University of Pittsburgh

TPF(5)-169: Development of an Improved Design Procedure for Unbonded Concrete Overlays

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Outline

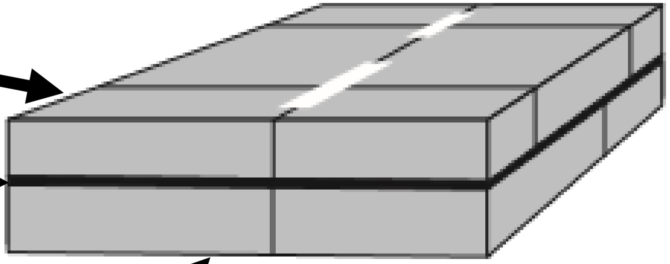
- A brief summary of the previous work
- Cracking modeling
- Rudimentary software
- Remaining work

Unbonded Overlays

Concrete overlay

Interlayer

Existing concrete pavement



Design Procedures

Design Factors	AASHTO	Corps of Engineers	Rollings	PCA	Minnesota	MEPDG
Analytical Model	Empirical equation: ($h^n = h^n - h_e^n$)	Empirical equation: ($h^n = h^n - h_e^n$)	Layered elastic theory	Plate theory/finite element model JSLAB	Corps of Engineers/PCA	Plate theory/finite element model ISLAB2000
Failure criteria	Deterioration in terms of serviceability loss	Cracking in 50% of slabs	Deterioration in terms of a structural condition index	Depends on failure criterion for full depth concrete design procedure	Not applicable	Transverse cracking and joint faulting
Interface condition	Considers overlay to be fully unbonded, n=2	Power in design equation is adjusted to account for level of bonding	Varies between full bonding and completely unbonded	Unbonded	Power in design equation is adjusted to account for level of bonding	Unbonded
Material properties	Modulus of elasticity and flexural strength for overlay concrete, k-value for subgrade	Equivalent required thickness, "h," as input to empirical equation	Modulus of elasticity and Poisson's ratio for all materials, and flexural strength of overlay concrete	Modulus of elasticity and modulus of rupture for overlay concrete, k-value for subgrade	Modulus of elasticity and modulus of rupture for overlay concrete, k-value for subgrade	Modulus of elasticity and Poisson's ratio for all materials, flexural strength coefficient of thermal expansion for overlay concrete

Design Procedures

Design Factors	AASHTO	Corps of Engineers	Rollings	PCA	Minnesota	MEPDG
Difference in strength/modulus of overlay and base pavement concrete	Not considered	Thickness of base pavement is adjusted	Included directly in calculation of stresses and design factors	Included directly in calculation of stresses and design factors	Not considered	Included directly in calculation of stresses and deflections
Cracking in base pavement before overlay	Effective thickness of base pavement is reduced	Effective thickness of base pavement is reduced	Modulus of elasticity of base pavement is reduced	Included directly in calculation of stresses using soft elements	Thickness of base pavement is reduced	PCC damage in the existing slab is considered through a reduction in its elastic modulus
Fatigue effects of traffic on uncracked base pavement	Effective thickness of base pavement is reduced	Effective thickness of base pavement is reduced	Included in terms of equivalent traffic	Not considered	Not considered	Not considered
Cracking of base after overlay	Not directly considered	Not directly considered	Modulus of elasticity of base is reduced to compensate for cracking under traffic	Not considered	Not considered	
Temperature curling or moisture warping	Assumes AASHTO Road Test conditions	Not considered	Not considered	Does not affect thickness selection	Not considered	Included directly in calculation of stresses and deflections
Joint spacing	Maximum joint spacing 1.75*hOL (JPCP)	No recommendation provided	No recommendation provided	Maximum joint spacing in feet is 1.75*h_OL(in) (JPCP)	15 ft if 7 in < hOL < 10.5 in; 20 ft if hOL > 10.5 in	Included directly in calculation of stresses and deflections

Design Procedures

Design Factors	AASHTO	Corps of Engineers	Rollings	PCA	Minnesota	MEPDG
Joint load transfer	Thickness increased if not doweled	Dowels assumed	Not considered	Not specified for overlay but considered in evaluation of base pavement	Dowels assumed	Included directly in calculation of deflections
Drainage	Included in thickness design by empirical coefficient	Not considered	Requires retrofit of drainage system (if necessary)	Edge drains are recommended where pumping and erosion has occurred in the existing slab.	Edge drains and permeable interlayer for all pavements, interceptor drains when overlay is wider than the base pavement.	Requires retrofit of drainage system (if necessary)
Interlayer	Recommends 1-in min. thick AC interlayer or permeable open-graded interlayer	No recommendation provided	No recommendation provided	Thin interlayer (<0.5 in) if extensive repair work performed. Thick (>0.5 in) otherwise.	>1 in >2 in if base pavement is badly faulted and/or has a rough profile	1-2 in

Interlayer

- Separates horizontal movements of the overlay and existing pavement
- Provides uniform support to the overlay
- May provide additional drainage

- Many overlay failures are attributed to poor performance of the interlayer
- Design recommendations (if any) are prescriptive
- The use of non-woven fabric interlayers has been recently proposed

TPF-5(269) Development of an Improved Design Procedure for Unbonded Concrete Overlays

Original Project

- University of Minnesota (PI: Lev Khazanovich)
- University of Pittsburgh (co-PI: Julie Vandenbossche)
- Dr. Mark Snyder (consultant)

Since November 2017

- University of Pittsburgh (Lev Khazanovich and Julie Vandenbossche)
- Dr. Mark Snyder (consultant)

TPF-5(269)

- Field studies
- Lab testing
- Analytical modeling
- Performance modeling

Field studies: lessons learned

Factors affecting interlayer performance

- Erodibility – Stripping of interlayer adjacent to joints leads to interlayer erosion.
- Strength/stiffness – There is a potential for consolidation or crushing of interlayer adjacent to transverse joint if strength or stiffness are inadequate.
- Permeability – Drainage within interlayer reduces pressure build-up.

US 23 in MI (courtesy of Andy Bennett)

MnROAD Cell 305

Lab Study

Mechanisms Investigated:

1. Ability to prevent reflective cracking
2. Stiffness of interlayer
3. Friction along interlayer system
4. Vertical resistance to uplift – pull off

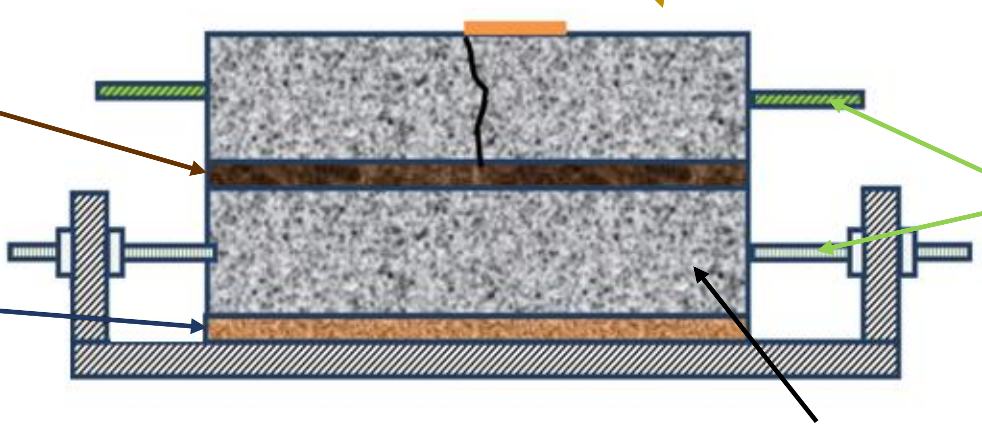
Specimen setup

Overlay Concrete

- Conventional Paving Mix
- Target flexural strength = 650 psi

Interlayer

- Geotextile fabric
- Open & Dense HMA



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)

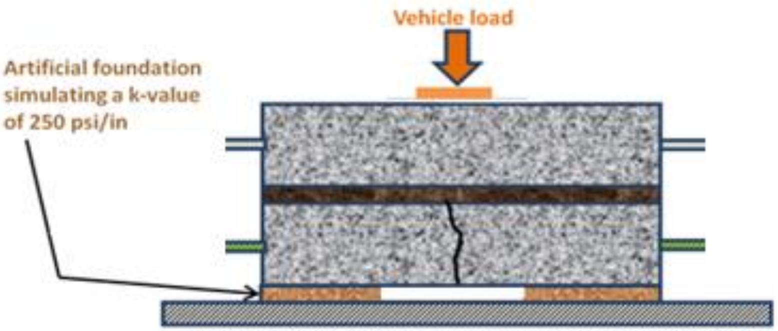
Interlayers

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

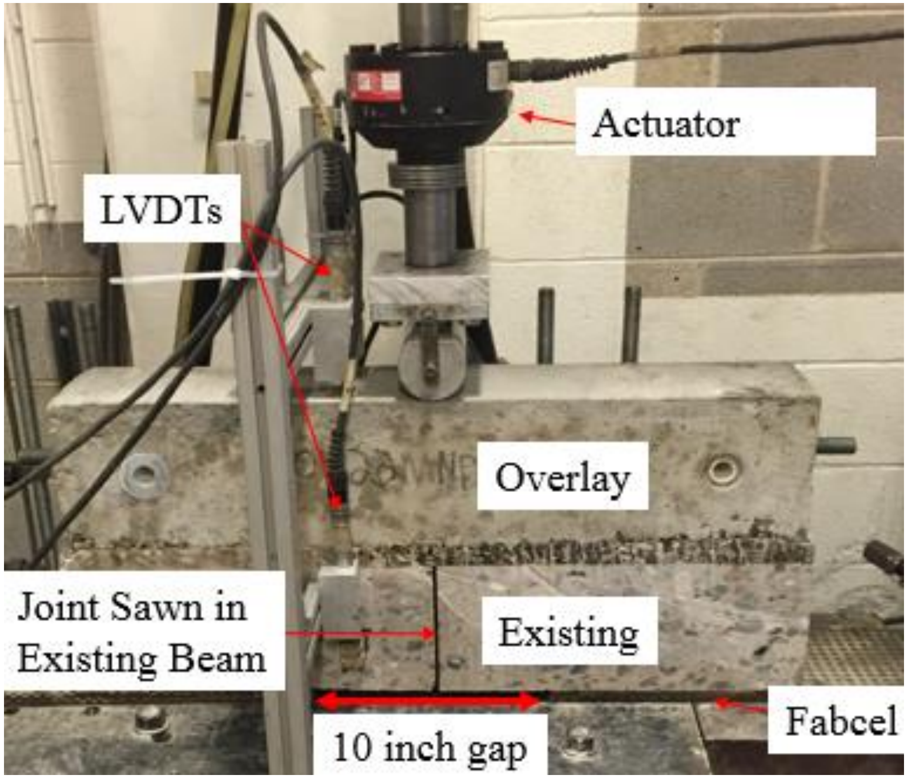
Propex Reflectex - 15 oz/yd^2 fabric = F15
Propex Geotex 1001N – 10 oz/yd^2 fabric = F10

