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Integrated Fracture Mechanics and Finite Element Analysis of an Electrically Conductive Concrete Heated Pavement System

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Abstract: The construction of electrically-conductive heated-pavement system includes embedding electrodes in the conductive layer of the pavement. These electrodes are necessary for developing electric current in the conductive layer of the pavement system and ultimately for heat generation. Therefore, the structural performance of this pavement under the expected loading should be evaluated considering the existence of the electrodes. An interesting research topic in the construction of pavement systems is employing methods for preventing the potential for cracks. Therefore, in this study, two finite-element models of a bottom-up crack in an electrically-conductive heated-pavement system are developed: *i)* a model with no electrodes, *ii)* a model that includes electrodes, and the structural responses of these two systems under a loading that simulates an airfield traffic load are compared, revealing the difference the existence of the electrodes inside the pavement would cause in the system's structural performance . The outcomes of this study provide guidance for the construction processes of electrically-conductive heated-pavement systems in minimizing the potential for cracking due to the existence of electrodes.

1 INTRODUCTION

Electrically conductive concrete (ECON) is used in pavement systems to generate heat through Joule heating process by conducting electrical current to increase the temperature of the pavement surface and remove ice and snow during winter weather events (Sassani, et al. 2018; Sadati, et al. 2018). The construction of electrically-conductive heated-pavement systems includes embedding electrodes, typically stainless steel circular bars, within the top conductive concrete layer of the pavement to generate heat through electrical current flow. Recently, test slabs of an ECON heated-pavement system were built at the Des Moines International Airport in Des Moines, IA, and at the Iowa Department of Transportation (DOT) headquarters building in Ames, IA, both located in ASHRAE Climate Zone 5A (cool-humid) (ASHRAE 2007). These slabs are being monitored for their performance. While thermal performance of ECON has shown promise (Sadati, et al. 2017; Sadati, et al. 2018), one key question remaining in the design of such systems is how the presence of embedded electrodes impacts the structural performance of the pavement under its expected loading conditions.

Crack initiation mechanisms and propagation analysis are significant aspects in studying structural performance of pavement systems (Kaya, et al. 2017; Rezaei-Tarahomi, et al. 2017b). Although crack growth analysis in reinforced concrete has been the topic of several previously-published studies, there has been no specific study on ECON pavement systems. The theoretical basis for crack propagation has been previously established (Williams and Ewing 1984), and the equations describing stress at a crack tip can be found in a study by Mirsayar, et al. (2018). These equations are based on three basic motion modes for the crack: *i)* opening, *ii)* in-plane shear and, *iii)* out-of-plane shear (Ameri, et al. 2016), and the total stress at a crack tip can be calculated as a combination of these three basic modes. Several research papers focused on analyzing crack growth in pavement systems have used finite-element (FE) models. For example, Gaedick, et al. (2009) developed an FE model used to study crack growth due to fatigue, enabling study of the life cycle of large pavement slabs using fracture mechanics theories. Because of the high computational cost of such FE analysis, Ceylan, et al. (2010) suggested developing an artificial neural network model (ANN) based on FE analysis results. This ANN model results in a significant reduction in computational costs of predicting stress intensity factors for top-down cracking in pavements. As another example, Ameri, et al. (2011) developed a 3D FE model of an asphalt concrete pavement system for investigating top-down cracking. Stress intensity factors (SIF) for the three cracking modes can be introduced as a significant data set for use in investigating stresses at the tip of a crack. The same concept was adapted and used in the present study to determine the impact of embedded electrodes on bottom-up crack growth in ECON pavement systems.

As such, this paper aims to evaluate the structural performance of ECON, specifically focusing on bottom-up crack propagation through the pavement profile. To do this, FE models of the pavement structure were developed to study the potential impact of electrodes on crack propagation. Two FE models of a crack in an ECON-heated pavement system have been developed: (i) one without embedded electrodes, and (ii) one with embedded electrodes. The structural response of these two systems under a given set of loading conditions that simulates expected airfield traffic loads, have been compared, and this comparison provides valuable information about the structural performance of this newly-developed type of system.

