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Modeling Pavement Behavior under FWD and Moving Load

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Outline

- **Finite Element Modeling of Pavement**
- **Modeling Pavement Behavior under FWD and Moving Load**
- **Case Study: Instrumented Runway Analysis**
- **Summary and Model Applications**

Introduction

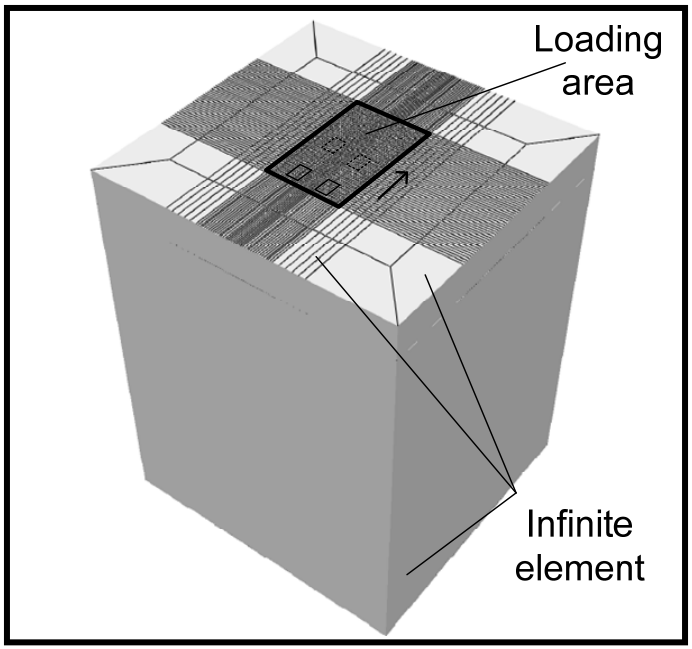
- **Airport pavement performance is affected by aircraft loading, structure features, material properties, and environmental conditions**
- **In-situ pavement responses are critical to mechanistic pavement design and long-term performance prediction**
- **Two approaches to understand airport pavement behavior**
  - Field instrumentation
  - Numerical modeling

Motivation

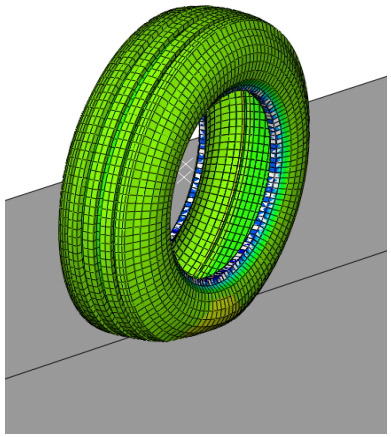
- **Traditional pavement analysis cannot capture**
  - Viscoelastic asphalt mixture
  - Nonlinear anisotropy of unbound material
  - Structure discontinuity (interface, joint, crack, etc)
- **Tire-pavement interaction is a complicated phenomena**
  - Transient moving load with dynamic excitation
  - Interface contact stresses are not uniform
  - Increasing trend of aircraft load and tire pressure
- **Long-lasting pavement design needs an accurate mechanistic pavement model**

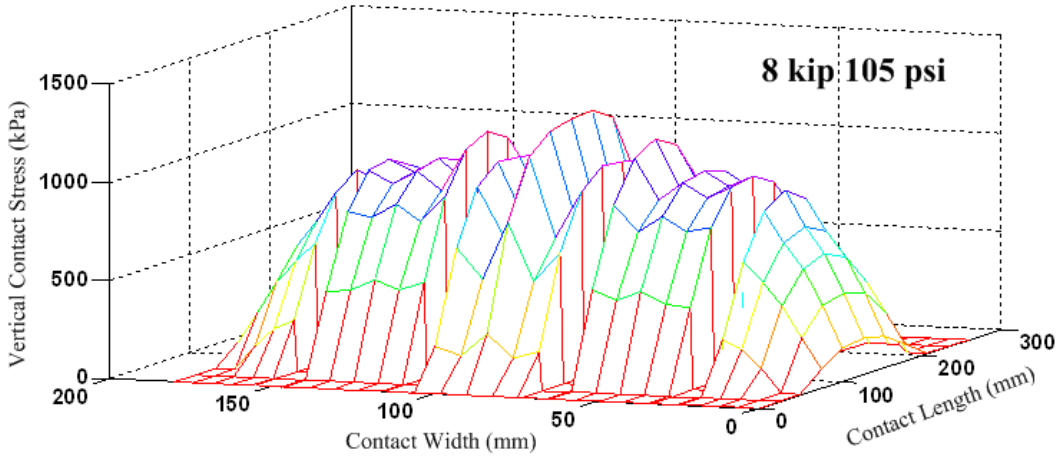
3-D FE Pavement Modeling

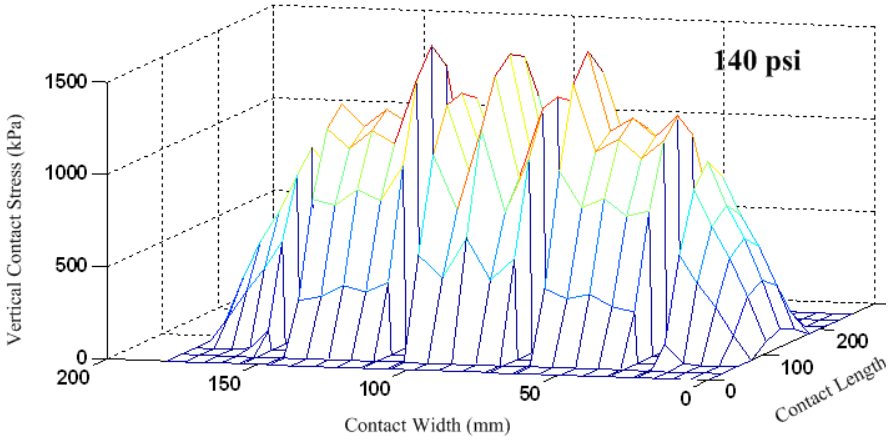
- Moving tire load with non-uniform contact area and stress
- Quasi-static or dynamic analysis
- Viscoelastic asphalt layer
- Nonlinear anisotropic unbound layer
- Frictional interface