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 non-uniform support conditions exist
- Fabric tends to increase resistance to reflective cracking when compared to HMA

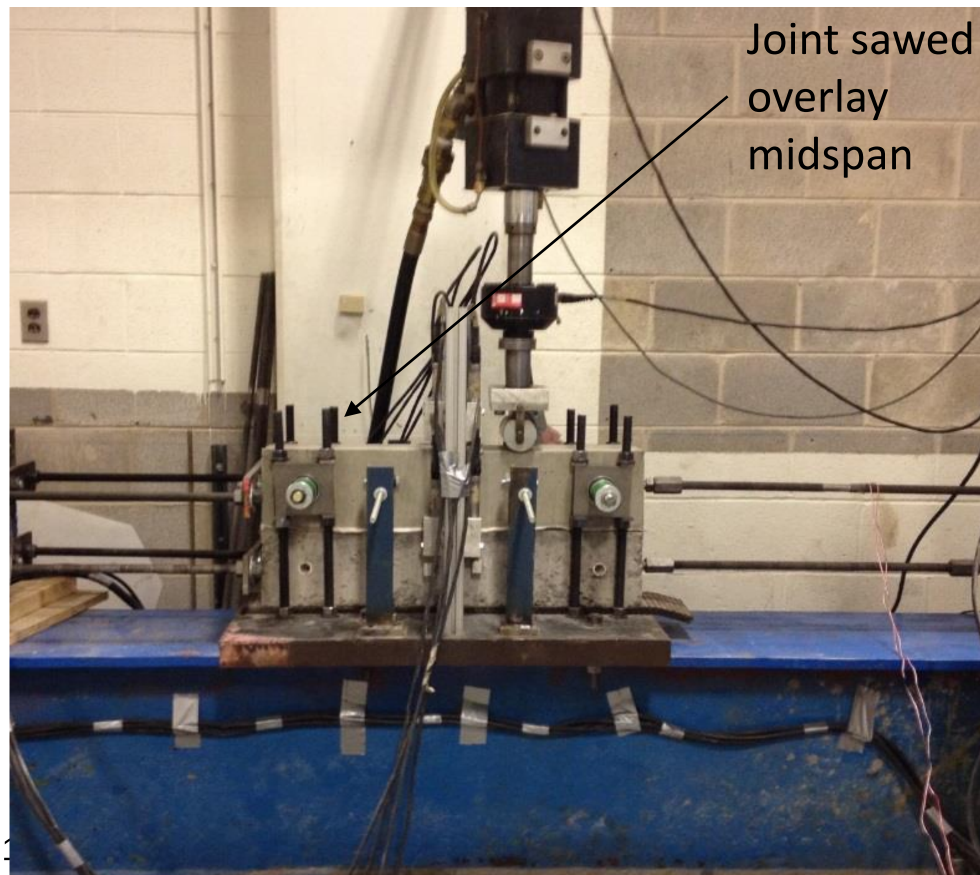
Interlayer Resilience

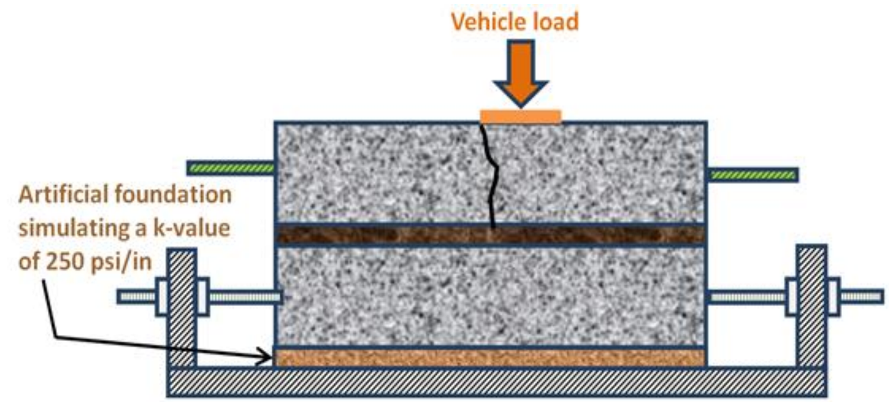
Reduced stiffness

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

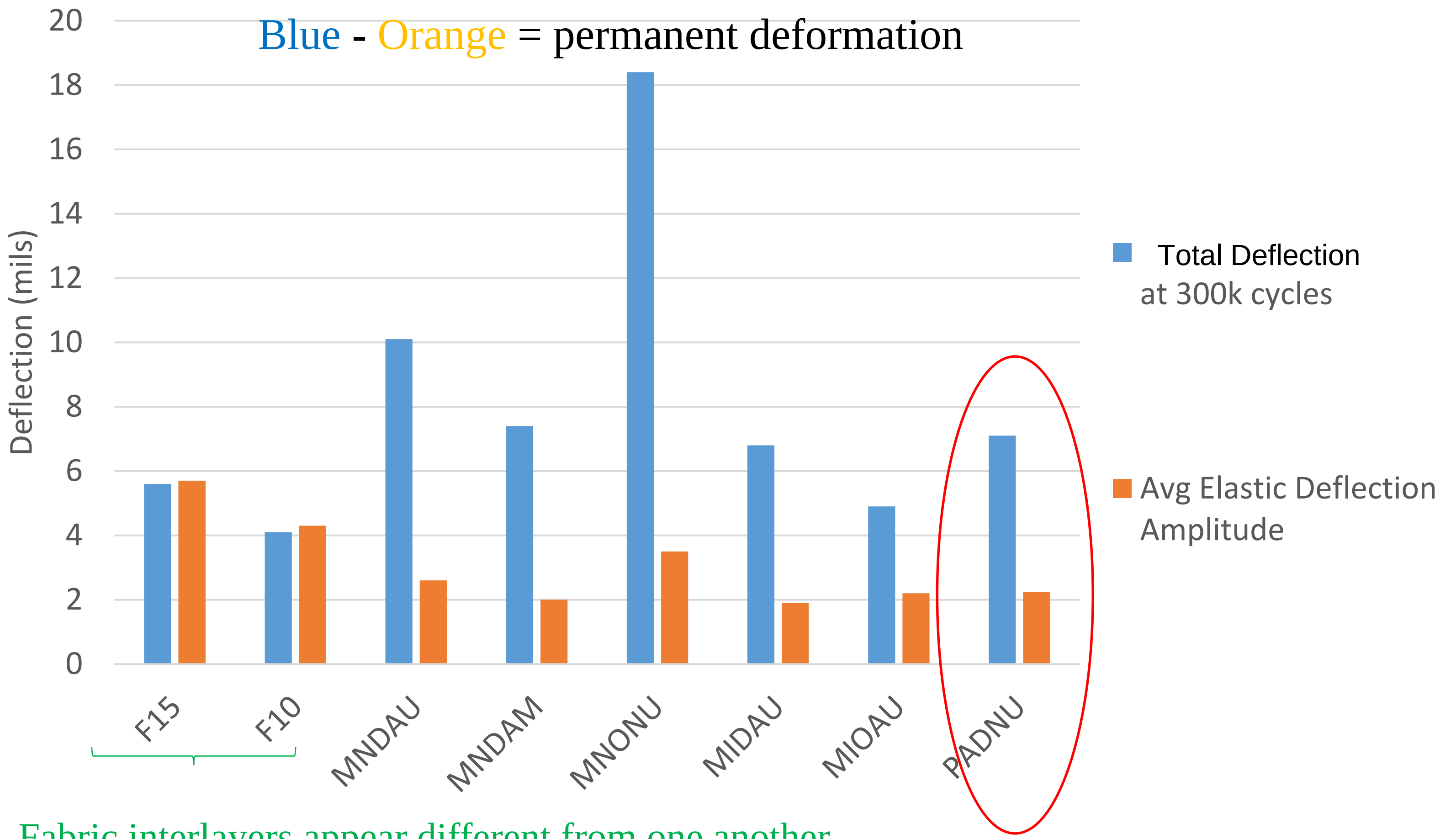
Properties Monitored

- Max deflections
- Differential deflections
- LTE



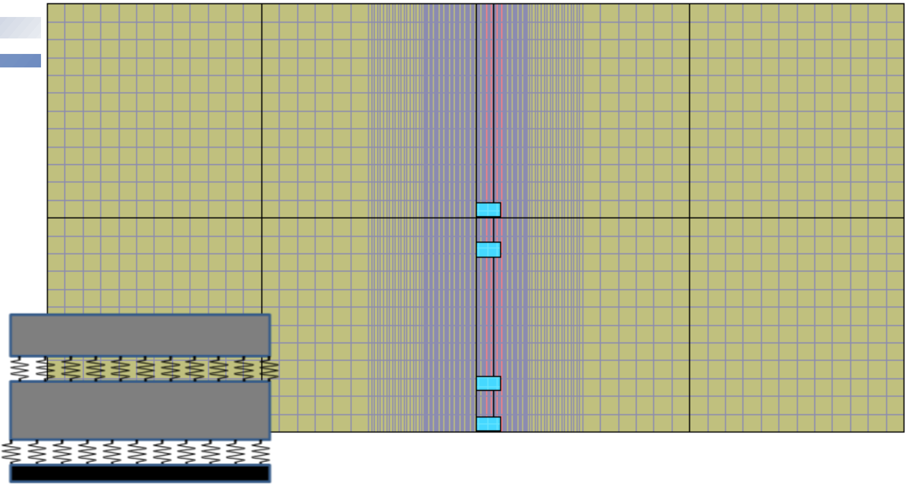


Elastic Deflection and Permanent Deformation



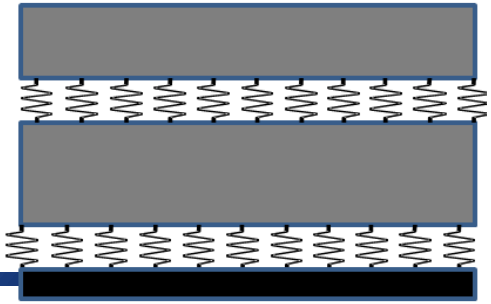
- Fabric interlayers appear different from one another
- Elastic responses of the fabric are different from all asphalt interlayers
- MN open graded asphalt appears different from other asphalts

