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A New Flexible Pavement Design Framework for Cracking using Using HMA Fracture Mechanics and the Critical Condition Concept

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Outline

- Background and Overview of HMA Fracture Mechanics Model and the Critical Condition Concept
- Determination of Input Parameters
- Field Predictions
- Implementation into Pavement Design
- Summary

Background and Overview of HMA Fracture Mechanics Model and the Concept of a Critical Condition

FDOT Multiyear Study

Mechanisms of Top-Down Cracking

- Stiffness Gradients (Temperature differential, Aging)
- Thermal Stresses
- Truck tire ribs induced tension
- Residual viscoelastic stresses

Fracture Models for Mixtures and Pavements

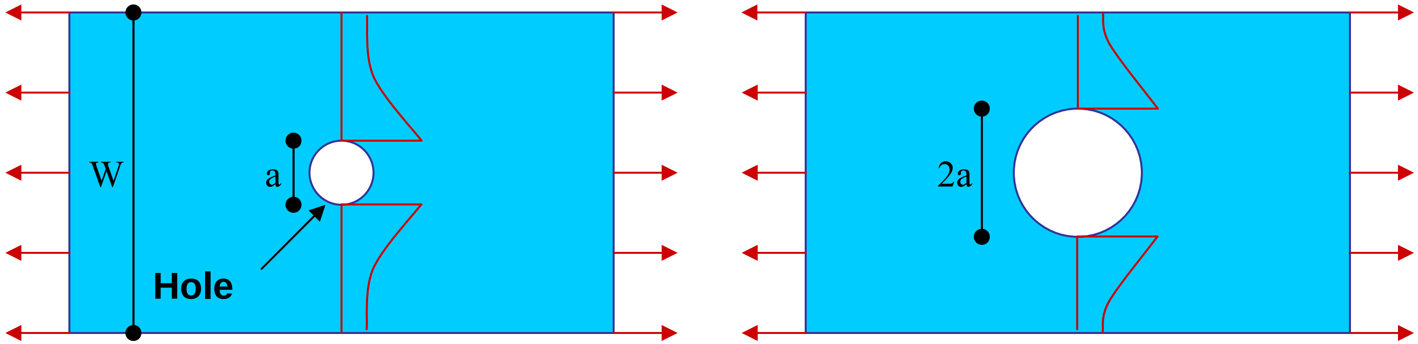
- Simpler Testing and Design Calculations

Fracture Mechanics

- A Theory That Predicts the Effects of Cracks in Materials
- Importance
  - Cracks intensify stresses
    - Distinct from and greater than stress concentrations
  - Stress intensities accelerate distress and can dictate failure mechanism
  - Characteristics and distribution of cracks affect mixture fracture resistance

