COMPUTATIONAL SIMULATIONS OF A FULL-SCALE REFLECTIVE CRACKING TEST

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PRESENTED FOR THE
2010 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2010

ABSTRACT

Prediction and simulation of load-related reflective cracking in airfield pavements require three-dimensional models in order to accurately capture the effects of gear loads on crack initiation and propagation. In this paper, we demonstrate that the Generalized Finite Element Method (GFEM) enables the analysis of reflective cracking in a three-dimensional setting while requiring significantly less user intervention in model preparation than the standard FEM. This novel computational tool is used to simulate a full scale reflective cracking simulator being considered for the National Airport Pavement Test Facility (NAPTF). This paper demonstrates how numerical simulations enable the evaluation of three-dimensional crack behavior, particularly the study of vertical crack propagation versus crack channeling. These findings lead to a better understanding of the mechanisms controlling reflective cracking and help test designers in the selection of test simulator geometry, boundary conditions, and in selecting sensor types and locations.

1. INTRODUCTION

While significant progress has recently been made in the development of mechanistic analysis tools for pavements with asphalt overlays, there is still work to be done to simplify the analysis tools and testing requirements to make them usable by practitioners. Such models would combine the relative strengths of mechanics-based models, i.e., physical correctness, and those of empirical approaches, i.e., the efficiency of the solution.

The need for true 3D modeling of reflective cracking complicates the development of computational models using standard finite element methods. The Generalized Finite Element Method (GFEM) as reported in : Babuska [1,2], Oden [7], Duarte [3], Moës [5,6], Sukumar [8]; adds flexibility to the FEM while retaining its attractive features. The GFEM enables the understanding of reflective cracking mechanisms in a 3D setting while requiring significantly less user intervention in model preparation (, refer to Garzon [4] for further details). As such, it provides support for the development of mechanistic based design procedures for airfield overlays that are tolerant to reflective cracking.

In this paper a preliminary model proposed a full scale reflective cracking simulator at National Airport Pavement Test Facility (NAPTF) is presented. In this analysis two objectives are pursued. 1) Estimate required actuator forces as a function of various design parameters, such as friction coefficients, debonding between PCC and AC overlay, strength of base, etc; 2) Evaluate 3D crack behavior, particularly vertical crack propagation versus crack channeling, which will help inform the Federal Aviation Administration (FAA) as to sensor types and placement for their full scale tests.

2. COMPUTATION OF FORCES ON ACTUATORS

In order to support a preliminary design of a mode I full scale reflective cracking simulator at NAPTF two models were created. This preliminary design consists of two 15’x15’ concrete slabs joined by an asphalt overlay on top (see Figure 1).

The first model called ABAQUS model, is discretized using 8 node hexahedrons and because of the symmetry of the problem only a strip of the slabs is modeled (no crack is considered in this model). The dimensions of the model are 30 feet in the longitudinal direction, 13 inches of height and 1 inch of thickness. It has 26,118 degrees of freedom (dofs) with variable size of elements where the smallest elements are close to the PCC joint. The size of the smallest element edge is 0.16 inches. This model is used mainly for the computation of the required actuator forces as a function of various design parameters such as: bottom interface, debonding between PCC and AC overlay, strength of base and material assumptions. This model uses the capabilities of Abaqus software to analyze the problem using the Finite Element Method (see Figure 2).

The second model called GFEM model, was created using 4 node tetrahedrons enriched to polynomial order (p=3) and is presented in Figure 1. The dimensions of the model are 30 in the longitudinal direction, 13 inches of height and 30 feet in the transversal direction. This model has 15,701 nodes with variable size of elements where the smallest elements are close to the PCC joint. Additionally using the capabilities of the GFEM program, mesh refinement is performed close to the PCC joint having the smallest element edge to be 0.0078 inches. Furthermore automatic third order polynomial enrichment of nodes is applied to the mesh to increase accuracy of the results. This model was used to verify the initial results comparing them to the ABAQUS model and later on to study the behavior of the reflective crack. This model is solved using the Generalized Finite Element Method. This section presents current findings.

