University of Pittsburgh

Development the Faulting Model for Unbonded Concrete Overlays of Existing Concrete Pavements (UBOLs)

Tasks 2 & 9
Tasks 3 & 4

TAP Meeting TPF 5-269
December 20th, 2016

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Research objectives and approach

Develop a mechanistic-empirical faulting model for UBOL

- Interlayer system characterization through lab investigation (Tasks 2 & 9)
  - Structural model inputs
  - Interlayer characterization
  - Interlayer performance criteria

- Faulting model framework
  - Structural model development (Tasks 3)
  - Establish differential energy (Tasks 4)
  - Faulting prediction equations (Tasks 4)

Factors affecting interlayer performance

- Erodibility – Stripping of interlayer adjacent to joints (Faulting model-field data)


US 23 in MI (courtesy of Andy Bennett)

- Strength/stiffness– Reduce potential for consolidation or crushing of interlayer adjacent to transverse joint (Min. E* criteria-lab & field data)

- Permeability – drainage within interlayer reduces pressure build-up (Min. permeability criteria-field data)

MnROAD Cell 305

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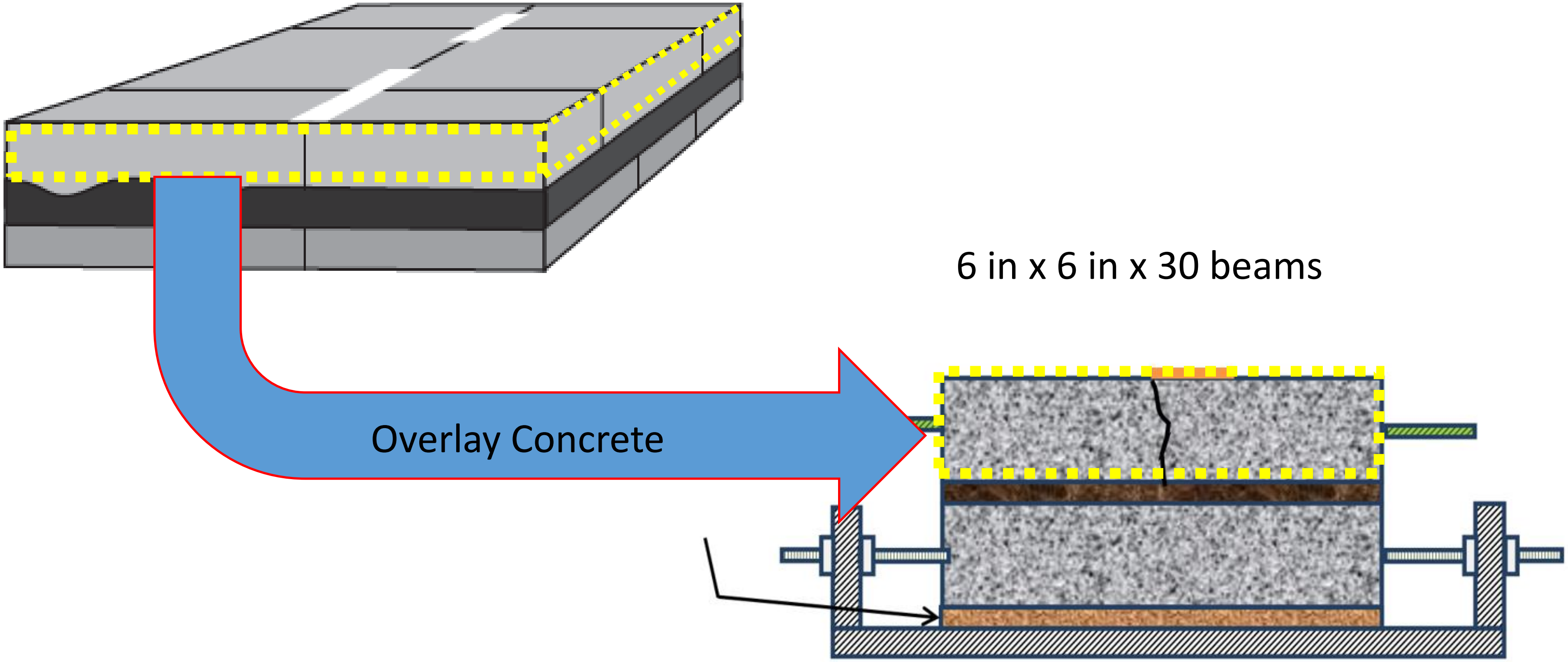
Laboratory study (Task 2 & 9)

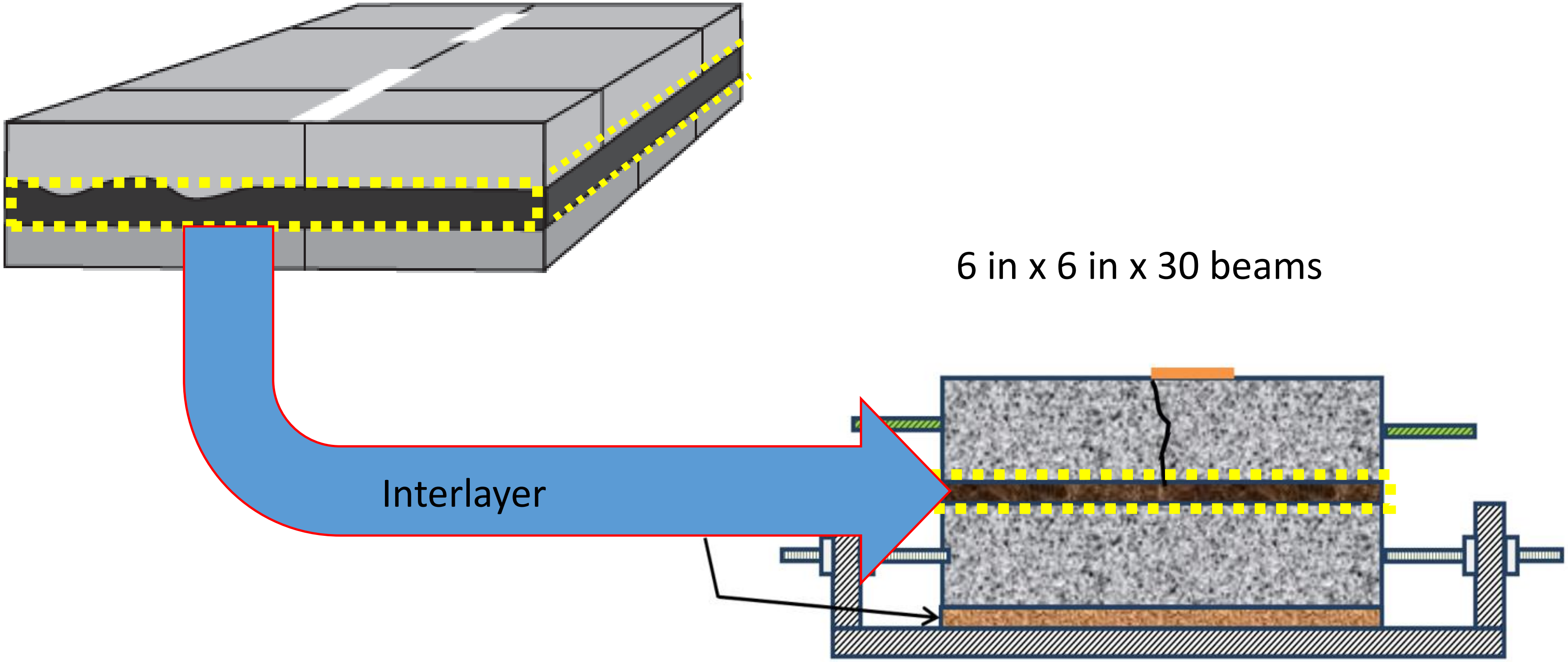
Mechanisms Investigated:

1. Stiffness of interlayer – LTE & deflections
   - Structural model inputs
   - Min. strength or stiffness criteria
2. Friction along interlayer system
   - Structural model inputs
   - Joint activation
3. Ability to prevent reflective cracking
   - Structural model inputs
   - Interlayer performance
4. Vertical resistance to uplift – pull off
   - Interlayer performance

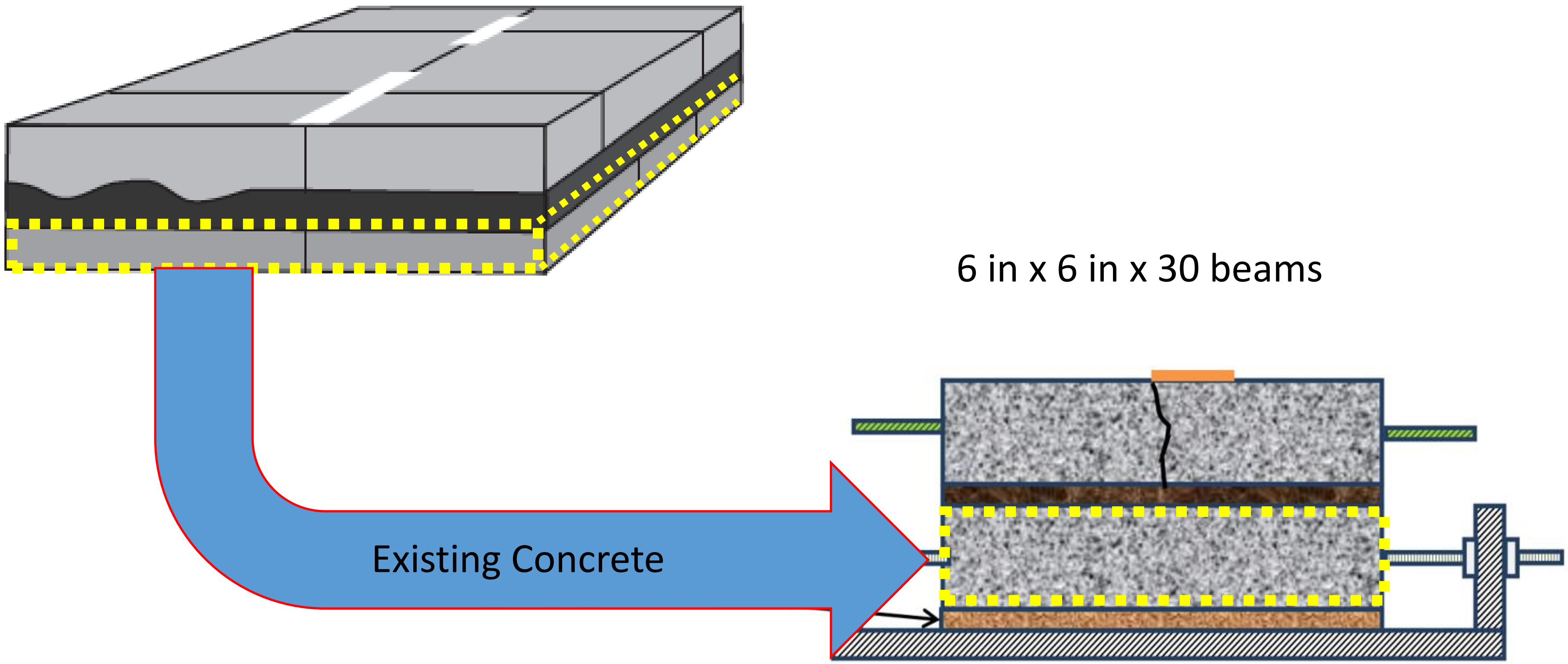
Laboratory specimens



Laboratory specimens



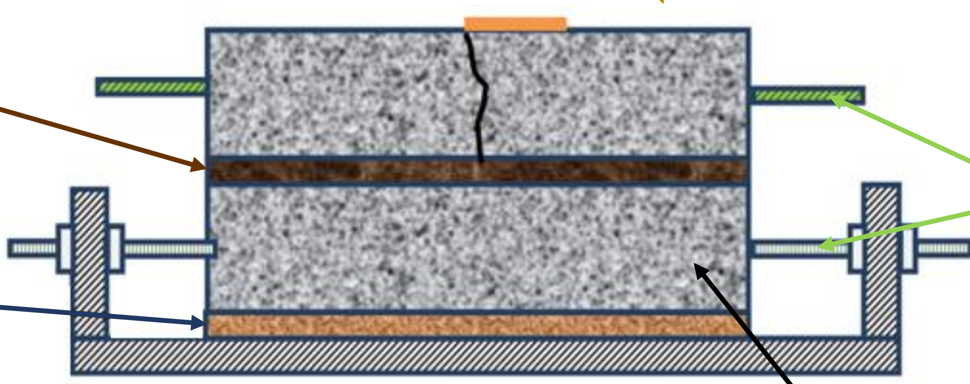
Laboratory specimens



Specimen setup

Overlay Concrete
- Conventional Paving Mix
- Target flexural strength = 650 psi

Interlayer
- Geotextile fabric
- Open & Dense HMA



Threaded Steel Rods

Two layers of neoprene pad
- Fabcell-25
- k = 200 psi/in

Existing Concrete
- HES Mix – simulate aged concrete
- Target flexural strength = 850 psi
- OR in-service PCC from composite pavement (asphalt IL)