Stress Intensity ≠ Stress Concentration

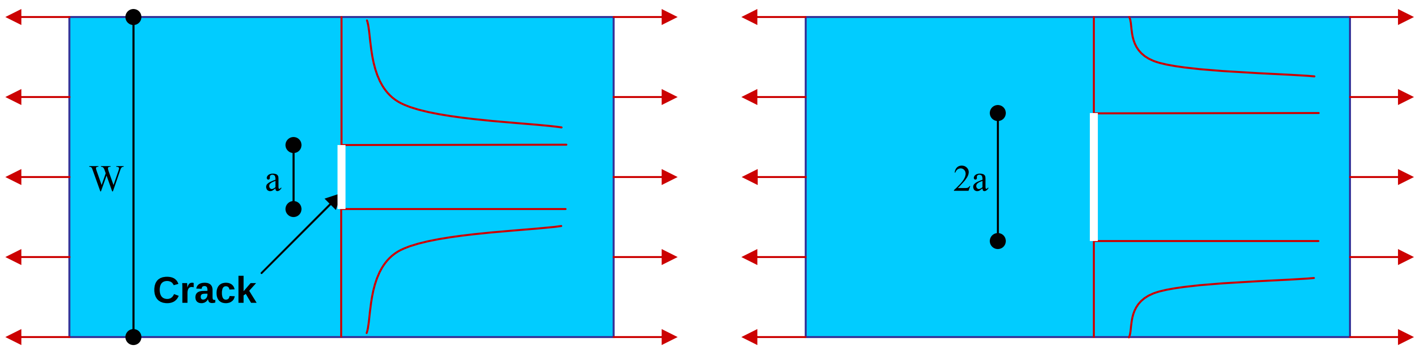
Hole/Void



$St_1 = St_2$

Crack

$\sigma_{max} = 3\sigma$ $\sigma_{max} = 3\sigma$

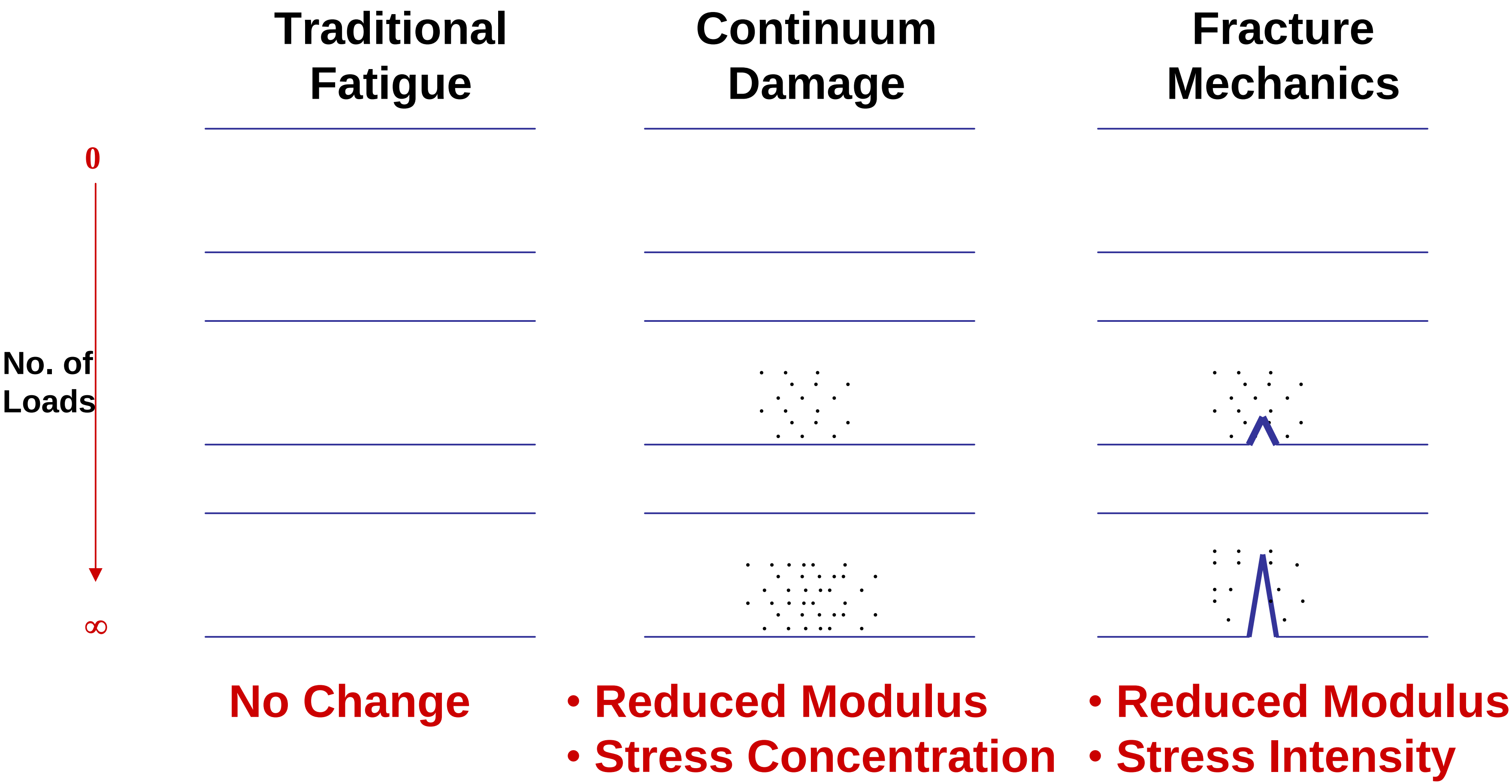


$K_1 < K_2$

$K_1 = \sigma\sqrt{\pi a}$ $K_2 = \sigma\sqrt{2\pi a}$

*** For a<<W**

Representing Cracking Mechanism in Pavements



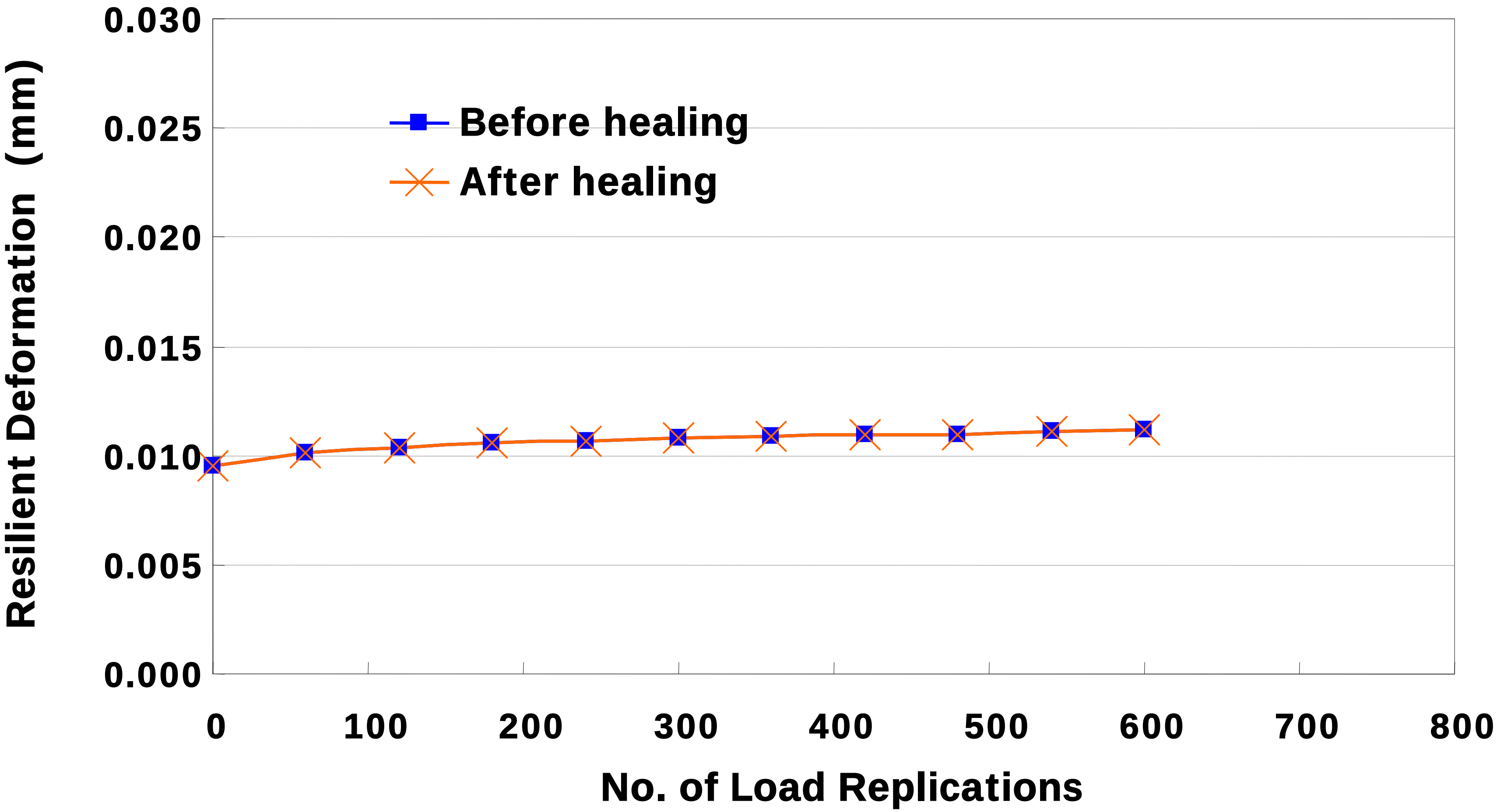
HMA Fracture Mechanics

- VE Fracture Mechanics Model
- Predicts Crack Initiation and Growth Based on DCSE (energy associated with damage)
- Incorporates Fracture Threshold
  - Crack does not propagate with each load
  - Crack growth is stepwise, not continuous

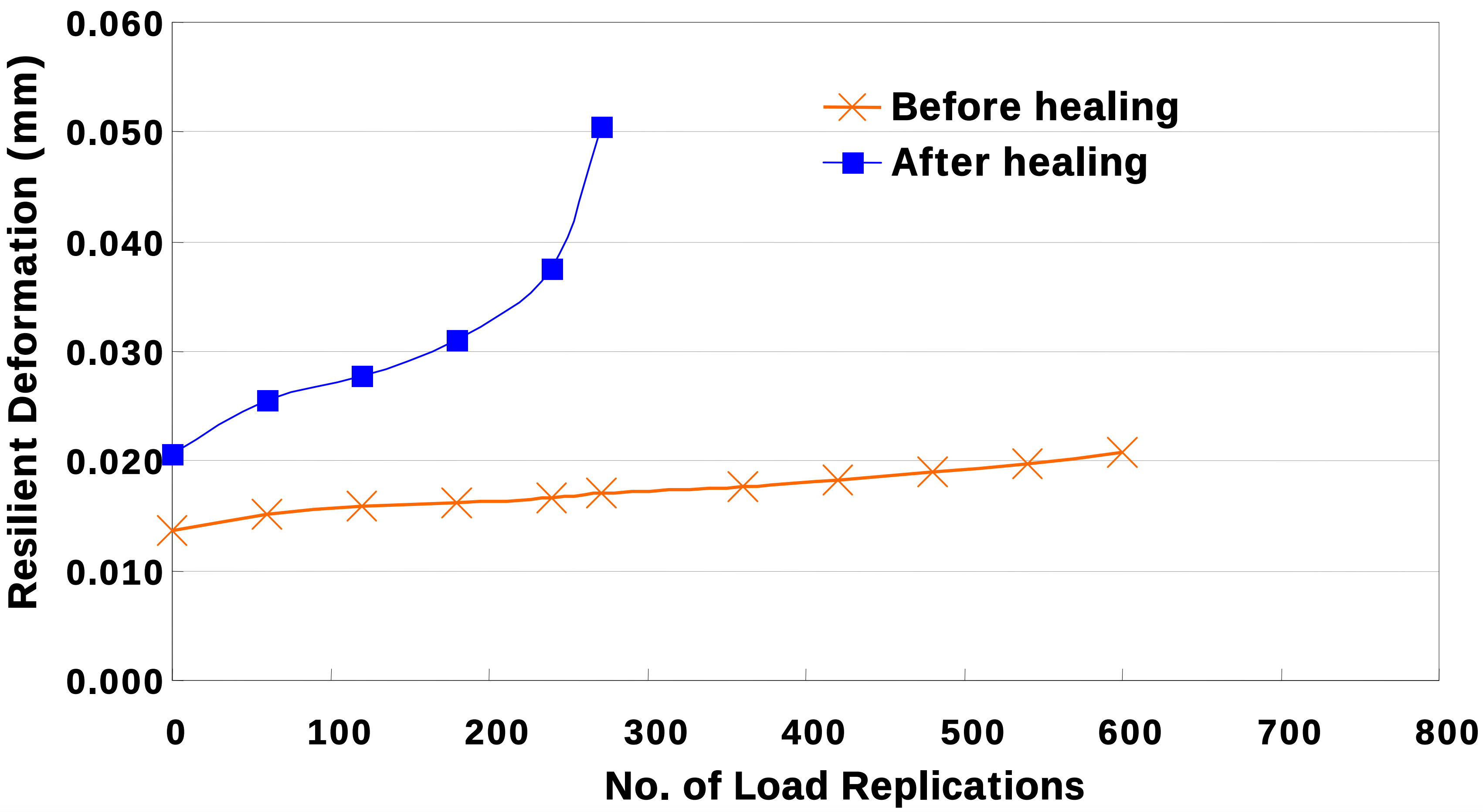
Failure Limits – Key Observations

- Damage = Micro-cracks
- Failure = Macro-crack initiation or growth
  - Driven primarily by tension
- Not all damage is permanent
  - There is a **threshold** – separates damage from fracture (crack initiation or growth)
  - Damage is cumulative only when the threshold is exceeded
  - Damage below the threshold is healable