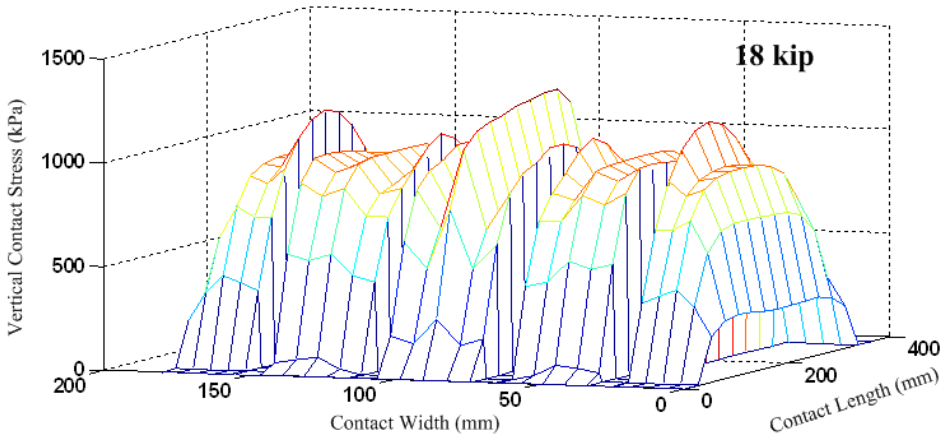


Tire-Pavement Interaction: Load and Pressure



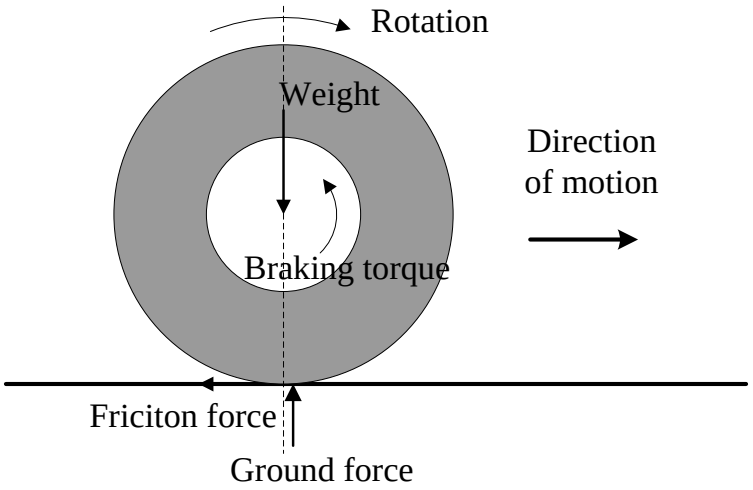


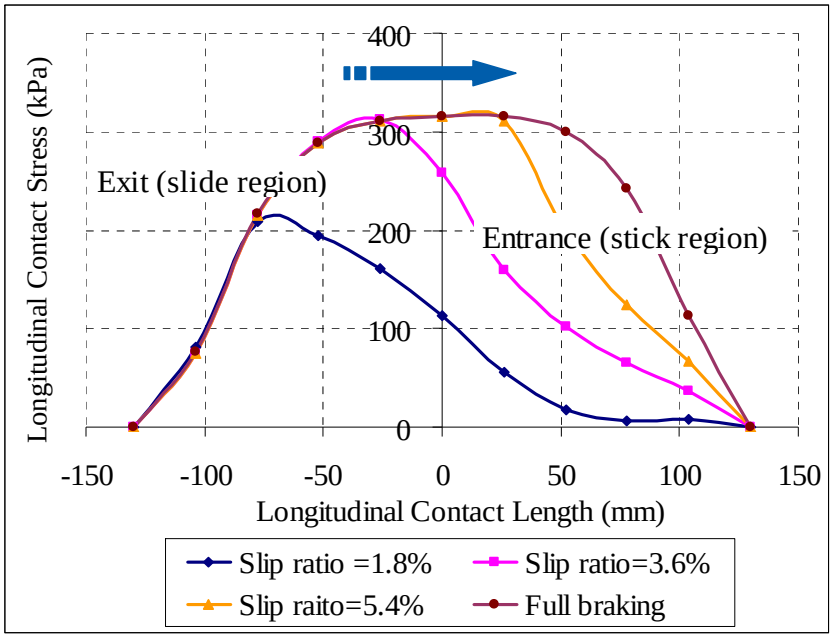


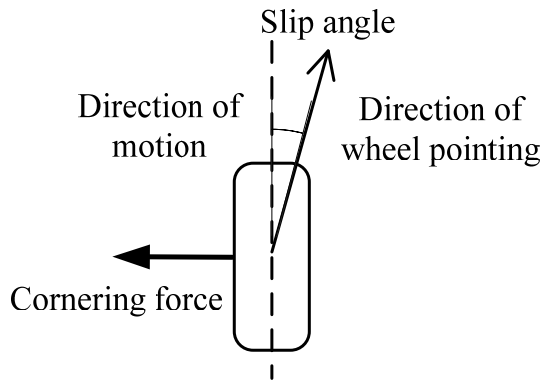


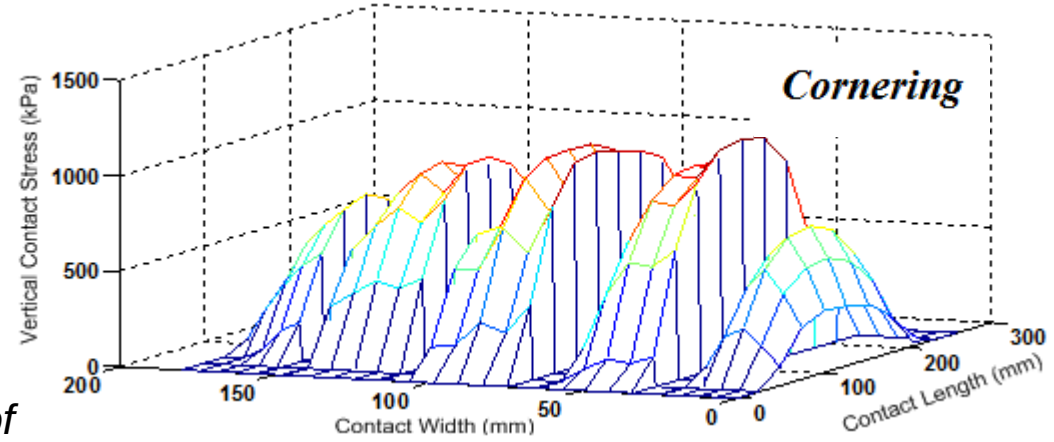
(Wang et al., International Journal of Pavement Engineering, 2012)

Tire-Pavement Interaction: Braking and Cornering





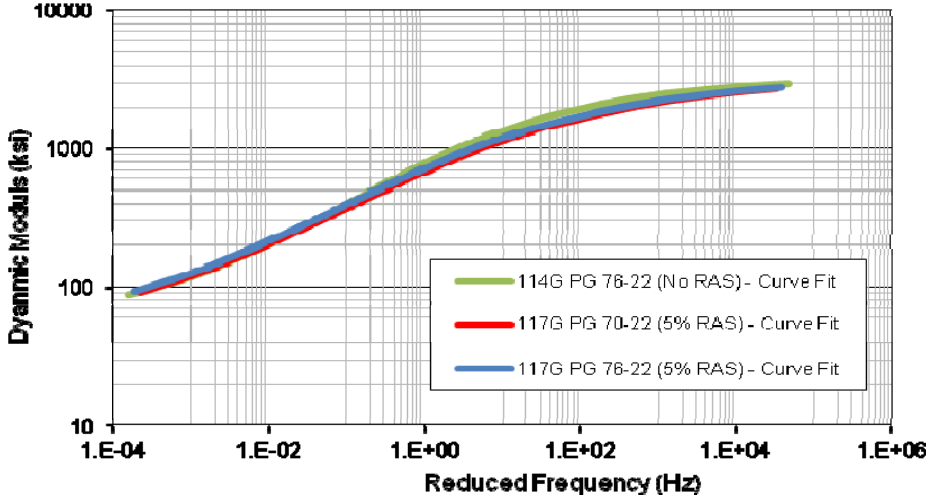


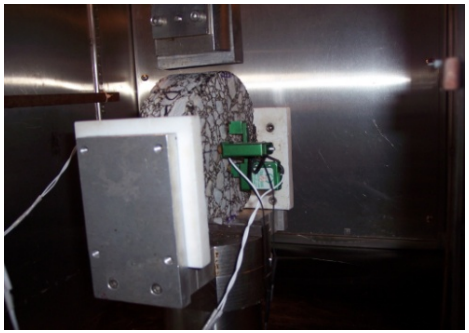


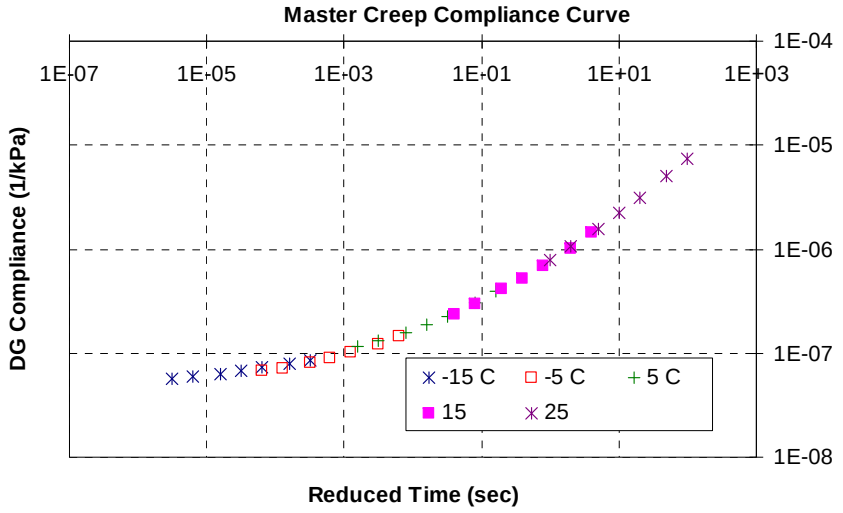
(Wang et al., International Journal of Pavement Engineering, 2012)

Viscoelastic Material Characterization

- **Dynamic Modulus and Creep Compliance**







Modulus of Unbound Material

- **Resilient modulus**

$$M_r = \frac{\sigma_d}{\varepsilon_r}$$

M_r = resilient modulus;

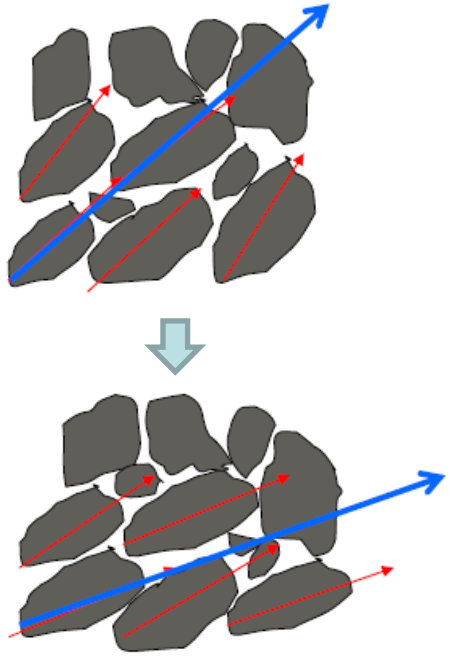
σ_d = repeated applied deviator stress; ε_r = recoverable strain

- **Nonlinear cross-anisotropic modulus**

Vertical modulus $$M_r^v = k_1 p_a (\frac{\theta}{p_a})^{k_2} (\frac{\tau_{oct}}{p_a} + 1)^{k_3}$$

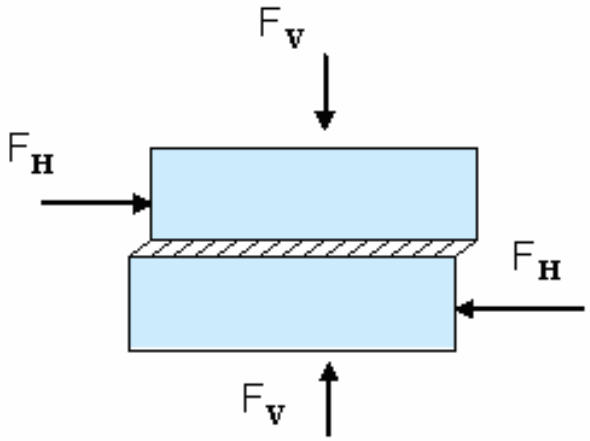
Horizontal modulus $$M_r^h = k_4 p_a (\frac{\theta}{p_a})^{k_5} (\frac{\tau_{oct}}{p_a} + 1)^{k_6}$$

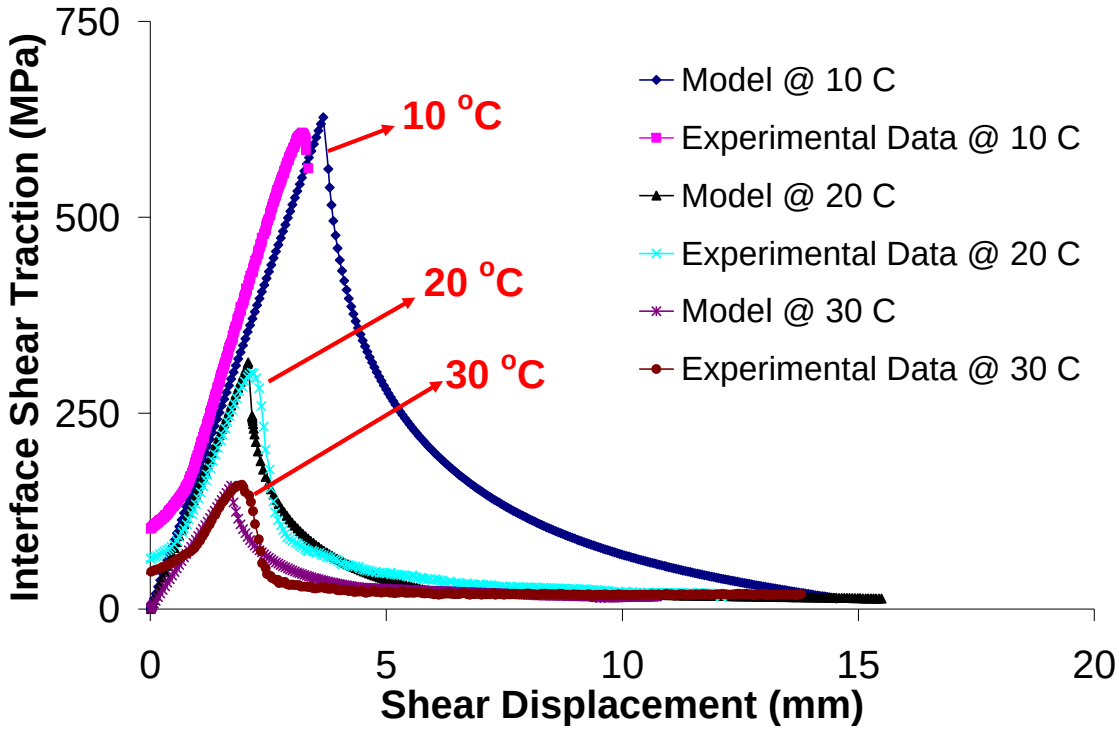
Shear modulus $$G = k_7 p_a (\frac{\theta}{p_a})^{k_8} (\frac{\tau_{oct}}{p_a} + 1)^{k_9}$$