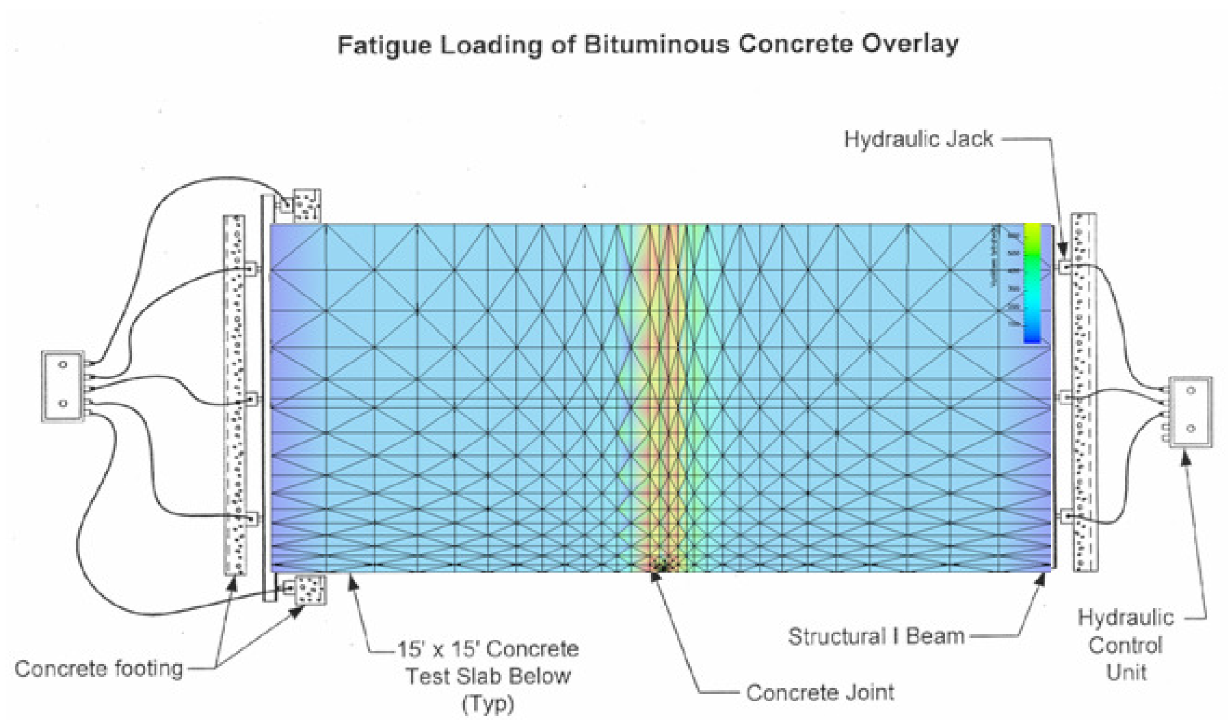


Figure 1. NAPTF Reflective Cracking Test Section Design

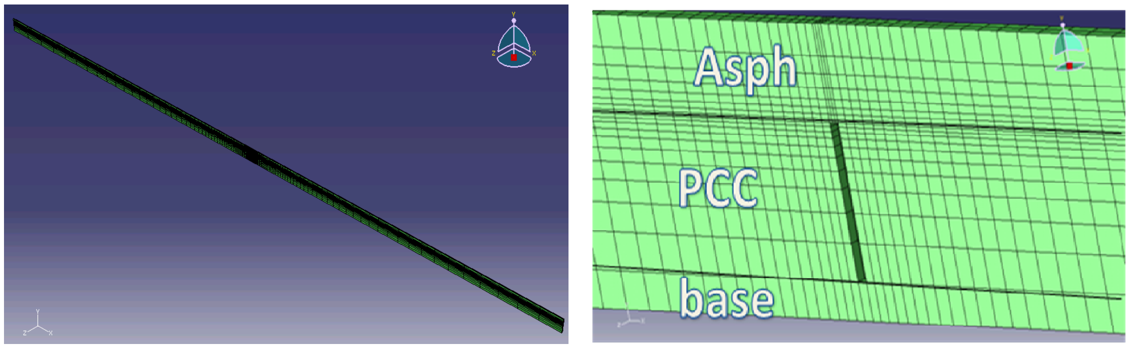


Figure 2. ABAQUS model used to estimate forces on actuators. Only a slice of the test section is modeled since no cracks are considered

2.1 LINEAR ANALYSIS

As a first idealization of the problem, we assumed that frictions forces between the PCC and the base were constant. This reduces the problem to a linear simulation which can be performed quickly. Both ABAQUS and GFEM solvers were used mainly as a mean to verify our computations. Figure 3 shows a close view of the PCC joint in the GFEM model. The material properties for this model are assumed to be linear elastic with Young's modulus of 200,000 psi for the asphalt layer and 4,000,000 psi for the concrete layer. The Poisson's ratio for the asphalt layer is assumed to be 0.35 while 0.15 is assumed for the concrete layer.

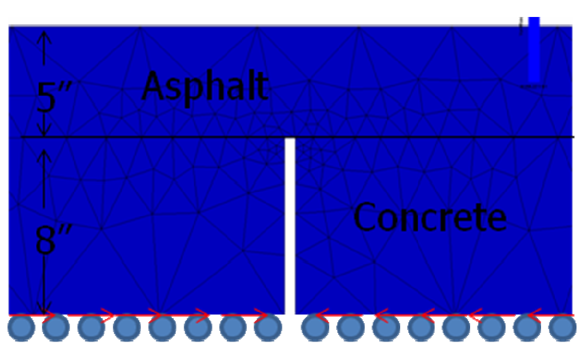


Figure 3. GFEM model used to estimate forces on actuators

Our goal was to find the forces required to produce an opening of 0.006 inches at the PCC joint as a function of three values of friction coefficient between PCC and base. The values considered were; μ=0, μ=0.35 and μ=1. The first one assumes a frictionless contact, the last one assumes the highest possible friction force and the second one assumes friction contact between concrete and gravel. For each one it was found that a slightly different initial imposed displacement at the sides of the model was needed in order to obtain the desired joint opening. Results are shown in Figure 4.