Evidence of Healing



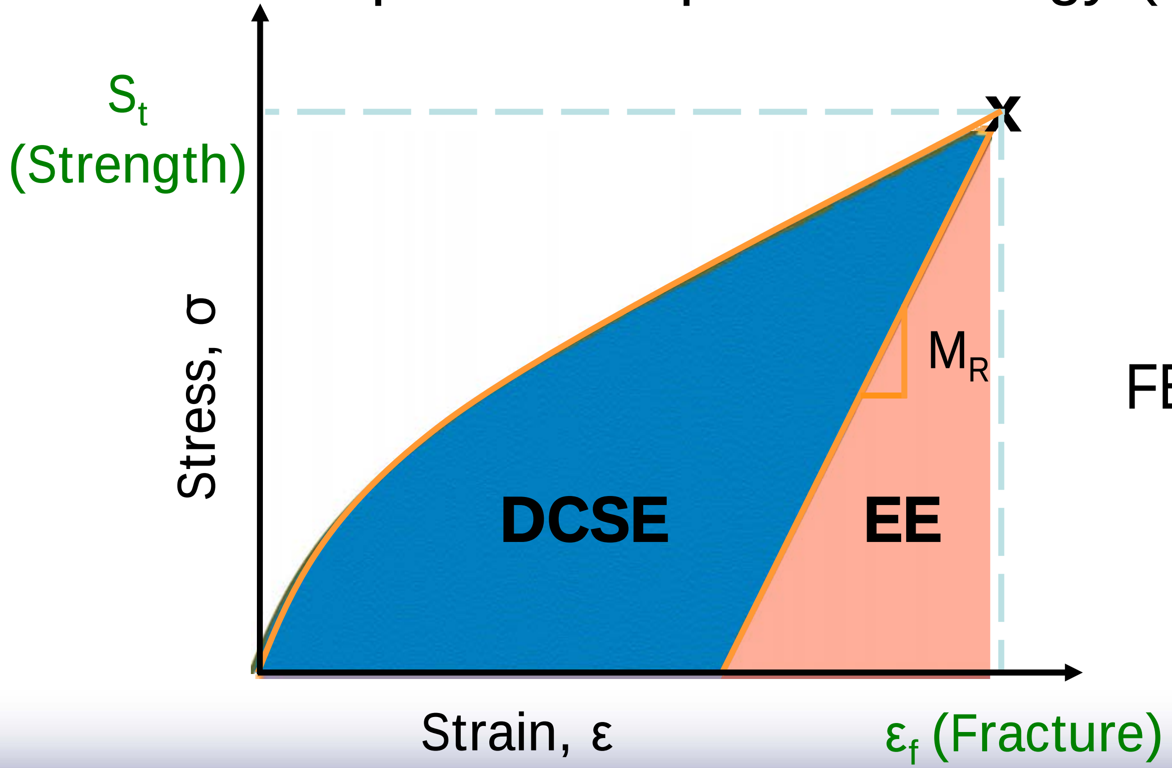
Evidence of the Threshold



The Threshold

The Strain Energy required to initiate and/or propagate a crack:

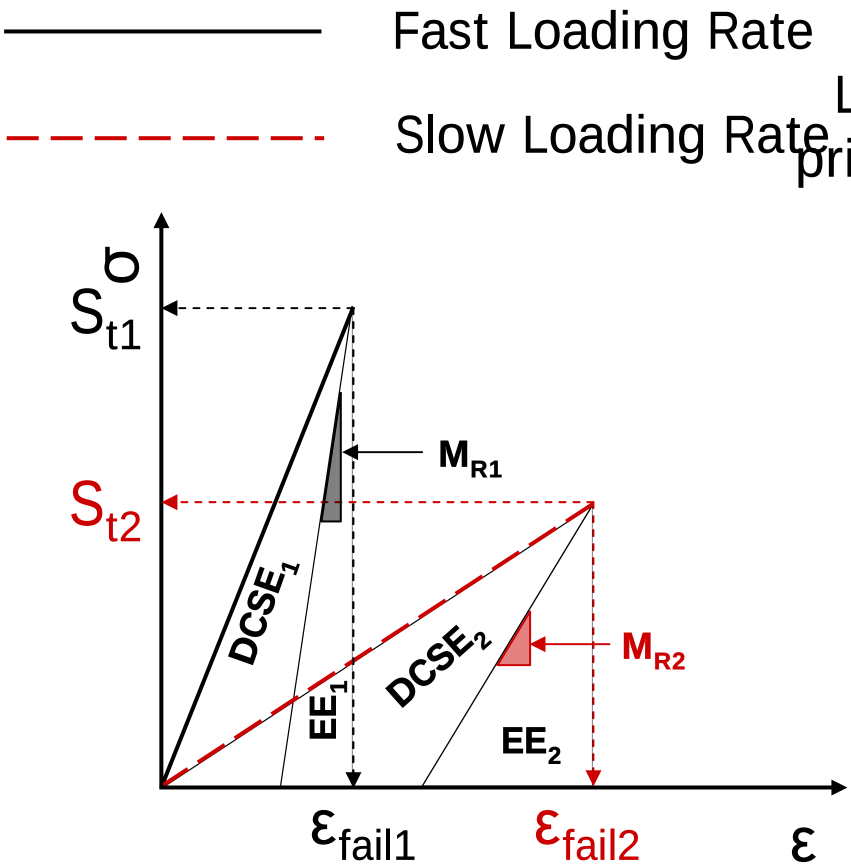
- Total Fracture Energy (FE) = creep + elastic
- Dissipated Creep Strain Energy (DCSE) = creep only



FE = DCSE + EE

Fracture Energy Failure Limits

Strength (Fracture) Test



Low Damage prior to Fracture		High Damage prior to Fracture
S_{t1}	>	S_{t2}
ε_{fail1}	<	ε_{fail2}

