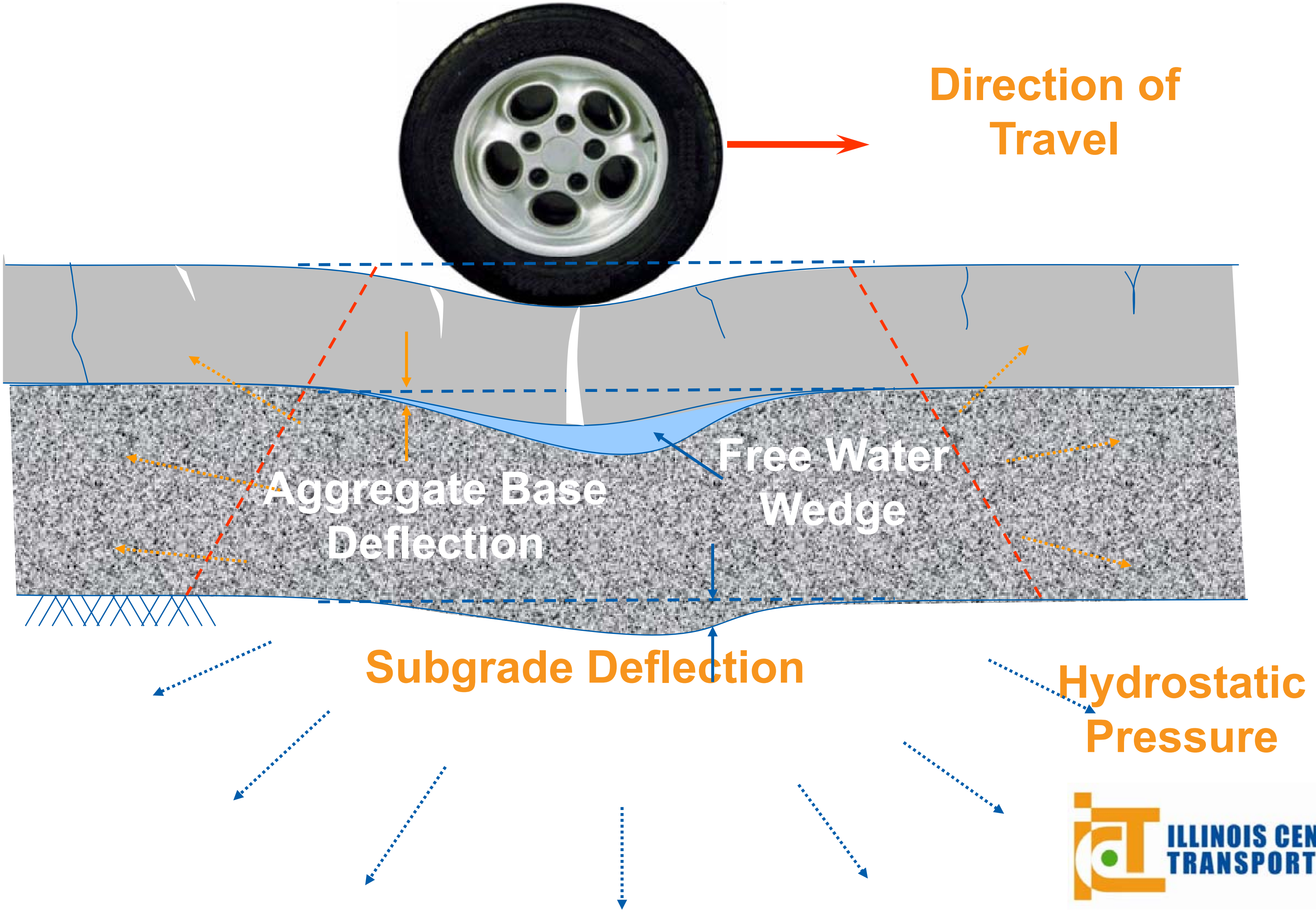
Towards Long Lasting Pavement Design: Pavement Response to Actual Loading

Imad L. Al-Qadi

University of Illinois at Urbana-Champaign

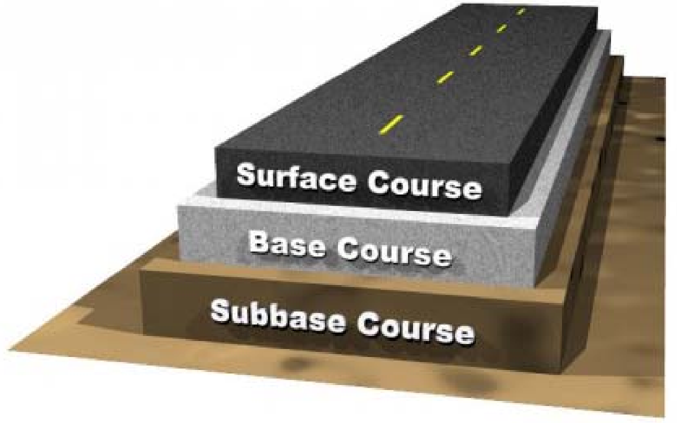
Flexible Pavement



ILLINOIS CENTER FOR TRANSPORTATION

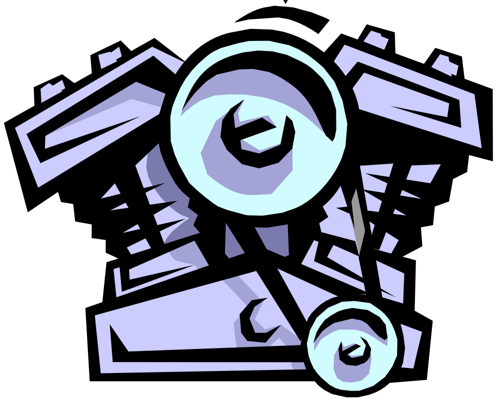
Factors Affecting Flexible Pavement Performance

- Hot-Mix Asphalt (HMA) characteristics
  - Aggregate size, shape, texture and gradation
  - Binder stiffness and content
  - Air void content
- Loading conditions
  - Vehicle speed
  - Tire type, load and pressure
  - Traffic wandering
- Pavement structural design
  - Layer thickness and stiffness
  - Interface condition
  - Base and subgrade support
- Environmental factors
  - Temperature
  - Moisture

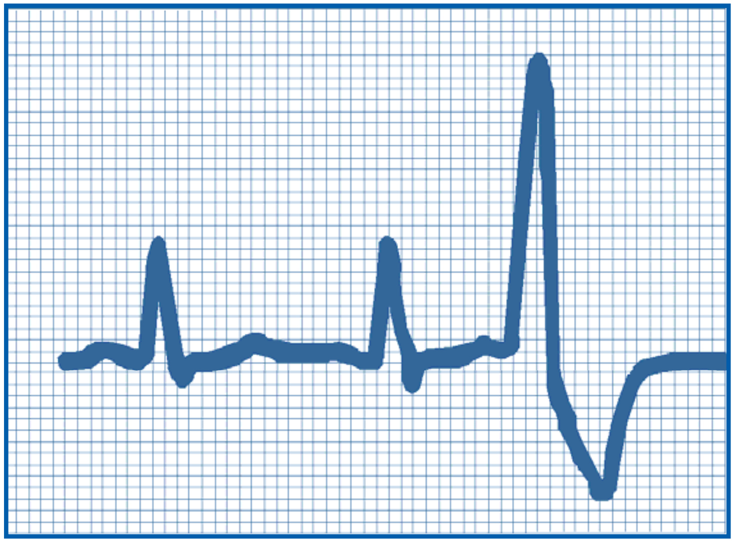


Current MEPDG Analysis Approach

- **Poisson's Ratio**
- **Complex Modulus, E***
- **IDT Strength**
- **Thermal Contraction**
- **Creep Properties**



Analysis Engine
(LEA/ FE)



Pavement Response

After MEPDG

ILLINOIS CENTER FOR TRANSPORTATION

Shortcomings of Current Approach

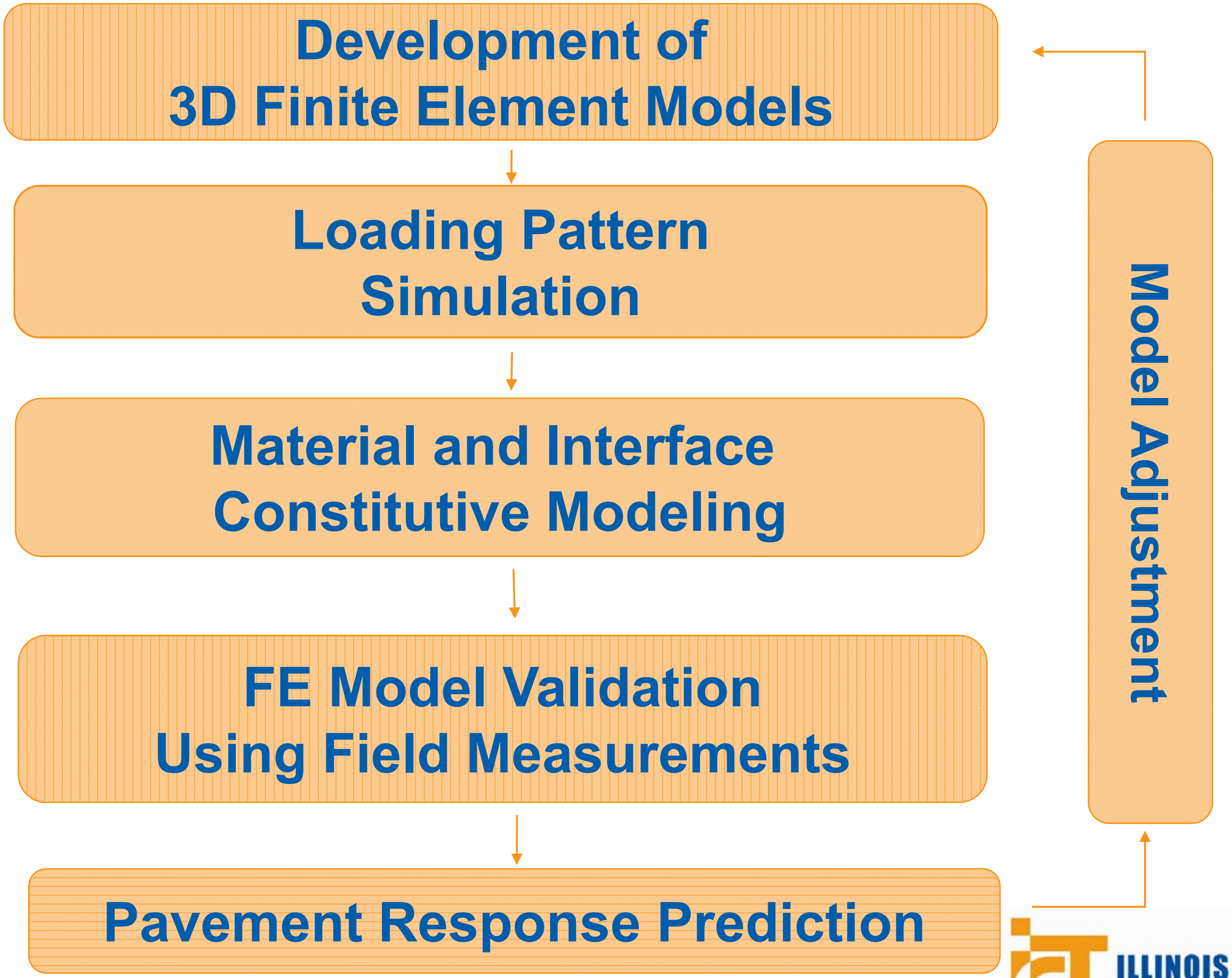
- **Vehicular loading:**
  - Static and stationary circular loading
  - Uniform vertical contact stresses
- **Hot-Mix Asphalt Properties:**
  - Elastic properties corresponding to single temperature and loading rate
- **Damage transfer functions:**
  - Rutting: compressive strain only
  - Fatigue: tensile strain only
  - Neglecting effect of shear strain

ILLINOIS CENTER FOR
TRANSPORTATION

Solutions

- **Understand real vehicle loading**
  - Moving load, surface contact stresses, dynamic effect …
- **Utilize advanced finite element approaches**
  - Appropriate material characterization and interface bonding condition
- **Outcome**
  - Critical pavement responses for pavement damage prediction