Interlayers

Roadway	Asphalt Description	Ave. Asphalt Thickness	Specimen Designation
US-131, MI	Old, dense graded	1 in	MIDAU
US-131, MI	Old, open-graded	2 in	MIOAU
I-94, MnROAD	Old, dense graded, milled	0.875 in	MNDAM
I-94, MnROAD	Old, dense graded, unmilled	2.75 in	MNDAU
US-169, MN	New, open graded (PASRC)	1.75 in	MNONU
SR-50, PA	New, dense graded	1 in	PADNU

Propex Reflectex - 15 oz/yd^2 fabric = F15
Propex Geotex 1001N – 10 oz/yd^2 fabric = F10

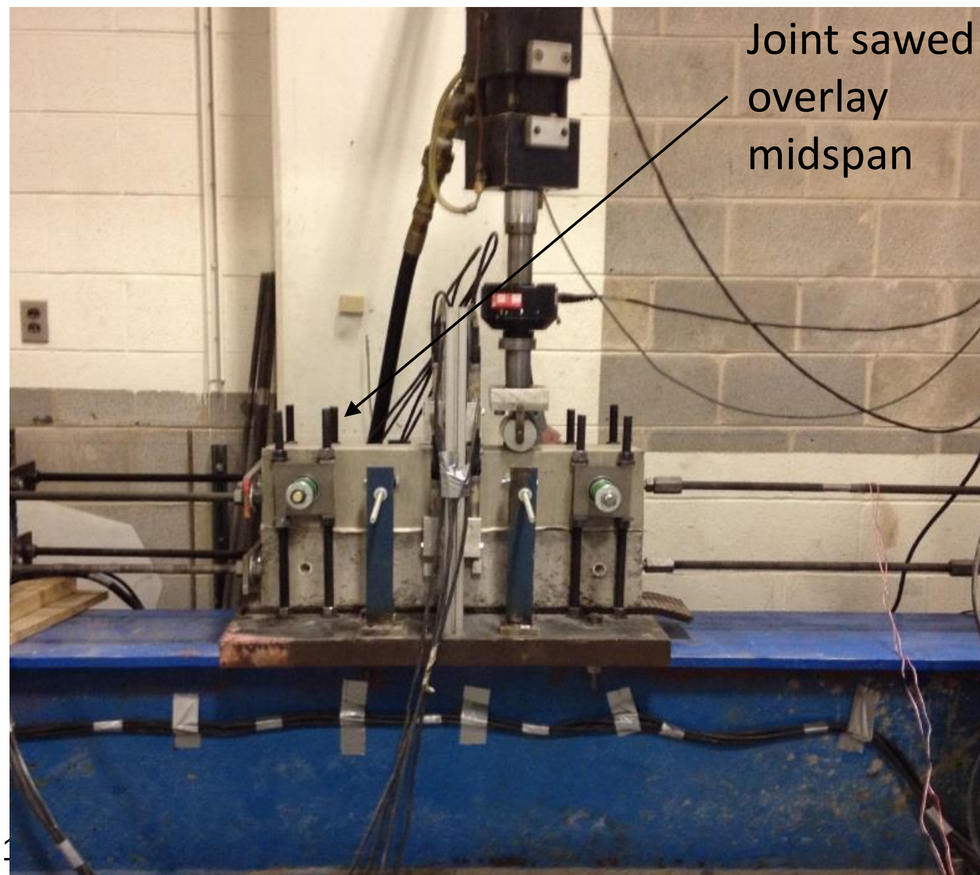
1. Stiffness of interlayer system

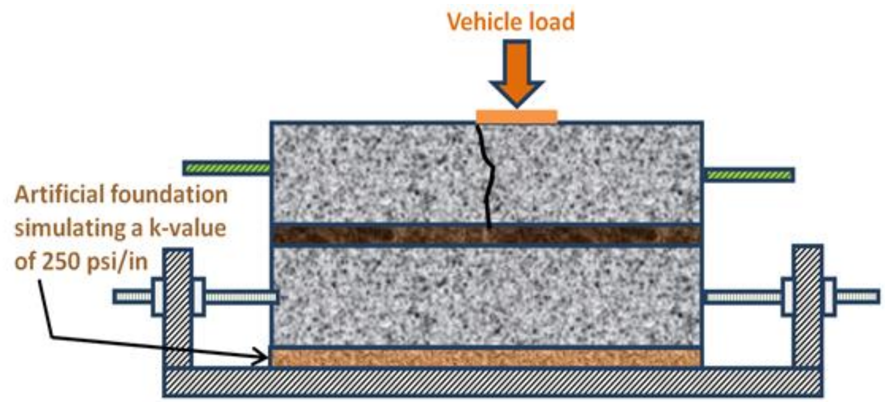
Reduced stiffness

- Differential movements absorbed by interlayer
- Large deflections when vehicle loads are applied

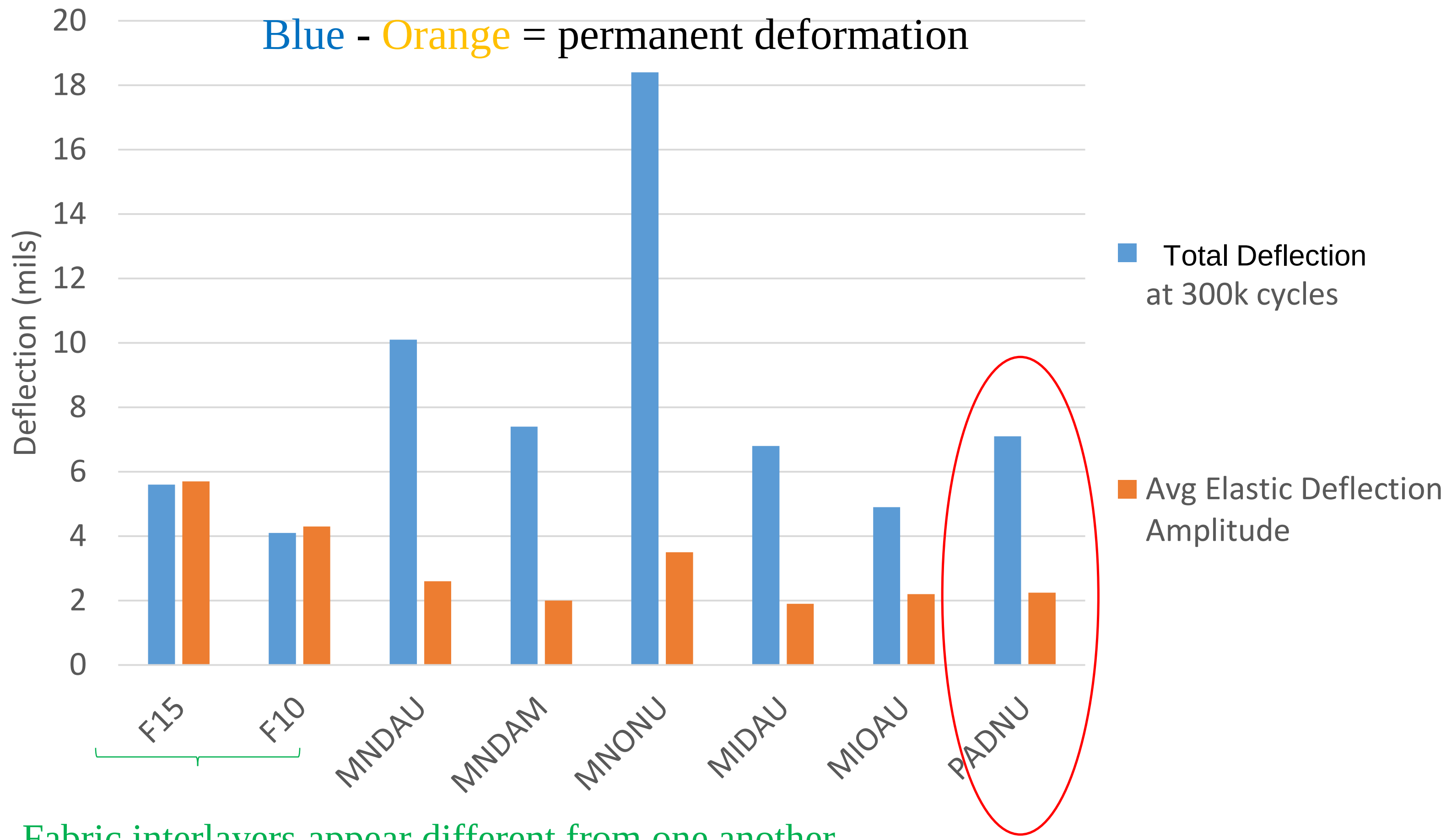
Properties Monitored

- Max deflections
- Differential deflections
- LTE





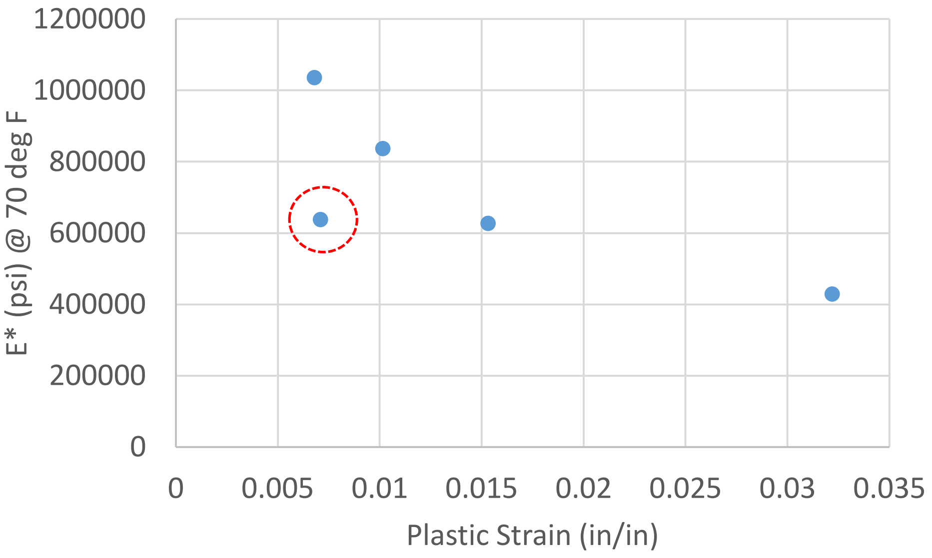
Elastic deflection and permanent deformation

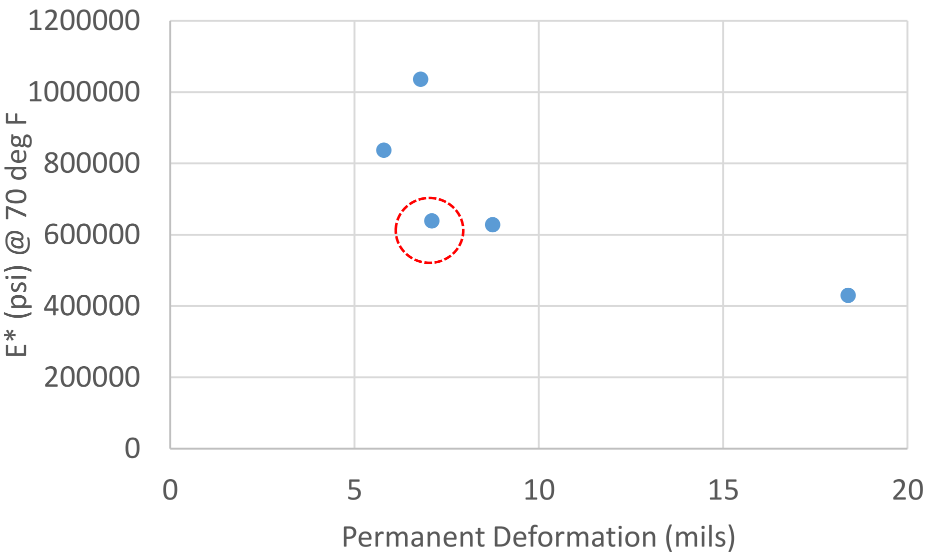


- Fabric interlayers appear different from one another
- Elastic responses of the fabric different from all asphalt interlayers
- MN open graded asphalt appears different from other asphalts