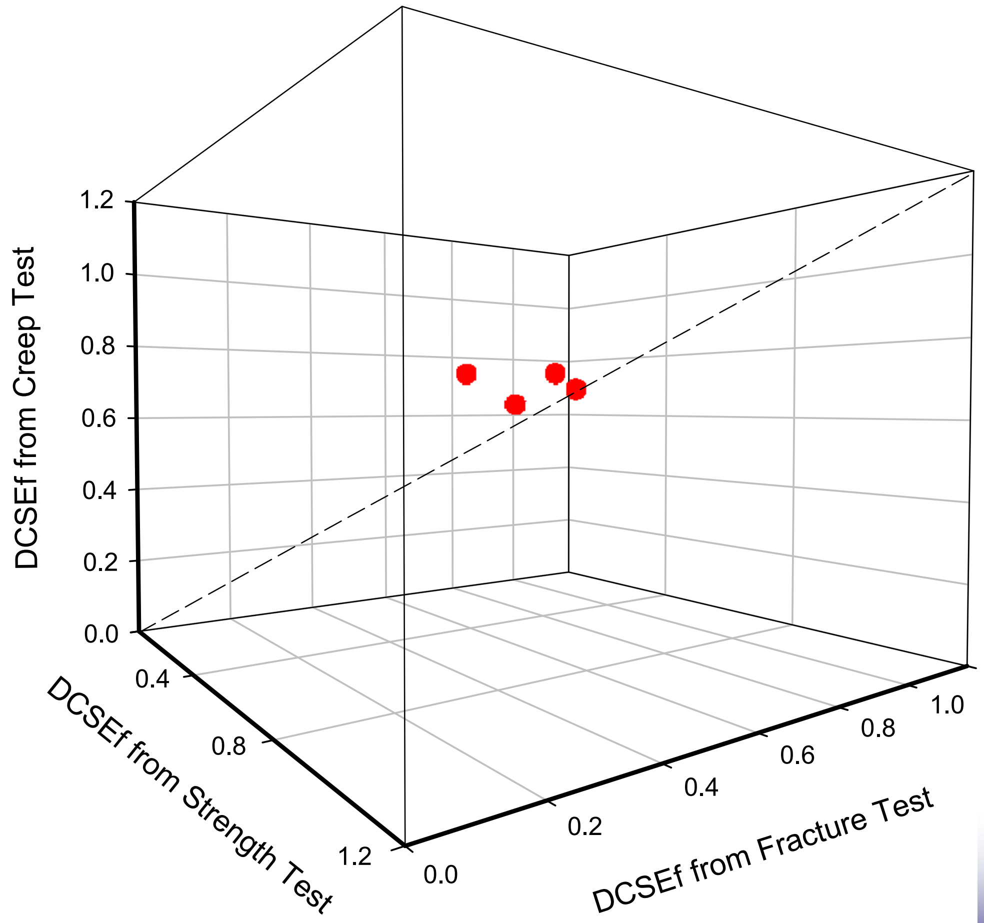
However

$DCSE_1 \cong DCSE_2$

$FE_1 \cong FE_2$

The Threshold

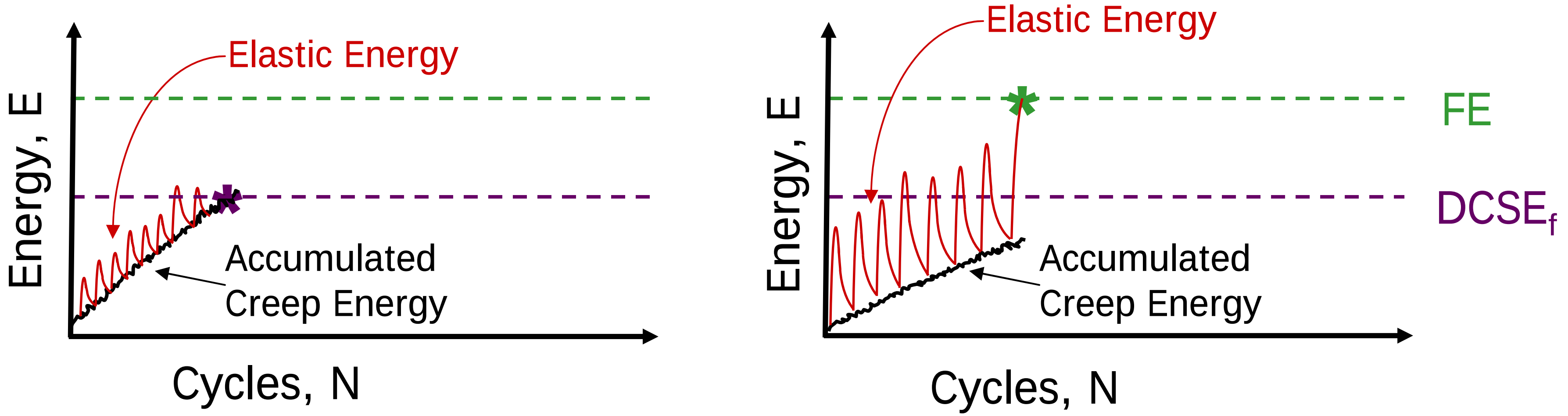
- The threshold is **fundamental** – independent of mode of loading and specimen geometry
  - Strength
  - Cyclic
  - Creep



Failure Threshold

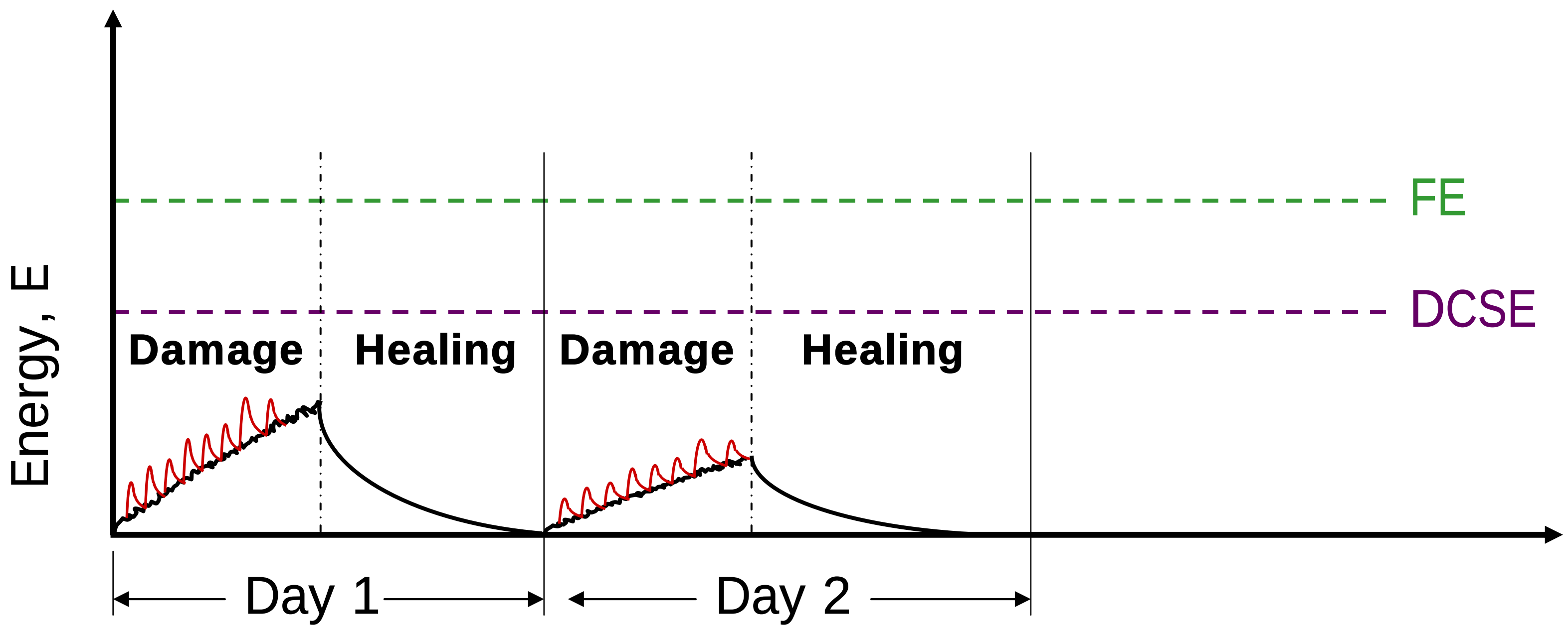
The material can fail in two ways:

- If the accumulated creep exceeds the $DCSE_f$
- If the accumulated creep plus the elastic exceeds the FE

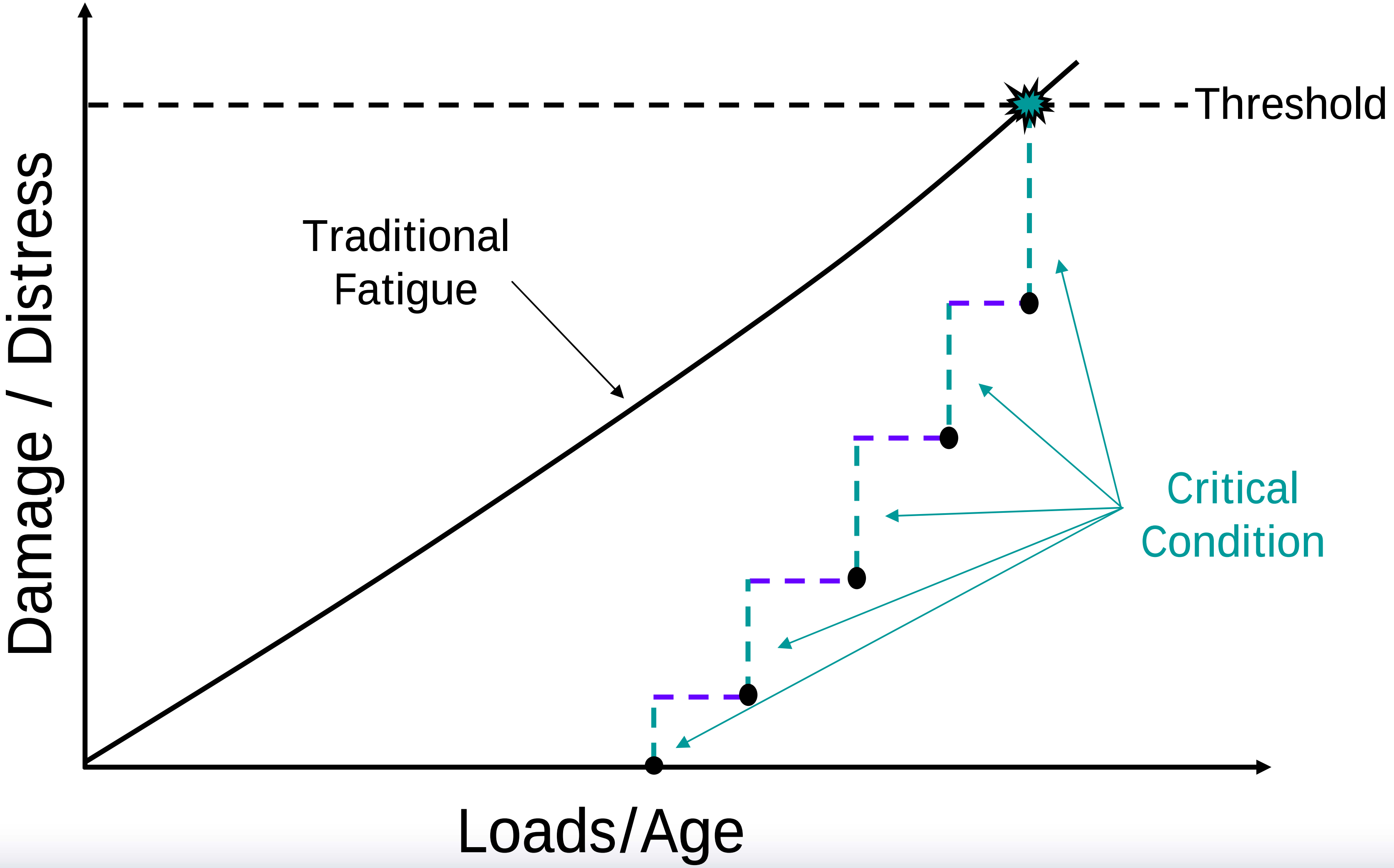


Failure Threshold and Healing

Potential loading conditions in the field



Cracking Mechanisms



Endurance Limit (Carpenter et al, 2003)

- Mixture can withstand an indefinite number of load applications without failing → "Perpetual Pavement"
- Two possibilities
  - There is a micro-damage threshold
  - The rate of healing equals or exceeds the rate of damage

