

# HMA Fracture Mechanics

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Pavement Performance Prediction Symposium  
Laramie, Wyoming



# Objectives

- Define Fracture Mechanics and Illustrate Its Importance
- Illustrate How Fracture Mechanics Can Explain Changes in Failure Mechanisms When Other Theories may not
  - Fracture mechanics is necessary
- Describe and Illustrate the Key Features of HMA Fracture Mechanics
- Illustrate How Fracture Mechanics Can Help to Optimize Mixture and Pavement System Design
- Briefly Discuss Emerging Tools for Fracture Simulation in Pavements



# 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



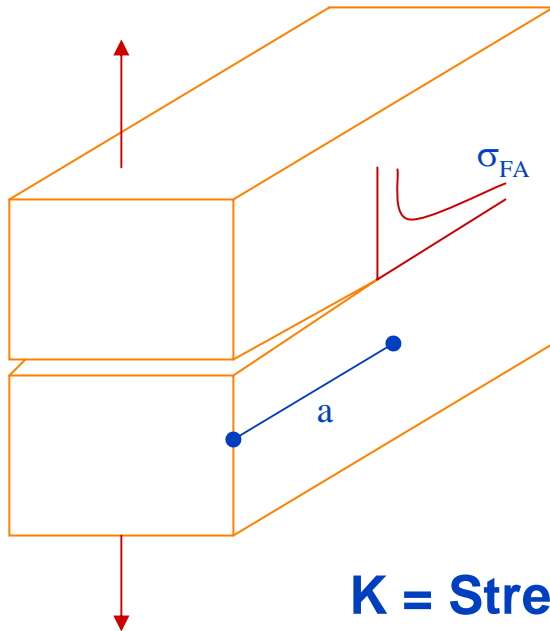
# Applications

- Identify/Design Pavement Systems to:
  - Resist crack initiation
  - Stop or minimize propagation
- Establish Guidelines for Mixtures that Resist Initiation and Propagation
- Identify Effective and Simple Test Methods and Parameters to Evaluate Fracture Resistance of Mixtures and Pavement Systems

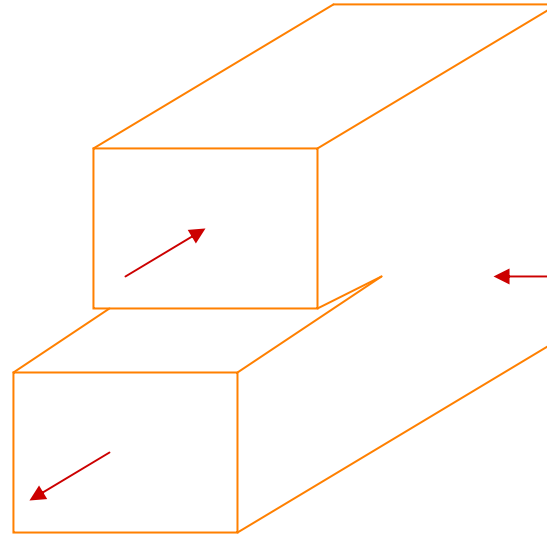


# Basic Theory

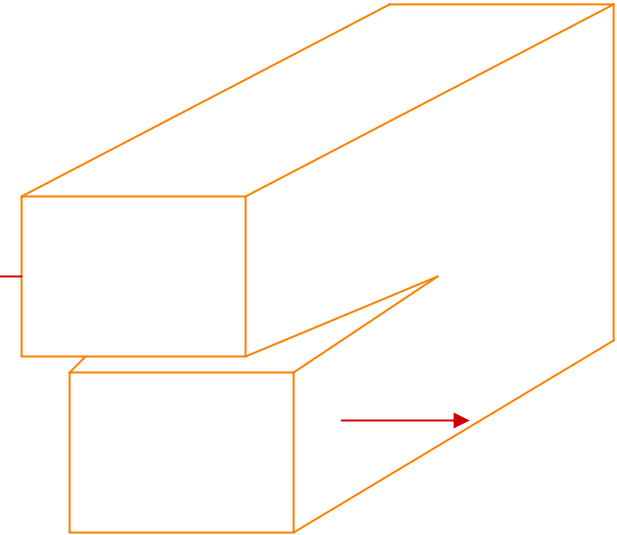
Mode I



Mode II



Mode III



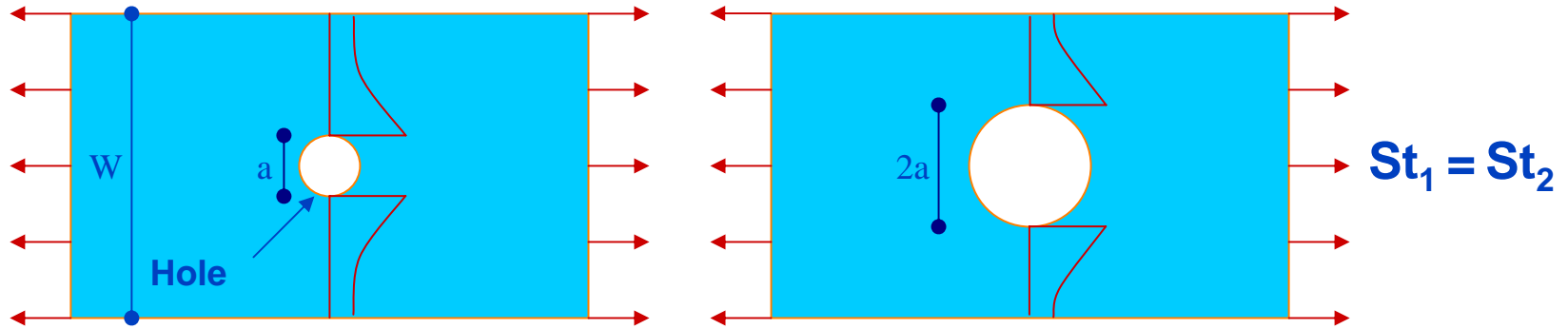
$K = \text{Stress Intensity Factor} = f(\sigma_{FA}, \text{geometry})$

$K_I = \text{Mode I Stress Intensity Factor} \cong \sigma_{FA} \sqrt{\pi a}$

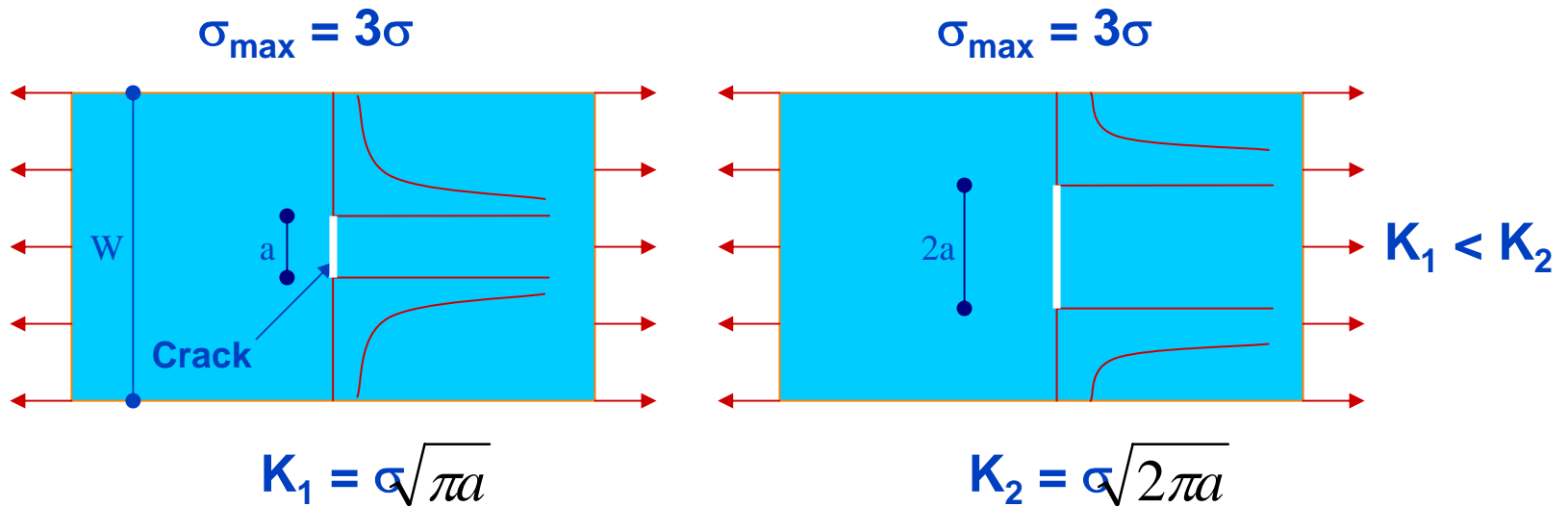
- Fracture @  $K_{IC}$  (one-time event)
- Controlled Crack Growth @  $K < K_{IC}$

# Stress Intensity $\neq$ Stress Concentration

## Hole/Void



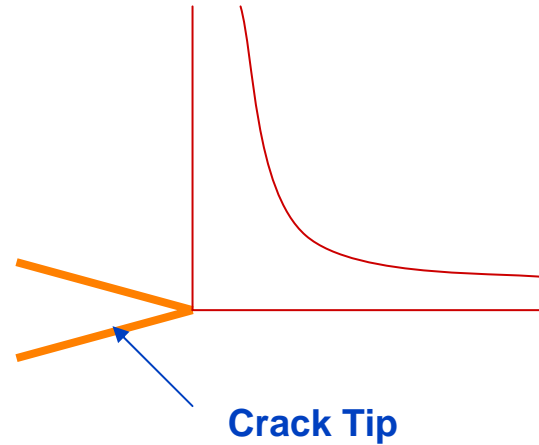
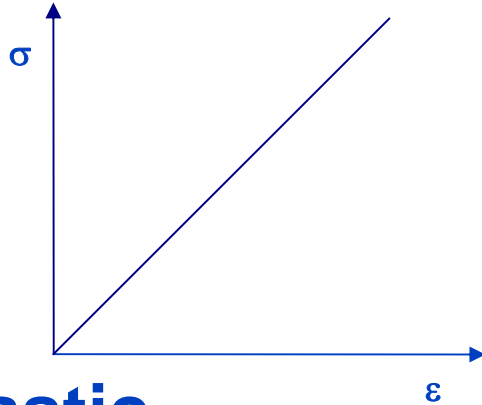
## Crack



