Computational Multi-Scaling for Use as a Flexible Pavement Design Tool

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Abstract:

Pavement design is a formidable challenge due to significant variations in roadway design constraints, locally available materials, environmental conditions, and cost considerations. For these reasons, the design of roadways has until recently been performed empirically by relying on performance statistics from previously constructed roadways. However, with the rise of the high-speed computer, semi-empirical methods have recently been developed, such as AASHTO's Mechanistic-Empirical Pavement Design Guide (MEPDG). While MEPDG has made an attempt to implement sound scientific principles to the roadway design methodology, many effects have not yet been implemented within this new strategic tool.

In this poster, a computational model is described in detail and various pavement design examples are provided. It is shown herein via several example simulations that this new mechanistic-based model is capable of improving the accuracy of the pavement design process for both urban and rural roadways, using both conventional and recycled materials. These example simulations include predictions of both evolutionary pavement cracking and permanent damage as functions of cyclic loading. The results quantitatively demonstrate variations in pavement performance resulting from varying volume fractions of additives, fines, and aggregate, as well as asphalt layer thickness and base layer consolidation, all of which are critical to the production of accurate cost models.

Background:

Theoretical Model Development:

- Pavements often undergo cracking on multiple length scales.
- Cracks can number into the hundreds per cubic meter of the roadway.
- Length scales associated with roadway cracking and the global roadway length scale are widely separated. An example of this is found in Fig. 2
- A two-way coupled multi-scaling approach is the ideal solution, as shown in Fig. 1.