Interface Characterization

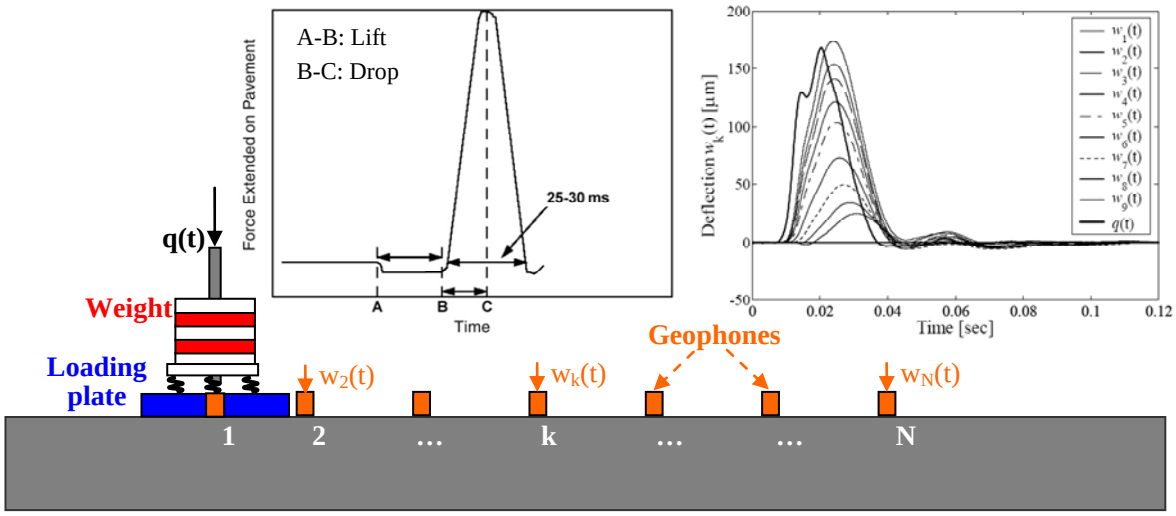
- **Fully-bonded (tied) interface between asphalt layers**
  - Affected by tack coat and construction quality
- **Coulomb friction model at asphalt-base and base-subgrade interface**



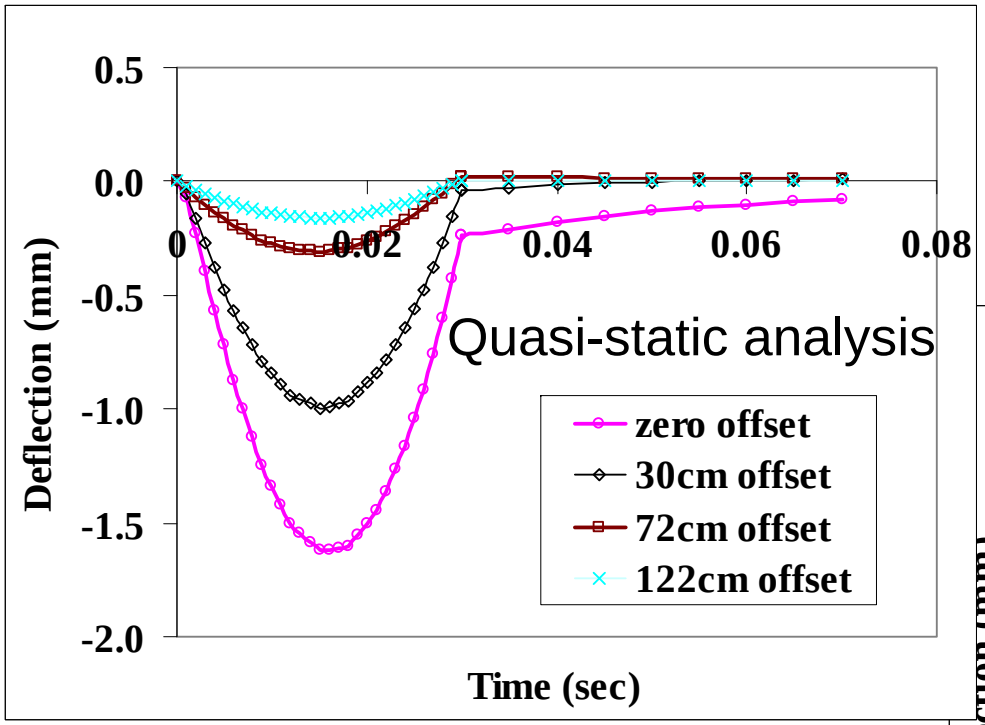


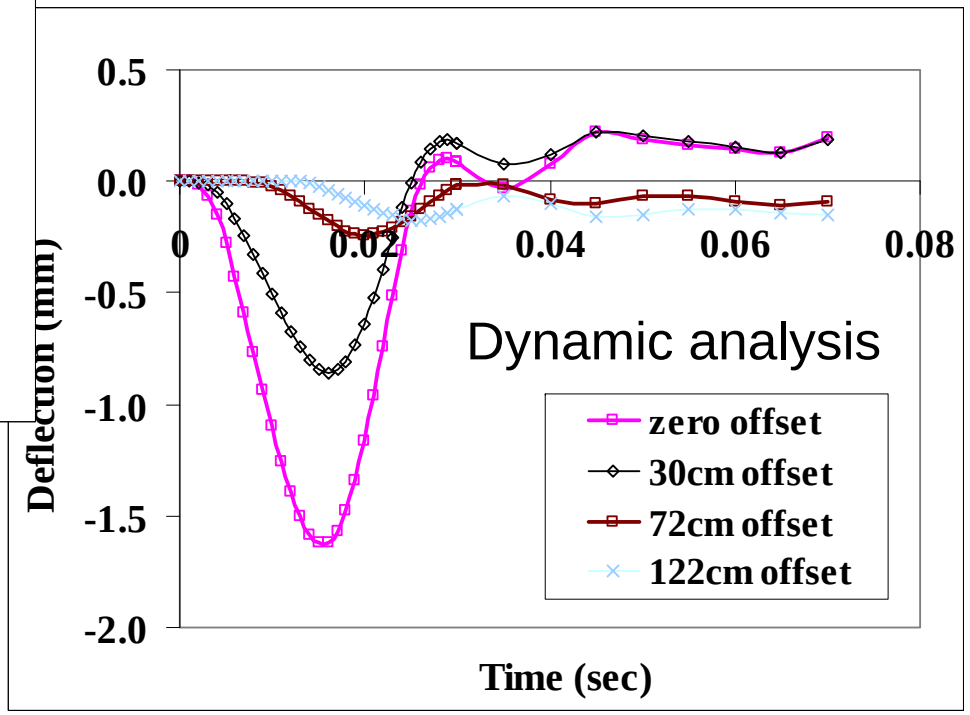
Pavement Responses under FWD Loading

- **FWD loading (30ms duration) simulates vehicle loading at 65-80km/h**
  - Modeled as half-sine loading usually
- **Falling Weight Deflectometer (FWD) test is used to**
  - Evaluate pavement structural capacity
  - Backcalculate pavement layer modulus



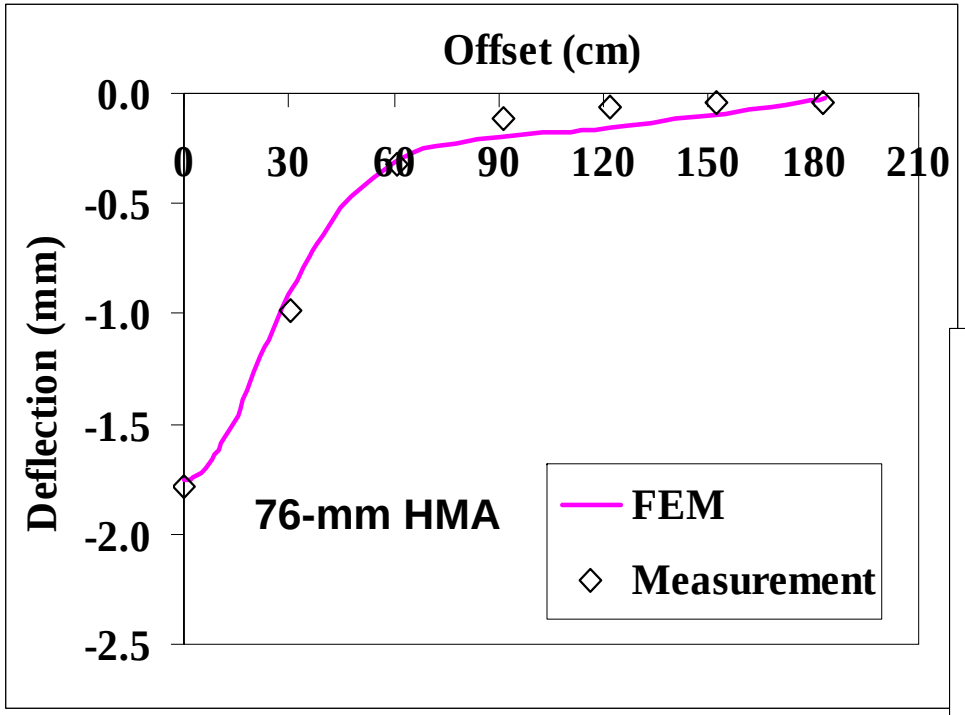
Effect of Dynamic Analysis on Deflection History

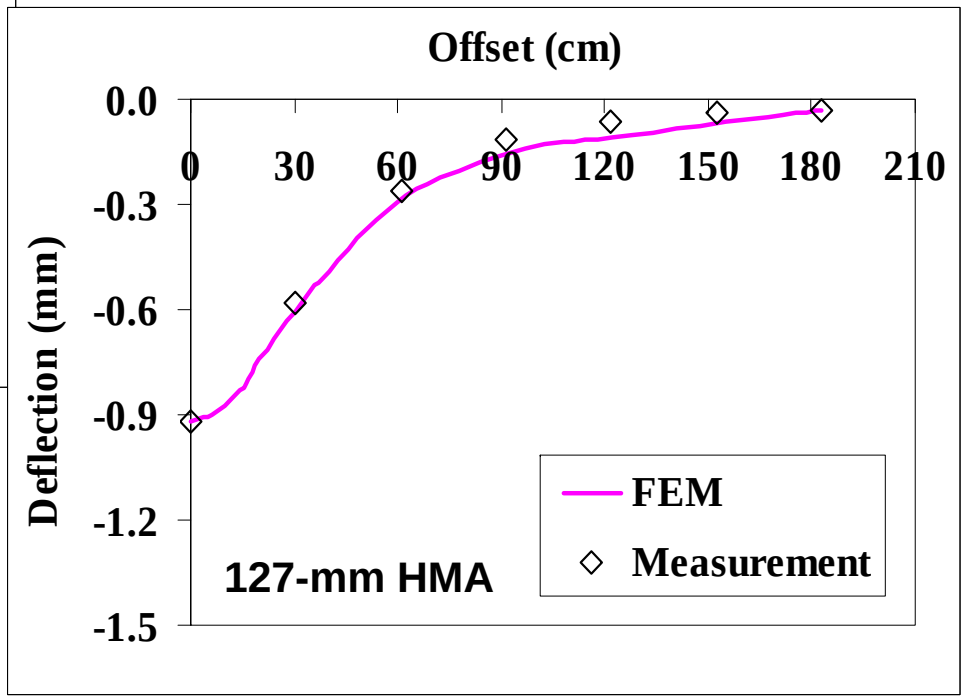




(Al-Qadi and Wang, Transportation Research Record, 2011)

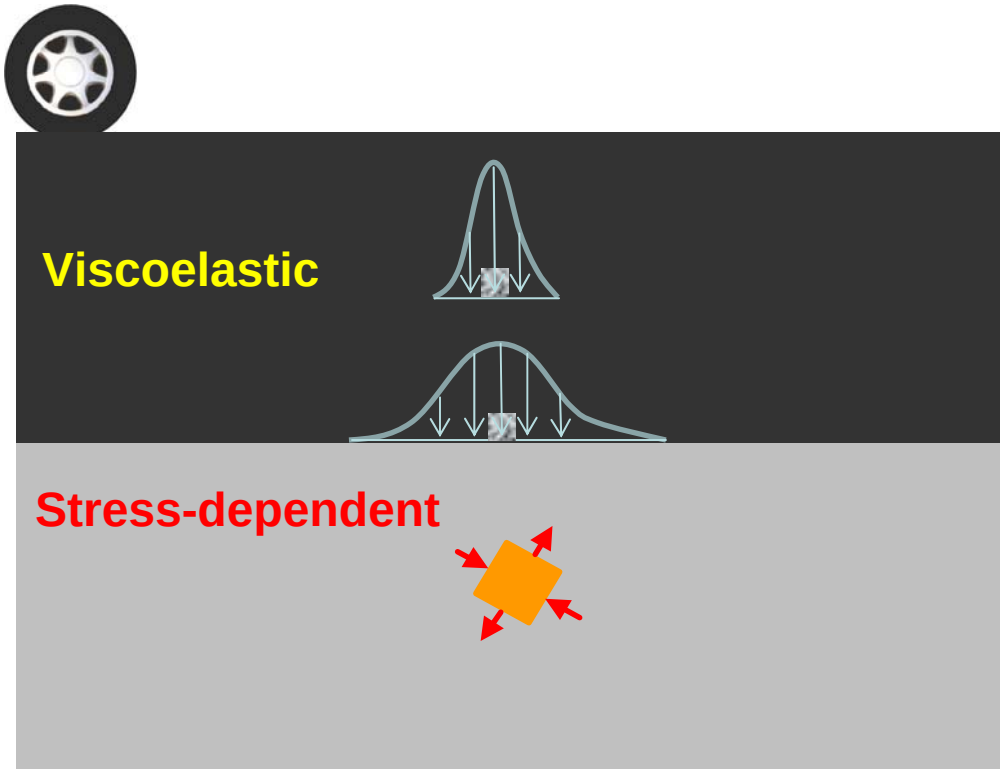
Calculated and Measured Deflection Basins



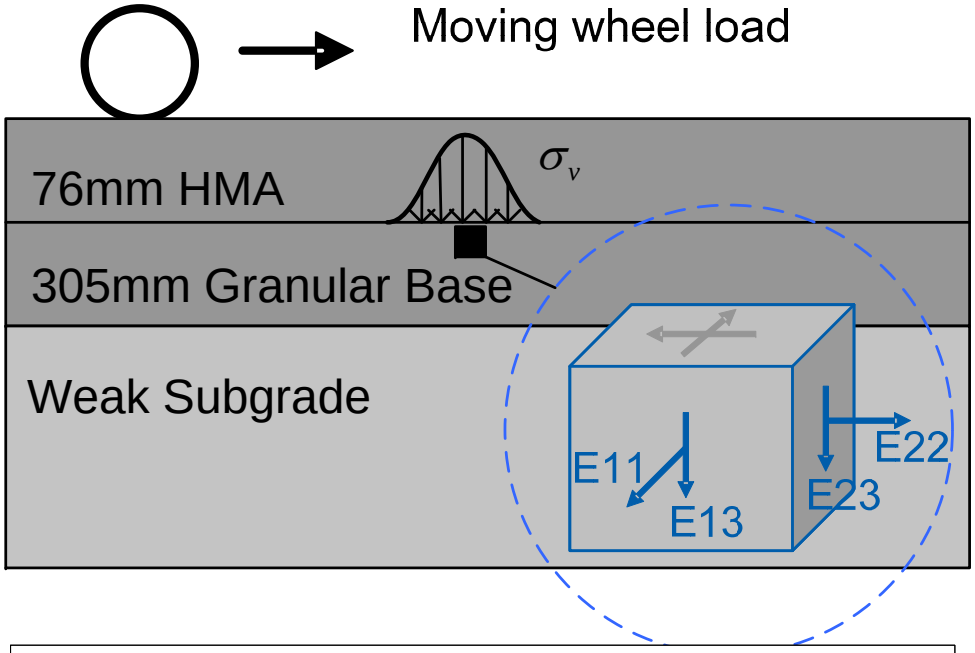


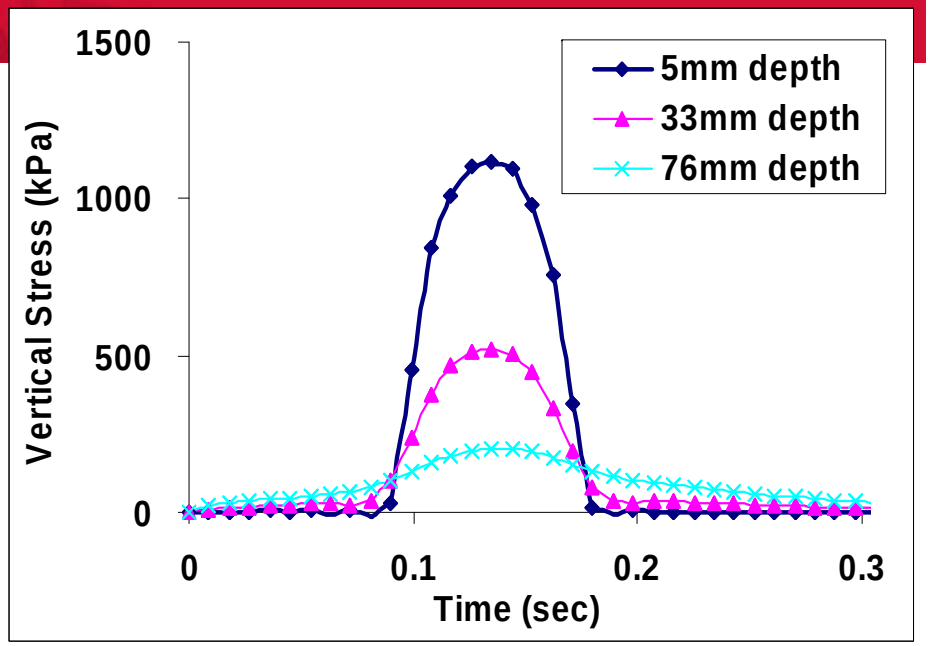
(Al-Qadi and Wang, Transportation Research Record, 2011)

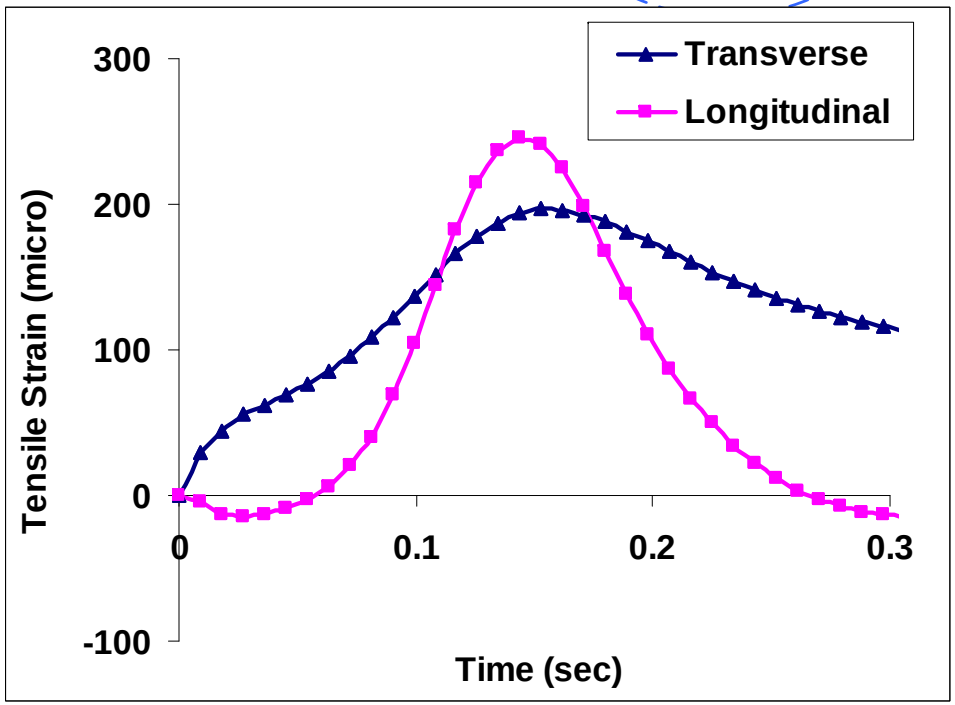
Pavement Response under Moving Load

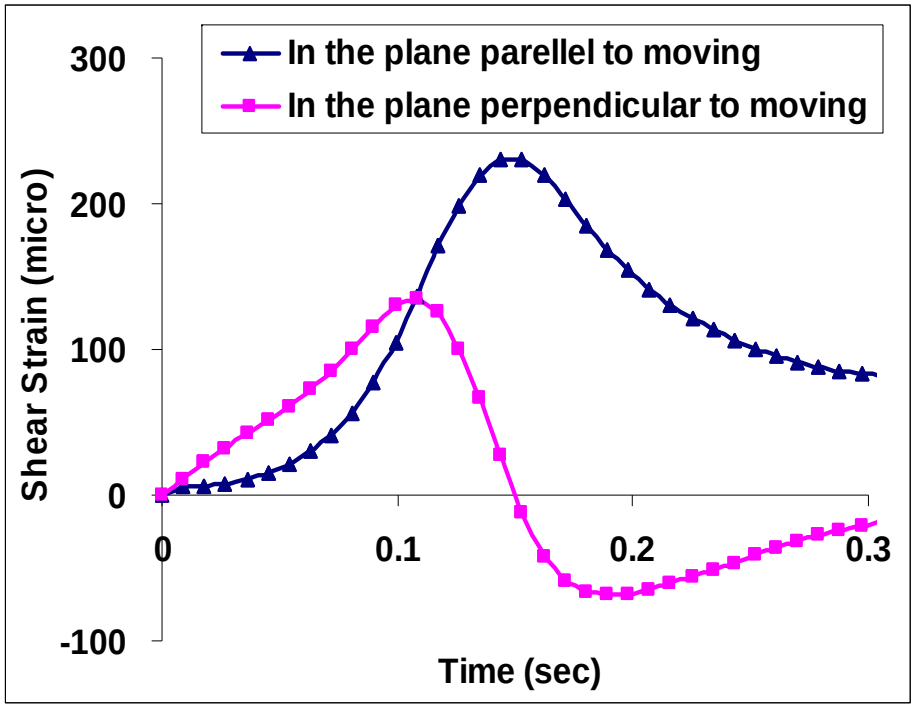


- **Loading time varies at various pavement depths and directions**
- **Principal stresses rotate under a moving load**

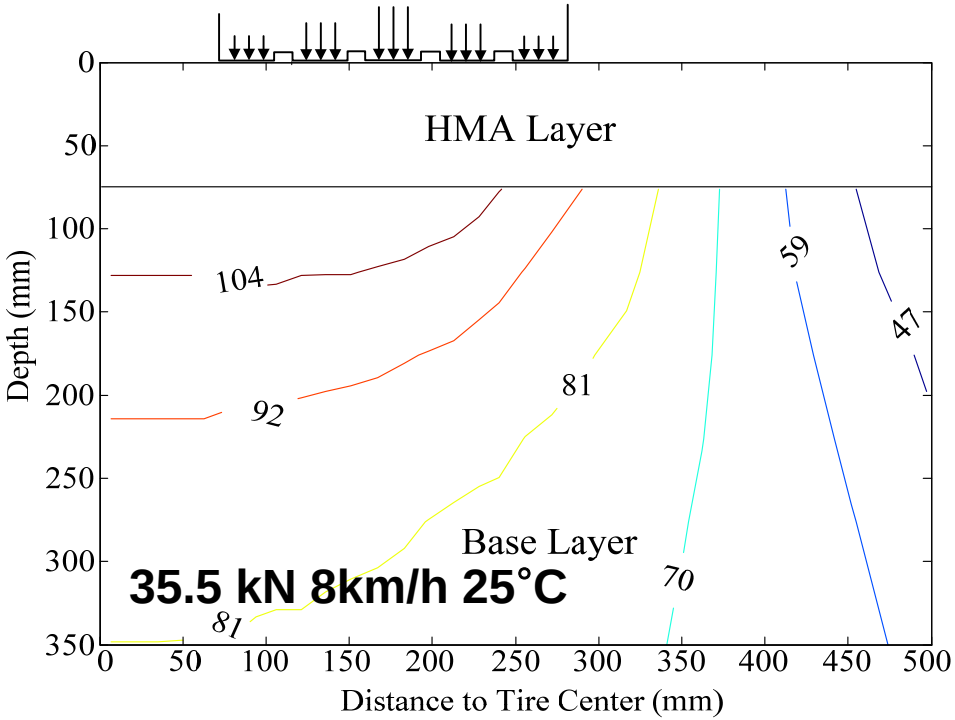

Moving wheel load
76mm HMA
305mm Granular Base
Weak Subgrade
σ_v
E11
E13
E22
E23

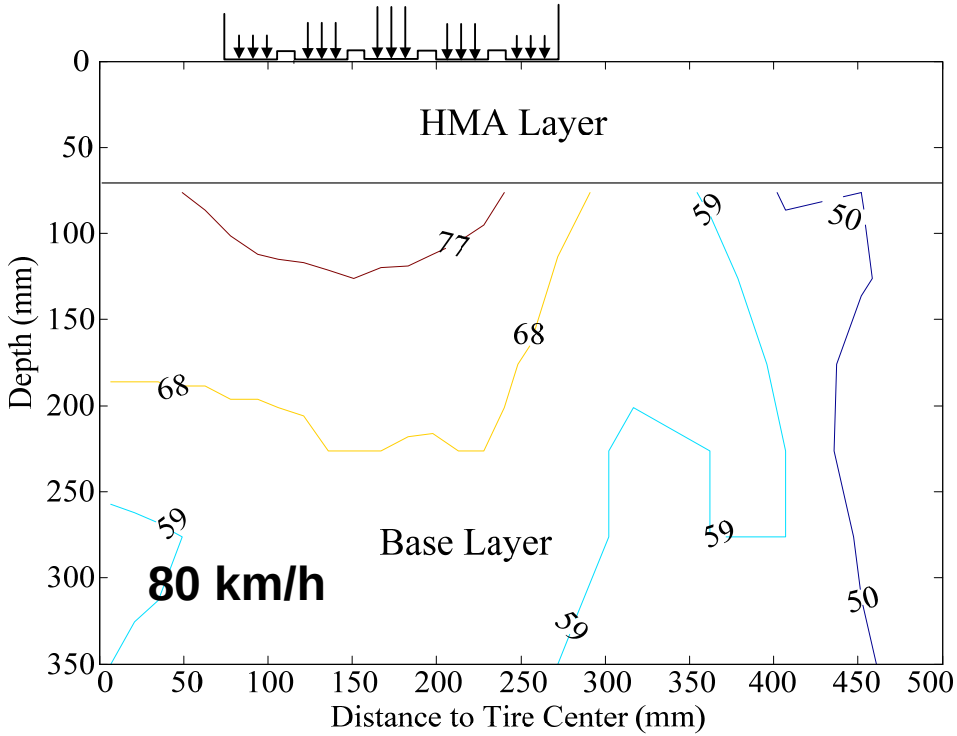

Vertical Stress (kPa)
1500
1000
500
0
0
0.1
0.2
0.3
Time (sec)
5mm depth
33mm depth
76mm depth


Tensile Strain (micro)
300
200
100
0
-100
0
0.1
0.2
0.3
Time (sec)
Transverse
Longitudinal


Shear Strain (micro)
300
200
100
0
-100
0
0.1
0.2
0.3
Time (sec)
In the plane parellel to moving
In the plane perpendicular to moving

Base Moduli at Various Loading and Environmental Conditions

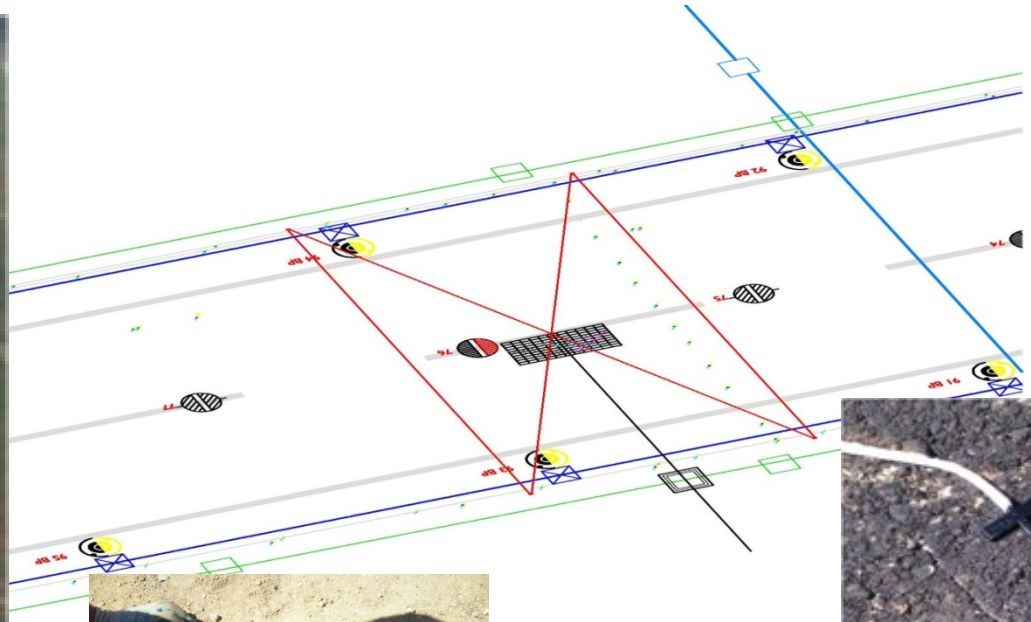


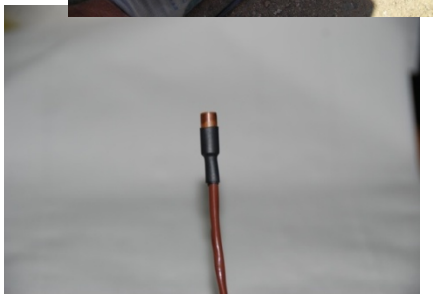


(Wang and Al-Qadi, Journal of Engineering Mechanics, ASCE, 2013)

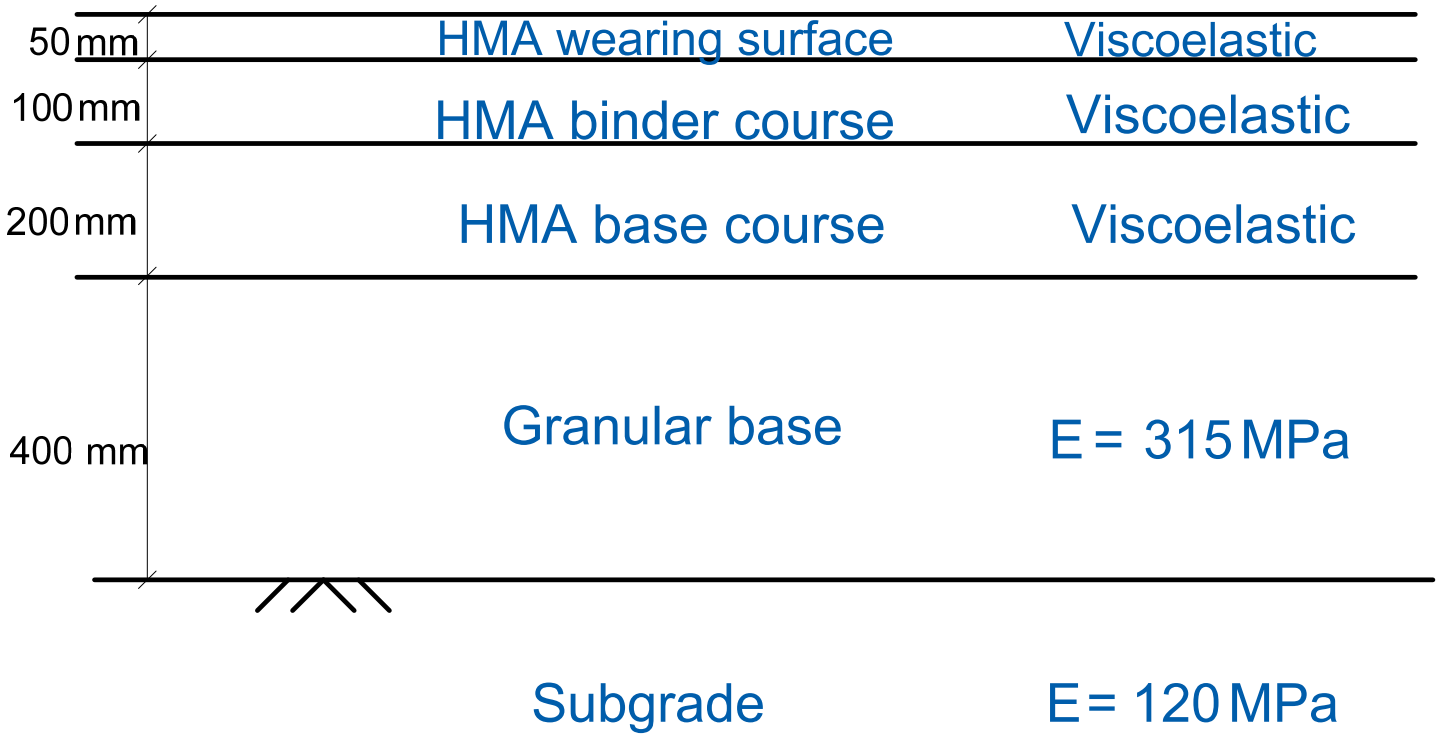
Case Study: Modeling of Instrumented Runway Pavement

Cagliari Airport Runway





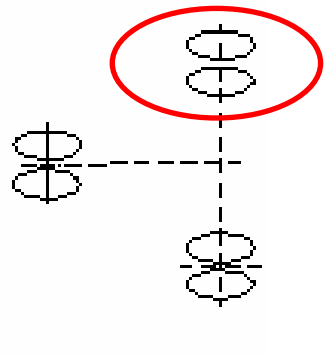
Runway Pavement Structure



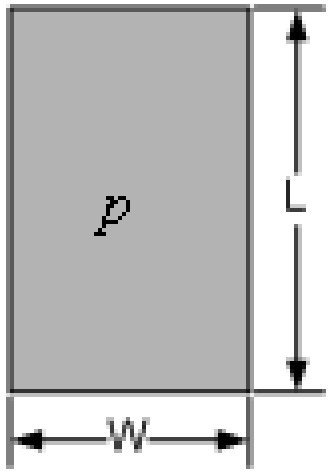
- **Field cores taken from HMA layer for creep compliance test**
- **FWD test used to backcalculate elastic moduli of base and subgrade**

Aircraft Loading

Loading condition	Aircraft type	Aircraft operation	Total weight (tons)	Load on one landing gear (two tires) (kN)	Tire inflation pressure (MPa)	Speed (km/h)
1	B737-800	Takeoff	79	368	1.28	120
2		Landing	66.3	309	1.28	100
3	MD80	Takeoff	63.5	296	1.23	31
4		Takeoff	63.5	296	1.23	240



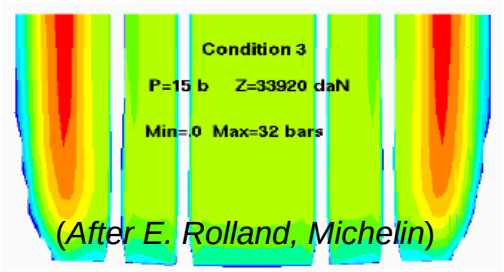
Uniform vs. Non-uniform Contact Pressure Assumptions



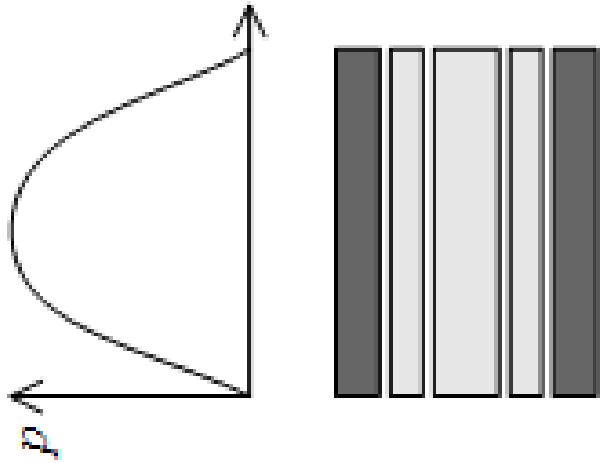
p = tire pressure

W/L = 0.6 – 0.7

Uniform



(*After E. Rolland, Michelin*)

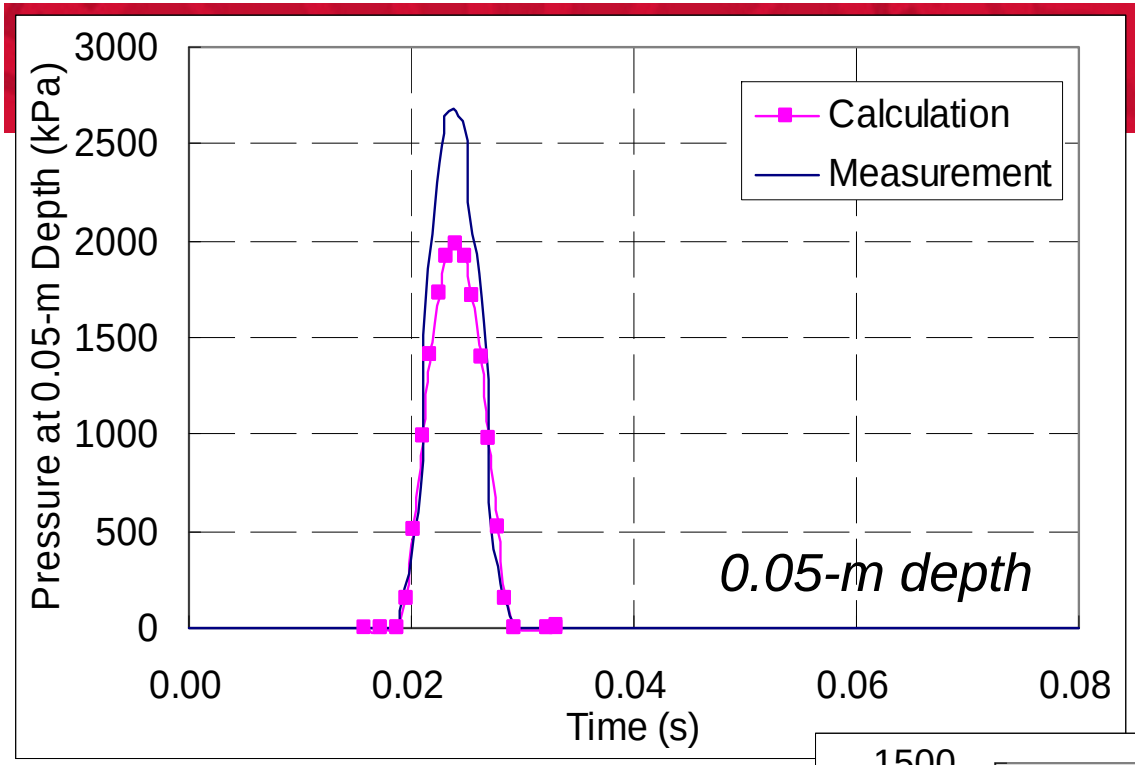


Edge ribs: peak = 2.2 × tire pressure

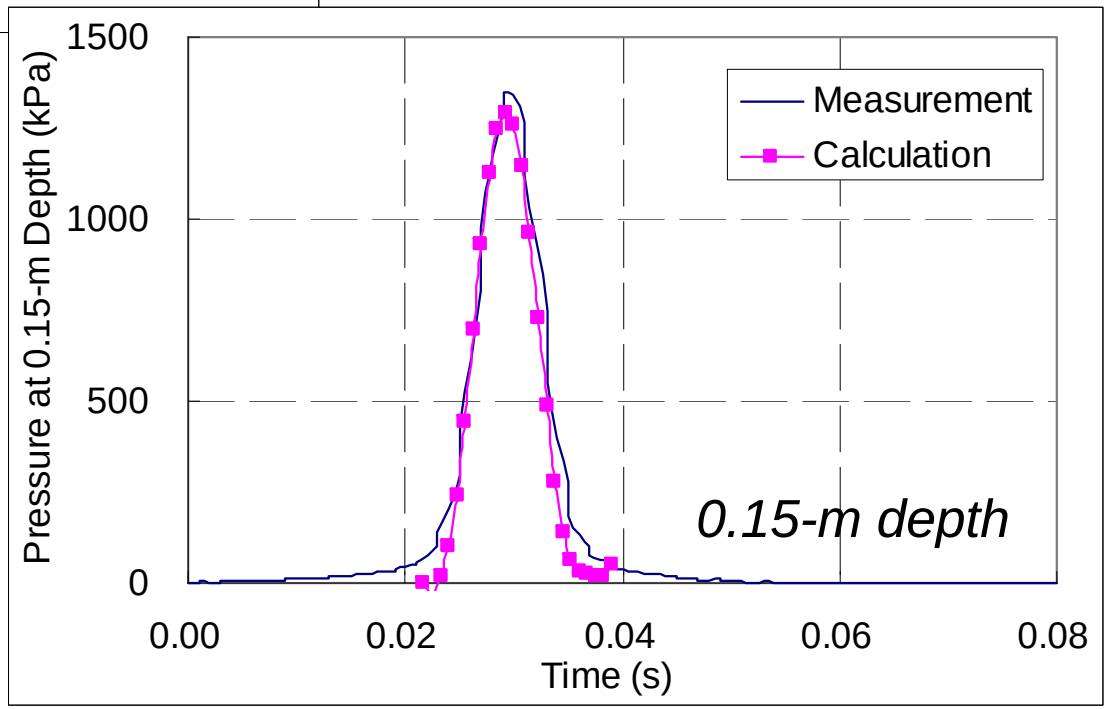
Center ribs: peak = 1.18 × tire pressure

Non-uniform

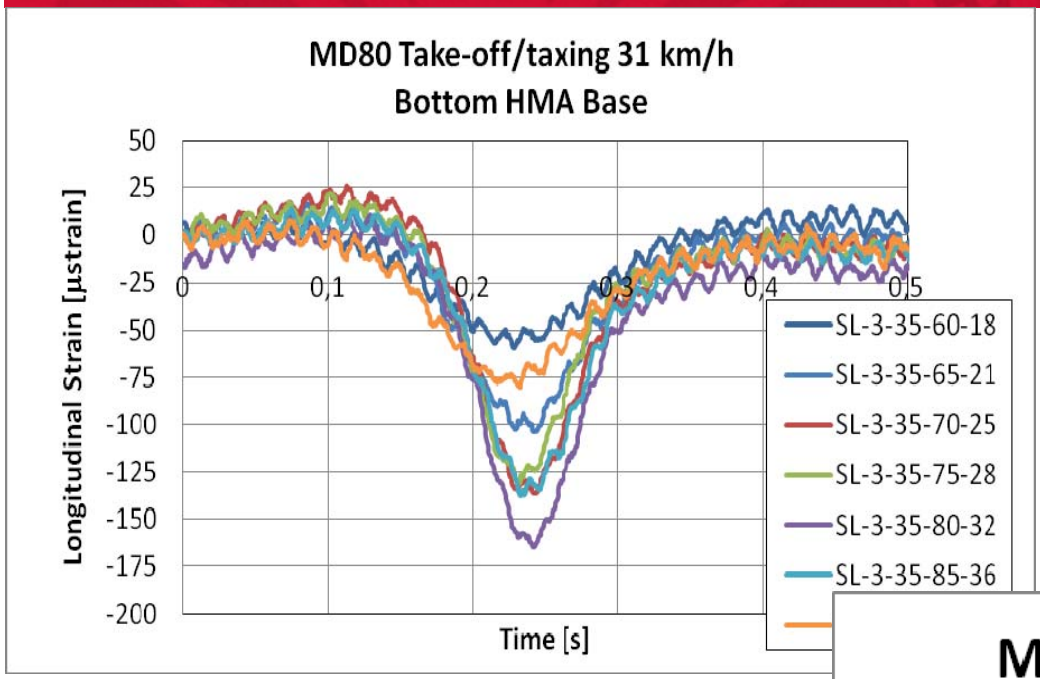
Calculated vs. Measured Pressure

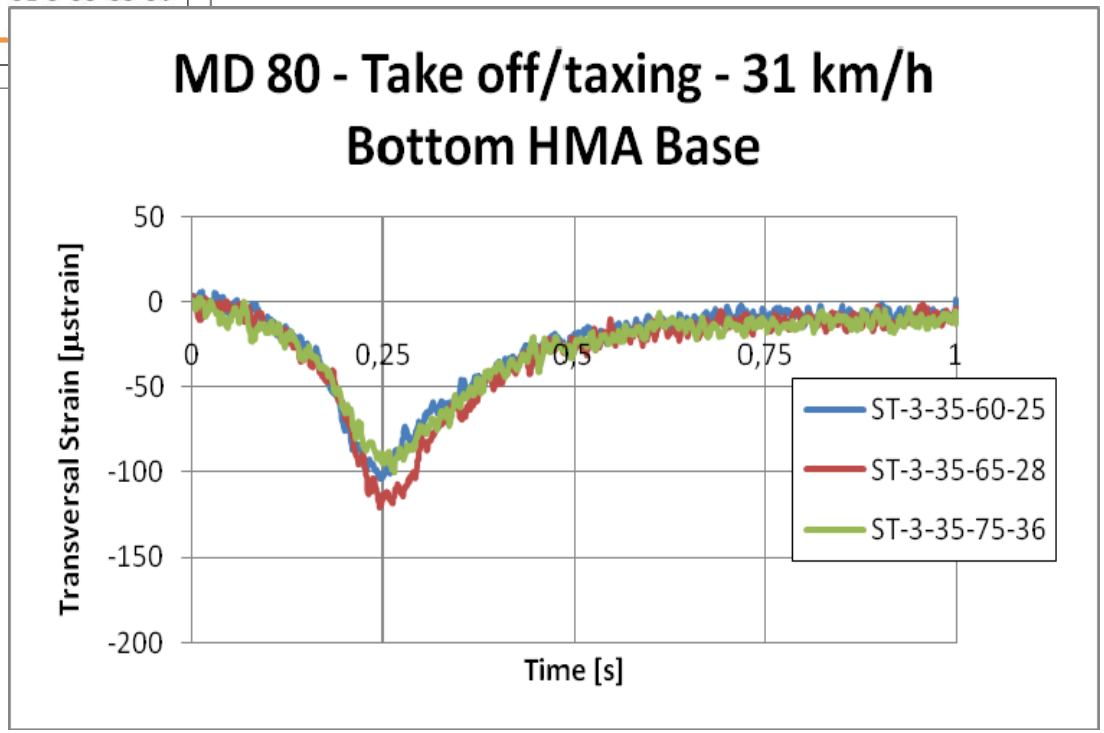


Non-Uniform Contact Stress



Typical Measured Strain Responses

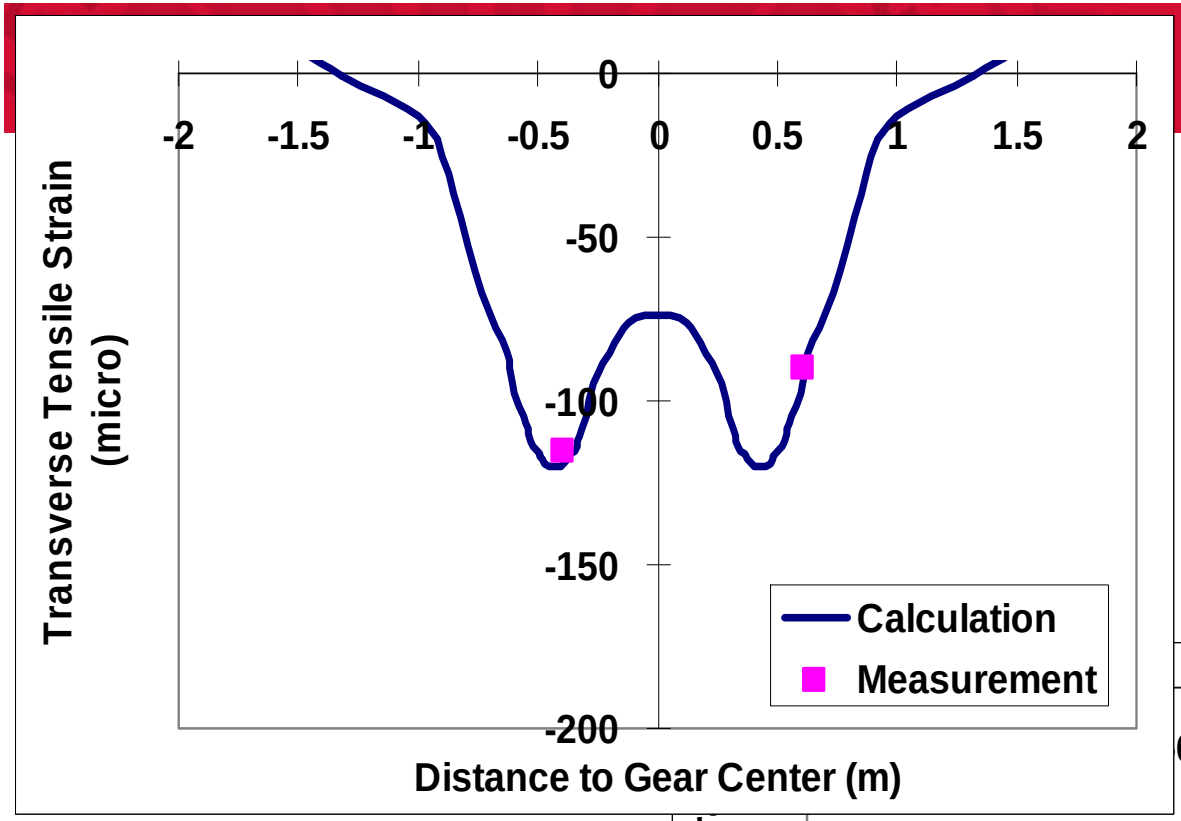


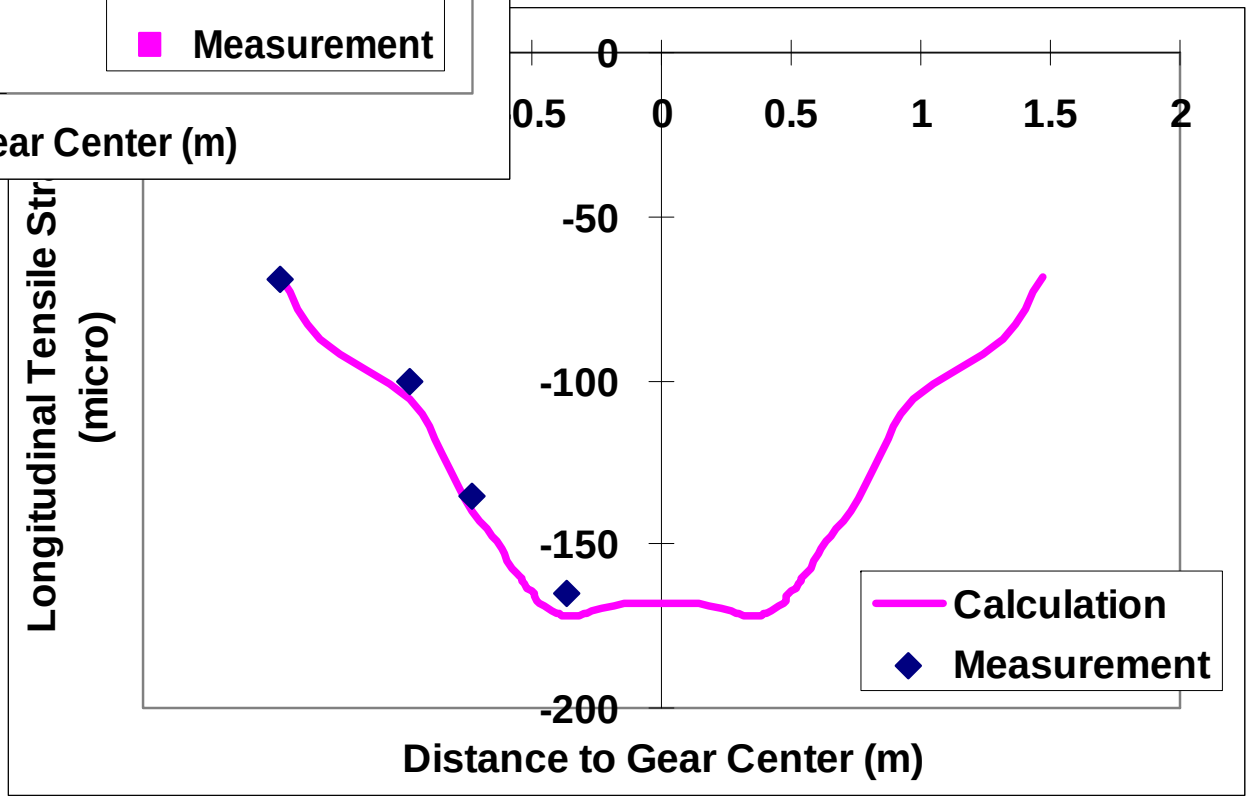


Measured vs. Calculated Tensile Strains (1)

Loading condition	Depth (m)	Horizontal strain	Measurement (micro)	Calculation (micro)
1	0.05	Longitudinal	-75	-125
	0.15	Transverse	-95	-46
	0.35	Transverse	160	136
2	0.05	Longitudinal	-175	-141
	0.15	Longitudinal	-75	-65
	0.35	Longitudinal	125	159
	0.35	Transverse	170	118
3	0.05	Longitudinal	-110	-136
	0.35	Longitudinal	165	170
	0.35	Transverse	115	120
4	0.05	Longitudinal	-90	-125
	0.15	Transverse	-60	-47
	0.35	Transverse	85	102

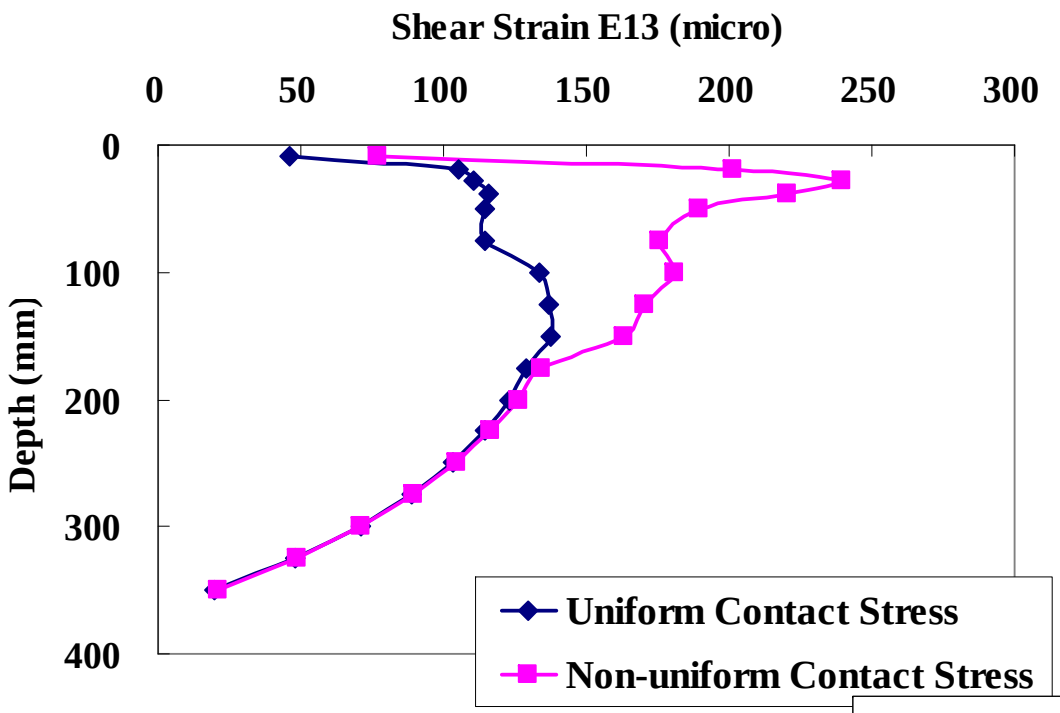
Measured and Calculated Tensile Strains (2)

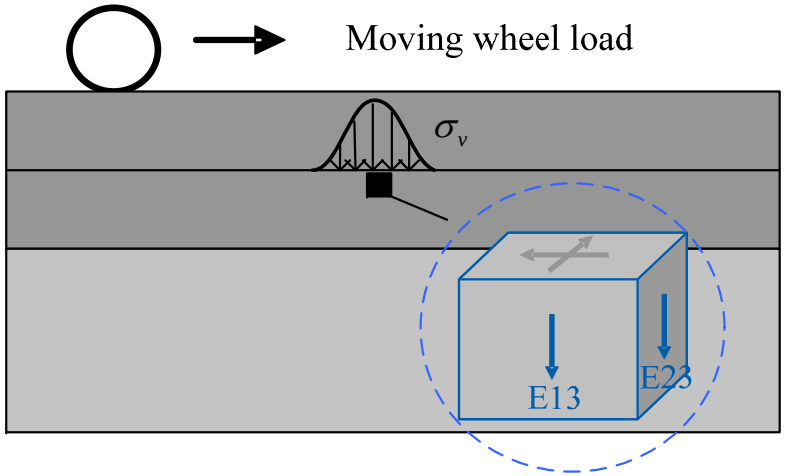


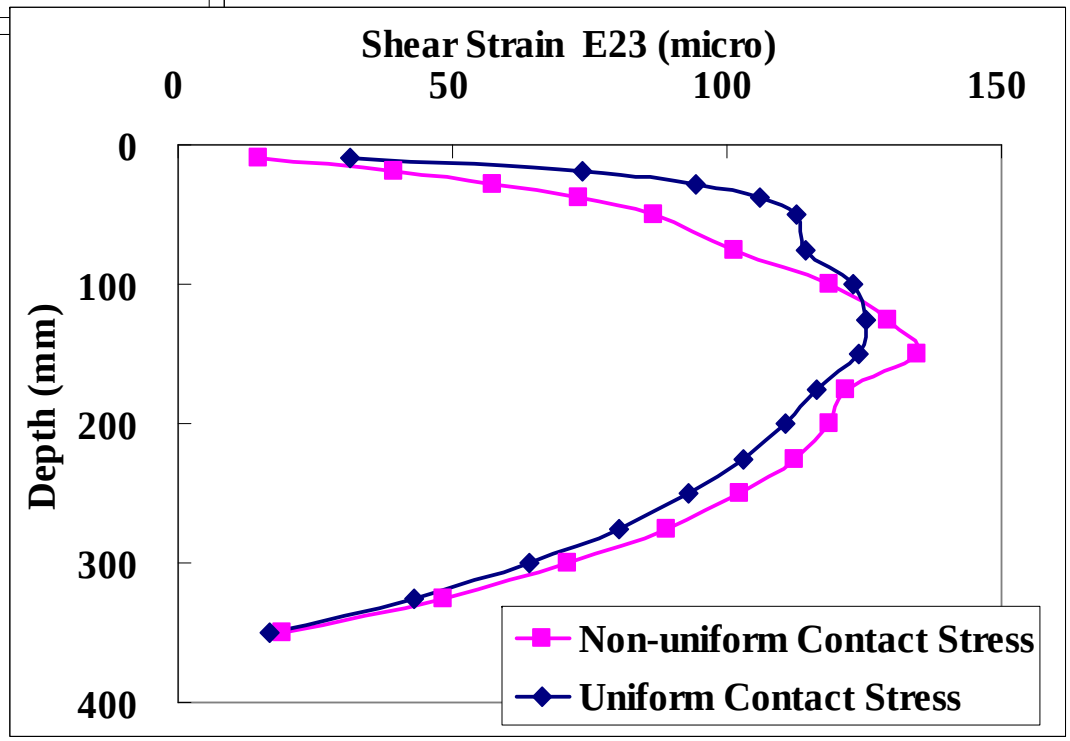


MD-80

Effect of Contact Stress on Shear Strains







Effect of Layer Interface Condition

Type of response	Location	Pavement response at different interface conditions		Response changes
		Full bonding	Friction (μ=1.0)	
Transverse tensile strain (micro)	Bottom of asphalt layer	**114**	**165**	**+45%**
Longitudinal tensile strain (micro)		**155**	**243**	**+57%**
Shear strain in the plane parallel to moving direction (micro)	Shallow depth of HMA layer	**239**	**225**	**-6%**
Shear strain in the plane perpendicular to moving direction (micro)		**135**	**153**	**+13%**

Summary

- **Accurate pavement response prediction requires realistic loading simulation and appropriate material modeling**
  - Non-uniform contact stresses; moving load…
  - Viscoelastic HMA; Nonlinear anisotropic granular base…
- **3-D FE models were built to simulate FWD testing and predict pavement responses under aircraft loading**
  - Results are consistent with the measured deflection basin and field instrumentation measurements
- **The model can lead to better understanding long-term pavement performance under varied climatic and operating conditions**

Model Applications

- **Understand dynamic loading effects** (multiple wheel load, high tire pressure, braking, landing)
- **Evaluate the effects of environment on pavement performance** (thermal gradient, moisture condition)
- **Evaluate the effects of specific design and construction and material variations**
- **Predict stress states under vehicular loading used for material performance tests**
- **Analyze pavement structure with discontinuities** (delamination, debonding, reflective cracking)
- **Backcalculate modulus form falling weight deflectometer (FWD) test**

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Thank You
Questions ?

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