Mechanistic Framework



Development of 3D Finite Element Models

Loading Pattern Simulation

Material and Interface Constitutive Modeling

FE Model Validation Using Field Measurements

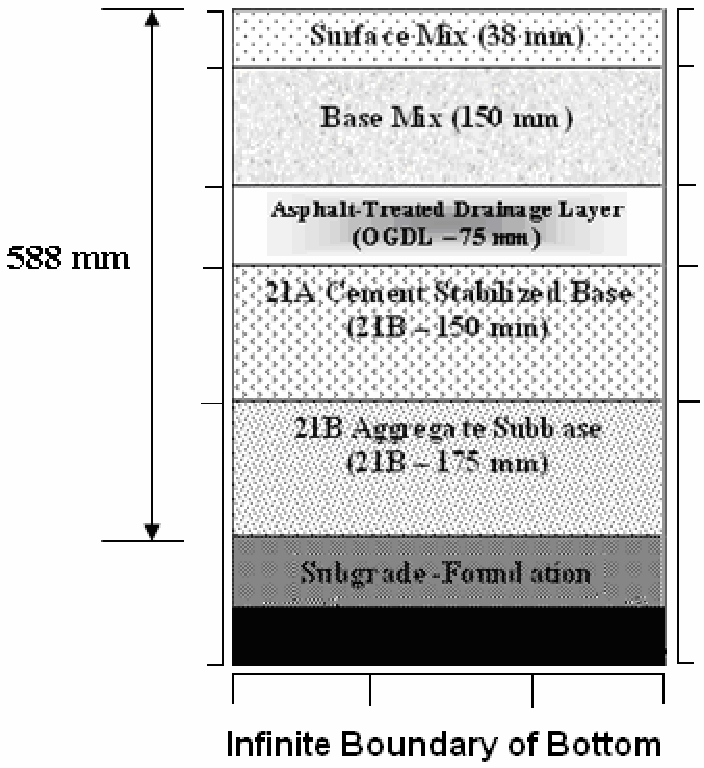
Pavement Response Prediction

Model Adjustment

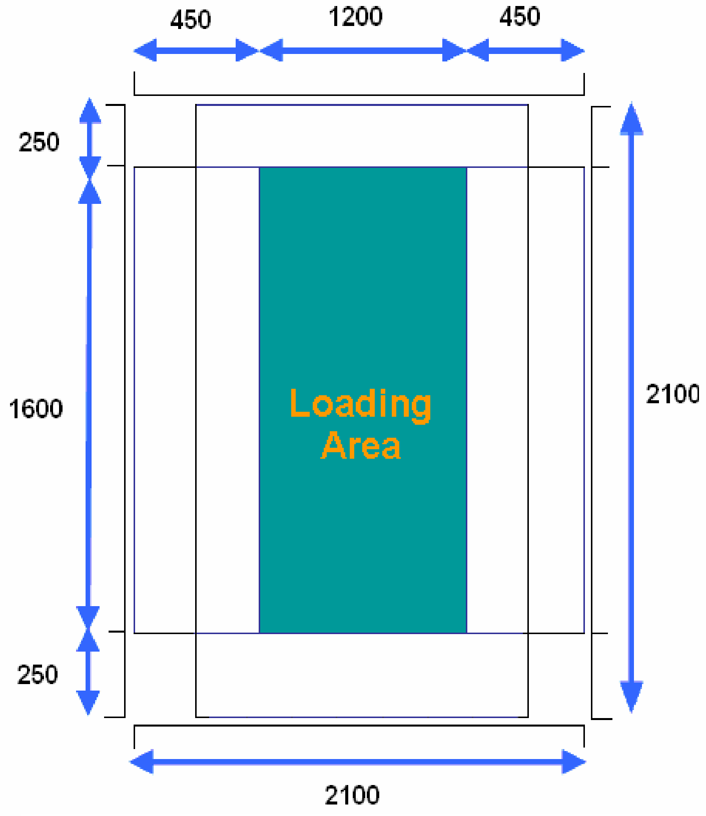
ILLINOIS CENTER FOR TRANSPORTATION

3D FE Pavement Model

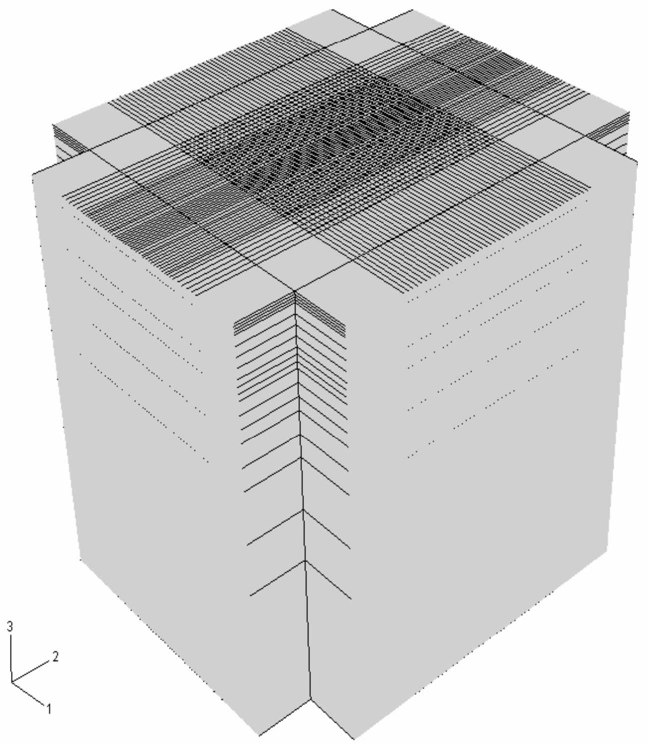
Pavement Design



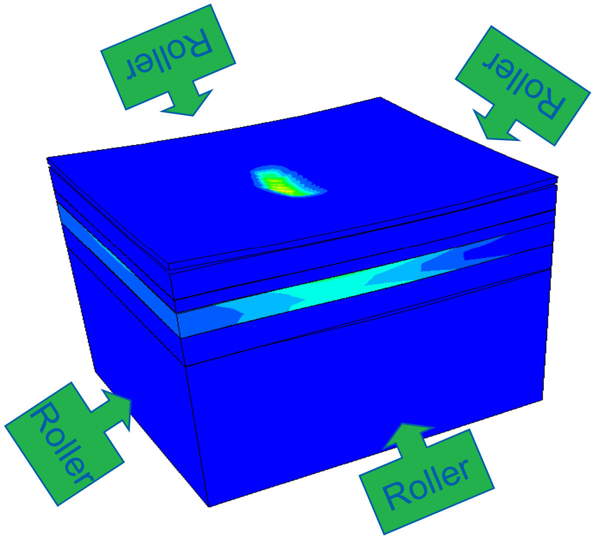
In-Plane Dimension (mm)