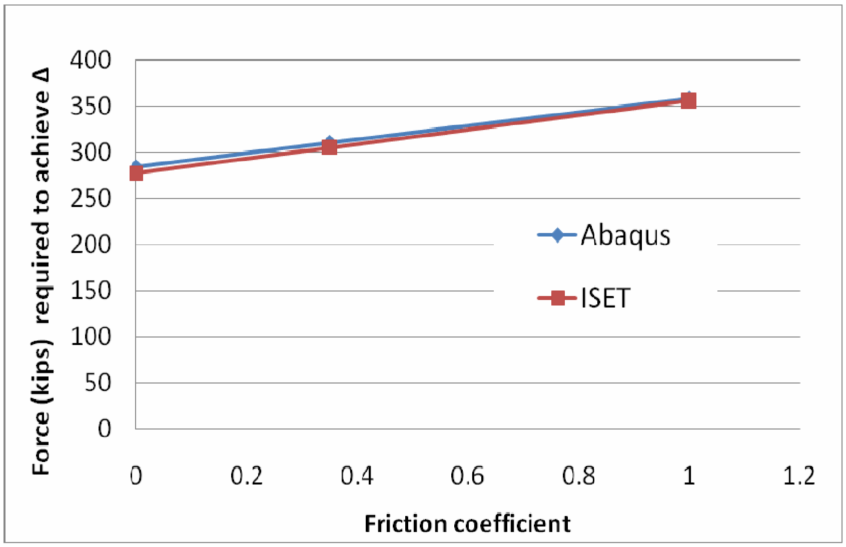


Figure 4. Results for Linear Analysis

Similar results were found for both GFEM and ABAQUS. The GFEM model was used later for crack analysis (Section 3), while the ABAQUS model was used for non-Linear analysis.

2.2 NON-LINEAR ANALYSIS

The next model used in our investigation considers nonlinear contact between the PCC and the base. Only the 2-1/2 D ABAQUS model is used in this section. Instead of loading the bottom of the PCC with friction forces, an interface for contact was created between the concrete layer and the base. Gravity forces were included with an assumed weight for asphalt concrete and cement concrete of 140 pounds per cubic foot. Again, three cases of friction were studied: μ=0, μ=0.35 and μ=1. Material properties are the same as in the previous case. Figure 5 shows the results.

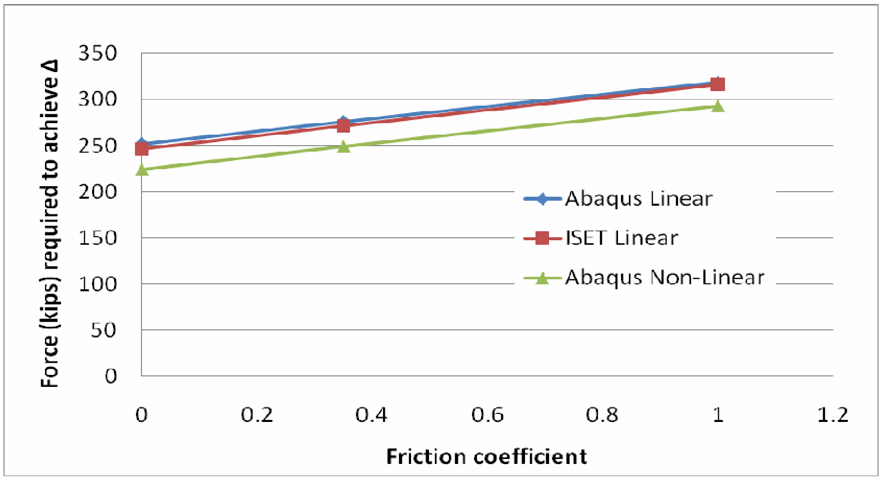


Figure 5. Non-Linear Analysis results

For all three cases, we found that the non-linear analysis gives lower force values compared to the linear analysis. The deformed model observed after the analysis exhibits some non-intuitive behavior, see Figure 6. Bending is present in the PCC pavement such that the regions away from the joint are not longer in contact with the base. Also, the tip of the bottom of the joint is highly stressed in the simulation.