2 METHODOLOGY

An ECON pavement system includes an ECON layer, a portland cement concrete (PCC) layer, and a base layer constructed on a subgrade, as shown in the schematic illustration in Figure 1. The ECON layer is considered to be a bounded overlay on the PCC layer in which electrodes are anchored to the PCC layer, and the ECON material is then poured around them, ultimately burying them within the ECON layer.

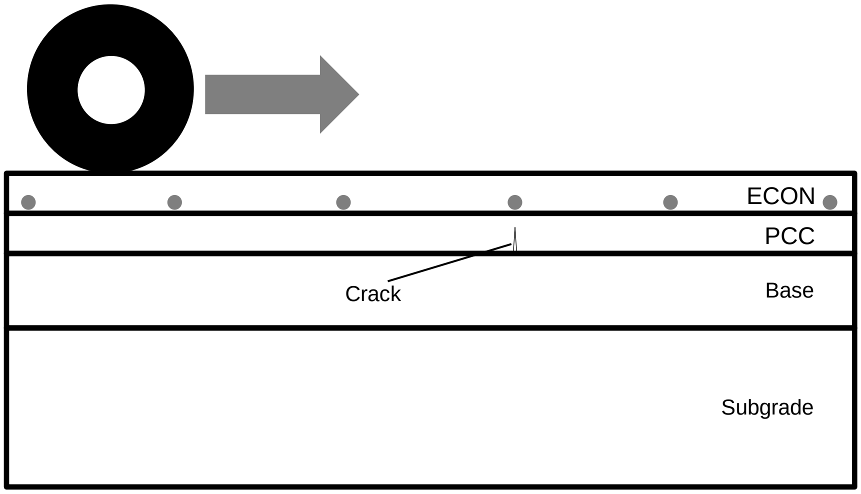

Figure 1: Schematic drawing of ECON pavement system under dynamic loading

To study the impact of electrodes on the structural capacity of an ECON pavement system, tensile stress distribution and crack propagation in the PCC layer directly under the ECON layer was investigated, since this is the location of the maximum tensile stress (Rezaei-Tarahomi, et al. 2017a). The most common parameter in the design of rigid or composite pavements for airfield applications is the stress intensity at the bottom of the PCC layer, and this study also uses fracture mechanics theories to investigate crack propagation at this location. Stress intensity factors (K_I, K_{II}) and energy release rate (*J-integral*) were calculated as representational factors for crack propagation, with K_I and K_{II} representing the stress distribution at the tip of the crack. K_I reflects the stress intensity of the crack in mode *I* of crack propagation, the opening mode, while K_{II} reflects mode *II* of crack propagation, the sliding mode, as illustrated in Figure 2.

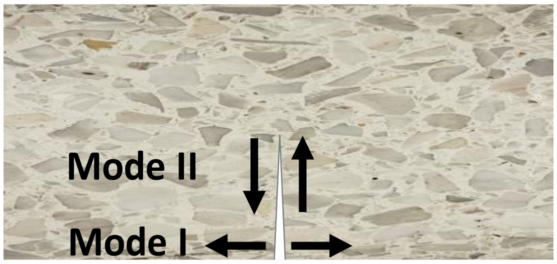

Figure 2. Crack growth modes

To study the impact of the electrodes on crack propagation, two 2D FE models of all pavement layers, one with and one without electrodes, was created in ABAQUS (2018),. As a naming convention, the model without electrodes is named *model A* and the model with electrodes is named *model B*. The electrodes are circular bars 2 cm in diameter. The ECON layer is 9 cm thick, the PCC layer is 10 cm thick, the base is 20 cm thick, and the subgrade is modeled assuming a 200 cm layer thickness. Material properties for all layers were adapted from a study by Rezaei-Tarahomi, et al. (2017; 2019). All model components were meshed using element type CPE4R**,** a 4-node bilinear element suitable for plain strain analysis. In *model B*, a finer mesh was used at locations directly adjacent to the electrodes to account for their geometry changes and to produce a mesh with appropriate proportionality for element sizes. Totals of 2,000 and 2,250 elements were modeled for *model A* and *model B*, respectively, as shown in Figure 4 and Figure 4 that illustrate the meshes used for the pavement layers, the electrodes, and the crack at the bottom of the PCC layer.