Interlayer resistance to consolidation/ crushing

- Establish min. E* or strength criteria



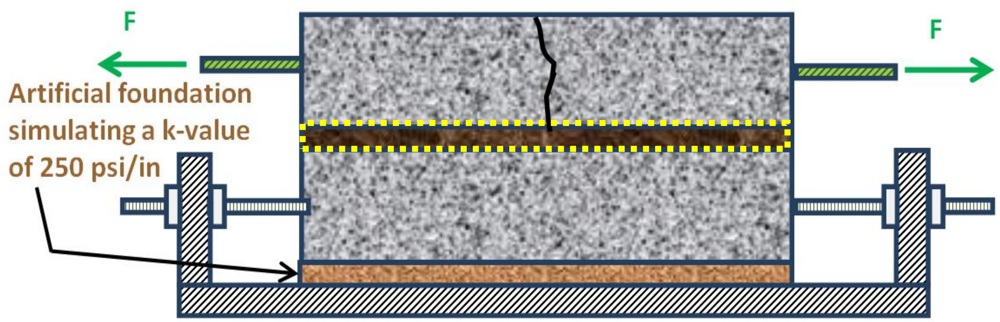


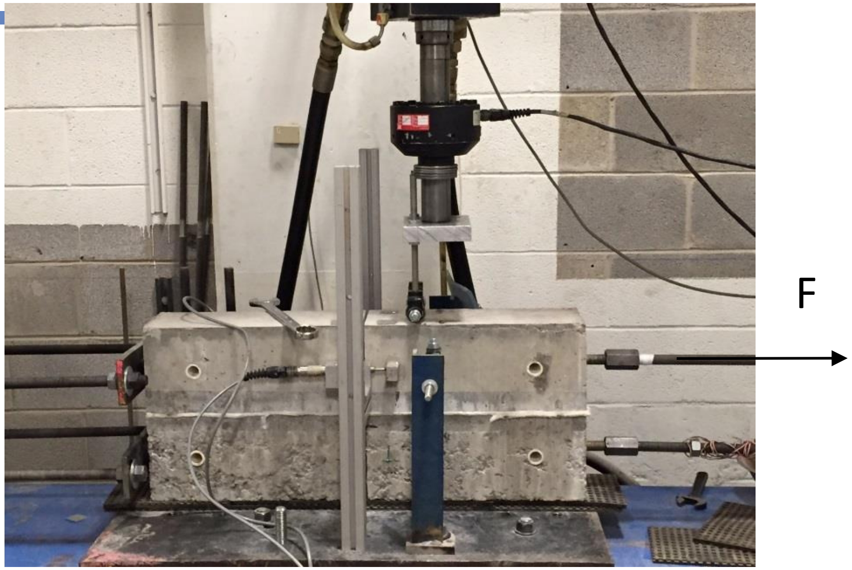
E* established using Witczak equation

Conclusions

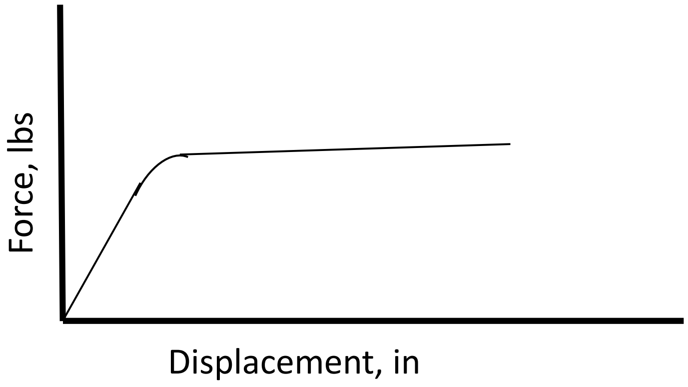
- Both fabrics maintained the same magnitude of deflection and LTE
  - Potentially indicating greater fatigue resistance
  - Less susceptible to loss of support due to interlayer degradation
- Large permanent deformation can occur in some asphalt interlayers
  - Can lead to a loss of support under the overlay in the wheelpath
- Guidance for min. E* criteria for interlayer

2. Friction along interlayer (interface friction)





- Similar setup for first beam test
- Friction dictates shear transfer between layers
- Force (F) vs. horizontal displacement relationship



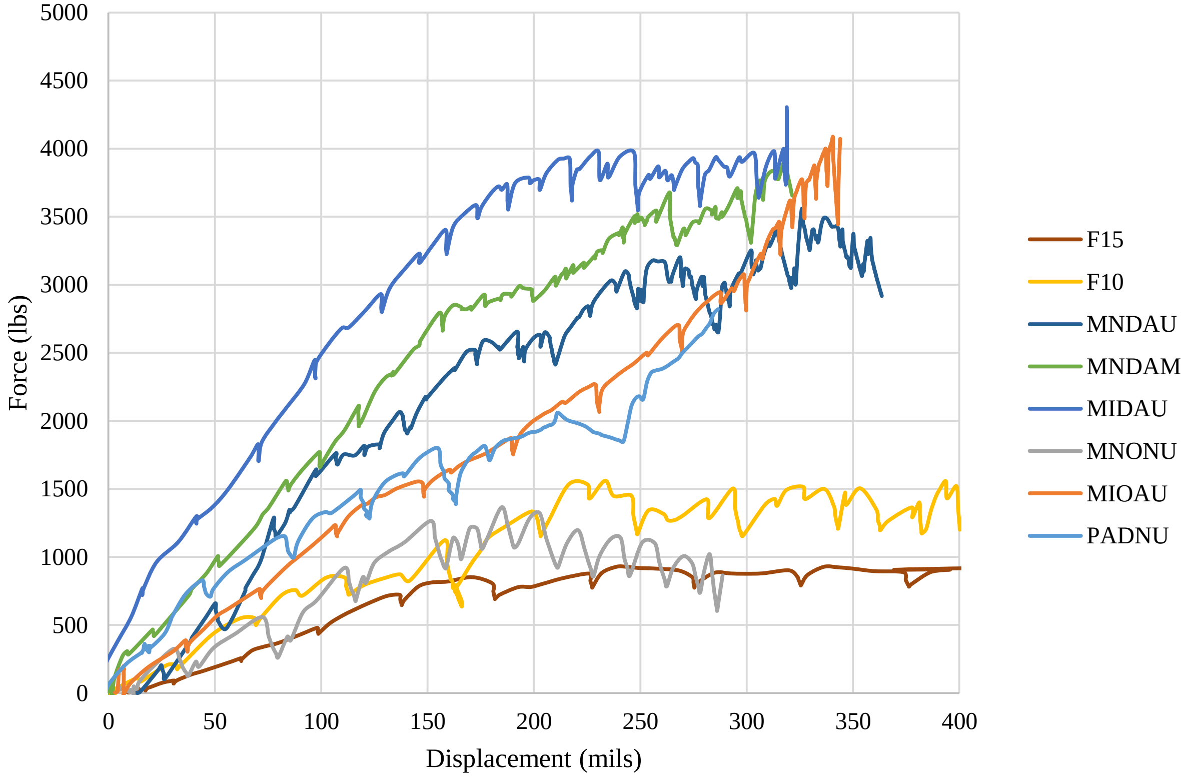
- Instrumented threaded rod used to record force
- LVDTs used to record displacement

Modified push-off test: 2 phase loading

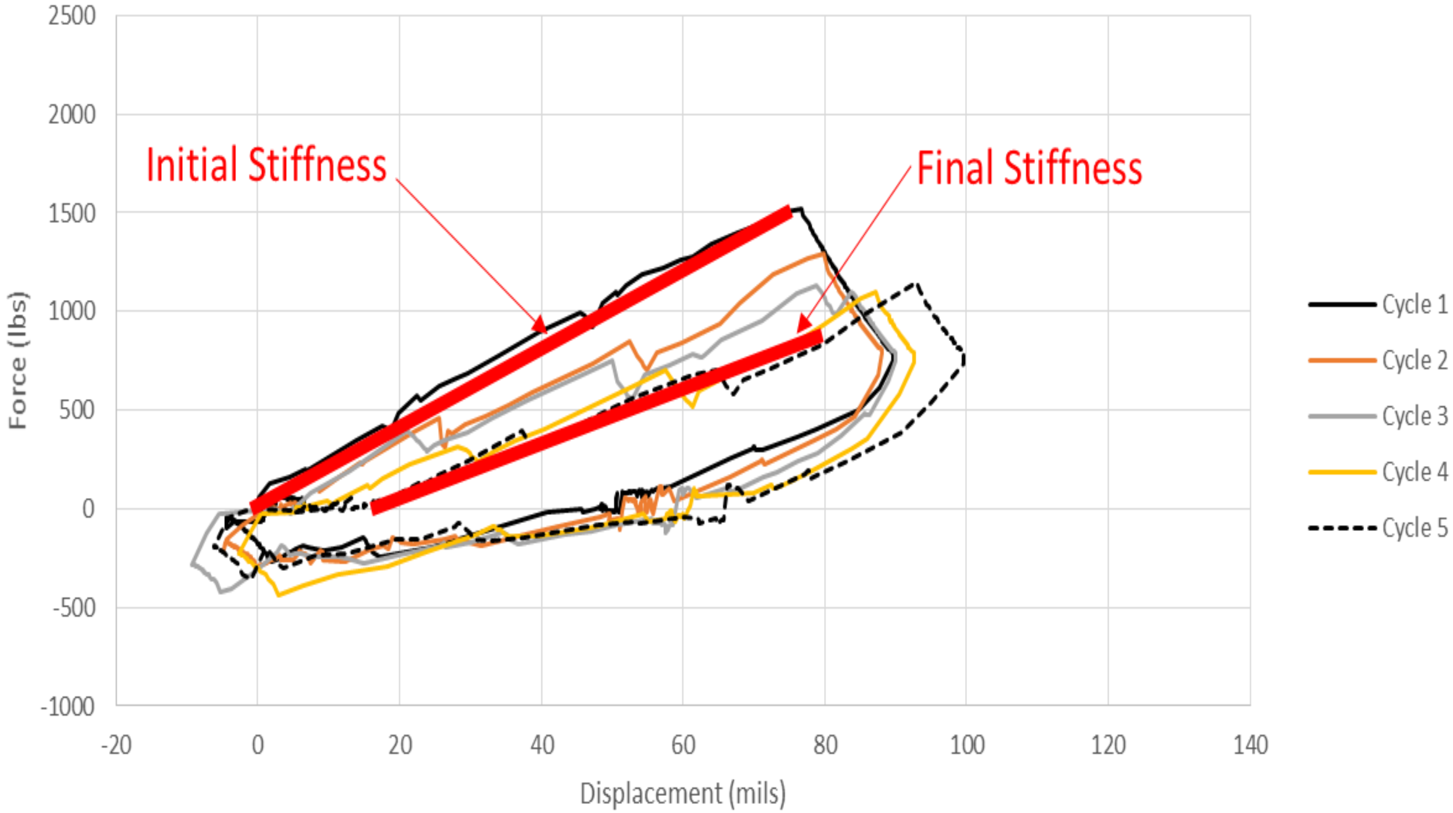
- Phase 1 - cyclic loading phase
  - Load is applied until the loaded portion of the overlay is ~ 80 mils.
  - System is relaxed until the force is relatively constant
  - Load completely removed
  - Load is applied in the opposite direction to reach initial position
  - Repeated 5 to 8 times for each test
- Phase 2 - ultimate loading phase
  - Specimen loaded to failure

Load until failure

1. Fabric is similar to MNONU
2. PADNU similar to MIOAU
3. Dense graded are similar



Example data



Results

Interlayer (Code)	Initial Stiffness (psi/in)	Final Stiffness (psi/in)	Ultimate Resistance (psi)
F15-Glued	61	37	13
F15-Pinned	50	40	26
F10-Glued	104	87	22
F10-Pinned	98	29	21
MNDAU	234	167	39
MNDAM	333	263	59
MIDAU	336	317	>62
MNONU	217	55	16
MIOAU	169	136	63
PADNU	215	124	32

Compared Interlayers	P-Value	
	Initial Stiffness	Final Stiffness
Fabric vs Open Graded	**<0.0001**	0.20
Fabric vs Dense Graded	**<0.0001**	**<0.0001**
Open Graded vs Dense Graded	**<0.0001**	**<0.0001**
Fabric, initial vs final	0.057	
Dense Graded, initial vs final	**0.004**	
Open Graded, initial vs final	0.055	

