracture mechanisms and a better performance prediction of fracture-related damage and failure in the asphalt mixtures and pavement structures. This is an extremely complicated issue, because the asphaltic mixtures and structures are highly heterogeneous, inelastic, nonlinear, rate dependent, and temperature sensitive, and demonstrate cracks in multiple length scales incorporated with multiphysical aspects such as moisture damage and material aging. To that end, this section introduces some recent attempts (obviously not all) made by civil engineering researchers to advance fracture test methods that characterize the CZ fracture parameters and to explore CZ models that more accurately represent the fracture process of bituminous materials in a summarized form.

Experimental efforts to characterize the cohesive zone fracture properties

To characterize the fracture properties of asphalt mixtures, three geometries have typically been pursued by researchers. They are (1) single-edge notched beam (SE(B)) specimen, (2) disc-shaped compact tension (DC(T)) specimen, and (3) semicircular bending (SCB) specimen, as shown in figure 6.

Figure 6. Three primary test methods used to assess asphalt mixture fracture properties.

The most common geometry used for the fracture testing of asphalt concrete has probably been the single-edge notched specimen (SE(B); Mobasher et al. 1997, Marasteanu et al. 2002). To obtain the cohesive fracture energy, Wagoner et al. (2005a) proposed a testing protocol that uses the SE(B) geometry. Wagoner et al. (2005a) concluded in their studies that SE(B) testing is probably the most promising fracture test based on test control, crack front development, test repeatability, and mixed-mode fracture. Song et al. (2006b) and

Kim et al. (2009) used the methodology proposed by Wagoner et al. (2005a) to calibrate cohesive fracture parameters used in their FEM and DEM simulations, respectively. The main problems with the use of SE(B) geometry to routinely obtain fracture properties of asphalt mixtures are that the fabrication of specimens in the laboratory becomes impractical, and that it is not often viable to extract beam specimens from mixtures in the field.

The compact tension test is a part of ASTM E399-90 (2002) and recommended as an alternative to the SE(B) test. Although the compact tension test can be performed with both rectangular and disc-shaped compact specimens, the DC(T) specimen has typically been used in the characterization of asphalt concrete fracture properties because the specimen can be easily prepared by compacting asphalt mixtures with a Superpave Gyratory Compactor. Significant work has been conducted by researchers (Wagoner et al. 2005b, 2005c) on the development of the DC(T) fracture testing protocol. They modified the original ASTM DC(T) geometry, which is usually for metallic materials, by moving the location of the loading holes to reduce failure at the loading holes. The researchers also set the thickness of the specimens to 50mm and the notch length to 19mm to maximize the ligament area. At different testing temperatures (-20 , -10 and 0°C) and loading rates, the fracture energy was simply computed by the area under the load–crack mouth opening displacement curve normalized by the area of the fracture surface. The researchers found that as the temperature increased, the fracture energy increased, and as the loading rate increased, the fracture energy decreased. The DC(T) test is now specified as ASTM D7313-07a (2007).

One simpler alternative to the SE(B) and the DC(T) is the SCB test originally proposed by Chong and Kuruppu (1984, 1988). The SCB specimen has since been used by many researchers (Chong et al. 1989, Basham et al. 1990, Khalid and Artamendi 2008, Mohammad and Kabir 2008, van Rooijen and de Bondt 2008) to obtain the fracture toughness, fracture energy and stress-softening curves of various types of brittle and quasi-brittle materials. The SCB is advantageous due to its relatively simple testing configuration, more economical aspects in specimen fabrication (two testing specimens are produced from one cylinder sample) and repeatable testing results. Another benefit of SCB testing is that it can possibly be used to determine mixed-mode (Modes I and II) fracture toughness by adjusting the angle of the notch (Chong and Kuruppu 1988). According to studies (Molenaar and Molenaar 2000, Li 2005, Li et al. 2005), the SCB test can identify fracture characteristics in a sensitive manner depending on the testing temperatures, materials used in the mixtures and loading conditions (e.g., rates). Li (2005) used acoustic emission (AE) techniques incorporated with SCB fracture testing to obtain relevant information about the fracture process in asphalt mixtures. AE is regarded as a useful tool for obtaining information about the microscopic damage during fracture and allows for a better understanding of the relationship between the microstructural events and the macroscopic performance. Although the SCB test geometry has presented advantageous aspects compared to other geometries, several drawbacks should be noticed. Wagoner et al. (2005b) indicated that the 150mm diameter of SCB specimens could lead to a relatively short (or insufficient) fracture ligament, which should be as large as possible to produce a reliable fracture property. In addition, the crack propagation with the SCB geometry creates an arching effect with high compressive stress, which further reduces the effective ligament, creating potentially invalid testing results.

