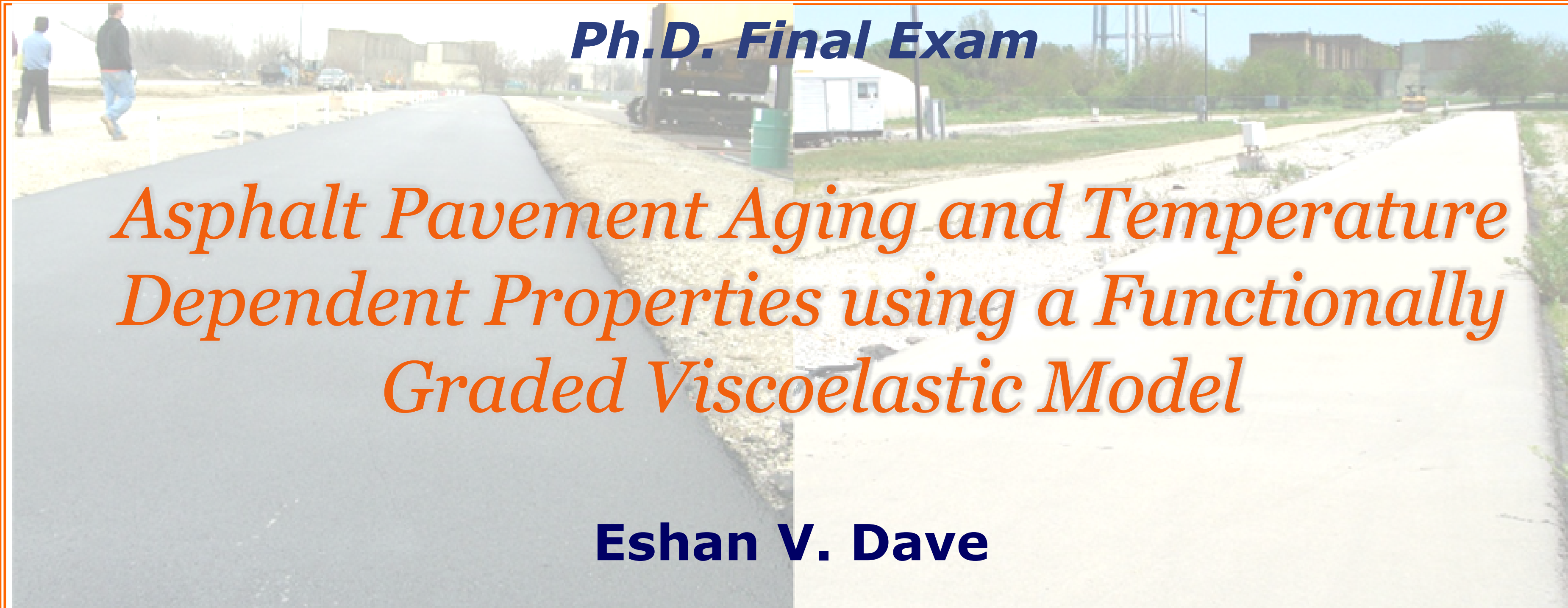
Ph.D. Final Exam

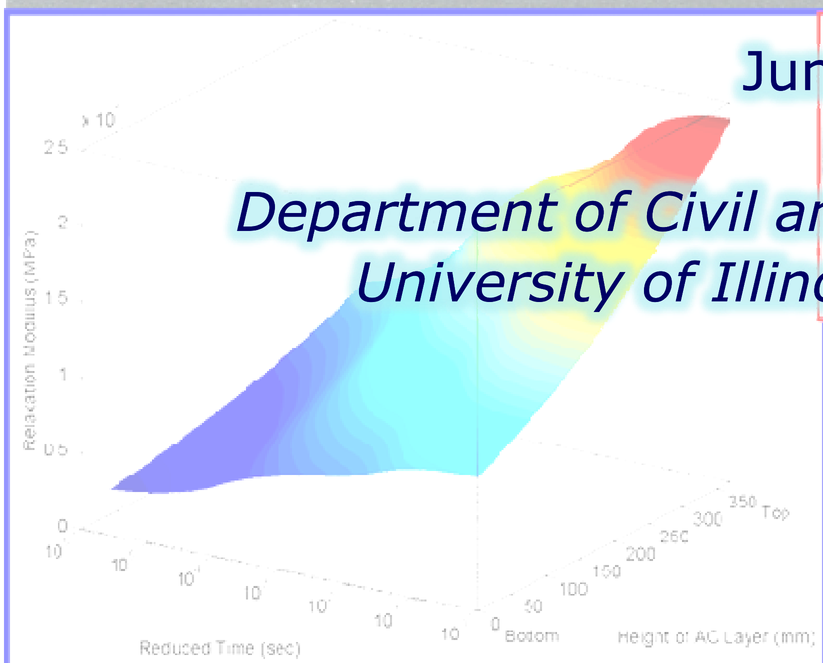


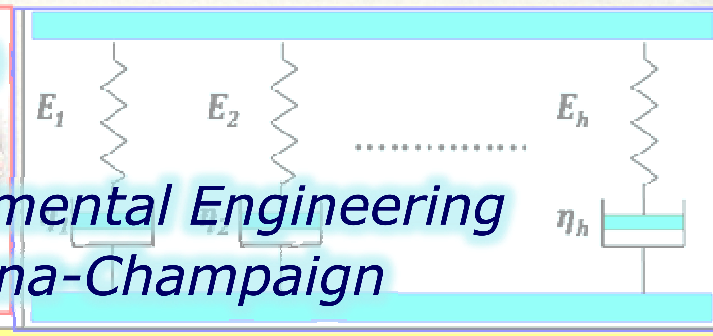
Asphalt Pavement Aging and Temperature Dependent Properties using a Functionally Graded Viscoelastic Model

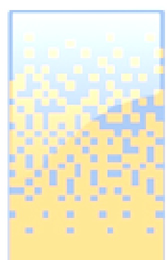
Eshan V. Dave

June 5th 2009

Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign







$$G(t)=\sum_{i=1}^{m}N_i\left[G(t)\right]_i;K(t)=\sum_{i=1}^{m}N_i\left[K(t)\right]_i$$

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Sincere gratitude to:

- William G. Buttlar
- Glaucio H. Paulino
- Harry H. Hilton
- Phillip B. Blankenship
- Hervé DiBenedetto

- All colleagues and friends

Acknowledgements

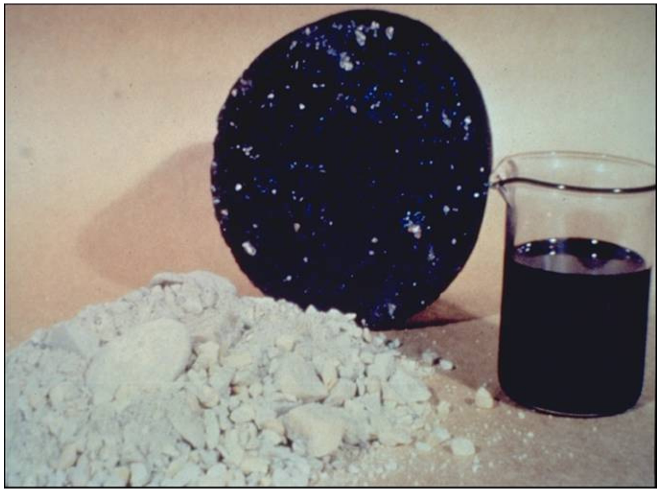
- NSF-GOALI Program: Project CMS 0219566
- Koch Materials Company / SemMaterials L.P.
- USDOT Nextrans Research Center
- FHWA Pooled Fund Study: TPF-5(132)

U.S. Department of Transportation
Federal Highway Administration

Functionally Graded Viscoelastic Asphalt Concrete Model

- Motivation and Introduction
- Viscoelastic Characterization of Asphalt Concrete
- Viscoelastic FGM Finite Elements
- Correspondence Principle Based Analysis
- Time Integration Analysis
- Application Examples: Asphalt Pavement
- Summary and Conclusions

Asphalt Concrete



- Constituents:
  - Asphalt Binder
  - Aggregates

- Asphalt Binder:
  - Derived from Crude Oil
  - Many times modified with polymers to enhance properties
  - Undergoes oxidative aging (stiffening) with time

- Asphalt Concrete (Asphalt Mixture)
  - Large fraction produced as hot-mix asphalt (HMA)
  - Most common form of pavement surfacing material (96% of pavement surface in United States)

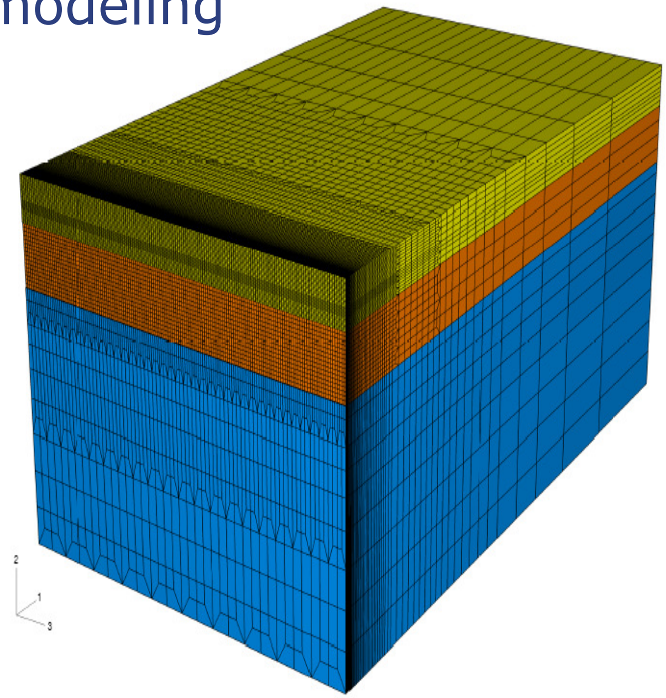
Motivation

- Cracking in Asphalt Concrete Pavements and Overlays:
  - *Reflective cracking*
  - *Thermal cracking*

- Big Picture:
  - Predict reflective and thermal cracking in asphalt concrete pavements
  - Design pavements and overlays (with/without interlayers) to prevent thermal/reflective cracking

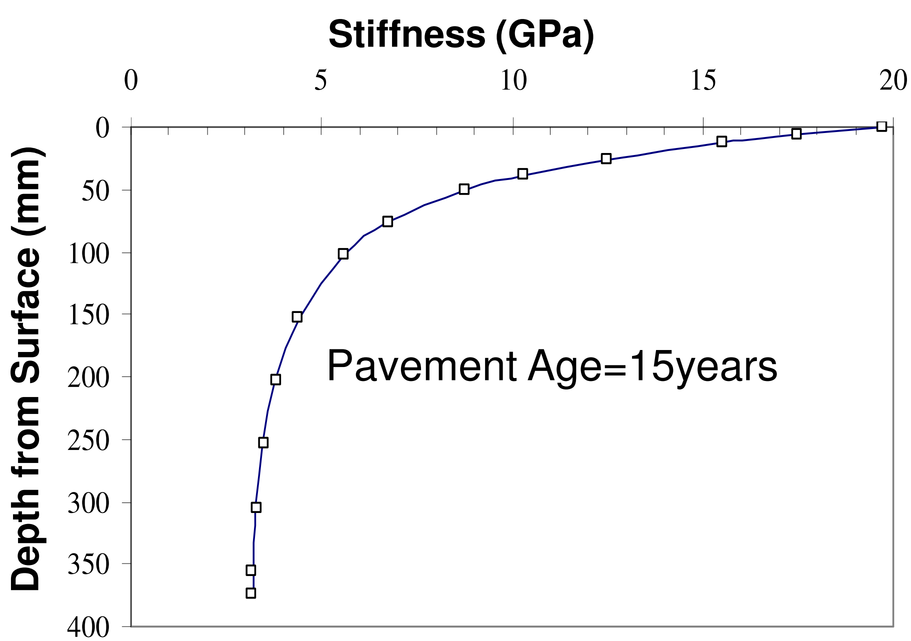
Motivation: Progress in Recent Years

- Significant improvements have been made towards accurate simulation of asphalt pavement systems:
  - Viscoelastic characterization and modeling
  - Fracture energy measurements
  - Cohesive zone fracture model
  - Integrated studies

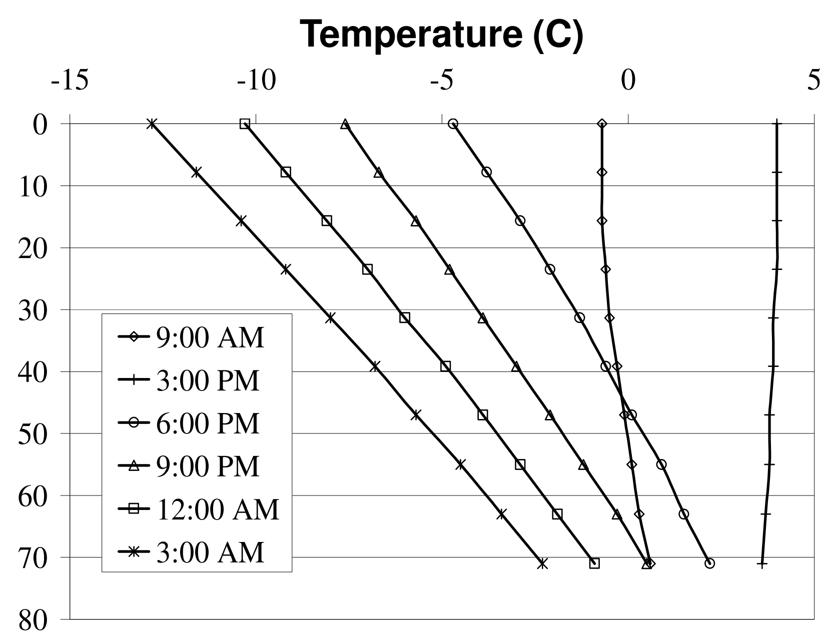


Pavements are Non-Homogeneous Structures

- Sources:
  1. *Oxidative aging*
  2. *Temperature dependence of material properties*
  3. *Other sources (construction, additives etc.)*

