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Finite element cohesive fracture modeling of airport pavements at low temperatures

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A B S T R A C T

Low temperature cracking induced by seasonal and daily thermal cyclic loads is one of the main critical distresses in asphalt pavements. The safety of aircraft departure and landing becomes a crucial issue in runways when thermal cracks occur in airport pavements. The low-temperature fracture behavior of airport pavements was investigated using a bilinear cohesive zone model (CZM) implemented in the finite element method (FEM). Nonlinear temperature gradients of pavement structures were estimated based on national weather data and an integrated climate prediction model. Experimental tests were conducted to obtain the numerical model inputs such as viscoelastic and fracture properties of asphalt concrete using creep compliance tests, indirect tensile strength tests (IDT), and disk-shaped compact tension (DC(T)) tests. The finite element pavement fracture models could successfully predict the progressive crack behavior of asphalt pavements under the critical temperature and heavy aircraft gear loading conditions.

1. Introduction

Cracks in highways are significant causes of structural degrading and they increase the maintenance and rehabilitation cost of pavement. The cracking phenomenon can occur through daily thermal changes and heavy traffic loads, i.e., trucks in highways and aircrafts in airports (Kim and Buttlar, 2002). Cyclic temperature variations are believed to be one of the primary causes of pavement cracking, especially in very cold climates (Rigo, 1993). It was described that both seasonal and daily temperature changes cause the thermal contraction of pavements and produce the critical tensile stress in pavement materials (Mukhtar and Dempsey, 1996). In cold climatic areas, cracks often occur upon the completion level of pavement rehabilitation in traditional pavement structures after the first or second winter (Buttlar and Bozkurt, 2002). When heavy traffic loads are applied onto the pavement surface at cold temperature, the tensile stress in pavement materials becomes critical due to the high stress concentration at the weakest or discontinuing points of pavement (Lytton, 1989). The thermal cracks are more significant in the airport pavements of cold regions due to the thicker pavement layers and the impact loads by heavy aircraft gears. Furthermore, the frequent maintenance and rehabilitation of airport pavements has caused many aircraft delays in international airports.

In this study, a cohesive zone model approach was applied to represent the crack initiation and propagation of asphalt pavement in the finite element method (FEM). Using an enhanced integrated climate model (EICM) developed by the American Association of State Highway and Transportation Officials (AASHTO), nonlinear temperature gradients through pavement layers could be obtained based on the US National Weather Database (NCHRP 1-37A, 2004). The determined temperature gradients were projected into pavement fracture models to investigate the thermal crack behavior in airport pavements. Also, heavy aircraft loading conditions were applied into FE pavement fracture models to understand the fracture behavior of pavements in thermo-mechanical loading conditions. Viscoelastic properties and fracture parameters of asphalt materials were obtained by a series of experimental tests and they were used as the input values of FE fracture models to characterize the fracture behavior of airport pavements.

2. Constitutive laws

2.1. Cohesive zone model

The cohesive zone model is an efficient tool to predict the damage evolution in the fracture process zone located ahead of a crack tip in materials. This model, which involves nonlinear constitutive laws described by displacement jump and the corresponding traction along the interfaces, provides a proper phenomenological approach to simulate various fracture behaviors such as crack nucleation, crack initiation, and crack propagation. Fig. 1 schematically illustrates the fracture process zone, defined as the distance between a cohesive crack tip where the traction is maximum and a material crack tip where a traction-free region develops (traction is assumed to be zero). Therefore, the process zone describes the region between the points of no damage (full load carrying capacity) and the points of complete failure (no load-bearing capacity). Along this zone, crack nucleation, crack bridging and crack propagation occur. As the displacement jump increases due to an increase of external force or compliance in the

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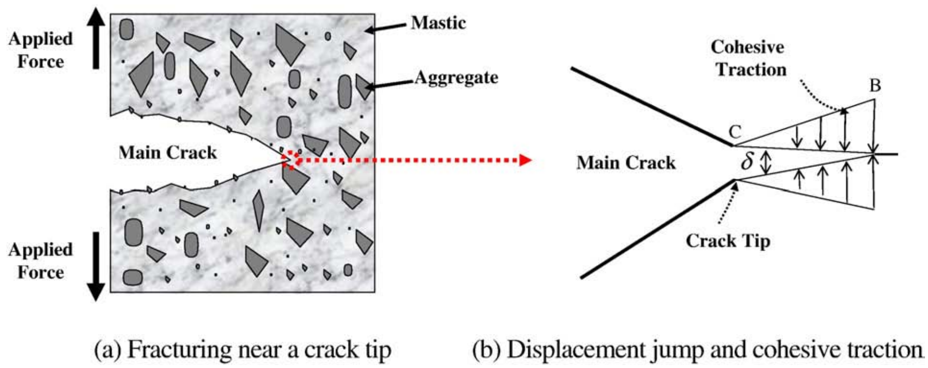

Fig. 1. Concepts of fracturing in asphalt concrete.

structure, the traction first increases, reaches a maximum, and decays to zero. Various fracture mechanisms depend on the material strength (σ_c), critical displacement (δ^c) and fracture energy (G_f), which represent the constitutive cohesive zone model parameters.

