COHESIVE

Computation of Homogenized Evolutionary Stress in Inhomogeneous Viscoelastic Entities

University of Nebraska Lincoln

Micromechanics Modeling of Asphalt Mixtures Considering Material Inelasticity and Fracture

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Micromechanics

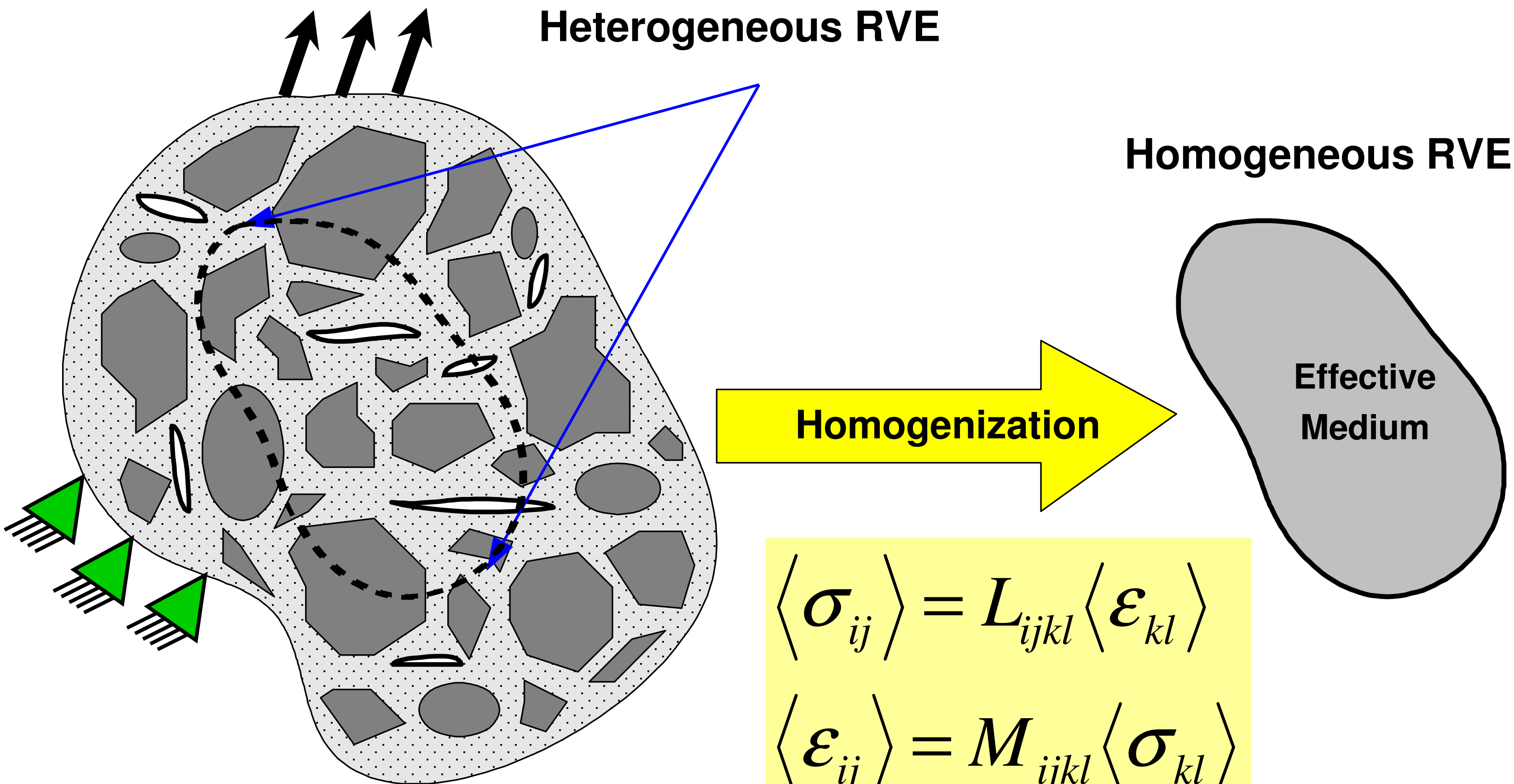
- A theory to determine **effective properties of composites** from known properties and phase geometry of the constituents of the composites.

- Constitutive responses at the mixture-level are estimated in terms of **constituent-level parameters** (geometry and properties).

- The effective properties of the idealized homogeneous medium are typically estimated by using **homogenization** principles.

- The homogenization principle is typically applied to the characteristic dimension of a volume element referred to as the **representative volume element (RVE)** which is large enough so that the estimate of effective properties is independent of the volume element size: total body responses and RVE responses are the same.

Concept of Micromechanics



$$\langle \sigma_{ij} \rangle = L_{ijkl} \langle \varepsilon_{kl} \rangle$$

$$\langle \varepsilon_{ij} \rangle = M_{ijkl} \langle \sigma_{kl} \rangle$$

The homogenization process is complicated and requires great care, since rigorous operation of it needs exact solutions for the stress and strain fields in the composites.

Analytical Micromechanics

For Particulate Composites:

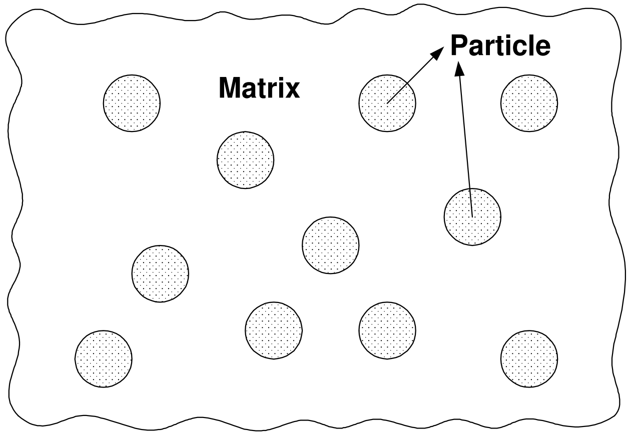
- ❑ The pioneering work by Einstein (1906) → linking the effective viscosity to the particle content of a suspension consisting of smooth, equal-sized particles.

- ❑ They are more scientifically-based than empirical methodologies that usually intend to predict the behavior of the heterogeneous media based on the statistical analysis of databases which are sometimes regional and case-specific.

- ❑ Dewey (1947), Kerner (1956), Eshelby (1957), Hashin (1962, 1965, 1970, 1983), Hashin and Shtrikman (1963), Walpole (1966), Hill (1965), Halpin (1969), Christensen (1969), Christensen and Lo (1979), Nielsen (1970), Lewis and Nielsen (1970), Roscoe (1972), Mori and Tanaka (1973), and many more.

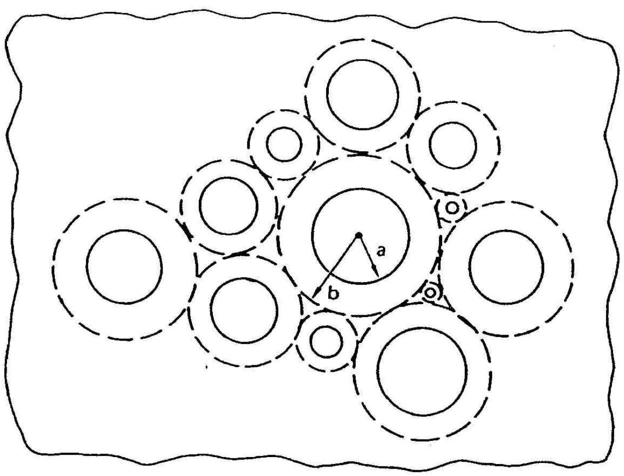
Example Analytical Models

Dilute Suspension System (Dewey 1947)



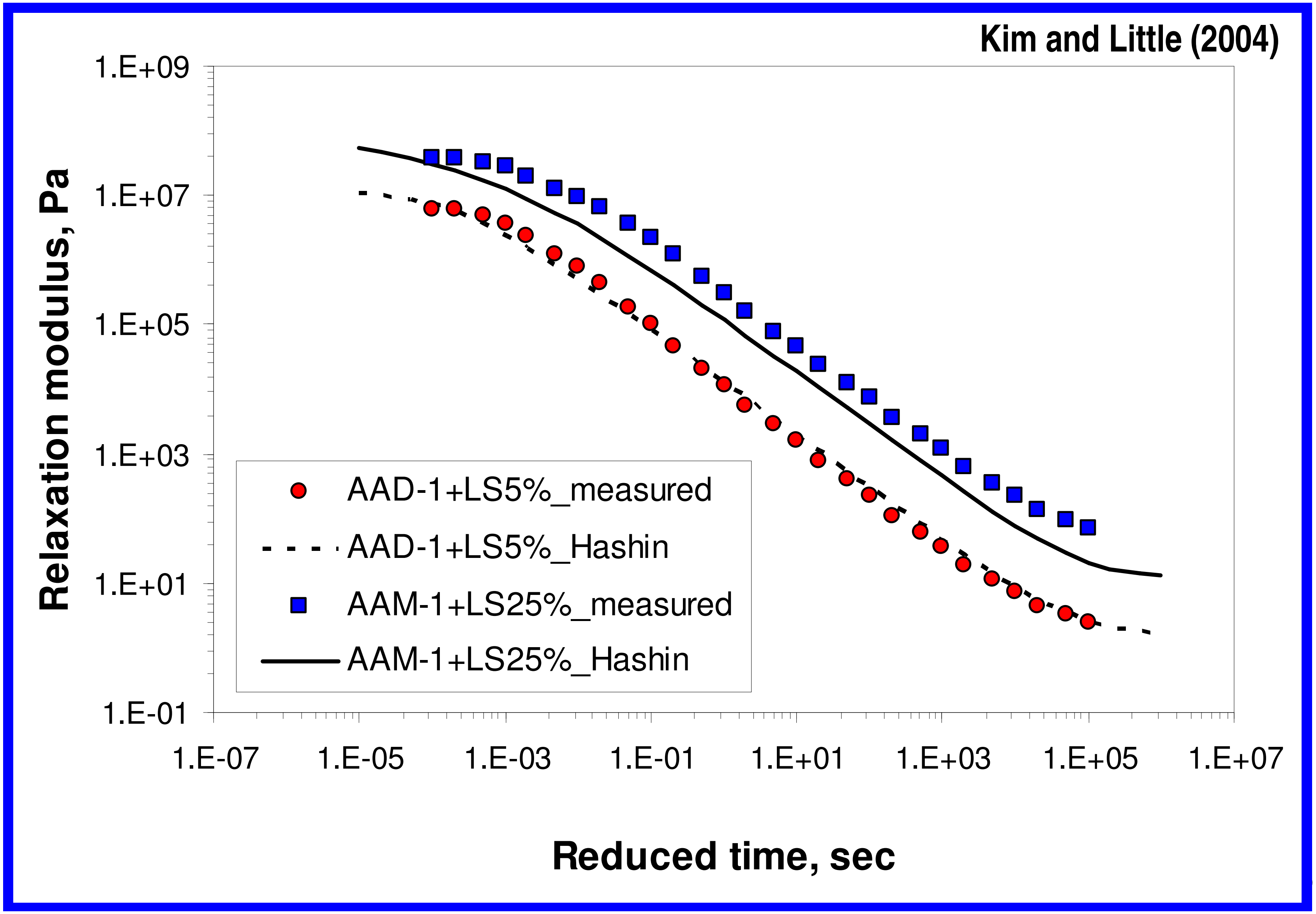
$$\frac{G_c}{G_m} = 1 - \frac{15(1-\nu_m)\left(1-\frac{G_p}{G_m}\right)V_p}{7-5\nu_m+2(4-5\nu_m)\left(\frac{G_p}{G_m}\right)} \Rightarrow 1+\frac{5}{2}V_p$$

Nondilute Elastic Suspension (Hashin 1962)

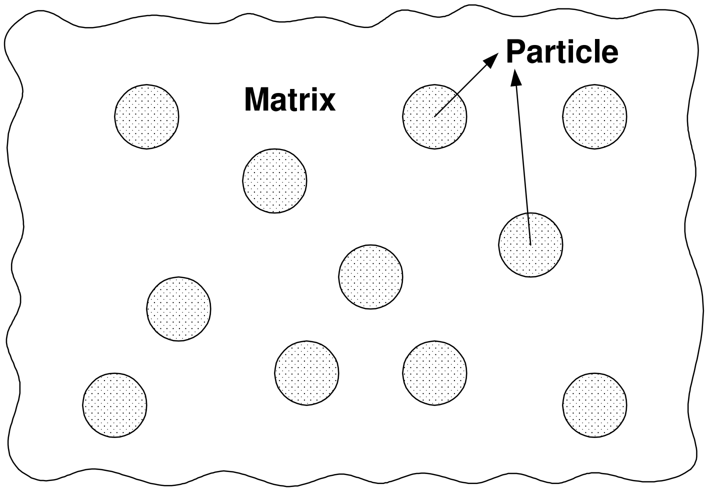


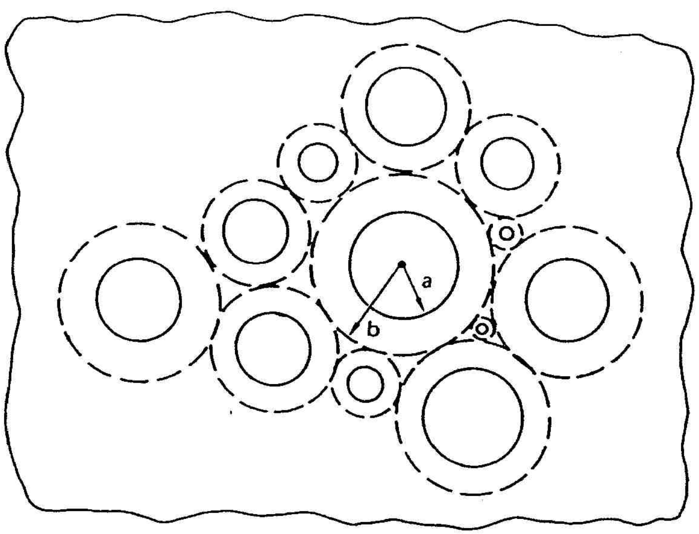
$$\frac{G_c}{G_m} = 1 + \frac{15(1-\nu_m)\left(\frac{G_p}{G_m}-1\right)V_p}{7-5\nu_m+2(4-5\nu_m)\left[\frac{G_p}{G_m}-\left(\frac{G_p}{G_m}-1\right)V_p\right]}$$

Example Analytical Models



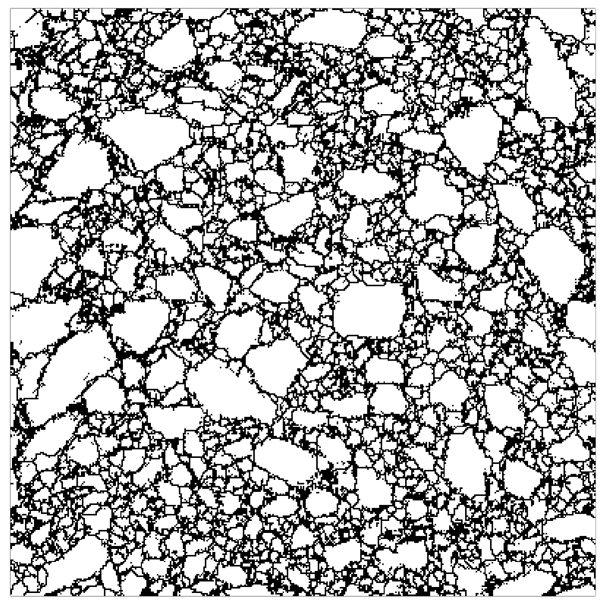
Our Real Problem is…





VS

- Extremely Complicated Geometry
- Inelastic Constitutive Behavior
- Damage in Multiple Length Scales



No analytical solution is available to solve our real problems !!

Computational Approaches

- It is the much better way to account for the complicated geometry (heterogeneity) and material inelasticity (viscoelasticity) in a more realistic scale.

- Applications of **Finite Element Method**: Masad et al. 2001; Papagiannakis et al. 2002; Sadd et al. 2003; Soares et al. 2003; Dai et al. 2005; Aragão et al. 2009; Aragão et al. 2010; etc.

- Applications of **Discrete Element Method**: Buttlar and You 2001; Kim and Buttlar 2005; Abbas et al. 2005; You and Buttlar 2004, 2005, 2006; Dai and You 2007; You et al. 2009; etc.

Modeling Benefits

- Micromechanical model can provide an analysis/design tool governed by constituent-level design variables.

- Micromechanics approach accounts for various modeling complexities (heterogeneity, inelasticity, anisotropy, multiple damage forms) in a more detailed manner and realistic scale.

- Micromechanics approach can reduce laboratory experiments because it merely requires individual mixture constituent parameters as model inputs.

- Computationally intensive sometimes, but it can be tied to multiscale modeling principles to improve computing efficiency.

We will talk about...

Micromechanics Modeling of AC Mixtures

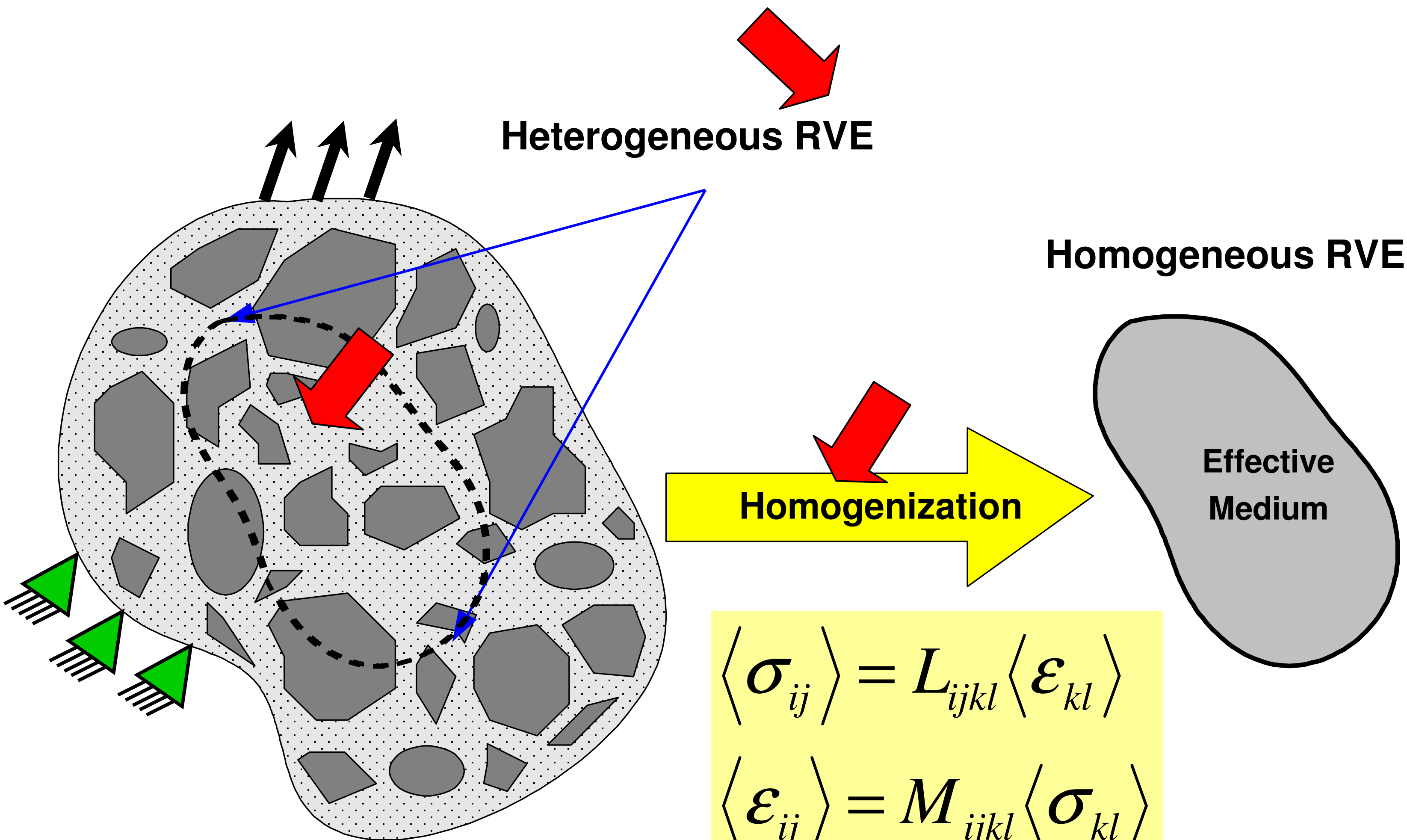
Modeling without Damage

- RVE Study of Asphalt Concrete Microstructure
- Modeling Framework and Model Inputs
- Model Outputs and Comparisons with Test Results

Modeling with Damage (by Fracture)

- Modeling Framework
- Model Inputs and Simulation Outputs
- Model Limitations and Challenges

Modeling without Damage

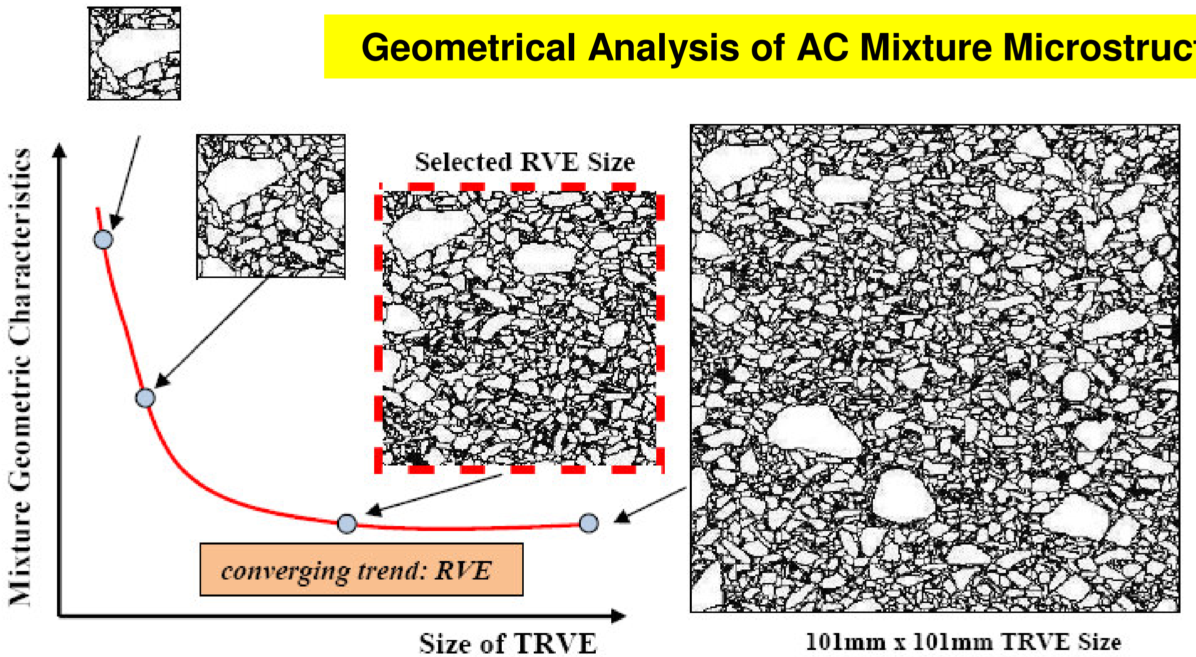


$$\langle \sigma_{ij} \rangle = L_{ijkl} \langle \varepsilon_{kl} \rangle$$

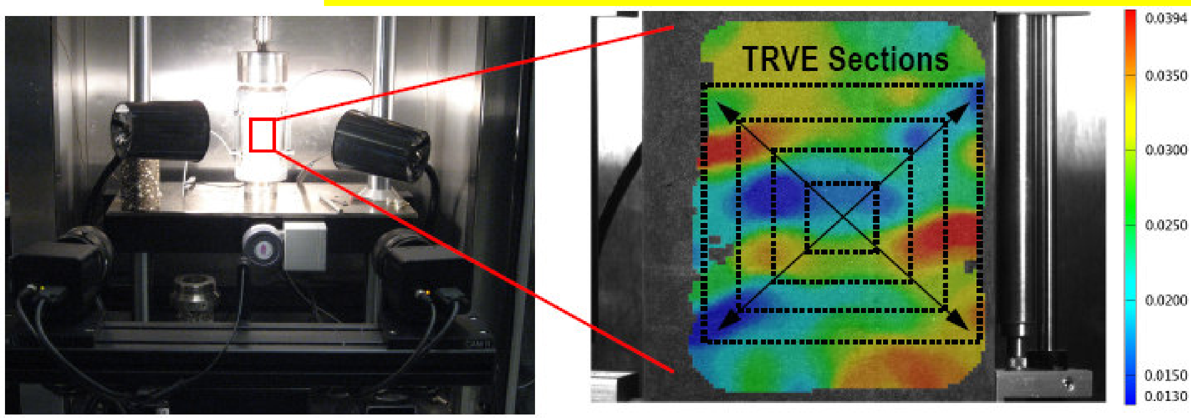
$$\langle \varepsilon_{ij} \rangle = M_{ijkl} \langle \sigma_{kl} \rangle$$

RVE Study of AC Microstructure

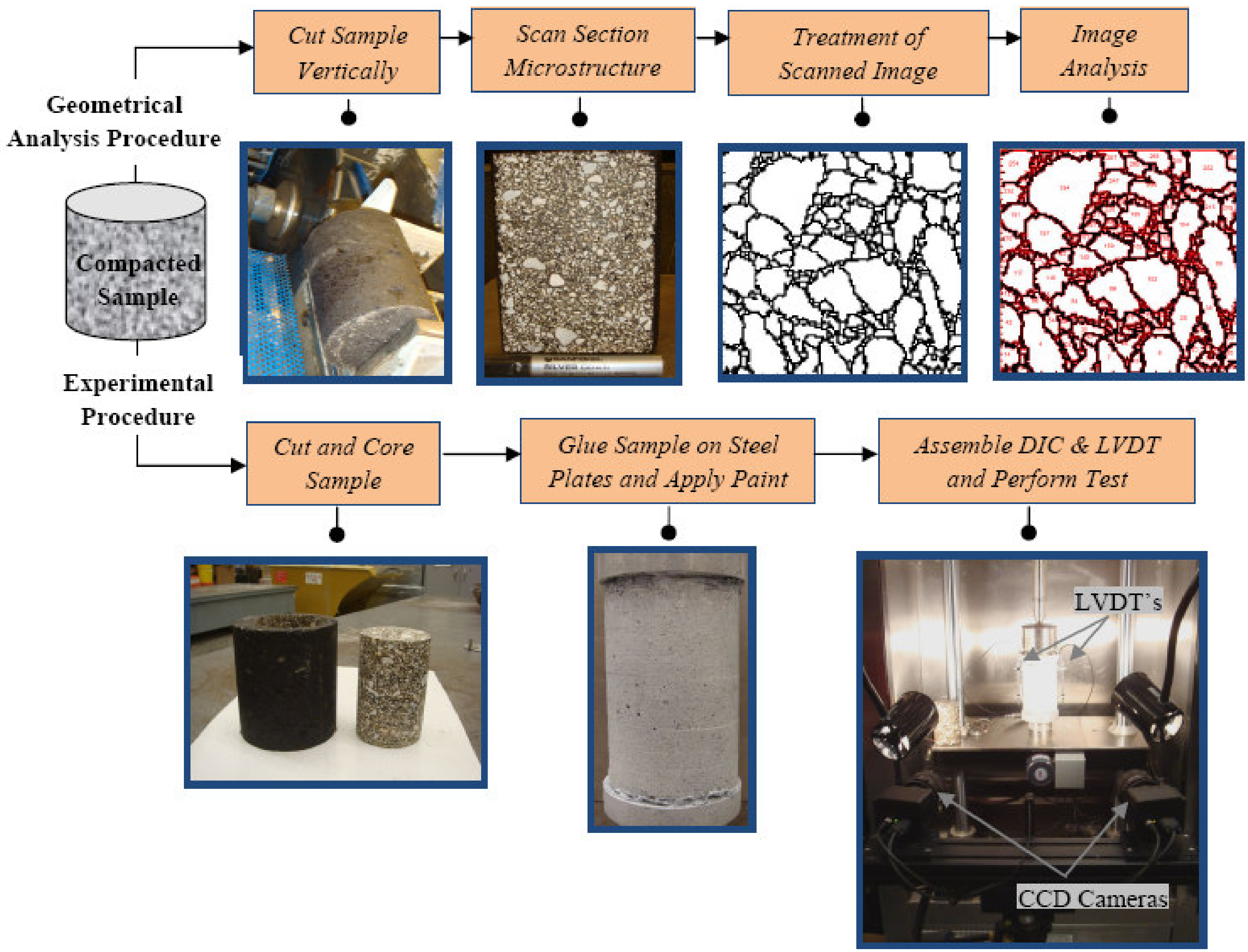
Geometrical Analysis of AC Mixture Microstructure



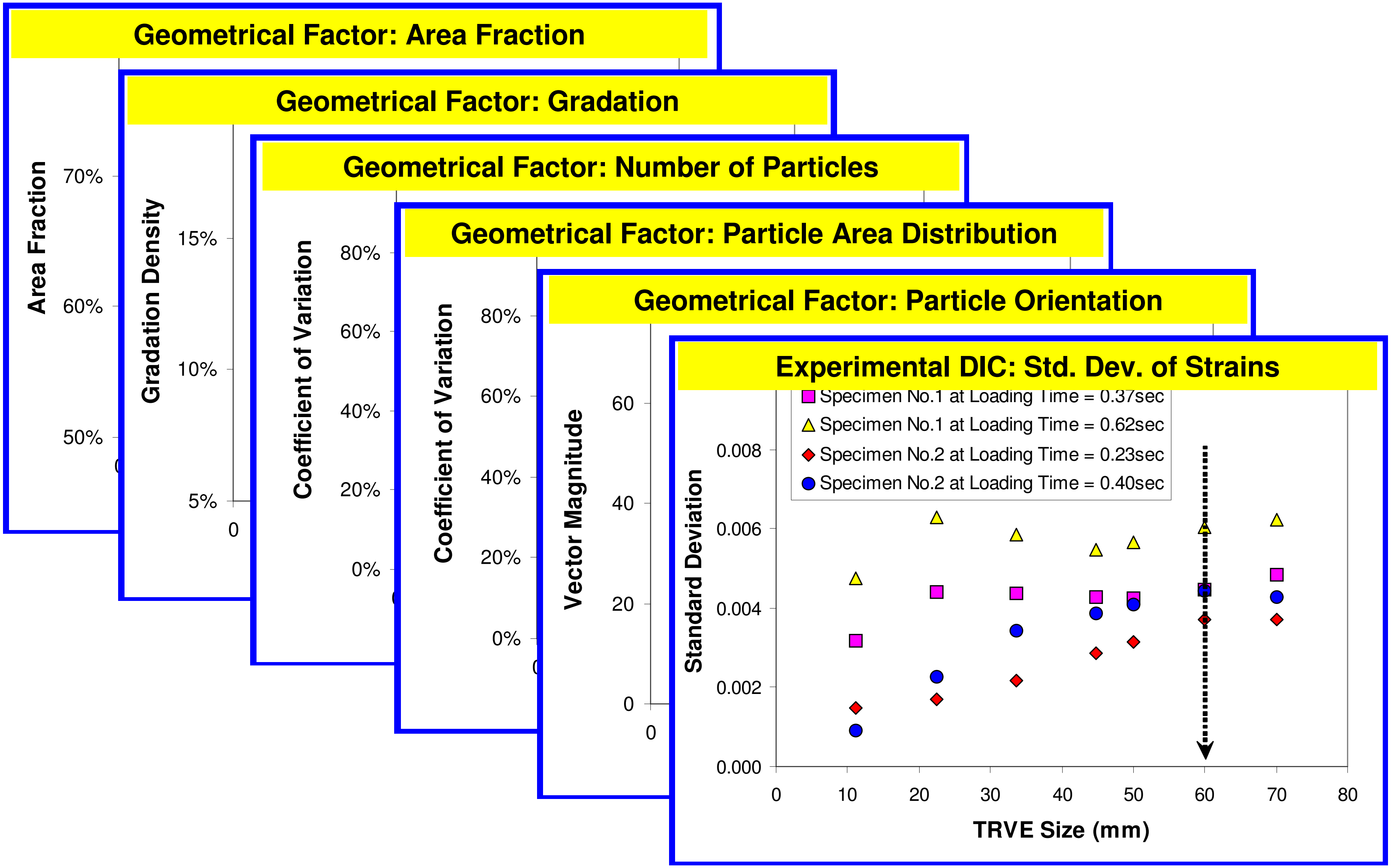
Experimental DIC Analysis of AC Mixture



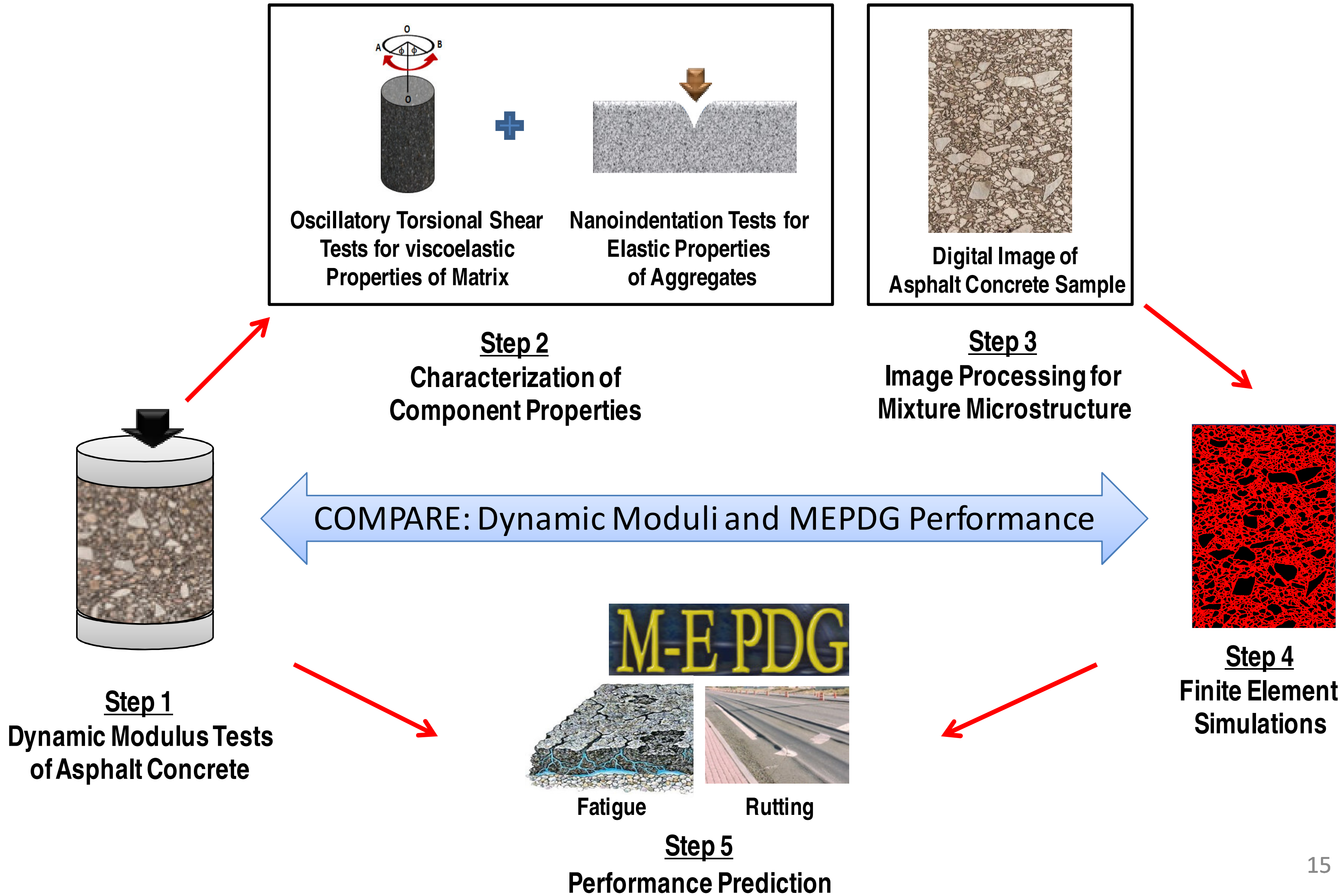
RVE Study of AC Microstructure



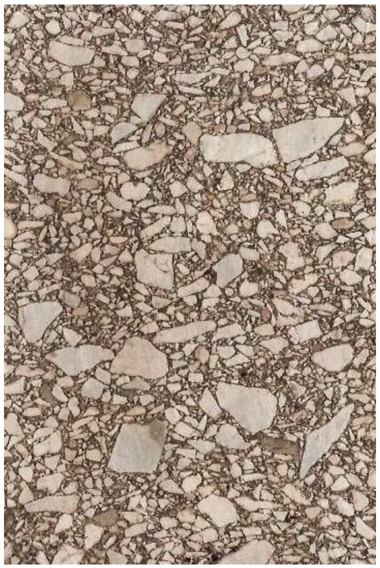
RVE Study of AC Microstructure



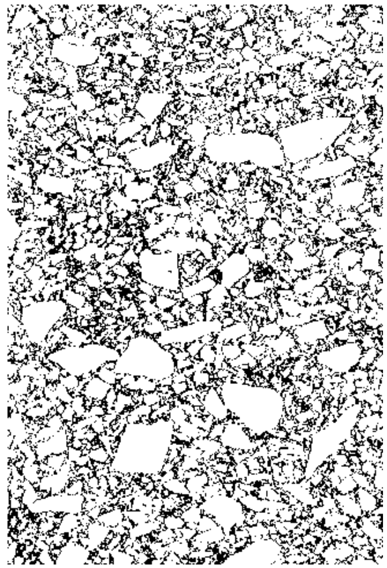
Modeling Framework and Inputs



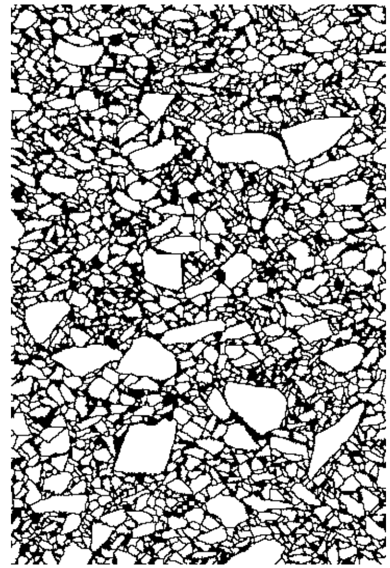
Model Inputs: Geometry



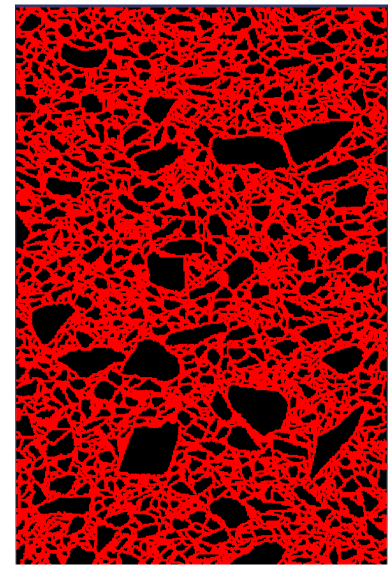
Original Gray Image



B-W Image before Treat



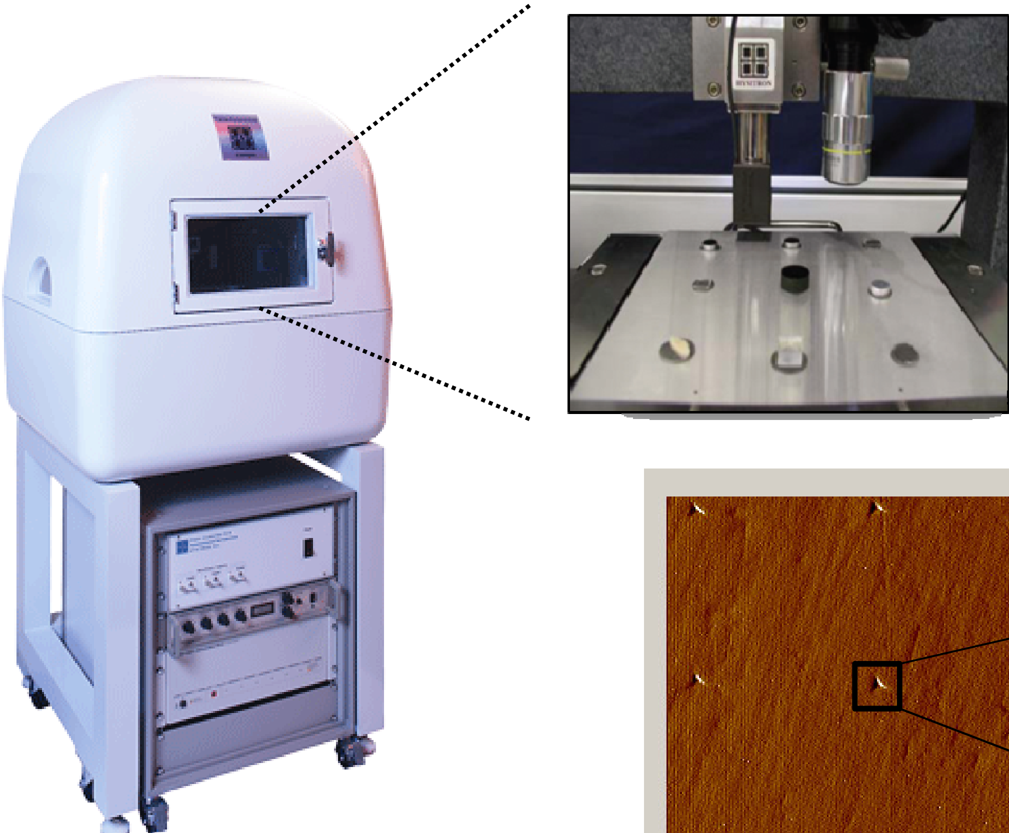
B-W Image after Treat

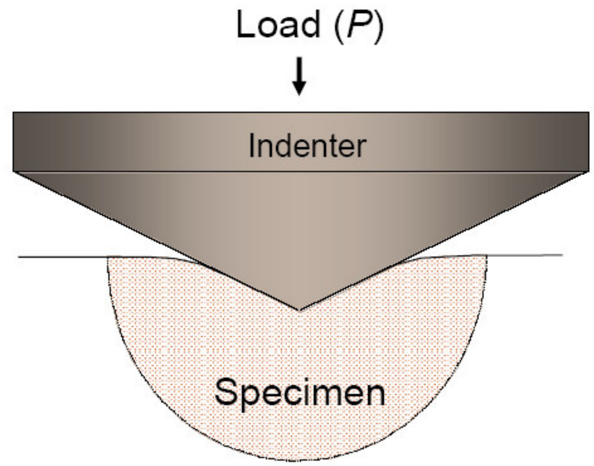


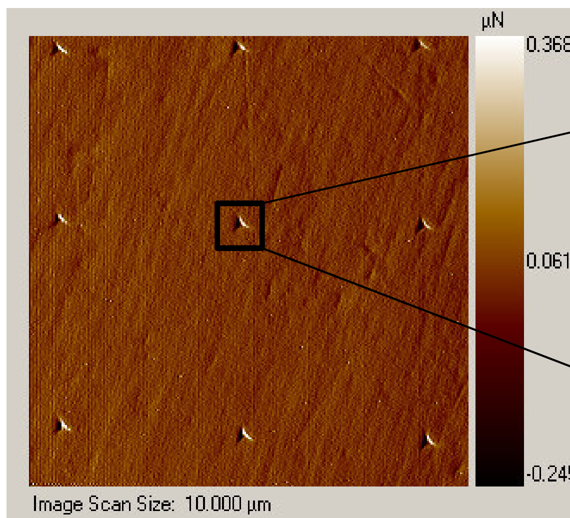
Finite Element Mesh

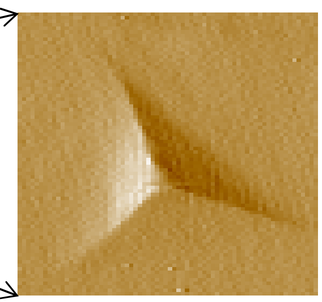
- **Image treatment needs great care so as not to violate the mixture microstructure characteristics such as gradation, orientation, and angularity.**
- **2-D B-W image → 2 separate phases: white coarse aggregates (retained on No.16 sieve) and black matrix phase (binder + aggregates passing No.16 sieve + entrained air voids).**
- **The treated image of the mixture microstructure is discretized to produce finite element meshes which are based on image pixel size (0.25mm by 0.25mm).**

Model Inputs: Aggregate Properties







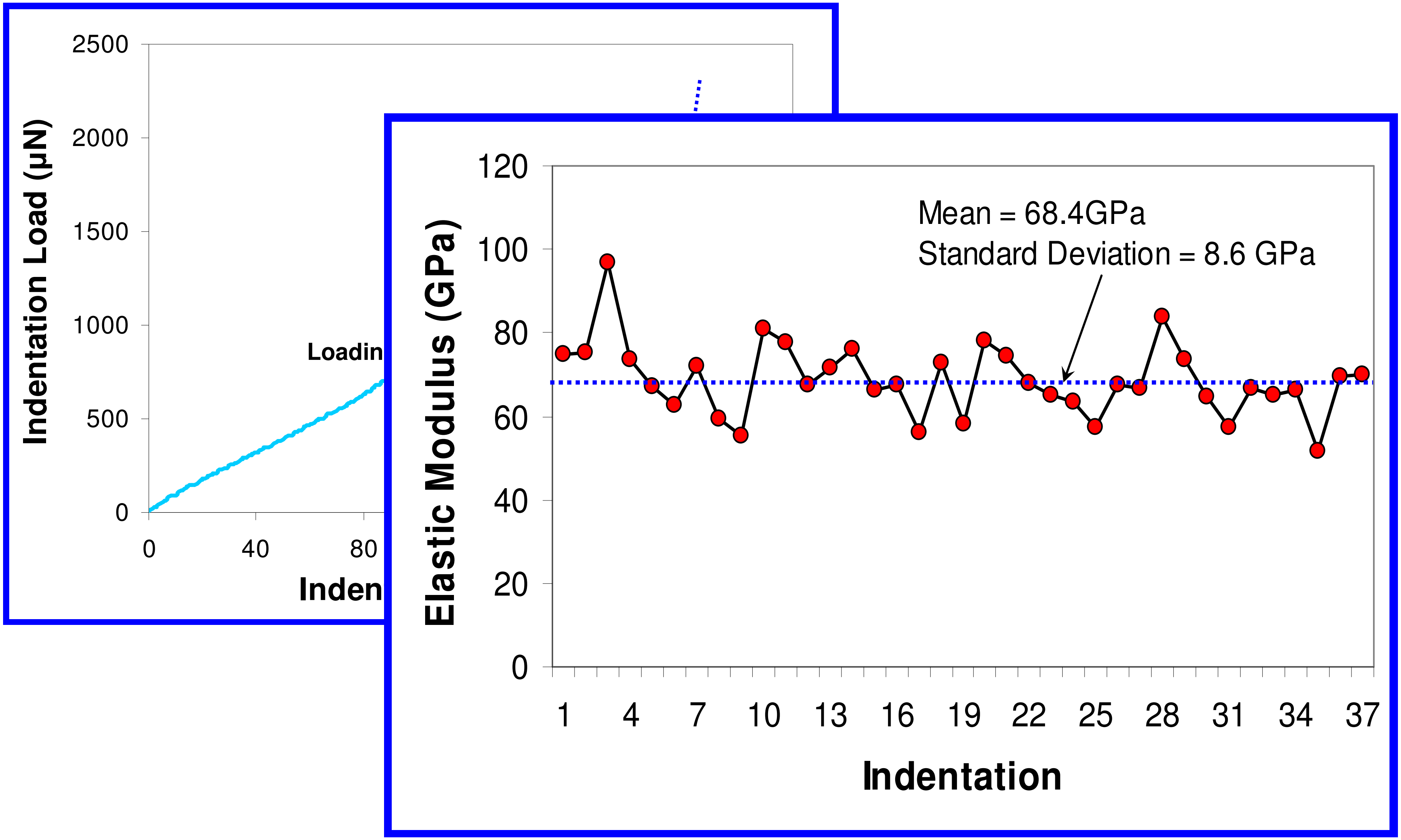


Scan Size
2.9 µm x 2.9 µm

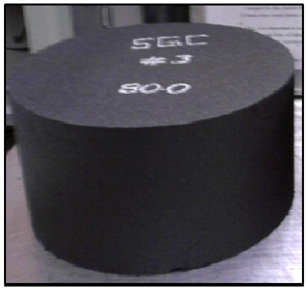
Limestone with 9 indents

Magnified View

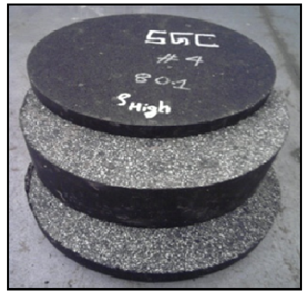
Model Inputs: Aggregate Properties



Model Inputs: Matrix Properties



Bulk Sample



Slicing

Coring

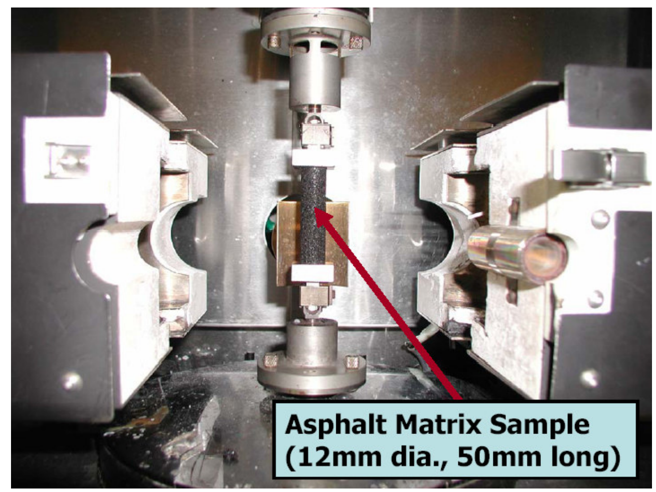
Matrix Samples

Mix Design of Matrix Phase

- ➢ Gradation → mixture gradation excluding coarser aggregates (white phase: aggregates retained on No.16)
- ➢ Binder Content = total binder – binder absorbed by the coarser aggregates – binder to form thin film (12 μm) coating the coarser aggregates

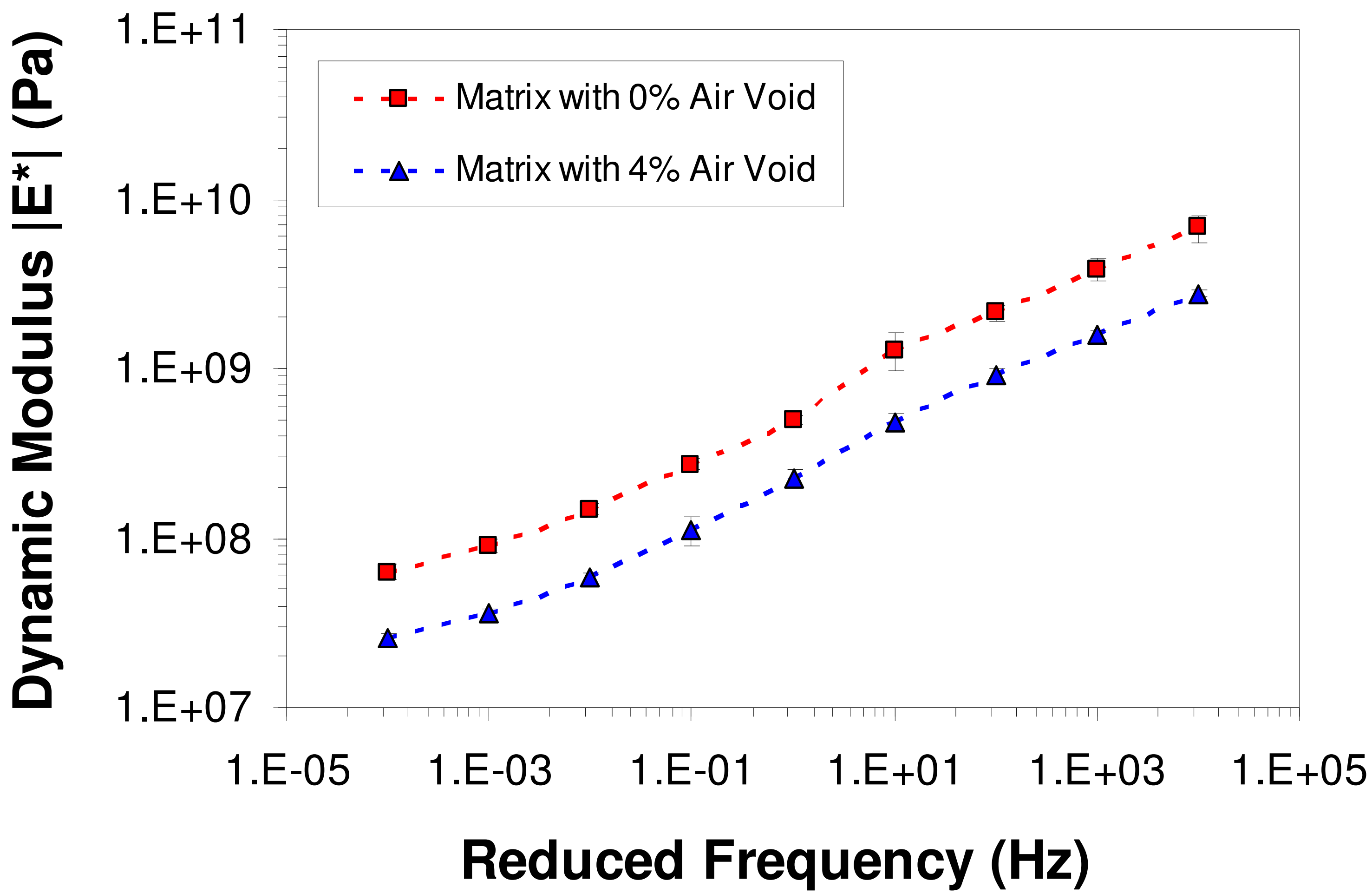
Compaction Density of Matrix Phase

- ➢ Unknown because of unknown air voids in the matrix
- ➢ Two extreme cases (0%, 4% of air voids) were tried.

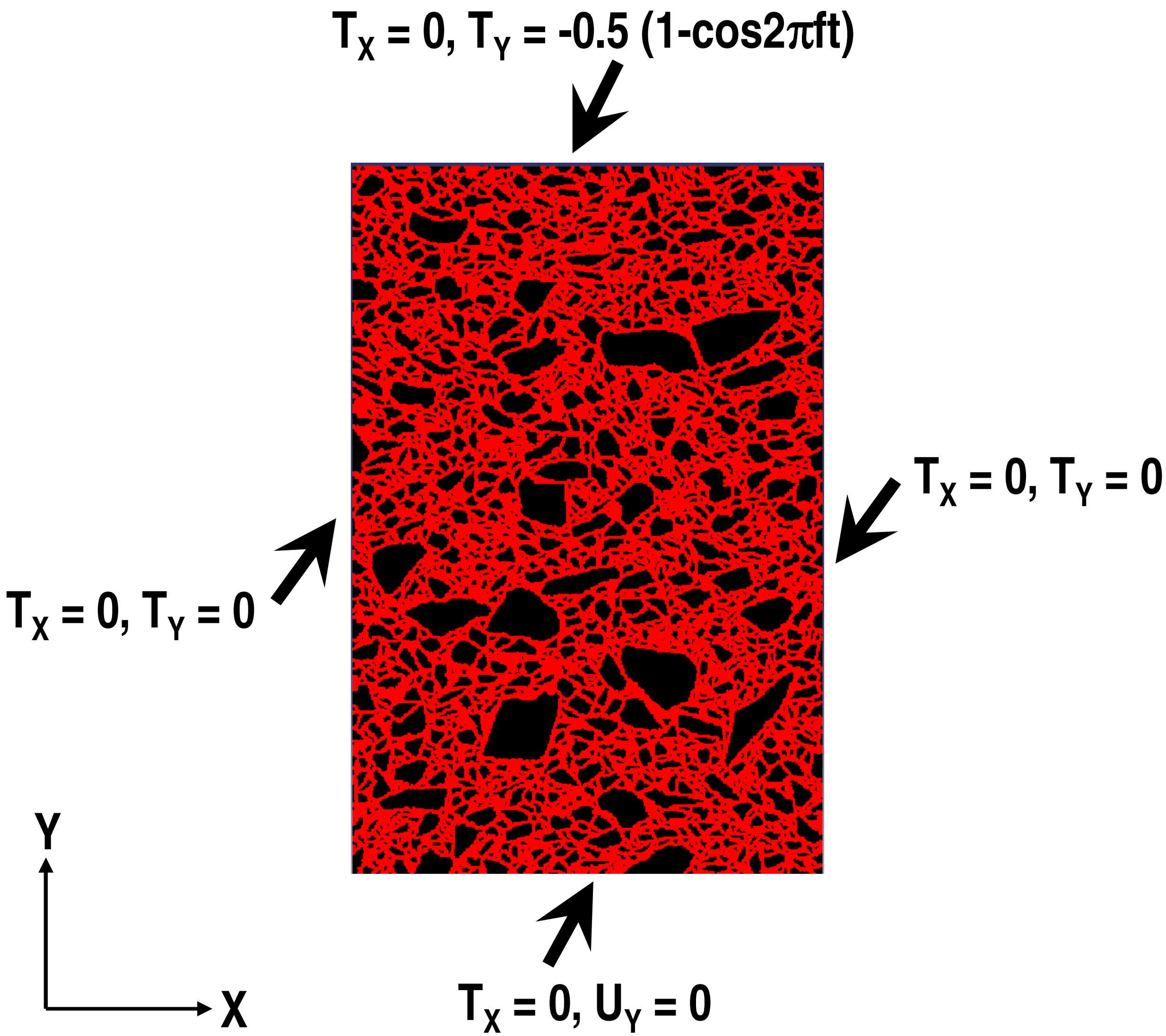


Kim *et al.* (2002, 2003, 2004, 2006), Song *et al.* (2005), Masad *et al.* (2008), Castelo *et al.* (2008), etc.

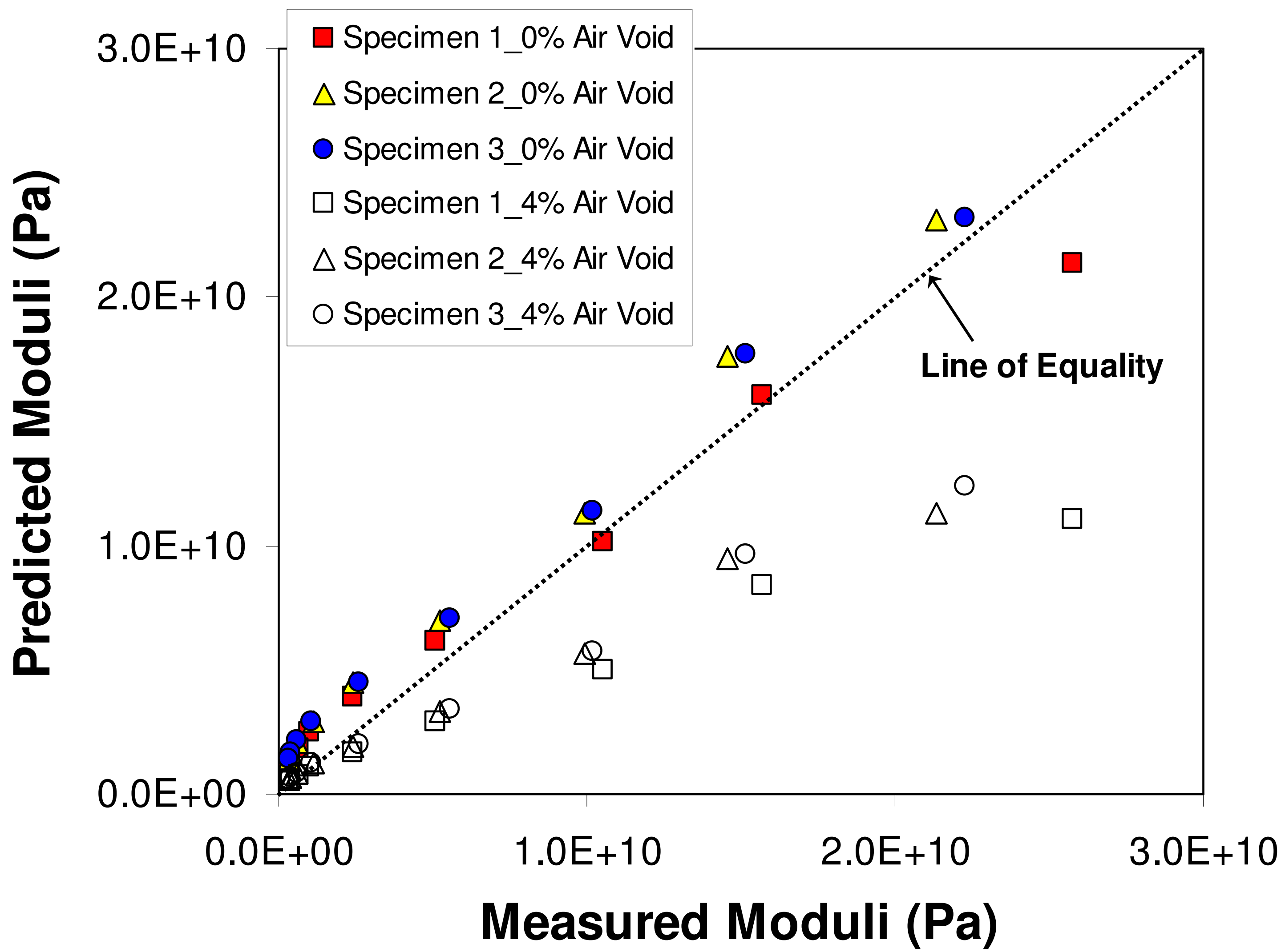
Model Inputs: Matrix Properties



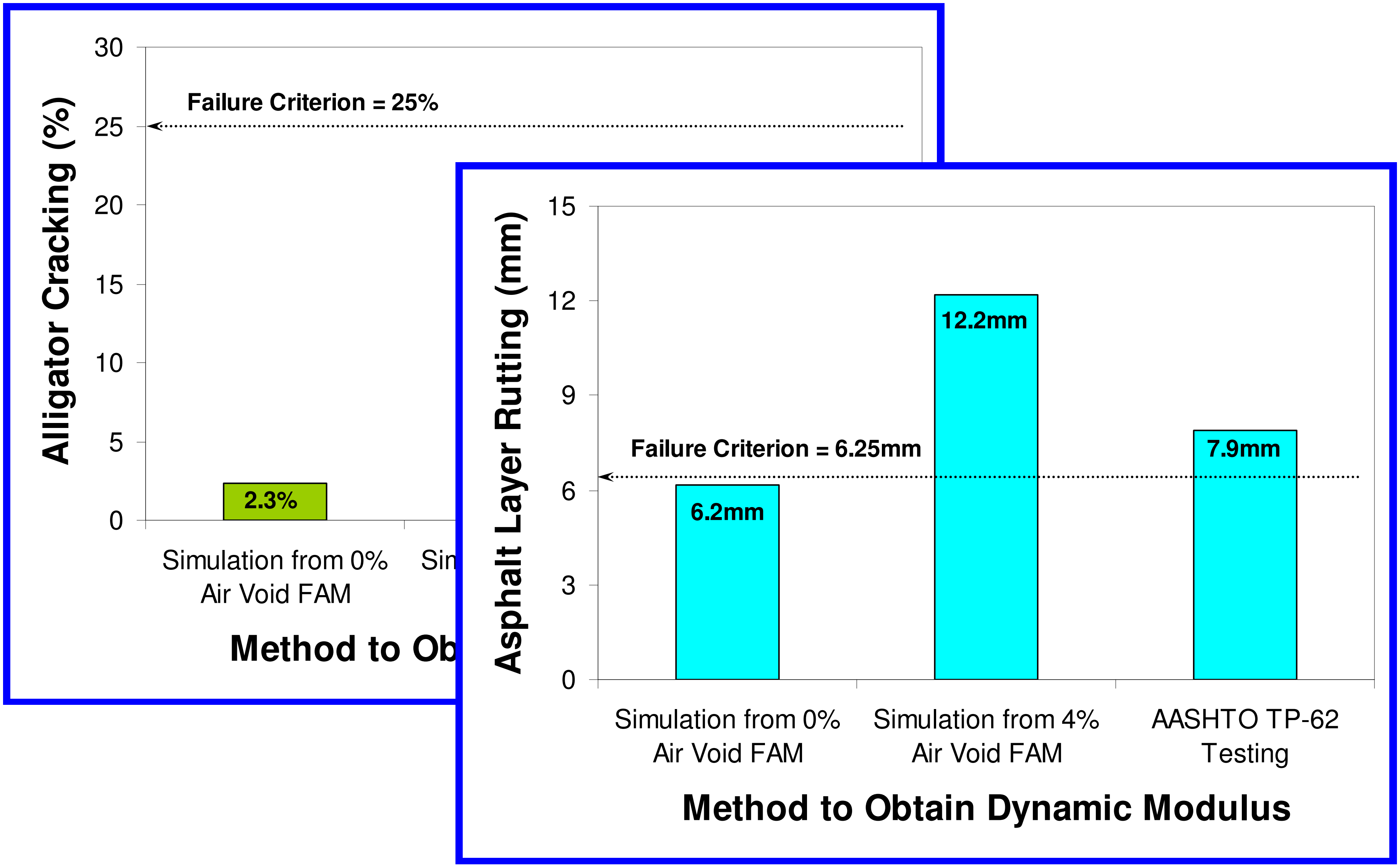
Model Inputs: Boundary Conditions



Model Outputs: Comparison



Model Outputs: MEPDG



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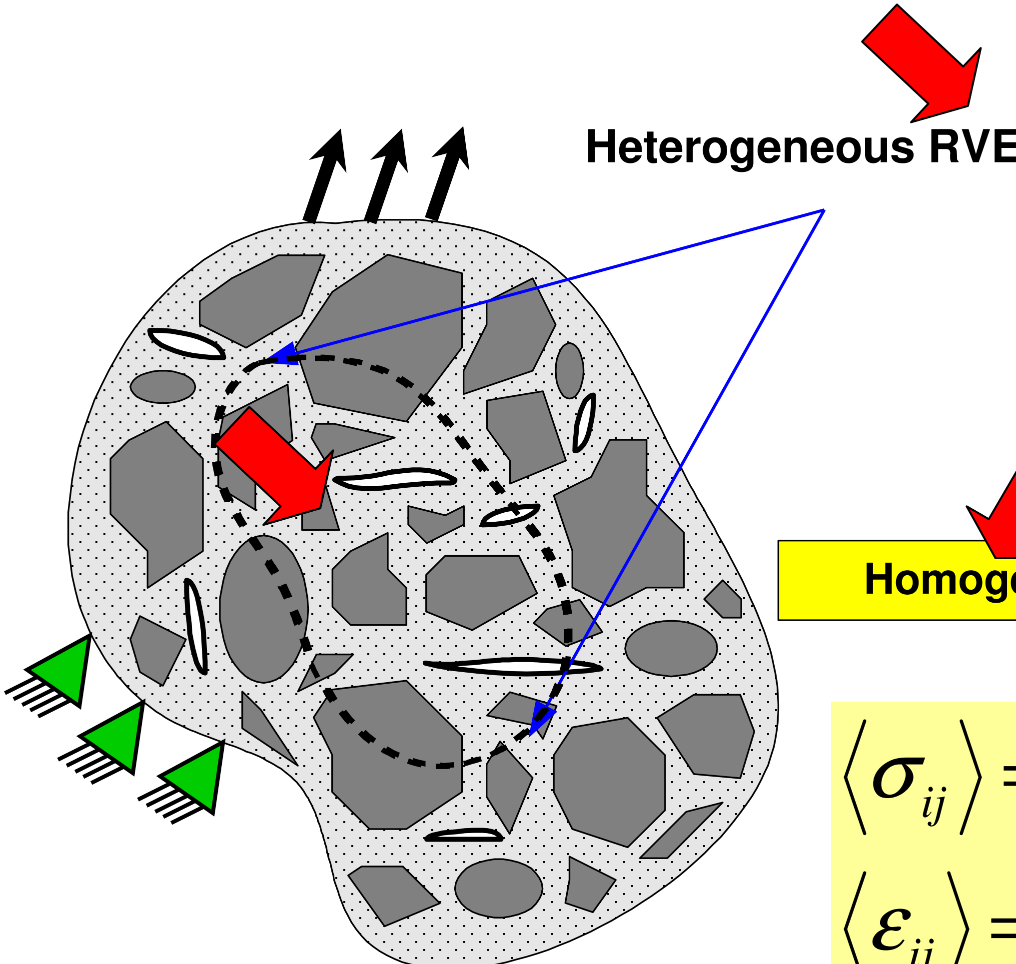
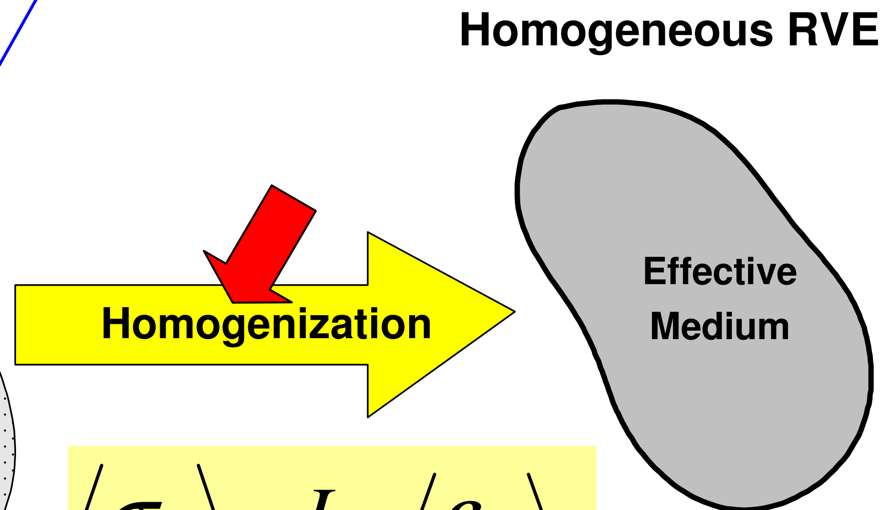
Modeling with Damage



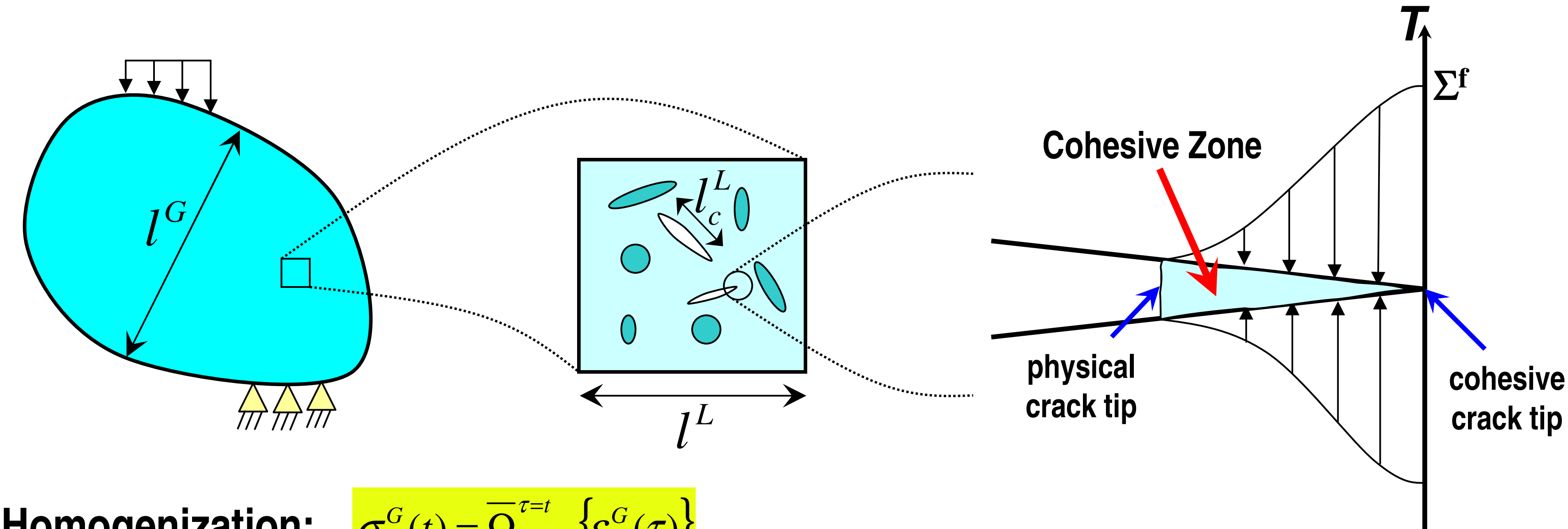


$$\langle \sigma_{ij} \rangle = L_{ijkl} \langle \varepsilon_{kl} \rangle$$

$$\langle \varepsilon_{ij} \rangle = M_{ijkl} \langle \sigma_{kl} \rangle$$

Modeling Framework

Homogenized Global Scale **Heterogeneous Local Scale RVE with Cracks**



Homogenization: $\sigma_{ij}^G(t) = \overline{\Omega}_{\tau=-\infty}^{\tau=t}\left\{\varepsilon_{kl}^G(\tau)\right\}$

where, $\sigma_{ij}^G = \overline{\sigma_{ij}^L} \equiv \frac{1}{V^L}\int_{\partial V^L} \sigma_{ij}^L n_k^L x_j^L dS$

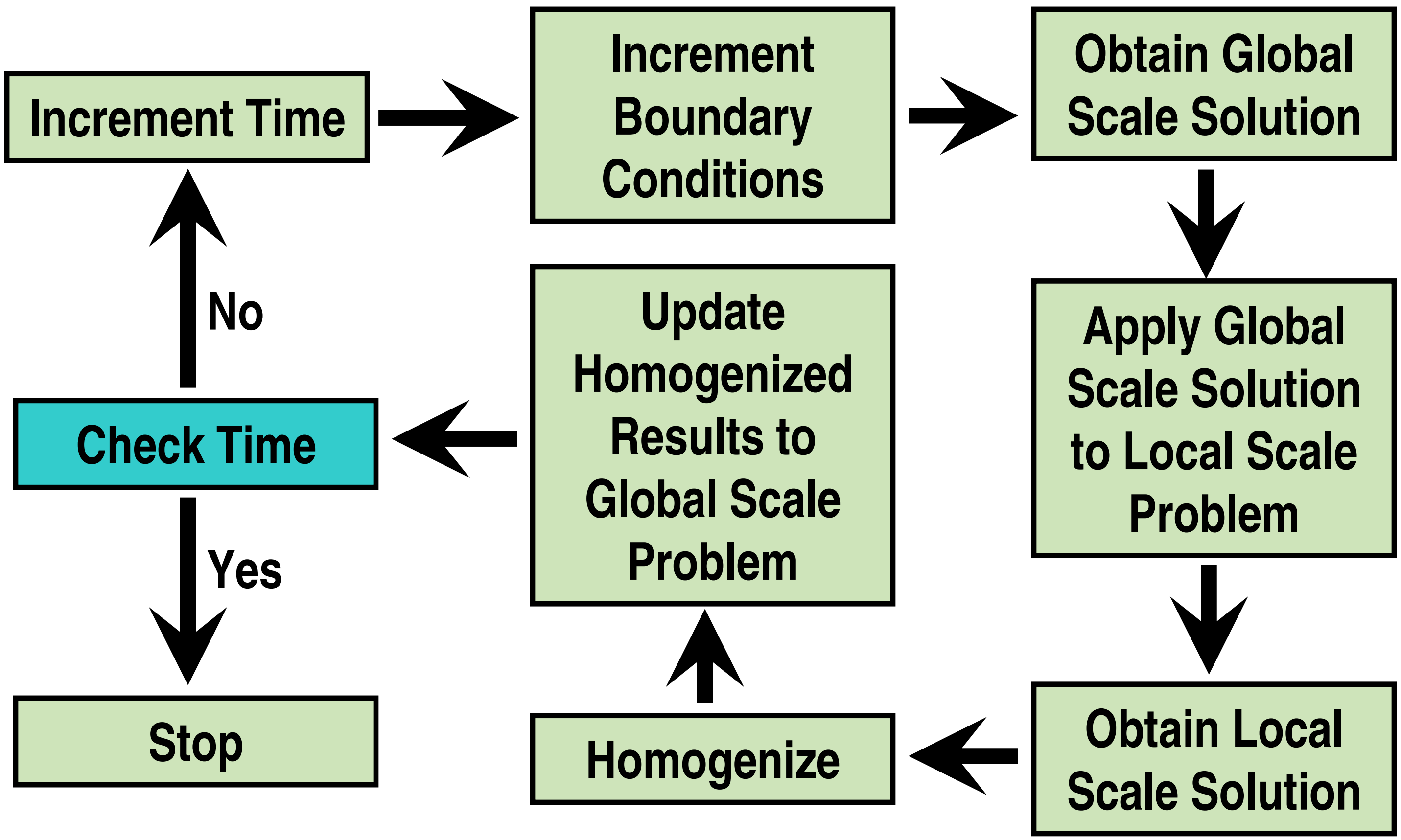
$$\varepsilon_{ij}^G = E_{ij}^G + e_{ij}^G \equiv \overline{E_{ij}^L} + \overline{e_{ij}^L}$$

where, $\overline{E_{ij}^L} = \frac{1}{V^L}\int_{\partial V_E^L} \frac{1}{2}\left(u_i^L n_j^L + u_j^L n_i^L\right) dS$

$$\overline{e_{ij}^L} = \frac{1}{V^L}\int_{\partial V_I^L} \frac{1}{2}\left(u_i^L n_j^L + u_j^L n_i^L\right) dS$$

Modeling Framework

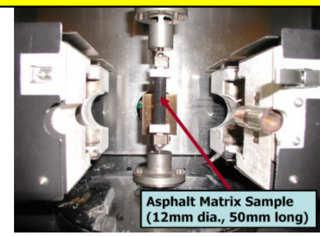
A ***two-way couple multiscale*** strategy is adopted to accurately account for spatial and time dependence due to viscoelasticity and crack evolution.

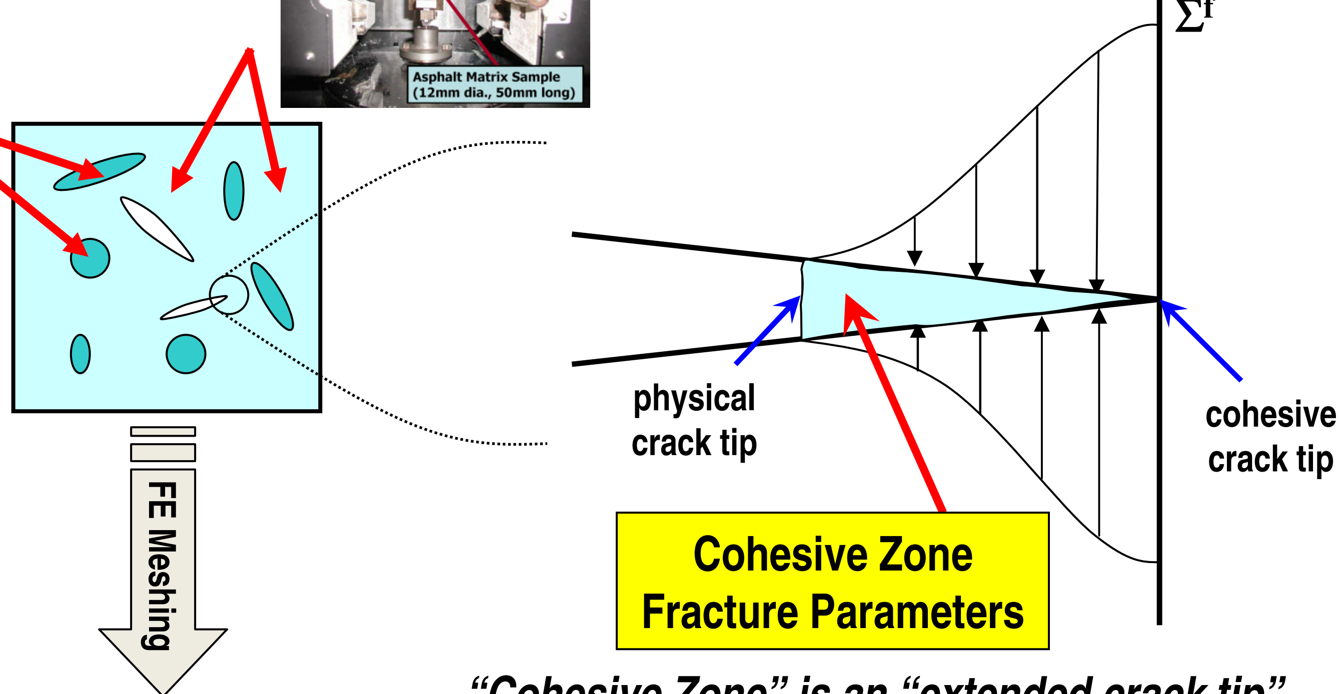


Model Inputs

Elastic Aggregate Properties by Nanoindentation

Viscoelastic Matrix Properties by DMA



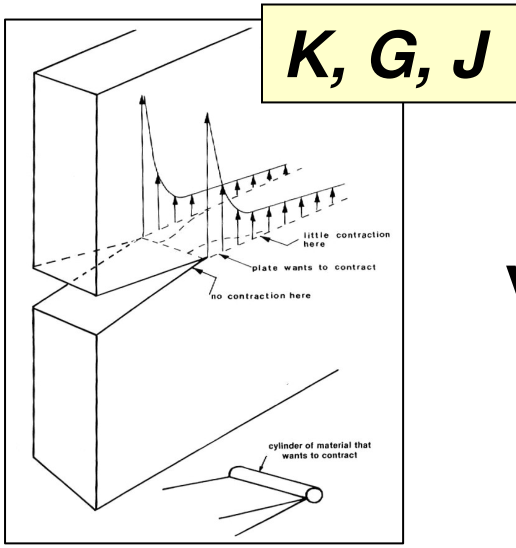


Cohesive Zone Fracture Parameters

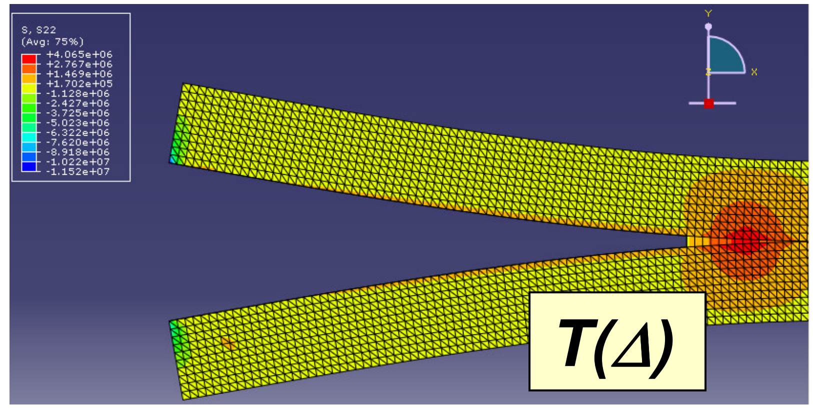
Geometry Considering Mixture Microstructure

"Cohesive Zone" is an "extended crack tip" where separation takes place and is resisted by cohesive tractions (Ortiz and Pandolfi 1999).

Features (Benefits) of CZM

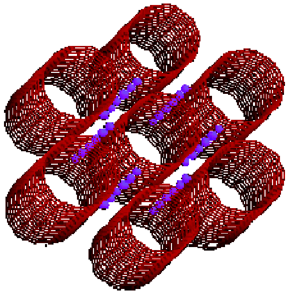


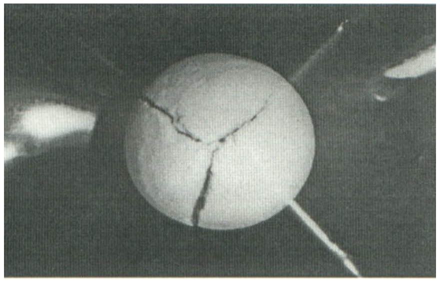
versus



- CZM can physically create multiple cracks in composites simultaneously.
- CZM can be applied to various material constitutions under the same concept.
- CZM can capture the inelastic fracture phenomena (such as rate-dependency) more accurately than the traditional fracture mechanics approaches.
- CZM eliminates singularity of stress.
- CZM is convenient to be implemented into computational techniques (e.g., FEM).
- It is an ideal framework to model stiffness, strength, and damage (nucleation-initiation-propagation) in an integrated manner by the *T-Δ* relationship.
- Applications: geomaterials, biomaterials, concrete, metals, polymers, etc.

Applications of CZM





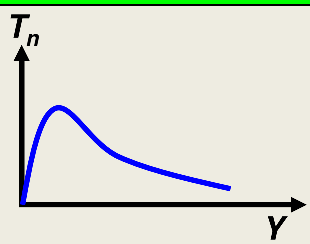
- Hillerborg et al. 1976: ficticious crack model; concrete
- Bazant et al. 1983: crack band theory; concrete
- Morgan et al. 1997: earthquake rupture propagation; geomaterial
- Planas et al. 1991: concrete
- Eisenmenger 2001: stone fragmentation; brittle-bio materials
- Amruthraj et al. 1995: composites

- Grujicic 1999: fracture behavior of polycrystalline; bicrystals
- Costanzo et al. 1998: dynamic fracture
- Ghosh 2000: Interfacial debonding; composites
- Rahulkumar 2000: viscoelastic fracture; polymers
- Liechti 2001: mixed-mode, time-dependent rubber/metal debonding
- Ravichander 2001: fatigue

- Tvergaard 1992: particle-matrix interface debonding
- Tvergaard et al. 1996: elastic-plastic solid; ductile fracture metals
- Brocks 2001: crack growth in sheet metal
- Camacho and Ortiz 1996: impact
- Dollar 1993: Interfacial debonding ceramic-matrix composites
- Lokhandwalla 2000: urinary stones biomaterials

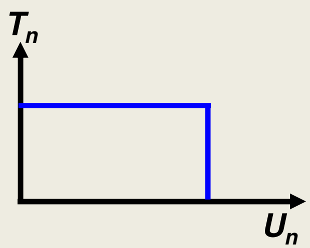
Various CZMs Developed

Barenblatt (1959, 1962)



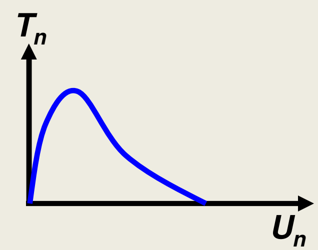
1[st] CZ concept for perfectly brittle materials

Dugdale (1960)



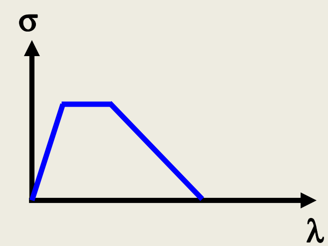
Cohesive stress equal to yield stress of material

Needleman & Xu (1987, 1990, 1993)



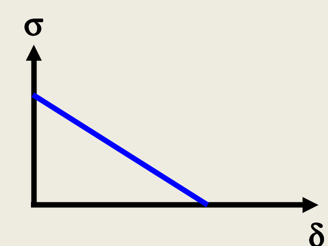
Polynomial or Exponential CZ models

Tvergaard (1990, 1992)



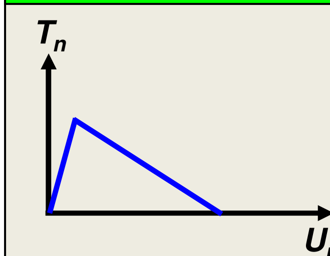
Crack growth in elasto-plastic materials

Camacho & Ortiz (1996)



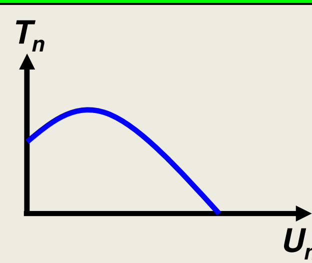
Extrinsic linear softening model for impact

Guebelle & Baylor (1997)



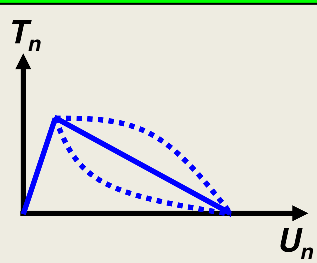
Bilinear intrinsic model for low-velocity impact

Allen (1999, 2001)



Nonlinear viscoelastic CZ model

Park et al. (2009)



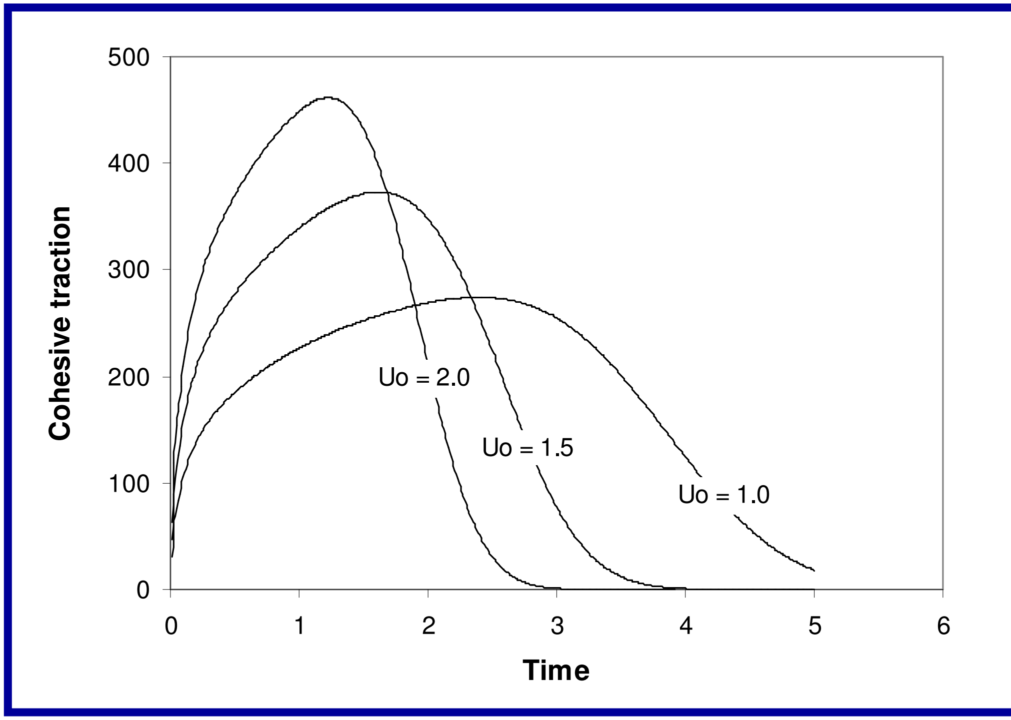
Unified potential-based CZ model

Viscoelastic CZ Model

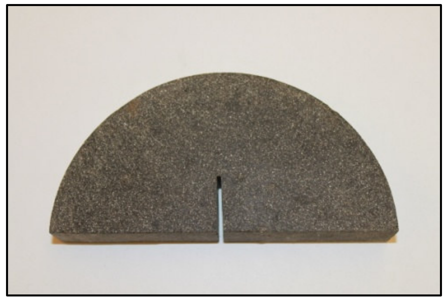
Model by Allen and Searcy (2001)

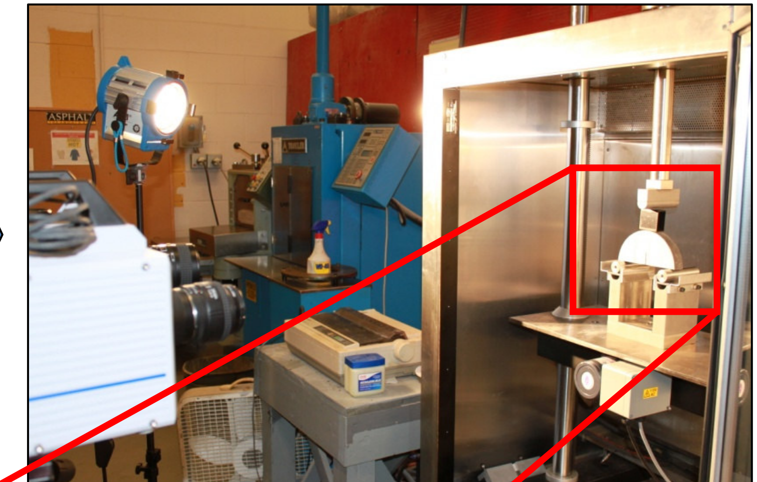
$$T_i(t) = \frac{\Delta_i(t)}{\delta_i \cdot \lambda(t)}\left[1-\alpha(t)\right]\cdot\left[\Sigma_i^f + \int_{t_0}^{t} E_{cz}(t-\tau)\frac{\partial\lambda(\tau)}{\partial\tau}\,d\tau\right] \quad (i = n, t, s)$$

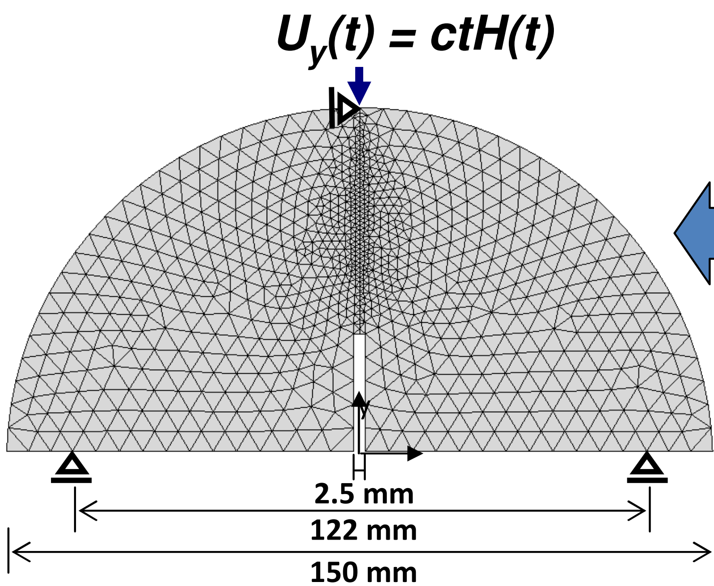
- Averaged Traction: $T_i(t)$
- CZ Displacement: $\Delta_i(t)$
- Stress Level to Initiate CZ: Σ_i^f
- Linear Viscoelastic Relaxation Modulus: $E_{cz}(t-\tau)$
- CZ Length Parameter: δ_i
- Euclidean Norm of CZ Displacements: $\lambda(t)$
- Damage Evolution Function: $\alpha(t)$

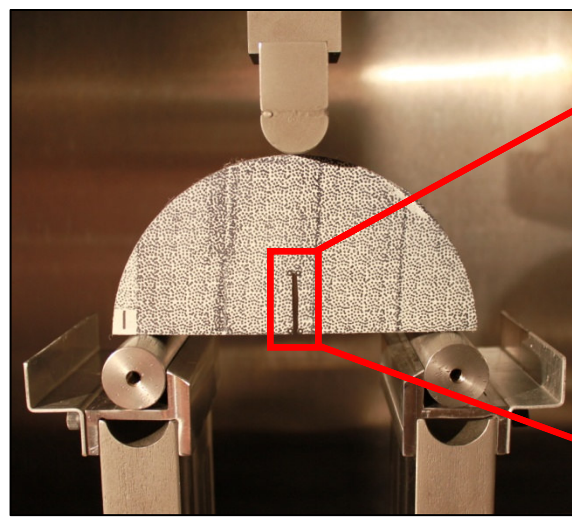


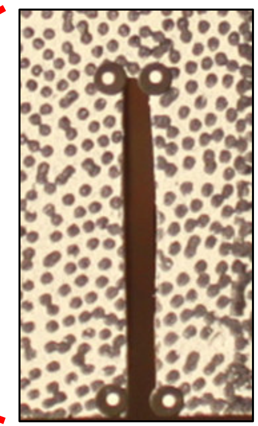
Model Inputs: CZM Parameters



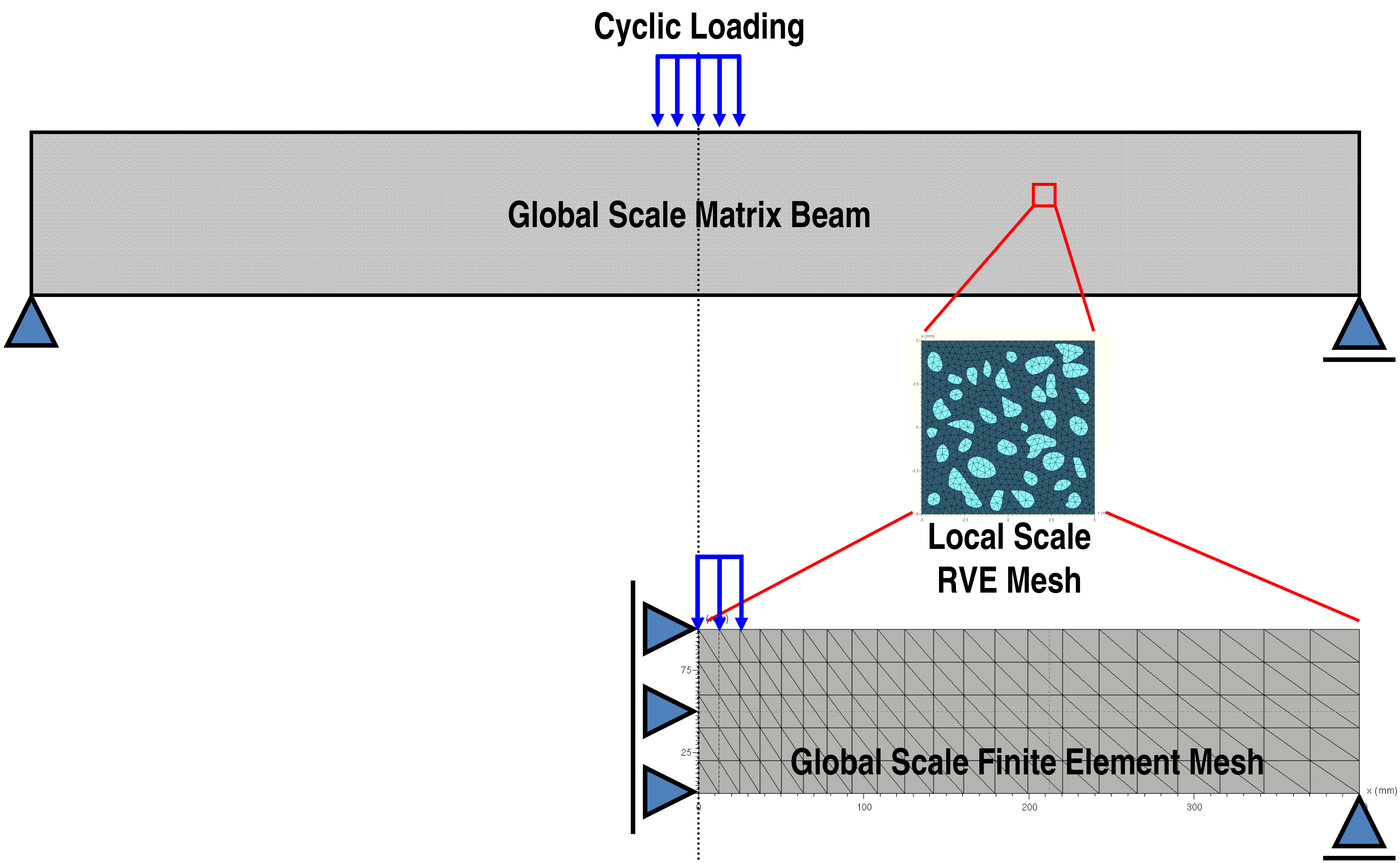




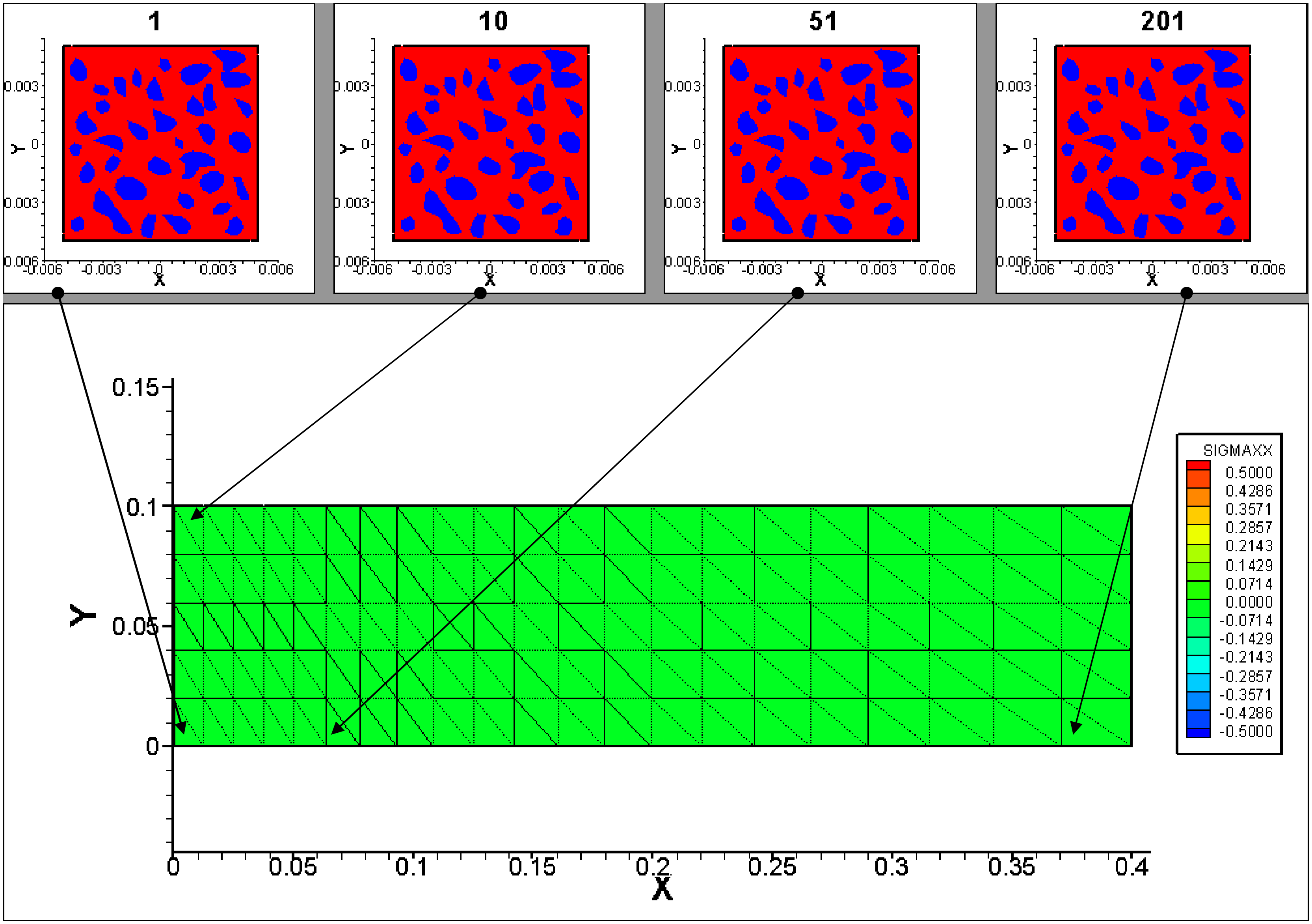




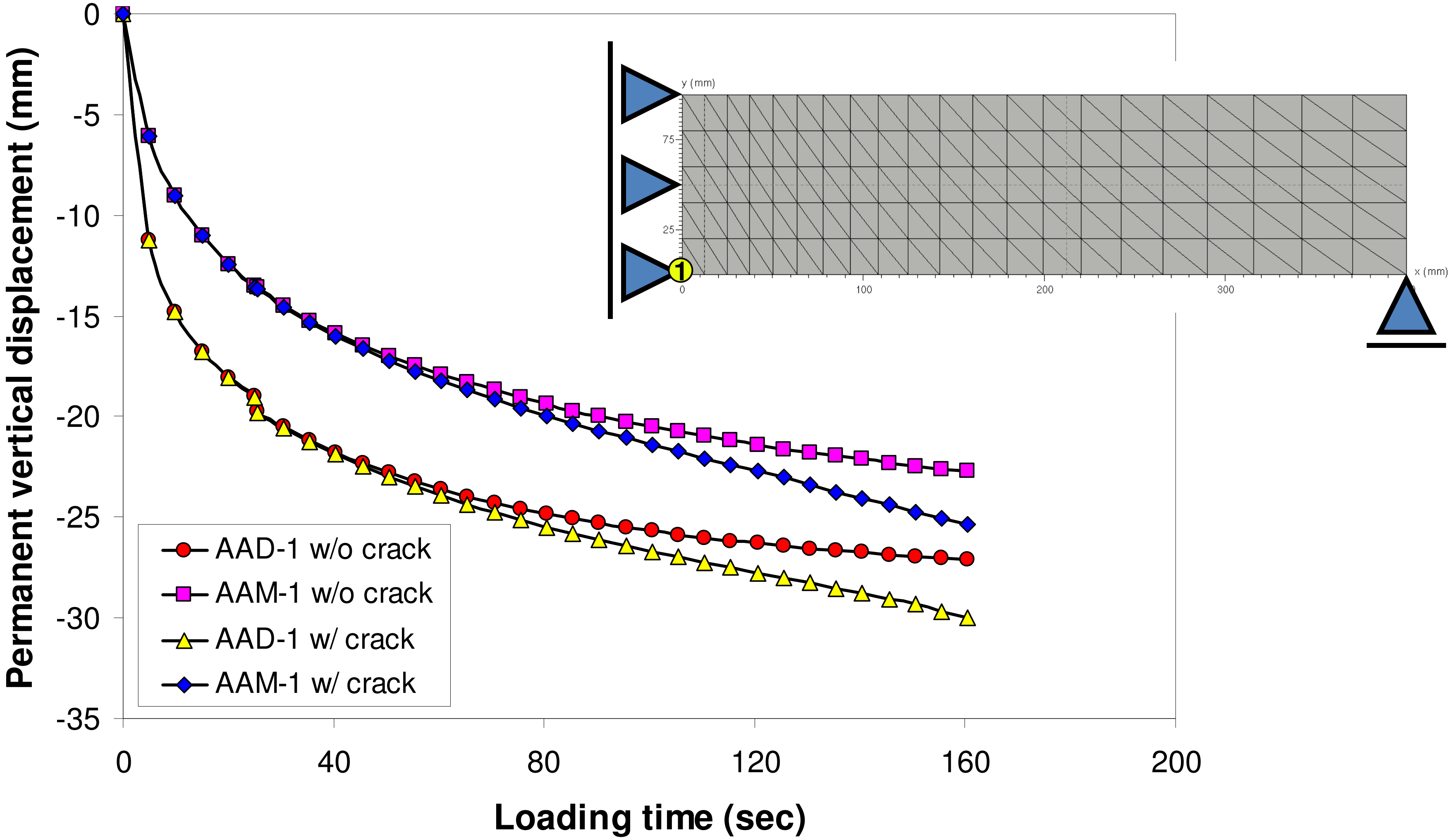
Model Application



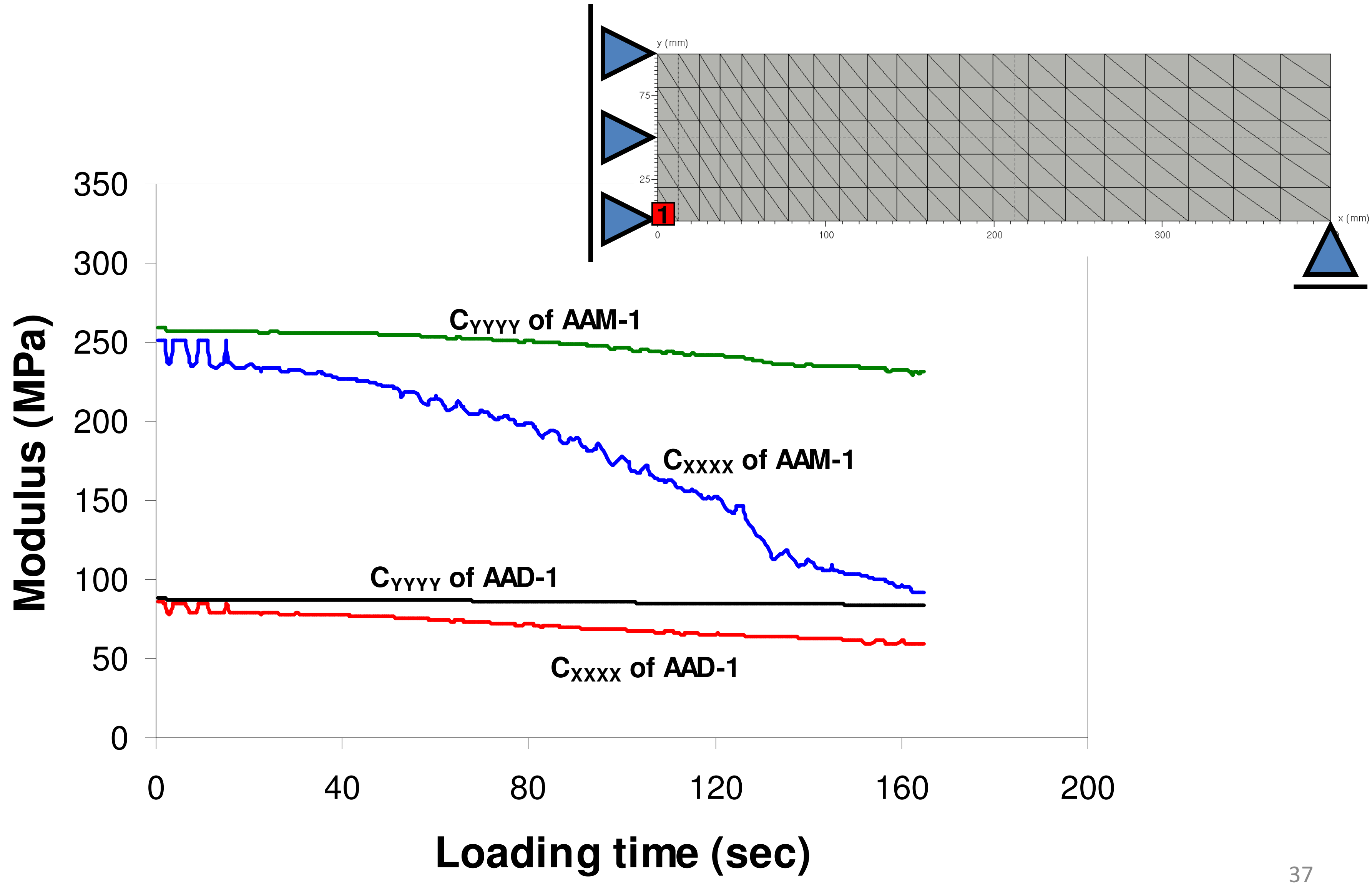
Model Outputs (Contours)



Model Outputs (Node No.1)



Model Outputs (Element No.1)



Model Limitations/Challenges

Cohesive Zone Modeling of Fracture

- ❑ **Rate-dependent** fracture behavior
- ❑ Characterization of **mixed-mode fracture properties**
- ❑ Characterization and modeling of **adhesive (matrix-aggregate interface) fracture**

Computational Micromechanics Modeling

- ❑ Identification of **representative volume elements** with cracks
- ❑ Explicit modeling of **air voids**
- ❑ Other necessary **materials constitutive relations**
- ❑ Implementation of **aging and healing**
- ❑ Model **validation and calibration**
- ❑ Extension from 2D modeling to **3D simulation**

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THANK YOU!