Totski Model



- Model accounts for
  - overlay
  - existing slab
  - subgrade support
  - "cushioning" property of the interlayer using Totski springs layer
- Joints in the overlay do not necessarily match joints in the existing pavements
- Unlike AASHTO M-E, the structural model does not convert the existing pavement and overlay into a single-layer system

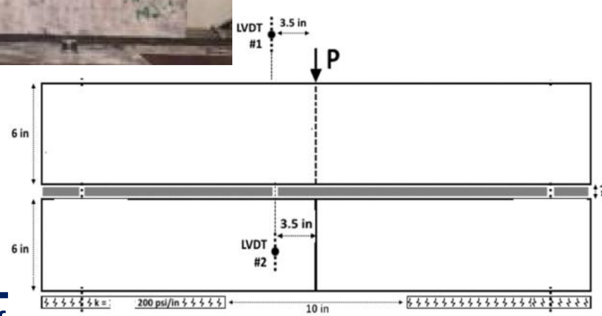
Totski Model

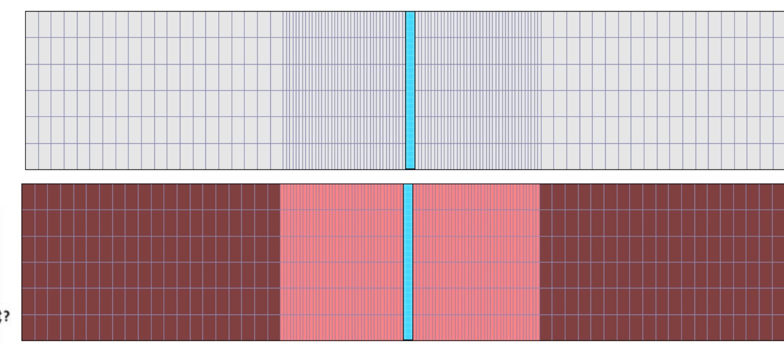


- Advantages of Totski approach:
  - Computationally efficient (big concern for finite element models)
  - Already incorporated into ISLAB2005
  - Can be adopted for more sophisticated models (e.g., 3D joint faulting) without issue
  - Modeling of gaps between the overlay and existing pavement
- Requires estimate of interlayer spring coefficient

Modeling reflective cracking beam behavior and interlayer response

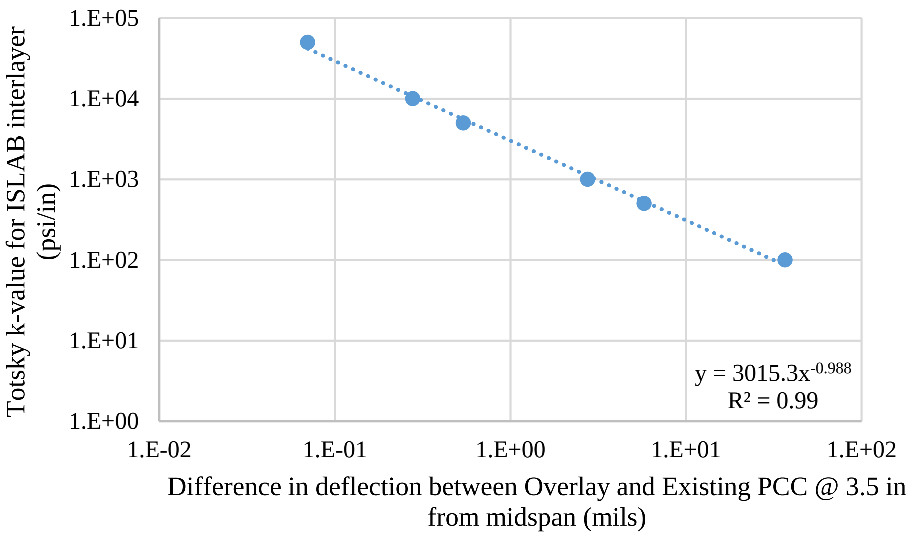
- 2D finite element simulation of reflective cracking beams using ISLAB2005
- Factorial of simulations created for exact beam dimensions and support conditions
  - Interlayer coefficient varied from 10 to 50,000





Totski Interlayer k-value

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



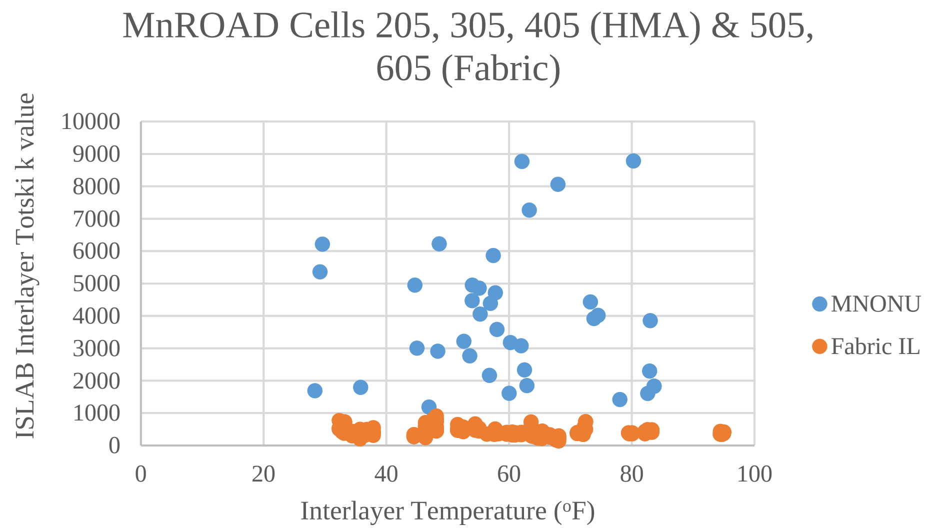
Totski Interlayer k-value

Interlayer Type	Average Totski 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

- Average lab and FWD for asphalt yields Totski k-value of approximately 3500 psi/in
- Average lab and FWD results is 425 psi/in for nonwoven geotextile fabric interlayer

Totski Interlayer k-value Backcalculation

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



Comparison between means of established Totski k-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

Performance Modeling

- AASHTOWare Pavement ME
  - Transverse cracking model
  - Faulting model (subgrade erosion)

  Interlayer properties are ignored!

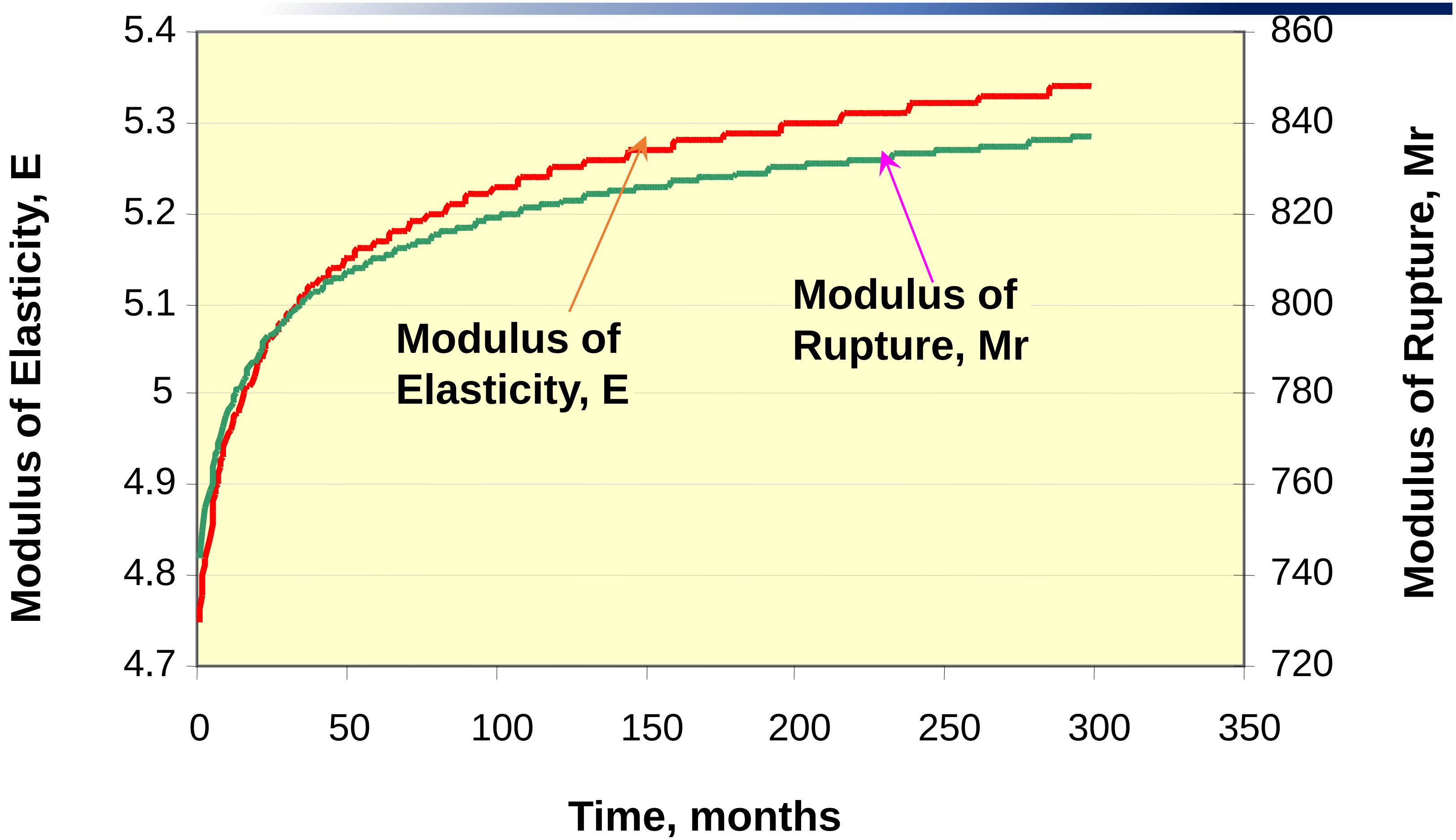
- This study
  - Cracking modeling
    - Transverse cracking model
    - Transverse joint damage model (corner/longitudinal cracking)
  - Faulting model

  Interlayer stiffness and degradation are accounted for!

