Development of New Methodologies for Mechanistic Design of Asphalt Overlays

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FAA COE Project Review and Project Proposal Meeting

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Outline

- Tasks and Progress
- Selected Research Results
- 2-Minute Primer on GFEM
- Etc.
- Proposed Research Items
Reflective Cracking

- Reflective cracking is very complex airfield distress mechanism; likely a result of combined environmental and gear loading effects.

- Cracks can begin to appear as soon as the first winter after construction.

- Can cause the acceleration of other pavement distresses through water infiltration, stripping in HMA layers, and loss of subgrade support.

- The key challenge is the geometric discontinuity which makes modeling much more complex and tedious.

* Kim and Buttlar (2002)
RC Model Evolution

- Empirical Models
- “Simple” FEM Models – Strength of Materials Approach
- LEFM Approach
- Cohesive Zone Modeling Approach
- Reduced Physics (Surrogate Model)
- New Design Method

More Physics, More Complexity, More Difficult to Implement

Understand Physics of Problem (Distress Mechanism)

Simplify Problem
(from a point of understanding)
Task Progress

- Revised Literature – Complete
- Comprehensive Report on Reflective Cracking Simulation
  - Draft Report is now Complete
- 3D Modeling - Underway
  - GFEM Approach
Literature Overview

- Phenomenon and causes of reflective cracking
- Current FAA design procedures for flexible overlay systems
- Limitations of conventional FE pavement modeling
- Current experimental research on RC
- Current numerical simulations on reflective cracking
  - Including University of Nottingham (UK), TU Delft (Netherlands), University of California-Davis, Texas A&M (Texas Transpiration Institute), University of Illinois at Urbana-Champaign, among others
- Generalized FE Modeling
Recent Fracture Modeling Approaches

**J-Contour Approach (LEFM) – Chapter 4**
- Can be used to study the mixed-mode loading condition (combined opening and shearing).
- Provides reliable, numerical estimates of stress concentration at the crack tip.
- **Can not** be used directly with viscoelastic material.
- **Does not** directly predict crack propagation.

→ *Simplified approach requiring less computational effort.*

**Cohesive Zone Model Approach – Chapter 5**
- Can study mode-I and mixed-mode loading conditions.
- Can model crack nucleation, initiation, and propagation.
- Compatible with elastic and viscoelastic bulk material behavior.
- Can be used in conjunction with realistic thermal gradients.

→ *More realistic approach but needs more computational effort.*
Description of FE Fracture Model

Both Gears Loading

Center Position = 236 in

Undeformed

PCC-1 PCC-2

PCC-3

PCC-4

PCC-5

PCC-6

Deformed

Joint-1

Joint-2 (crack)

Joint-3

Joint-4

Joint-5

AC Overlay

PCC

Subbase

Crack Tip
Key LEFM Findings

- Two Slabs is not Enough
  - Five Slab model works well
- Thermal and Mechanical Loads Play Significant Role
- Complex Cracking Mechanisms can Occur
  - Such as Counterflexure-driven RC
Cohesive Zone Fracture Model

(a) Fracturing in Asphalt Concrete
(b) Cohesive Fracture Concept at a Crack Tip
(c) Bilinear Cohesive Fracture Model

\[ \Phi = \int_{0}^{\delta_{sep}} \sigma(\delta) d\delta \]
Schematic of DC(T) Fracture Test

Crack Mouth Opening Displacement (CMOD) Gage

Used to Obtain Fracture Energy, and can be used to Estimate Material Tensile Strength
Key CZM Findings

- Comprehensive 2D modeling of airfield reflective cracking is possible
  - Viscoelastic bulk elements
  - Softening type fracture model
  - Compatible with AASHTO T332 and ASTM D7313-06 (creep compliance, fracture energy)
  - Five slab model
  - Thermal and B77 Loading

- Thermally-induced cracking (top-down and bottom-up) is very realistic
  - Comprehensive results presented in report
  - Particularly relevant to GAA and unloaded airfield locations

- Some limitations encountered for realistic, load-associated crack propagation simulations (need 3D, but how to discretize mesh)
- Led to recommendation of GFEM for large 3D simulations
Generalized Finite Element Method

- Basic idea
  \[
  \text{GFEM} = \text{Galerkin Method (like in the classical FEM)} + \text{GFEM Shape Functions}
  \]

- GFEM can be interpreted as a FEM in which shape functions are built as
  \[
  \phi_i^\alpha = \varphi_\alpha L_{i\alpha}, \quad i \in I(\alpha)
  \]

- Allows construction of shape functions which represent well the physics of the problem
- Enables fully automated modeling of 3-D cracks
- Can be combined with standard FEM

[Oden, Duarte & Zienkiewicz, 1998]
Modeling 3-D Fractures with GFEM

- **Standard FEM**
  - Faces of elements must fit crack surface
  - Double nodes to represent discontinuity

- **Generalized FEM**
  - Enrichment functions represent discontinuity
  - Cracks can cut elements

- Construction of 3-D models can be quite labor intensive

- Construction of 3-D models can be fully automated/hidden from user
Automated analysis of 3-D cracks

- Surface crack in a slab

- Simply insert crack geometry on an existing (possibly coarse) FEM mesh

- Adaptive GFEM *automatically* refines and enriches model crack
Automated analysis of 3-D cracks

- Automated mesh refinement around crack front
  - $h$-refinement applied to elements intersecting crack front
Fully Automated 3-D Crack Propagation

- Automated mesh refinement and unrefinement for crack propagation

- Automated 3-D crack propagation
Fully Automated 3D Crack Propagation

- Boundary conditions and initial crack surface

3D mesh courtesy of ABAQUS, Inc.

- Off front view

- Perspective view

- Method is robust and can handle complex 3-D problems
RC Research Direction
Current and Proposed

- **Current:**
  - GFEM – Large-scale 3D modeling
    - Start With Realistic 3D, Multi-slab Domain, Simplified Material Properties
  - Enhanced TCMODEL
    - Rapid Prediction of Non-Load Associated Thermal and Reflective Cracking

- **Proposed:**
  - Continued efforts to adapt GFEM to pavement overlay modeling
    - Viscoelastic Bulk
    - Improved Fracture Model
  - Study Effects of PG Grades on Crack Stability
Council of University Transportation Centers Awards Banquet

- Congressman James Oberstar (Chairman of the Committee on Transportation and Infrastructure)

- Jim White
Thank You!!