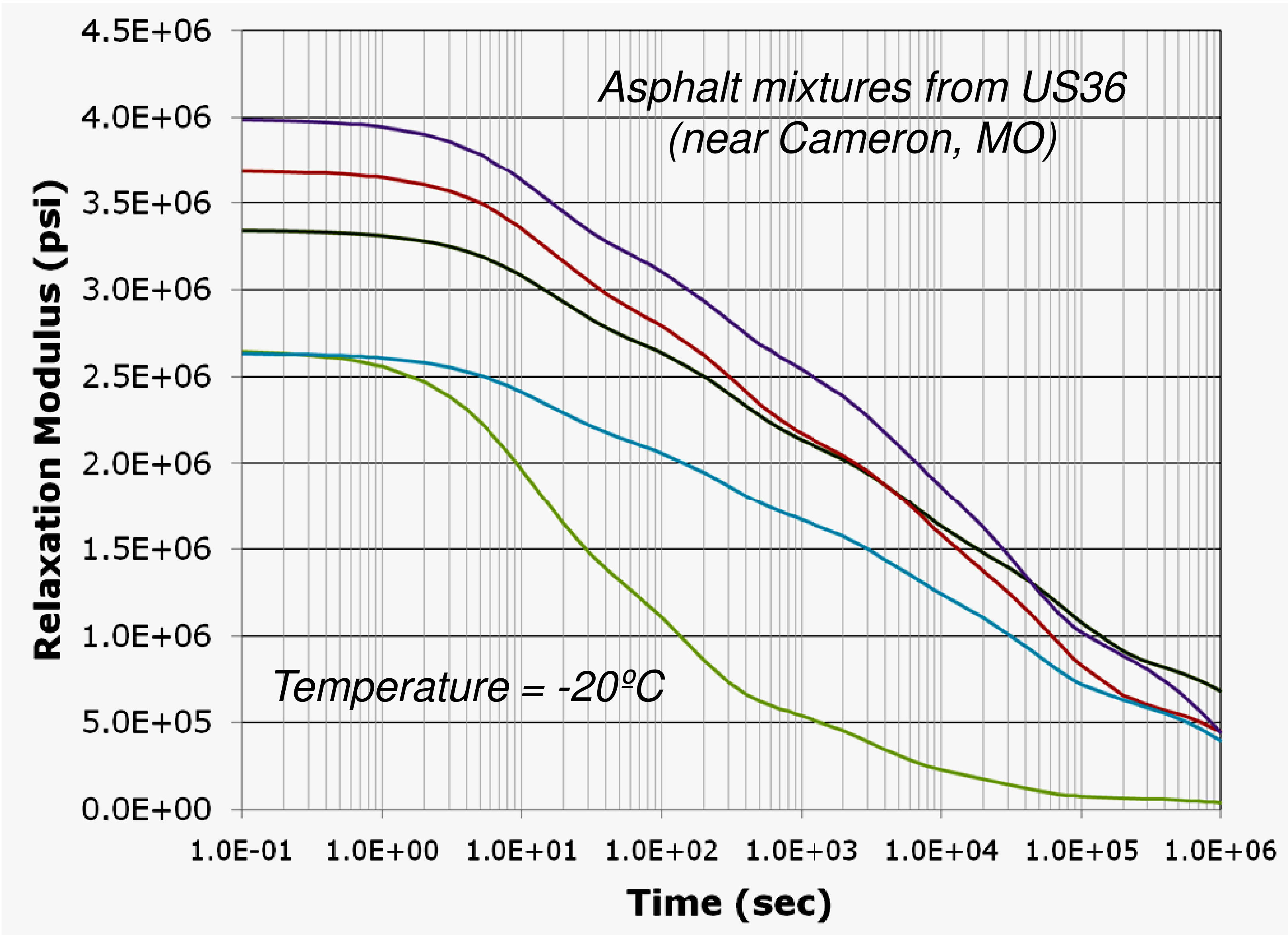


Aging gradient generated using "Global aging model" by Mirza and Witczak (1996)



Temperature profiles generated using "EICM" from AASHTO MEPDG (2002)

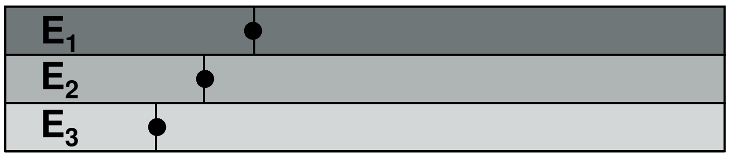
Asphalt Concrete is Viscoelastic



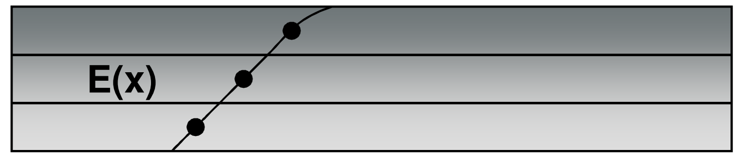
Motivation

Simulation Approaches for Non-Homogeneous Structures

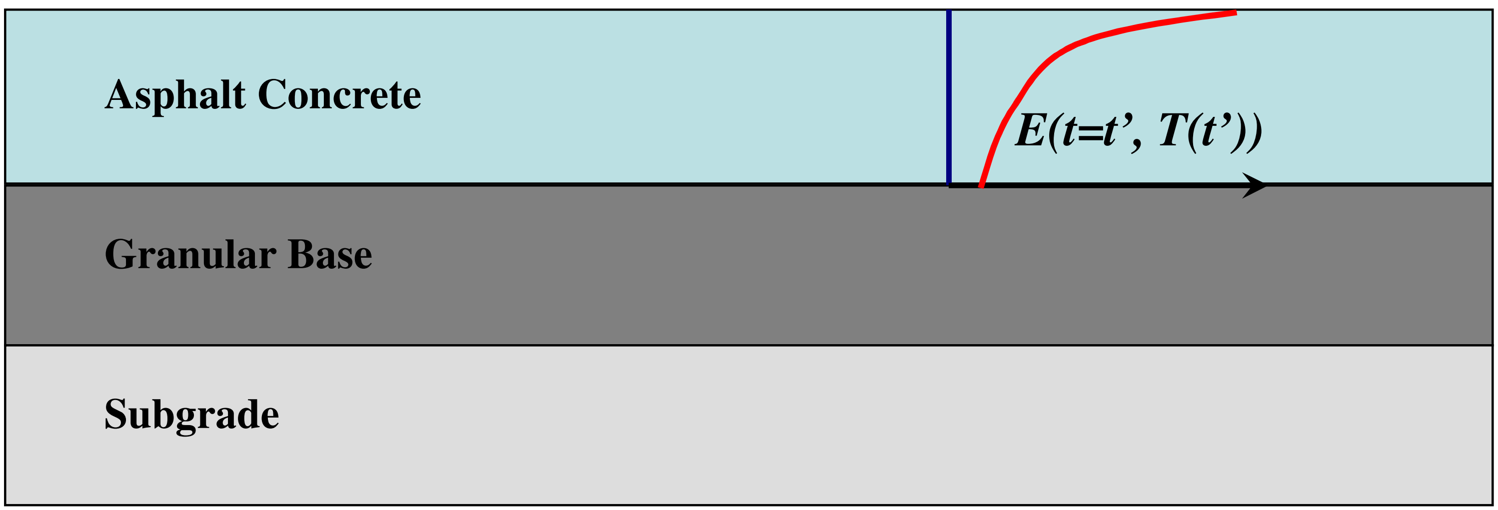
Layered



Graded

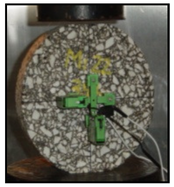


- Layered approach is the current state of practice
  - AASHTO MEPDG (Aging Gradient)



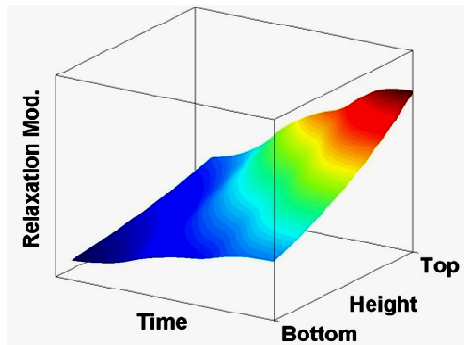
Pavement Analysis and Design

Viscoelastic Lab Characterization:
(Chapter 3)
(a) Aging Levels
(b) Test Temperatures



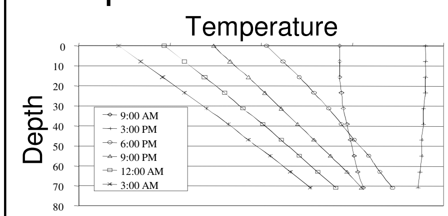
Anticipated aging conditions (based on distress type and design life)

Viscoelastic FGM Properties



Pavement structure and field conditions

Temperature distribution



Viscoelastic FGM finite-element method (Chapters 4 and 5)
(a) CP-Based Analysis
(b) Time-Integration Analysis

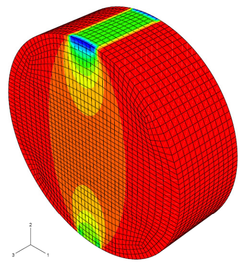
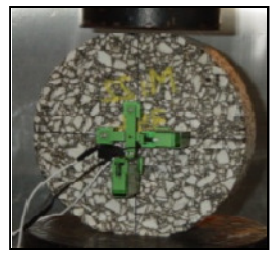
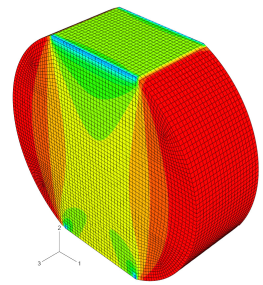
Pavement Analysis and Design:
(a) Study of critical responses (e.g. tensile strains at bottom of AC layer)
(b) Prediction of pavement performance
(c) Comparison of design alternatives (structure and/or materials)
Few examples shown in Chapter 6

Objectives

- Develop efficient and accurate simulation scheme for asphalt concrete pavements
- Viscoelastic characterization of asphalt concrete (Chapter 3)
- Viscoelastic analysis
  a) Correspondence Principle (Chapter 4)
  b) Time Integration Scheme (Chapter 5)
- Account for:
  – Aging gradients
  – Temperature dependent property gradients
- Simulate asphalt concrete pavements and overlay systems (Chapter 6)

Functionally Graded Viscoelastic Asphalt Concrete Model

- Motivation and Introduction
- Viscoelastic Characterization of Asphalt Concrete

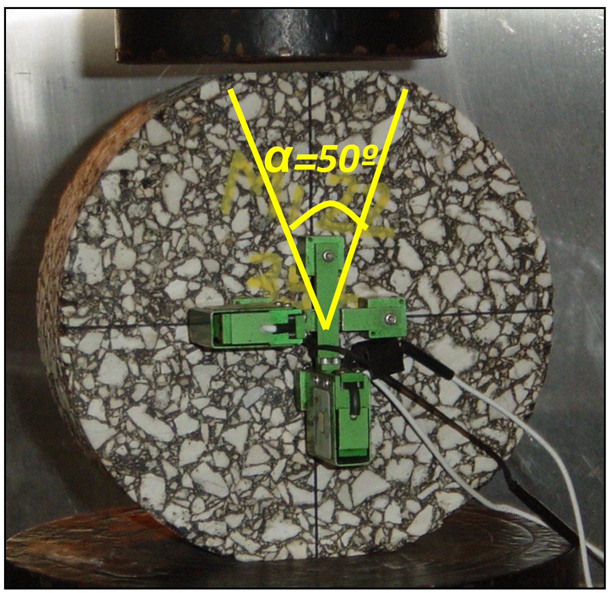
- Viscoelastic FGM Finite Elements
- Correspondence Principle Based Analysis
- Time Integration Analysis
- Application Examples: Asphalt Pavement
- Summary and Conclusions

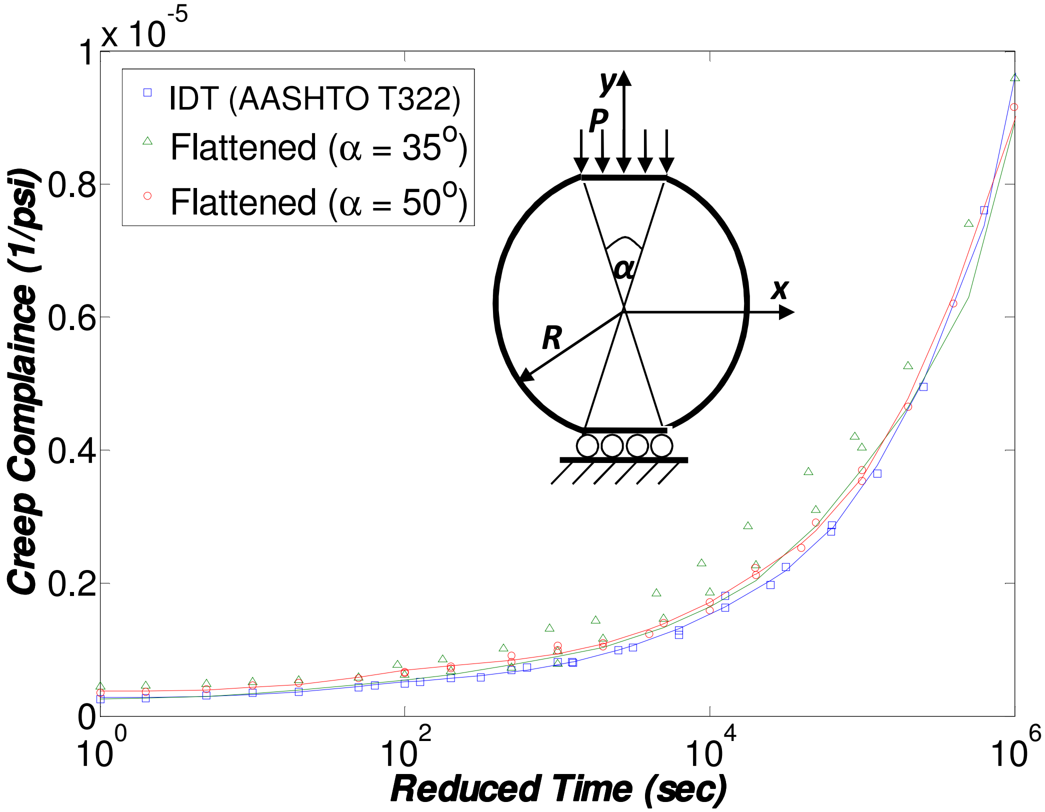
Viscoelastic Characterization

- Asphalt concrete samples
- Use of indirect tensile test (IDT), AASHTO-T322
- Softer/Compliant Mixtures → Crushing under loading head

Flattened IDT Test

- Increase contact area to prevent crushing under loading head
- Viscoelastic solution to bi-axial loading
- Results indicate flat IDT as a viable alternative to IDT