Determination
of
Model (Input) Parameters

Mixture Properties

Superpave Indirect Tensile Test:

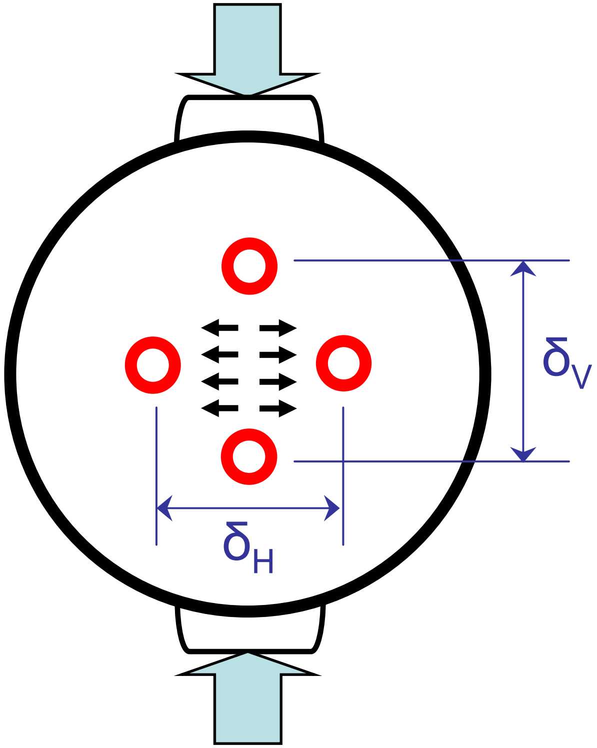
1. Resilient modulus (Cyclic loading)
2. Creep (Constant load with time)

$$D(t) = D_0 + D_1 t^m$$

- Dissipated energy $\propto$ creep rate

3. Strength (Increase load until fracture)

- Energy limits



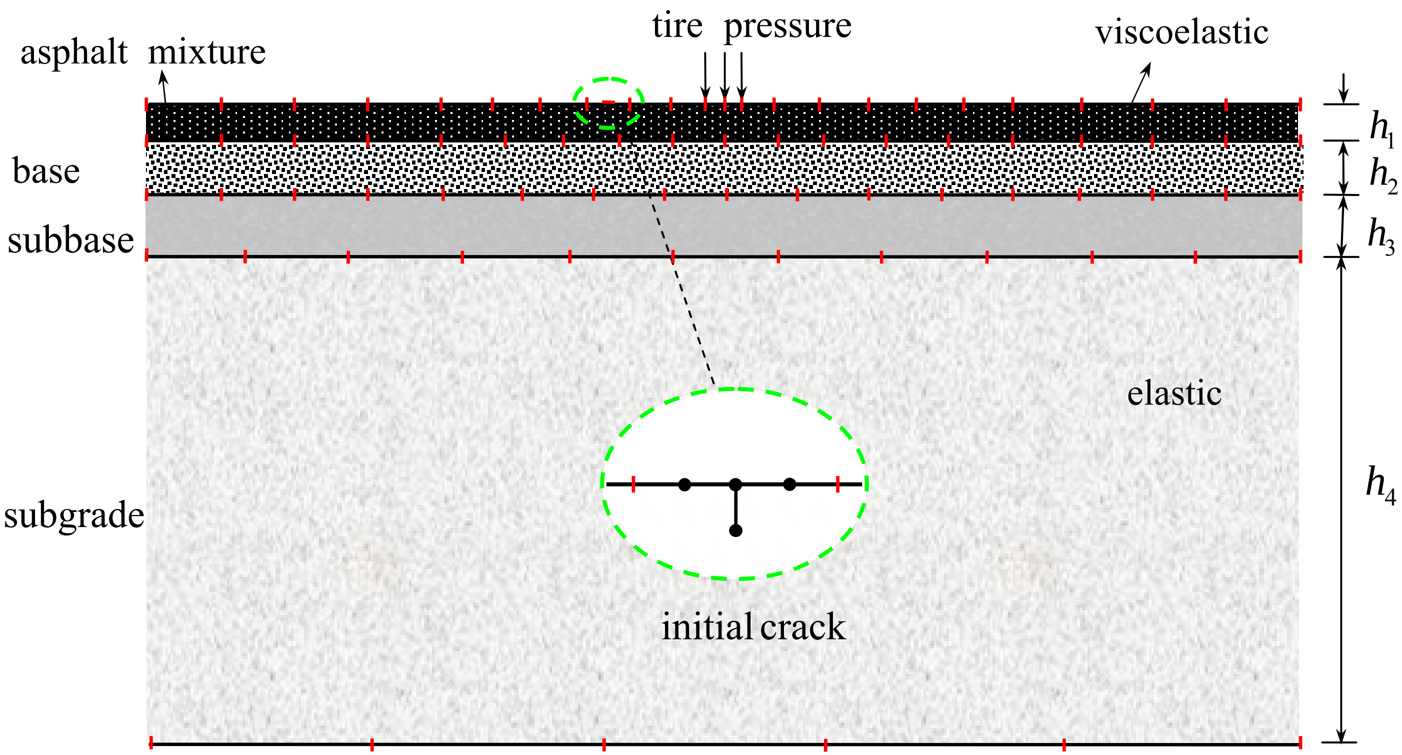
Field Prediction Results

Modeling of Field Test Sections

Multiple pairs of poor and good performing sections throughout Florida

- Over 18 pairs (36 sections) to date

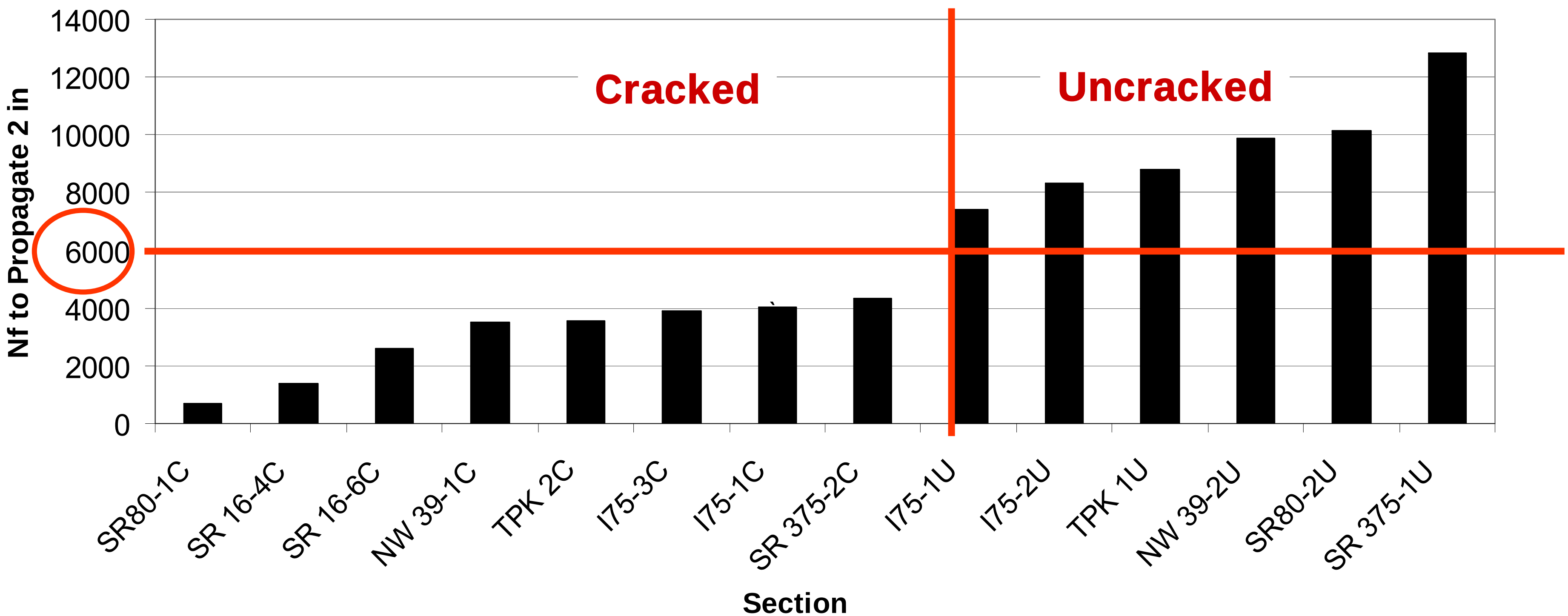
Boundary Element Model of Pavement Structure



- Assumption: Asphalt layer is linearly viscoelastic; the rest layers are linearly elastic

Predicted Load Cycles to Failure for Field Sections with Known Top-Down Cracking Performance

- Used the HMA Fracture Model to calculate Number of Cycles to Failure (N_f) for crack to propagate 2”

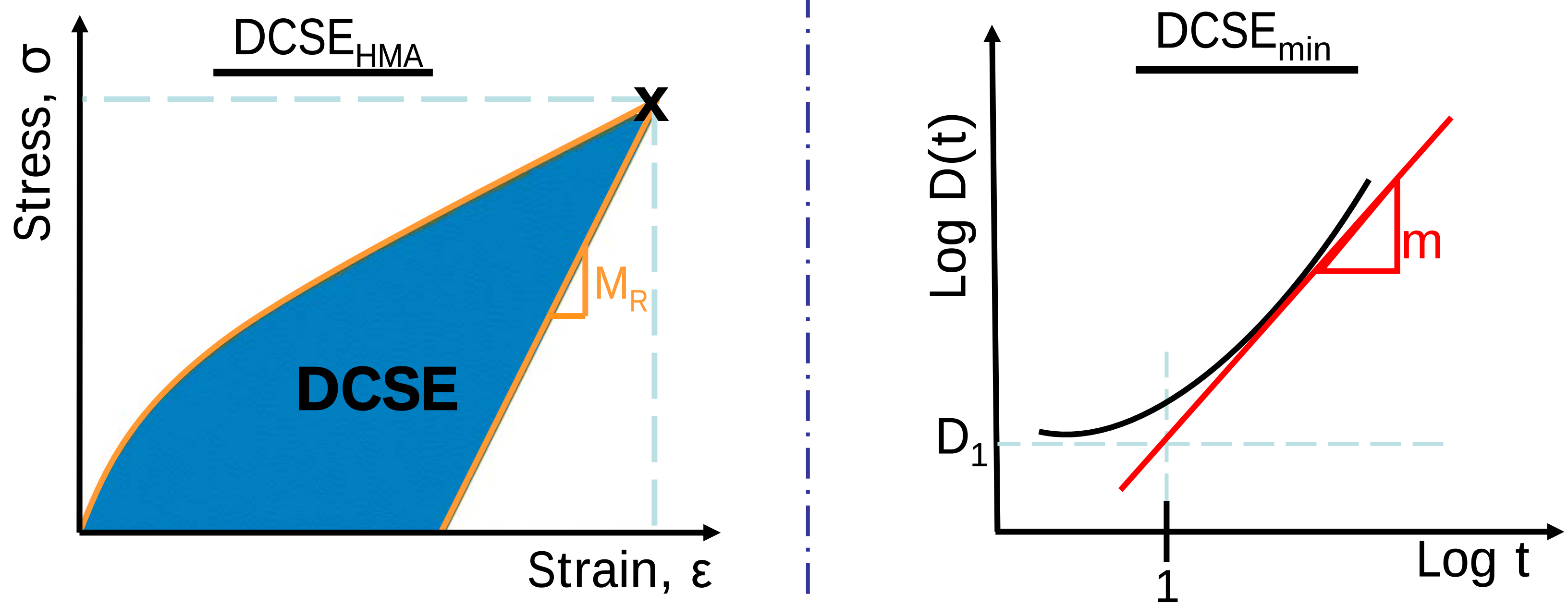


- The model was able to distinguish cracked from uncracked pavement sections

Implementation into Pavement Design

First Step: Use the Energy Ratio Concept

- The $DCSE_{HMA}$ has to be greater than the $DCSE_{min}$ for good cracking performance:



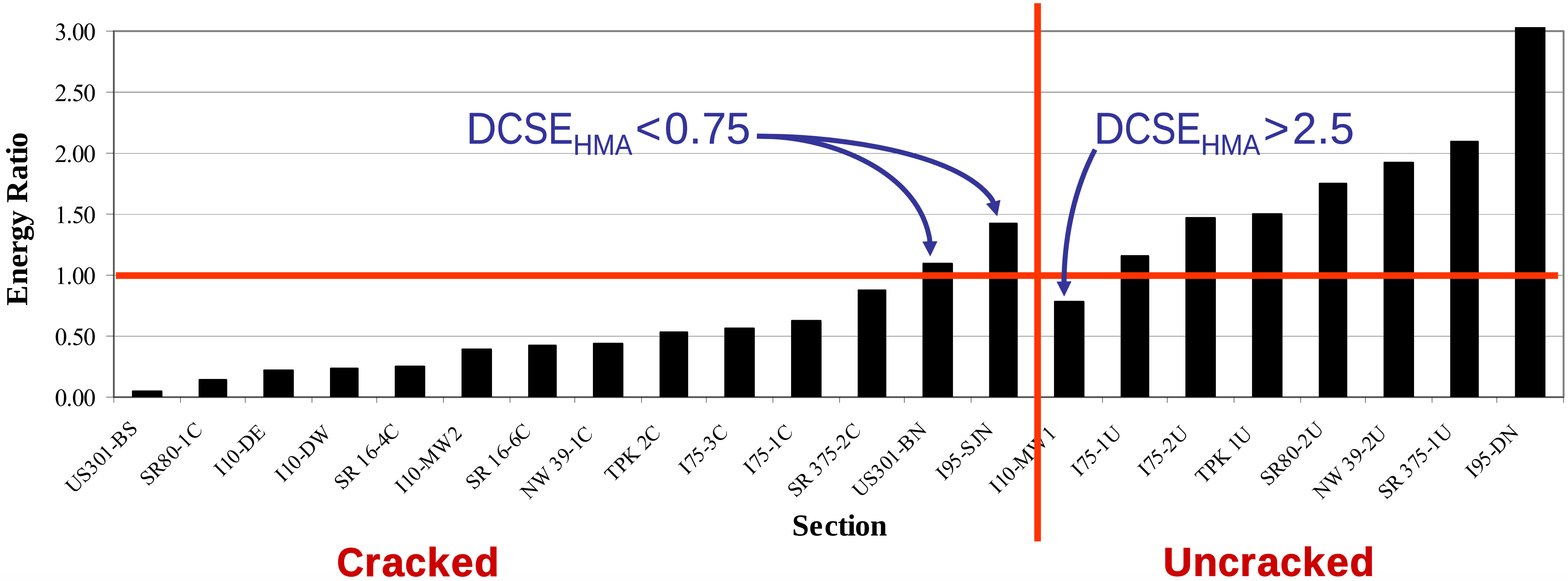
$DCSE_{HMA} = AREA$

$DCSE_{min} = m^{2.98} D_1 / A$

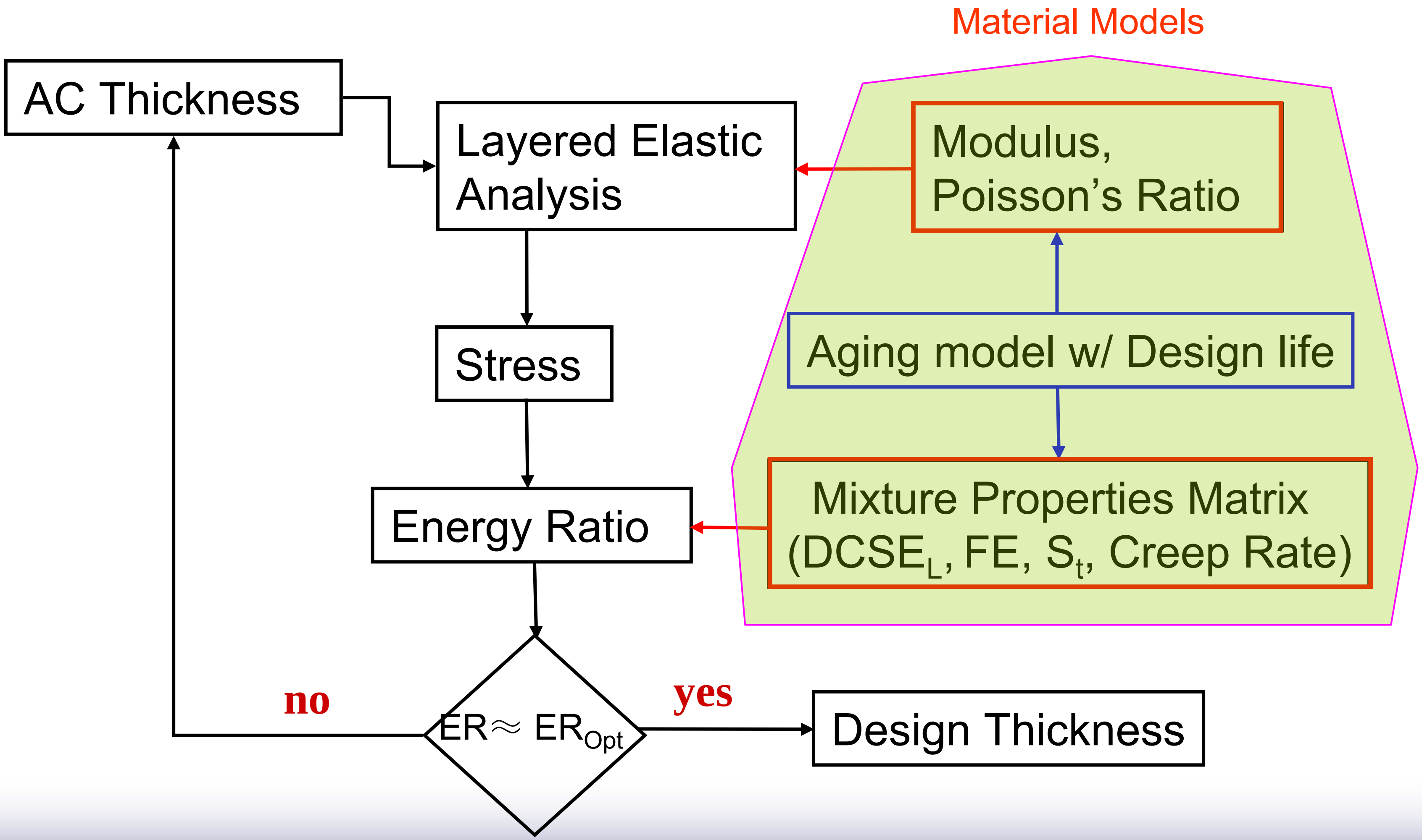
$$\text{ENERGY RATIO} = \frac{DCSE_{HMA}}{DCSE_{min}} > 1$$

Energy Ratio Results

- Examined all sections
- Performance criteria: ER>1 ; $DCSE_{HMA}$>0.75



M-E Design Flowchart – Level 3



Definition of $ER_{optimum}$ For Design

- Based on previous analyses, the optimum ER (minimum ER required) for design can be defined as

$$ER_{optimum} = \gamma / \varphi$$

Takes into account both the traffic and reliability effects

where

γ is the traffic factor

φ is the resistance factor

Higher reliability
↓
Lower resistance factor
↓
Higher required minimum ER

Higher traffic load (ESALs)
↓
Higher traffic factor
↓
Higher required minimum ER

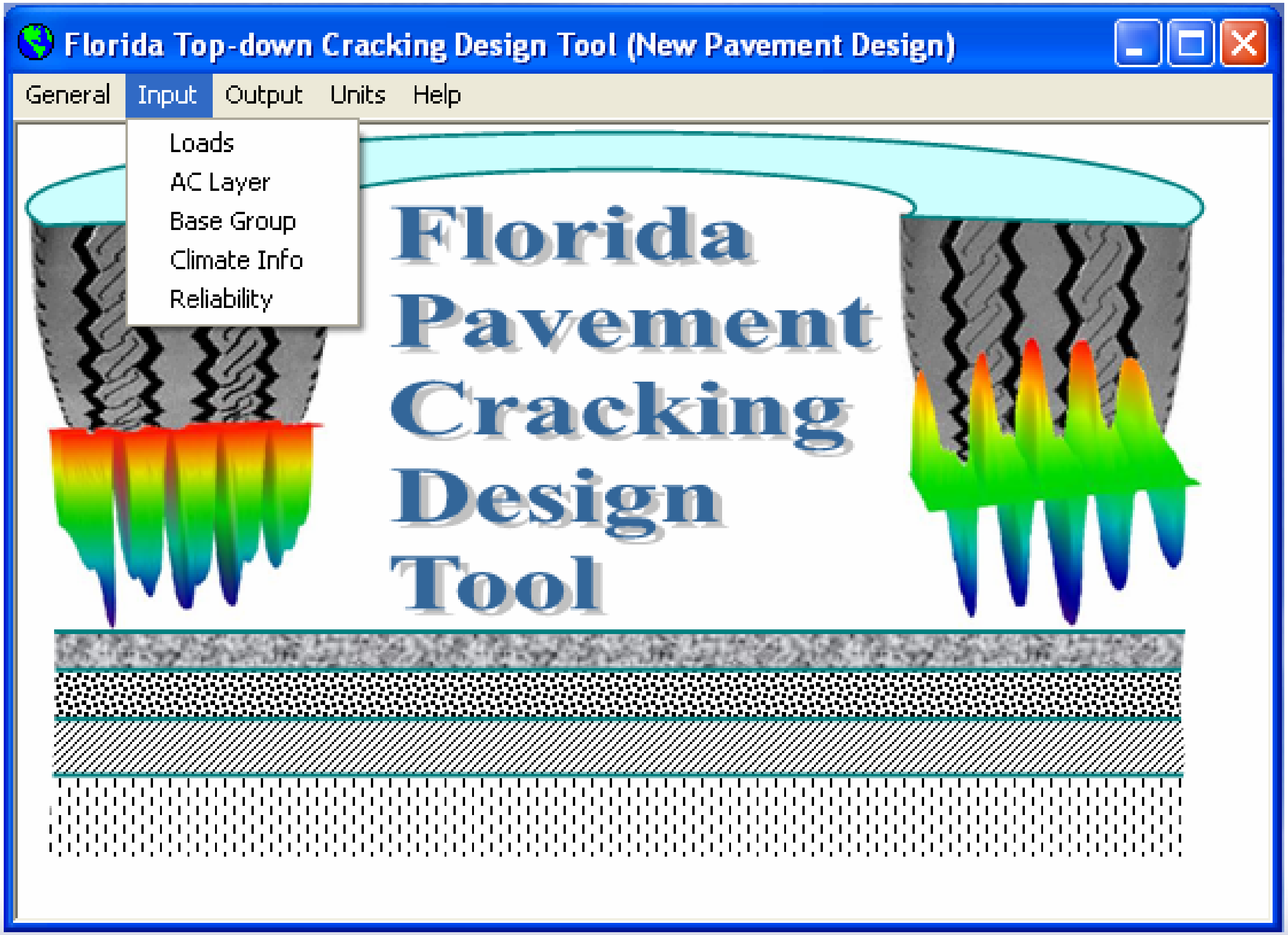
Mixture Properties

- Binder Viscosity
  - Global aging model and correction
- Elastic Properties – needed for stress calculation
  - $|E^*|_{AC}$: obtained from the master curve (MEPDG 1-37A & Florida version)
  - Poisson's ratio can be estimated from E_{AC}
- Superpave IDT parameters – needed for ER calculation
  - Creep parameters (m-value, D_0, D_1)
  - Energy limits (FE and $DCSE_L$)

    Estimated from basic relations developed based on the master curve and aging model
  - Tensile strength S_t (Obtained from the stiffness)

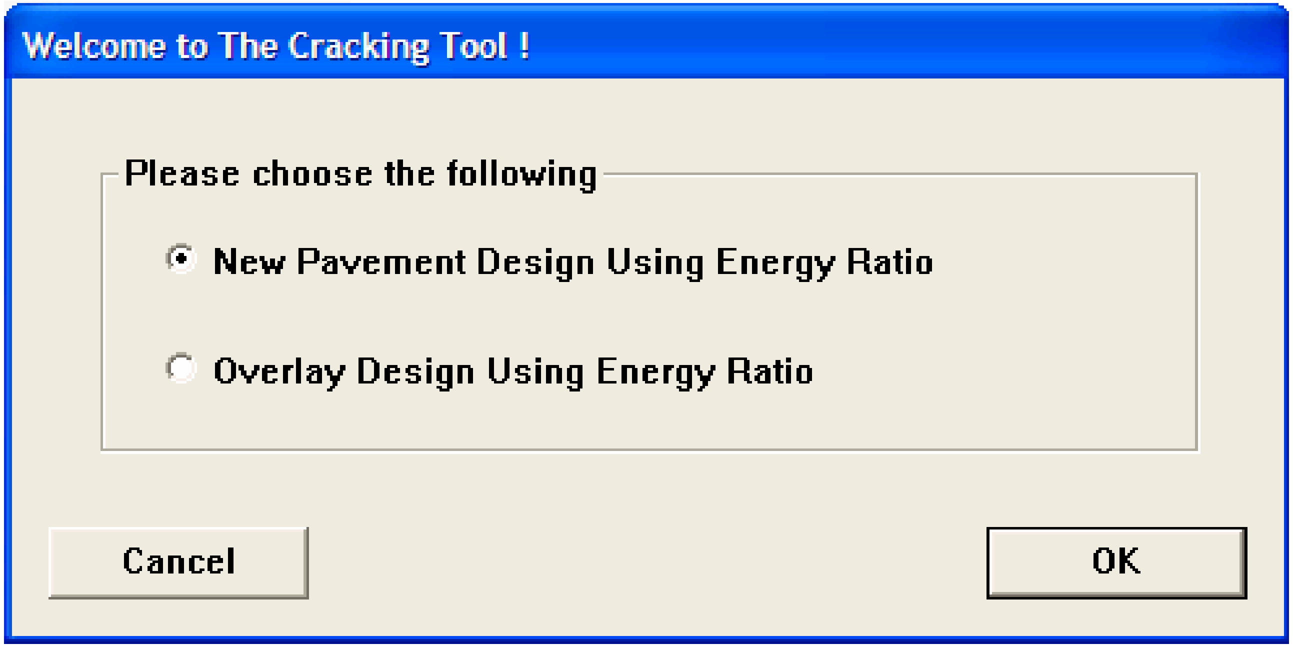
Windows-Based Top-Down Cracking Design Tool