Conclusions

- Initial and final stiffness different
  - Open graded & fabric are exceptions
- PADNU similar to MNONU and MIOAU
- Initial stiffness important for short panels
  - Not all joints activate initially
  - Rate of fault development can vary greatly between joints
  - Data for incorporating 6x6 ft faulting model (Task 9)
    - Lab data
    - Jt widths measured for 6x6ft UBOL in PA
    - Faulting data from field (for each jt and not ave of all jts)

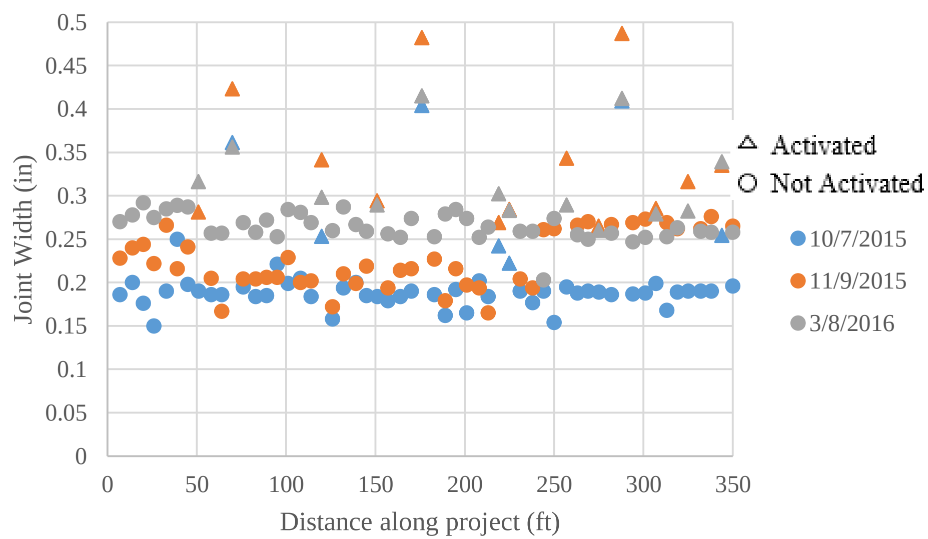
SR 50 UBOL (Task 9)

PADNU

Pavement Age (weeks)	Activated joints	Ave. activated joint width (in)	Ave. un-activated joint width (in)	Ave. distance between activated joints (ft)
2.5	40/400	0.316	0.190	61
7	56/400	0.393	0.253	47
24	60/400	0.349	0.266	44

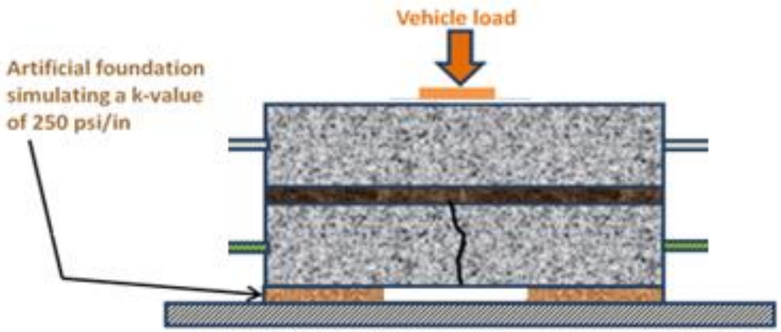
Un-activated joint (Approx. 0.25-in wide)

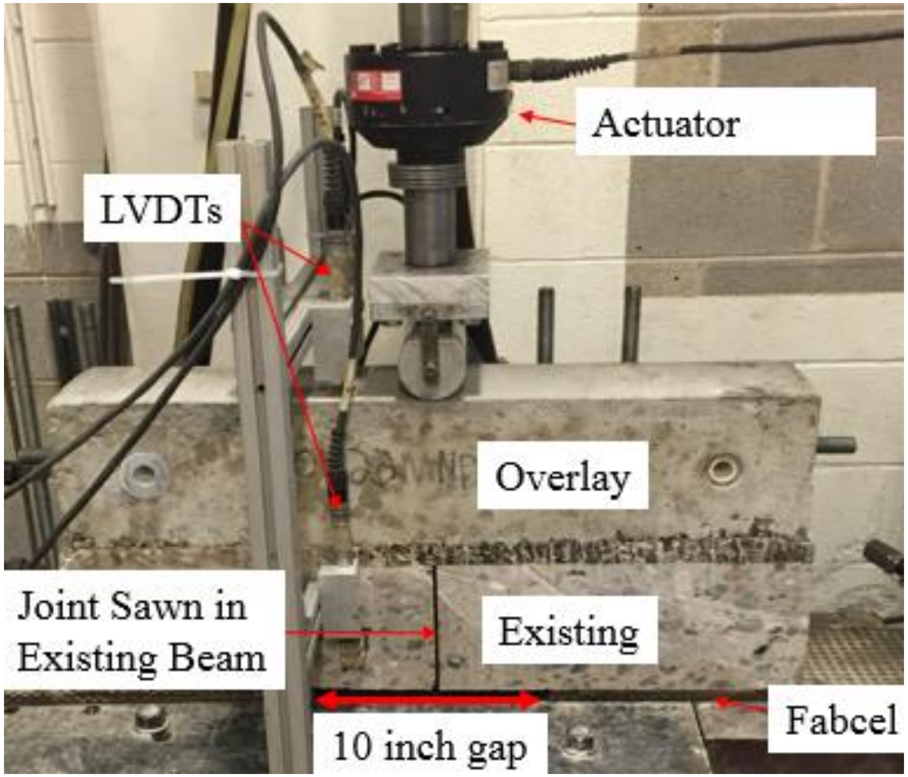
Activated joint (Approx. 0.5-in wide)



3. Ability to prevent reflective cracking

- Load increased until reflective crack generated





- 2 LVDTs record overlay beam disp
- 2 LVDTs record existing beam disp
- Recorded 3.5 in to the left of the load

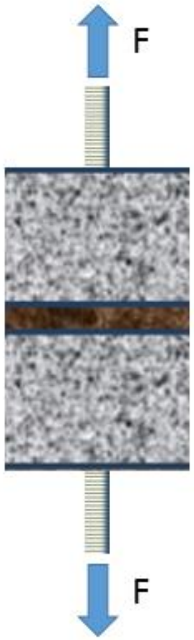
Sufficient "cushion" to prevent reflective cracking?

Conclusions

- “True” reflective cracking rarely occurs in the field unless nonuniform support conditions exist
- Fabric tends to increase resistance to reflective cracking when compared to HMA
- MI open graded HMA appears to perform better than other HMA interlayers

4. Direct Tension Test (DTT)

- Effect of curling/warping stresses
- Measure vertical deformations within interlayer
- Measure strength
- 4 dia. x 8 inch specimens for fabric interlayers
- HMA specimens cut from Reflective cracking beams (Mechanism 3)
- Same mix designs used for beam tests



Results

Code	Peak Load (lbs)	Displacement at Peak Load (mils)	Location of Break
F15	18	64	Glued Interface
	16	61	Glued Interface
F10	31	139	Glued Interface
	38	120	Glued Interface
MNDAU	255	33	Middle of asphalt
	251	42	Middle of asphalt
MNDAM	262	10	Bond w/ Existing Concrete (into asphalt)
	392	13	Bond w/ Existing Concrete (into asphalt)
MNONU	169	12	Middle of asphalt
	208	12	Bond w/ Existing Concrete (into asphalt)
MIDAU	586	22	Bond w/ Overlay Concrete
	411	13	Bond w/ Overlay Concrete
MIOAU	206	4	Bond w/ Existing Concrete (into asphalt)
	142	6	Bond w/ Existing Concrete
PADNU	305	9	Bond w/ Existing Concrete
	289	13	Bond w/ Existing Concrete

Compared Interlayer Types		P-value
Fabric	Dense graded	0.0001
Fabric	Open graded	0.0007
Dense graded	Open graded	0.005

Conclusions

- Small force and high displacement at peak force for both fabrics
  - Fabric interlayers provide no resistance to upward curl
- Asphalt provides varying resistance
  - Type of asphalt and the degree of bond strength at the interface
  - Subject to change depending on asphalt temp and occurrence of stripping, erosion, or consolidation

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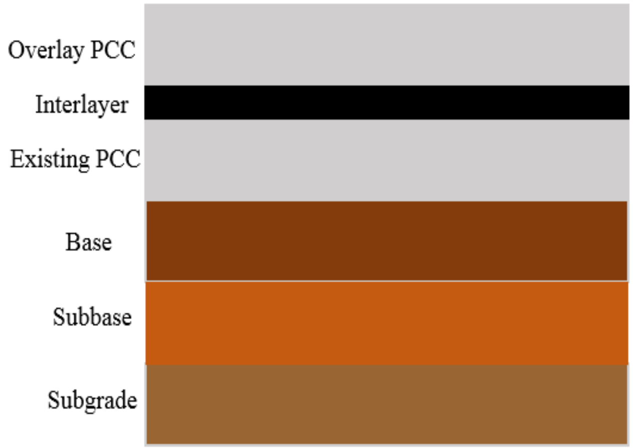
Pumping

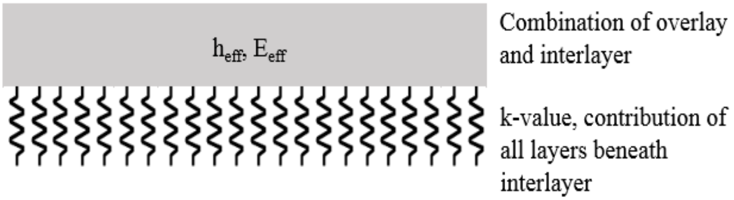
The following 4 factors must be present:

1. Differential deflections
2. Moisture
3. Unstabilized fines
4. Wheel loads

Pavement ME limitations

- Modeled as newly constructed JPCP
  - Interlayer is the base layer





- Limited calibration database used to calibrate same performance models as JPCP
- UBOL initial calibration - 30 obs for faulting
- Newly JPCP initial calibration - 560 obs for faulting