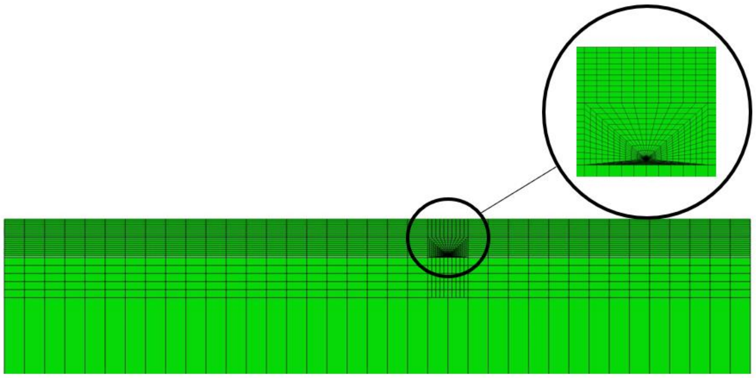

Figure 3: The FE models of the pavement system without electrodes (model A)

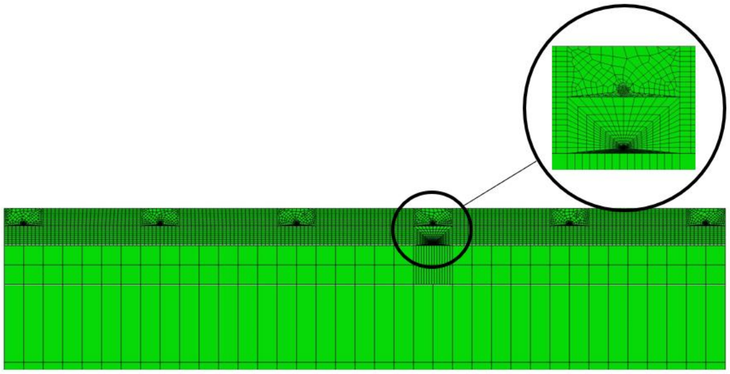

Figure 4: The FE models of the pavement system with electrodes (model B)

Since in ABAQUS a seam can be used to simulate crack growth, a crack was created by inserting a seam in the model. The seam is originally closed but can become open when subjected to loading. During the meshing process, overlapping duplicate nodes used to support simulation of crack growth are generated along the seam, with the finest size mesh in the model at the crack location.

Since the main application of ECON is for airfield pavement systems, the model loading applied to the pavement was based on a real-world scenario for a taxiing aircraft. Based on available flight data (FlightAware 2019), the most common aircraft type found at the Des Moines International Airport is an A320. Since the actual amount of load used is not particularly critical because this paper is a comparative study of *model A* and *model B*, the load applied by an A320 aircraft was considered for this study. The tire footprint length of the landing gear for the A320 aircraft is 50 cm and the pressure exerted on the slab surface is a total of 1440 kPa. This information was used in applying a uniform load to simulate the tire load. A moving load on the pavement was also modeled to simulate the load applied through the landing gear wheels to the slab surface. Crack analysis performed in ABAQUS produced intensity factors for the cracks in both *model A* and *model B*. The higher the intensity factor, the greater the potential for crack growth.

3 RESULTS AND DISCUSSION

The results of the study reflect stress distributions at the bottom of the PCC layer, and the appropriate stress intensity factors are presented in this section. Figure 5 displays the tensile stress at a given point at the bottom of PCC slab layer when the load is moving over the ECON layer surface, representing the highest tensile stress developed in the pavement. As shown in the figure, the critical tensile stress for the pavement with ECON and the plain concrete differ insignificantly between the models. Since the model is studied in the X-Y plane and electrodes are placed in the Z direction, the load is mainly carried by the ECON and the PCC layers.