Modeling efforts to address fracture in asphalt mixtures and pavements

Recently, the CZ modeling concept has been actively implemented in the modeling of asphalt concrete, particularly to simulate fracture with the consideration of the bulk material inelasticity. It is well known that asphaltic materials are rate dependent and temperature sensitive due to the asphalt binder phase in the mixture. Thus, the assumption of linear elasticity for the bulk material is not appropriate to produce accurate results. Examples of research efforts considering the viscoelasticity of the bulk material in asphalt mixtures are presented in various studies including Souza et al. (2004), Kim et al. (2005, 2006, 2007), Song et al. (2006a), Kim and Buttlar (2009) and Aragão et al. (2011). More particularly, Kim et al. (2005, 2006, 2007) have employed the nonlinear viscoelastic CZ model developed by Allen and his colleagues (Yoon and Allen 1999, Allen and Searcy 2001) to simulate the fracture and damage behavior of asphalt mixtures at intermediate temperatures. In order to predict material-specific and rate-dependent viscoelastic fracture of asphalt media, they performed laboratory tests to obtain the linear viscoelastic properties as well as the nonlinear viscoelastic fracture parameters of the asphalt phase and incorporated those parameters into the FEM model.

Kim et al. (2006, 2007, 2010a, Aragão et al. 2011) have also incorporated the CZ models into a computational modeling framework that considers mixture heterogeneity. As exemplified in figure 7, the approach is based on the finite element modeling of mixture microstructure. Individual mixture components (i.e., asphalt matrix phase, which is subject to cracking, and coarse aggregates that are not associated with fracture) are separately modeled with their material properties measured from laboratory tests.

Figure 7. Microstructure finite element modeling with intrinsic cohesive zone elements.

In order to characterize the CZ fracture properties of the asphalt matrix phase, which is a mixture of asphalt binder and fine aggregates, Aragão and Kim (2010, 2011) have conducted fracture tests of the asphalt matrix mixture with SCB geometry, as shown in figure 8. The testing has been incorporated with the use of a digital image correlation (DIC) sys-

tem that can monitor the displacement and strain fields on the overall surface of the specimen. The DIC analysis helps characterize the fracture behavior more realistically so that the determination of CZ properties can be more effectively performed.

Figure 8. SCB fracture test of an asphalt matrix sample incorporated with the DIC.

The computational approach considering mixture heterogeneity has been attempted by many researchers (Buttlar and You 2001, Masad et al. 2001, Papagiannakis et al. 2002, Sadd et al. 2003, Soares et al. 2003, You and Buttlar 2004, 2005, 2006, Abbas et al. 2005, Dai et al. 2005, Dai and You 2007, Kim and Lutfi 2008, You et al. 2009, Aragão et al. 2010) because it can effectively account for multiple length scales and mixture heterogeneity by considering individual mixture constituents separately with the aid of well-developed numerical techniques. The computational modeling approach incorporated with the mixture microstructure and CZ fracture can produce great benefits in the sense that this approach requires only the fundamental properties of mixture constituents for the simulation, which results in considerable savings in both time and cost because the model can significantly reduce time-consuming and expensive laboratory performance tests of mixture samples.

Although the computational techniques based on the mixture microstructure have been shown to be extremely versatile in directly addressing the effects of heterogeneity, inelasticity and damage growth in multiple forms in the asphaltic mixtures and structures, the asphaltic composites that contain thousands of irregularly shaped, randomly oriented inclusions (particles, voids, etc.) along with a number of potential crack sites at different length scales would require a highly refined mesh. The solution for such problems requires the use of a tremendous amount of computational time and effort, which is not always feasible with the currently available computing power. These limitations have led researchers to seek alternative approximate approaches that can account for the hierarchical structure of heterogeneous materials without having to model every microstructural detail, but still considering the most important ones.

To that end, researchers have developed and used a multiscale modeling approach (Feng et al. 2008, Soares et al. 2008, 2009, Kim et al. 2010a, 2010b, Lutfi et al. 2010), which

has rarely been applied to pavement materials and structures, as an ideal alternative to predict larger scale structural behavior with much less computational effort but still considering microstructure details and fracture in multiple length scales. The multiscale modeling has been attempted by many researchers in various disciplines, as demonstrated in a number of studies (Fish and Wagiman 1993, Fish and Belsky 1995, Oden and Zohdi 1997, Feyel 1999, Lee et al. 1999, Oden et al. 1999, Feyel and Chaboche 2000, Fish and Shek 2000, Ghosh et al. 2001, Raghavan et al. 2001, Haj-Ali and Muliana 2004, Souza and Allen 2010). In the multiscale approach, a separate scale analysis is performed at each of the smaller structural scales within the macroscopic body. Damage can also be modeled explicitly at each length scale by incorporating appropriate types of fracture/damage mechanics modeling such as the CZ model into the analysis.

Another interesting implementation of the CZ concept in the damage modeling of asphaltic materials has been pursued by Caro et al. (2010a, 2010b). They used a commercial finite element package, ABAQUS, to simulate moisture-induced damage in asphalt concrete mixtures. Based on the sequentially coupled modeling technique, they studied the effect of moisture diffusion with the mechanical performance of asphalt mixtures by means of two different mechanisms: reduction in the linear viscoelastic relaxation modulus of the asphalt matrix as a function of the amount of moisture present in the material and deterioration of the adhesive fracture properties of the asphalt matrix–aggregate interfaces as a function of the amount of moisture. They simulated the nucleation, initiation and propagation of adhesive fracture at the aggregate–asphalt matrix interfaces through the CZ modeling technique.