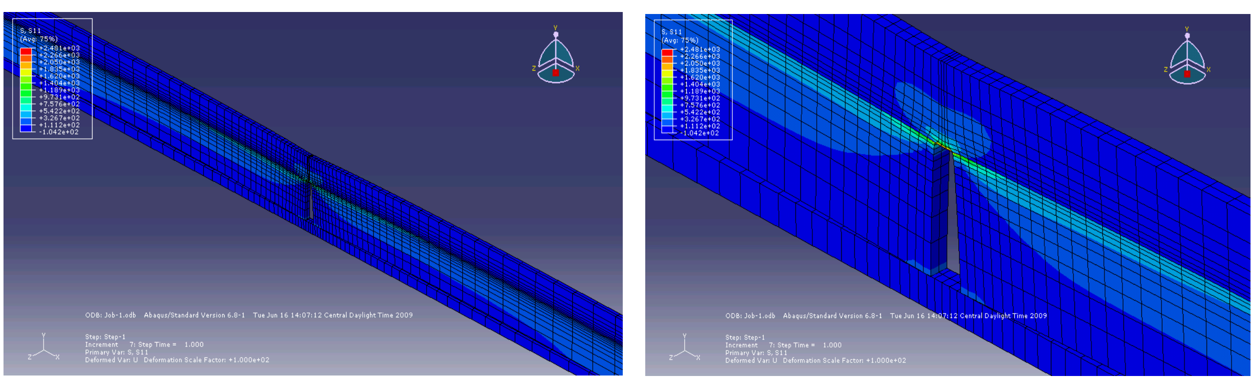


Figure 6. Deformed model in non-linear analysis

2.2.1 NON-LINEAR ANALYSIS: EFFECT OF BASE STIFFNESS

To check if the behavior discussed in the previous section depends on the base stiffness, we repeated the analysis with three different Modulus of elasticity values for the base: E=4 $*10^6$, 4 $*10^5$ and 4 $*10^4$. The following results not only show the force in the horizontal direction but also the stress in the vertical direction at the two locations. The first location is the last element on the side of the model, and the second position is the element at the bottom tip of the joint in which the higher stresses are expected (see Figure 7).

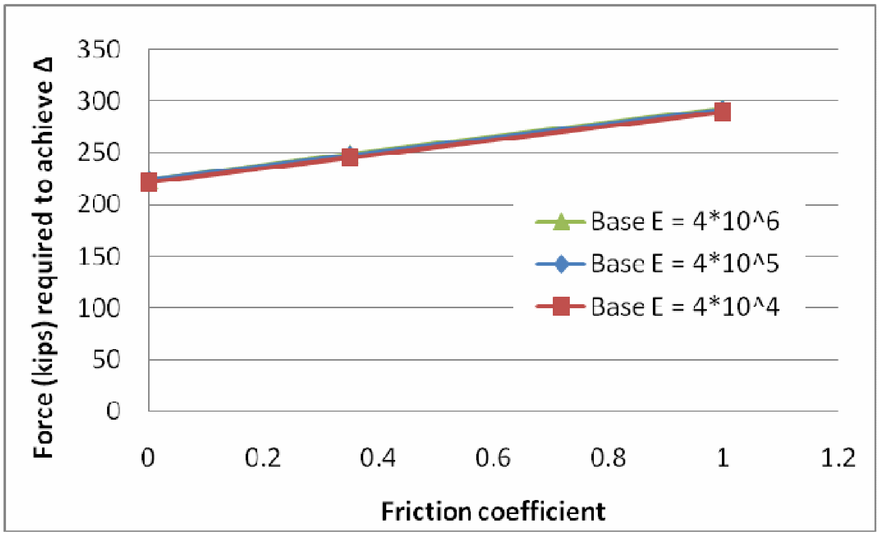


Figure 7 a). Non-linear analysis results with different bases: Horizontal force

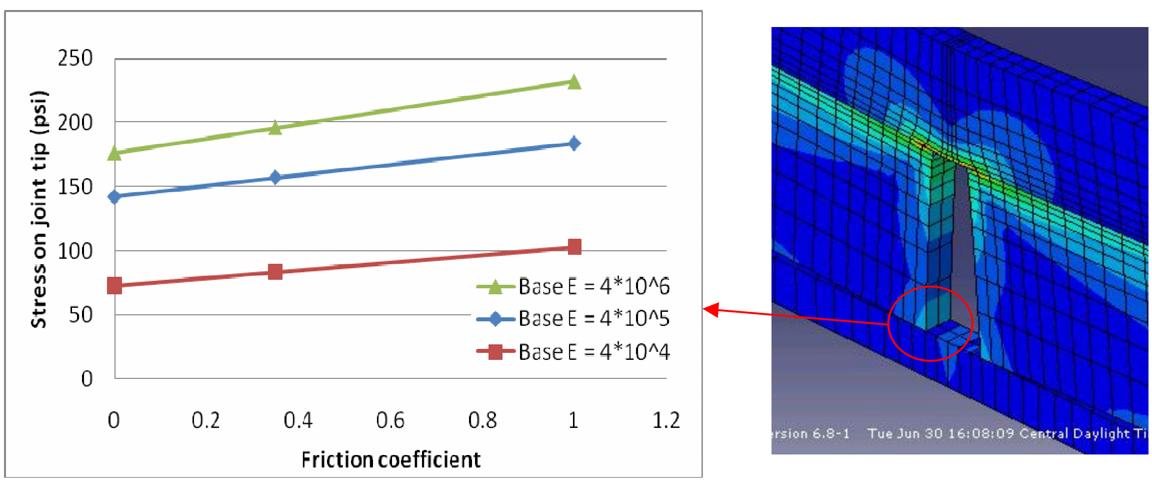


Figure 7 b). Non-linear analysis results with different bases: Normal stress at the edge of PCC

The results show that the horizontal forces does not vary much with base stiffness, but the normal stress at the bottom edge of the PCC joint does decrease significantly when a softer base is present. This is important to keep in mind at the time of design to avoid local damage of the PCC.