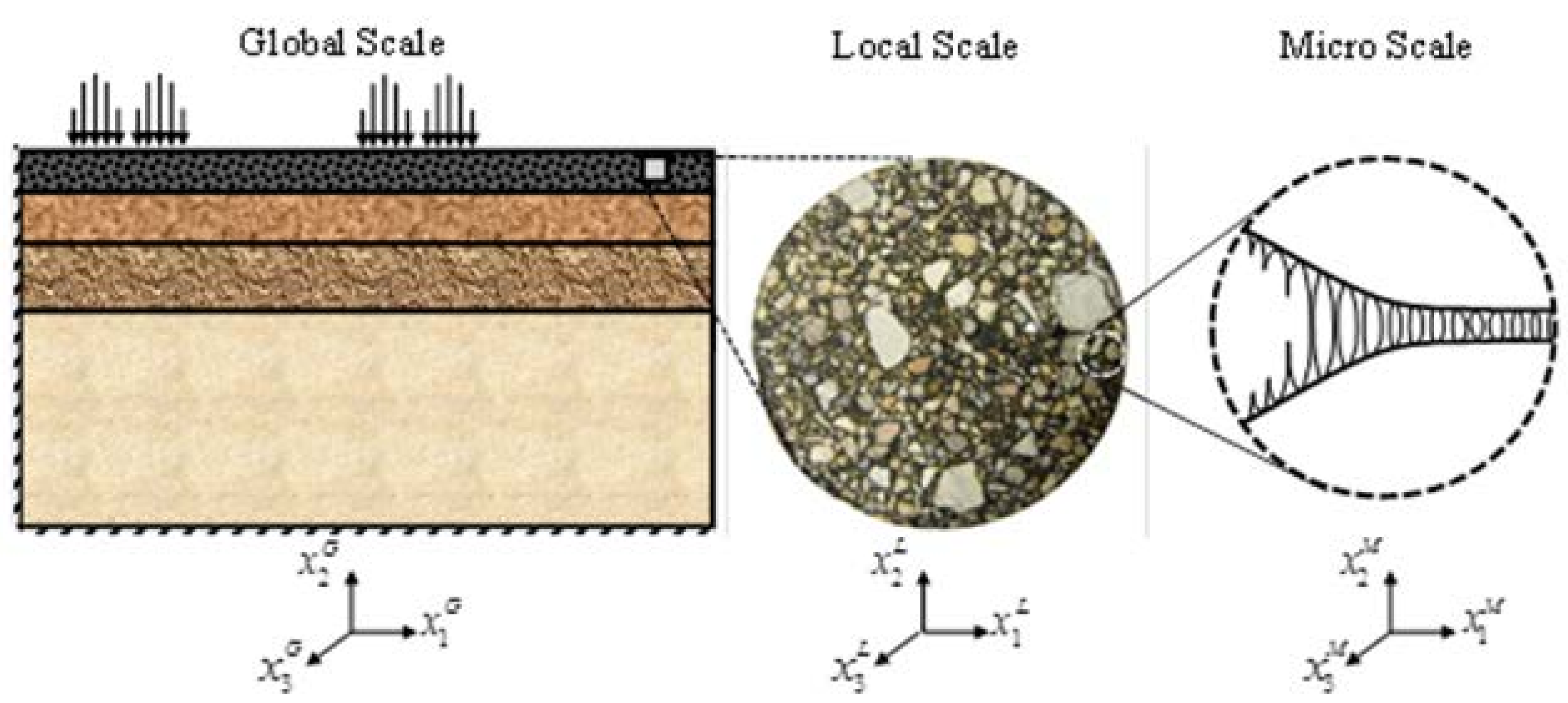

Fig. 1 Multiscale Concept

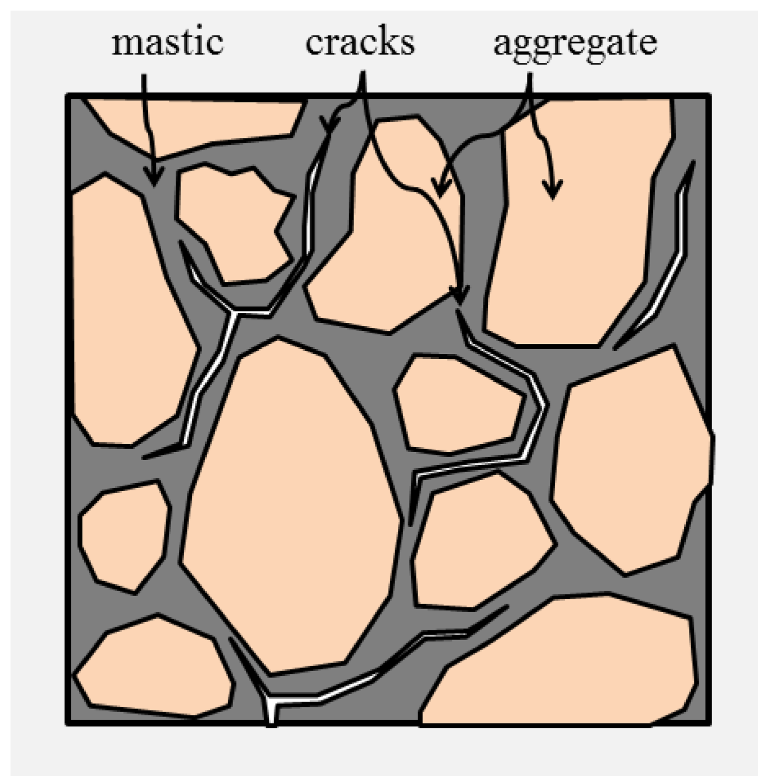

Fig. 2 Generic RVE with Cracks

The Micro-Scale Model:

- The microscale is modeled as a cohesive zone, as shown in Fig. 3.
- The cohesive zone is conceived as an evolving fibrillated region on the micro-scale ahead of a crack tip on the local scale.
- Cohesive zone material constants are obtained from experiments.
- Cohesive zone model is utilized to model the evolution of cracks.