Cracking Model

- PavementME (MEPDG) framework:
  - Effect of PCC age on concrete strength and stiffness
  - Axle load spectrum
  - Curling analysis
  - Effect of built-in curling
  - Incremental damage analysis
- Significant modifications

PCC Strength Gain



Uses MEPDG Level 3 curves

Traffic Analysis

- MEPDG default axle spectrum distribution
- AADTT for the first year
- Linear traffic volume growth model

Curling Analysis

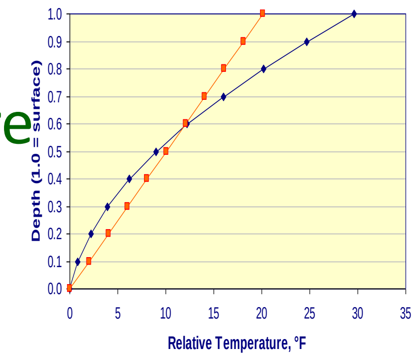
- EICM is used to predict hourly temperature profile through PCC based on historical hourly climatic data
- Both daytime (positive) and nighttime (negative) thermal gradient probability distributions are obtained

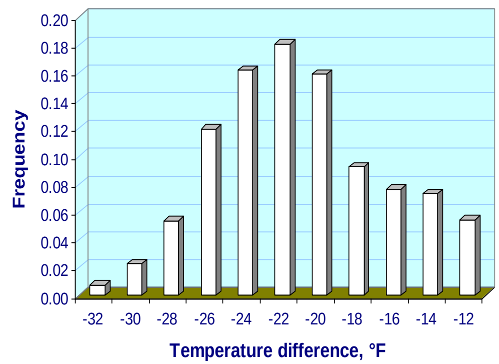
Curling Analysis

- Temperature distribution that distorts PCC slabs is characterized in terms of **equivalent temperature gradient affecting bending analysis**
- Nonlinear temperature component is accounted for analytically

Curling Analysis

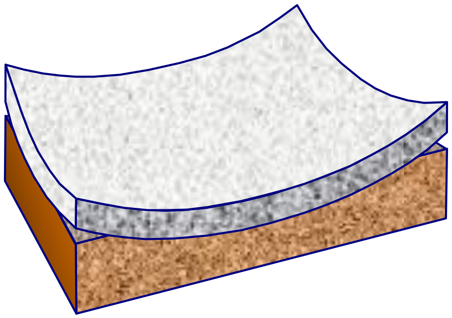
Actual Temperature Gradient





Frequency distribution of linearized hourly temperature gradients

Built-in Curling



$$TG_{BuiltIn} = f\left(Design \,\&\, Site\ Factors\right)$$

Empirical relationship based on calibration results

Incremental Damage Analysis

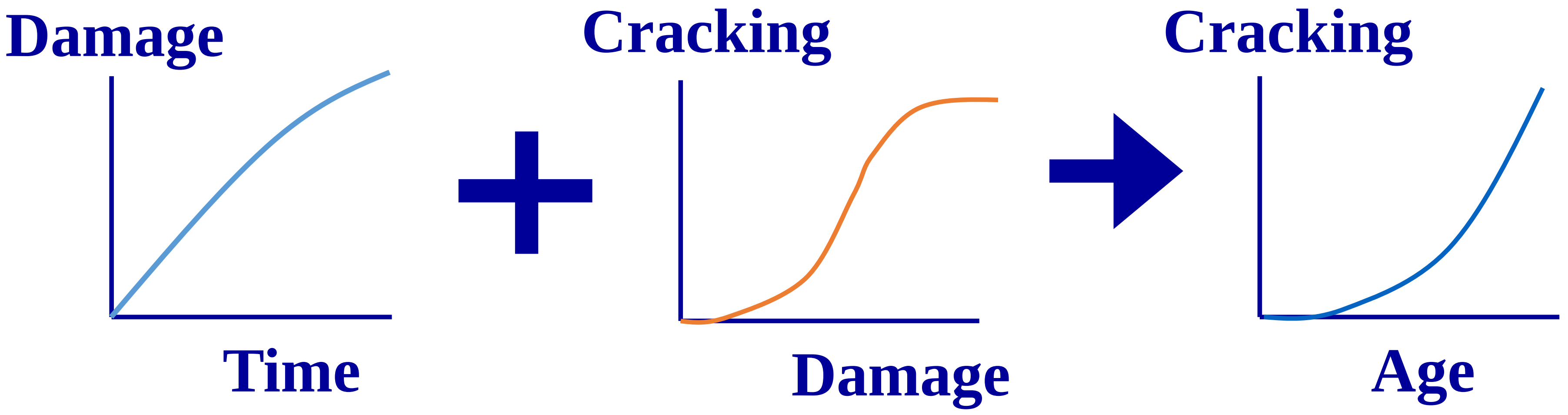
$$Fatigue\ Damage = \sum_i \sum_j \sum_k \sum_l \sum_m \sum_n \frac{n_{ijklmn}}{N_{ijklmn}}$$

$$Log(N) = 2.0 * \left(\frac{M_r}{\sigma_{total}} \right)^{1.22} + 0.4371$$

n_{ijklmn} = Applied number of load applications at condition i,j,k,…
N_{ijklmn} = Allowable number of load applications at condition i,j,k,…

i = Age ; k = Axle combination; j nonlinear temperature gradient
l = Load level; m = Temperature gradient; n = Traffic path

Cracking Prediction



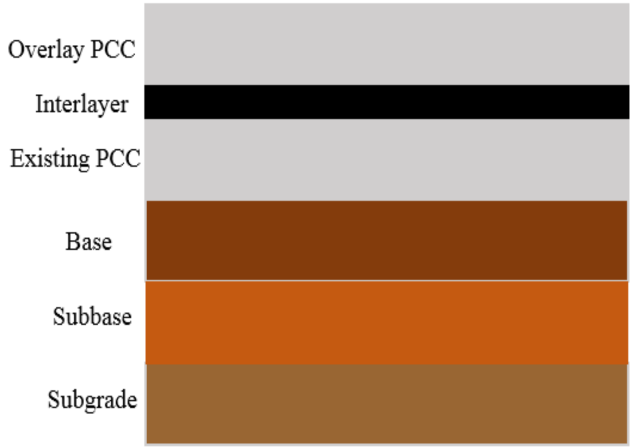
AASHTOWare **Pavement ME (MEPDG)**

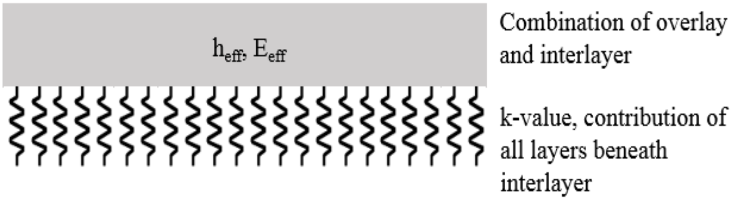
- Adapted MEPDG performance prediction models for new pavements
- Empirical stiffness reduction factors for distresses in the existing pavement

$$E_{BASE/DESIGN} = C_{BD} \times E_{TEST}$$

MEPDG Unbonded Overlay Cracking Model

- Modeled as newly constructed JPCP





- Joints in the overlay match joints in the existing slab
- Existing pavement is considered a base of the overlay
- Deflection basins of the overlay and the existing pavements are the same
- Interlayer deterioration is ignored

TPF(5)-169 Cracking Model

- Toski model for structural responses
  - Independent curling of the overlay and existing pavement
  - Composite bending behavior
  - Mismatched joints in the overlay and existing pavements
- Modified temperature frequency analysis
- Interlayer deterioration

TPF(5)-169 Cracking Model

- Modified built-in curling analysis (NCHRP 1-51 approach)
- Longitudinal edge and transverse cracking analysis
- Monte Carlo-based reliability analysis (MnPAVE Rigid-based approach)

Curling Analysis

- EICM used to predict hourly temperature profile through PCC based on historical hourly climatic data
- For each hour, the temperature distribution is approximated using quadratic distribution

$$T(z) = A + B z + C z^2$$

Curling Analysis

- Linear gradient and non-linear stresses at the surfaces are determined (Choubane and Tia 1992, Khazanovich 1994)

$$T_L(z) = T_0 + B\,z \qquad \Delta T_L \quad B\,h$$

$$\sigma_{Nxx}(z) = \sigma_{Nyy}(z) = \frac{C\,E}{1-\mu}\,\alpha\left[\frac{h^3}{12} - z^2\right]$$

- Frequencies of combinations of B and C are determined (Hiller and Roesler 2010)

Frequency Table

C

ΔT_L

	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
-24.8994	0	0	0.00117	0.00223	0	0	0	0	0	0
-23.0144	0	0.00106	0.00493	0.01397	0.00023	0	0	0	0	0
-21.1352	0	0.00376	0.01725	0.0493	0.00141	0	0	0	0	0
-19.2559	0.00141	0.0061	0.01878	0.08462	0.00622	0	0	0	0	0
-17.371	0.00282	0.00681	0.01526	0.07418	0.01514	0.00399	0	0	0	0
-15.4917	0.00106	0.00634	0.01291	0.05692	0.0311	0.00481	0.00258	0	0	0
-13.6124	0.00129	0.00552	0.00939	0.03263	0.03474	0.0061	0.00587	0	0	0
-11.7275	0.00117	0.00552	0.00669	0.01068	0.00657	0.00599	0.00692	0	0	0
-9.8482	0	0.00329	0.00599	0.00646	0.0027	0.00716	0.00646	0.00305	0	0
-7.9689	0	0.00211	0.00692	0.00681	0.00493	0.00669	0.00458	0.00552	0	0
-6.084	0	0.00117	0.00469	0.00751	0.00716	0.00634	0.00317	0.0088	0	0
-4.2047	0	0	0.0054	0.00704	0.00505	0.0054	0.0027	0.00892	0.00176	0
-2.3255	0	0	0.00305	0.00857	0.00505	0.00458	0.00282	0.00599	0.00376	0
-0.4405	0	0	0	0.00751	0.00493	0.00411	0.00399	0.00552	0.00411	0
1.4387	0	0	0	0.00516	0.00786	0.00481	0.00282	0.00657	0.00552	0.00106
3.318	0	0	0	0.00246	0.00634	0.00587	0.00364	0.00751	0.00775	0
5.2029	0	0	0	0	0.0061	0.00704	0.00657	0.00716	0.00528	0
7.0822	0	0	0	0	0.00364	0.00516	0.00869	0.00845	0.0054	0.00188
8.9615	0	0	0	0	0.00094	0.00481	0.00493	0.00505	0.00563	0.00141
10.8464	0	0	0	0	0.00047	0.00235	0.00634	0.00681	0.00399	0.00211
12.7257	0	0	0	0	0	0.00188	0.00246	0.00376	0.00293	0.00141
14.605	0	0	0	0	0.00023	0	0.00176	0.00293	0.00235	0
16.4899	0	0	0	0	0.00059	0	0	0.00117	0.00188	0
18.3692	0	0	0	0	0.00059	0	0	0	0.00129	0