2.2.2 NON-LINEAR ANALYSIS: EFFECT OF DEBONDING

Experimentation has shown significant debonding between the asphalt layer and the concrete layer. This section investigates the effect of this mechanism on the horizontal force required to open the joint. Different debonding stages are considered: From zero debonding to 6 inches of debonding between PCC and AC (see Figure 8). Results are shown in Figure 9. Significant force reduction is observed when the model experiences debonding.

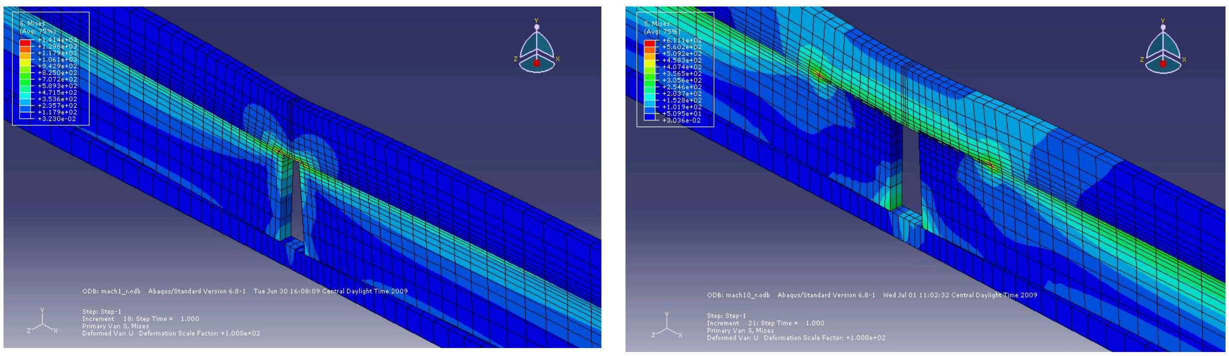


Figure 8. Simulations without (left) and with (right) debonding between PCC and AC

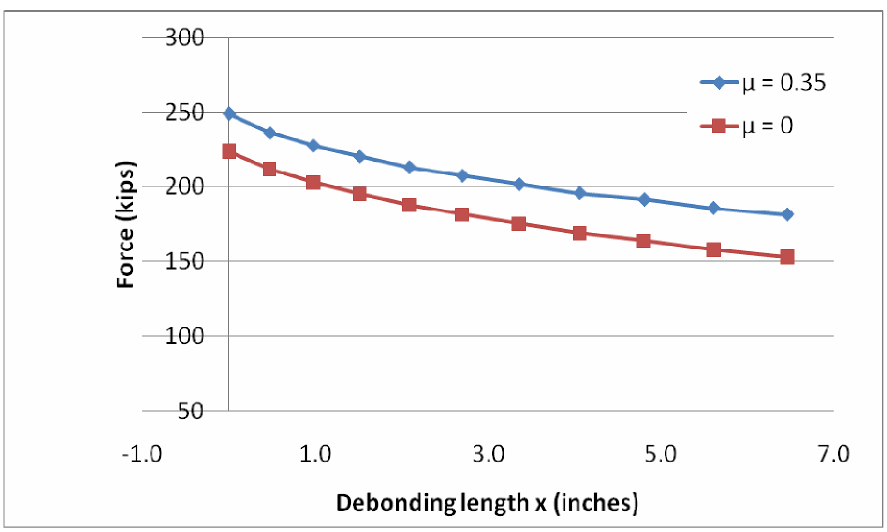


Figure 9. Debonding analysis results

2.3 LINEAR VISCOELASTIC MATERIAL PROPERTIES.

The next step was to include viscoelastic material properties into the ABAQUS model and repeat the analysis presented above.

The material properties are assumed to be linear viscoelastic isotropic with an Initial Young's modulus of E_o = 605,433 psi at 20 ^{o}C and a constant Poisson's ratio v=0.3. The linear viscoelastic behavior is represented by a generalized Maxwell model by assuming the shear relaxation modulus and the bulk relaxation modulus functions in the Prony series from Eq. (1) and (2) respectively.

$$G(t) = G_\infty + \sum_{i=1}^{N} G_i \ e^{\frac{-t}{\tau_i}} \qquad (1)$$

$$K(t) = K_\infty + \sum_{i=1}^{N} K_i \ e^{\frac{-t}{\tau_i}} \qquad (2)$$

Where:

G_∞, K_∞ = Represent the long-term bulk and shear moduli

τ_i = relaxation times

One prony series was used and it assumes that the shear relaxation modulus and the bulk relaxation modulus functions satisfy the linear viscoelastic model. The prony series is listed in Table 1. Also the Williams-Landel-Ferry Equation was used to analyze the model at different temperatures with the following shift factors: C1 = 28.44, C2 = 293.84. The loading time for the simulation was of 1 second. In this simulation, no friction was considered in the model. The results are compared with those from the elastic material model in Figure 10.

Table 1.
Prony Series used in model.