Design Software

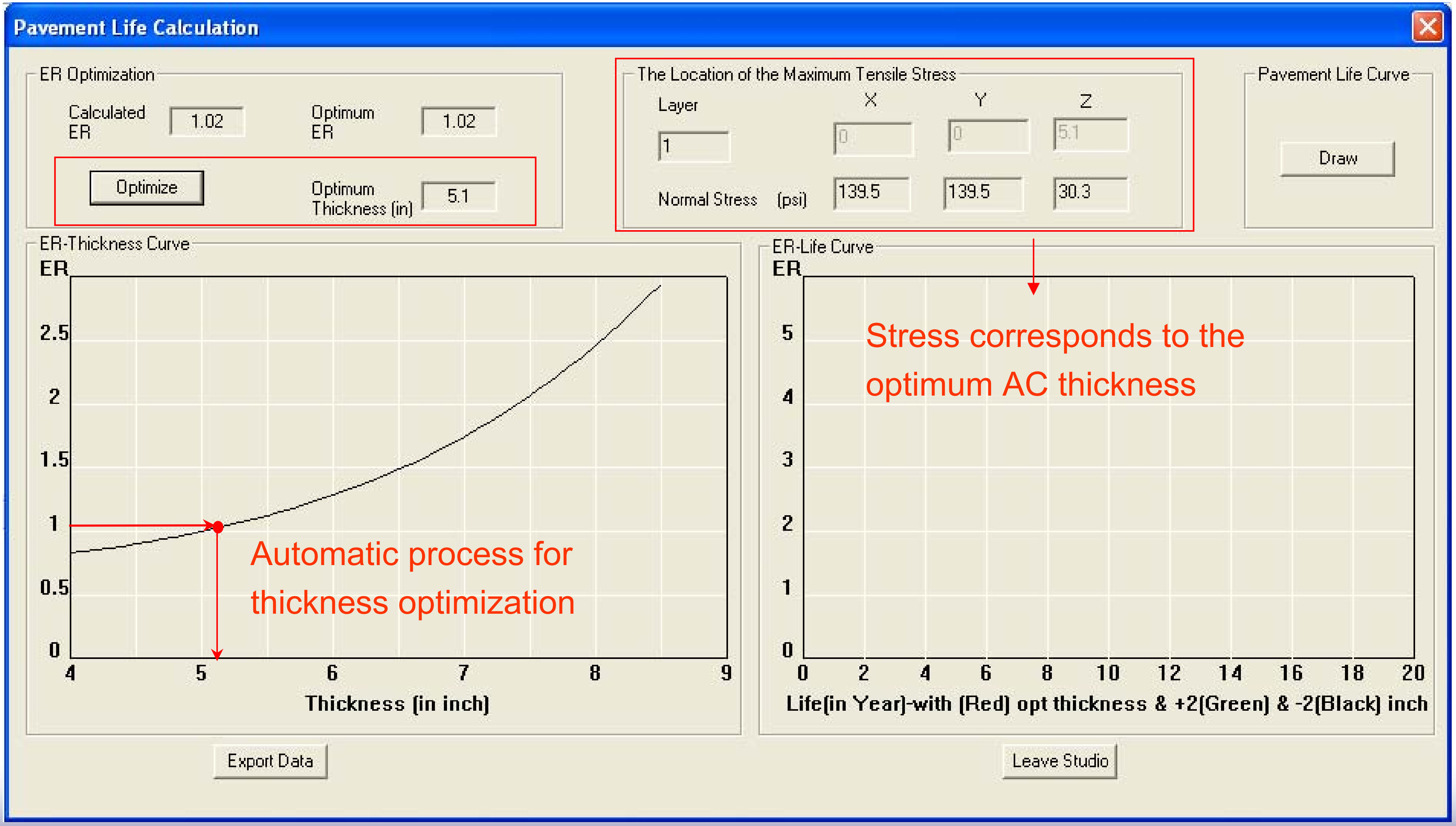


Design Studio

- New Pavement Design using Energy Ratio
- Overlay Design using Energy Ratio

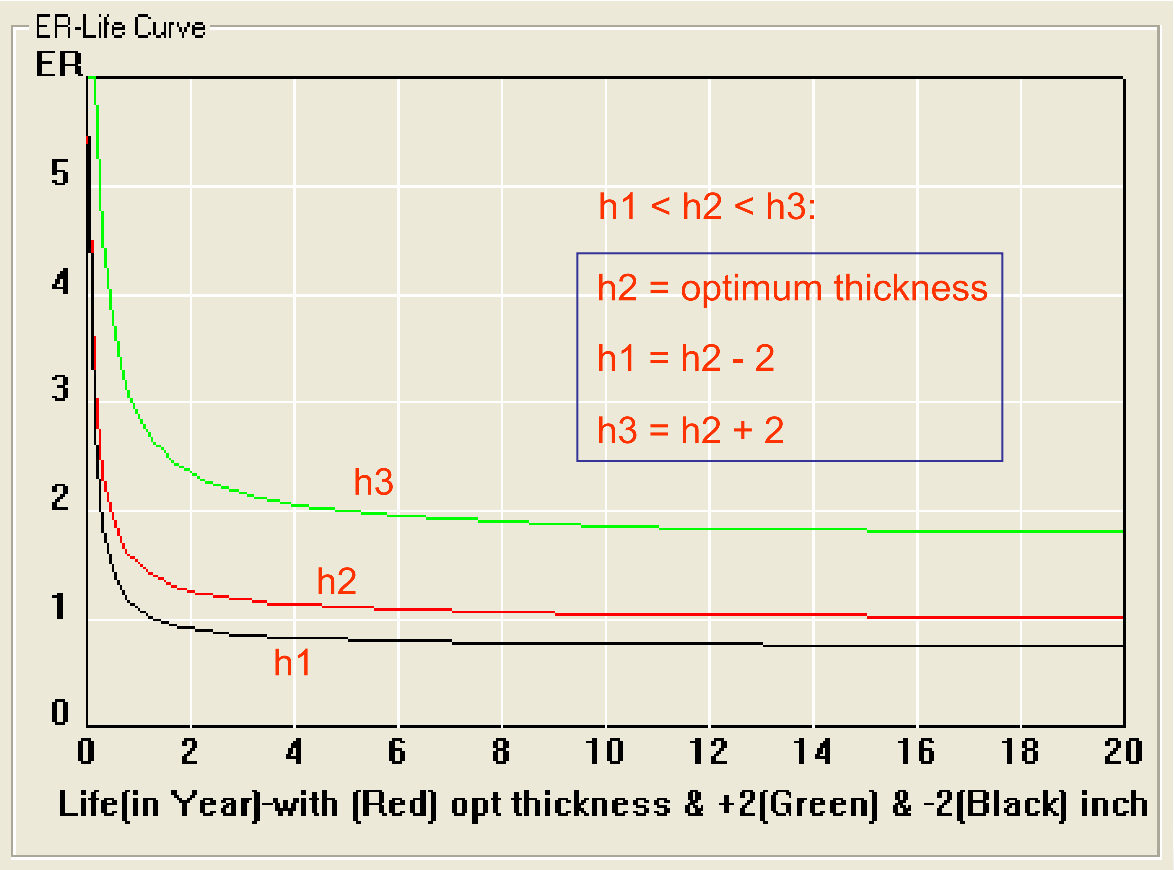


Output: Pavement Life Calculation



ER-Pavement Life Curve

- Variation of ER with pavement age for different AC thicknesses
  - ER drops down significantly in the first couple of years
  - Sensitivity of ER to thickness is shown in the graph



Summary

- A new M-E pavement design tool for top down cracking based on HMA Fracture Mechanics, Energy Ratio, and the Critical Condition Concept

  - Combines mixture fracture properties with pavement thickness design
  - Validated on more than 30 field sections
  - Thickness design optimized for
    - traffic level and reliability
    - mixture type
    - binder type
  - The thickness optimization is an automated process

Question?

Would a Paradigm Shift in Pavement Analysis and Design Increase Our Understanding and Accuracy of Cracking Performance Prediction?

- Traditional Fatigue Approach
  - Continuous cumulative distress
  - Repeated averaged conditions
  - Structure homogeneous with time/loads
  - Mechanism constant
- Critical Condition Approach
  - Stepwise discontinuous distress
  - Few critical design conditions
  - Structure changes with time/loads
  - Mechanism changes

Questions