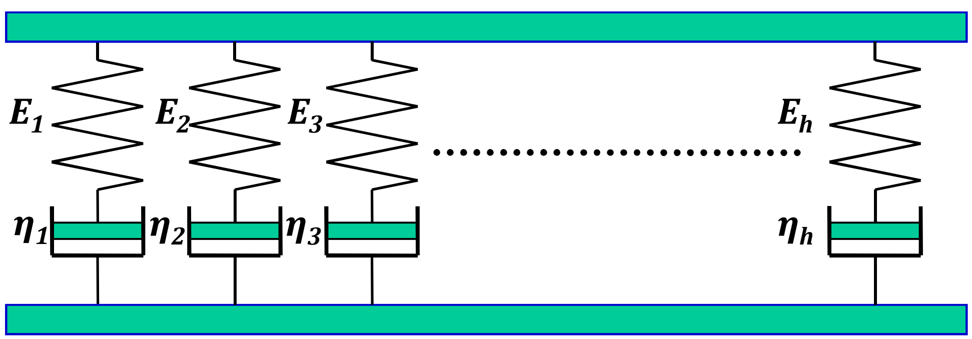
Viscoelasticity: Commonly used models for asphaltic materials

- Could be classified as:
  - Prony series forms (Generalized models)
  - Parabolic models
  - Others

- Prony series form: Generalized Maxwell Model

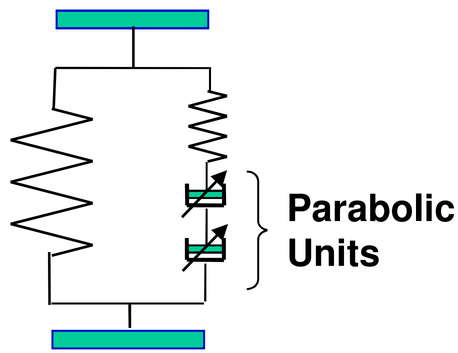
$$E(t) = \sum_{i=1}^{h} E_i \, Exp\left[-t/\tau_i\right]$$

$$\tau_i = \frac{\eta_i}{E_i}$$



Viscoelasticity: Constitutive models

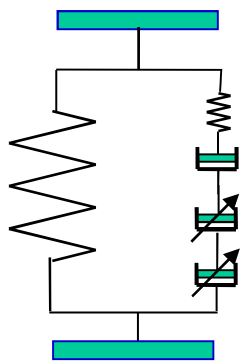
- Parabolic Models:
  - Huet-Sayegh Model (1965):



Parabolic Unit (time dependent dashpot) :

$$\varepsilon(t) = \frac{\sigma}{A} t^{k}, \; 0 < k < 1$$

  - 2S2P1D Model: Di Benedetto et al. (2005, 2007)



- Fewer parameters compared to generalized models
- Shared parameters between asphalt binders, mastics and mixtures

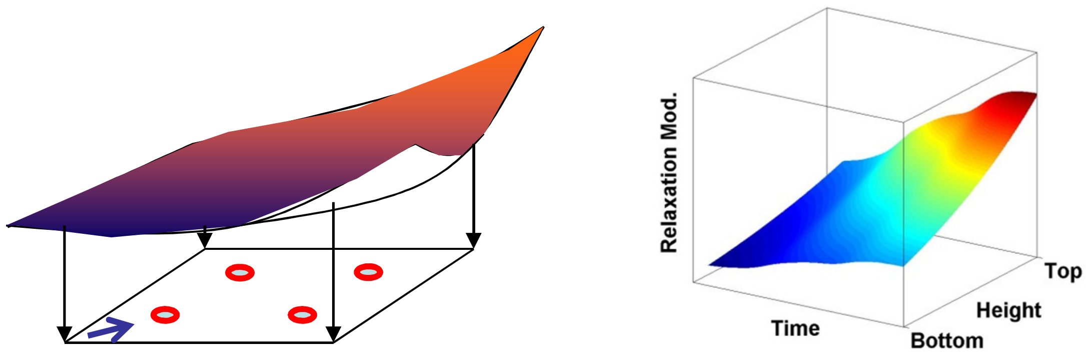
- Other Models: Power law, sigmoidal etc.

Viscoelasticity: Prony Series Models

- Generalized Maxwell model is selected for the current study:
  - Applicability to asphaltic and other viscoelastic materials
  - Flexibility w.r.t. fitting of experimental data
  - Equivalence between compliance and relaxation forms
  - Transformations are well established
  - Compatibility with previous research (e.g. GOALI study, ABAQUS etc.)
  - Availability of model parameters for variety of asphalt mixtures

Functionally Graded Viscoelastic Asphalt Concrete Model

- Motivation and Introduction
- Viscoelastic Characterization of Asphalt Concrete
- Viscoelastic FGM Finite Elements



- Correspondence Principle Based Analysis
- Time Integration Analysis
- Application Examples: Asphalt Pavement
- Summary and Conclusions

Viscoelasticity: Basics

- Constitutive Relationship:

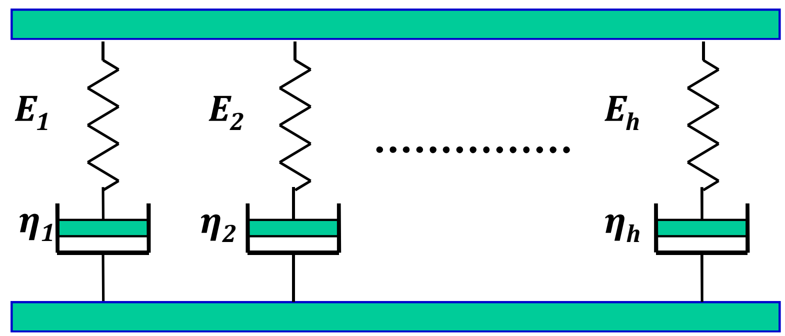
$$\sigma(x,t) = \int_{t'=-\infty}^{t'=t} C\left(x, \xi - \xi'\right) \frac{\partial \varepsilon\left(x,t'\right)}{\partial t'} dt'$$

σ : Stresses, $C(x,\xi)$: Relaxation Modulus, ε : Strains

- Model of Choice: Generalized Maxwell Model

$$C(x,t) = \sum_{h=1}^{N} E_h(x) \, Exp\left[-\frac{t}{\tau_h(x)} \right]$$

Relaxation Time, $\tau_h = \dfrac{\eta_h}{E_h}$



- Time-Temperature Superposition

Reduced Time, $\xi(x,t) = \int_{0}^{t'} a(T,x,t) \, dt'$

Viscoelasticity: Correspondence Principle

- Correspondence Principle (Elastic-Viscoelastic Analogy): "Equivalency between transformed (Laplace, Fourier etc.) **viscoelastic** and **elasticity** equations"

Elastic

$$\sigma^d = 2G\varepsilon^d$$

$$\sigma = 3K\,\varepsilon$$

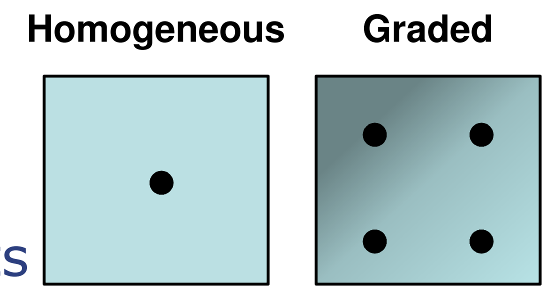
Transformed Viscoelastic

$$\tilde{\sigma}^d = 2\tilde{G}\tilde{\varepsilon}^d$$

$$\tilde{\sigma} = 3\tilde{K}\,\tilde{\varepsilon}$$

- Extensively utilized to solve variety of nonhomogeneous viscoelastic problems:
  - Hilton and Piechocki (1962): *Shear center of non-homogeneous viscoelastic beams*
  - Mukherjee and Paulino (2003): *Correspondence principle for viscoelastic FGMs*

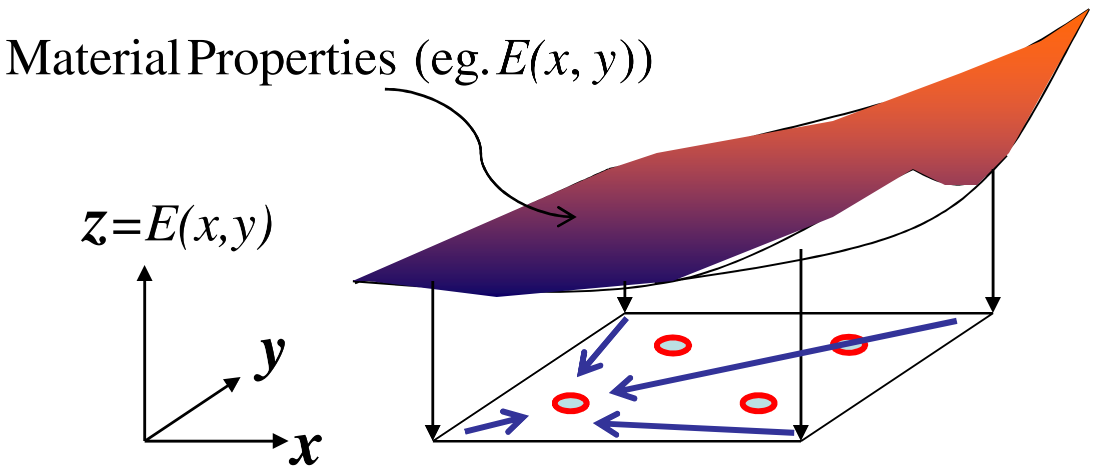
Graded Finite Elements



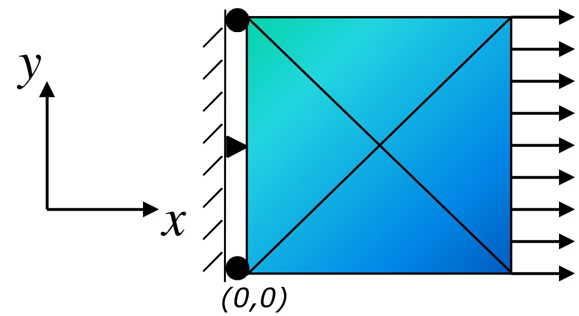
- Graded Elements: Account for material non-homogeneity within elements unlike conventional (homogeneous) elements
- Lee and Erdogan (1995) and Santare and Lambros (2000)
  - Direct Gaussian integration (properties sampled at integration points)
- Kim and Paulino (2002)
  - Generalized isoparametric formulation (GIF)
- Paulino and Kim (2007) and Silva et al. (2007) further explored GIF graded elements
  - Proposed patch tests
  - GIF elements should be preferred for multiphysics applications
- Buttlar et al. (2006) demonstrated need of graded FE for asphalt pavements (elastic analysis)

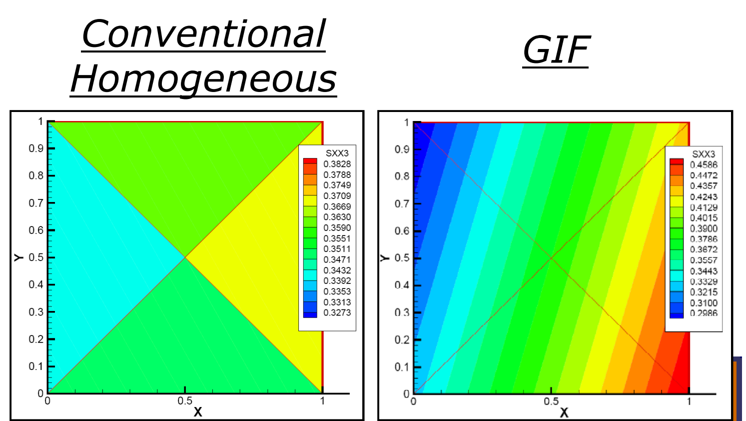
Generalized Isoparametric Formulation (GIF)

- Material properties are sampled at the element nodes
- Iso-parametric mapping provides material properties at integration points
- Natural extension of the conventional isoparametric formulation



$$E(x,y) = E_0 Exp[3x - 2y]$$





$$E(t) = \sum_{i=1}^{m} N_i \left[E(t) \right]_i$$

N_i = Shape function corresponding to node, i

m = Number of nodes per element

General FE Implementation

- Variational Principle (Potential):

$$\pi = \int_{\Omega_u} \int_{t'=-\infty}^{t'=t} \int_{t''=-\infty}^{t''=t-t'} \frac{1}{2} C\left[x, \xi\left(t-t''\right) - \xi'\left(t'\right)\right] \frac{\partial \varepsilon\left(t'\right)}{\partial t'} \frac{\partial \varepsilon\left(t''\right)}{\partial t''} dt'\, dt''\, d\Omega_u$$

$$- \int_{\Omega_\sigma} \int_{t''=-\infty}^{t''=t} P\left(x, t-t''\right) \frac{\partial u\left(t''\right)}{\partial t''} dt''\, d\Omega_\sigma$$

Where, π is Potential, ε are strains for body of volume Ω_u,

P is the prescribed traction on surface Ω_σ and u is the corresponding displacement

- Stationarity forms the basis for problem description:

$$\delta\pi = \int_{\Omega_u} \int_{t'=-\infty}^{t'=t} \int_{t''=-\infty}^{t''=t-t'} \left\{ C\left[x, \xi\left(t-t''\right) - \xi'\left(t'\right)\right] \frac{\partial \varepsilon\left(t'\right)}{\partial t'} \frac{\partial \delta\varepsilon\left(t''\right)}{\partial t''} \right\} dt'\, dt''\, d\Omega_u$$

$$- \int_{\Omega_\sigma} \int_{t''=-\infty}^{t''=t} P\left(x, t-t''\right) \frac{\partial \delta u\left(t''\right)}{\partial t''} dt''\, d\Omega_\sigma = 0$$

Non-Homogeneous Viscoelastic FEM

- Equilibrium:

$$K_{ij}\left(x,\xi(t)\right)u_j(0)+\int_{0^+}^{t} K_{ij}\left(x,\xi(t)-\xi\left(t^{'}\right)\right)\frac{\partial u_j\left(t^{'}\right)}{\partial t^{'}}dt^{'}=F_i\left(x,t\right)$$

- Solution approaches:

1. Correspondence Principle (CP)

$$\left[K^0\left(x\right)s\tilde{K}^t\left(s\right)\right]_{ij}\tilde{u}_j\left(s\right)=\tilde{F}_i\left(x,s\right)$$

$\tilde{a}(s)$ is Laplace transform of $a(t)$; s is transformation variable

$$\tilde{a}(s)=\int_0^{\infty} a(t)\,Exp[-st]dt$$

2. Time-Integration Schemes

- *Recursive Formulation*

Non-Homogeneous Viscoelastic FEM

1. Correspondence Principle (CP)

- Benefits:
  - Solution does not require evaluation of hereditary integral
  - Direct extension of elastic formulations
- Limitations:
  - Inverse transformations are computationally expensive
  - Transform/Convolution should exist for material model and boundary conditions

2. Time-Integration Schemes (Recursive formulation)

- Benefits:
  - Fewer limitations on material model and boundary conditions
- Limitations:
  - Convergence studies are required to determine time step size
  - Elaborate formulation and implementation

- **Both are explored in this dissertation**

Functionally Graded Viscoelastic Asphalt Concrete Model

- Motivation and Introduction
- Viscoelastic Characterization of Asphalt Concrete
- Viscoelastic FGM Finite Elements
- Correspondence Principle Based Analysis

$$\sigma^d = 2G\varepsilon^d$$
$$\sigma = 3K\varepsilon$$

$$\tilde{\sigma}^d = 2\tilde{G}\tilde{\varepsilon}^d$$
$$\tilde{\sigma} = 3\tilde{K}\tilde{\varepsilon}$$

- Time Integration Analysis
- Application Examples: Asphalt Pavement
- Summary and Conclusions

CP-Based Implementation (Ch. 4)

$$\left[K^{0}\left(x\right)s\tilde{K}^{t}\left(s\right)\right]_{ij}\tilde{u}_{j}\left(s\right)=\tilde{F}_{i}\left(x,s\right)$$

Define problem in time-domain (evaluate load vector $F_i(x,t)$ and stiffness matrix components $K_{ij}^{0}(x)$ and $K_{ij}(t)$)

↓

Perform Laplace transform to evaluate $\tilde{F}_i(x,s)$ and $\tilde{K}_{ij}^{t}(x,s)$

↓

Solve linear system of equations to evaluate nodal displacement, $\tilde{u}_i(s)$

↓

Perform inverse Laplace transforms to get the solution, $u_i(t)$

↓

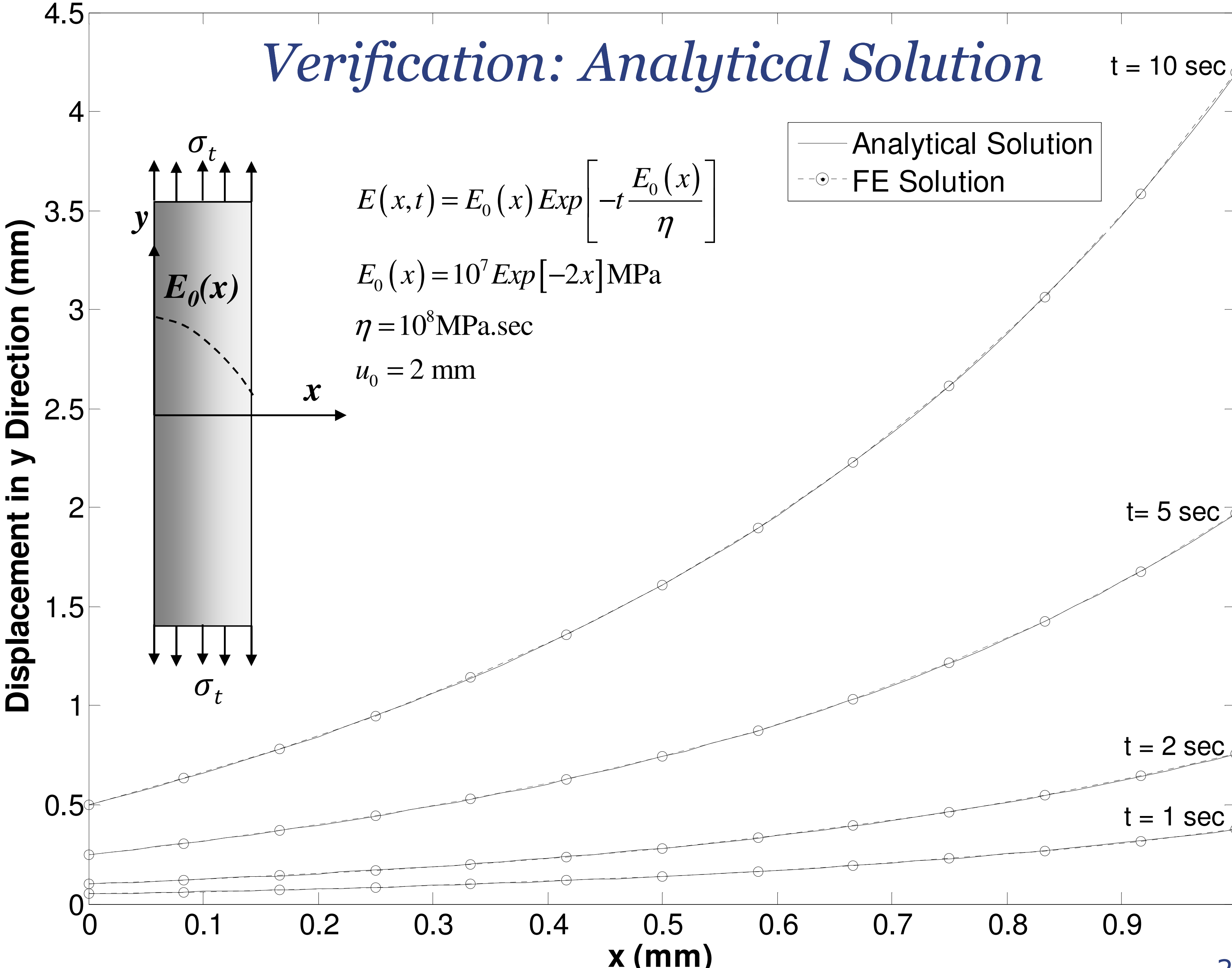
Post-process to evaluate field quantities of interest

Collocation is chosen as method of choice

Verification examples:

1. Analytical solution (Creep extension shown here)
2. Comparison with commercial software

Verification: Analytical Solution



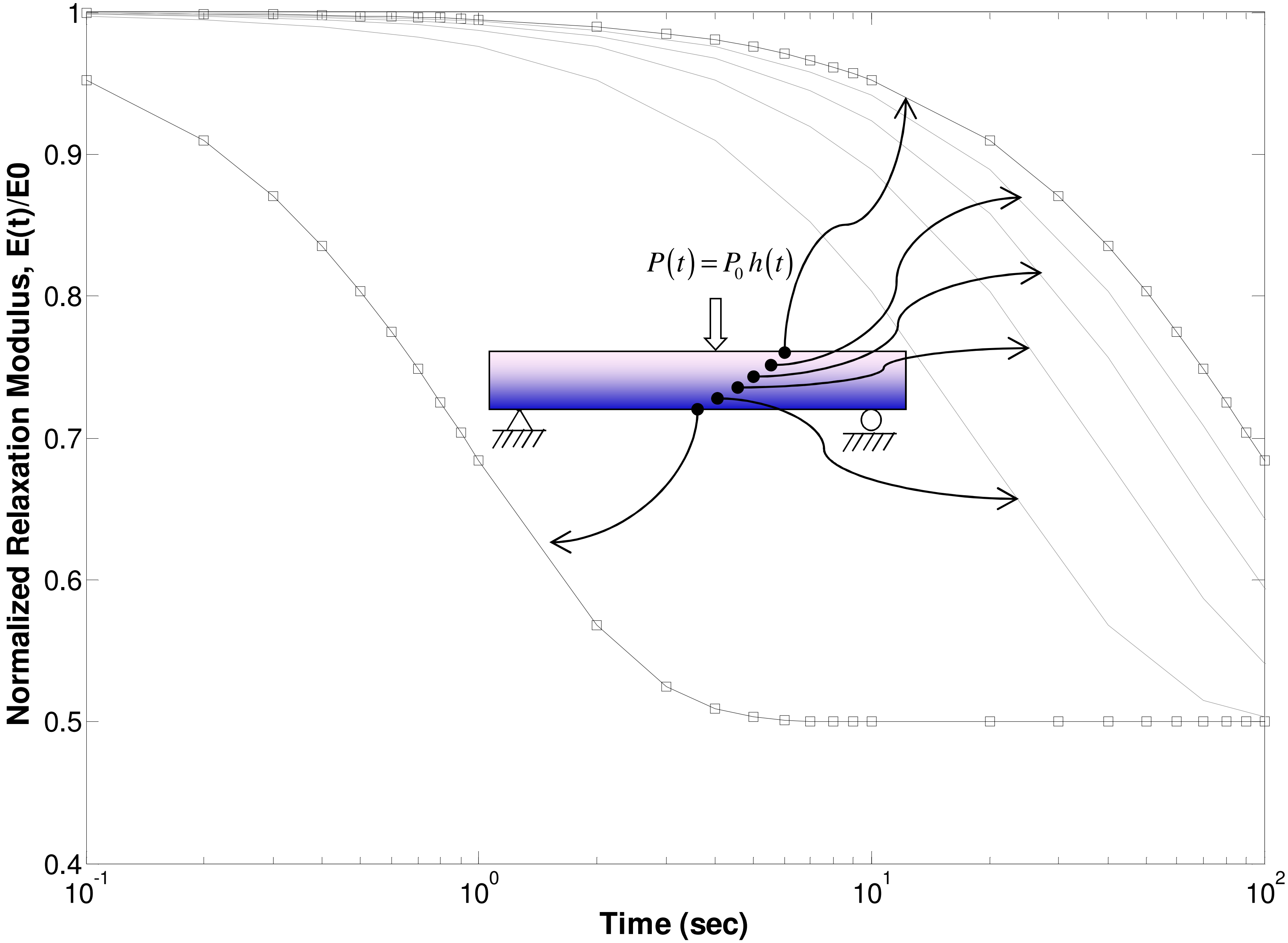
$$E(x,t) = E_0(x)\,Exp\left[-t\frac{E_0(x)}{\eta}\right]$$

$$E_0(x) = 10^7\,Exp[-2x]\,\text{MPa}$$

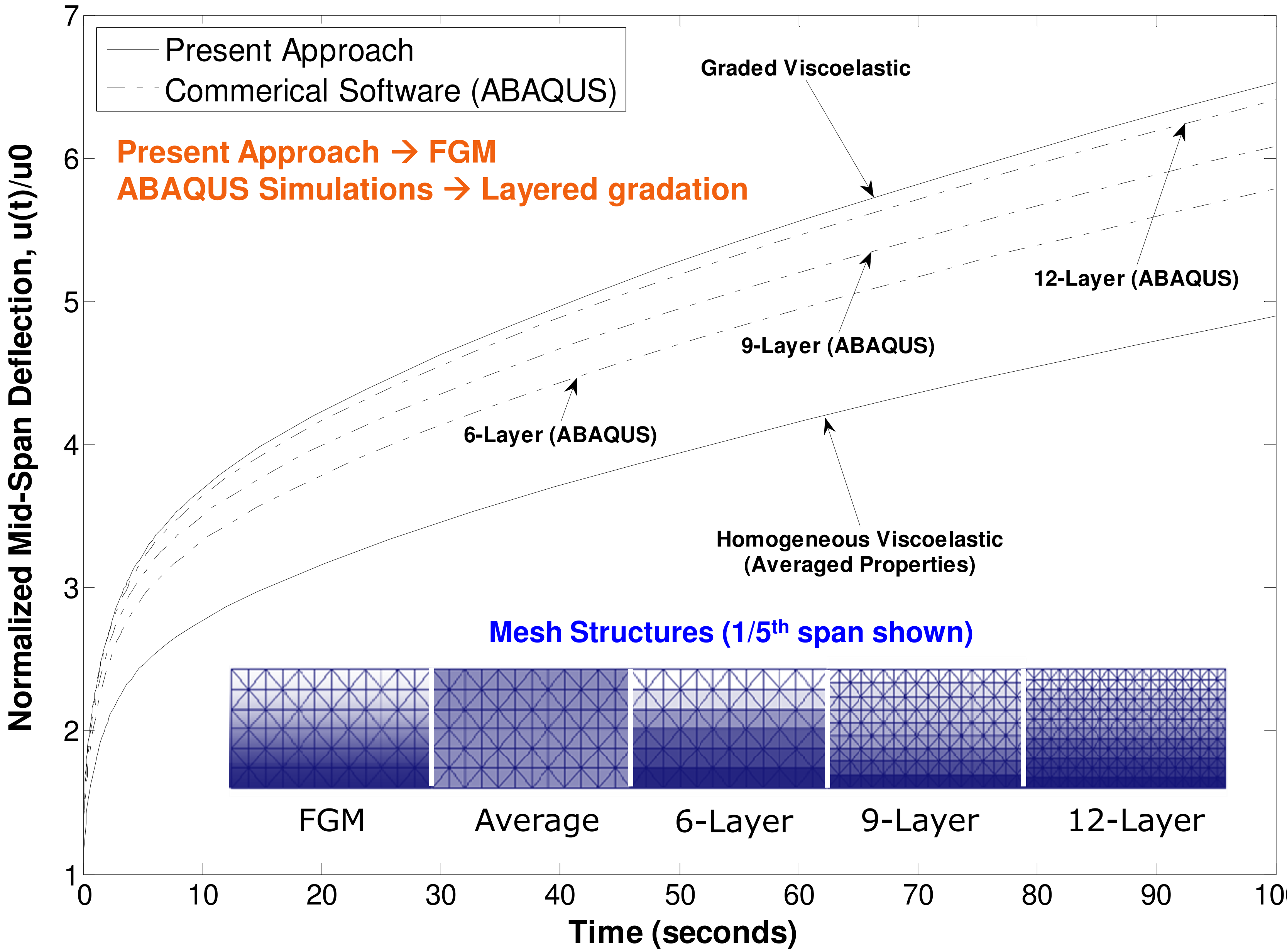
$$\eta = 10^8\,\text{MPa.sec}$$

$$u_0 = 2\text{ mm}$$

Verification with ABAQUS: Material Gradation

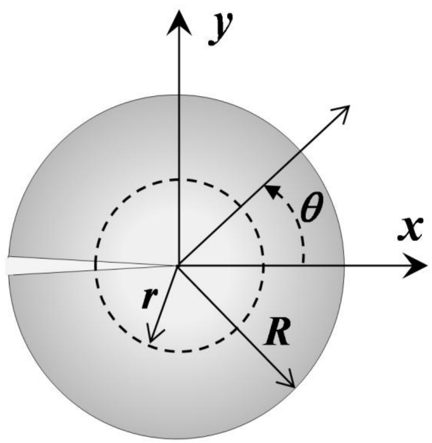


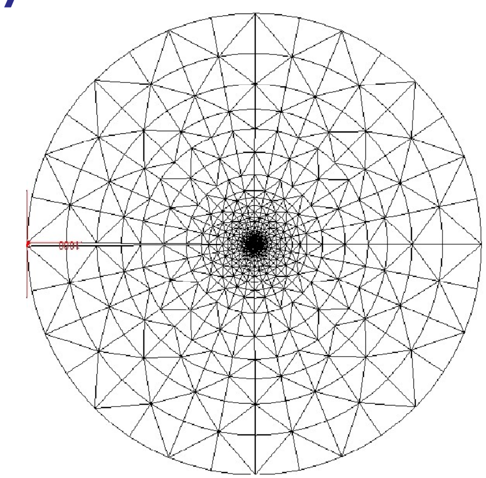
Verification: Comparison with ABAQUS



Functionally Graded Viscoelastic Asphalt Concrete Model

- Motivation and Introduction
- Viscoelastic Characterization of Asphalt Concrete
- Viscoelastic FGM Finite Elements
- Correspondence Principle Based Analysis
- Time Integration Analysis





- Application Examples: Asphalt Pavement
- Summary and Conclusions

Time Integration Approach (Ch. 5)

$$K_{ij}(x,\xi)u_j(0)+\int_{0^+}^{t} K_{ij}(x,\xi-\xi')\frac{\partial u_j(t')}{\partial t'}dt' = F_i(x,t)$$

- Above could be solved sequentially using Newton-Cotes expansion (material history effect needs to be considered)

$$u_j(t_n)=\left[K_{ij}(x,0)+K_{ij}(\xi_n-\xi_{n-1})\right]^{-1}\begin{Bmatrix} 2F_i(t_n)-\left[K_{ij}(\xi_n)-K_{ij}(\xi_n-\xi_1)\right]u_j(0) \\ -\sum_{m=1}^{n-1}\left[K_{ij}(\xi_n-\xi_{m-1})-K_{ij}(\xi_n-\xi_{m+1})\right]\boxed{u_j(t_m)} \end{Bmatrix}$$

- Alternatively, recursive formulation could be developed that requires only few previous solutions

Time-Integration Analysis (Ch. 5)

Recursive Formulation (Yi and Hilton, 1994):

$$\left[\sum_{h=1}^{m}\left(K_{ij}^{e}(x)\right)_h\cdot\left[\left(v_{ij}^{1}(x,t_n)\right)_h\Delta t-\left(v_{ij}^{2}(x,t_n)\right)_h\right]\frac{2}{\Delta t^2}\right]u_j(t_n)=F_i(t_n)$$

$$+\sum_{h=1}^{m}\left[\left[\left(K_{ij}^{e}(x)\right)_h\cdot Exp\left[-\frac{\xi(t_n)}{\left(\tau_{ij}(x)\right)_h}\right]\right]\right]\left\{\left(v_{ij}^{1}(x,t_{n-1})\right)_h\left[u_j(t_{n-1})\frac{2}{\Delta t}+\dot{u}_j(t_{n-1})\right]\right.$$

$$\left.-\frac{2}{\Delta t^2}\left(v_{ij}^{2}(x,t_{n-1})\right)_h\left[u_j(t_{n-1})+\dot{u}_j(t_{n-1})\Delta t\right]-u_i(t_0)+\left(v_{ij}^{1}(x,t_0)\right)\dot{u}_j(t_0)\right\}+\left(R_i(t_n)\right)_h\Big]$$

Where,

$$\left(v_{ij}^{1}(x,t_n)\right)_h=\int_0^{t_n}Exp\left[-\xi(t')/\left(\tau_{ij}(x)\right)_h\right]dt';\ \left(v_{ij}^{2}(x,t_n)\right)_h=\int_{t_{n-1}}^{t_n}\left(v_{ij}^{1}(x,t')\right)_h dt'$$

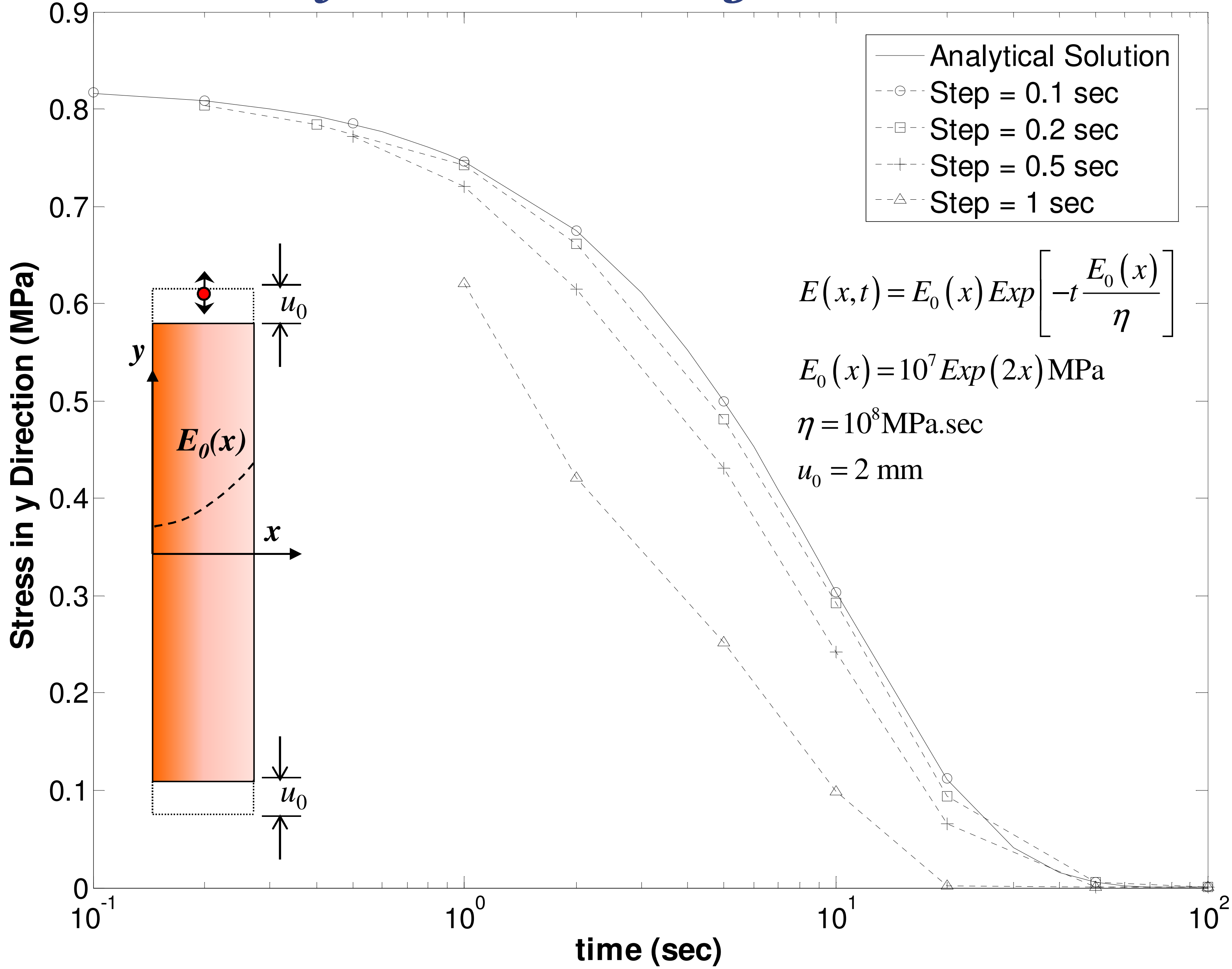
$$\left(R_i(t_n)\right)_h=K_{ij}^{e}\cdot Exp\left[-\xi(t')/\left(\tau_{ij}(x)\right)_h\right]\cdot\left(v_{ij}^{2}(x,t_n)\right)_h\ddot{u}_j(t_{n-1})$$

$$+Exp\left[-\xi(t')/\left(\tau_{ij}(x)\right)_h\right]\left(R_j(t_{n-1})\right)_h$$

Verification examples:

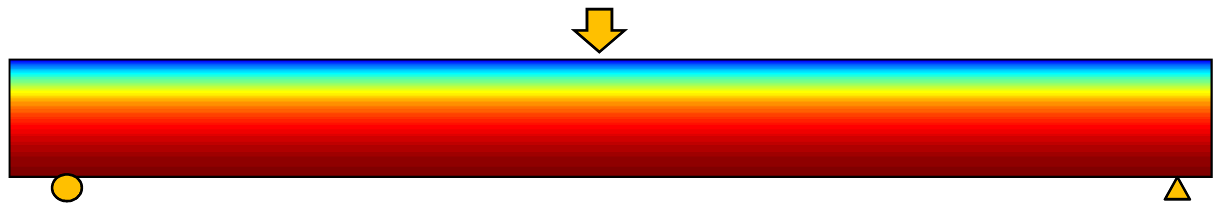
1. Analytical solution (Stress relaxation shown here)
2. Comparison with commercial software

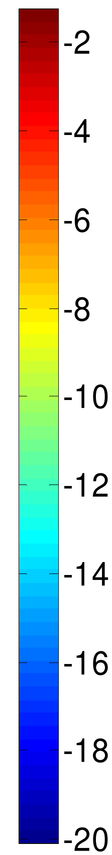
Verification: Analytical Solution



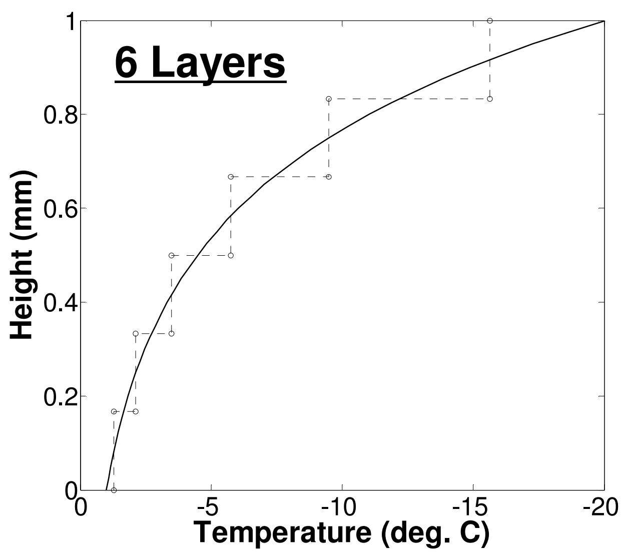
Verification: Comparison with ABAQUS

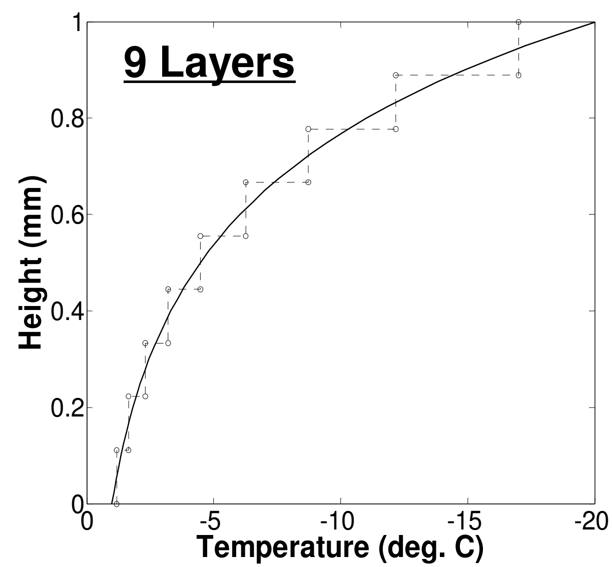
- Temperature Dependent Property Gradient
  - ABAQUS Simulations: Using layered gradation
  - Temperature distribution → $T(y) = -e^{3y}$