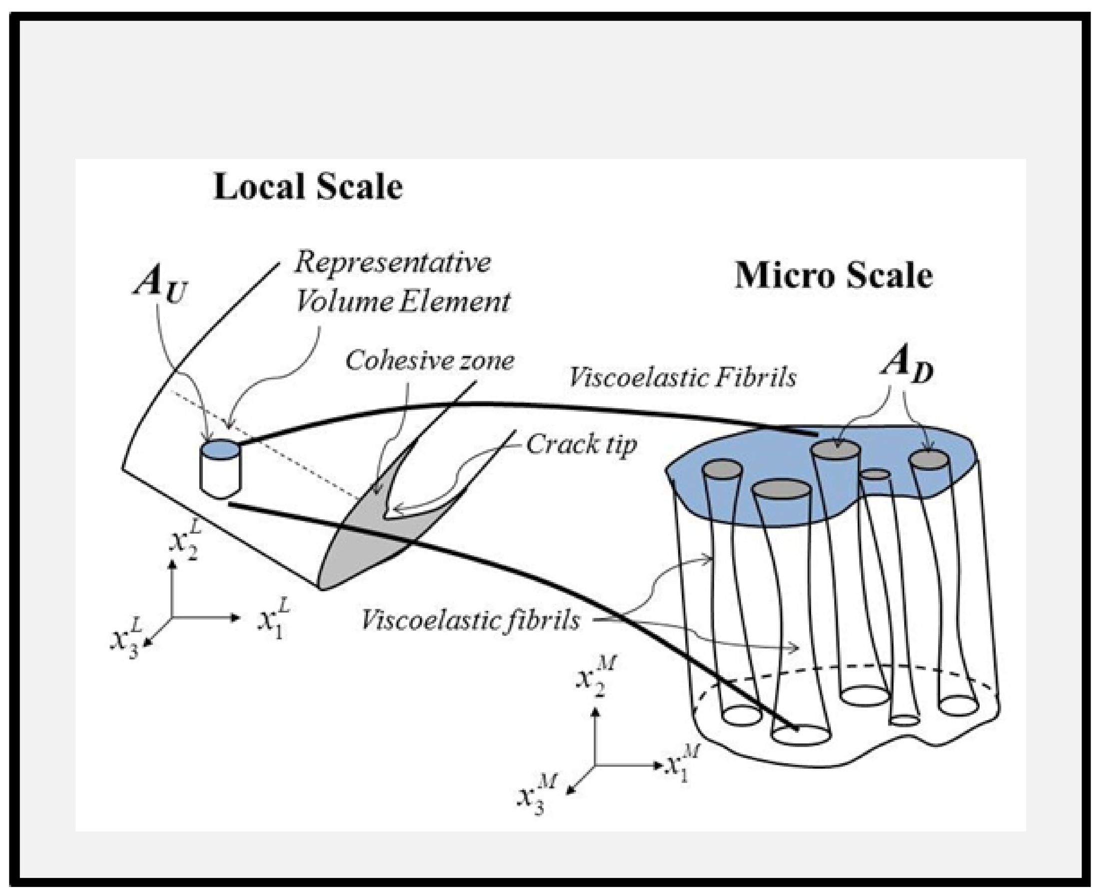

Fig. 3 Micro Scale model

The Local-Scale Model:

- The local scale is represented by a Representative Volume Element (RVE).
- The local scale analyses are performed recursively wherever micro-cracking is anticipated in the asphaltic concrete.
- There are cracks within the RVE, and each crack at the local scale analysis affects the global scale analysis.
- Both material viscoelasticity and the evolution of cracking are at the local scale. See Fig. 4.