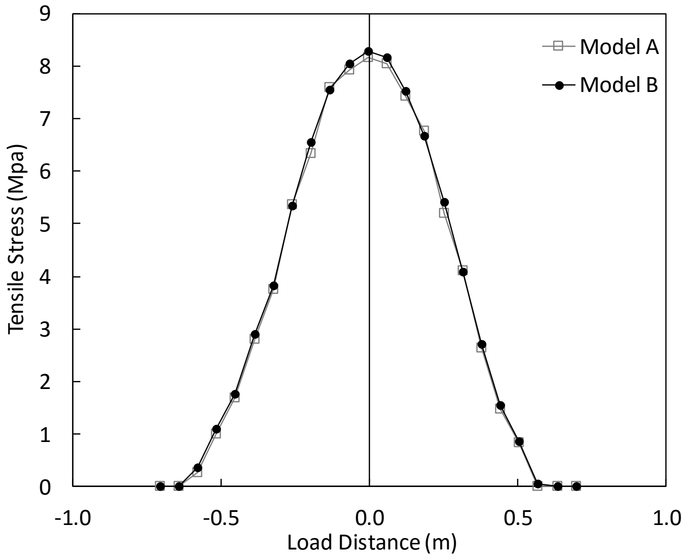

Figure 5: Tensile stress at the bottom of the PCC slab for models A and B

Figure 6 illustrates K_I variation for *models A* and *B* with respect to load distance from the crack plane. Since K_I reflects the opening mode of crack propagation, maximum stress intensity occurs when the load is near the crack. Figure 6 shows no significant difference between *model A* and *model B*'s crack growth in terms of crack-opening mode, indicating that the inclusion of electrodes does not significantly influence crack growth and fatigue life of the PCC slab.

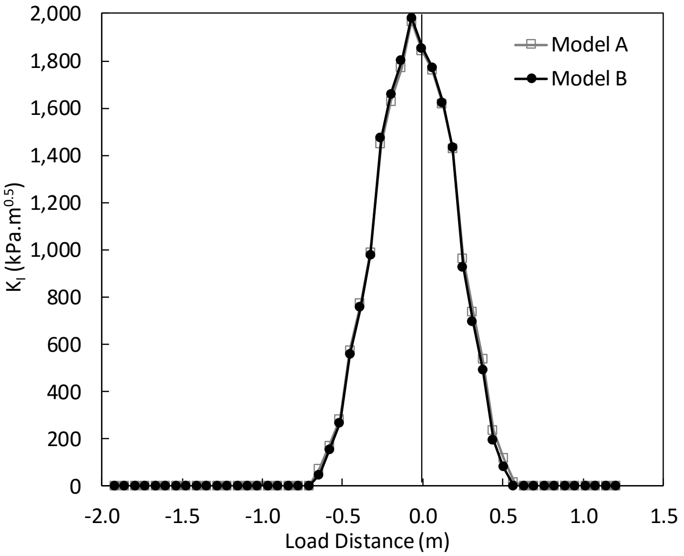

Figure 6: Stress intensity factor in mode I (K_I) for models A and B

The crack growth condition in mode *II*, shown in Figure 7, indicates that the stress intensity in sliding mode at the crack tip for both models is very close, i.e., using circular steel bars in ECON as electrodes did not significantly affect crack growth in sliding mode. Unlike K_I, the maximum K_{II} was obtained when the load was located immediately before or after the crack, not at the top of the crack. Comparing Figure 6 and Figure 7 demonstrates that the dominant mode of crack propagation is mode *I*, the opening mode.

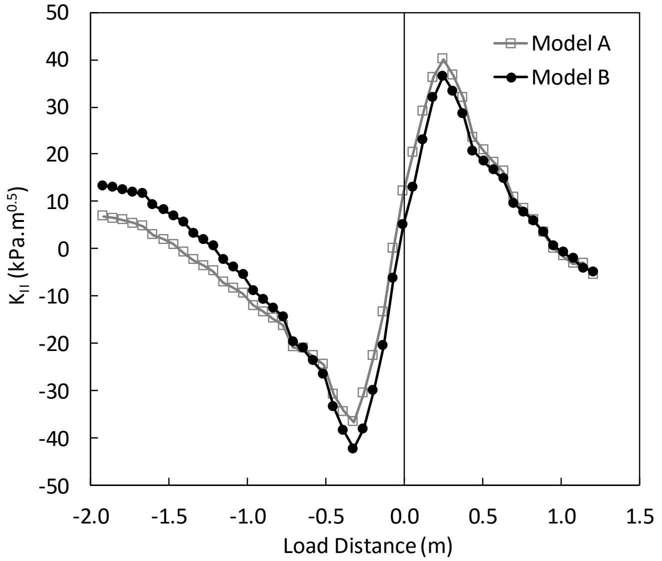

Figure 7: Stress intensity factor in mode II (K_{II}) for models A and B

The energy release rate (*J-integral*) is another parameter used in this study for investigating crack growth in the PCC slab. *J-integral* is the reduction in elastic energy associated with the crack increase per unit area (J/m^2), and the crack propagates when the energy release rate reaches a critical energy release rate, with a higher *J-integral* indicating that the crack is more likely to grow. Figure 8 depicts the *J-integral* variation associated with load distance from crack. Like with K_I and K_{II}, the energy release rates for *model A* and *model B* are very similar, indicating that cracks in a pavement with embedded electrodes and a pavement without embedded electrodes have similar likelihoods of propagation and may have similar growth rates.

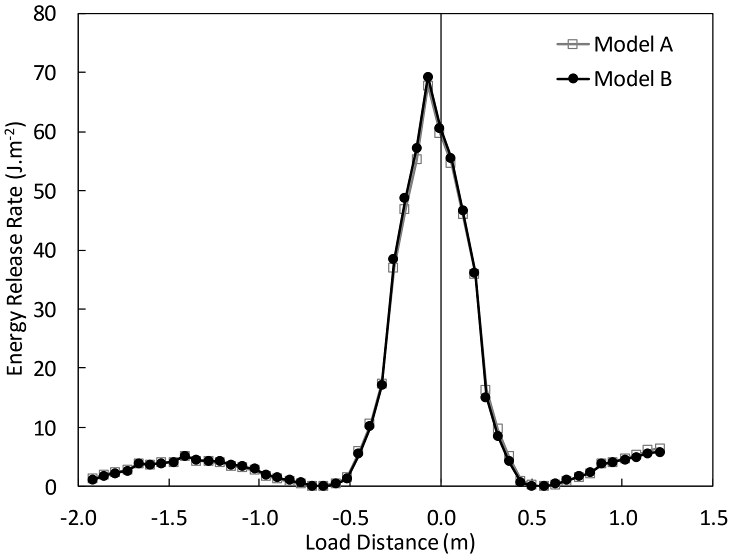

Figure 8: Energy release rate for models A and B

4 CONCLUSIONS

A 2D FE model of an ECON pavement system was created and crack propagation parameters were compared to those obtained from a regular rigid pavement system's FE model. The objective of this comparative study was to investigate the impact of embedded electrodes in an ECON pavement system, and stress intensity factors in modes I and II and energy release rates for bottom-up cracks were compared for these two pavement system models. The results indicate that presence of the electrodes is not likely to impact the bottom-up crack propagation, assuming all other pavement-system design parameters are the same, because the electrodes do not impact the tensile stress in the longitudinal direction. Since the study was on a 2D model, gear configuration was not considered, and it should also be noted that thermal loading, not considered in this study, could have a considerable impact on crack growth. Moreover, including the effects of adjacent slabs could potentially affect the results. While considering these limitations in future studies, their impact on top-down cracks will be investigated and fatigue analysis performed to more completely evaluate the life cycles of ECON pavement systems.

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