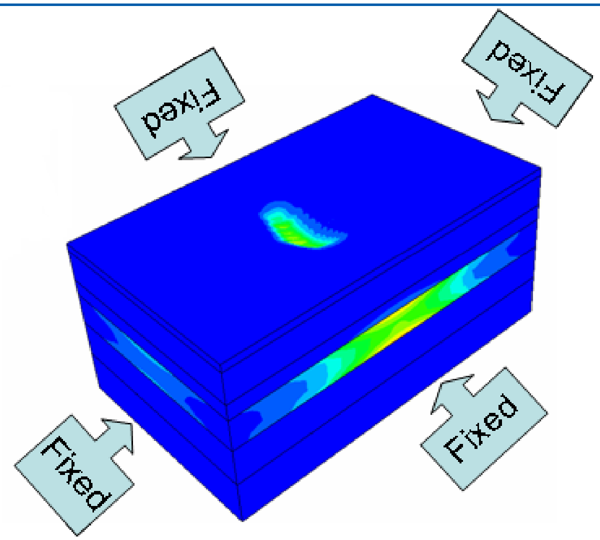


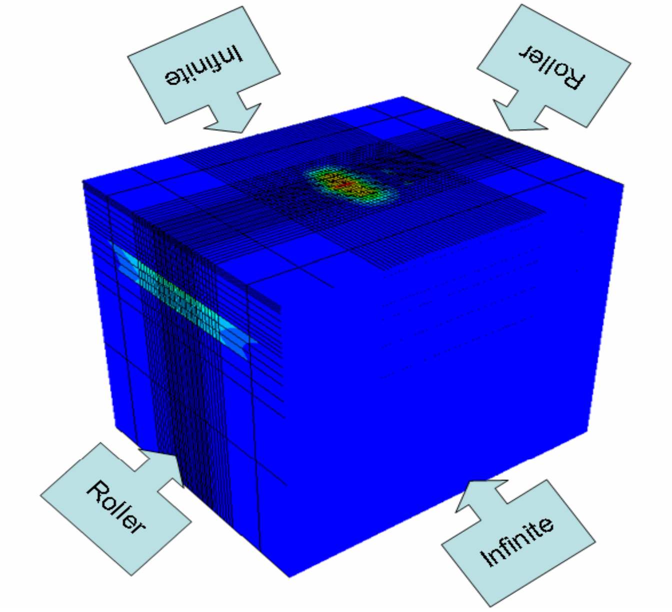
Infinite Domain

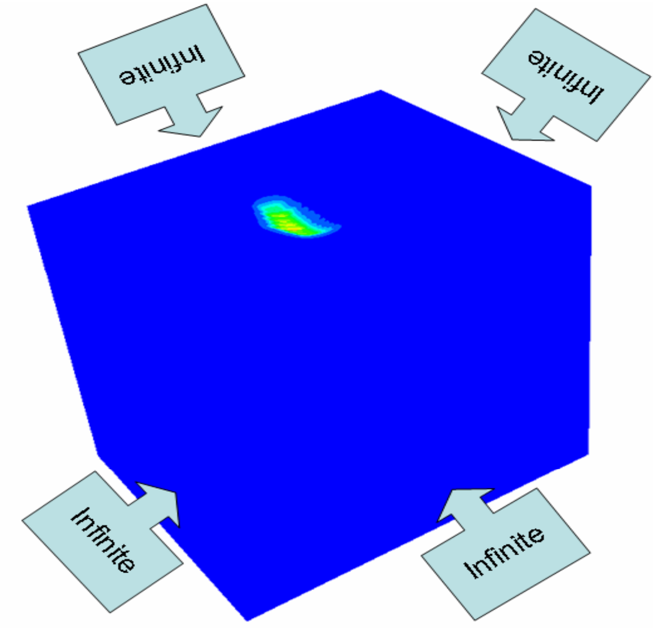


Boundary Condition Effect









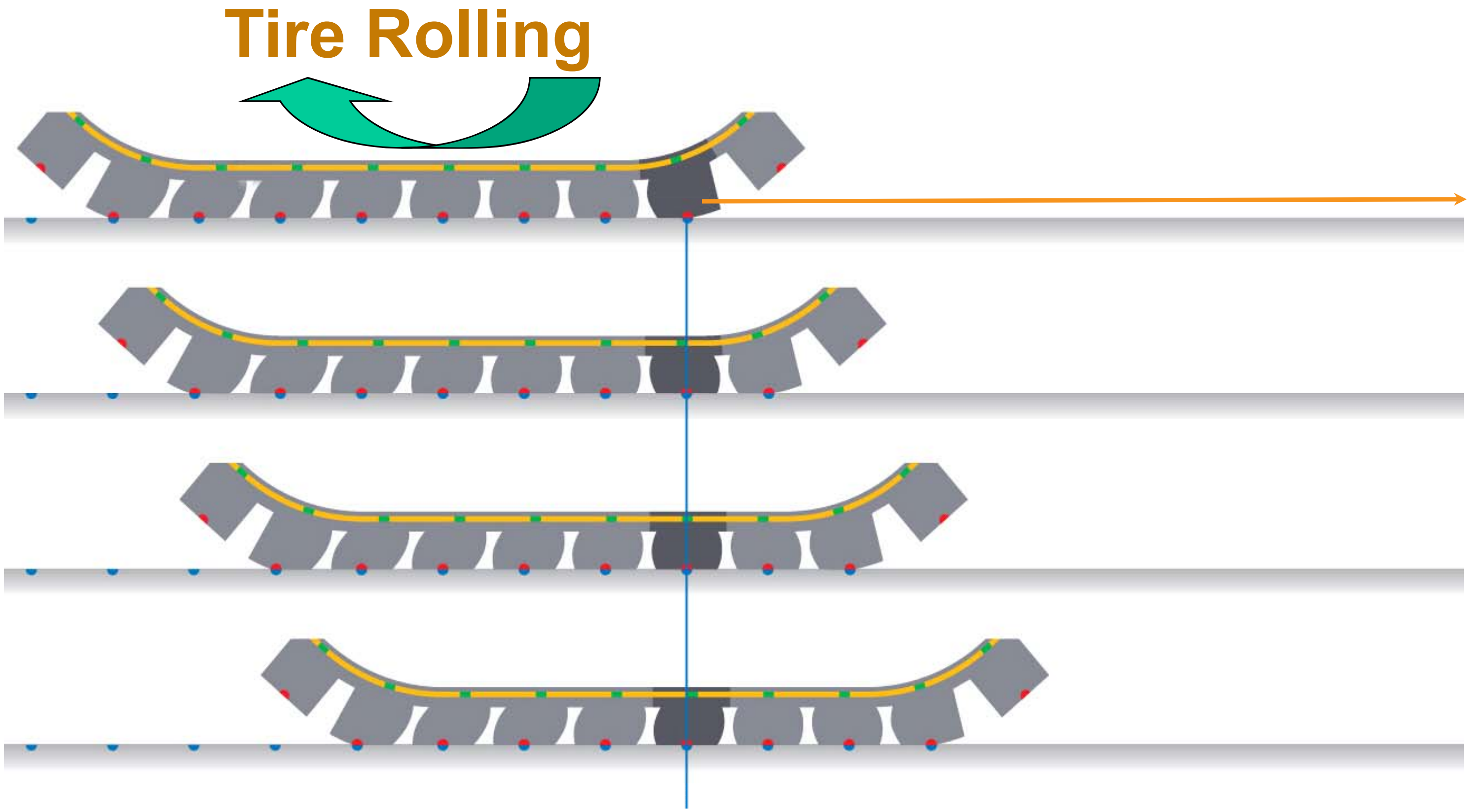
Dynamic Analysis

- **Structure response under dynamic loading depends on the ratio of load frequency to natural frequency of the structure**
  - Flexible pavement natural frequency = 6-14Hz
  - Vehicle loading frequency = 0-10Hz
- **Dynamic analysis considers mass inertia and damping forces effect on pavement responses due to a moving load**
- **Implicit dynamic analysis is selected**

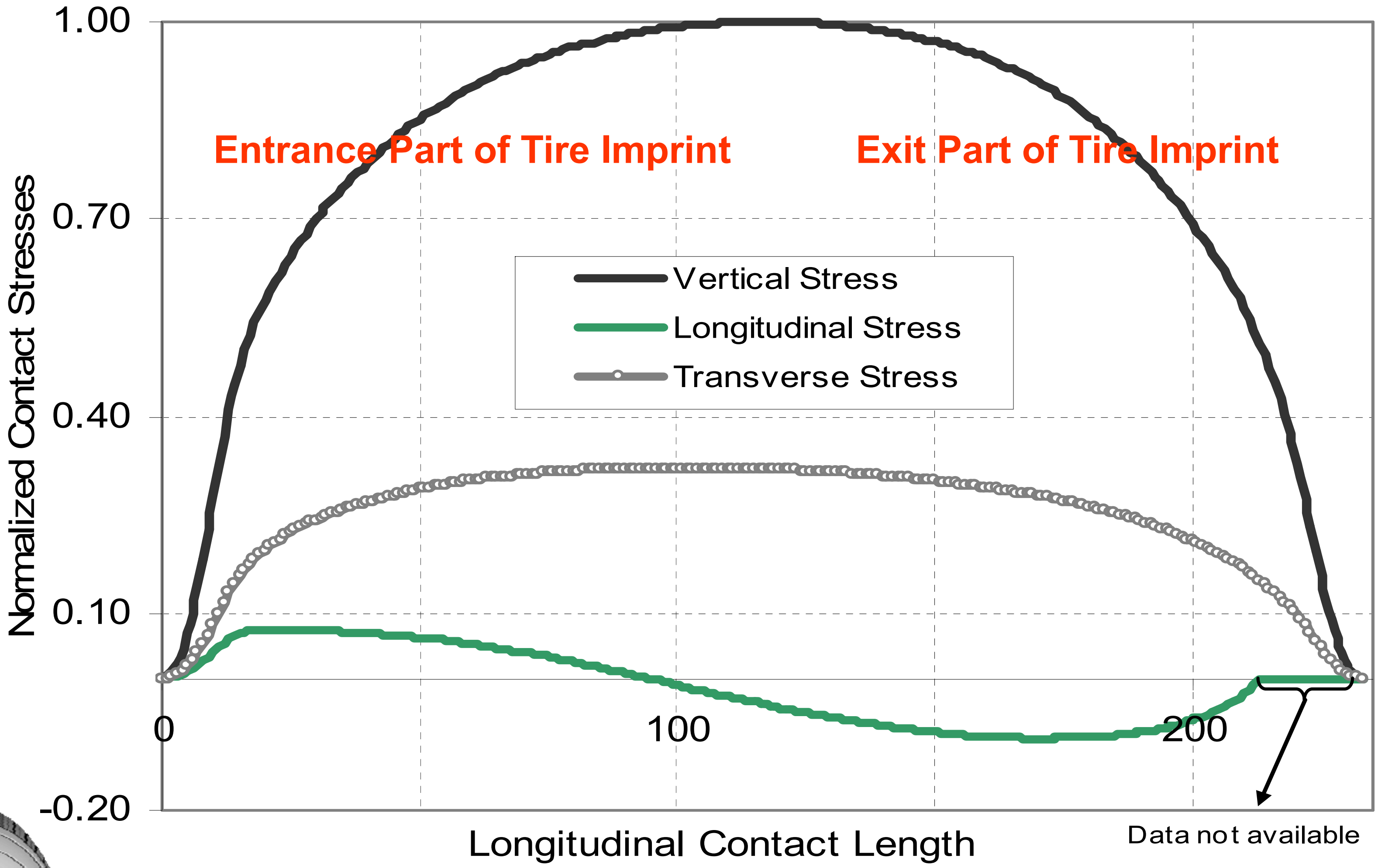
ILLINOIS CENTER FOR TRANSPORTATION

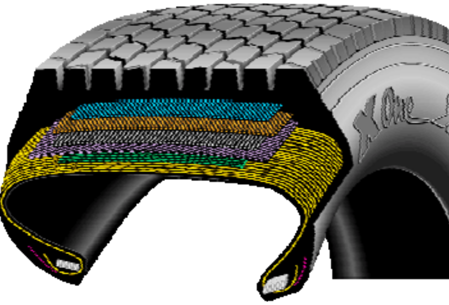
Tire Contact Stress Measurement

- ☐ Three Horizontal Data-Triggering Points in a Tread
- ☐ Cover Whole Longitudinal Contact points