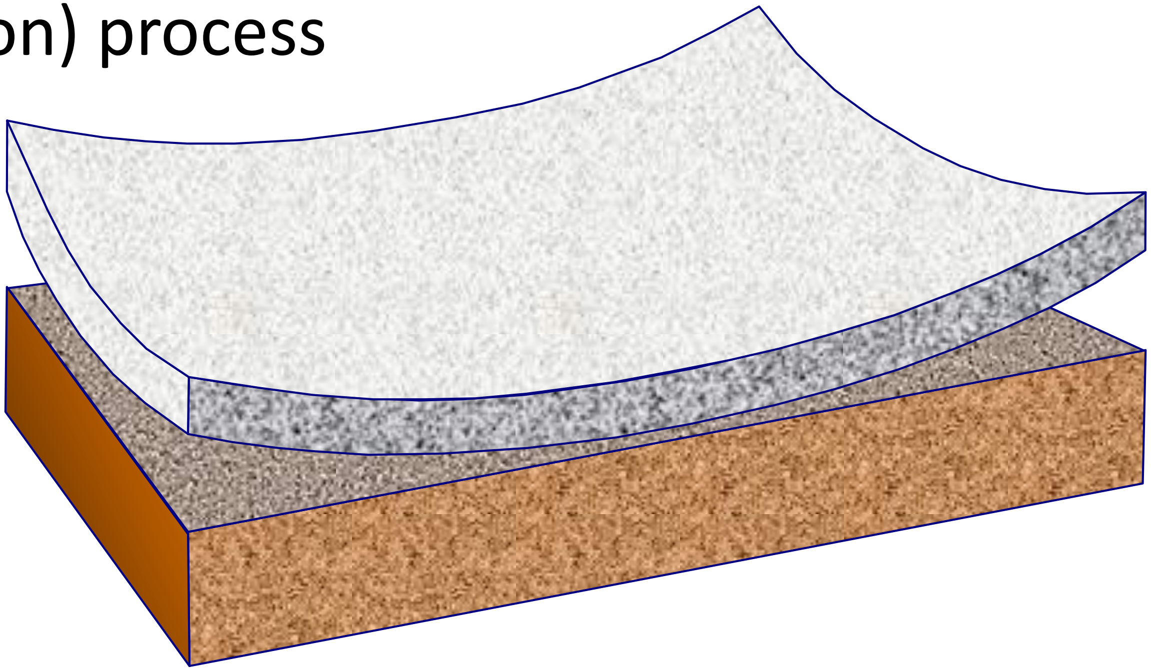
*Adjusted for built-in curling

EICM Analysis

- 70 weather stations
- Overlay thickness 4, 6, 8, and 10 in
- Frequency tables generated for each case
- Interpolation for other thicknesses

Permanent (Built-in) Curling

- Due to irreversible shrinkage
- Due to temperature gradient during concrete solidification (hydration) process



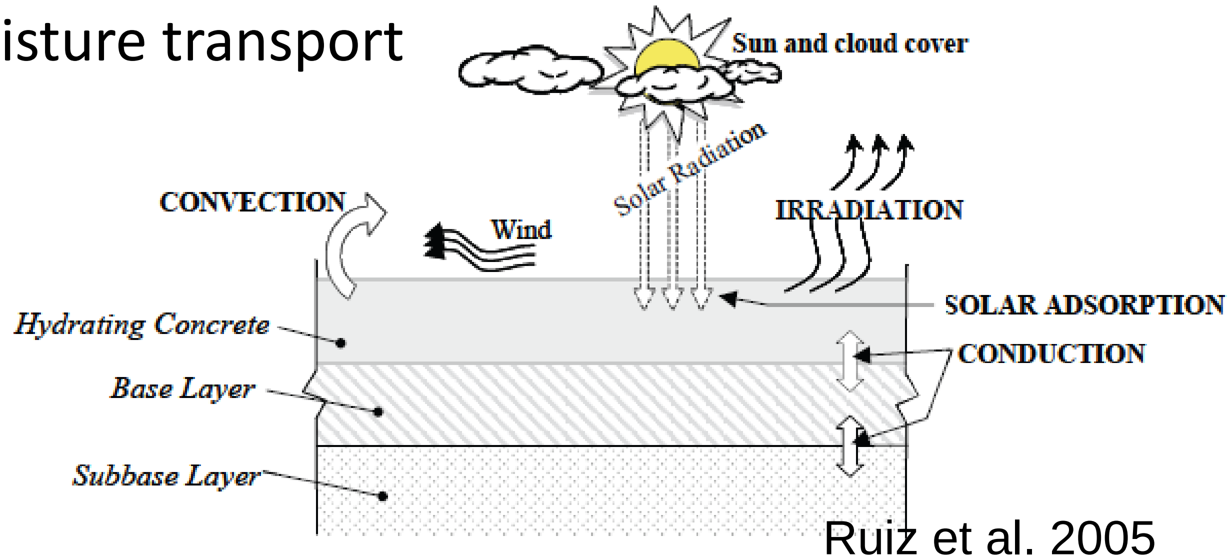
(Eisenmann and Leykauf, 1994; *Yu, Khazanovich, Darter, and* Ardani 1998; Yu and Khazanovich 20
Vandenbossche 2006)

Permanent (Built-in) Curling

Permanent (Built-in) Curling

To accurately model built-in curling, first several days of concrete pavement should be simulated precisely

- Cement hydration process
- Ambient temperature and humidity, solar radiation, and wind
- Heat transfer & moisture transport
- Concrete creep
- Concrete shrinkage
- Concrete fracture (joint formation)



Ruiz et al. 2005

Permanent (Built-in) Curling

- PavementME

$$\Delta T_{Built-in} = -10\ ^{o}F$$

- NCHRP 1-51 (Khazanovich and Tompkins 2017)

$$\Delta T_{Built-in} = -10\ ^{o}F \pm A$$

where A depends on the ratio between the PCC slab and base stiffnesses

Permanent (Built-in) Curling

- TPF(5)-169

$$\Delta T_{Built-in} = -10\ {}^{o}F \pm A$$

where A depends on the interlayer stiffness and joint spacing

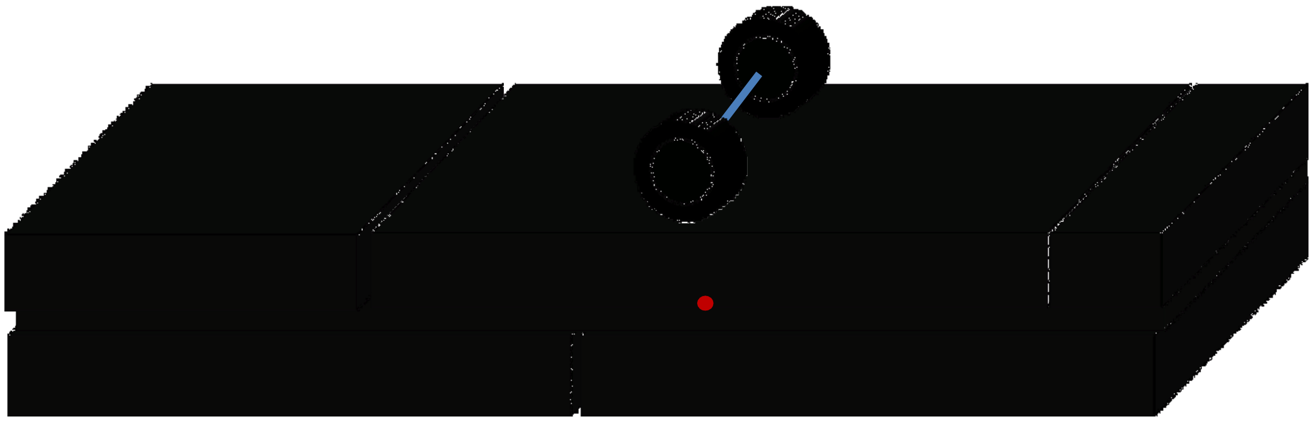
- $\Delta T_{Built-in} = -10\ {}^{o}F + A$ is used for daytime curling analysis
- $\Delta T_{Built-in} = -10\ {}^{o}F - A$ is used for nighttime curling analysis

Stress Analysis

- Several factorials of ISLAB2000 Totski model runs (more than 50,000 cases)
- Several NNs for top-down cracking and joint damage analysis
  - w/o voids in the interlayer
  - with voids in the interlayer
- NCHRP 1-37A NNs for longitudinal edge loading analysis
- Westergaard solution for daytime curling analysis