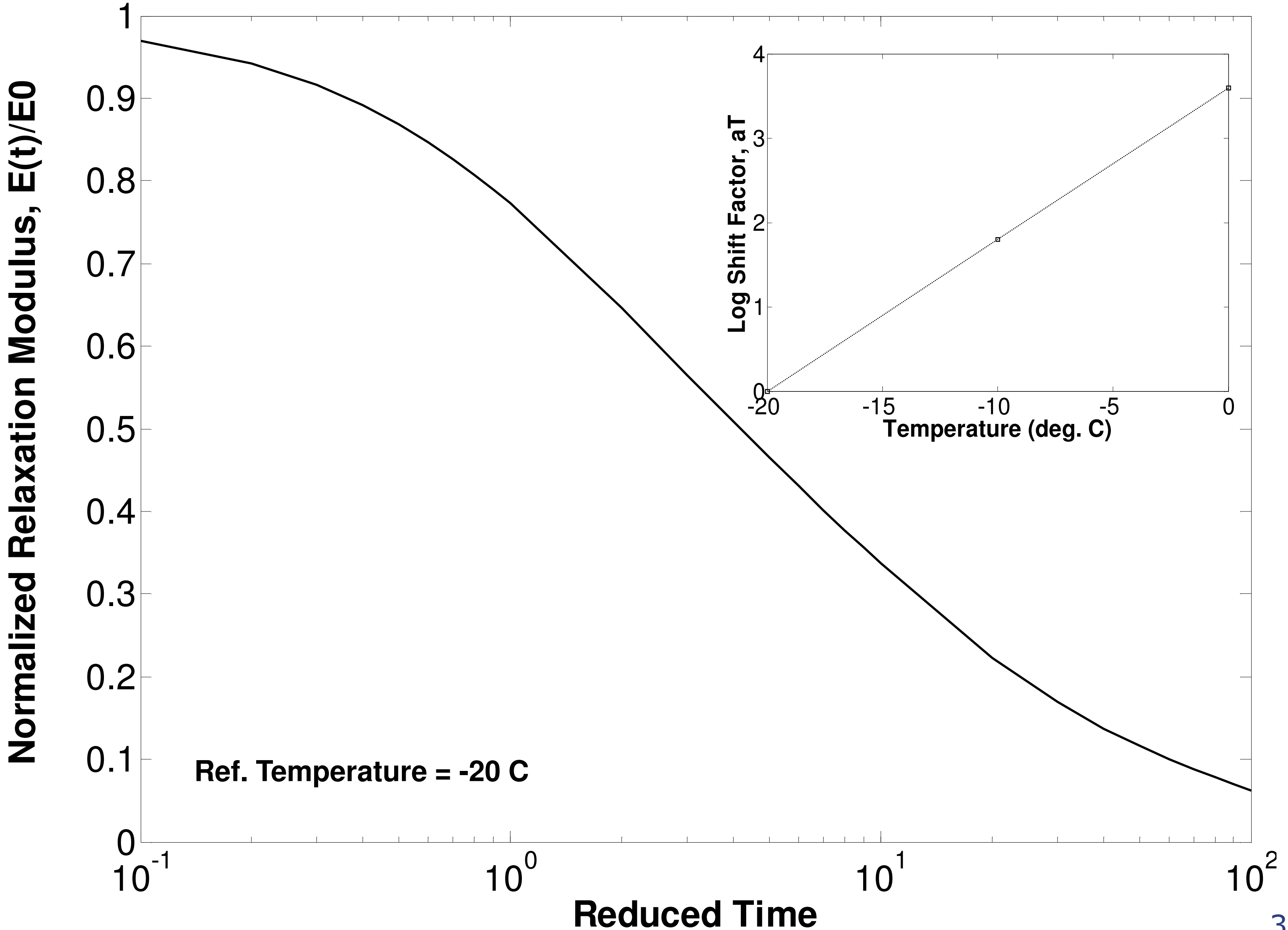


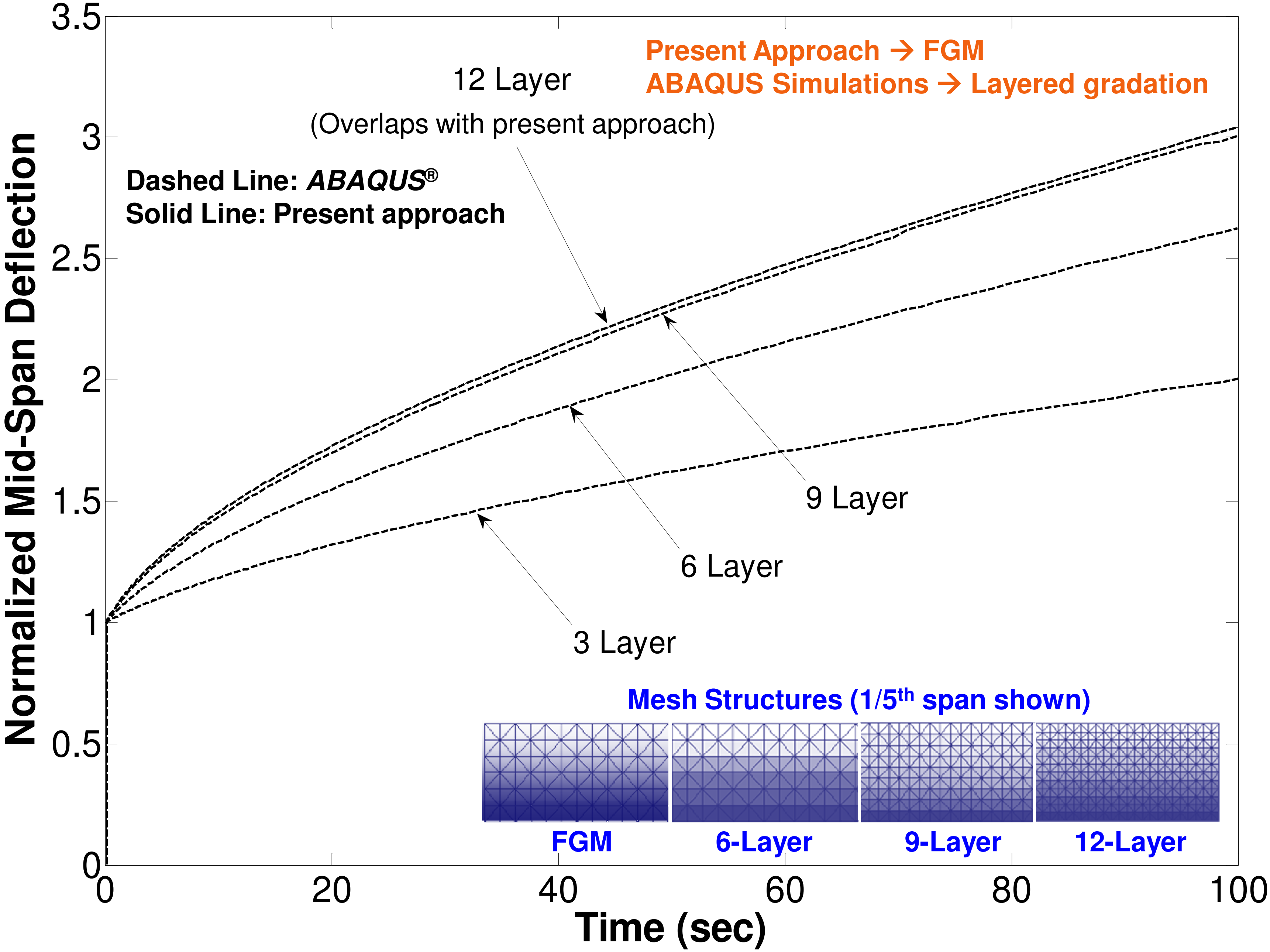
<u>TEMPERATURE INPUT</u>
Solid Line: FGM (Present Approach)
Dashed Line: Layered Approx. (ABAQUS)





Material Behavior





Present Approach → FGM
ABAQUS Simulations → Layered gradation
12 Layer
(Overlaps with present approach)
Dashed Line: *ABAQUS*®
Solid Line: Present approach
9 Layer
6 Layer
3 Layer
Mesh Structures (1/5th span shown)
FGM
6-Layer
9-Layer
12-Layer
Normalized Mid-Span Deflection
Time (sec)
0
0.5
1
1.5
2
2.5
3
3.5
0
20
40
60
80
100

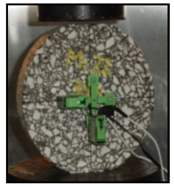
Functionally Graded Viscoelastic Asphalt Concrete Model

- Motivation and Introduction
- Viscoelastic Characterization of Asphalt Concrete
- Viscoelastic FGM Finite Elements
- Correspondence Principle Based Analysis
- Time Integration Analysis
- Application Examples: Asphalt Pavement

- Summary and Conclusions

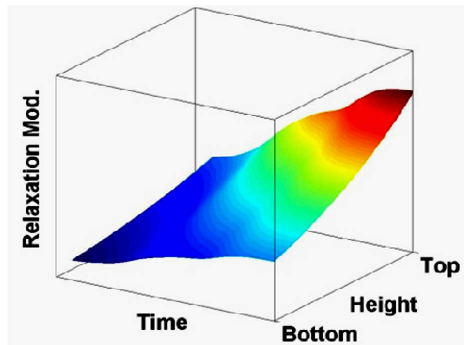
Pavement Analysis and Design

Viscoelastic Lab Characterization:
(Chapter 3)
(a) Aging Levels
(b) Test Temperatures



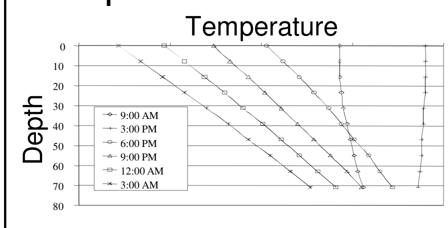
Anticipated aging conditions (based on distress type and design life)

Viscoelastic FGM Properties



Pavement structure and field conditions

Temperature distribution

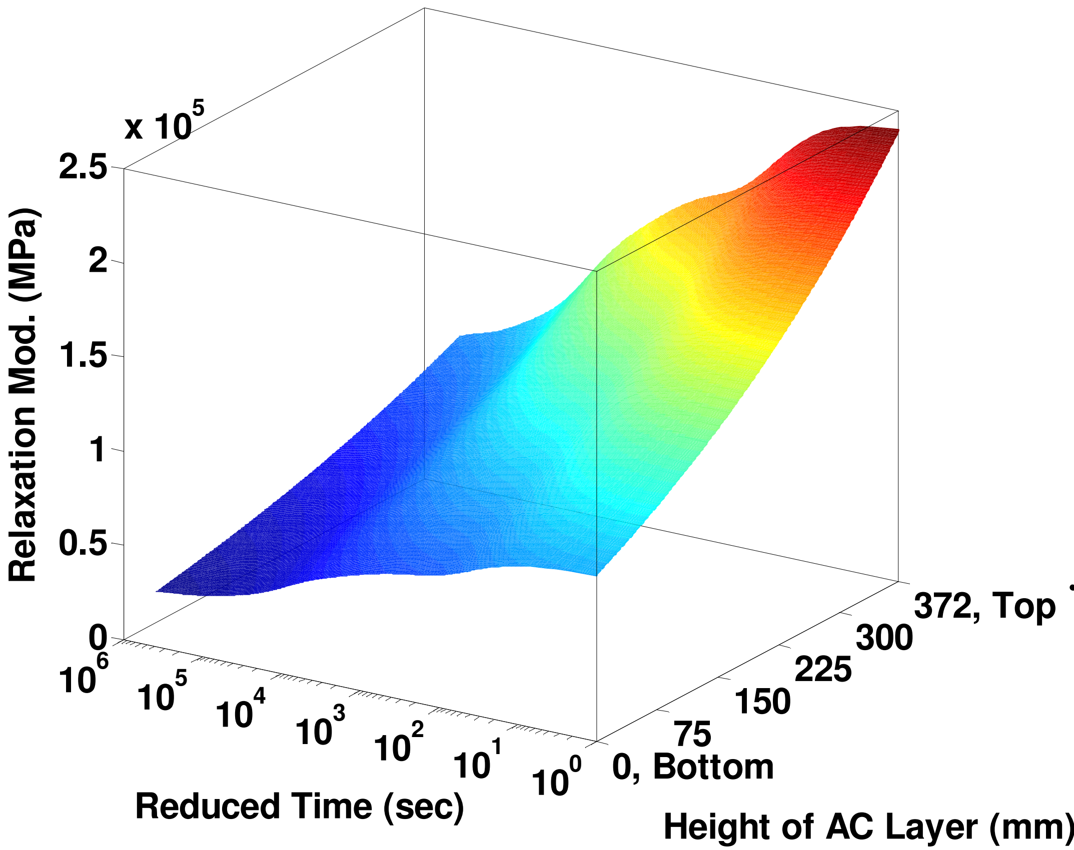


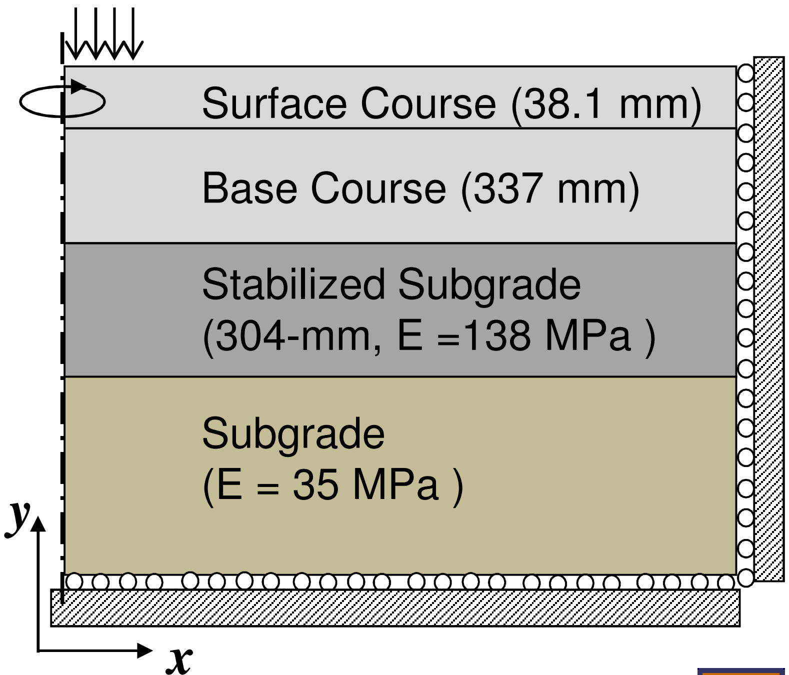
Viscoelastic FGM finite-element method (Chapters 4 and 5)
(a) CP-Based Analysis
(b) Time-Integration Analysis

Pavement Analysis and Design:
(a) Study of critical responses (e.g. tensile strains at bottom of AC layer)
(b) Prediction of pavement performance
(c) Comparison of design alternatives (structure and/or materials)
Few examples shown in Chapter 6

Example-1: Full Depth AC Pavement

- Based on I-155, Lincoln IL
- Single Tire load simulated (up to 1000 sec loading time)
- Aged material properties (Apeagyei et al., 2008)
  - Surface of AC: Long term aged
  - Bottom of AC: Short term aged

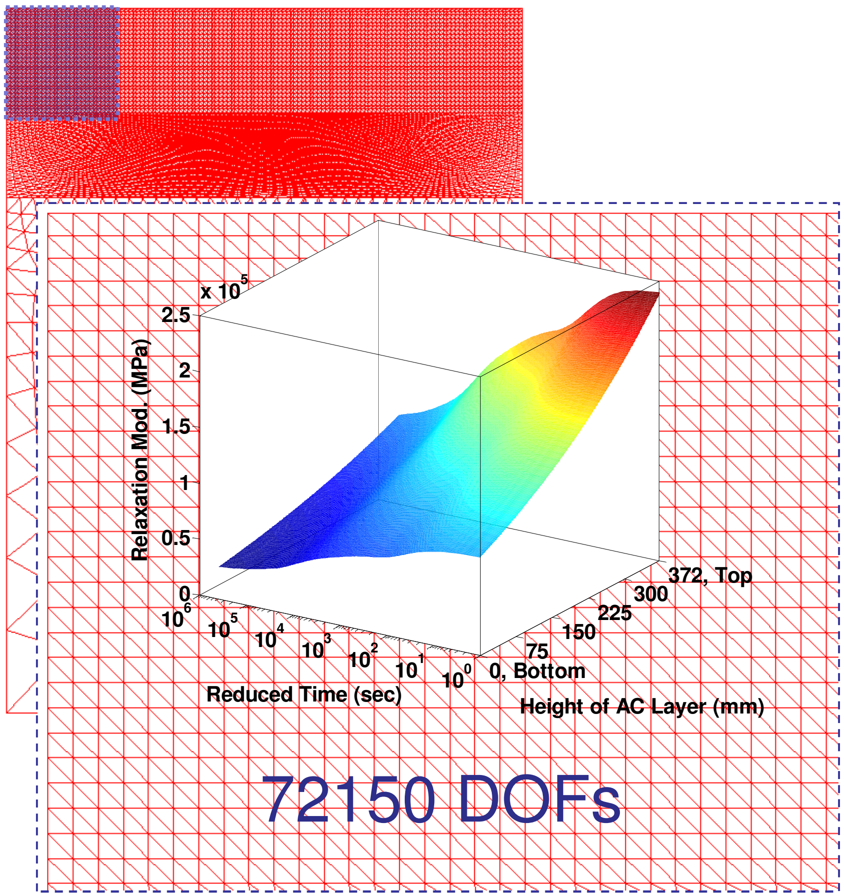




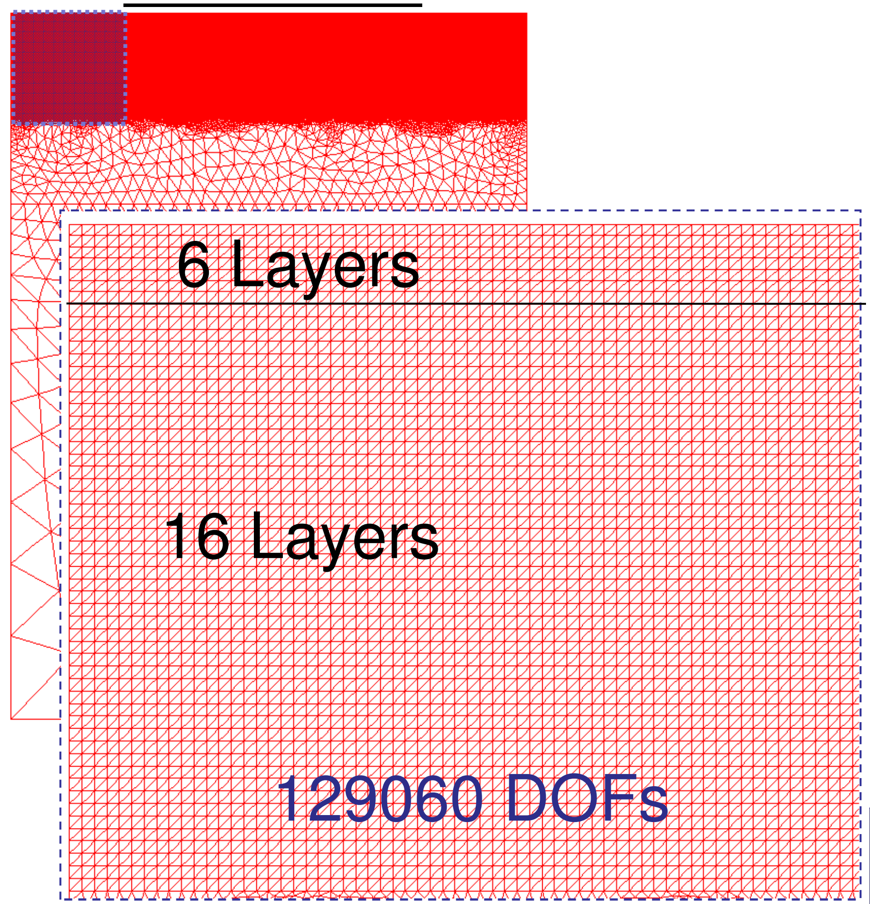
Example-1: FEM Discretization

- Two mesh refinement levels
  - Coarse mesh: Graded and Homogeneous simulations
  - Fine Mesh: Layered simulations