3D Tire-Pavement Contact Stresses



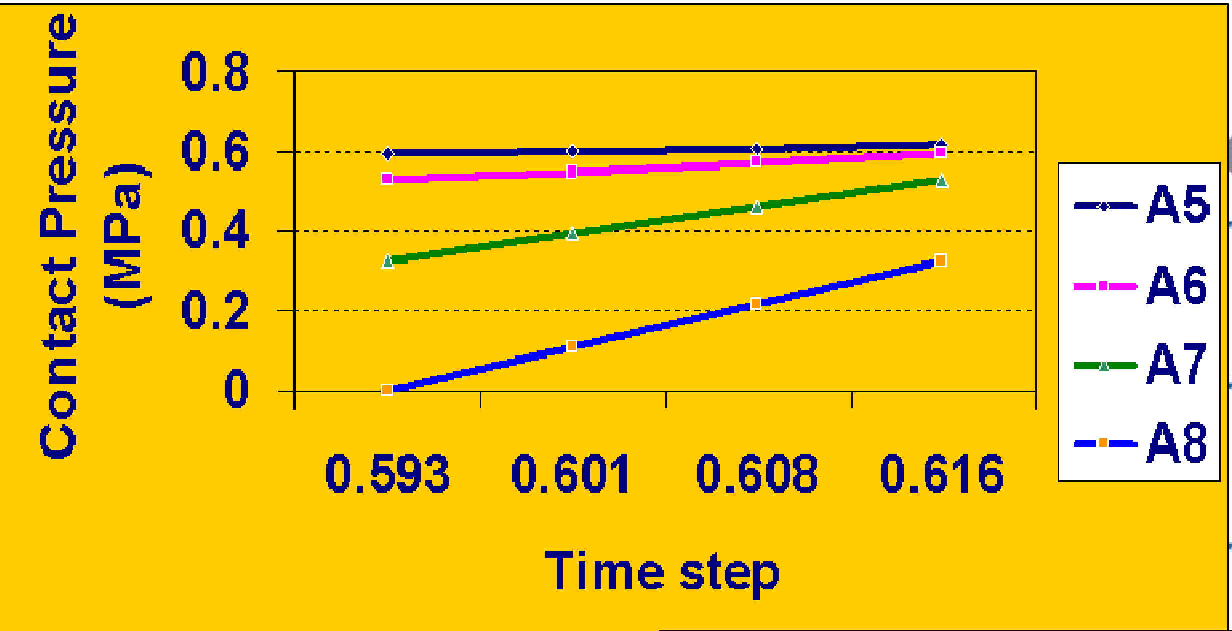


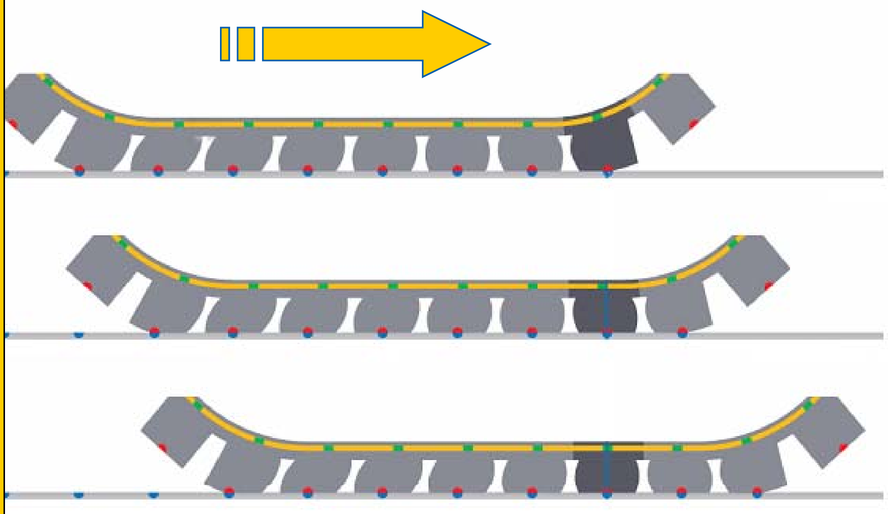
Moving direction

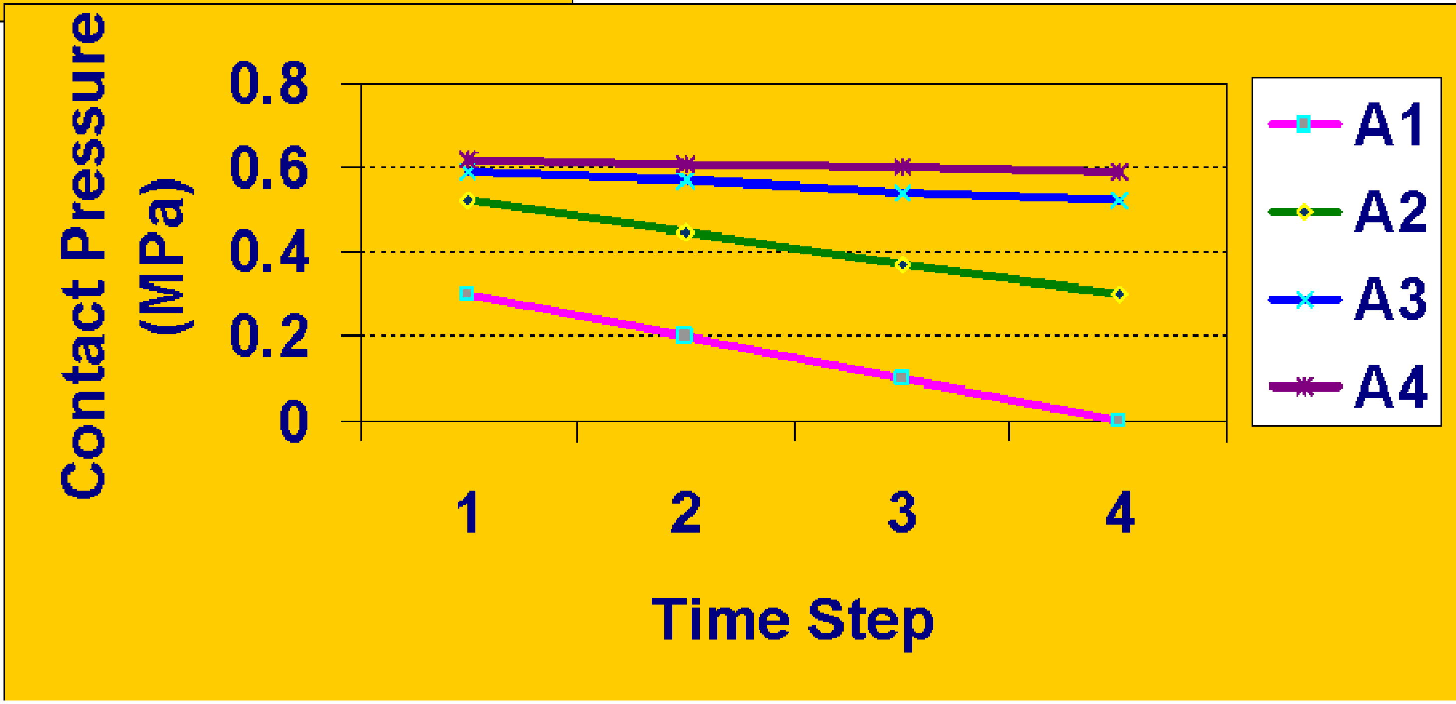
Moving Load Simulation

- Traditional method
  - Triangular, trapezoidal, rectangular amplitude in constant loading area
  - Pavement at different depths have same loading time
  - Impulsive loading (hammering)
- Continuous loading
  - Loading area changes as tire moving
  - Loading amplitudes are linearly varied with time for the entrance and exit parts of tire imprint

Loading Amplitudes (Entrance/ Exit)



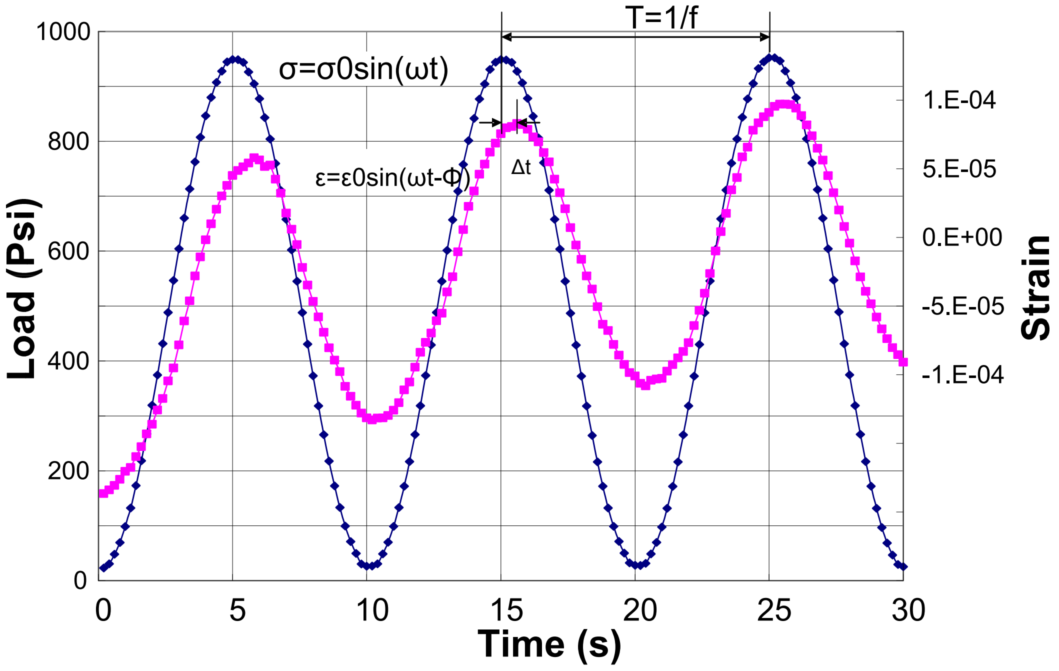




HMA Complex Modulus

- Experiment setup: uniaxial or indirect tensile
- Using Sigmoidal function for master curve

$$\log(E^*) = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log(t) - \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{295.25}\right)\right]\right\}}}$$



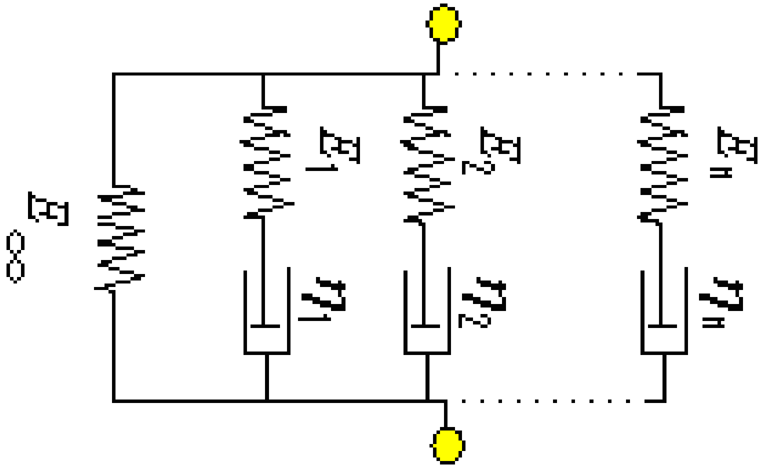
where,
E^* = complex modulus;
t = loading period;
T = temperature in ° Rankine;
ΔE_a, δ, β and γ = fitting parameters; and
Max = limiting maximum modulus.

ILLINOIS CENTER FOR TRANSPORTATION

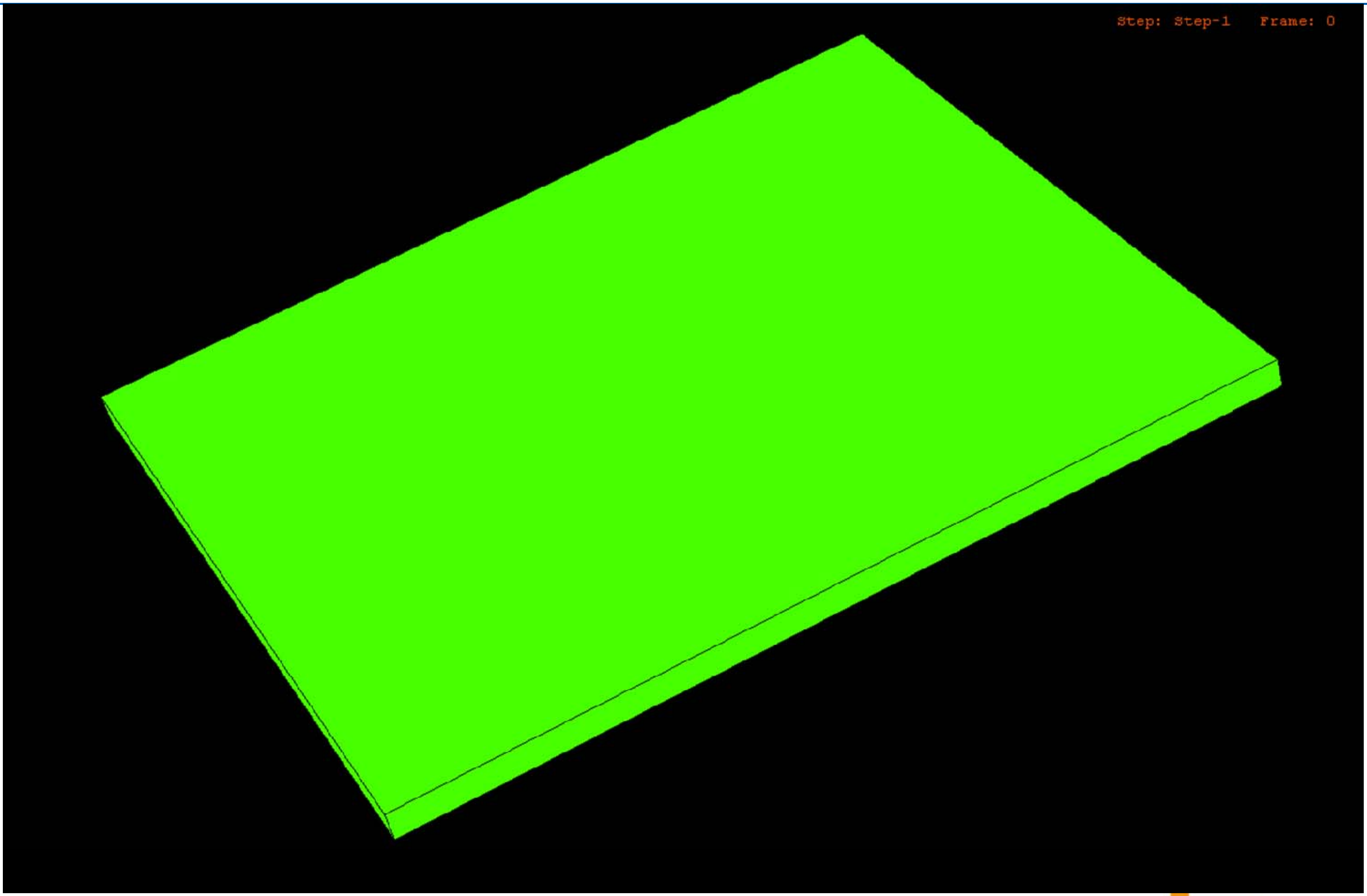
Linear Viscoelasticity

- **Generalized Maxwell Solid Model:**
  - **One spring and Maxwell elements in parallel**
- **Relaxation modulus:**
  - **Converted from complex modulus and expressed as Prony Series**