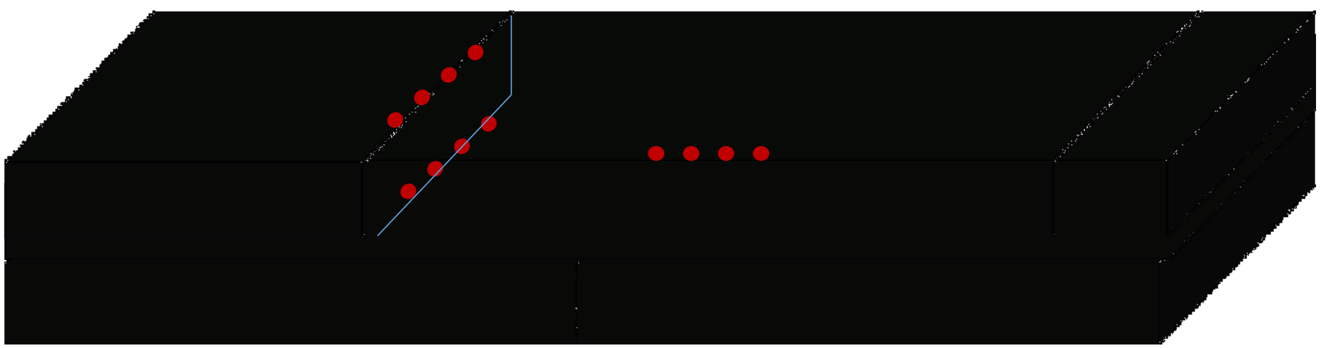
Stress Analysis

Bottom-up transverse cracking



Stress Analysis

Top-down and joint damage



NNs for Top-down and Joint Damage Analysis

- Overlay radius of relative stiffness
- Axle weight/overlay weight ratio
- Axle spacing
- Transverse joint LTE
- Korenev’s non-dimensional temperature gradient
- Overlay/shoulder LTE
- Void/no void

Similarity Concept

Two overlay structures are *similar* if

$$L_1 = L_2$$

$$\ell_1 = \ell_2$$

$$\frac{AGG_{x,1}}{k_{Tot,1}\ell_1} = \frac{AGG_{x,2}}{k_{Tot,2}\ell_2}$$

$$\frac{AGG_{y,1}}{k_{Tot,1}\ell_1} = \frac{AGG_{y,2}}{k_{Tot,2}\ell_2}$$

$$\frac{P_1}{h_1\gamma_1} = \frac{P_2}{h_2\gamma_2}$$

$$\varphi_1 = \varphi_2$$

γ = unit weight

Korenev's (1962) nondimensional temperature gradient

$$\sigma_2 = \frac{h_1\gamma_2\ell_2^{\,2}}{h_2\gamma_1\ell_1^{\,2}}\sigma_1 + \Delta\sigma_{NLT}$$

$$\varphi = \frac{2\alpha(1+\mu)\ell^2}{h^2}\frac{k}{\gamma}\Delta T$$

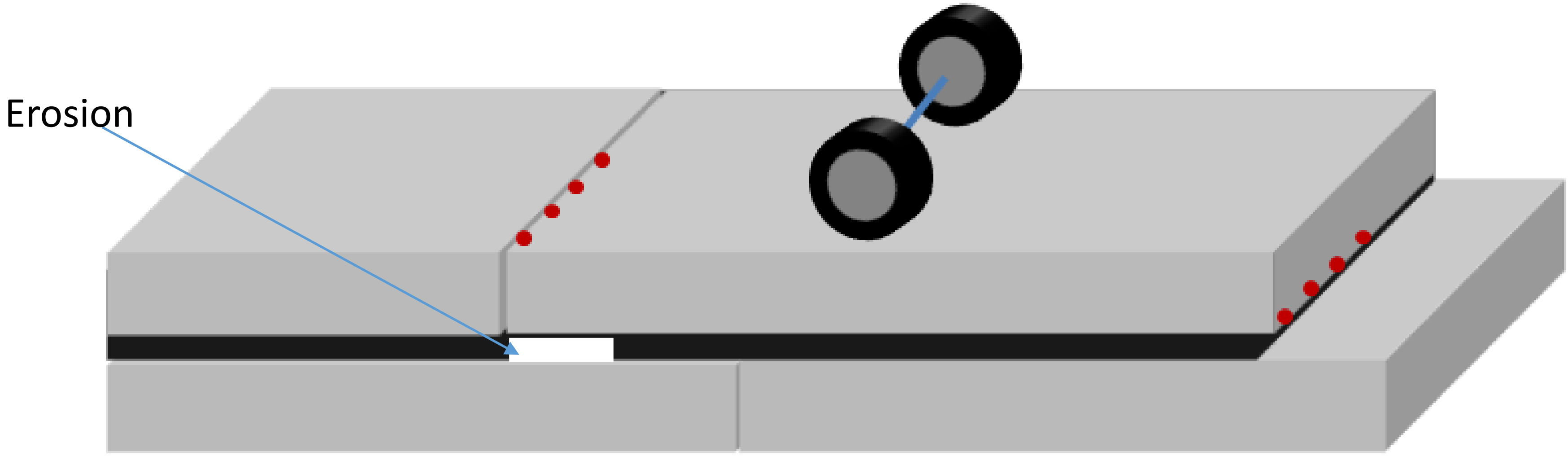
Incremental Damage Calculation

- Increment: 1 year
- Frequencies for linear and non-linear temperature gradients
- Stress and damage computations with and w/o void

$$Fatigue\ Damage = \sum_i \sum_j \sum_k \sum_l \sum_m \sum_n \frac{n_{ijklmn}}{N_{ijklmn}} \qquad Log(N) = 2.0 * \left(\frac{M_r}{\sigma_{total}}\right)^{1.22} + 0.4371$$

- Four types of fatigue damage
  - Longitudinal edge, bottom overlay surface (transverse bottom-up cracking)
  - Longitudinal edge, top overlay surface (transverse bottom-up cracking)
  - Transverse joint, top overlay surface (longitudinal/corner cracking)
  - Transvers joint, bottom overlay surface (longitudinal cracking)

Effect of Interlay Erosion



2 cases

- No void
- 24-in long, lane-wide void

Incremental Damage Calculation

- Damage computation for the increment

$$DAM_i = (1 - \Lambda_i)\, DAM_{i,w/o\ void} + \Lambda_i DAM_{i,w\ void}$$

Λ_i: interlayer deterioration index for the increment i.

Depends on the interlayer age and properties

Cracking Analysis

$$\%\ of\ Cracked\ Slabs = \frac{100\%}{1 + C_3\ DAM^{C_4}}$$

- Step 1
  - Top-down transverse cracking
  - Bottom-up transverse cracking
  - Top-down longitudinal cracking
  - Bottom-up longitudinal cracking

Cracking Analysis

- Step 2
  - Transverse cracking

$$TRCRACK = (TCRK_{\text{Bottom\_up}} + TCRK_{\text{top-down}} - TCRK_{\text{Bottom\_up}} * TCRK_{\text{top-down}})100$$

  - Longitudinal cracking

$$LCRACK = (LCRK_{\text{Bottom\_up}} + LCRK_{\text{top-down}} - LCRK_{\text{Bottom\_up}} * LCRK_{\text{top-down}})100\%$$

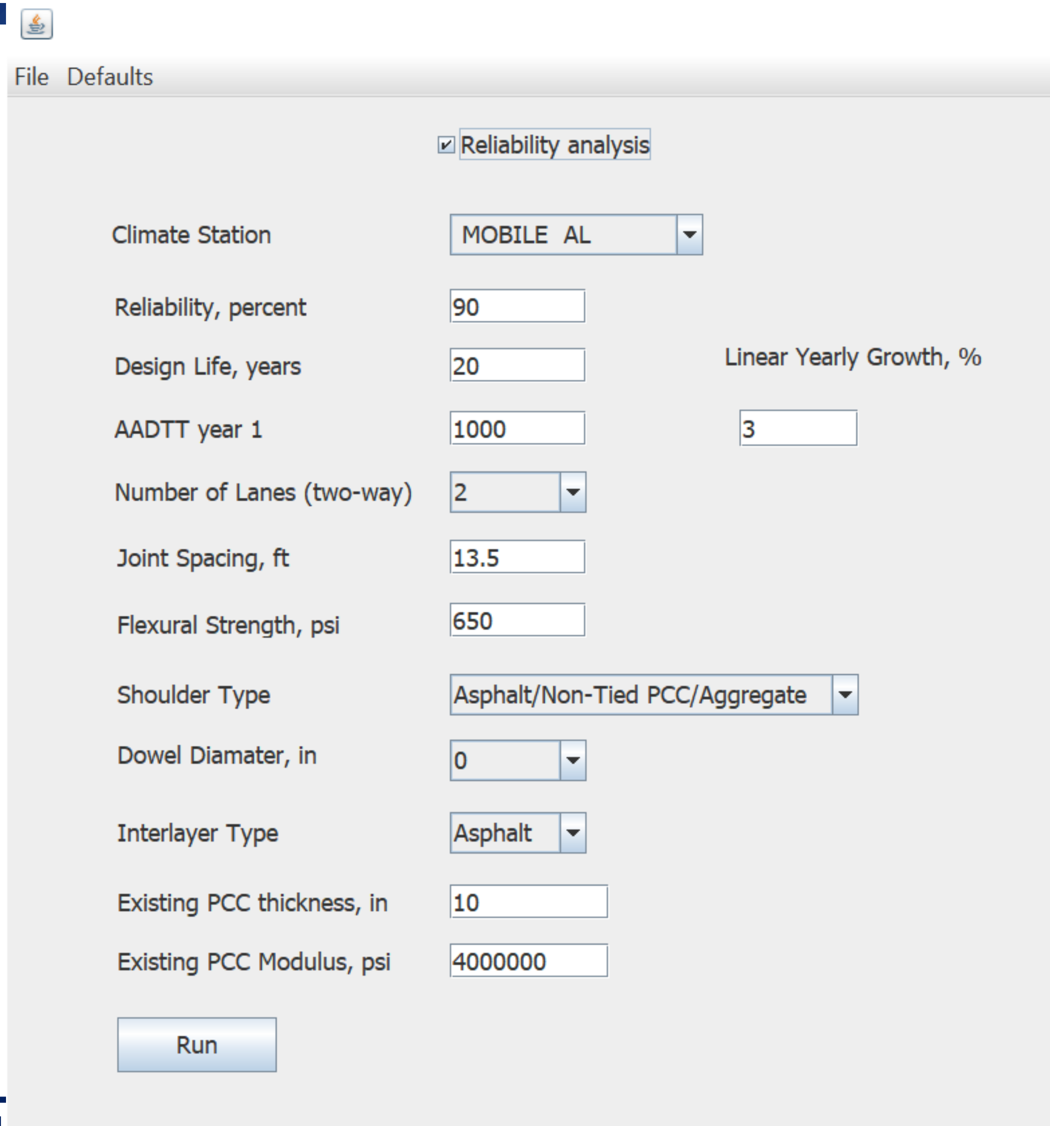
- Step 3: Total cracking

$$CRACK = (TRCRACK + \text{L}CRACK - TRCRACK * LCRACK) * 100\%$$

Reliability Analysis

- Inputs:
  - Reliability Level
  - Coefficient of variation of Overlay thickness
  - Coefficient of variation PCC strength
  - Allowable cracking level at the end of the design life
- Procedure
  - Perform simulation for a factorial of PCC overlay thicknesses and strengths
  - Determine the overlay thickness resulting in the percentage of thickness/strength combinations with cracking less than the specified allowable level