G_i	K_i	T_i
0.3848	0.3848	1.01E-10
0.1955	0.1955	3.26E-05
0.1510	0.1510	1.15E-03
0.1130	0.1130	4.29E-02
0.1016	0.1016	1.65E+00
0.0341	0.0341	4.93E+02

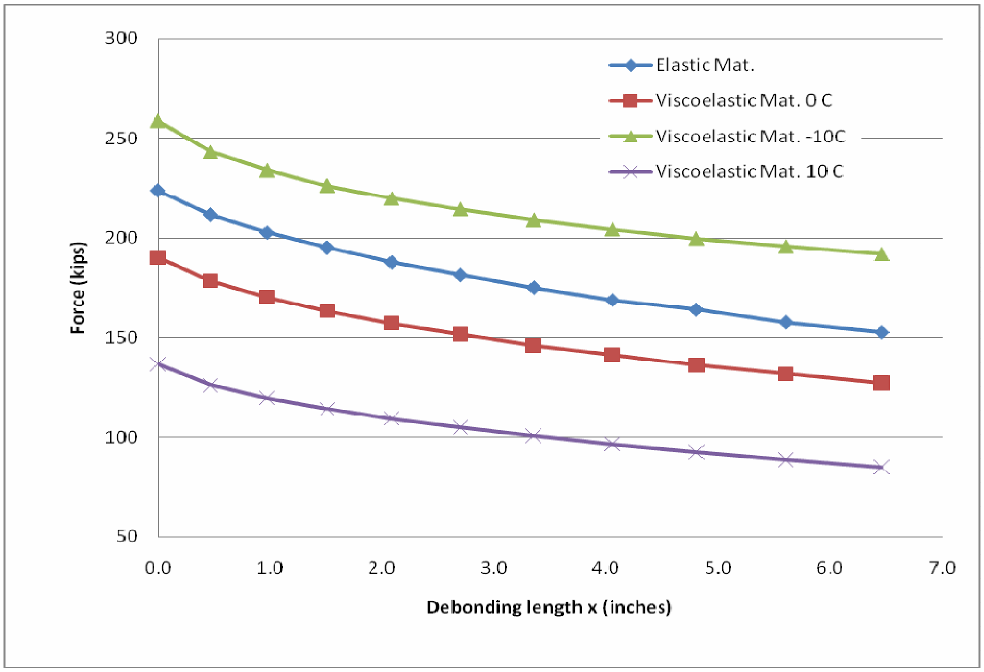


Figure 10. Debonding analysis results with viscoelastic material properties.

3. EVALUATION OF 3-D CRACK BEHAVIOR: PRELIMINARY RESULTS

A GFEM model was used to demonstrate that crack propagation is only driven by the joint opening and therefore we can neglect friction forces when performing crack growth simulations. We performed a linear analysis in which constant frictions forces were applied at the bottom of the model (at concrete layer) as illustrated in Figure 3. A constant joint opening of (0.006 inches) was used with different frictions forces. The stress intensity factors along the crack front were then assessed. Two different cases were studied: μ=0 and μ=1. The first one assumes a frictionless model, and the last one assumes the highest possible friction force. For each case, a slightly different displacement at the edges of the model is imposed. Figures 11 and 12 show details of the computational model.

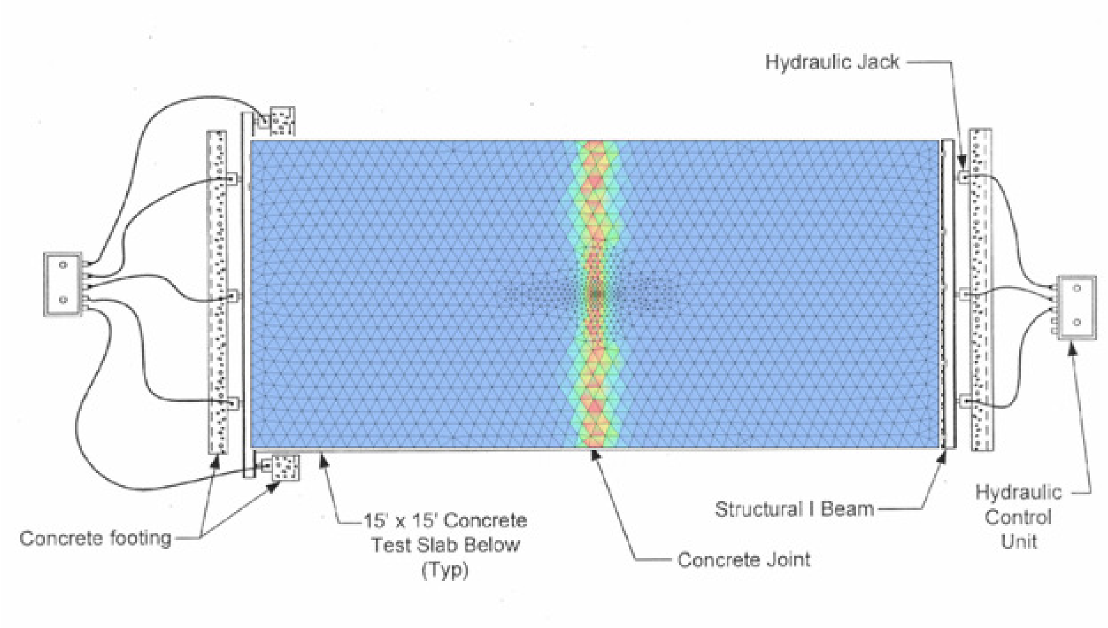


Figure 11. GFEM model to Support of NAPTF Reflective Cracking Test Section Design.