$$E(t) = E_0\left(1 - \sum_{i=1}^{N} E_i\left(1 - e^{-t/\tau_i}\right)\right)$$

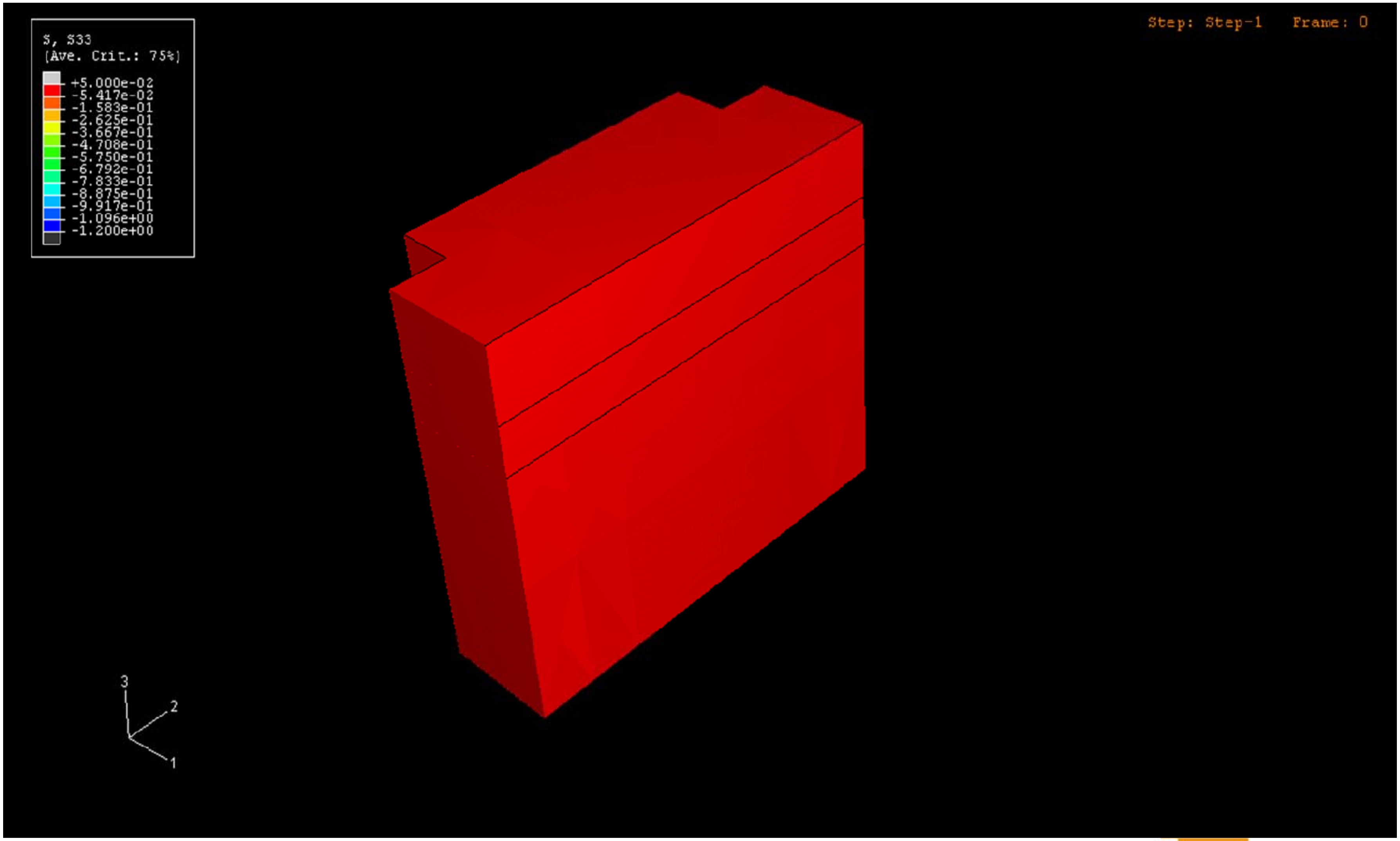


3D Dynamic Analysis: Viscoelastic Effect



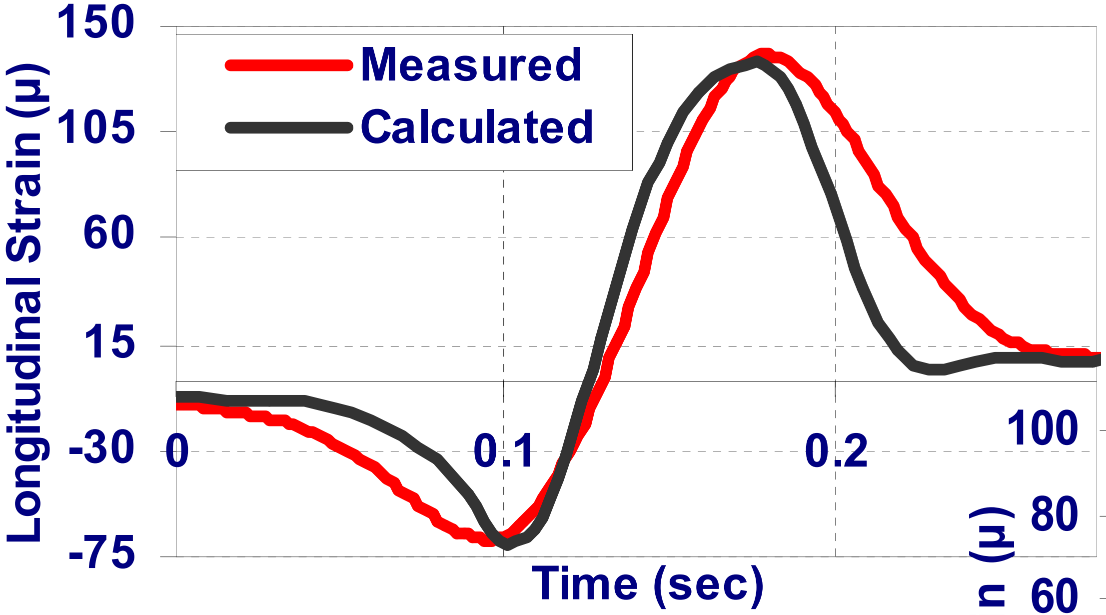
ILLINOIS CENTER FOR TRANSPORTATION

Stress under Transient Dynamic Loading

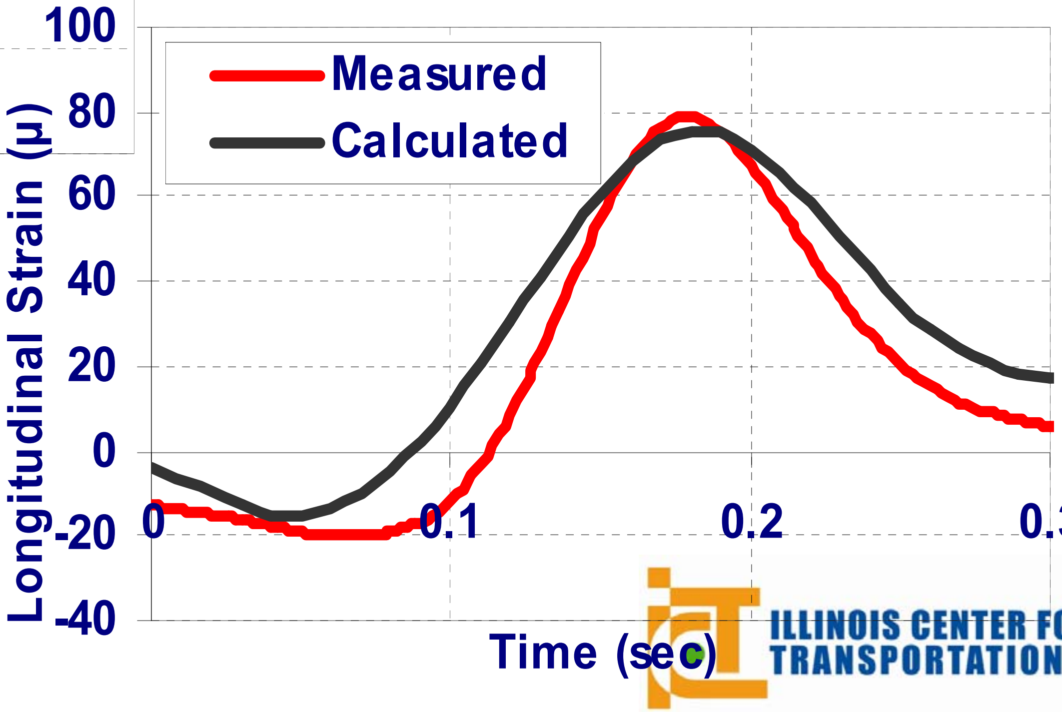


FE Model Validation

- Bottom of the wearing surface (38.1mm)



- Bottom of the HMA (188 mm)



ILLINOIS CENTER FOR TRANSPORTATION

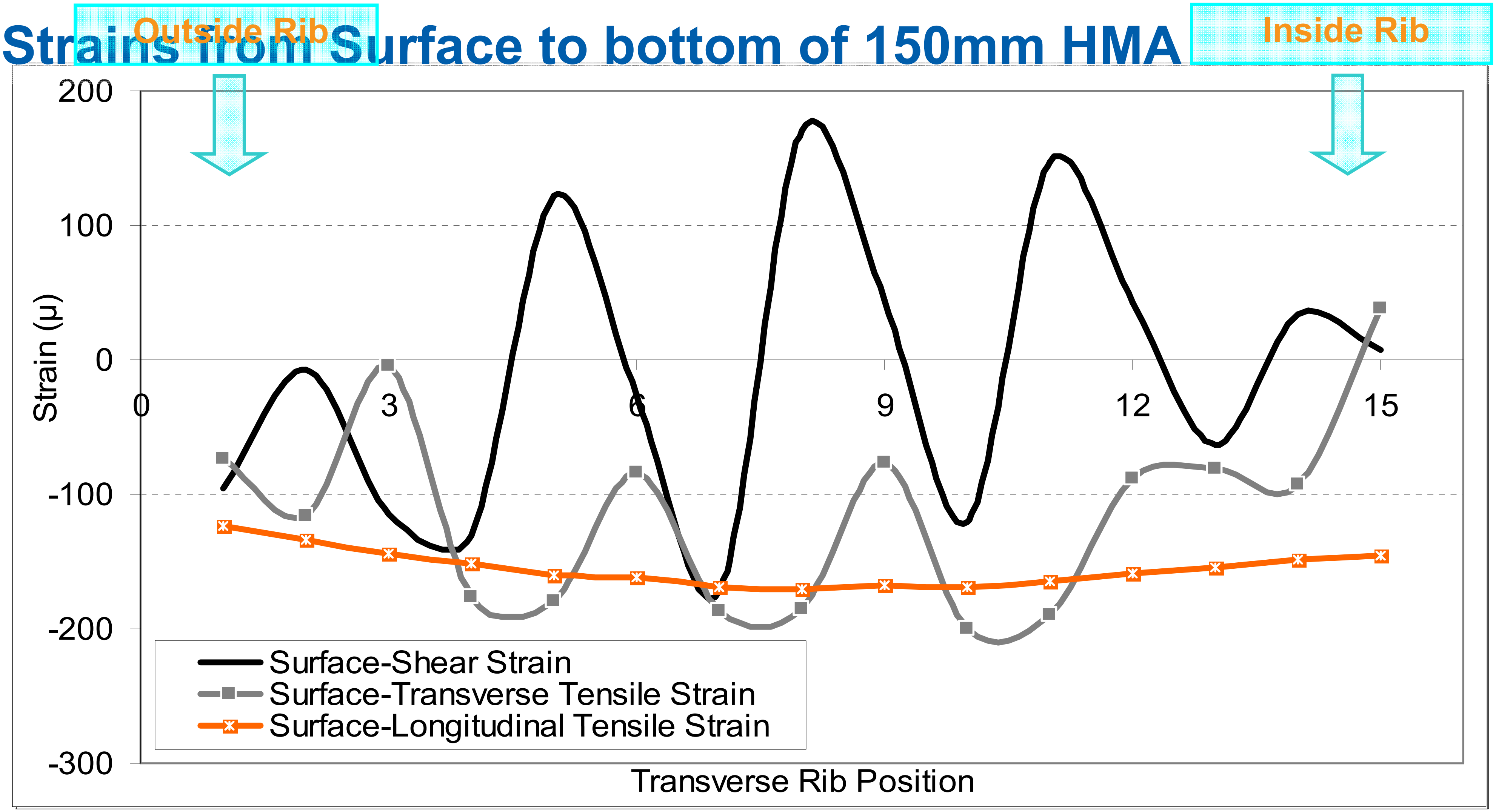
Pavement Damage Mechanism

- **Fatigue cracking**
  - Tensile strain at bottom of HMA
- **Surface cracking (top-down or “near-surface”)**
  - Tensile and shear strain
  - Thermal stress and aging effect
- **HMA rutting**
  - Shear flow
  - Densification
- **Subgrade permanent deformation**