Rudimentary Software

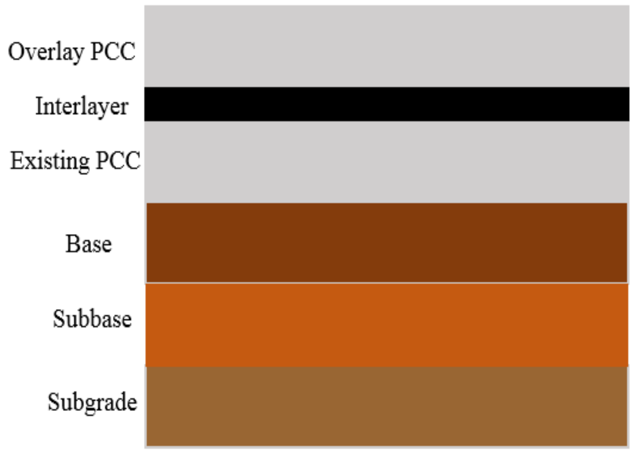


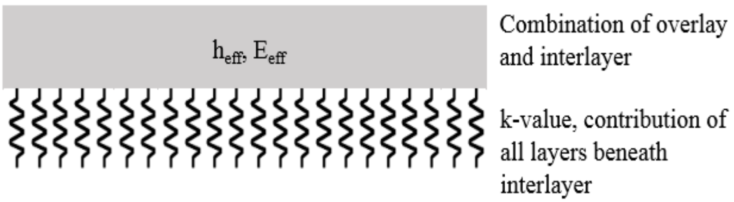
Remaining Work

- Add 6 ft x 6 ft slabs
- Check analysis for thin overlays (< 6 in)
- Increase the number of weather stations
- Incorporate the faulting model into the software
- Upgrade the interlayer deterioration model
- Provide default inputs

Pavement ME limitations

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





Pavement ME limitations

MEPDG Documentation Appendix JJ

- Erodibility index

Assigned integer value based upon base type

1 – extremely erosion resistant

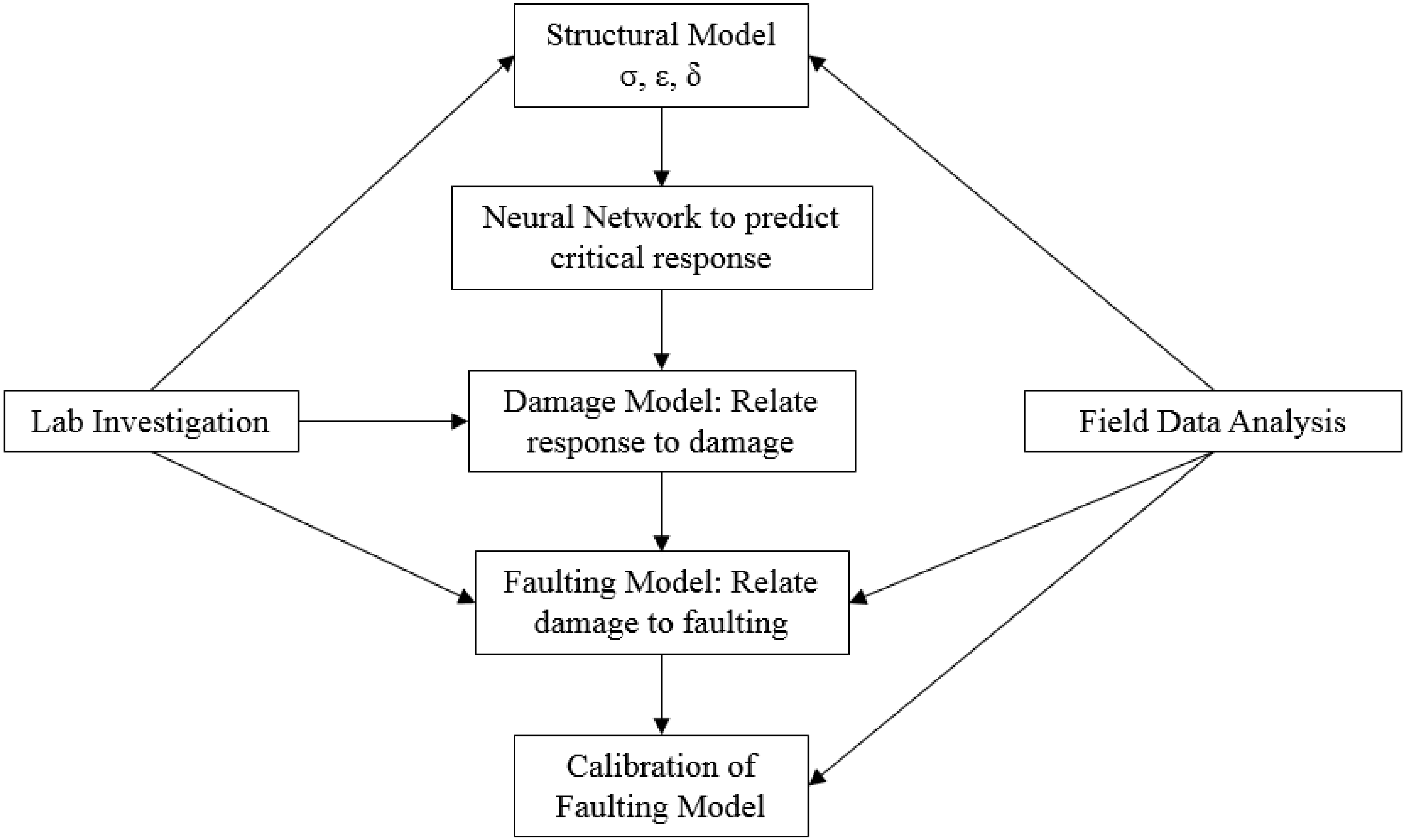
to

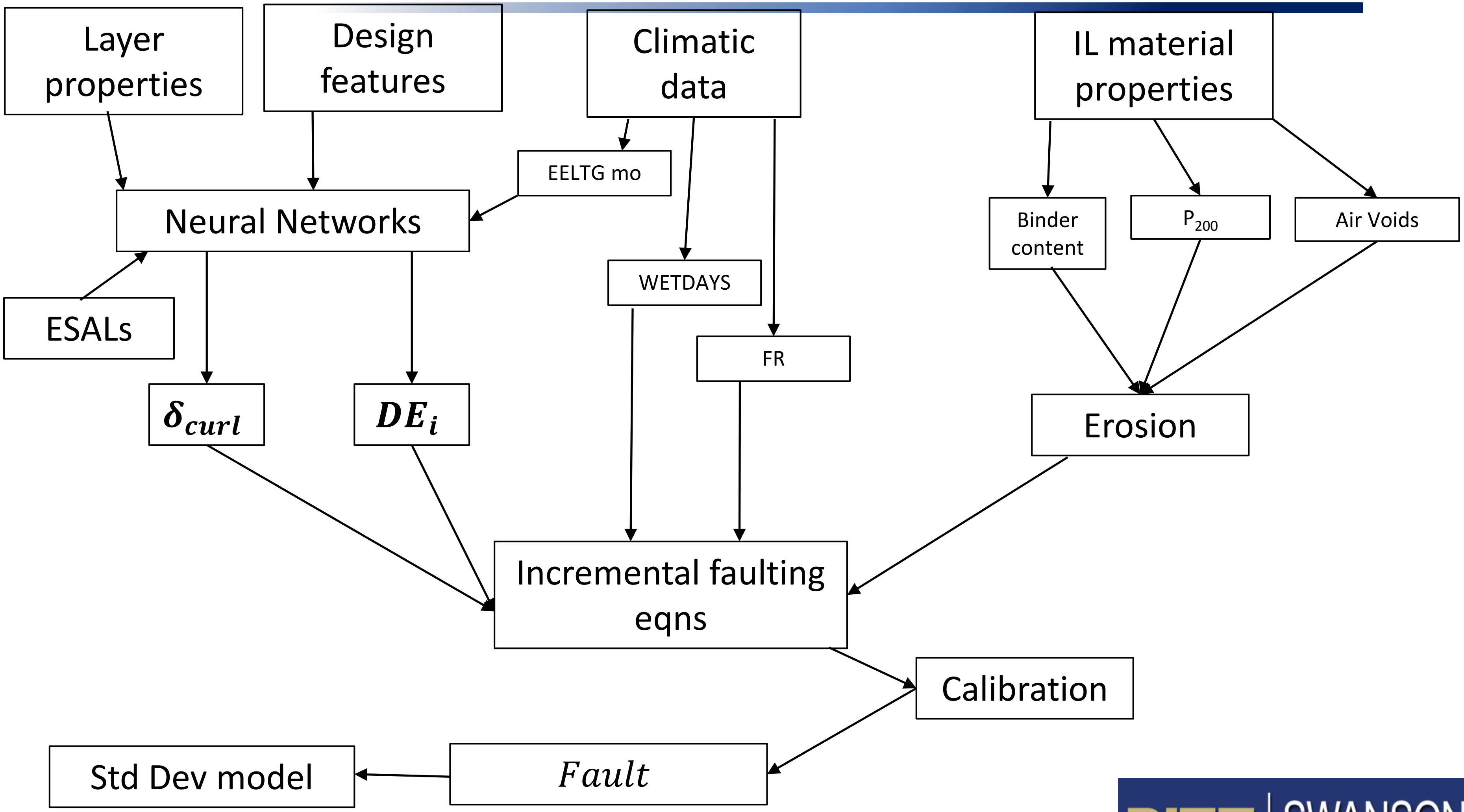
5 – very erodible

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 psi 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