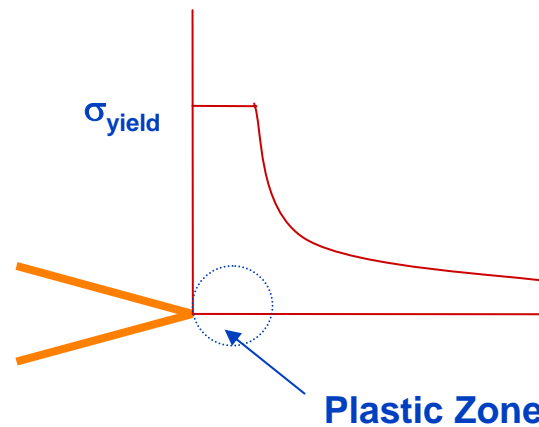
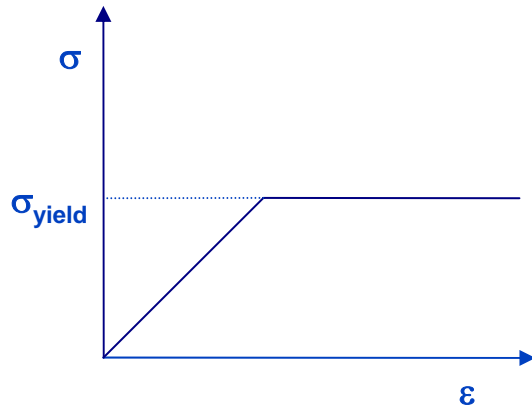
\* For  $a \ll W$

# FM Is Material Dependent.

## Elastic



## Elastoplastic



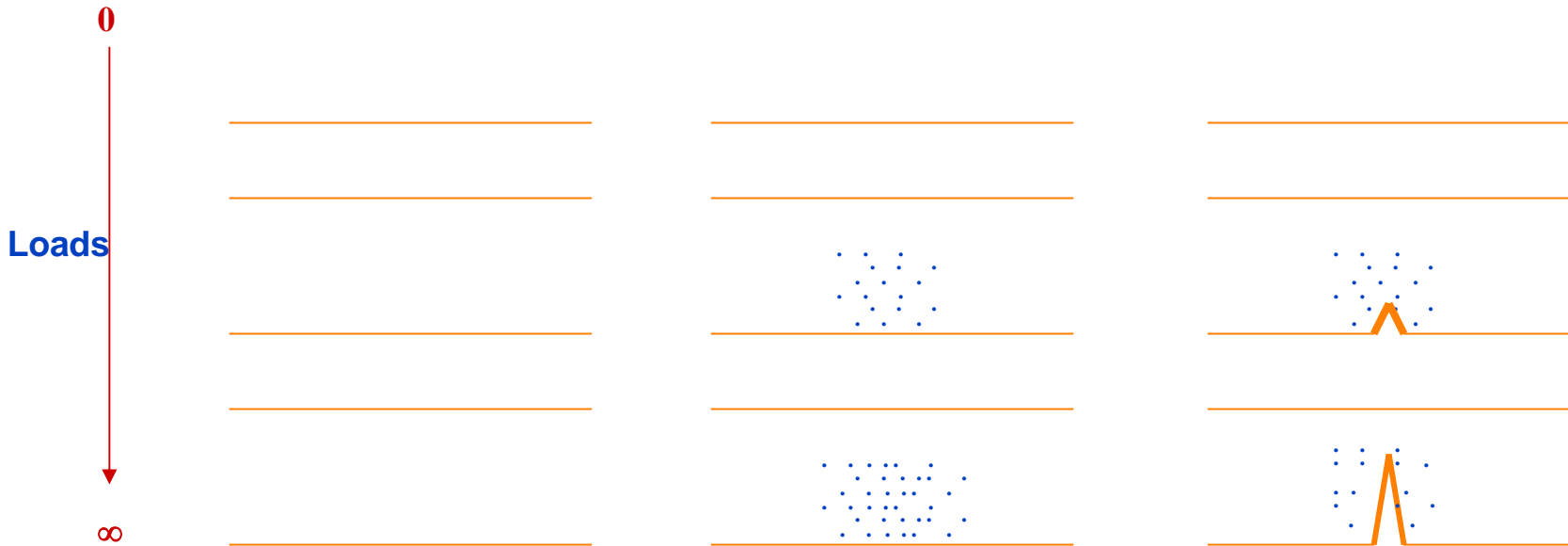
- Theory Depends on How Material Dissipates Stress (Energy) Near Crack Tip

# Representing Cracking Mechanism

**Traditional Fatigue**

**Continuum Damage**

**Fracture Mechanics**



**No Change**

- **Reduced Modulus**
- **Stress Concentration**

- **Geometry Change**
- **Stress Intensity**



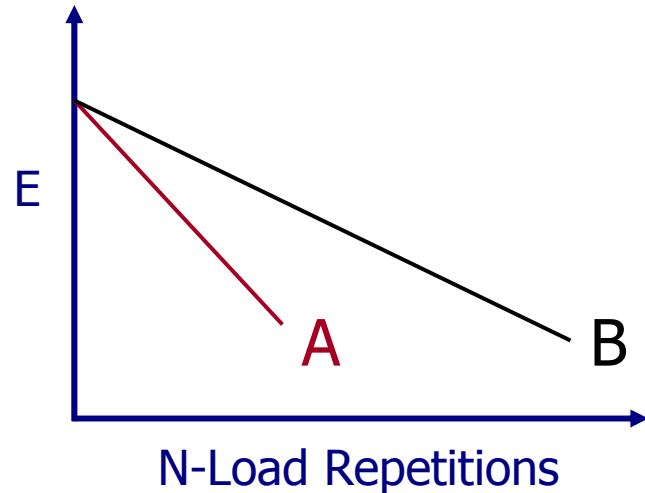
# Traditional Fatigue & Variations

- Cumulative Damage leads to fatigue failure
- $N_f = A \left( \frac{1}{\varepsilon} \right)^n$
- State of material never changes; no effect on response of material or pavement (i.e. no localization)
- No fundamental description of damage or “failure”



# Traditional Fatigue & Variations

Failure when  $E < \frac{1}{2}E_0$ ?

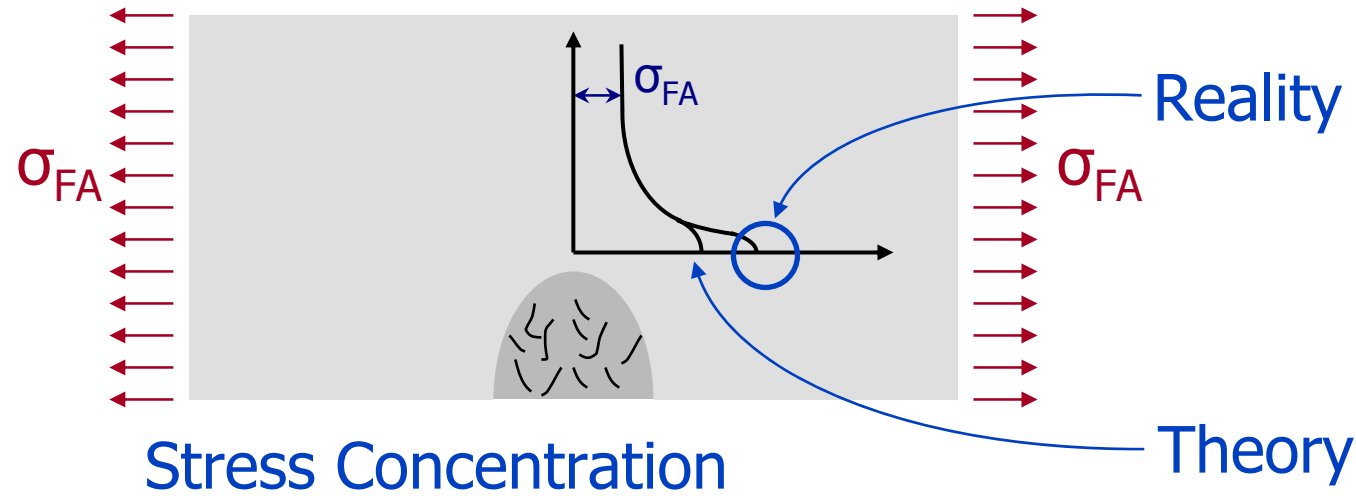


- Matl A damages faster than Matl B ( $E$  reduced in less reps). Does Matl A fracture faster than Matl B?
- Tolerance is independent of rate of damage. Matl A might have a higher threshold than B.

Need to consider the concept of a **threshold**

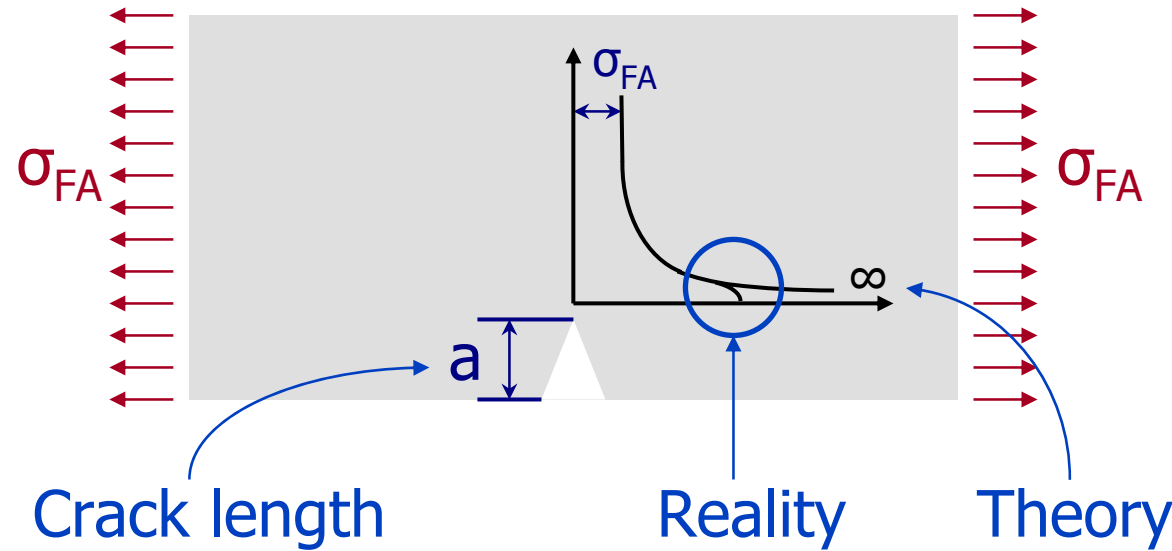


# Continuum Damage Mechanics



- Cumulative Damage leads to failure
- Micro-damage = Micro-cracks
- No fundamental description of "failure"
  - Failure =  $\frac{1}{2} E_0$
  - No stress intensities

# Fracture Mechanics



## Critical Condition

$K_I \equiv$  Tension Mode

$$K_I \cong \sigma_{FA} \sqrt{\pi a} \text{ (General)}$$

## Critical Stress Intensity Factor

$$K_{I(C)} \cong \sigma_{FA(C)} \sqrt{\pi a} \text{ (Critical)}$$

- When  $\sigma_{FA} = \sigma_{FA(C)} \rightarrow$  Uncontrolled Cracking
- When  $\sigma_{FA} < \sigma_{FA(C)} \rightarrow$  Controlled Crack Growth (crack will not go through the entire cross-section)

# Traditional Fracture Mechanics

## Example: LEFM

Paris Law  $\frac{da}{dN} = A(\Delta K)^n$

$A, n$  – material constants  
 $\Delta K$  – change in stress intensity

Basic Assumption:

Each time we load the material,  
the crack propagates

- Micro-damage = Macro-damage = Cracking
- No distinction between micro- and macro-cracks
- Propagation only



# HMA Fracture Mechanics

- Damage = DCSE accumulation (Micro-cracks)
- Fracture = Macro-crack initiation and growth
  - Driven primarily by tension
- There is a **threshold** – separates damage from failure
- Not all damage is permanent
  - Damage is permanent only when the threshold is exceeded
  - Damage below the threshold is healable

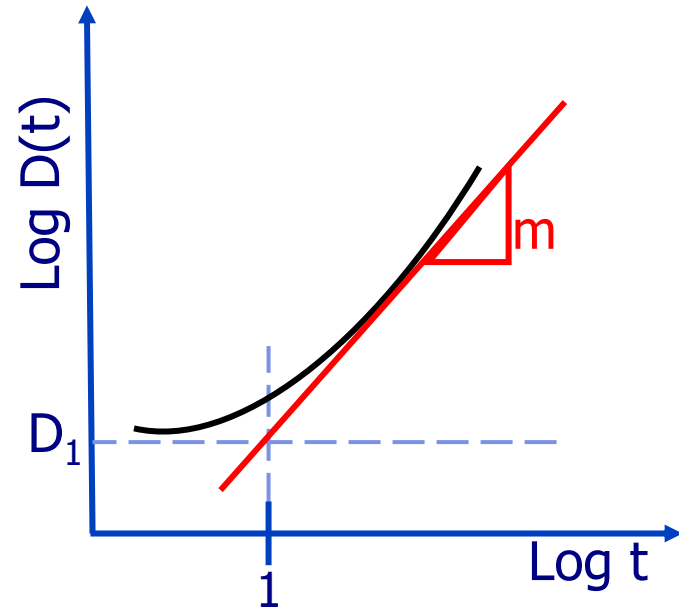
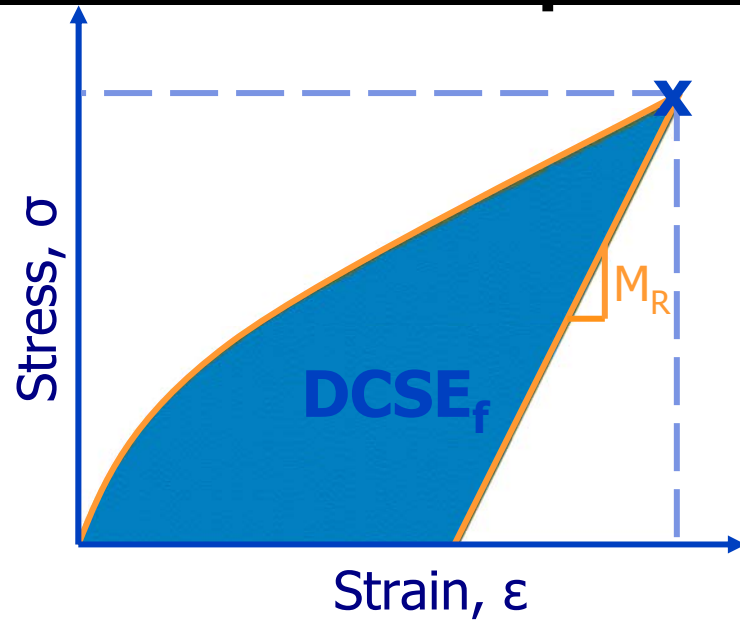


# HMA Fracture Model

- Calculates crack initiation and growth for a given level of applied stress
- Using:
  - Material properties
    - $m$ ,  $D_1$  for DCSE accumulation (tensile creep test)
    - $DCSE_f$  and FE thresholds (tensile strength test)
  - Structural model for stress distribution
    - FEM or BEM (more later)



# Material Properties

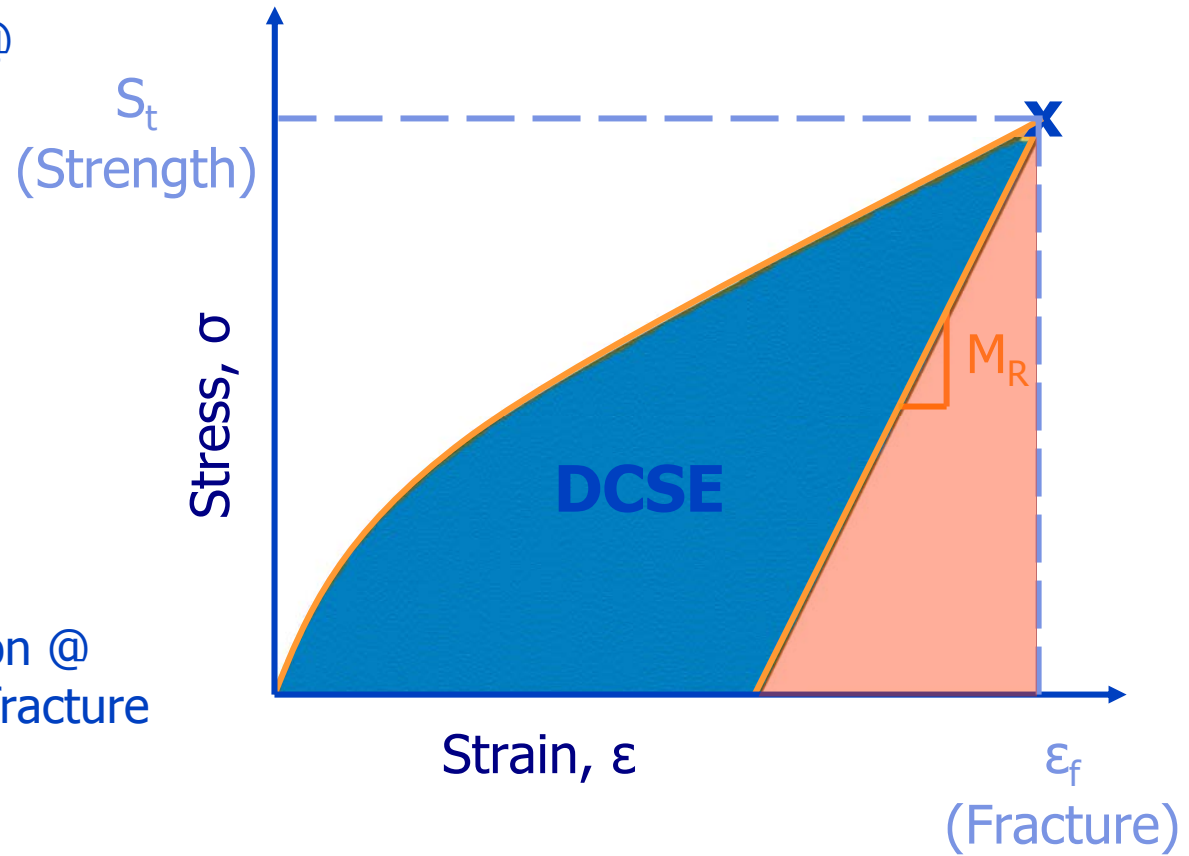
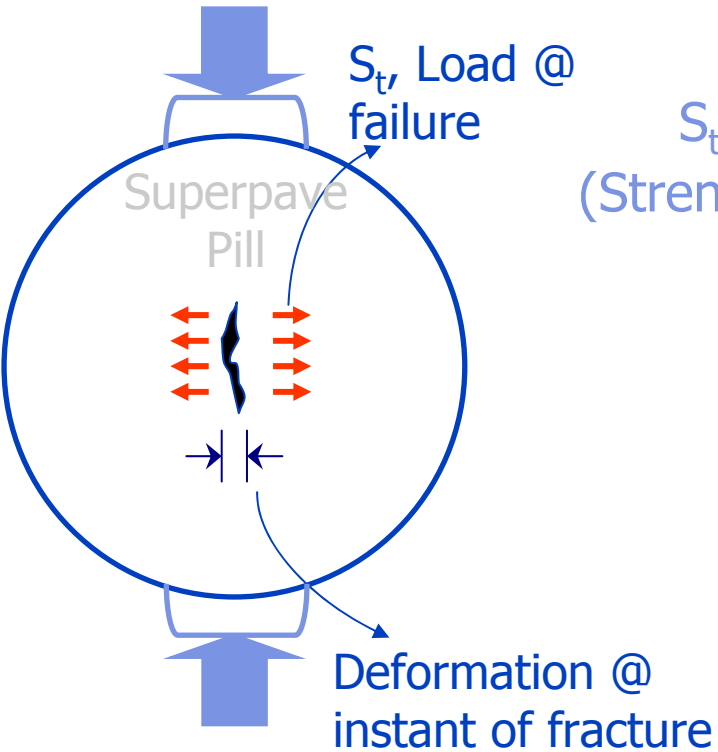


Fundamental properties control mixture damage and fracture

- $m$  and  $D_1$  control DCSE (damage)
- $DCSE_f$  limit controls crack initiation/growth

# Fracture Energy Failure Limits

Based on the  $M_R$  and Strength tests



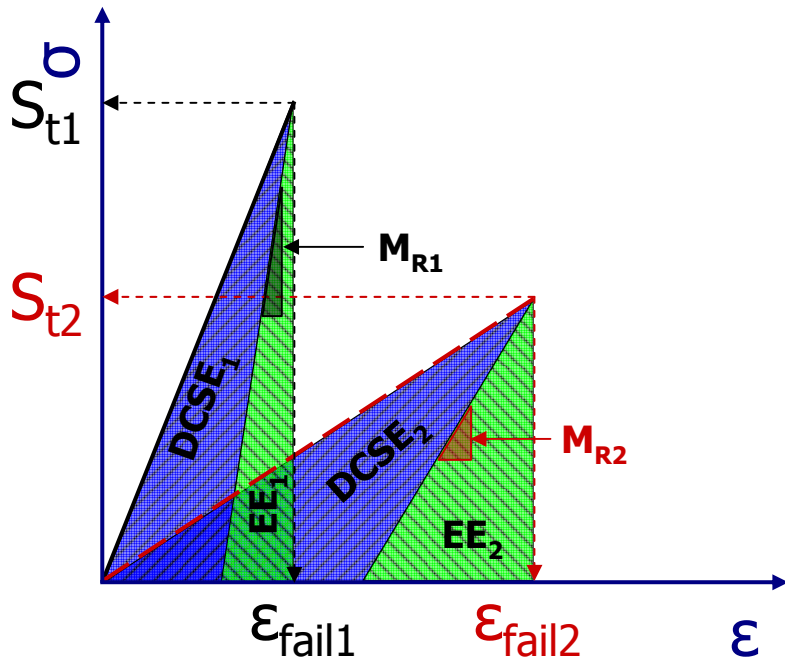
# Fracture Energy Failure Limits

## Strength (Fracture) Test

————— Fast Loading Rate

- - - - - Slow Loading Rate Low Damage prior to Fracture

High Damage prior to Fracture



$$S_{t1} > S_{t2}$$

$$\epsilon_{fail1} < \epsilon_{fail2}$$

However

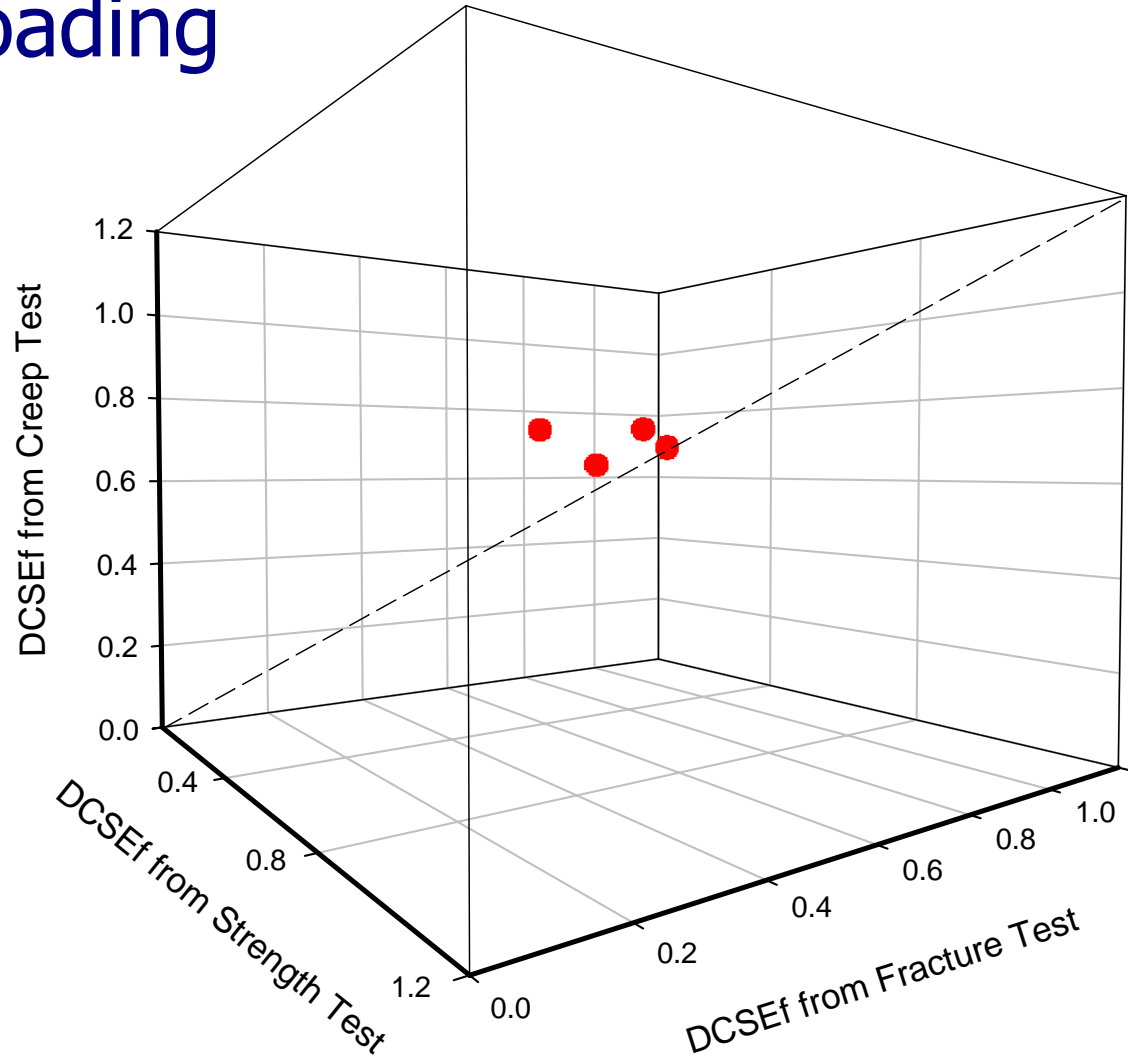
$$DCSE_1 \cong DCSE_2$$

$$FE_1 \cong FE_2$$



# The Threshold

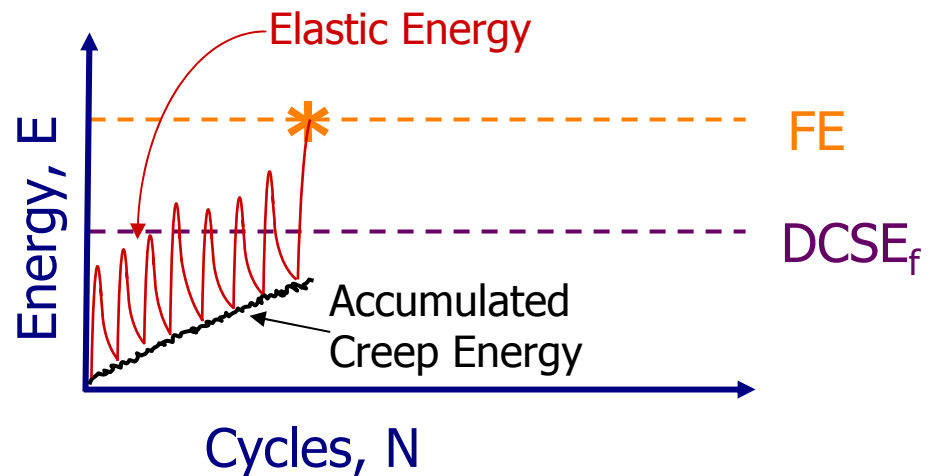
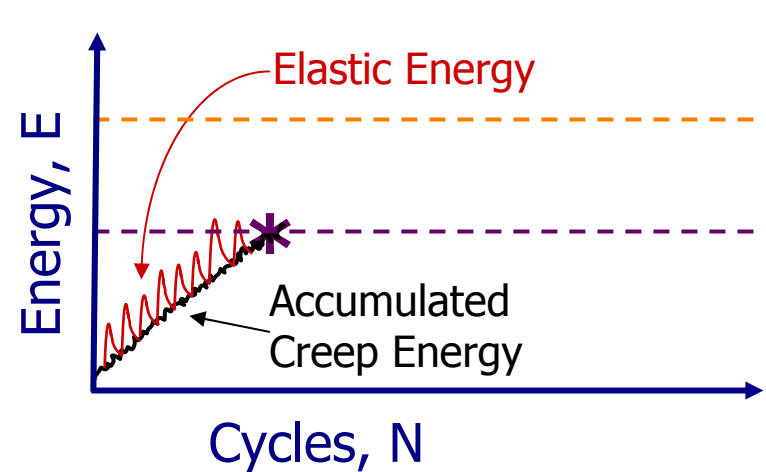
- The threshold is **fundamental** – independent of mode of loading
  - Strength
  - Cyclic
  - Creep



# Failure Threshold

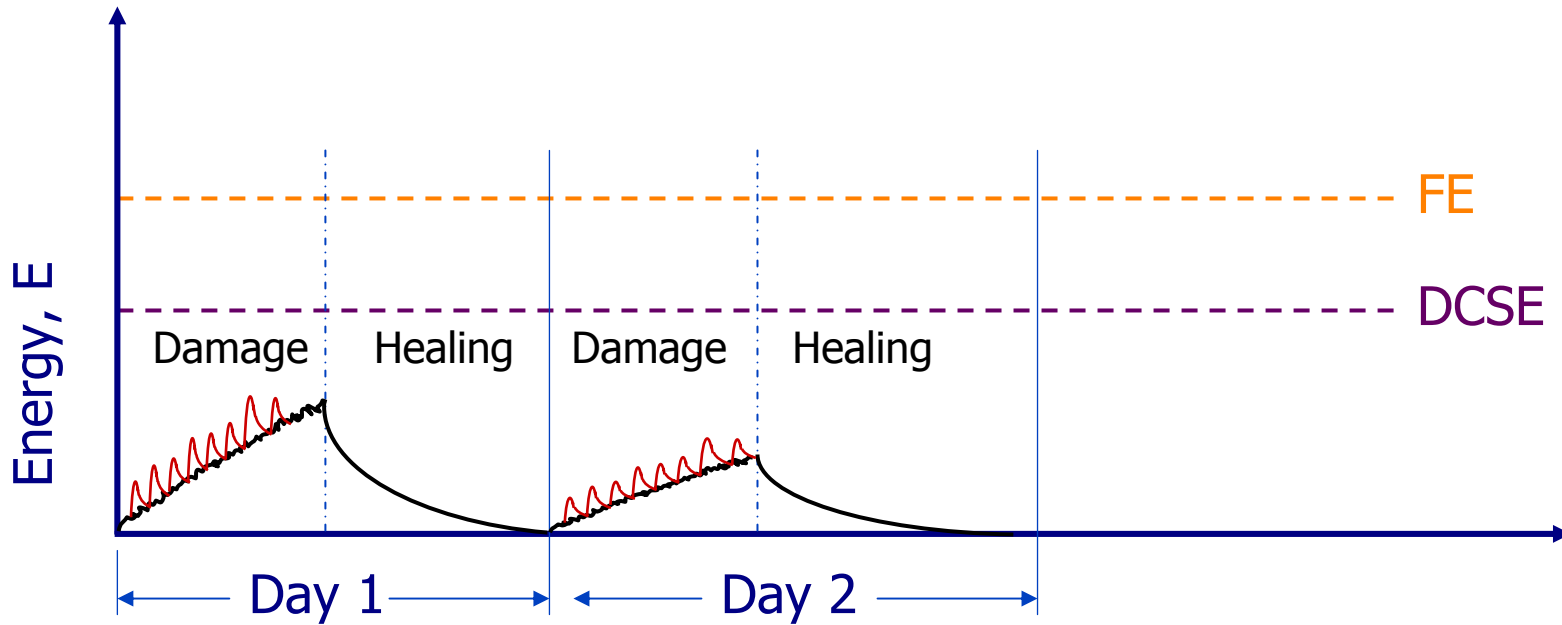
The material can fail in two ways:

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



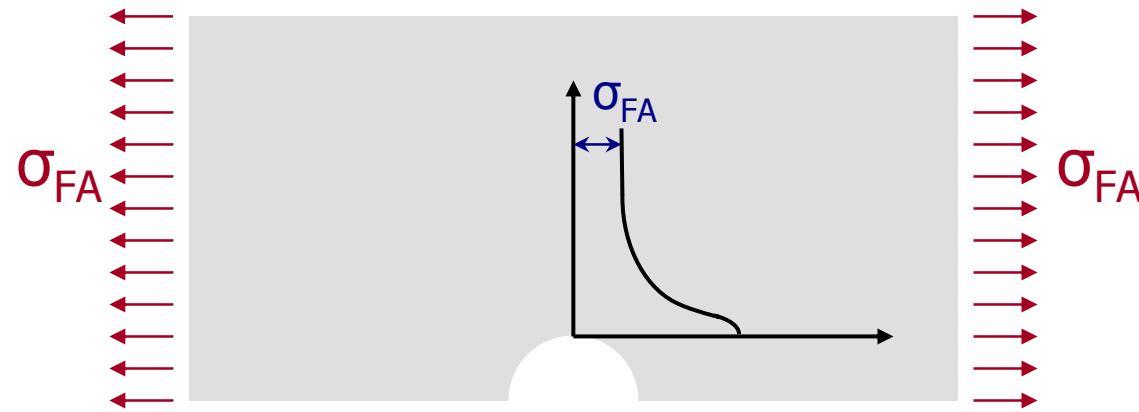
# Failure Threshold

## Potential loading conditions in the field

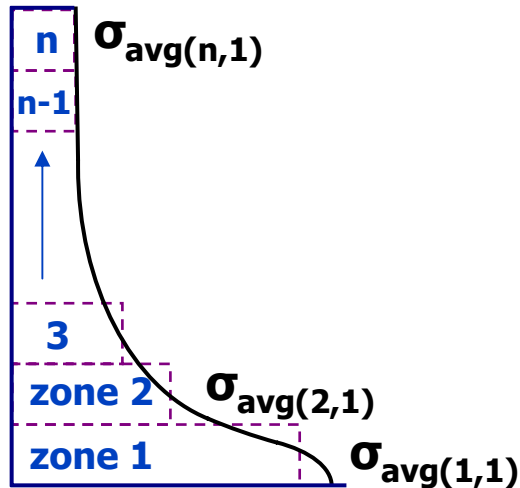


# Crack Initiation and Growth Model

## DCSE accumulation in each Zone



Crack initiates when DCSE exceeds DCSE limit in zone 1



$\sigma_{avg(i,j)}$

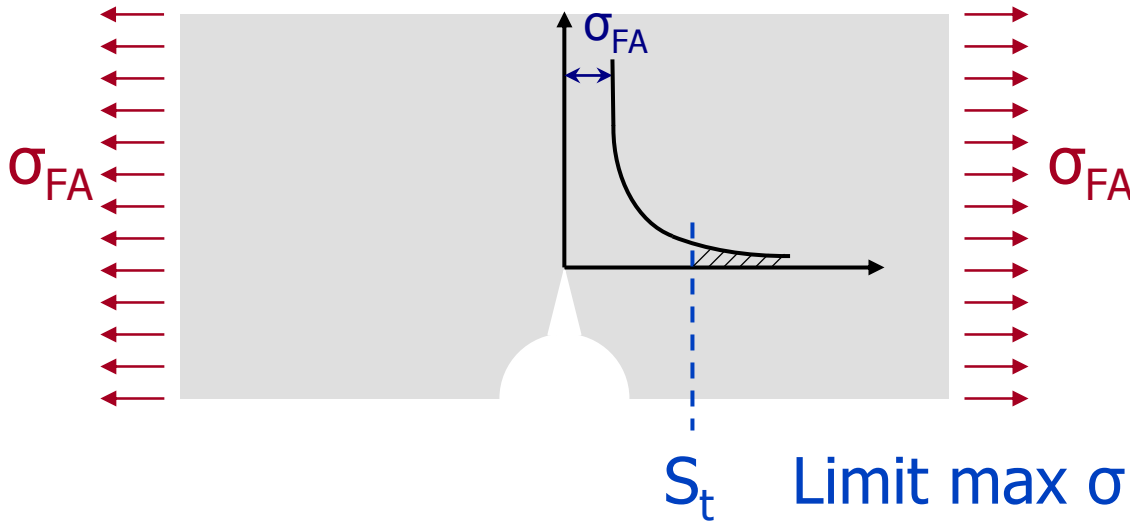
Where:

$i = \text{zone \#}$

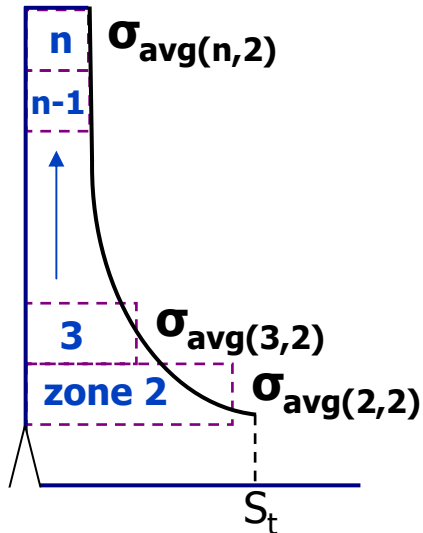
$j = \text{condition \#}$

# Crack Growth Model

## Crack Propagation Begins

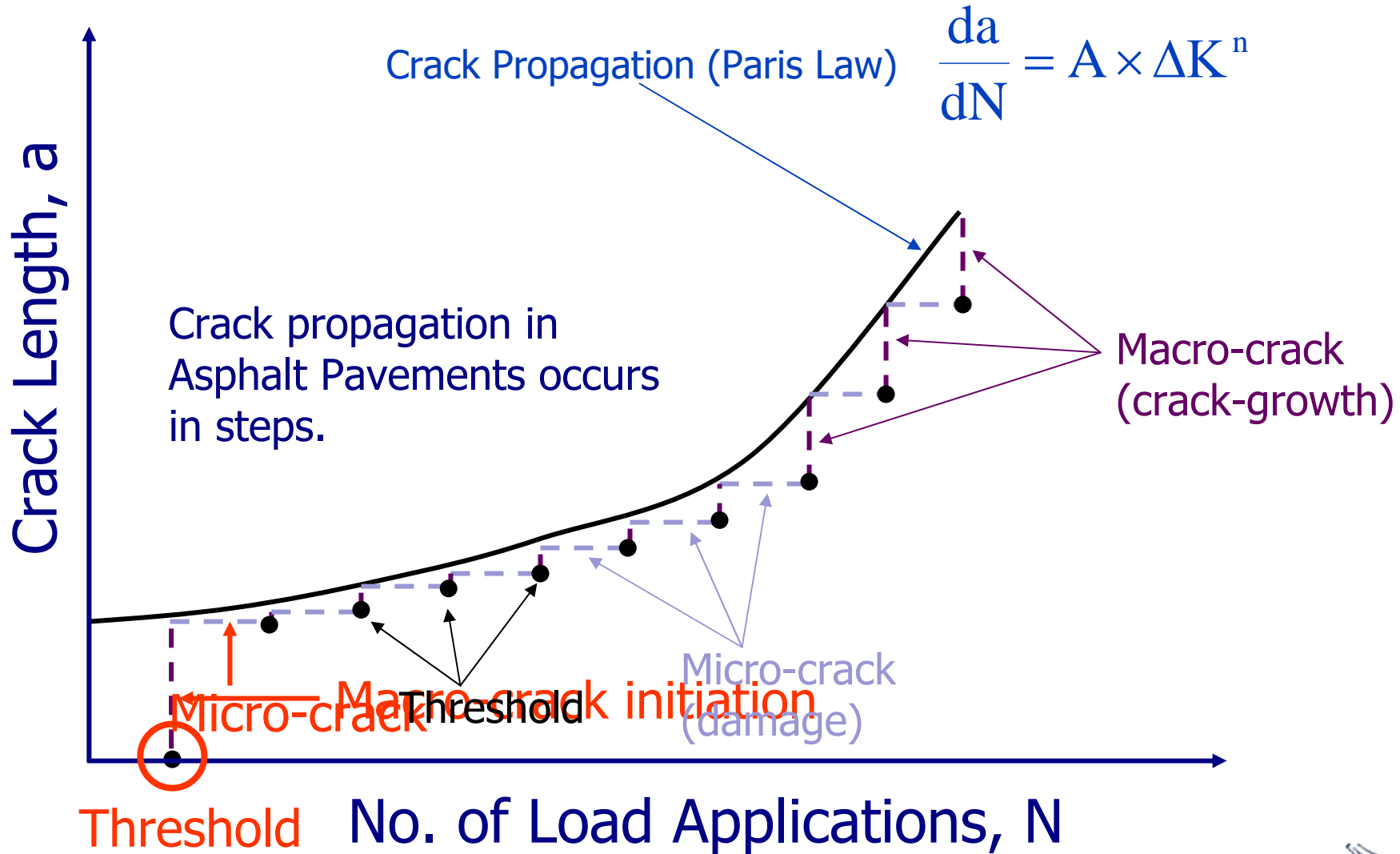


- Problem now changes from stress concentration to stress **intensity**
- Need new stress distribution

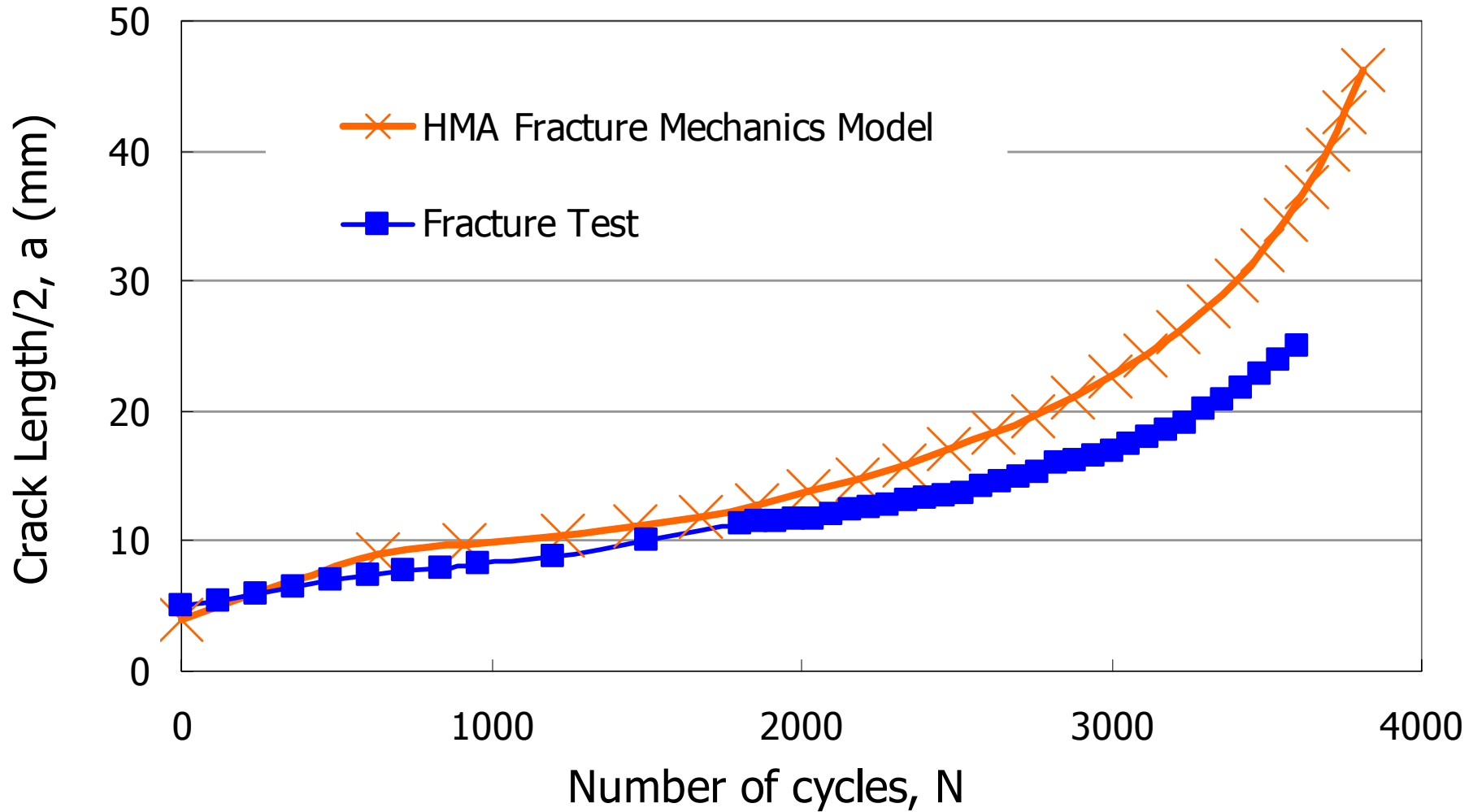


- The crack initiated through zone 1
- Stresses redistribute throughout the remaining zones
- Propagation continues only when DCSE/FE limit is exceeded in zone 2

# Crack Growth Model

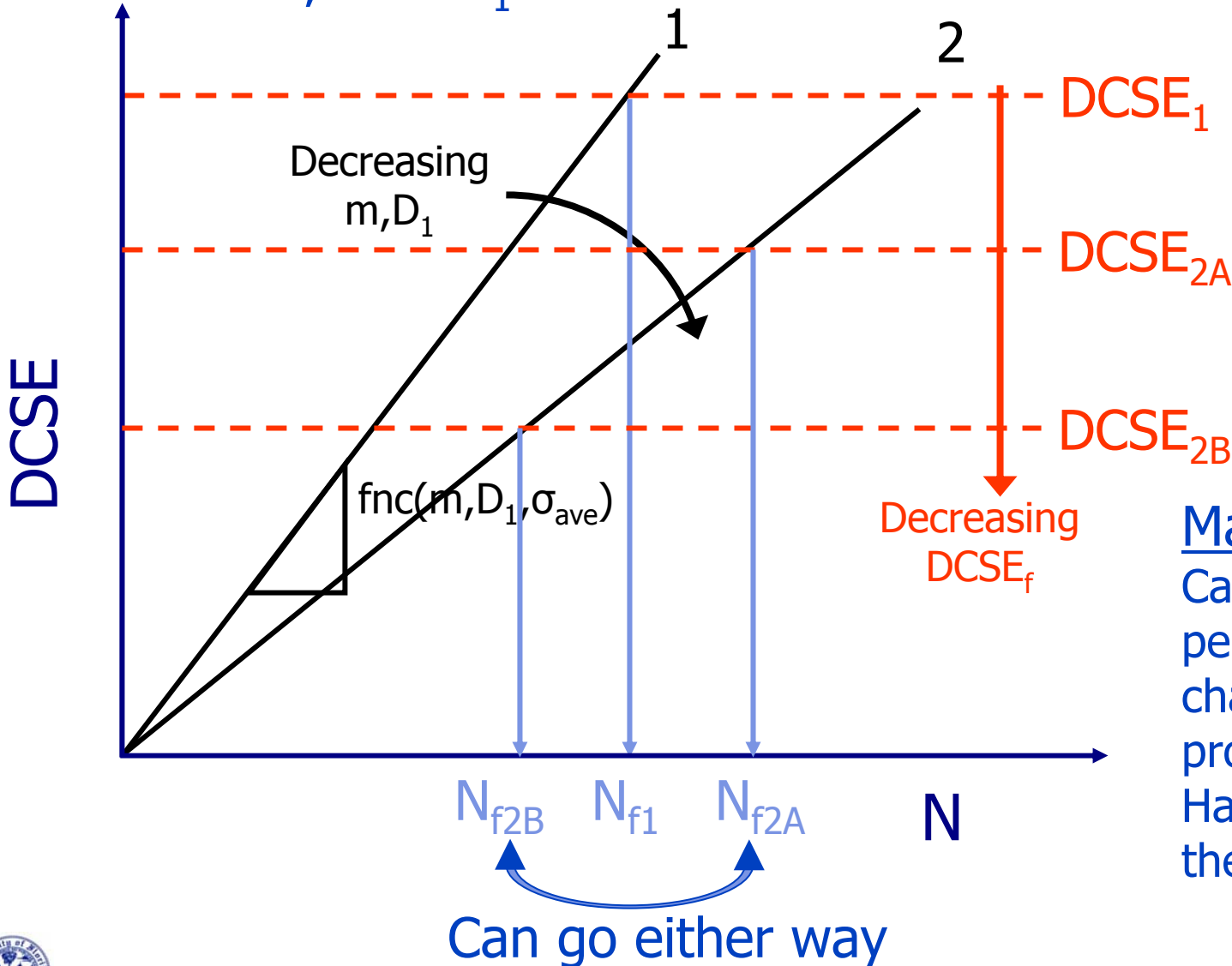


# Crack Growth Model



# HMA Fracture Model

DCSE,  $m$  &  $D_1$  are interrelated



Main Idea:  
Can not improve performance by changing a single property.  
Have to consider the entire system.

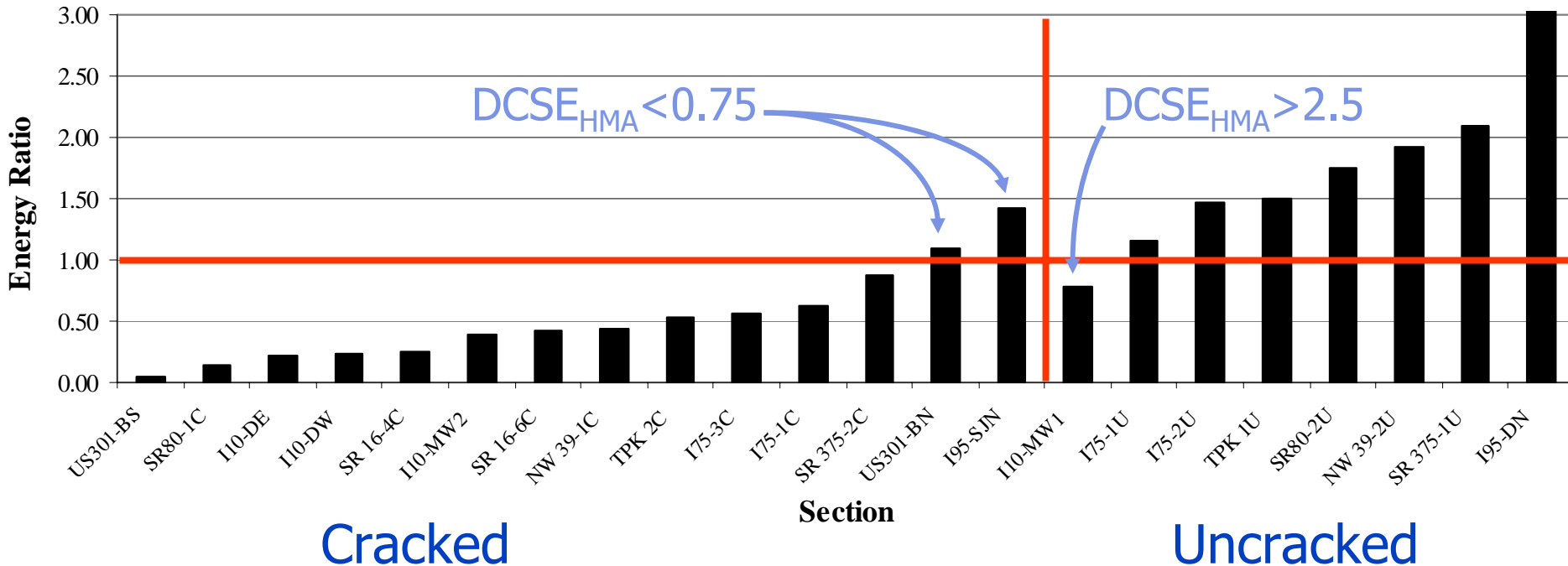
# Field Study

- 25 field test sections to-date.
  - Continuing study w/ 12 additional planned
- Comprehensive evaluation:
  - Volumetric properties
  - Material properties
  - Effect of traffic loads and tires
  - Pavement structure (pavement design)



# Energy Ratio Results

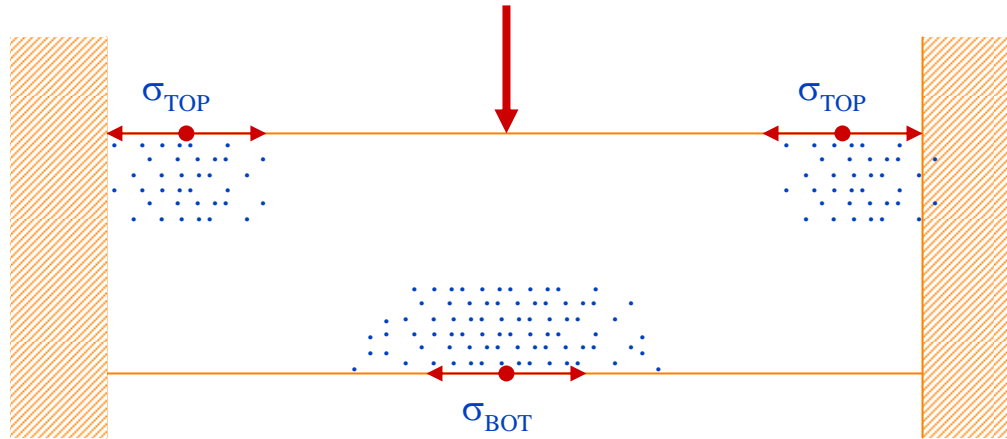
- Examined all sections
- Performance criteria:  $ER > 1$  ;  $DCSE_{HMA} > 0.75$



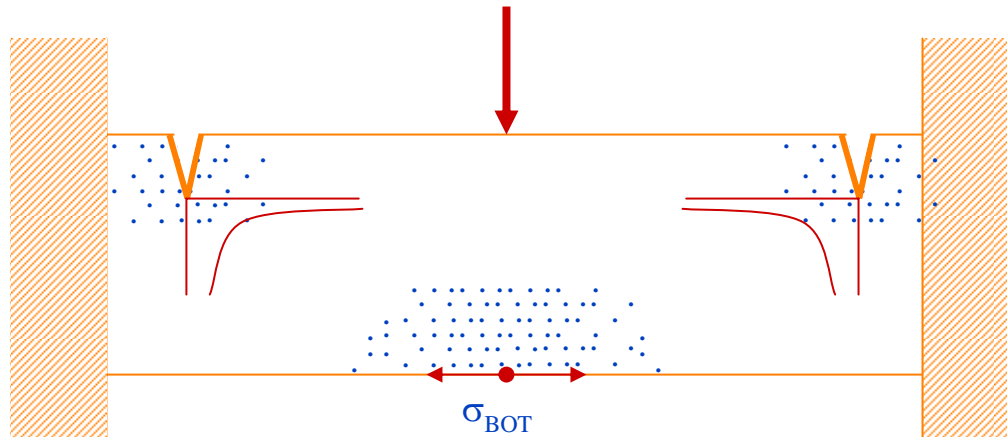
# Fracture Mechanics to Explain Failure Mechanisms in Pavement Systems



# Effect of Crack on Failure Mode



$\sigma_{TOP} = \sigma_{BOT}$   
Bottom Crack  
More Likely

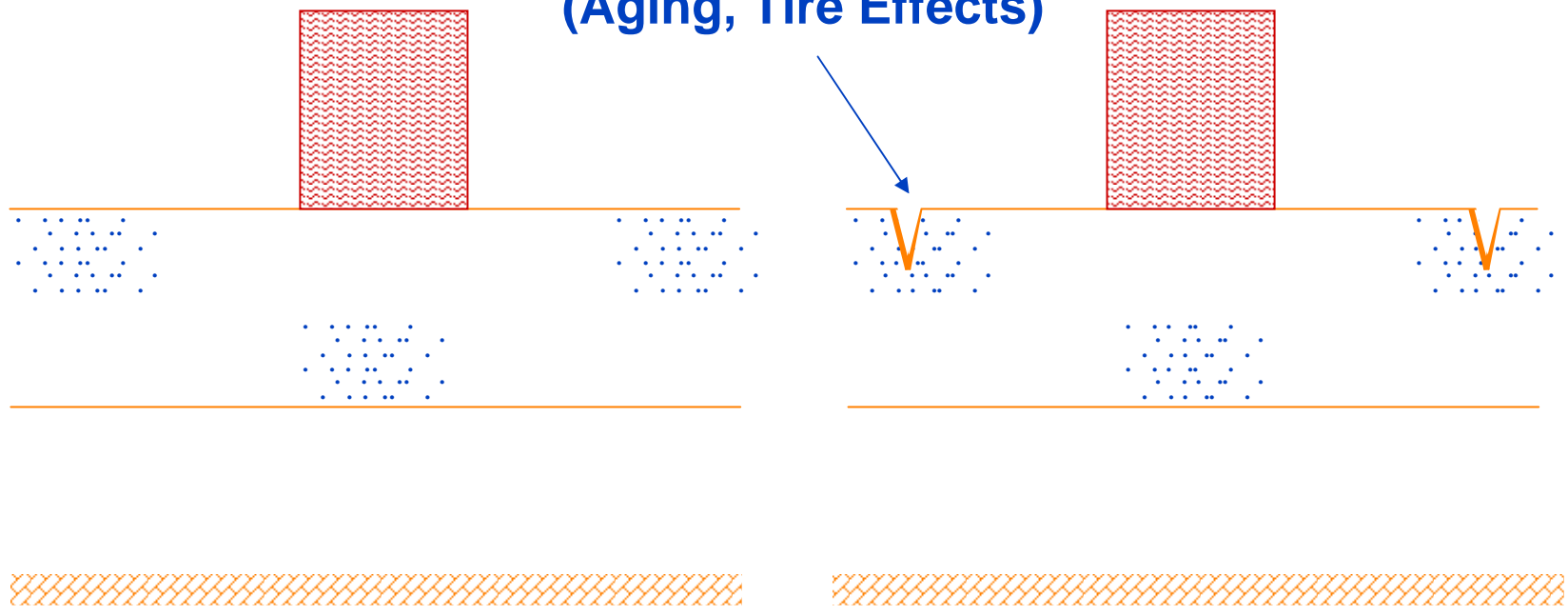


$\sigma_{TOP} = \sigma_{BOT}$   
But Intensity  
Makes  
Top Crack  
More Likely

**\*One Explanation for Top-down Cracking**

# Top-Down Cracking

Cracks Initiated by Other Mechanism  
(Aging, Tire Effects)



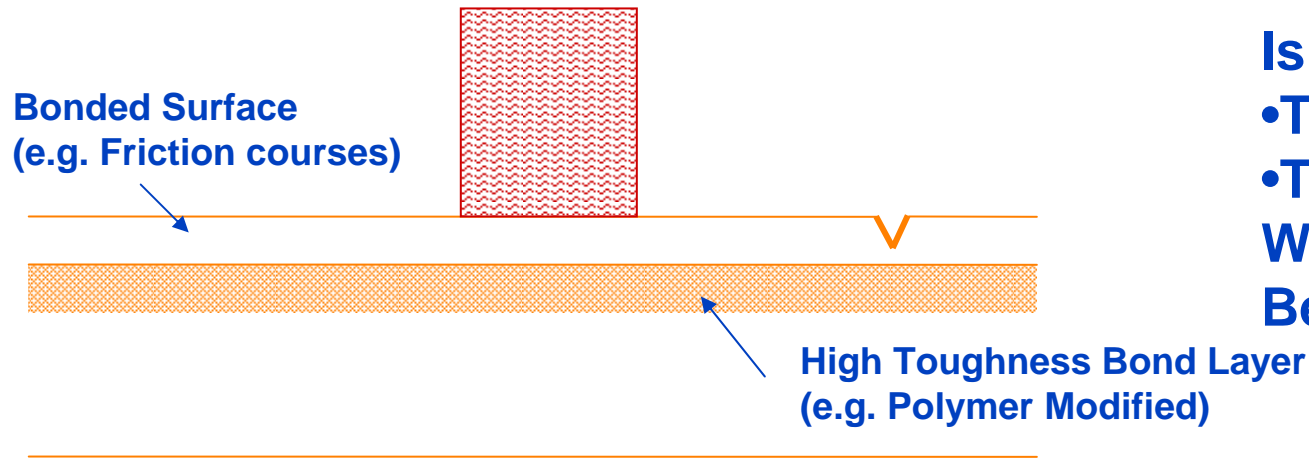
Generally Predicts  
Bottom Cracks

Top-Down Cracks  
More Likely



# Fracture Mechanics for Pavement System Solutions

## Example



**Is Bond Layer**  
•Tough Enough?  
•Thick Enough?  
**Will Crack Initiate Below Bond Layer?**

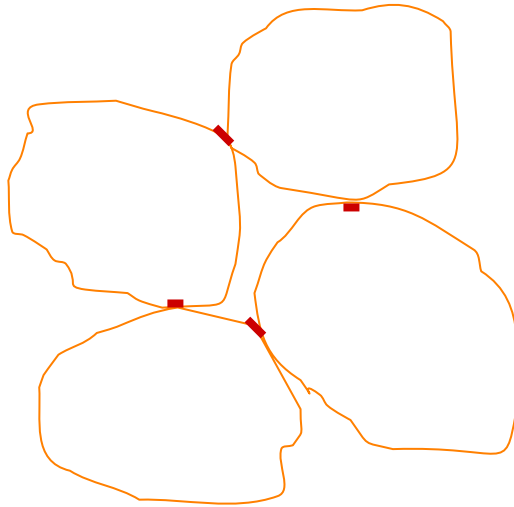
- **FM Can Be Used to Optimize the System.**
- **Develop Guidelines**

# Fracture Mechanics For Mixture Design

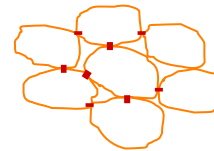


# Void/Flaw Structure and Distribution

Coarser



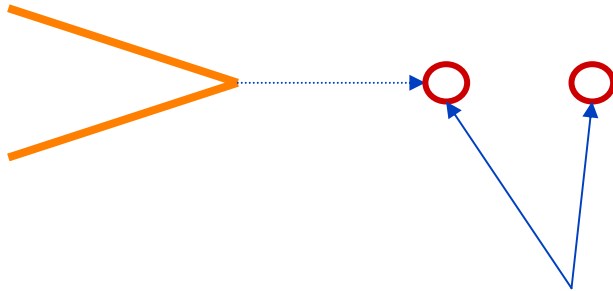
Finer



- **Microcracks Develop in Areas of High Stress Concentration**
- **Aggregate Structure/Resulting Microcrack Distribution Affects Fracture Resistance. (Note: Other Factors Also Important)**

# Modifiers And Fracture Mechanics

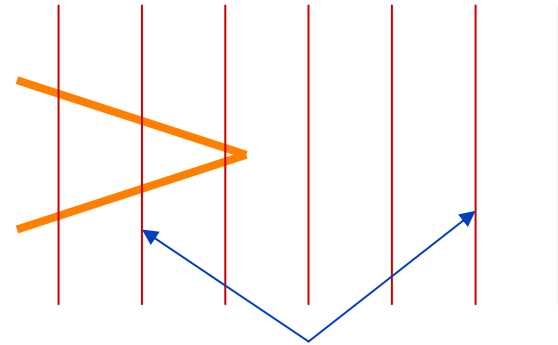
## Pinning



Holes or "Soft" Additive

**Holes or Additive Reduce  
Stress Intensity  
→ Mitigate Crack Growth**

## Polymers/Fibers



Polymers or Fibers

**Polymers or Fibers Reduce  
Stress Intensity  
→ Reduce Rate of Crack Growth**

# Fracture Simulators

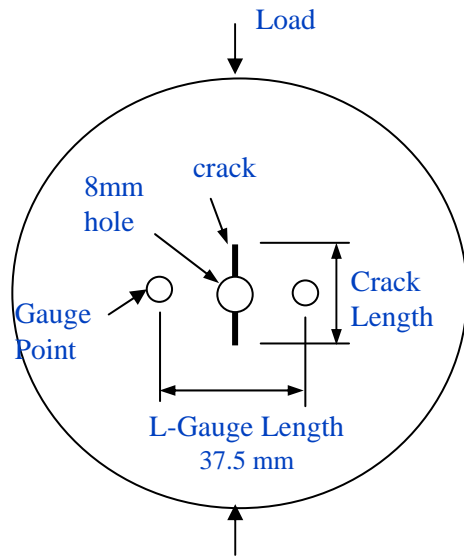


# Fracture Simulators

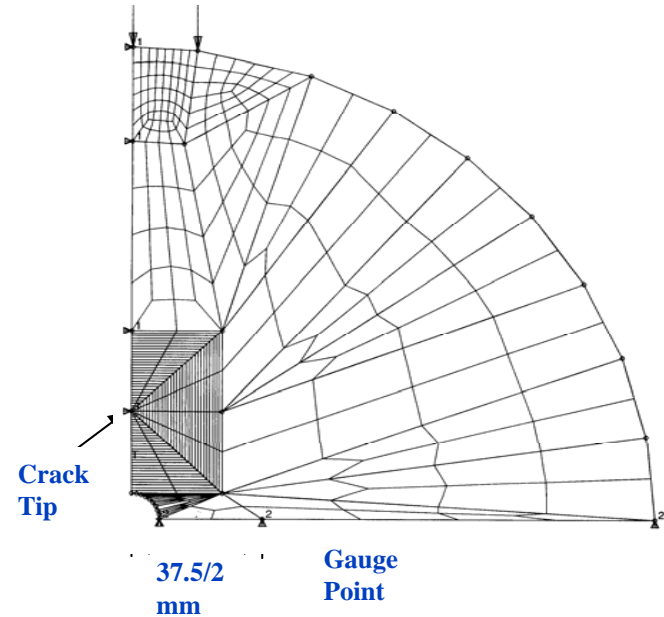
- Emerging Tools Based On
  - Finite Element Method
  - Boundary Element Method
    - Displacement Discontinuities
- Challenges
  - Continually changing geometry
  - Fine meshing required to capture rapid stress gradients near crack tip



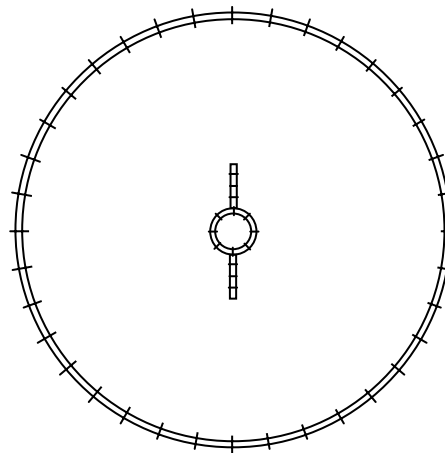
# FEM and DDM as Crack Simulators



IDT test

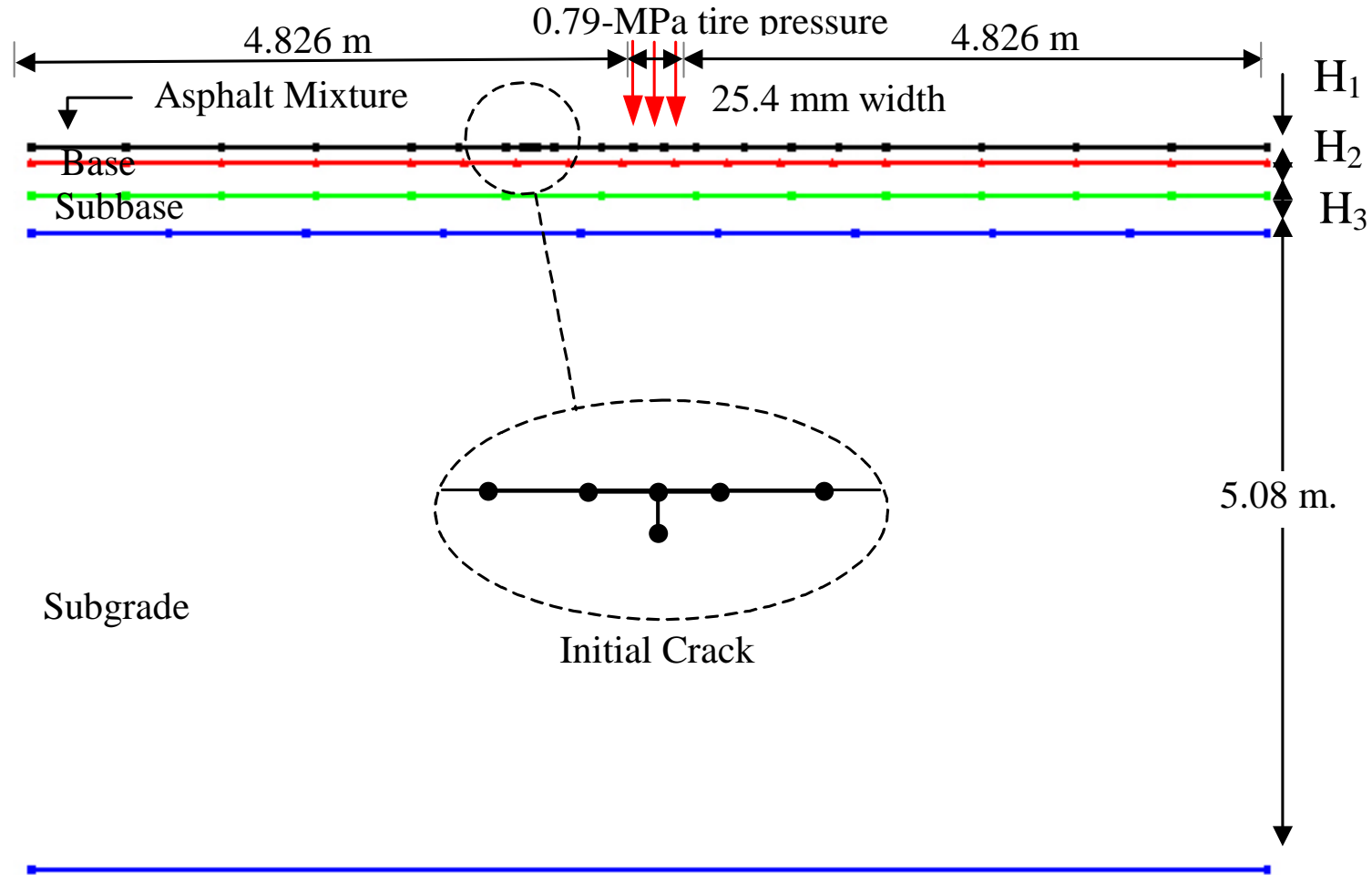


Model in FEM

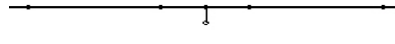


Model in DDM

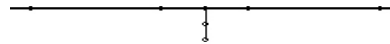
# Modeling of a Four-Layer Pavement Structure with a Crack



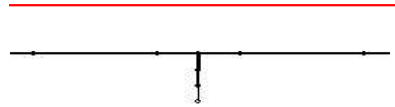
# Automated Crack Growth: Pavement Section on I-10



At beginning, 6.35-mm  
crack length



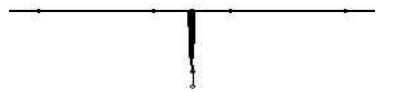
Crack growth Step 1,  
12.7-mm crack length  
after 72,999 loads



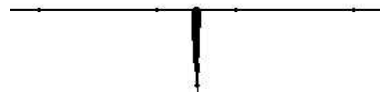
Crack growth Step 2,  
19.05-mm crack length  
after 113,590 loads



Crack growth Step 3, 25.4-  
mm crack length after  
146,059 loads



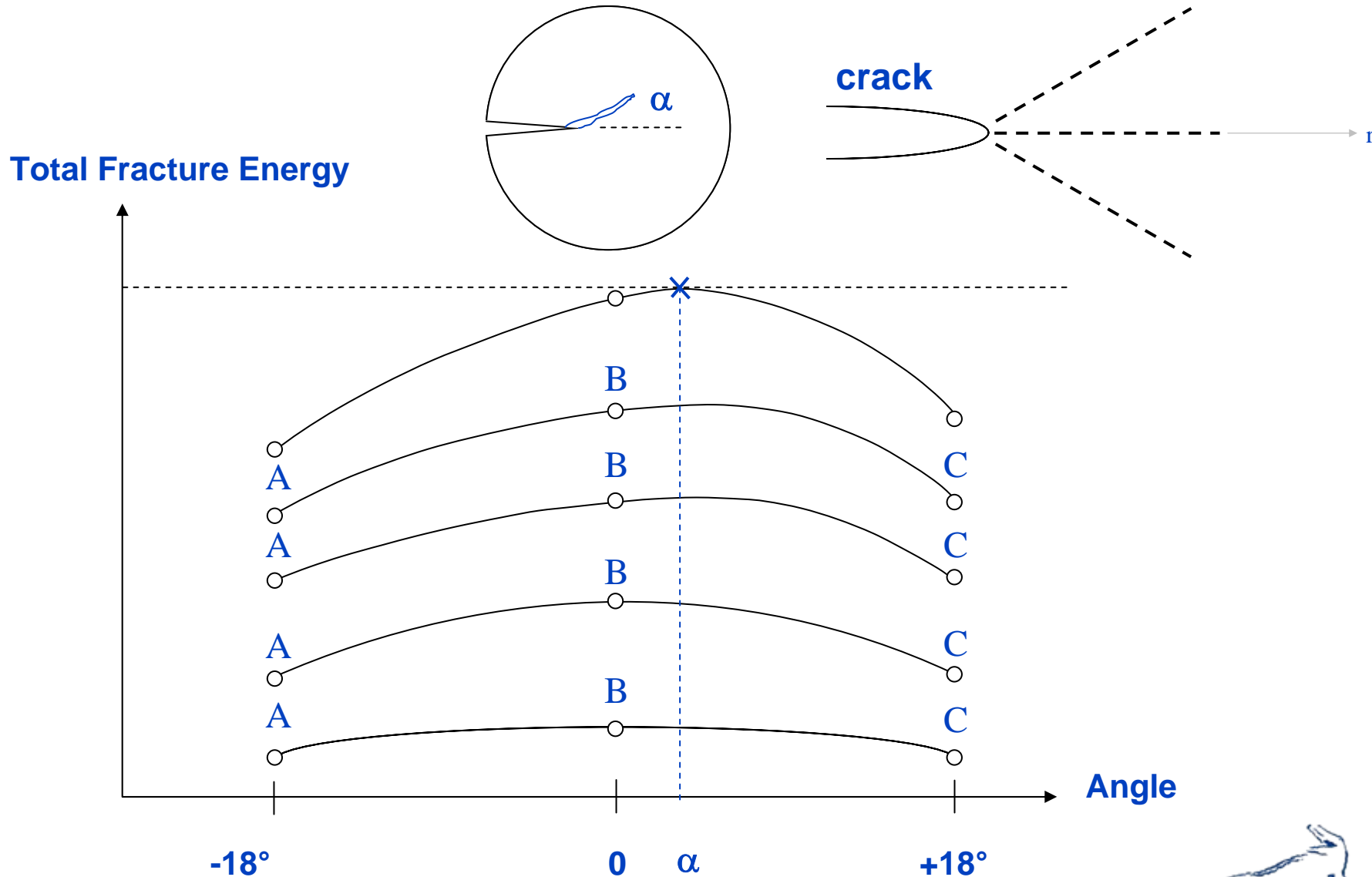
Crack growth Step 4,  
31.75-mm crack length  
after 176 736 loads



Crack growth Step 5, 38.1-  
mm crack length after  
208 447 loads



# Direction of Crack Growth



# HMA Fracture Mechanics: Summary

- An Important Tool for Continued Advancement of Pavement Systems and Mixtures that Mitigate Cracking
- Continued Development and Verification of Fracture Mechanics Theory and Understanding Will Lead To:
  - Pavement systems that mitigate cracking
  - Improved guidelines for fracture resistant mixtures
  - Simple and effective tests for asphalt material design, specification, and quality control
- Enhances Efforts and Understanding Being Pursued By Way Of Micro-structural and Damage Analysis