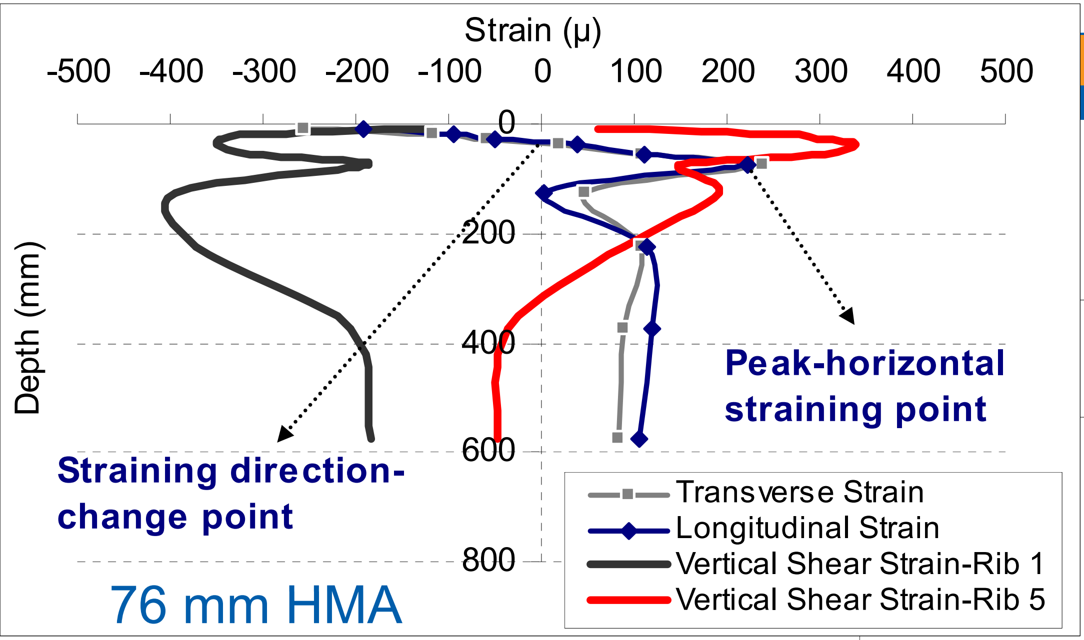
ILLINOIS CENTER FOR TRANSPORTATION

Strain Distribution in Depth

- Critical Strain within HMA
- Strains from Surface to bottom of 150mm HMA



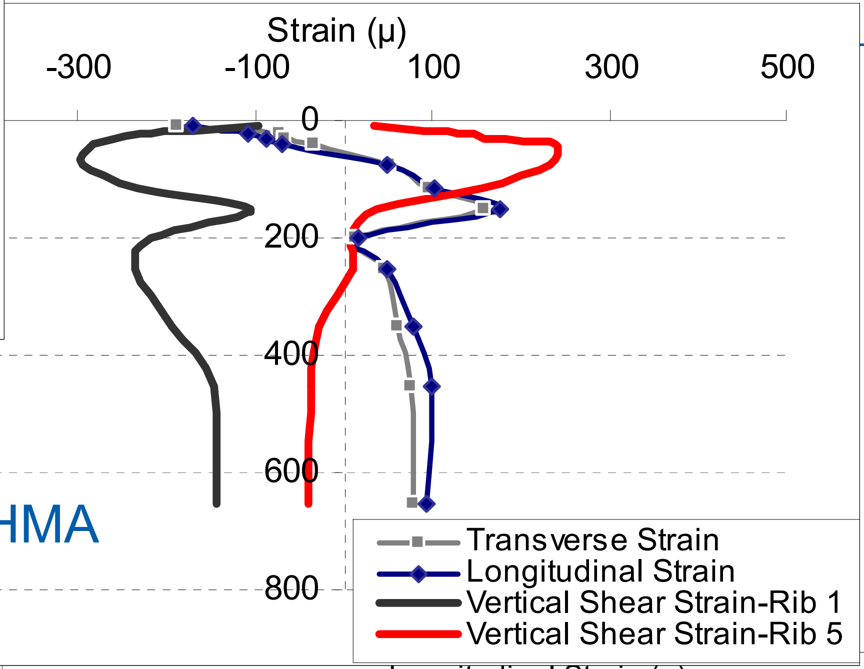
Tensile vs. Shear Strain



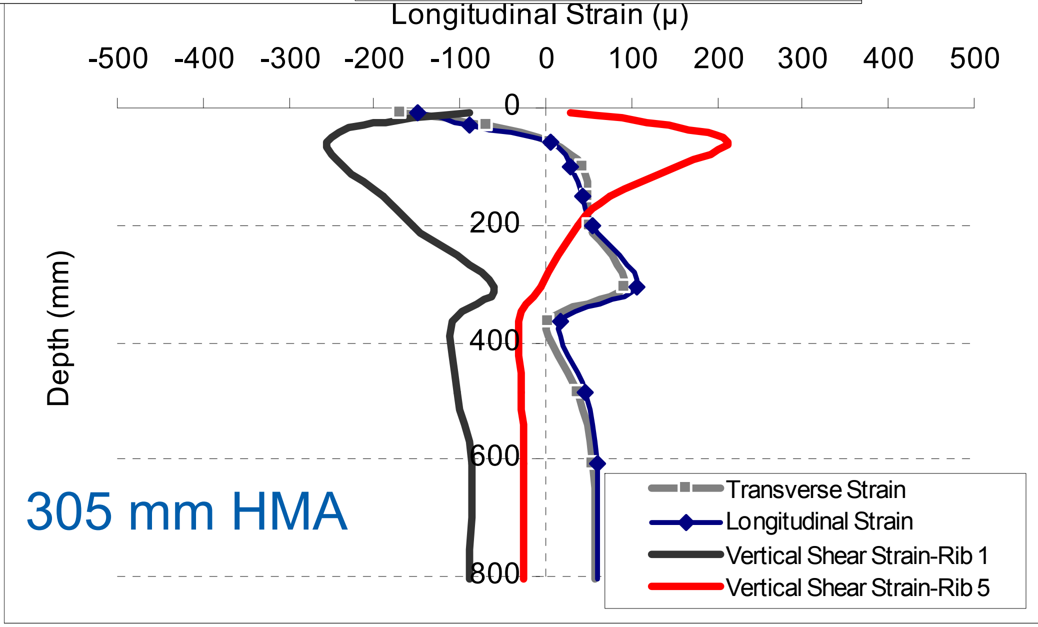
Peak-horizontal straining point

Straining direction-change point

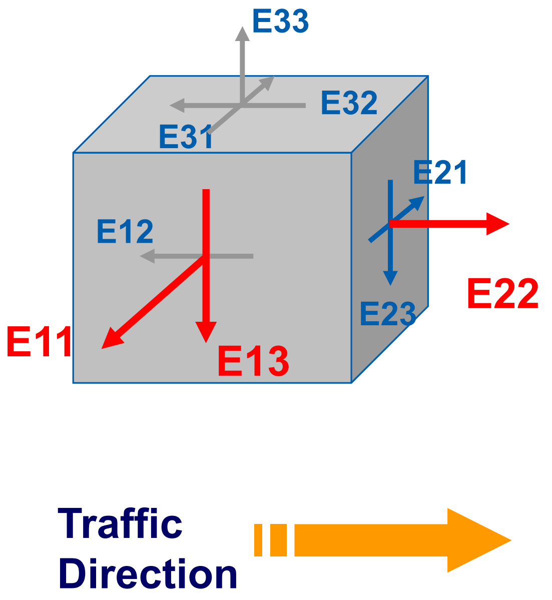
76 mm HMA



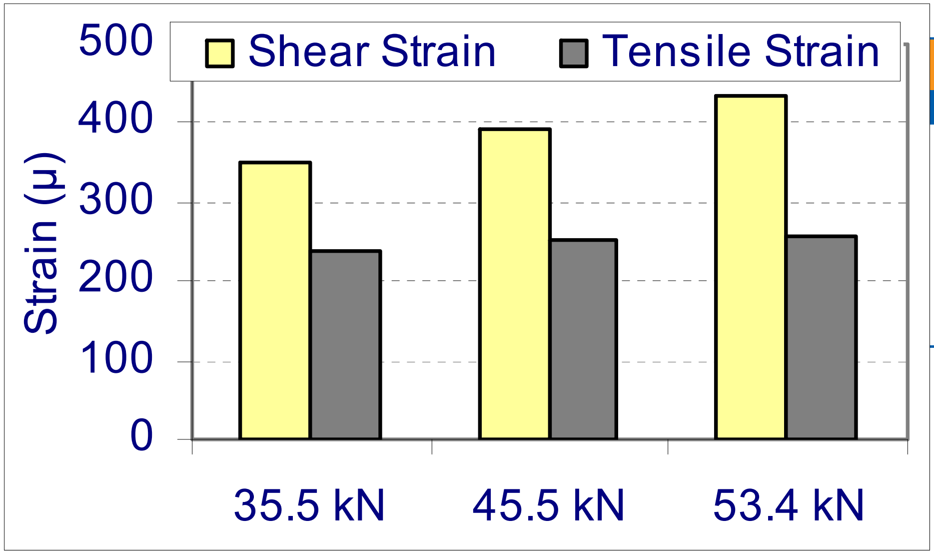
152 mm HMA



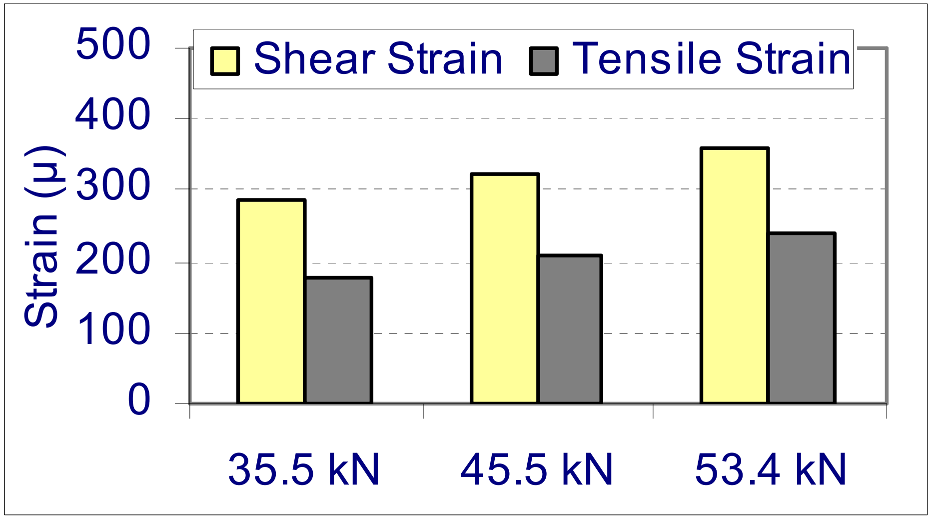
305 mm HMA



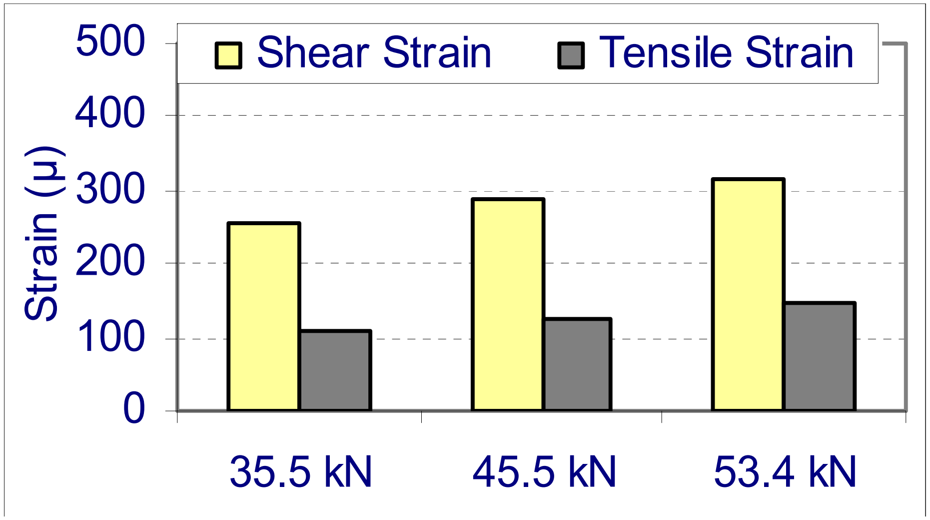
Critical Strain in HMA Layer (25 ºC)