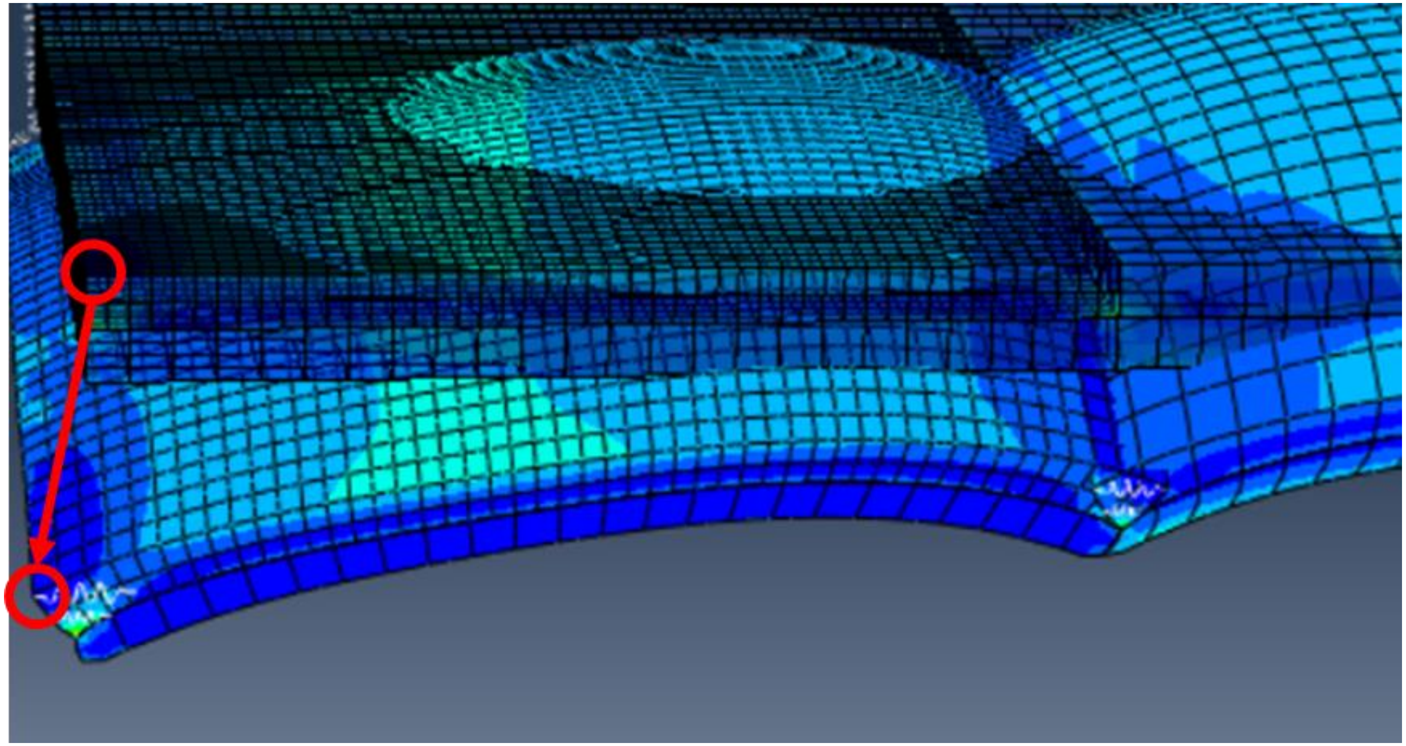

Layer properties
Design features
Climatic data
IL material properties
EELTG mo
Neural Networks
Binder content
P_{200}
Air Voids
WETDAYS
ESALs
FR
δ_{curl}
DE_i
Erosion
Incremental faulting eqns
Calibration
Std Dev model
$Fault$

Differential Energy

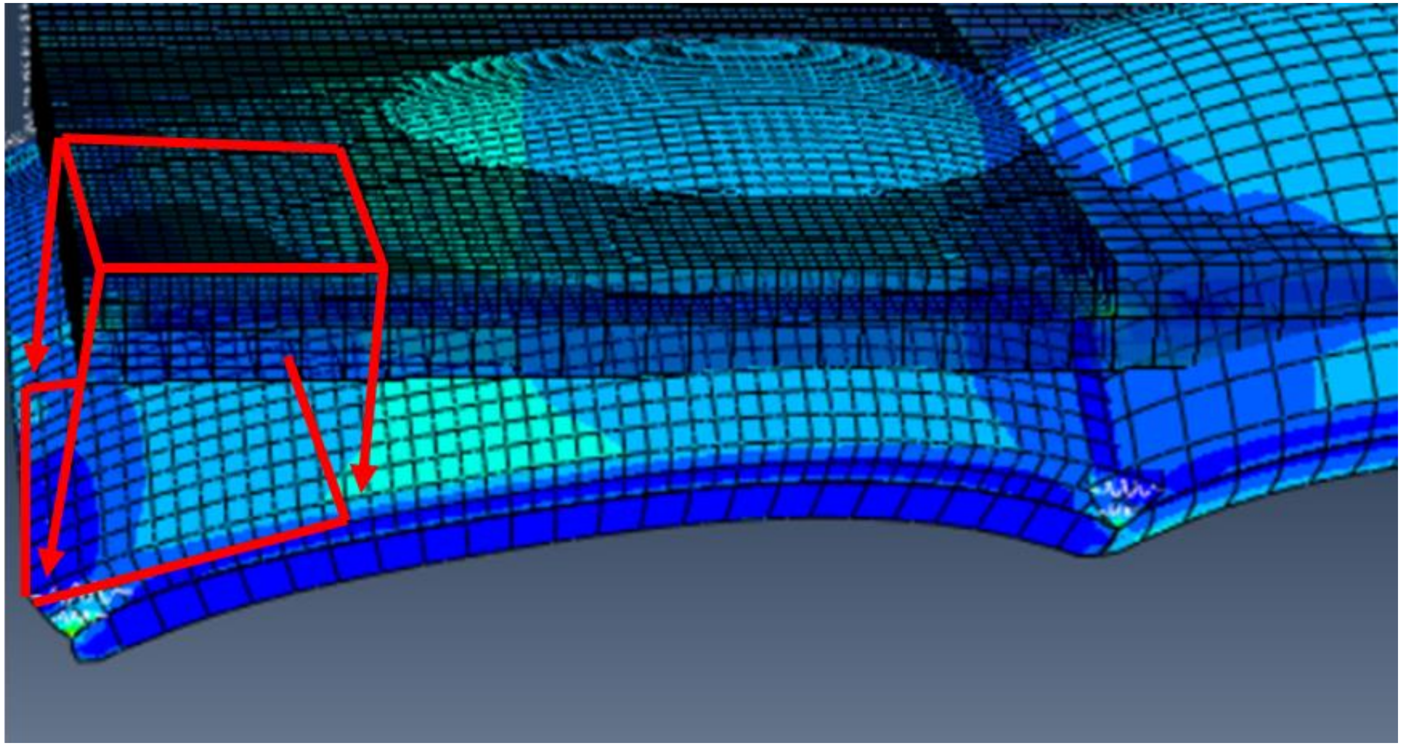
$$DE_m = n_i k \left(\frac{\Sigma\delta_{L,i}^2}{2} - \frac{\Sigma\delta_{U,i}^2}{2}\right)$$

- 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 = # of ESAL applications for month m

Predictive Model Response

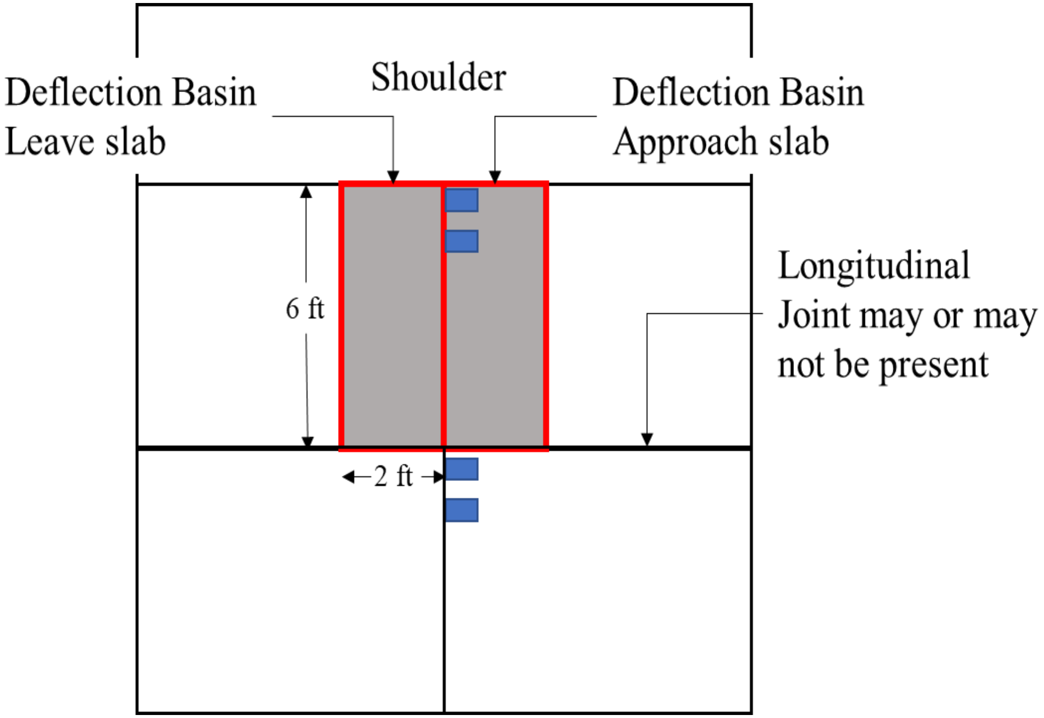


Predictive Model Response



Predictive Model Response

- Deflection Basin Approach Slab:
  - $\Sigma(\delta^2_{\Sigma L} * Area)$
  - 2 ft x 6 ft rectangle
- Deflection Basin Leave Slab:
  - $\Sigma(\delta^2_{\Sigma UL} * Area)$
  - 2 ft x 6 ft rectangle



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 (<32°F))
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)

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.

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

Faulting model

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

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

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

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

$C_1 = 3.0$

$C_2 = 2.5$

$C_3 = 35$

$C_4 = 0.001$

$C_5 = 0.015$

$C_6 = 2.202$

$C_7 = 80$

$C_8 = 0.0000002$

Erosion

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

$\alpha =$ 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 $(0.226, 0.247, 0.066)$

$$E = \begin{cases} (3.5628 * \alpha^2 - 3.7689 * \alpha + 1.0928) & \text{Undoweled pavements} \\ (3.0284 * \alpha^2 - 3.2036 * \alpha + 0.9283) & \text{Doweled pavements} \\ (3.5628 * \alpha^2 - 3.7689 * \alpha + 0.09) & \text{NWGF sections} \end{cases}$$

Erosion Calibration