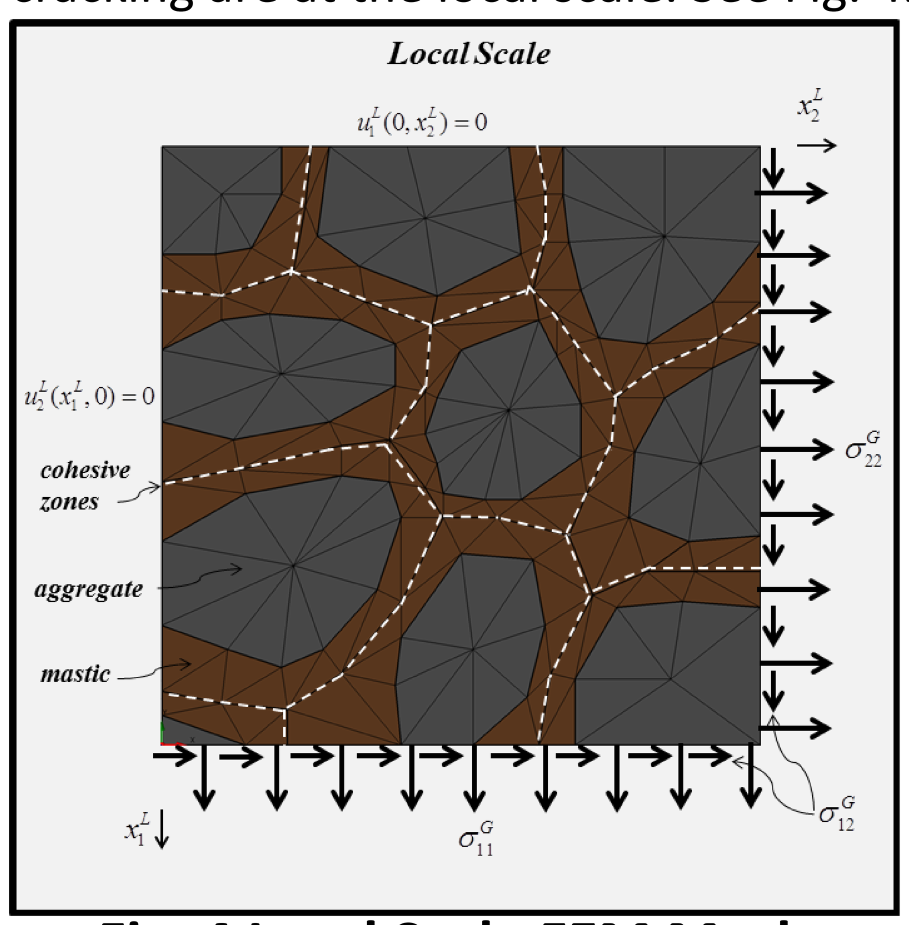

Fig. 4 Local Scale FEM Mesh

The Global-Scale Model:

- The global scale is represented by the entire roadway, as depicted in Fig. 5.
- The local solution is homogenized to obtain averaged material properties at the global length scale.
- The global scale modulus is a function of time and space, as it is based on both the local material viscoelasticity and the amount of damage accumulated from each of the local scale analyses.
- Base and subgrade layers are modeled as elastoplastic.

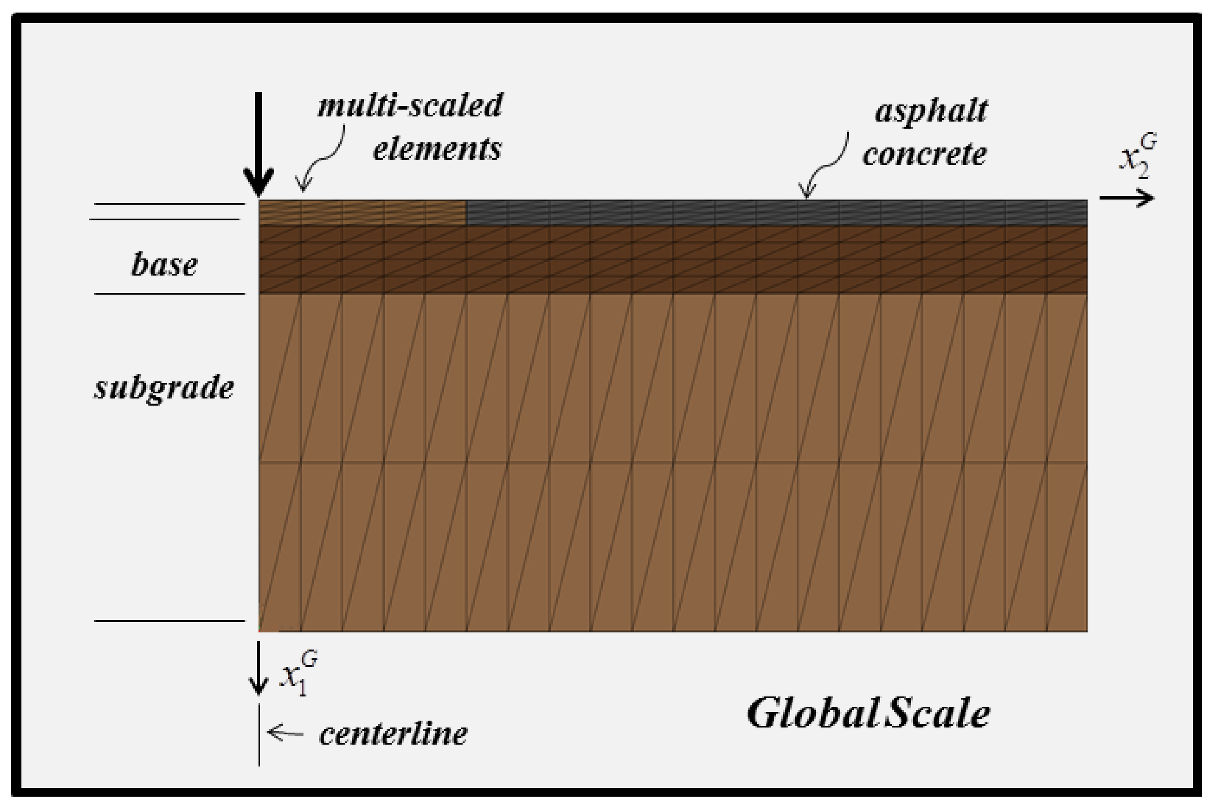

Fig. 5 Pavement Global FEM Mesh

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Pavement Design Using Multiscale Modeling

- The multi-scaling approach described herein is computationally intensive, especially when modeling the response of roadways to cyclic loading conditions.
- Significant insight can be gained for the purpose of designing roadways by modifying the design variables one by one and predicting the resulting roadway response for the first few loading cycles.

1. Effect of Aggregate Volume Fraction

- This example shows the evolution of cracking in the asphalt concrete layer for three volume fractions: 49%, 54%, and 59%.
- Fig. 6 depicts the evolution of cracking in the four local meshes closest to the load application point, as a function of the applied load. As can be seen from the figure, crack growth at the local scale decreases with distance from the point of load application.
- Fig. 7 shows the predicted specific crack density versus applied force for two RVE's, where specific crack density is the predicted total crack length within the RVE at any point in time divided by the maximum cracking allowed within the RVE mesh.
- This example demonstrates the ability of the two-way coupled multi-scaling approach to model damage as a function of spatial and temporal coordinates.