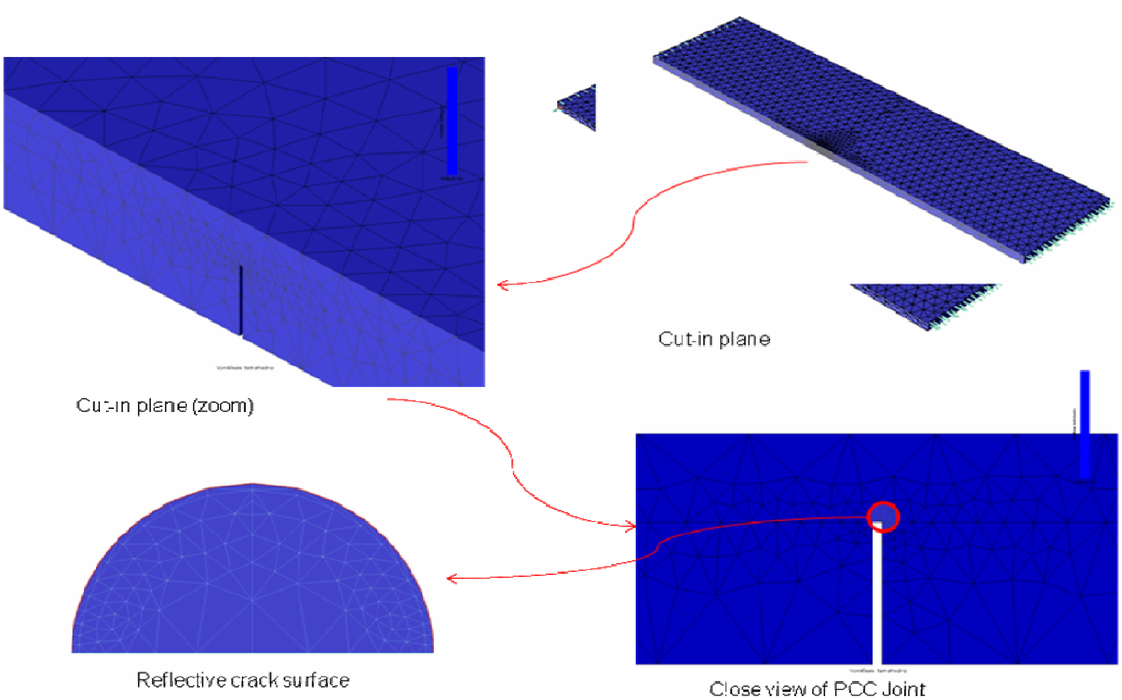
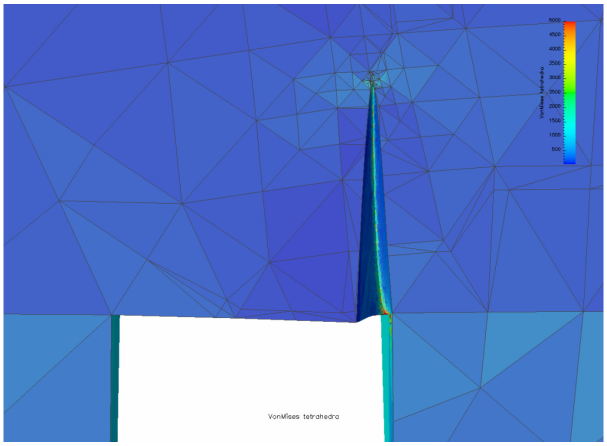


Figure 12. Details of GFEM model of 3D reflective crack.



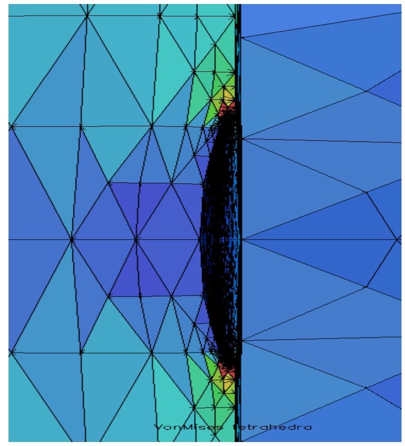


Figure 13. Cut-in plane of crack opening and bottom view of crack opening.

The reflective crack used for this analysis has the form of a half penny shaped crack of radius equal to 1 inch, inserted at the center of the model just above the PCC joint (see Figure 12). Using the capabilities of the GFEM software automatic mesh refinement was performed along the crack front until the element edge size (L) and crack size (a) ratio was L/a = 0.0039. Additionally, we carried out automatic enrichment of all nodes and step function enrichment for the elements cut by the crack surface to account for the discontinuity.

The analysis was performed for the frictionless model and the highest possible friction force at the bottom of the model. Stress intensity factors along the crack front are shown in Figure 14.