HMA =76 mm

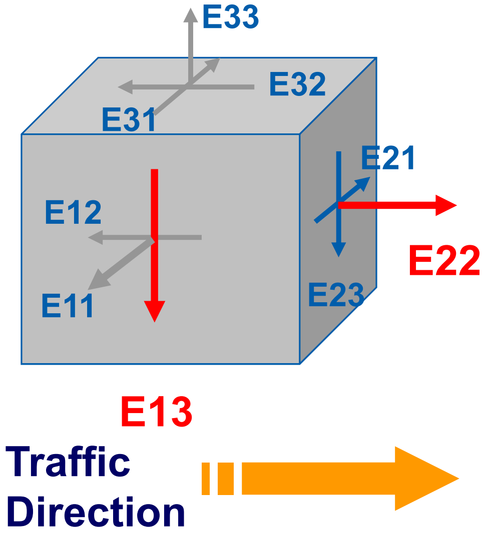


HMA=152 mm



HMA=305 mm

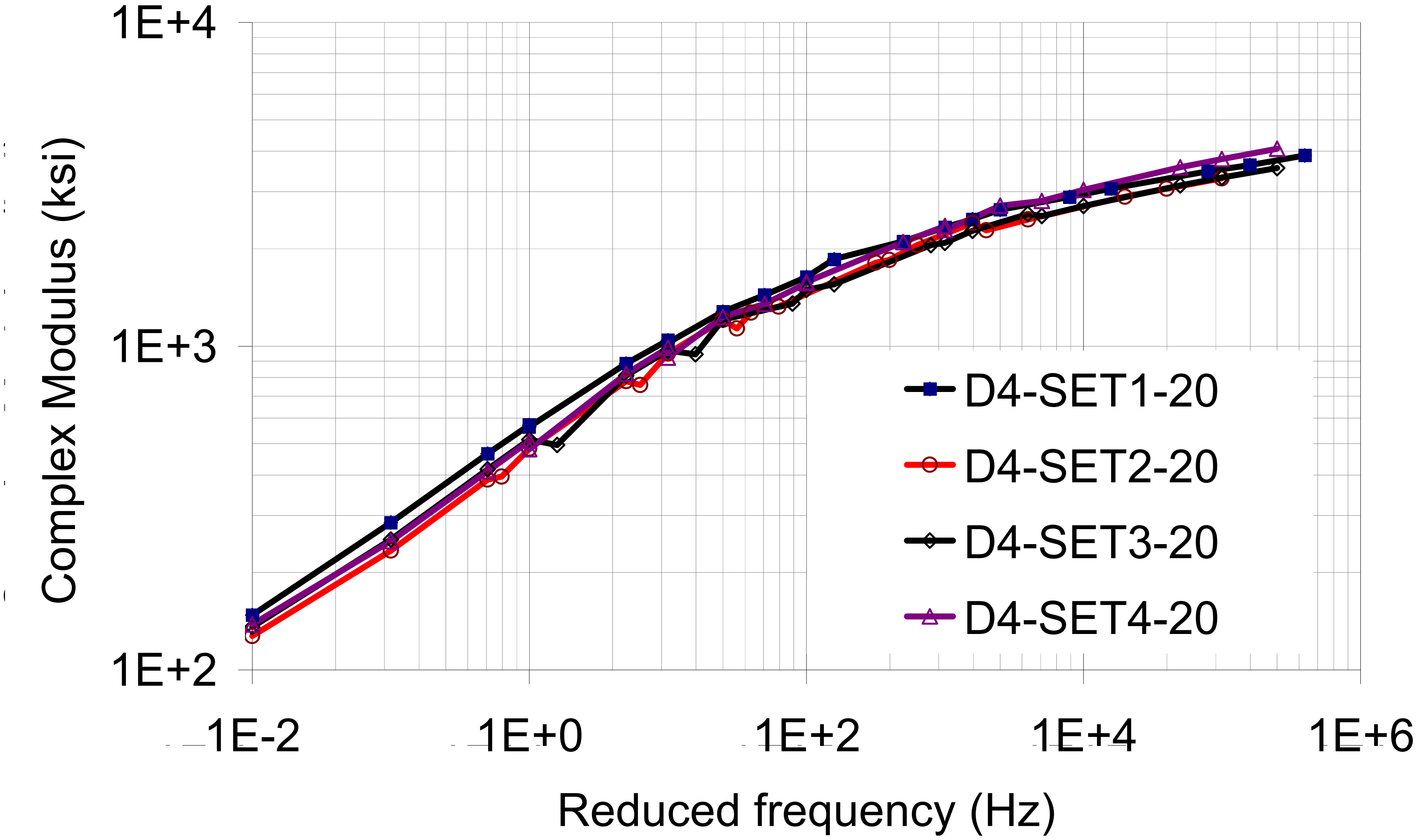
- **Shear Strain: Critical value within HMA**
- **Maximum Tensile strain at the bottom of HMA**