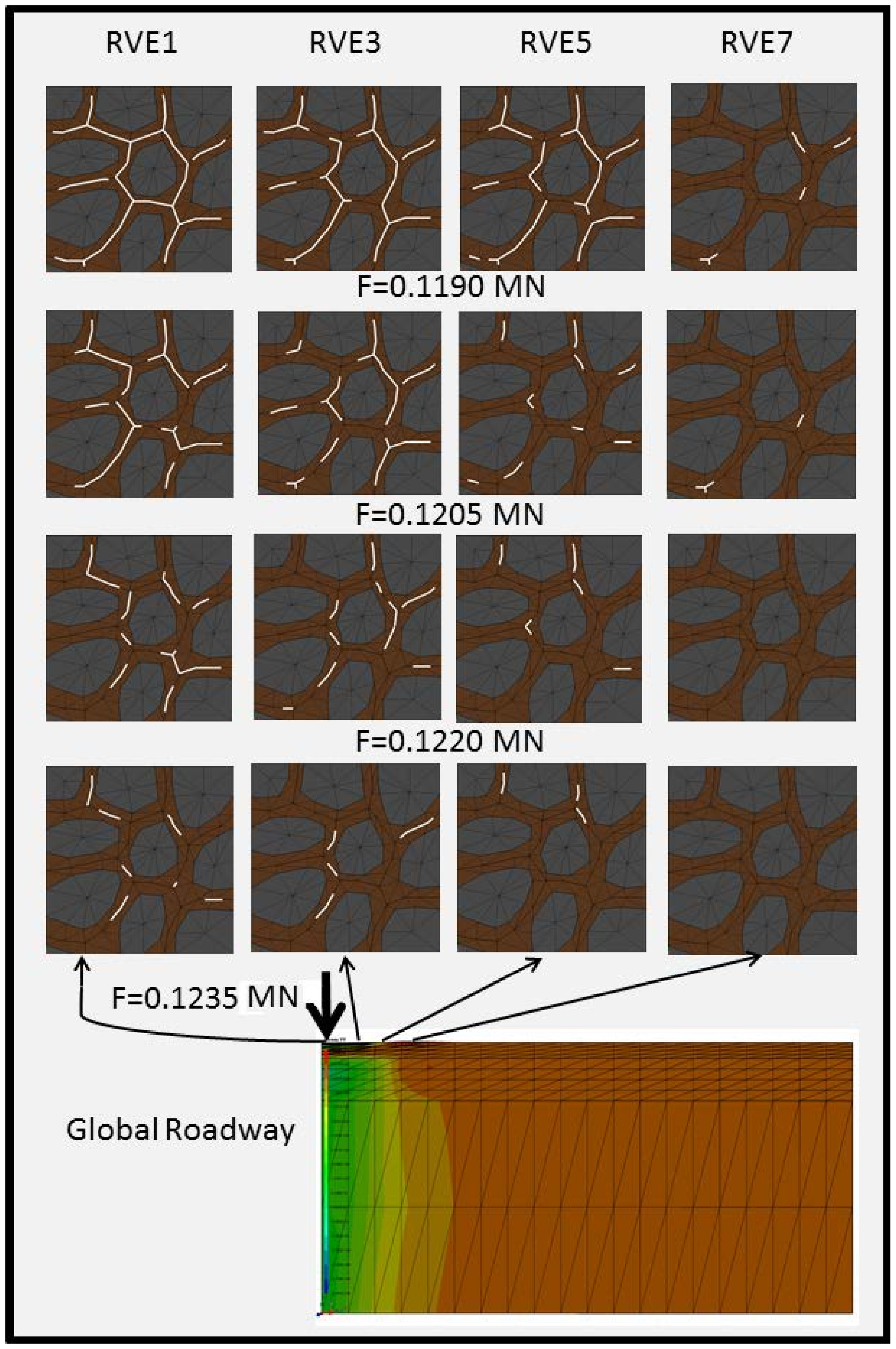

Fig. 6 Predicted Crack Growth in Selected RVE's (54% volume fraction)