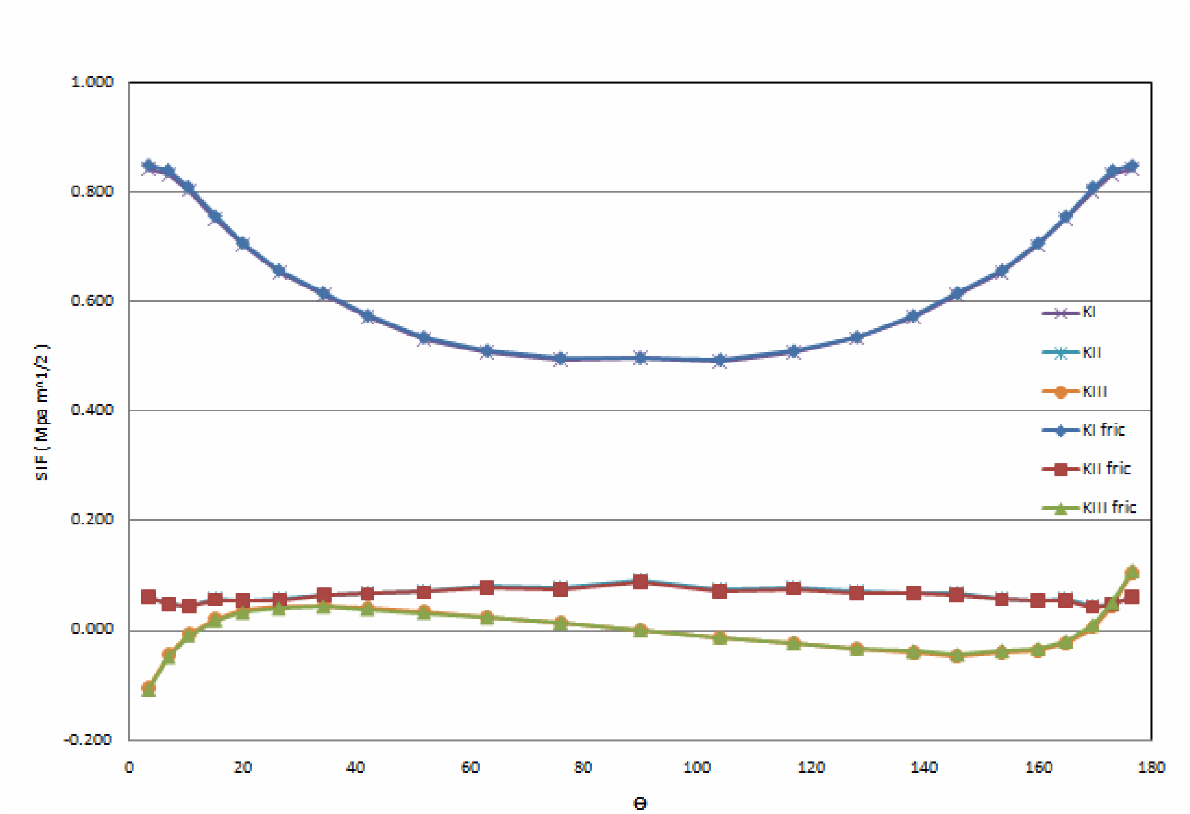


Figure 14. Stress Intensity factors along crack front.

Where:

θ is the position along the crack front in degrees.

KI, KII and KIII are the stress intensity factors for the frictionless model.

KI fric, KII fric and KIII fric are the stress intensity factors for the model with friction.

4. CONCLUTIONS

In summary, an actuator capacity in the range of 200-300 kips may be required for 15’ x 15’ slabs. The force can be lowered with reduced asphalt thickness, reduced joint opening, reduced slab width, increased testing temperature, reduced load frequency, or increased debonded length.

It was found that the base stiffness is not a major factor for total load requirements while the effect of the friction between PCC and base is moderate. It is unlikely that required actuator capacity can be reduced to under 100 kips.

Notice that results in Section 3 for both cases of friction μ=0 and μ=1 are the same. We could conclude that crack propagation is driven by the joint opening and friction can be neglected when the goal of the analysis is crack growth.

Since the problem is symmetric and the forces applied to the model were intended to reproduce only opening mode; Figure 14 shows very low stress intensity factors for mode II (shearing) and mode III (tearing) compared to mode I (opening), but all modes are still present.

It has been shown in Garzon [4] that reflective cracks in airfield pavements are subjected to mixed mode behavior with all three modes present and thus, realistic simulations must be performed in three-dimensions. This 3D analysis allowed us to determine if the crack will propagate towards the pavement surface or across the pavement, in a channeling orientation. By observing the stress intensity factors in Figure14, the values for *KI*, opening mode, are higher when the value of θ (position along the crack front) is close to 0 or 180 degrees. This would give higher energy release rate at these locations and therefore the crack would tend to propagate more along the longitudinal direction (Channeling) of the pavement than through the thickness. This information will help inform the Federal Aviation Administration (FAA) as to sensor types and placement for their full scale tests.

The simulation of this class of problems is quite challenging for standard finite element methods, because of the difficulties of creating a 3D mesh with elements that would fit the crack geometry and the amount of computational cost required. The generalized finite element removes some of the barriers faced by the FEM while retaining its attractive features. The simulation of three-dimensional crack growth in airfield pavements is currently the subject of our on-going research.

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