Pavement ME limitations

MEPDG Documentation Appendix JJ

- Erodibility index

Assigned integer value based upon base type

1 – extremely erosion resistant

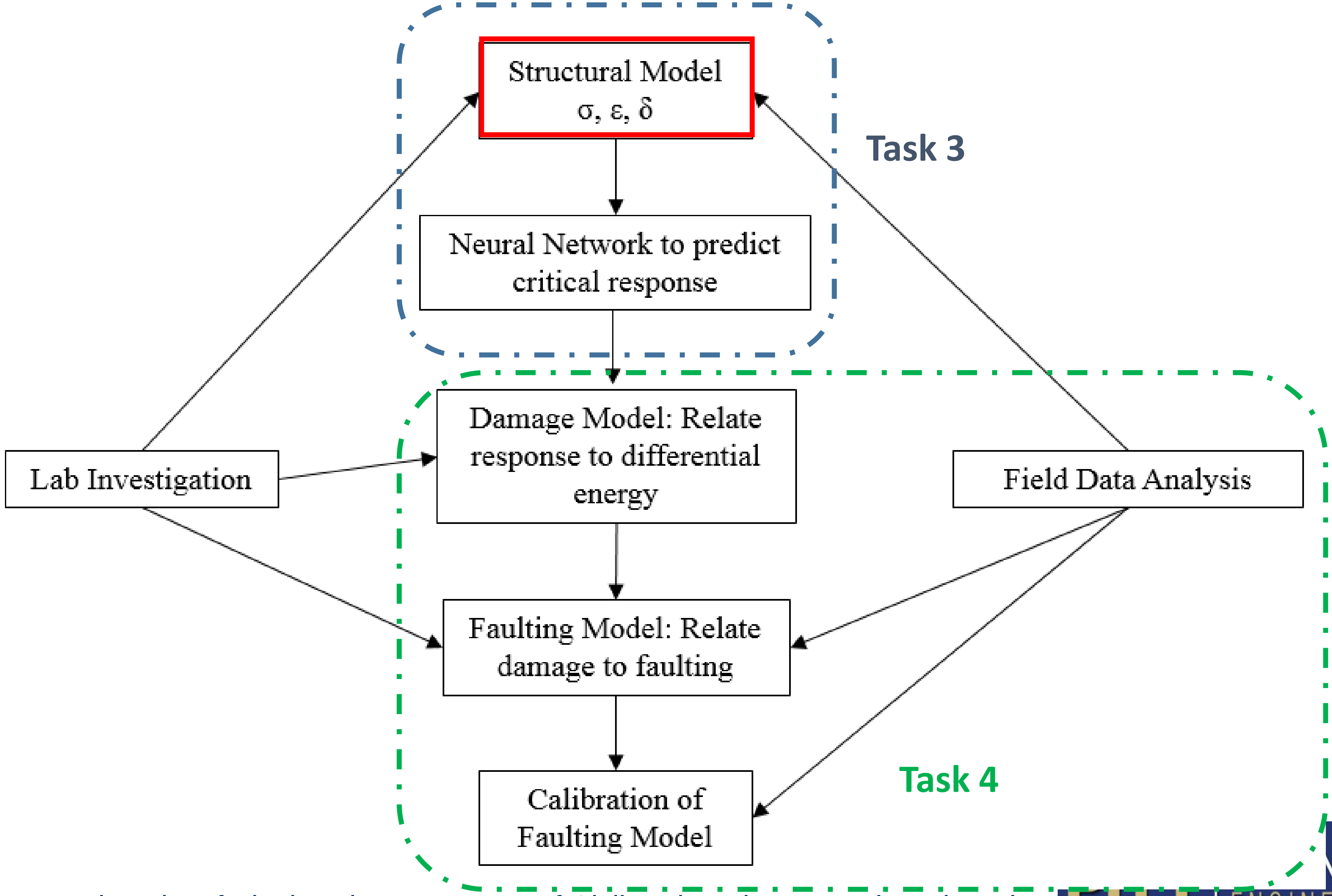
to

5 – very erodible

UBOL EROD = 1

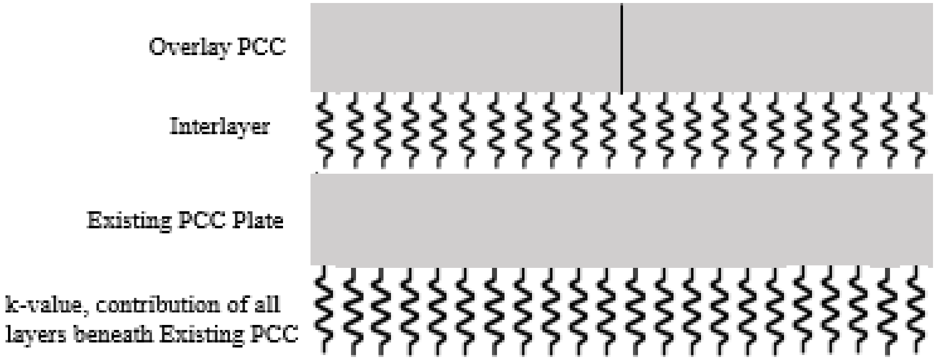
Erodibility Class	Material Description and Testing
1	(a) Lean concrete with approximately 8 percent cement; or with long-term compressive strength > 2,500 psi (>2,000 psi at 28-days) and a granular subbase layer or a stabilized soil layer, or a geotextile fabric is placed between the treated base and subgrade, otherwise class 2. (b) Hot mixed asphalt concrete with 6 percent asphalt cement that passes appropriate stripping tests and aggregate tests and a granular subbase layer or a stabilized soil layer (otherwise class 2). (c) Permeable drainage layer (asphalt treated aggregate or cement treated aggregate and with an appropriate granular or geotextile separation layer placed between the treated permeable base and subgrade.
2	(a) Cement treated granular material with 5 percent cement manufactured in plant, or long-term compressive strength 2,000 to 2,500 psi (1,500 to 2,000 psi at 28-days) and a granular subbase layer or a stabilized soil layer, or a geotextile fabric is placed between the treated base and subgrade; otherwise class 3. (b) Asphalt treated granular material with 4 percent asphalt cement that passes appropriate stripping test and a granular subbase layer or a treated soil layer or a geotextile fabric is placed between the treated base and subgrade; otherwise class 3.
3	(a) Cement-treated granular material with 3.5 percent cement manufactured in plant, or with long-term compressive strength 1,000 to 2,000 psi (750 psi to 1,500 at 28-days). (b) Asphalt treated granular material with 3 percent asphalt cement that passes appropriate stripping test.
4	Unbound crushed granular material having dense gradation and high quality aggregates.
5	Untreated soils (PCC slab placed on prepared/compacted subgrade)

Faulting model framework



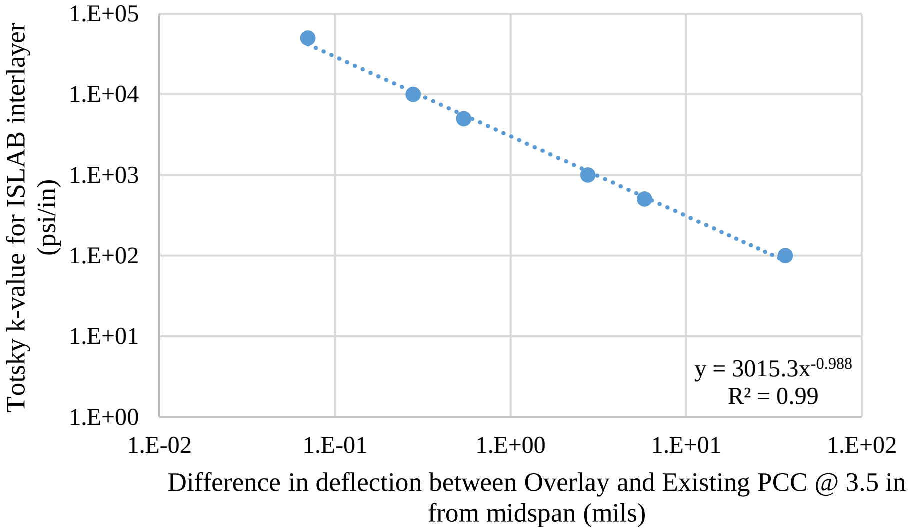
Structural model (Task 3)

- Need to model response of UBOL
- ISLAB utilized
  - FEM developed for multilayer rigid pavements
  - Used to develop NNs for Pavement ME
- Interlayer modeled as Totsky interface



Totsky interlayer k-value

- Deflection data from reflective cracking test
  - Test setup modeled in ISLAB
  - 1 kip response for different k-values



Totsky interlayer k-value

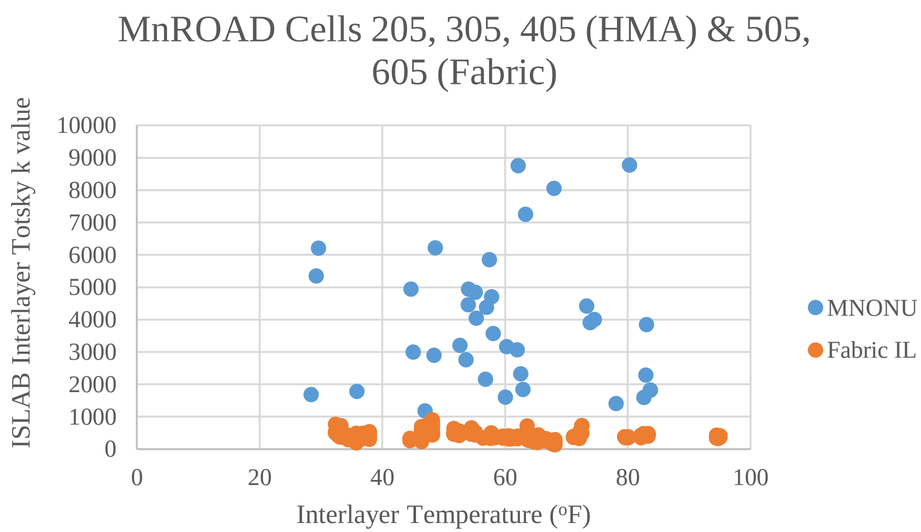
- Matched to difference in deflection for beam specimens
- Tukey's range test to compare means

Interlayer Type	Average Totsky k-value (psi/in)	Standard Deviation (psi/in)
F15	337	63
F10	372	55
MNDAU	3342	1262
MNDAM	3613	1175
MNONU	2555	901
MIDAU	4046	966
MIOAU	3566	1095
PADNU	3391	1533

Comparison	Difference of Mean Totsky coeff. Between Interlayers	95% Confidence Interval of Difference
MNDAU - F15	**3006**	**(208, 5803)**
MNDAM - F15	**3277**	**(479, 6074)**
MIDAU- F15	**3709**	**(912, 6507)**
MIOAU - F15	**3229**	**(432, 6027)**
PADNU - F15	**3054**	**(257, 5852)**
MNDAU - F10	**2970**	**(173, 5768)**
MNDAM - F10	**3241**	**(444, 6039)**
MNONU - F10	2183	(-615, 4980)
MIDAU- F10	**3674**	**(876, 6471)**
MIOAU - F10	**3194**	**(396, 5991)**
PADNU - F10	**3019**	**(221, 5816)**

Totsky interlayer k-value

- FWD data from MnROAD used to establish k-values for Cells 105 -605



Cell	Construction Date	Slab Size* (Length x Width) (ft x ft)	Dowels (in)	Overlay Concrete Thickness (in)	Interlayer Thickness (in)	Interlayer Type	Existing Concrete Thickness (in)
105	10/8/08	15 x 14	None	4	1	MNONU	7.5
205	10/8/08	15 x 14	None	4	1	MNONU	7.5
305	10/8/08	15 x 14	None	5	1	MNONU	7.5
405	10/8/08	15 x 14	None	5	1	MNONU	7.5 (cracked)
505	8/24/11	6 x 7	None	5	-	Fabric	7.5 (cracked)
605	8/24/11	6 x 7	None	5	-	Fabric	7.5

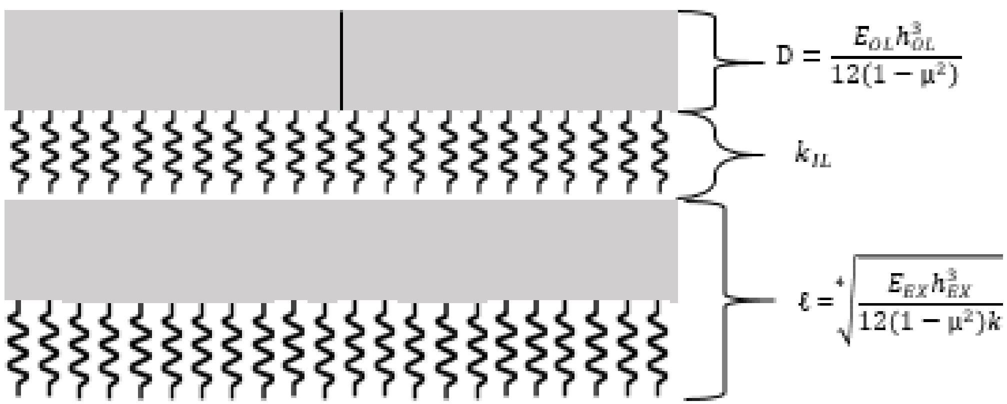
Totsky interlayer k-value

Comparison between means of established Totsky values	P-value of t-test for difference in means
Fabric LAB vs. MnROAD Fabric FWD	0.126
MNONU LAB vs. MnROAD Asphalt FWD	0.137
MnROAD Fabric FWD vs. MnROAD Asphalt FWD	<0.001

- k-values from FWD test data not statistically different from lab values for same interlayer
- Fabric and asphalt k-values established using FWD test data are statistically different from one another
- Average lab and FWD for asphalt gives Totsky value of approximately 3500 psi/in
- Average lab and FWD results is 425 psi/in nonwoven geotextile fabric interlayer

Factorial of parameters

- Parameters within structure combined
  - Decrease number of FEM runs



  - Neural networks developed to predict critical structural responses

Factorial of parameters

<table>
<tr><th>Parameter</th><th colspan="3"></th><th colspan="2"></th><th colspan="3"></th></tr>
<tr><td>Existing slab and foundation radius of relative stiffness, ℓ (in)</td><td colspan="3">20</td><td colspan="2">50</td><td colspan="3">80</td></tr>
<tr><td>Interlayer Totsky k-value (psi/in)</td><td colspan="3">2,000</td><td colspan="2">6,000</td><td colspan="3">10,000</td></tr>
<tr><td>Overlay Flexural Stiffness, D (lb-in)</td><td colspan="3">2.00E+07</td><td colspan="2">3.00E+08</td><td colspan="3">9.00E+08</td></tr>
<tr><td>Overlay PCC joint spacing x slab width (ft)</td><td colspan="3">6 x 6</td><td colspan="2">12 x 12</td><td colspan="3">15 x 12</td></tr>
<tr><td></td><td colspan="3"></td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td>Overlay Temp Difference (ºF)</td><td>-30</td><td>-20</td><td>-10</td><td>0</td><td>10</td><td>20</td><td>30</td><td>40</td></tr>
<tr><td></td><td colspan="3"></td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td>PCC Poisson’s ratio</td><td colspan="3">0.18</td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td></td><td colspan="3"></td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td>Longitudinal Lane shoulder LTE (%)</td><td colspan="3">Tied PCC (90 %)</td><td colspan="2">Asphalt (0 %)</td><td colspan="3"></td></tr>
<tr><td>Transverse Joint AGG Factor (psi)</td><td>100</td><td>1000</td><td colspan="2">10000</td><td>50000</td><td colspan="2">100000</td><td>1000000</td></tr>
<tr><td></td><td colspan="3"></td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td>Wheel wander (in)</td><td colspan="3">0</td><td colspan="2">4</td><td colspan="3">16</td></tr>
<tr><td>Single axle (lb)</td><td colspan="3">0</td><td colspan="2">18</td><td colspan="3">30</td></tr>
<tr><td>Tandem axle (lb)</td><td colspan="3">0</td><td colspan="2">36</td><td colspan="3">60</td></tr>
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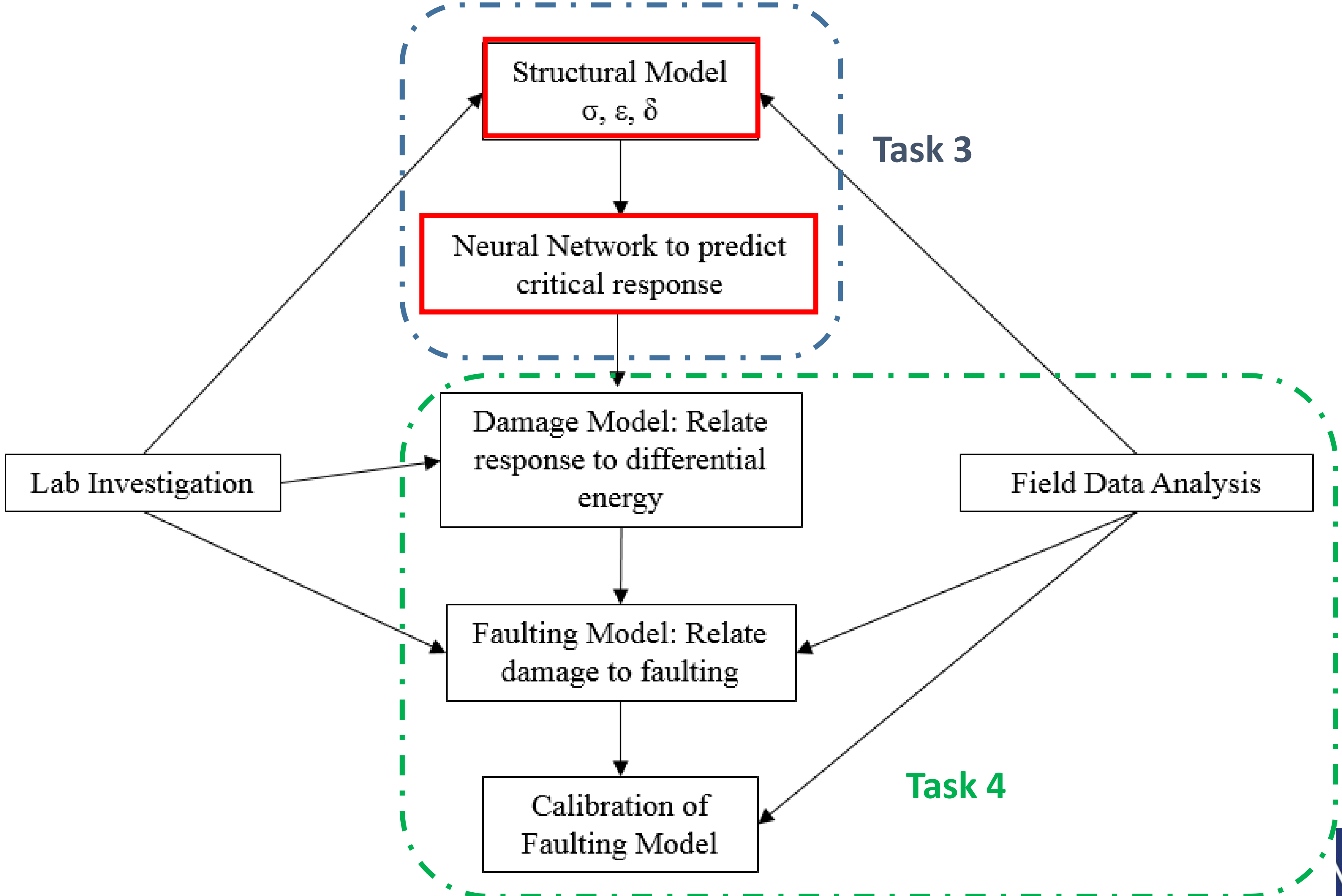
Faulting model framework



Neural network architecture

- 2 hidden layers of 20 neurons each
- Levenberg-Marquardt backpropagation algorithm
- Default split between the training, validation, and test sets (70%, 15%, and 15%)
- Each NN trained 10 times and results averaged over 10 networks.

$$\boldsymbol{NN_{\Sigma L,A}}(\boldsymbol{JTSpace}, \mathrm{l}_{\boldsymbol{OL}}, \mathrm{l}_{\boldsymbol{EX}}, \boldsymbol{LTE_{shoulder}}, \boldsymbol{AGG/k_{IL}}\mathrm{l}_{\boldsymbol{OL}}, \boldsymbol{\Phi}, \boldsymbol{q_i^*}, \boldsymbol{s})$$

$$\boldsymbol{NN_{\Sigma UL,A}}(\boldsymbol{JTSpace}, \mathrm{l}_{\boldsymbol{OL}}, \mathrm{lEX}, \boldsymbol{LTE_{shoulder}}, \boldsymbol{AGG/k_{IL}}\mathrm{l}_{\boldsymbol{OL}}, \boldsymbol{\Phi}, \boldsymbol{q_i^*}, \boldsymbol{s})$$

For single and tandem axles

$$\boldsymbol{NN_{\Sigma T}}(\boldsymbol{JTSpace}, \mathrm{l}_{\boldsymbol{OL}}, \mathrm{l}_{\boldsymbol{EX}}, \boldsymbol{LTE_{shoulder}}, \boldsymbol{AGG/k_{IL}}\mathrm{l}_{\boldsymbol{OL}}, \boldsymbol{\Phi})$$

Neural networks (basin sum deflection)

- $\Sigma\delta_{\Sigma L,i,A} = [NN_{\Sigma L,A}(JTSpace, \ell_{OL}, \ell_{EX}, LTE_{shoulder}, AGG/k_{IL}\ell_{OL}, \Phi, q_i^*, s)$
$-NN_{\Sigma L,A}(JTSpace, \ell_{OL}, \ell_{EX}, LTE_{shoulder}, AGG/k_{IL}\ell_{OL}, \Phi, 0, s)]$

- $NN_{\Sigma L,A}$= neural network for computing the basin sum deflection on loaded slab due to temperature curling and axle type A
- A = 1(single), 2(tandem)
- s = traffic wander (normally distributed in WP w/ σ = 10 in)

Revised from Pavement ME, which uses a only single corner deflection and not a deflection basin.

ing PITT SWANSON ENGINEERING

Neural networks (basin sum defl.)

- $\Sigma\delta_{\Sigma U,i,A} =$

$$[NN_{\Sigma U,A}(JTSpace, \ell_{OL}, \ell_{\mathrm{EX}}, LTE_{shoulder}, AGG/k_{IL}\ell_{OL}, \Phi, q_i^*, s) - NN_{\Sigma U,A}(JTSpace, \ell_{OL}, \ell_{\mathrm{EX}}, LTE_{shoulder}, AGG/k_{IL}\ell_{OL}, \Phi, 0, s)]$$

- $NN_{\Sigma U,A}$= neural network for computing basin sum deflections on unloaded slab due to temperature curling and axle type A
- A = 1(single), 2(tandem)
- s = traffic wander (normally distributed in WP w/ σ = 10 in)

Differential energy (Task 4)

$$DE_m = n_i k \left(\frac{\Sigma\delta_{L,i}^2}{2} - \frac{\Sigma\delta_{U,i}^2}{2}\right)$$

- DE_m=diff energy density deformation accumulated in month m
- $\Sigma\delta_{L,i}$ = sum deflections for loaded slab caused by axle loading
- $\Sigma\delta_{U,i}$ = sum deflections for unloaded slab caused by axle loading
- k = interlayer Totsky k value
- n_i = # of ESAL applications for month m

Nondimensional temp. gradient

- $$\Phi_m = \frac{2\alpha_{pcc}(1+\mu_{pcc})\ell_m^2}{h_{OL}^2}\frac{k}{\gamma} * \Delta T$$

Φ_m = nondimensional temp gradient for month m
h_{OL} = PCC thickness (in)
α_{pcc} = PCC CTE (in/in/°F)
μ_{pcc} = PCC Poisson's ratio
k = interlayer Totsky k value (psi/in)
ℓ_m = radius of relative stiffness for month m (in)
ΔT = temp difference (°F) = $EELTG * h_{OL}$-10 (Built-in temp difference)
$EELTG$ = Effective equivalent linear temperature gradient

$$\ell_m = \sqrt[4]{\frac{E_{pcc}(m) * H^3}{12(1-\mu^2) * k}}$$

$$E_{pcc}(m) = (1.0 + 0.12*\log_{10}(AGE/0.0767) - 0.01566*[\log_{10}(AGE/0.0767)]^2)* E_{pcc(28day)}$$

Normalized load/pavement weight ratios

$$q_i^* = \frac{P_i}{\gamma \quad * H}$$

q_i^*= adjusted load/pavement weight ratio

P_i = axle load (18000 lbs)

Initial joint stiffness parameters

- $\Delta S_{tot} = 0$=initial cum loss of agg. shear capacity
- $J_0 = \frac{38.20 * A_d}{h_{pcc}}$ = ini. nondimensional dowel stiffness
- $DOWDAM_0 = 0$ = Initial dam of dowel/PCC contact

- $J_d^* = \begin{Bmatrix} 118, if \frac{A_d}{h_{pcc}} > 0.835 \\ 52.52 \frac{A_d}{h_{pcc}} - 19.8, if 0.039 \leq \frac{A_d}{h_{pcc}} \leq 0.835 \\ 0.4, if \frac{A_d}{h_{pcc}} < 0.039 \end{Bmatrix}$ = Critical initial nondimensional dowel stiffness

- h_{pcc}=PCC slab thickness; $A_d = \frac{\pi d^2}{4}$=dowel area

Joint stiffness

$$JTWidth(m) = \max(12000 * c * JTSpace * (CTE * (T_c - T(m)) + \varepsilon_{sh}), 0)$$

$JTWidth(m)$ = Joint Width for month m (mils)

c = friction factor (0.65 for asphalt interlayers, 1.74 for fabric interlayer)

$JTSpace$ = Joint spacing in overlay (ft)

CTE = Overlay Coeff. of thermal Exp. (in/in/^{o}F)

T_c = concrete set temperature (^{o}F)

$T(m)$ = mean mid-depth overlay temp for month, m (^{o}F)

ε_{sh} = overlay shrinkage strain

Aggregate joint stiffness

- $S = 0.5 * h_{pcc} * e^{-0.032*jw} - \Delta S_{tot}$
- S = dimensionless aggregate joint shear capacity
- jw= joint opening in mils
- ΔS_{tot} = cumulative loss of shear capacity @ beginning of the current month

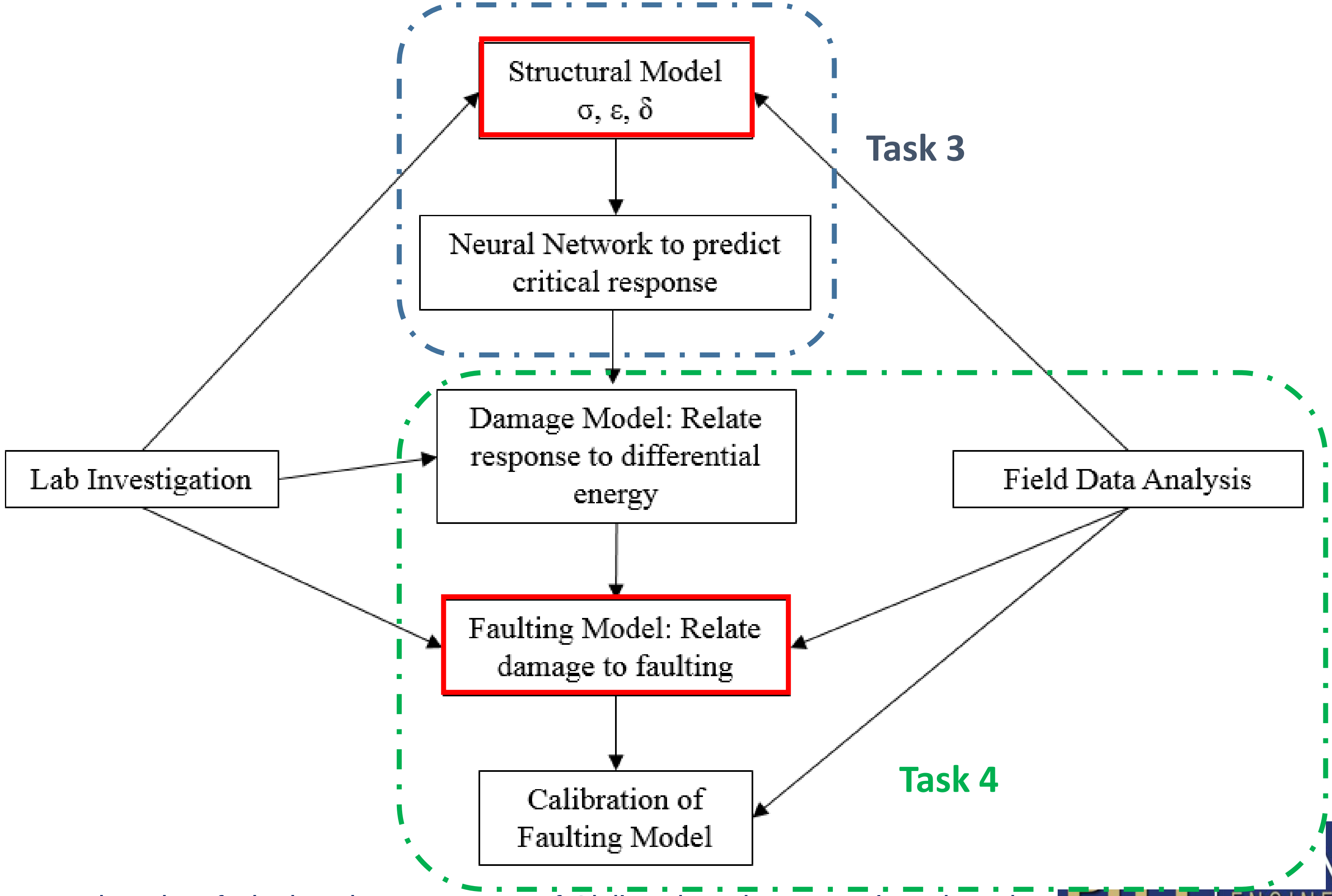
- Log(J_{AGG}) $= -28.4 * e^{-e^{-\left(\frac{S-e}{f}\right)}}$
- J_{AGG} = (Agg/kl) = joint stiffness of transverse jt for current increment
- e = 0.35
- f = 0.38
- S = joint shear capacity

Doweled joint stiffness

- $J_d = J_d^* + (J_0 - J_d^*)\exp(-\,DOWDAM)$

- J_d = nondimensional dowel stiffness
- J_0 = initial nondimensional dowel stiffness
- J_d^* = critical nondimensional dowel stiffness
- $DOWDAM$ = damage accumulated by doweled joint due to past traffic

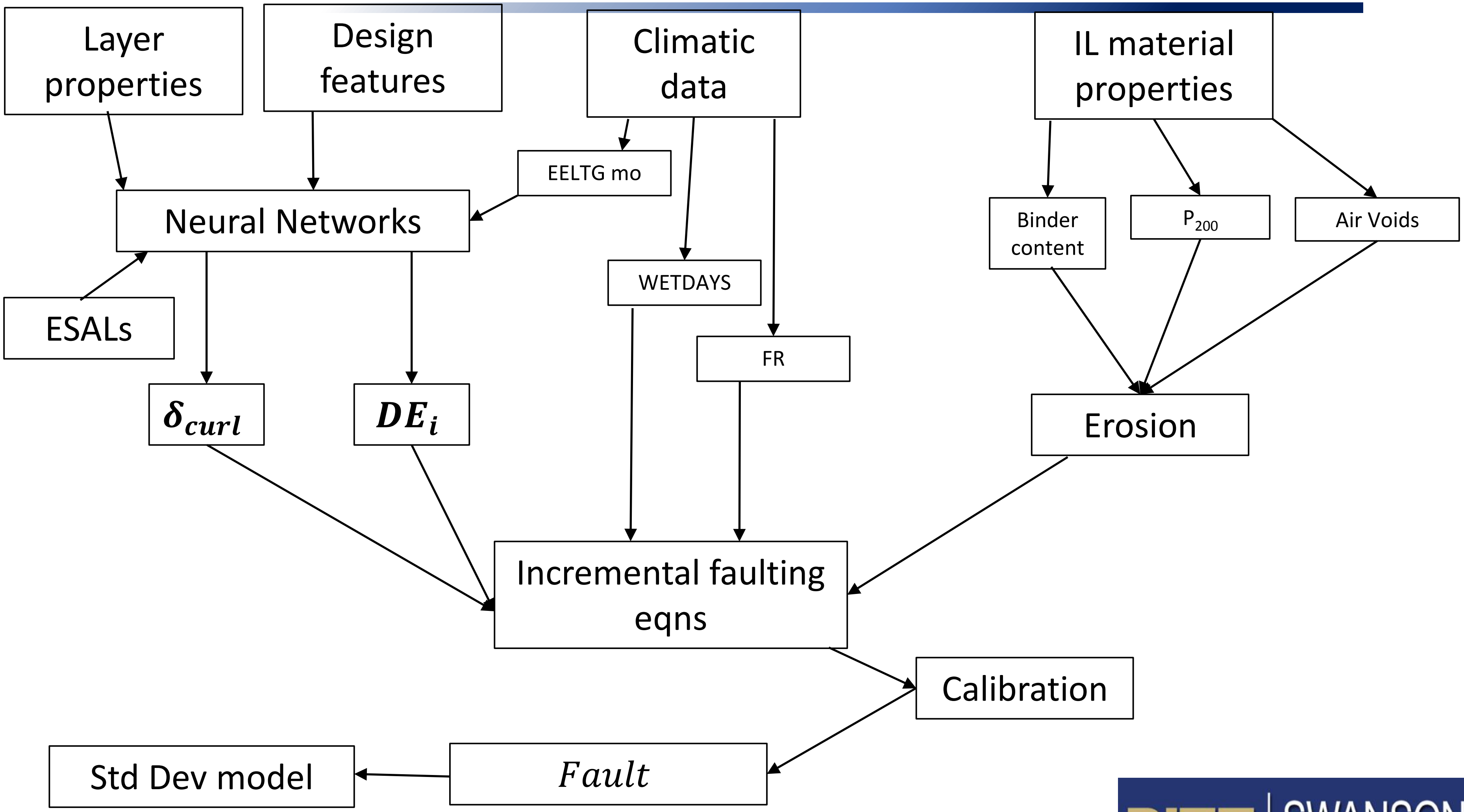
Faulting model framework



Faulting model development

- Modify Pavement ME series of equations to calculate incremental faulting
- Calibrate model with performance data
  - LTPP, MDOT, MnROAD
- Reliability/standard deviation model
  - Nonlinear regression using bins of predicted faulting

Faulting model framework



Climatic considerations

- EICM files used for each calibration section
- .tem file (hourly nodal temps through structure)
  - At one inch increments
  - Establish mean monthly mid depth overlay temperature
  - Establish hourly equivalent strain gradients
  - Temperature of interlayer used to establish Freezing Ratio (% time IL temp < 32^oF)
- .icm file (hourly air temp, precip, wind speed, %sunshine)
  - Establish WETDAYS and Mean Monthly Air Temp

Effective equivalent linear temperature gradients

- Assume 1 million ESALs applied through the course of a year, hourly distributed according to the percentages established in Pavement ME

- Establish monthly joint and overlay stiffness

- Determine monthly Differential Energy using hourly gradients

- Use fminsearch in MATLAB to determine a single temperature gradient which causes the same Differential Energy

Differential energy

$$DE_m = n_i k \left(\frac{\Sigma\delta_{L,i}^2}{2} - \frac{\Sigma\delta_{U,i}^2}{2}\right)$$

- DE_m=diff energy density deformation accumulated in month m
- $\Sigma\delta_{L,i}$ = sum deflections for loaded slab caused by axle loading
- $\Sigma\delta_{U,i}$ = sum deflections for unloaded slab caused by axle loading
- k = interlayer Totsky k value
- n_i = number of ESAL applications for month m

Faulting model

$$F_0 = \left(C_1 + C_2 * FR^{0.25}\right) * \delta_{curl} * [C_5 * E]^{C_6} * log(WETDAYS * P_{200})$$

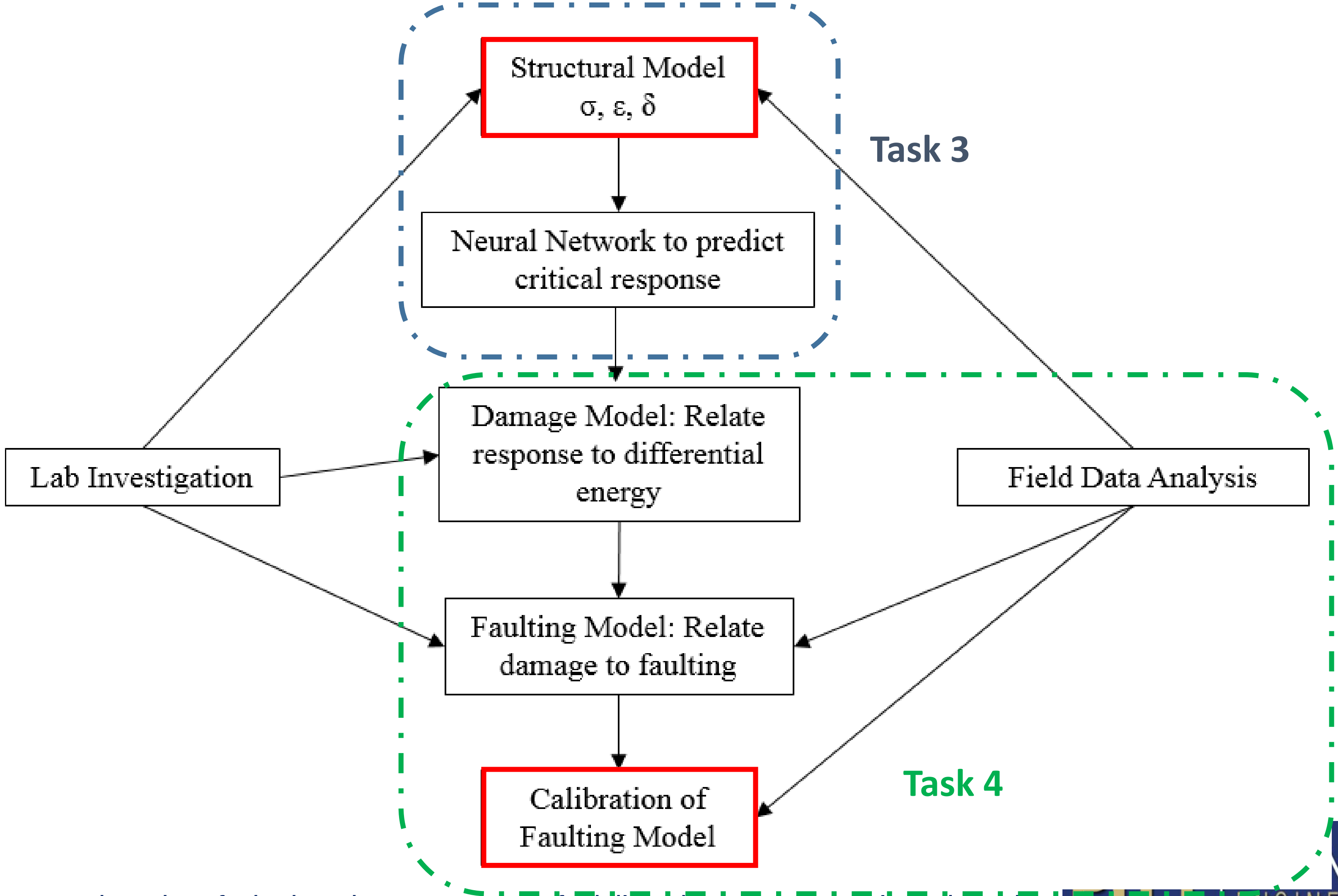
$$F_i = F_{i-1} + C_7 * C_8 * DE_i * [C_5 * E]^{C_6}$$

$$\Delta Fault_i = \left(C_3 + C_4 * FR^{0.25}\right) * (F_{i-1} - Fault_{i-1}) \quad * C_8 * DE_i$$

$$Fault_i = Fault_{i-1} + \Delta Fault_i$$

F_0 =initial maximum mean transverse joint faulting (in)
FR = base freezing index (% time that the top of the base is below freezing (<32ºF))
δ_{curl} = max mean monthly PCC upward slab deflection due to curling
E = erosion potential of interlayer: f(% binder content, % air voids, P_{200})
P_{200} = Percent of interlayer aggregate passing No. 200 sieve
WETDAYS = Average number of annual wet days (> 0.1 in of rainfall)
F_i =maximum mean transverse joint faulting for month i (in)
F_{i-1} = maximum mean transverse joint faulting for month i-1 (in)
DE_i = Differential energy density of accumulated during month i
$\Delta Fault_i$ = incremental monthly change in mean transverse joint faulting during month i (in)
C_1 ... C_8 = Calibration coefficients
$Fault_{i-1}$ = mean joint faulting at the beginning of month i (0 if i = 1)
$Fault_i$ = mean joint faulting at the end of month i (in)

Faulting model framework



Calibration

- Adjust calibration coeff. to minimize ERROR function
  - Shape of erosion function also fit based upon interlayer characteristics
- Macro driven excel spreadsheet was developed to calibrate the model
- Several calibration coeff. fixed
  - remaining coefficients varied to minimize error
  - switch coefficients being modified
- Bias of model must be considered in calibration coeff.

$$\mathrm{ERROR}(C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8) = \sum_{i=1}^{N} (\mathrm{FaultPredicted}_i - \mathrm{FaultMeasured}_i)^2$$

Calibration database

- 34 sections (9 different states, 1 Canadian)
  - 14 LTTP, 6 MnROAD, 14 MDOT
  - 163 data points
- 16 undoweled
- 2.5 – 33.5 yrs old (0.85 – 22.4 million ESALs)

Faulting model

$$F_0 = \left(C_1 + C_2 * FR^{0.25}\right) * \delta_{curl} * [C_5 * E]^{C_6} * log(WETDAYS * P_{200})$$

$$F_i = F_{i-1} + C_7 * C_8 * DE_i * [C_5 * E]^{C_6}$$

$$\Delta Fault_i = \left(C_3 + C_4 * FR^{0.25}\right) * (F_{i-1} - Fault_{i-1}) \quad * C_8 * DE_i$$

$$Fault_i = Fault_{i-1} + \Delta Fault_i$$

$C_1 = 8.3$

$C_2 = 0.9$

$C_3 = 2.3$

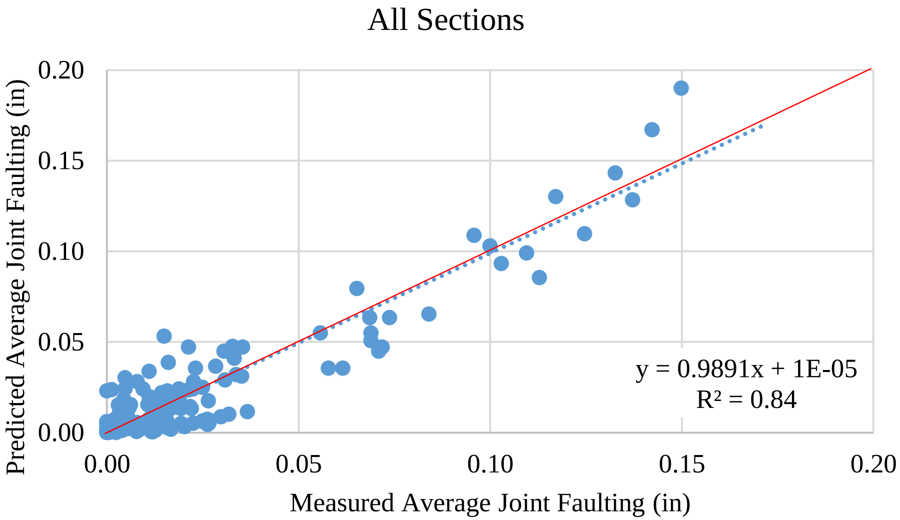
$C_4 = 0.001$

$C_5 = 0.17$

$C_6 = 4$

$C_7 = 4.4$

$C_8 = 0.0000036$



Erosion

$$\alpha = \log(1 + a * \%Binder + b * \%AV + c * P_{200})$$

α = Erodibility index

$\%Binder$ = Percent binder in asphalt interlayer

$\%AV$ = Percent air voids in asphalt interlayer

P_{200} = Percent passing No. 200 sieve in interlayer

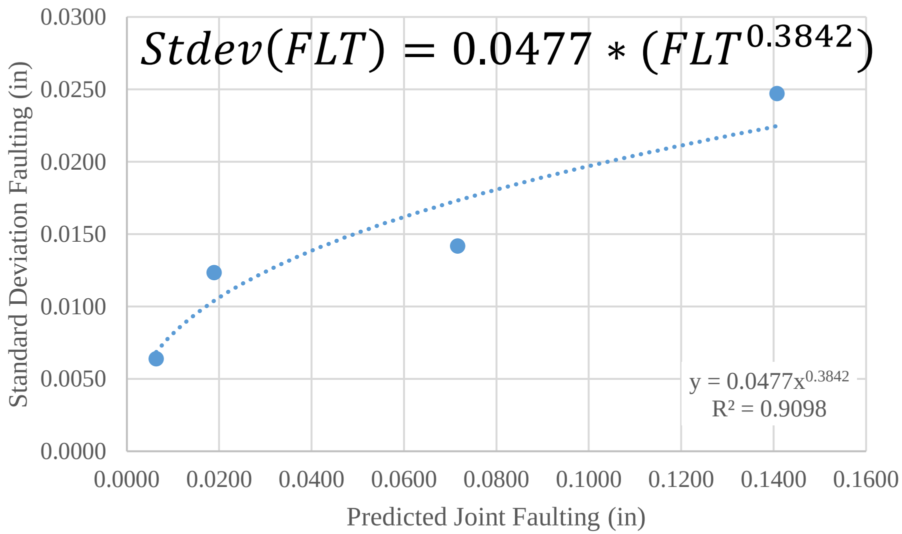
a, b, c = Calibration coefficients (0.196, 0.202, 0.00368)

$$E = \begin{cases} (1.1974 * \alpha^2 - 0.9933 * \alpha + 0.306) & \text{Undoweled pavements} \\ (1.0178 * \alpha^2 - 0.8443 * \alpha + 0.26) & \text{Doweled pavements} \\ (1.0178 * \alpha^2 - 0.8443 * \alpha + 0.1) & \text{NWGF sections} \end{cases}$$

Model adequacy checks and reliability

Hypothesis Testing and t-Test			
Test Type	Value	95% CI	P-value
Hypothesis 1: Intercept = 0	0.00001	-0.00194 to 0.00196	0.968
Hypothesis 2: Slope = 1	0.989	0.952 to 1.026	0.564
Paired t-test	-	-	0.801

$$Stdev(FLT) = 0.0477 * (FLT^{0.3842})$$

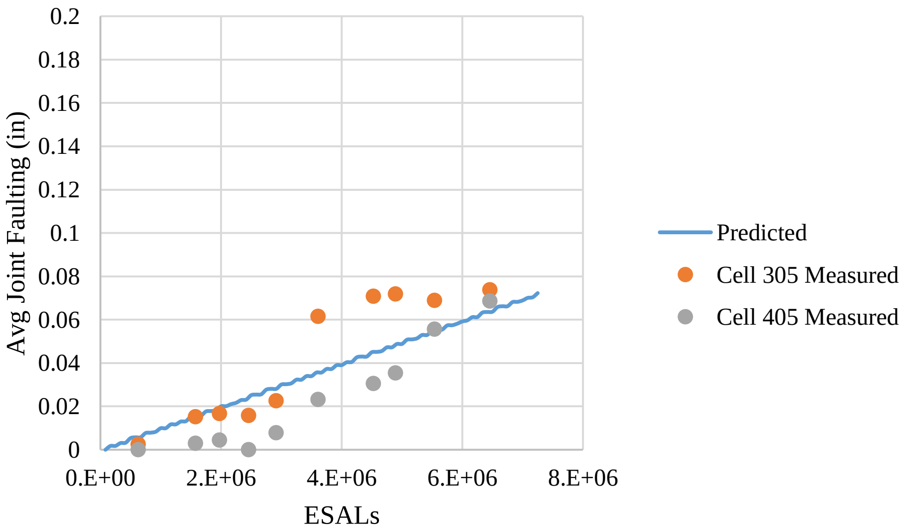


$$Fault(R) = Fault - Z_R * Stdev(FLT)$$

Reliability, R (%)	Std. Normal Deviate, Z_R
50	0
75	-0.674
90	-1.282
95	-1.645

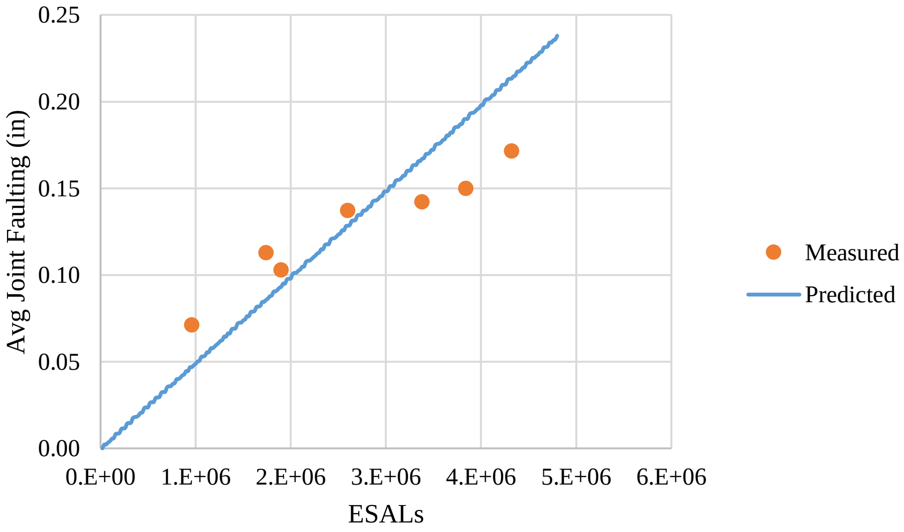
MnROAD Cells 305 & 405

- 5 in undoweled overlay
- Asphalt shoulder
- 15 ft joint spacing
- 1 in MNONU interlayer



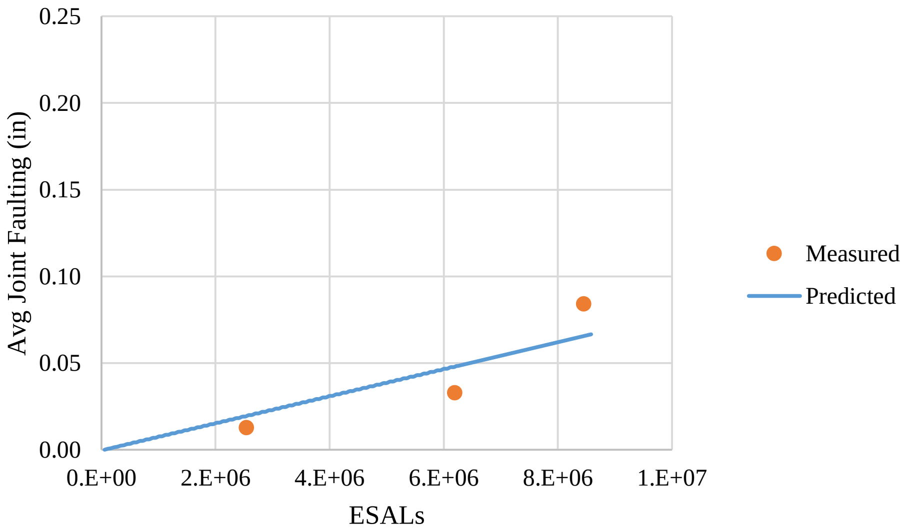
89-9018 Quebec

- 6 in undoweled overlay
- Asphalt shoulder
- 15 ft joint spacing
- Chip seal interlayer



6-9107

- 9 in undoweled
- Asphalt shoulder
- 12 ft joint spacing
- 1 in dense graded interlayer



Enhancements to be performed

- Expand 6x6 ft slab calibration to include asphalt interlayer
- Incorporate axle type and load spectra (currently just ESALs are used)
- Further refine erosion model
- Develop effective equivalent temperature gradient prediction equations (eliminates need to incorporate EICM directly into design tool)
- Transfer from MatLab into final design tool

Thank You

Any Questions?