The potential based exponential cohesive law proposed introduces undesirable artificial compliance due to initial slope of the exponential cohesive law (Xu and Needleman, 1994). As the number of cohesive elements increases, the initial contribution of each cohesive element increases and, as a consequence, the compliance induced is significant. To alleviate such problems, a bilinear model is introduced to reduce the compliance by adjusting the initial slope of cohesive law (Espinosa and Zavattieri, 2003; Rahulkumar et al., 2000). Notice that the parameter λ_{cr} is a non-dimensional constant in which the traction is a maximum, and is incorporated to reduce the elastic compliance by adjusting the pre-peak slope of the cohesive law. λ_{cr} can be determined by replacing the denominators in Eq. (1) with displacements (δ_n^1 for normal and δ_s^1 for shear) where the traction becomes the maximum. In other words, as the value of λ_{cr} decreases, the pre-peak slope of the cohesive law increases and as a result, artificial compliance is reduced. Herein, λ_{cr} of 0.01 was selected for asphalt materials based on verification results of DC(T) FE models and used to reduce the unnecessary compliance (Song, 2006). Non-dimensional effective displacement (λ_e) and effective traction (t_e) are defined as follows:

$$\lambda_e = \sqrt{\left(\frac{\delta_n}{\delta_n^c}\right)^2 + \left(\frac{\delta_s}{\delta_s^c}\right)^2} \text{ and } t_e = \sqrt{t_n^2 + t_s^2} \tag{1}$$

where, δ_n and δ_s denote normal opening and shear sliding displacements, respectively; δ_n^c and δ_c^s are critical values where complete separation, i.e. zero traction, occurs; and t_n and t_s denote normal and shear effective tractions.

For $\lambda_e < \lambda_{cr}$, the normal and shear tractions are given as (Dwivedi and Espinosa, 2003)

$$t_n = \sigma_c \frac{1}{\lambda_{cr}}\left(\frac{\delta_n}{\delta_n^c}\right) \text{ and } t_s = \sigma_c \frac{1}{\lambda_{cr}}\left(\frac{\delta_s}{\delta_s^c}\right). \tag{2}$$

For $\lambda_e > \lambda_{cr}$, the tractions are described by

$$t_n = \sigma_c \frac{1-\lambda_e}{1-\lambda_{cr}} \frac{1}{\lambda_e}\left(\frac{\delta_n}{\delta_n^c}\right) \text{ and } t_s = \sigma_c \frac{1-\lambda_e}{1-\lambda_{cr}} \frac{1}{\lambda_e}\left(\frac{\delta_s}{\delta_s^c}\right) \tag{3}$$

where, σ_c represents material strength.

The schematic representation of a bilinear cohesive zone model is shown in Fig. 2 and the shape of CZM depends on the selected value of λ_{cr}. Both traction and displacement were normalized by critical values where complement separation occurs. The initial slope of CZM can represent the initial compliance in the failure of materials. If λ_{cr} increases, then the initial slope of CZM decreases. The cohesive fracture energy (G_c) is computed by equating the area under the displacement–traction curve (Fig. 2) without normalizing, namely

$$G_c = \int_0^{\delta^c} T(\delta)d\delta = \frac{1}{2}\sigma_c\delta^c \tag{4}$$

where, $T(\delta)$ is the traction function and δ is the opening displacement.

A bilinear cohesive model was used in the form of a user element (UEL) subroutine in ABAQUS™ (HKS Inc., 2007). The material parameters used in the cohesive fracture model are fracture energy and tensile strength. In the current cohesive fracture approach, cracking in the pavement is simulated in the FE model by means of a specialized cohesive zone element. These elements are embedded in the mesh along the interface of regular finite elements.

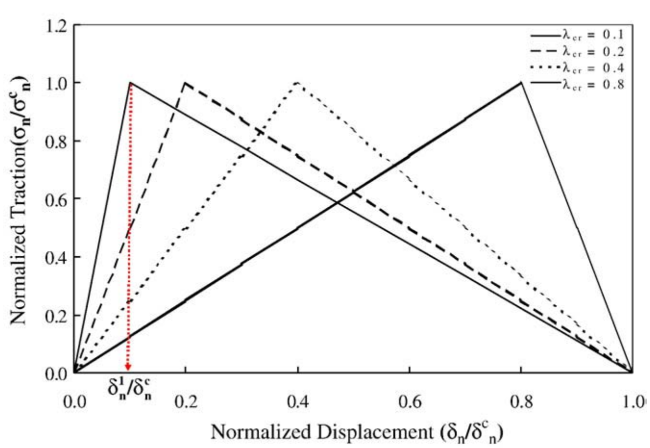

Fig. 2. Normalized parameters of the bilinear cohesive zone model.

Table 1
Creep compliance data tested by IDT at low temperatures.

Time (s)	Creep compliance (1/Ga) at different temperatures		
	−20 °C	−10 °C	0 °C
1	0.059	0.109	0.214
2	0.066	0.123	0.258
5	0.075	0.146	0.331
10	0.085	0.171	0.408
20	0.096	0.2	0.498
50	0.116	0.249	0.669
100	0.137	0.304	0.821
200	0.163	0.372	1.025
500	0.209	0.511	1.413
1000	0.257	0.674	1.192