The CZ model has also been applied to the fracture simulations of pavement structures. Baek and Al-Qadi (2008) used 3D finite element-based CZ model to investigate the reflective cracking mechanisms in hotmix asphalt (HMA) overlays and the ability of the steel reinforcement netting interlayer to retard reflective cracking. The study found that steel reinforcement netting placed between the HMA overlay and existing cement concrete pavement significantly delays reflective crack initiation. Another recent study was performed by Kim and Buttlar (2009), who employed the CZ model implemented in the FEM to investigate the low-temperature fracture behavior of airport pavements. The authors demonstrated that the finite element pavement fracture models could successfully predict the progressive crack behavior of asphalt pavements under critical temperature and heavy aircraft gear loading conditions.

As clearly indicated from the numerous efforts introduced herein, the CZ approach can be used to model various fracture-related events in many different asphaltic materials, mixtures and structures because of its excellent flexibility and compatibility with the commonly used numerical techniques: FEM and DEM.

Current challenges and future directions

In spite of the great promises and potential of the CZ-based fracture approaches, a number of challenges need to be overcome in order to move them into real practice. There is no test method that can comprehensively define the fracture properties of asphalt materials sub-

jected to various environmental conditions (temperatures and moisture) and loading conditions. At the current stage, no fracture test is available to accurately address mixed-mode fracture behavior, which is typically observed in pavement fracture. Most of the fracture test methods have mainly focused on identifying Mode I (opening-mode) fracture. In addition, no fracture model has been fully validated yet. The model for the next generation should appropriately address the current modeling challenges such as nonlinear-inelastic material behavior including the rate-dependent fracture, mixture heterogeneity, microstructure-dependent characteristics and the multiscale-multiphysics mechanical phenomenon. In these endeavors, numerical approaches incorporated with the CZ model seem to be appropriate because they can account for the different properties of the various mixture constituents, the heterogeneity of the mixtures, and the fracture process on a more realistic scale. However, as noted in many recent studies aforementioned in this paper, computational microstructure modeling has shown many technical challenges including (1) the proper consideration of air voids within the mixtures, (2) consideration of material-to-material interactions and (3) intensive computations (poor computational efficiency). The computational efficiency is greatly intensified if three-dimensional simulations are pursued.

Although a lot of problems and issues are raised, given the continuous growth expected in the computational power for the next decades and the various advanced ideas such as multiscale modeling, the extended FEM (the so-called XFEM or similarly the generalized FEM, G-FEM) proposed by researchers in other engineering/physics disciplines (Duarte and Oden 1996, Babuska and Melenk 1997, Daux et al. 2000, Duarte et al. 2000, Wells and Sluys 2001, Moes and Belytschko 2002, Belytschko et al. 2003), the mechanistic approaches to model fracture and damage in bituminous mixtures and pavements seem appropriate and unavoidable. These can provide powerful tools to accurately predict the mechanical responses of the complicated asphalt materials and mixtures with a maximized efficiency.

In preparation for the coming decades, efforts toward CZ modeling incorporated with microstructure characterization and multiscale and multiphysics modeling are timely and necessary; they reflect contemporary understanding of the analysis modeling approach of bituminous mixtures—a clear shift from the use of empirical approaches to the use of fundamental mechanics and materials science considering hierarchical length scales and microstructure. The success of the next generation performance prediction depends on the availability and quality of the model.

Concluding remarks

In the past several decades, bituminous materials/pavement researchers have performed extensive studies to better understand the mechanisms of various forms of cracking and to develop new test procedures and prediction models to improve asphalt pavement performance. One of the most notable trends is that more and more researchers rely on fracture tests based on the fundamentals to evaluate cracking resistance in a more accurate manner. Clearly, significant advances have been made over the past decade in the development of asphalt material fracture tests such as the SCB test and the DC(T). These tests have been

found to be vastly superior in their ability to distinguish between mixtures with different mixture ingredients.

Along with the use of fundamental fracture tests, the community has been interested in the use or development of better cracking models. Empirical models are typically limited to explain the cracking phenomenon at a fundamental level. Conversely, mechanics-based models rely on advanced mechanistic theories in describing the cracking process; therefore, these models can provide predictions that are more accurate and are not limited to specific cases. The mechanistic cracking models are generally considered more complex and hard to implement, but the CZ modeling approach is relatively clear to understand and provides vast benefits to the implementation with typical numerical techniques such as the FEM. Furthermore, the CZ models directly utilize laboratory fracture test data. These tools represent the cutting edge and, if deemed useful, could be feasibly implemented as a replacement for the fracture “engine” in the pavement design guide.

Application of the CZ modeling approaches to practical problems in our community does not seem to occur in the very near future at this moment. A lot is still to be learned, and the approach remains many challenges and questions. Nevertheless, efforts toward the mechanistic fracture approach, such as the CZ modeling, are timely and necessary for the future due to their significant benefits and potential. They reflect the contemporary shift from the empirical approaches to the use of mechanics and fundamentals in the analysis and modeling of bituminous mixtures and asphaltic pavements.

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