Coarse Mesh



Fine Mesh

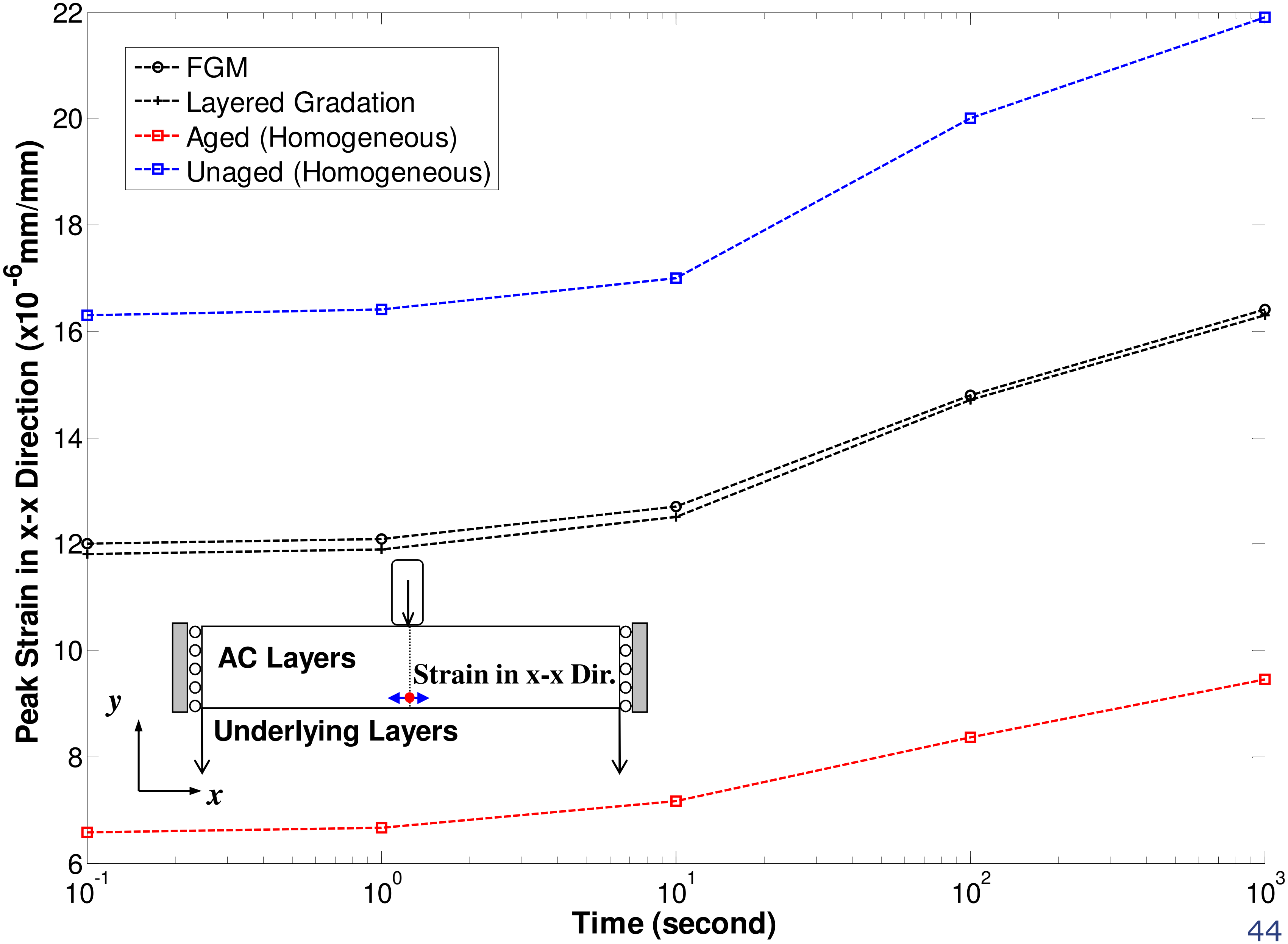


Example-1: Simulation Results

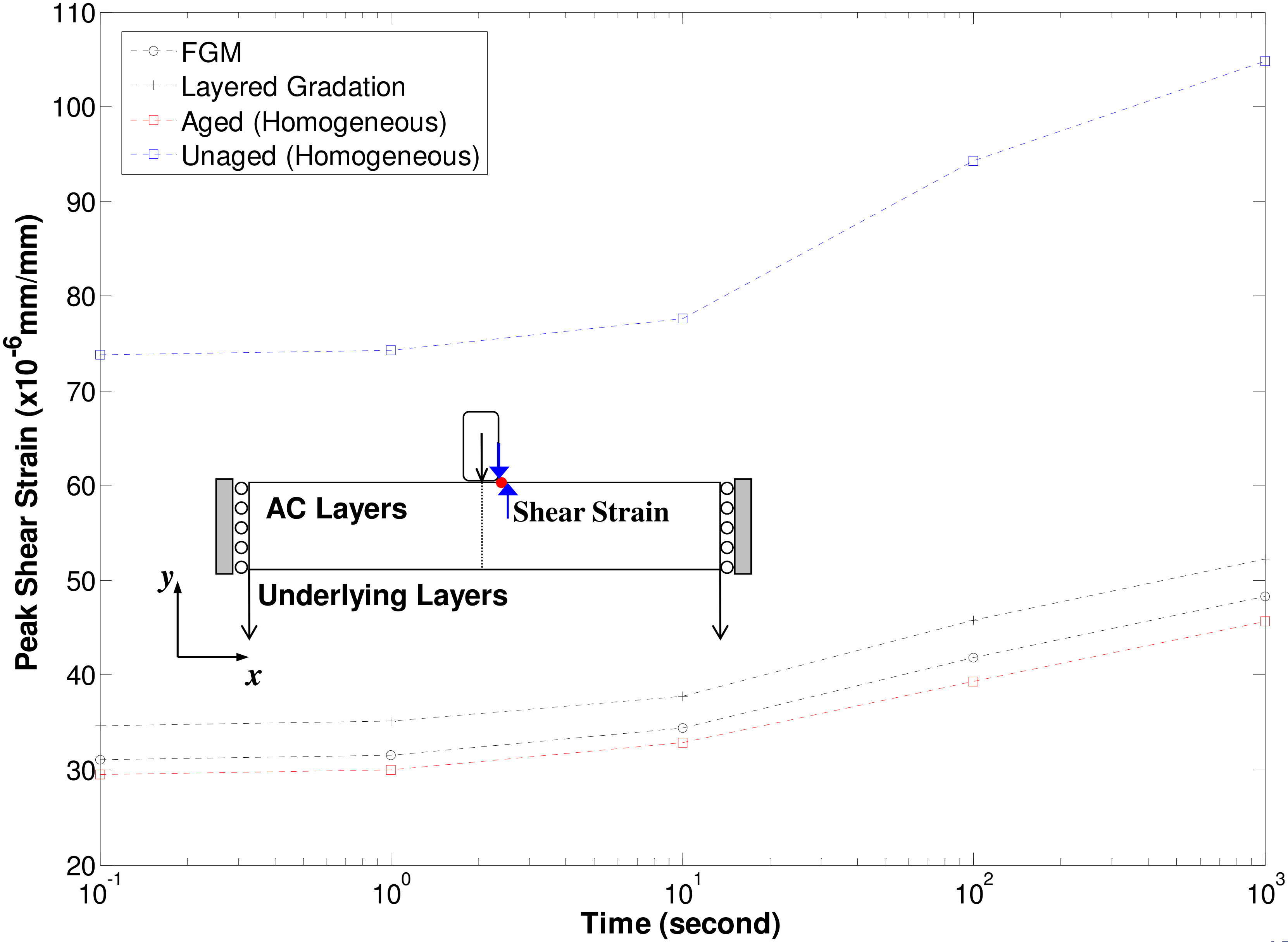
- Material Distributions:
  - FGM
  - Layered
  - Aged
  - Unaged

- Pavement Responses:
  - Tensile strain at bottom of asphalt layer (to investigate cracking and fatigue)
  - Shear strain at wheel edge (longitudinal cracking/rutting)
- Comparison of FGM and Layered predictions
  - Compressive strain at interface of asphalt layers

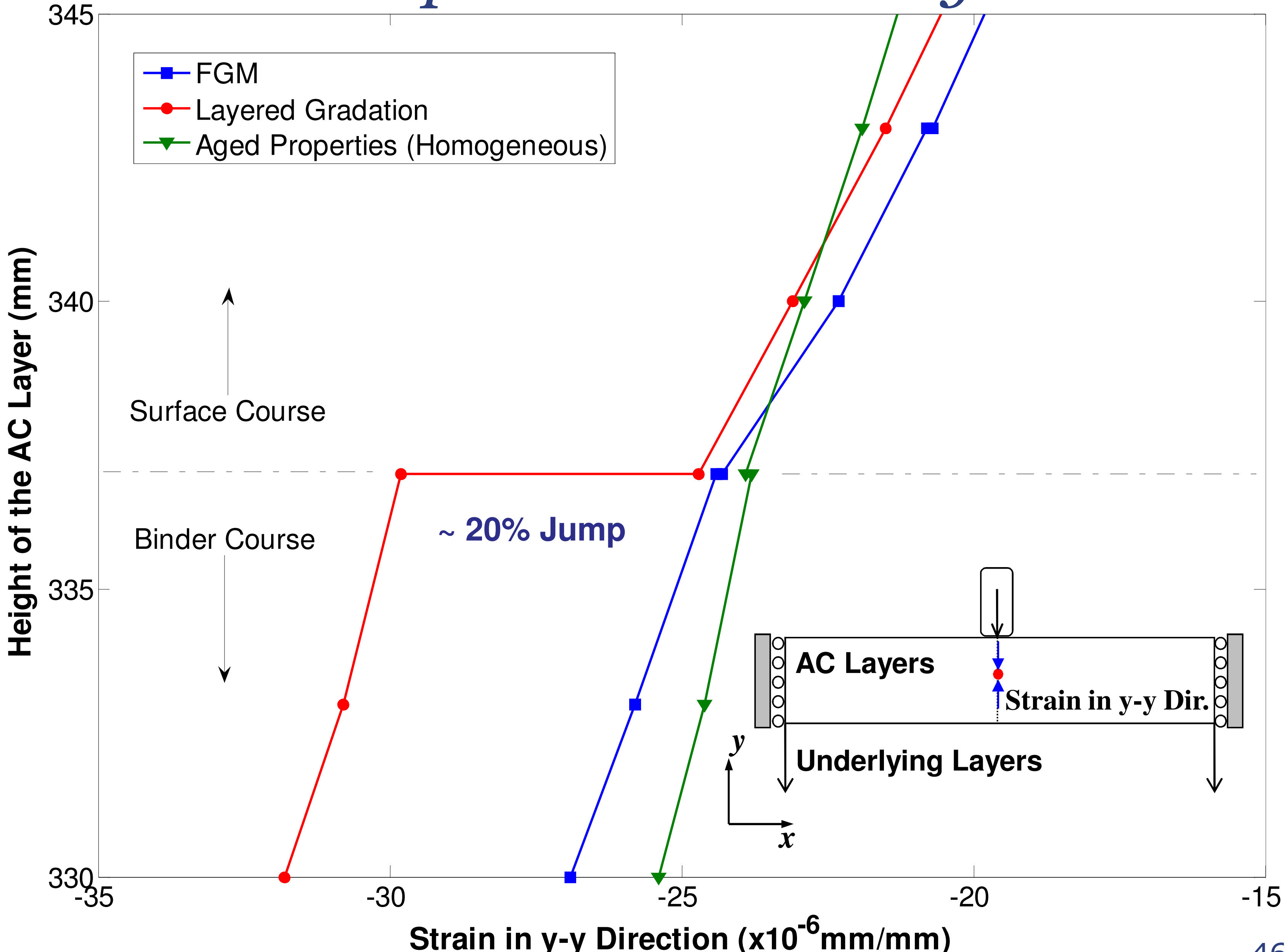
Example-1: Strain at Bottom of AC



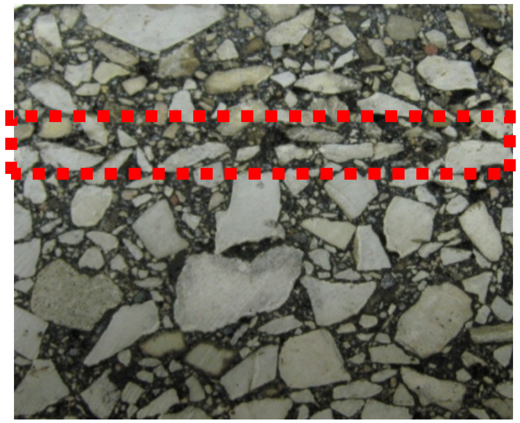
Example-1: Peak Shear Strain



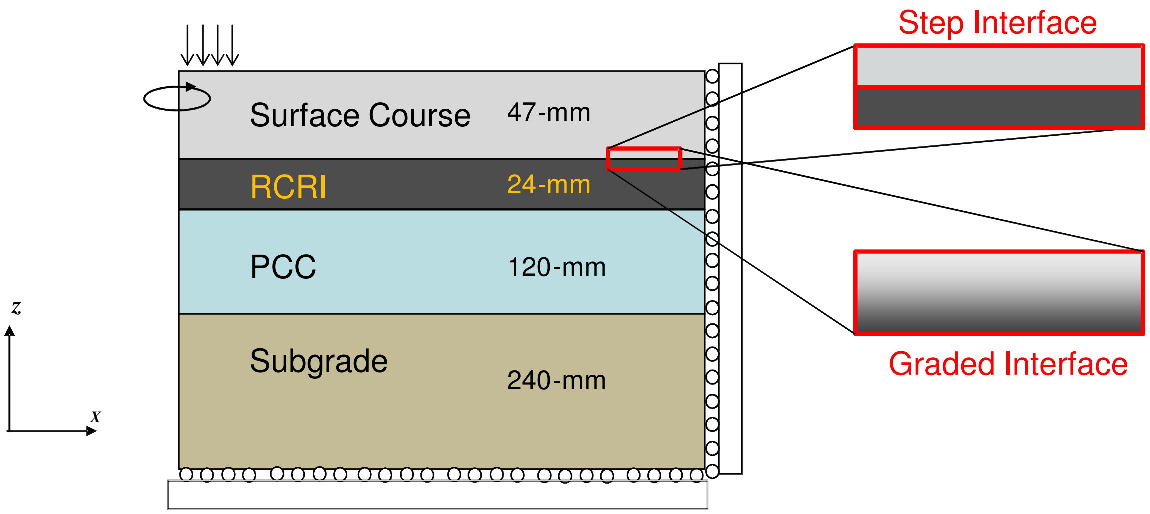
Example-1: FGM vs. Layered



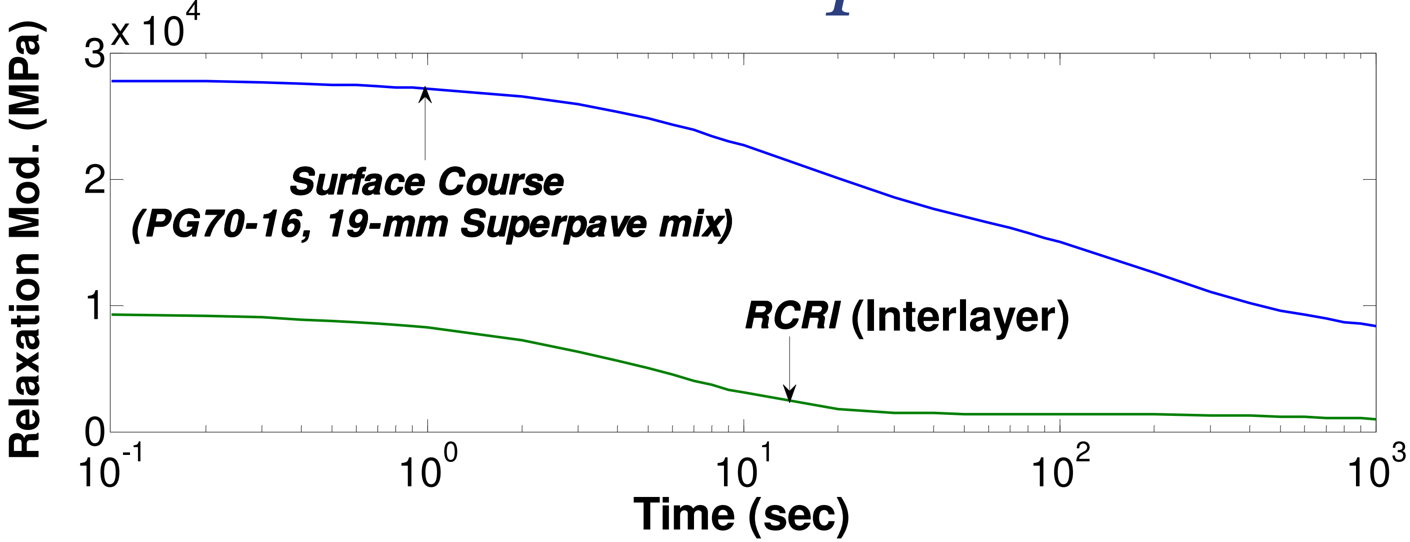
Example 2: Graded Interface

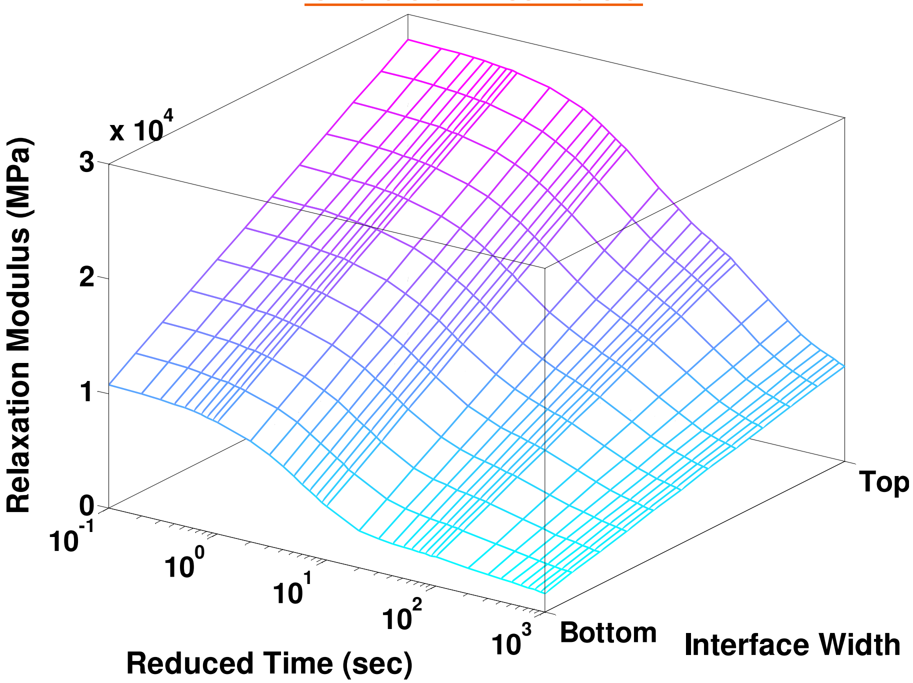


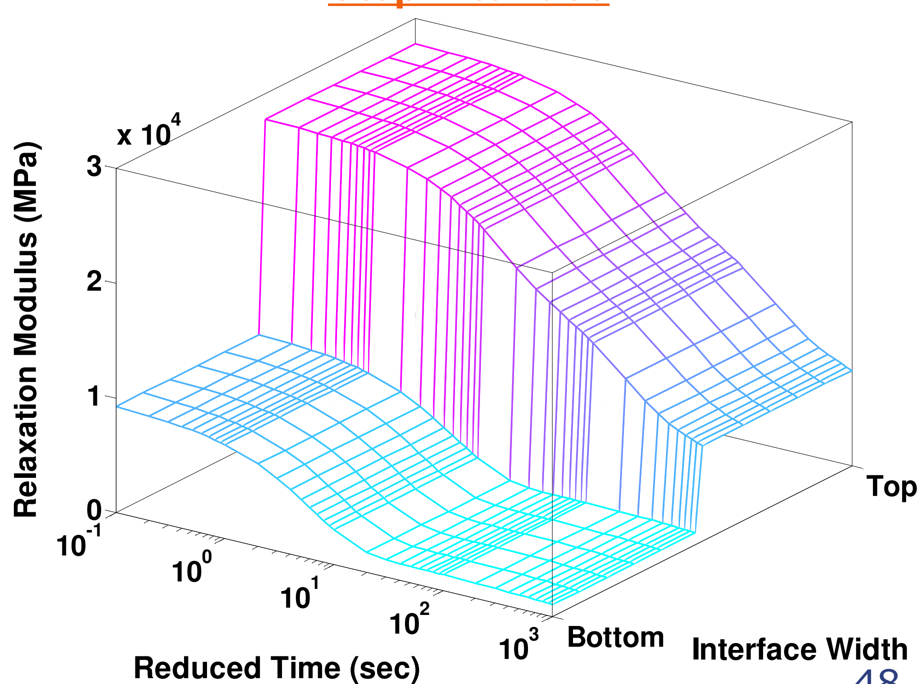
- Pavement: LA34, Monroe LA
- Two simulation scenario
  1. Step interface
  2. Graded interface



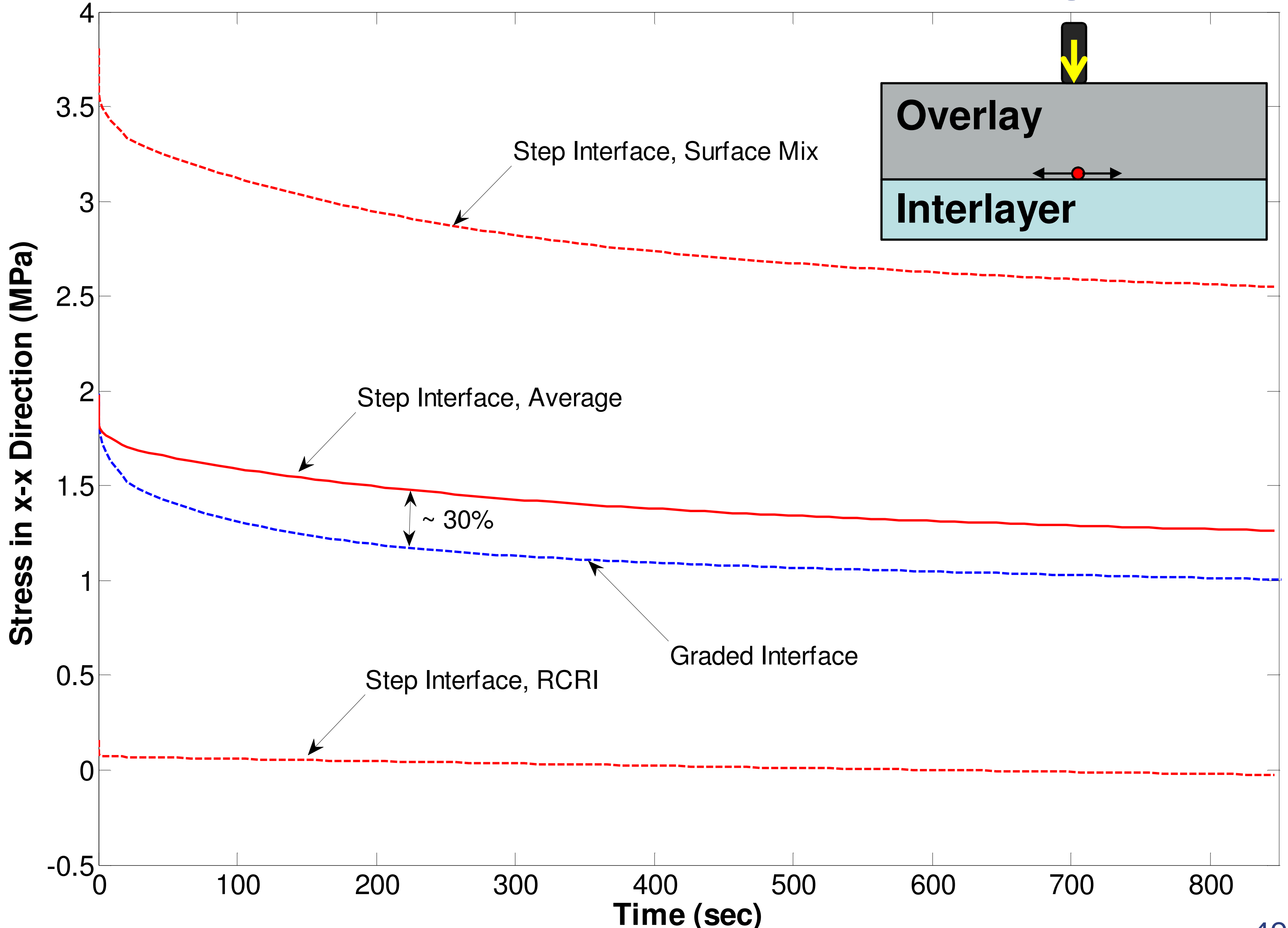
Material Properties







Peak Tensile Stress in Overlay



Functionally Graded Viscoelastic Asphalt Concrete Model

- Motivation and Introduction
- Viscoelastic Characterization of Asphalt Concrete
- Viscoelastic FGM Finite Elements
- Correspondence Principle Based Analysis
- Time Integration Analysis
- Application Examples: Asphalt Pavement
- Summary and Conclusions

Summary

- Viscoelastic graded finite elements using GIF are proposed
- Correspondence principle based formulation is developed and implemented
- Recursive formulation is utilized for time-integration analysis
- Verifications are performed by comparison of present approaches with:
  - Analytical solutions
  - Commercial software (*ABAQUS*)
- Asphalt pavement systems are simulated:
  - Aged pavement conditions
  - Graded interfaces

Conclusions

- Aging and temperature dependent property gradients should be considered in simulation of asphalt pavements
- Non-homogeneous viscoelastic analyses procedures presented here are suitable and preferred for simulation of asphalt pavement systems
- Proposed procedures yield greater accuracy and efficiency over conventional approaches
- Layered gradation approach can yield significant errors
  - Most pronounced errors are at layer interfaces in the stress and strain quantities.

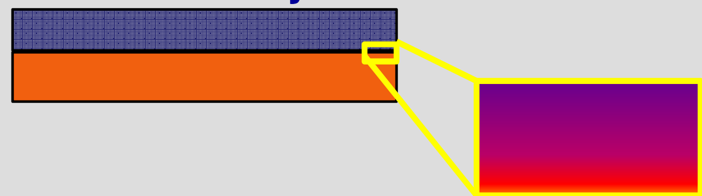
Conclusions (cont.)

- Interface between asphalt concrete layers can be realistically simulated using the procedures discussed in the current dissertation
- When using the layered approach, averaging at layer interfaces may lead to significantly different predictions as compared to the FGM approach
  - The difference is usually exaggerated with time when a significant viscoelastic gradation is present

Other Applications and Future Extensions

Micromechanical Predictions

Transition Layers Characteristics



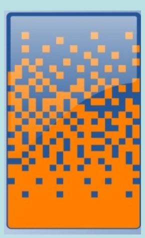
Graded Viscoelastic + Stress Dependent Model

Applications and Extensions

Other material models:
- 2S2P1D
- Power law etc.

Analysis of graded viscoelastic materials:
- Metals at high temperature
- Polymers
- Geotechnical materials
- PCC/FRC
- Biomaterials
- Food industry

Design of Viscoelastic FGMs



$E(x,t)$

ABAQUS UMAT Subroutine

Thank you for your attention!!

Questions??