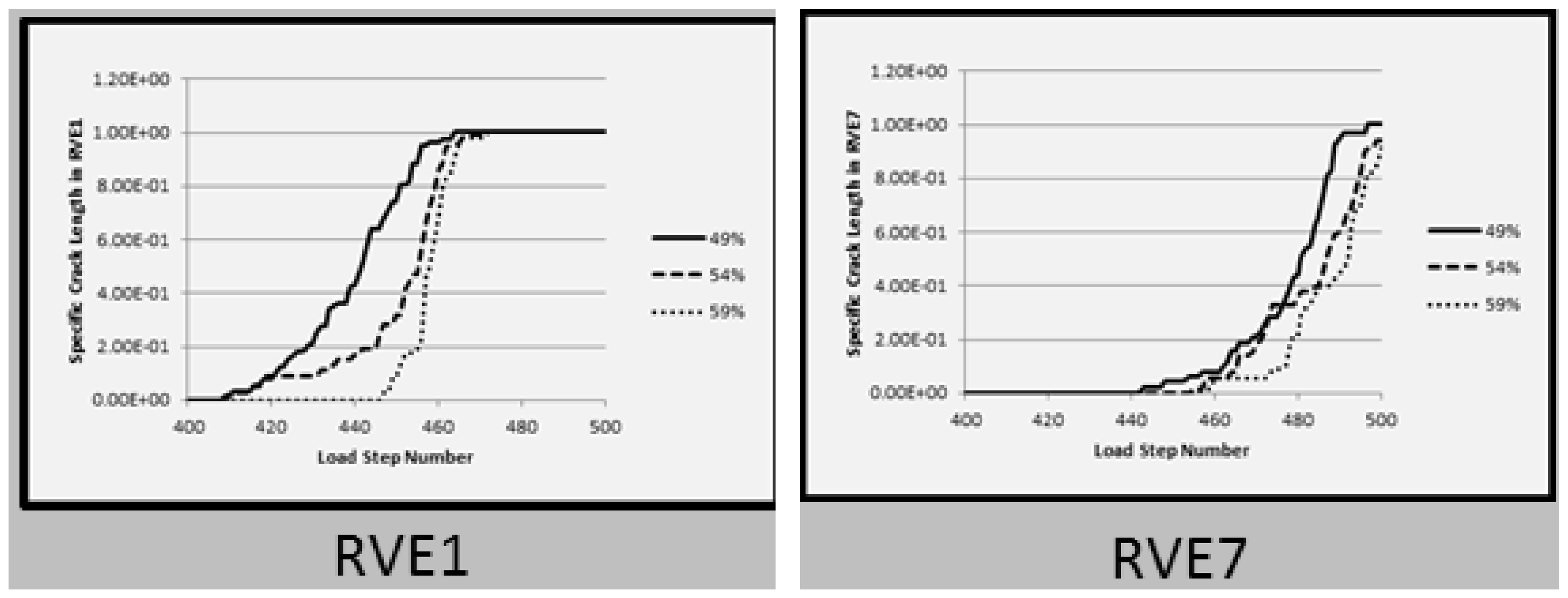

Fig. 7 Crack Length for Three Volume Fractions – Near and Away from the Load

2. Effect of Base Plasticity:

- Consider two cases, one wherein the base layer initial yield point is 6.0 MPA, and a second wherein the base layer is further consolidated so as to increase the initial yield point by 10%.
- Fig. 8 shows the maximum residual deformation (directly beneath the applied load).
- As can be seen in the figure, the predicted residual deformation for the weaker base material is predicted to be larger than the stronger base material for the first four cycles of loading, but on the fifth loading cycle the two (somewhat counterintuitively) reverse, with the predicted residual deformation becoming larger for the case wherein the base layer is further consolidated.
- As shown in Fig. 9, in this case the multi-scaling algorithm predicts that cracking in RVE3 will occur in the asphalt concrete slightly sooner if the base layer is further consolidated, thereby enhancing residual deformations in the roadway.

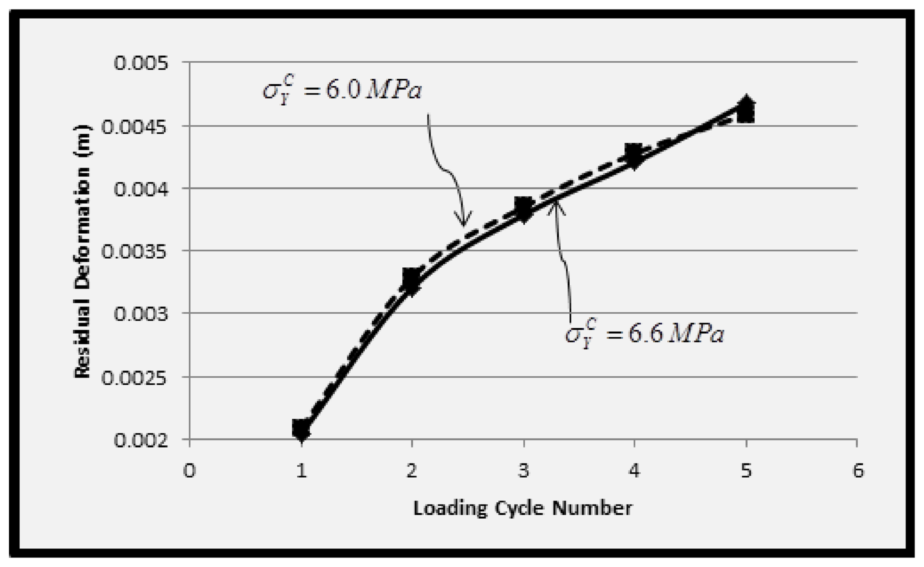

Fig. 8 Predicted Maximum Residual Deformation

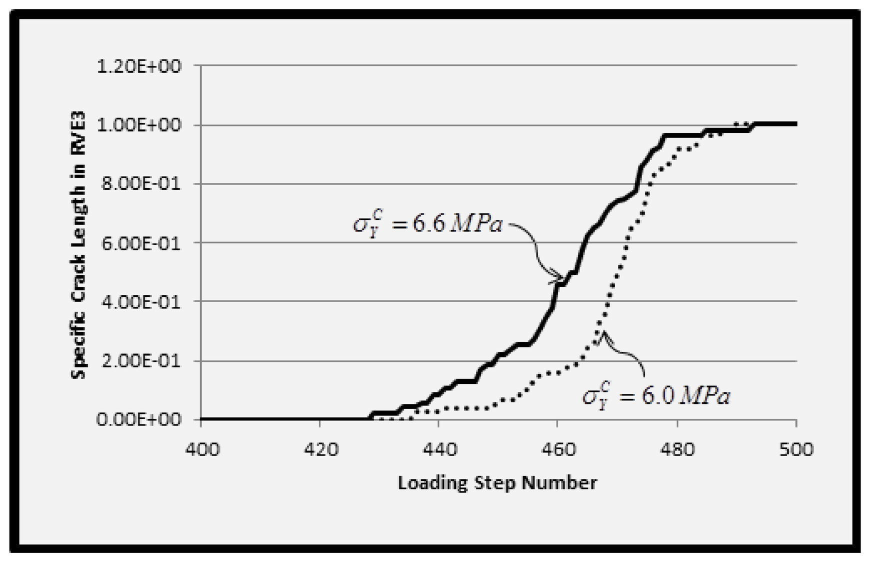

Fig. 9 Predicted Crack Length for Two Different Base Yield Points

3. Effect of Additives:

- Consider the case wherein the designer has access to an asphalt additive (e.g., lime) that produces a 10% increase in the cohesive zone properties.
- Predicted maximum residual deformation versus cycle number are shown for two cases in Fig. 8.
- There is a clear trend toward improved performance with the additive included in the asphalt concrete.

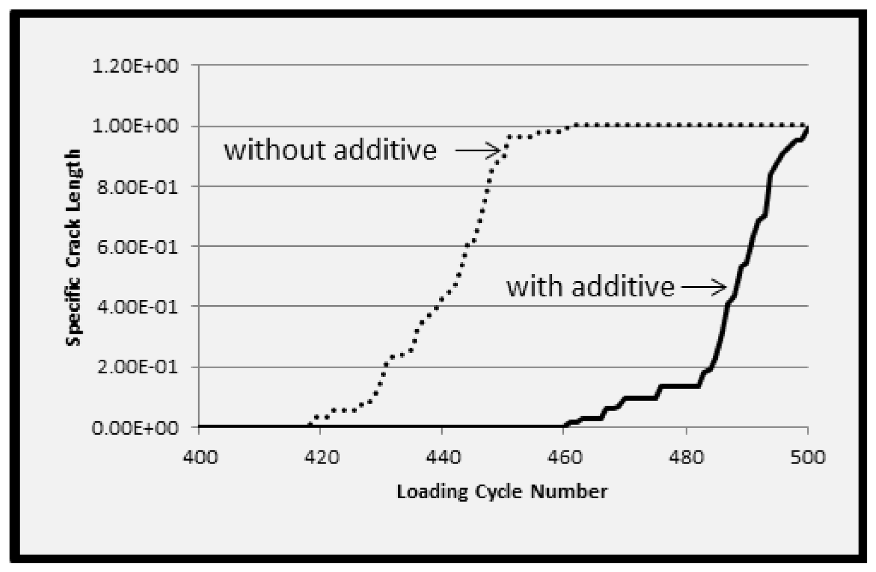

Fig. 10 Predicted Cracking for three HMAC thicknesses

Conclusions:

- A two-way coupled multi-scale algorithm has been introduced as a tool for designing pavement based on predicted roadway performance.
- The multi-scale approach has been shown to be sufficiently robust to account for the effects of both local and global design variables on roadway performance.
- This can be done without recourse to recursive and costly material property evaluation experiments.
- This approach can predict permanent deformations, and it also has the capability to predict the spatial evolution of cracking within the roadway.

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