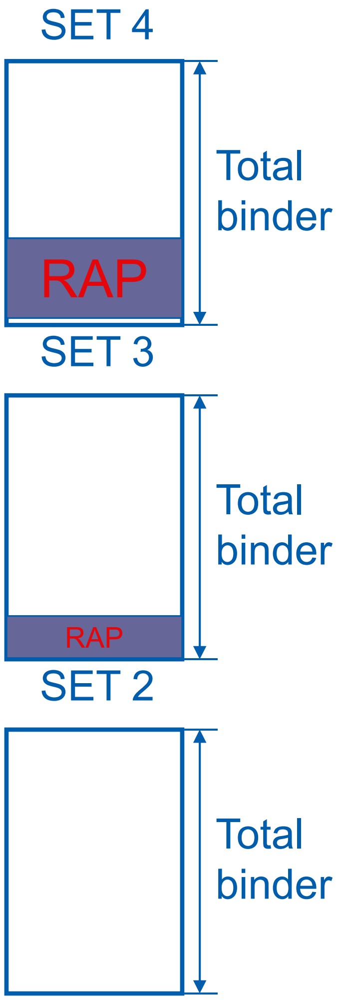


ILLINOIS CENTER FOR TRANSPORTATION

Impact of Using Recycled Materials

RAP's Binder Blending Scenarios @ 20% RAP




SET 4

RAP

Total binder

SET 3

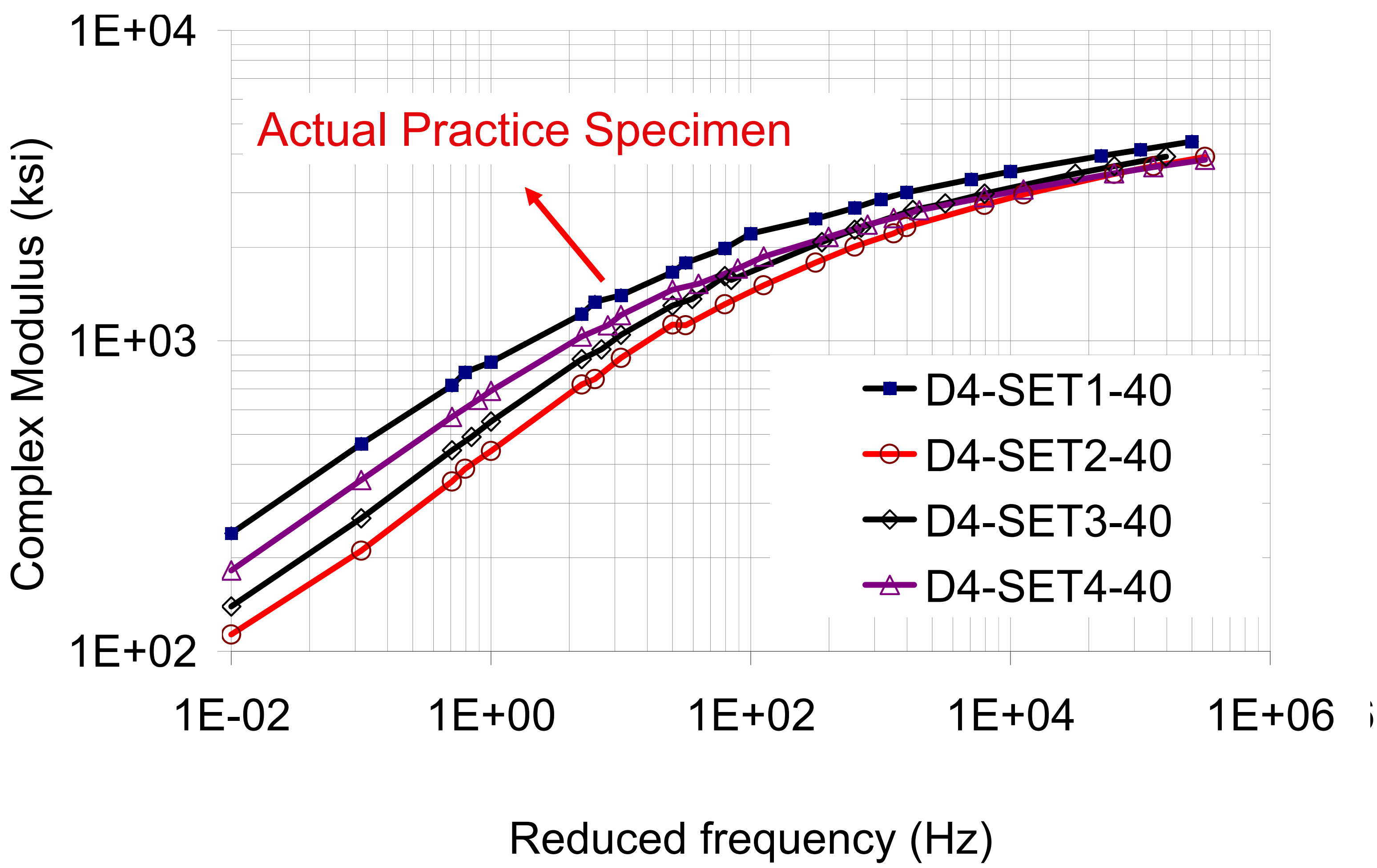
RAP

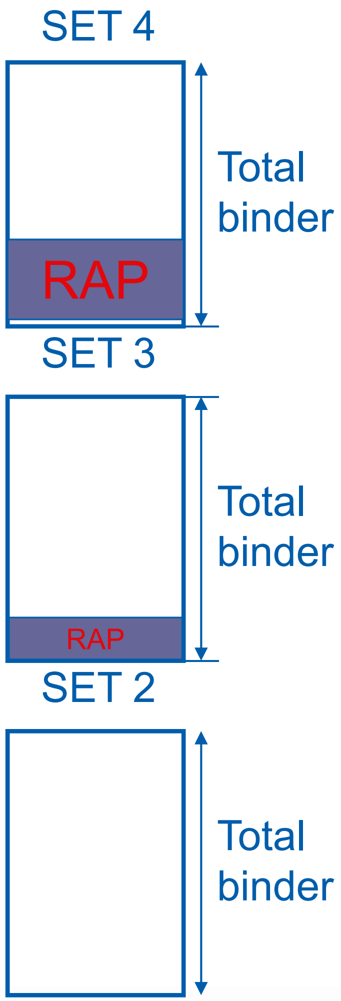
Total binder

SET 2

Total binder

RAP's Binder Blending Scenarios @ 40% RAP


Actual Practice Specimen

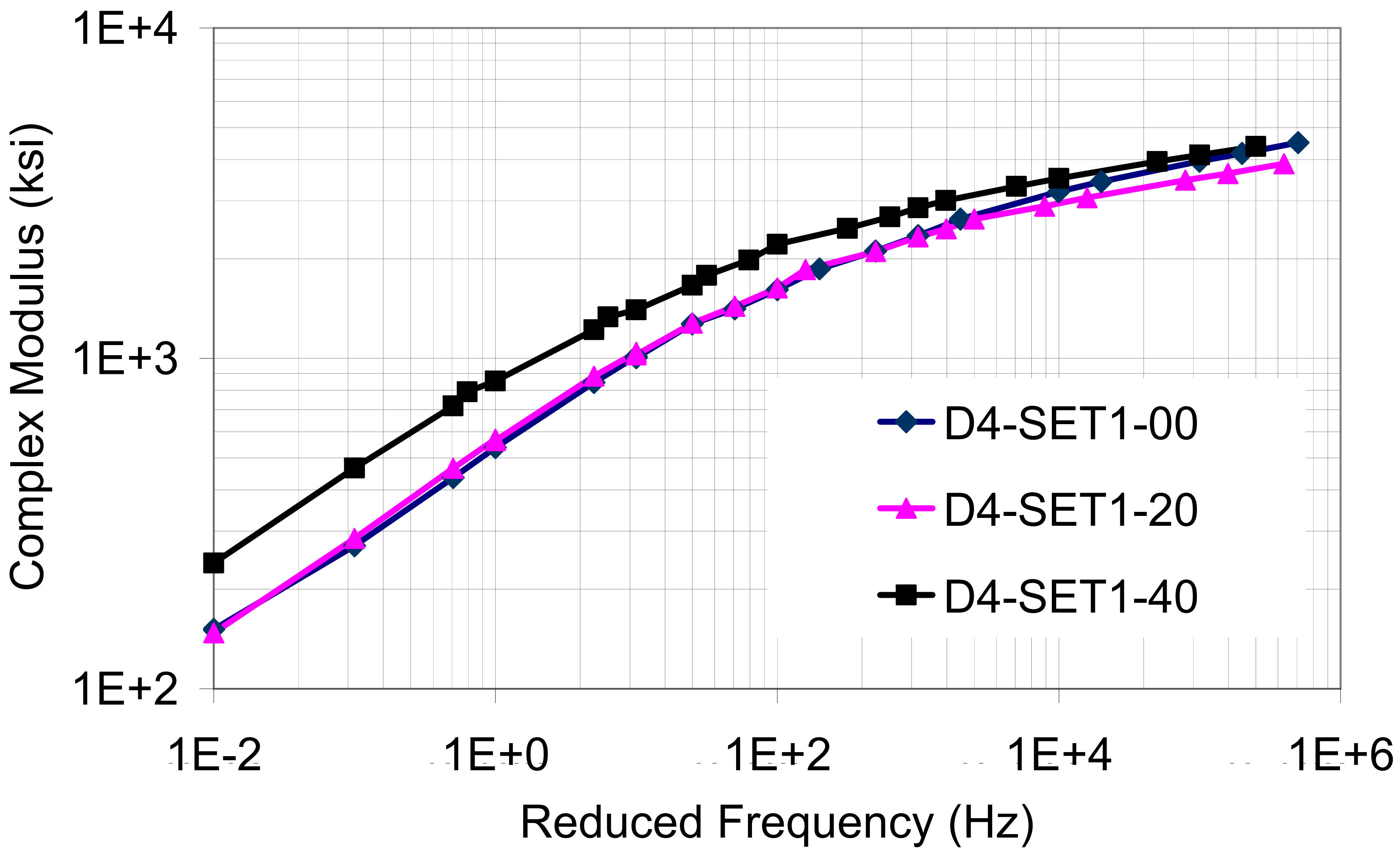

SET 4
RAP
Total binder

SET 3
RAP
Total binder

SET 2
Total binder

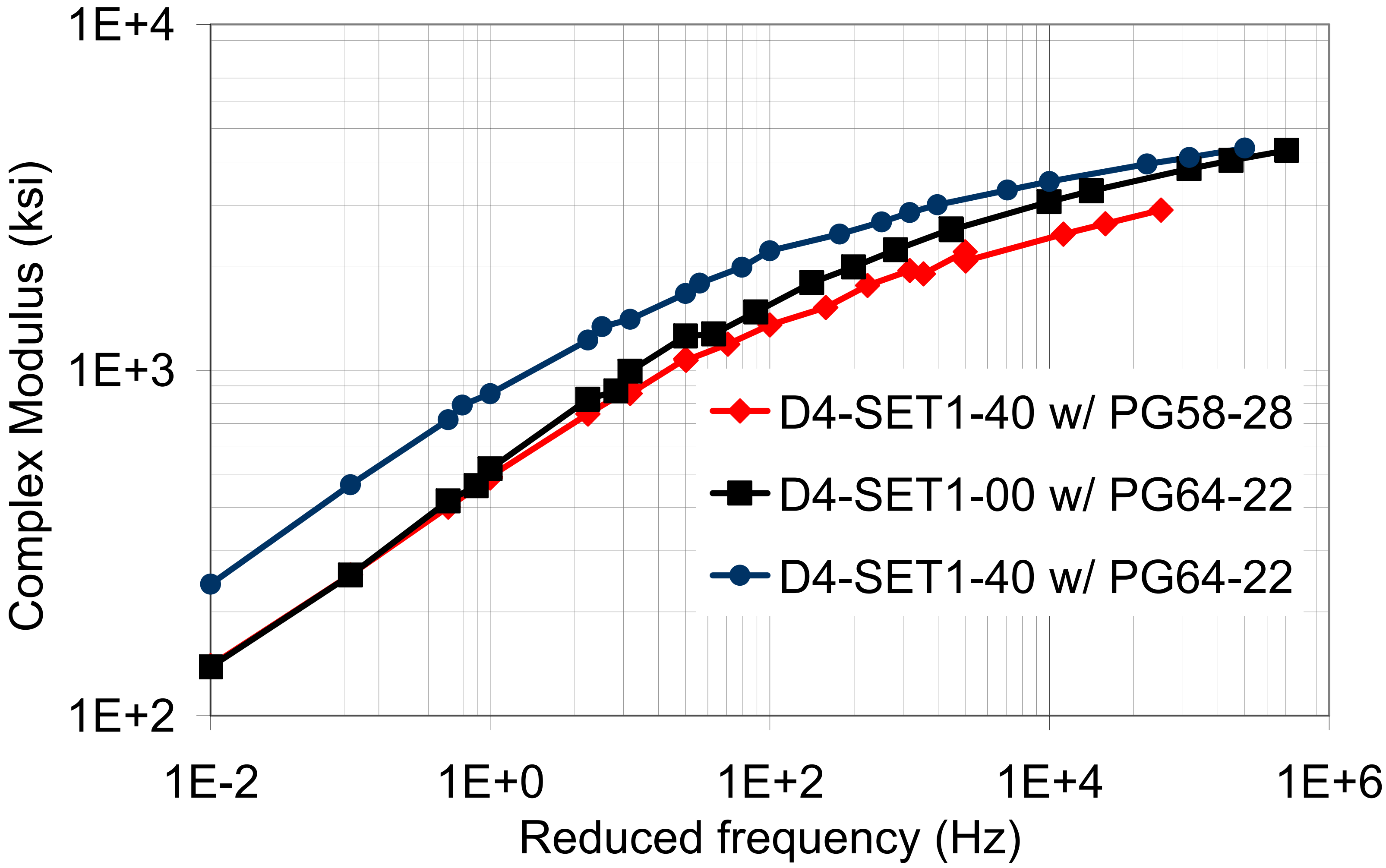
ILLINOIS CENTER FOR TRANSPORTATION

Complex Modulus Results

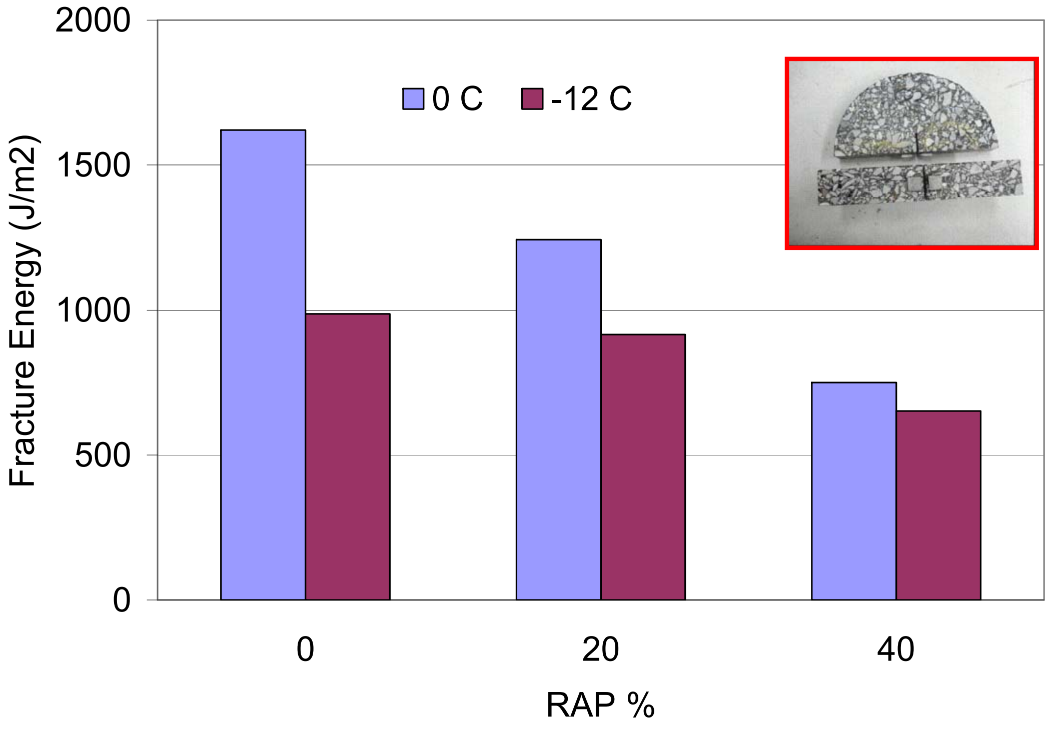


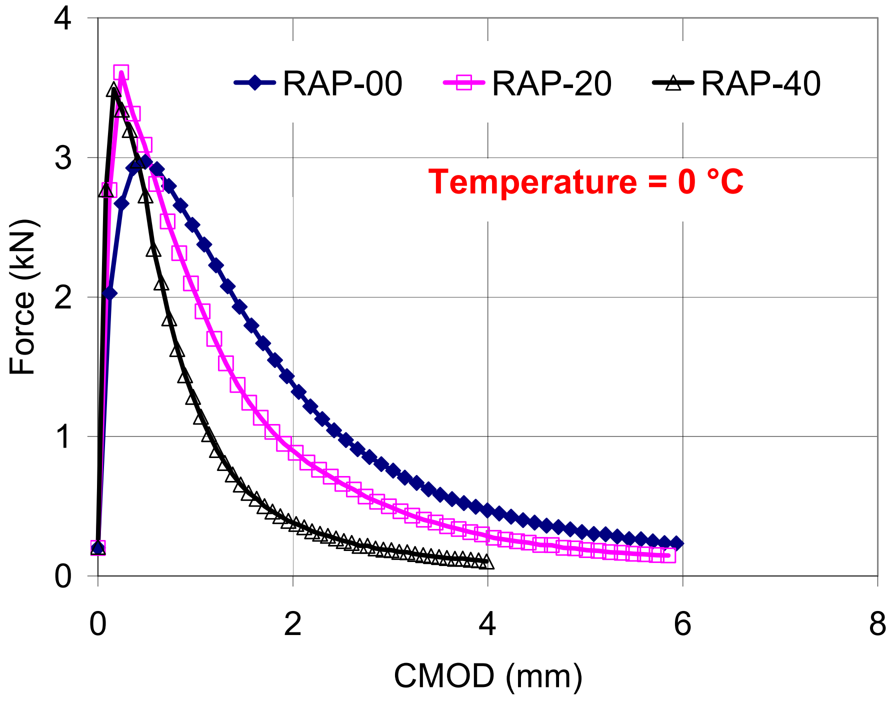
IS CENTER FOR TRANSPORTATION

Double Bumping Effect on Modulus



Fracture Energy w/ Varying RAP





Temperature = 0 °C

As RAP ↑, Fracture Energy ↓

Summary

- Accurate pavement response prediction requires realistic loading simulation and appropriate material and interface modeling
- 3D tire contact stresses (non-uniformity and tangential shear stress) may affect the prediction of top-down cracking, primary rutting, and occasionally fatigue damage
- Shear strains at pavement near-surface are significant; fresh look into "NEAR SURFACE CRACKING" is needed in thick pavement
- Find critical repose for each failure mechanism

ILLINOIS CENTER FOR TRANSPORTATION

Thank You

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN