Sixth Int l Purdue Conference on Concrete Pavement

DEVELOPMENT OF NEW STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURES FOR JOINTED CONCRETE PAVEMENTS

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OBJECTIVES

- Develop an Alternative Stress Estimation Procedure
- Validate ILLI-SLAB Program s Applicability
- Modify PCA Stress Analysis & Thickness Design Procedure
- Develop a User-friendly TKUPAV Program for Automatic Stress Calc. & Thickness Design
- Applicable to Metric & English Systems

RESEARCH APPROACH

- Westergaard s Closed-Form Solutions
- Effects of Curling & Warping
- ILLI-SLAB Solutions and Its Applicability
- Identification of Mechanistic Variables
- Development of Stress Prediction Models
- Modified PCA Stress Analysis and Thickness Design Procedure
- Development & Verification of TKUPAV Program

CLOSED-FORM SOLUTIONS / ILLI-SLAB F. E. MODEL

- Westergaard/ Bradbury
  - Loading Only
  - Thermal Curling
  - Loading Plus Curling
- ILLI-SLAB F. E. Model
  - Dimensional Analysis
  - Identification of Mechanistic Variables

EFFECTS OF CURLING & WARPING

- Thermal Curling Stress (Positive aT => Additional Stress)
- Moisture Warping Stress (Negative aM => Stress Reduction) (But Not Easy to Measure)
- Suggest to Include the Effect of Positive aT

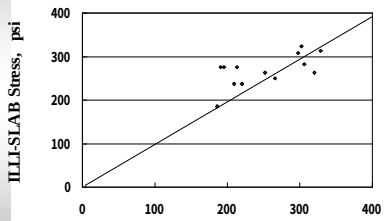
ILLI-SLAB Program

- Originally Developed by Tabatabaie , 1977
- Continuously Revised by Wong, Conroyd , Ioannides , 1980-1985
- Included Curling Analysis by Korovesis, 1986-1989
- Re-Compiled by Lee, 1995 (Microsoft FORTRAN PowerStation)

RESULTS OF ACTUAL FIELD MEASUREMENTS

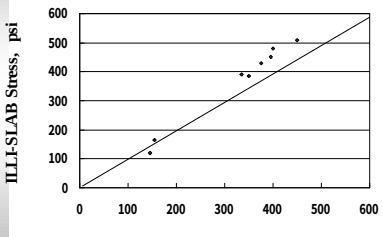
- Arlington Road Test
  - Edge Stress (Curling Only)
- AASHO Road Test
  - Edge Stress (Loading + Curling)
- Taiwan s Second Northern Highway
  - Corner Stress (Loading + Curling)
- Compared to ILLI-SLAB Results
- Validated Its Applicability

Arlington Road Test



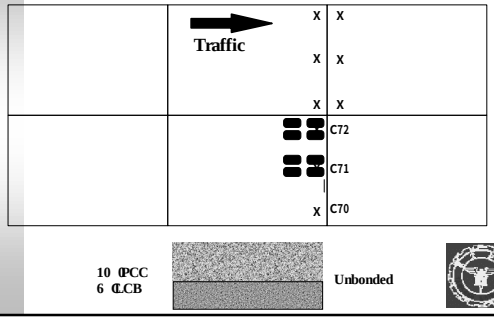
REF: Lee 1993

AASHO Road Test

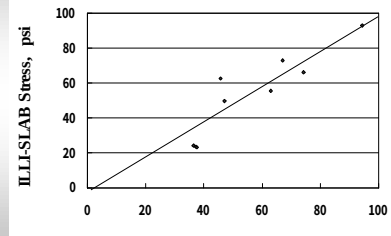


REF: Lee 1993

Taiwan s Second Northern Highway

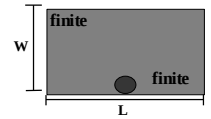


Taiwan s Second Northern Highway



Identification of Mechanistic Variables (Loading Only)

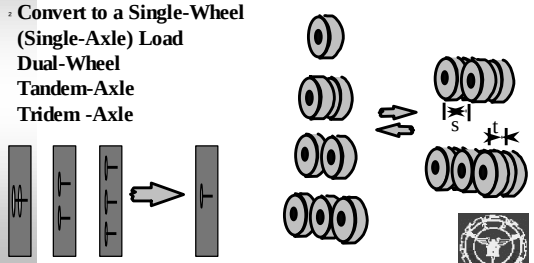
$$\frac{\pm h^2}{P}, \frac{\phi k^a}{P}, \frac{q^a}{P} =$$



$$f\left(a\ L\ W\ s\ t\ D_0\ AGG, \left(\frac{h_{eff}}{h}\right)^2\right)$$

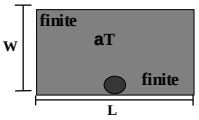
Effect of Wheel and Axle Spacing

- Convert to a Single-Wheel (Single-Axle) Load
  - Dual-Wheel
  - Tandem-Axle
  - Tridem -Axle



Identification of Mechanistic Variables (Loading + Curling)

$$\frac{\pm}{E}, \frac{\not{c}h}{a^2}, \frac{qh}{k a^2} =$$



$$f\left(\frac{a}{a}, \sim\Delta T, \frac{L}{a}, \frac{W}{a}, \frac{\not{\mu}h^2}{k a^2}, \frac{Ph}{k a^4}\right)$$

DEVELOPMENT OF STRESS PREDICTION MODELS

- Factorial F.E. Runs Based on the Dimensionless Mechanistic Variables
- Two-Step Modeling Approach
  - Projection Pursuit Regression (PPR)
  - Piece-wise Linear Regression
- S-PLUS Statistical Package
- Lee & Darter (TRR 1449)

Proposed Stress Prediction Models (Edge, Corner, Interior)

$$\pm_{cr} = \pm_w \cdot R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 + R_T \cdot \pm_c$$

$$\pm_w = \frac{P}{h^2} \times f_1\left(\frac{a}{a}\right)$$

$$\pm_c = \frac{1}{2} E \sim\Delta T \times f_2\left(\frac{W}{a}\right)$$

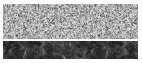
$R_1 \sim R_5, R_T$ = Prediction Models

MODIFIED PCA STRESS ANALYSIS & THICKNESS DESIGN PROCEDURES

- Review PCA Thickness Design Procedure
  - Equivalent Stress Calculation
  - Fatigue Analysis
- PCA s Simplifications and Limitations
- Modified Equivalent Stress Calculation
- Modified PCA Fatigue Analysis & Thickness Design Procedures

PCA THICKNESS DESIGN

- J-SLAB Program (Edge Stress)
- Equivalent Stress Calculations
- Fatigue Analysis (& Erosion Analysis)
- But Did NOT Consider Curling Stress
- PCAPAV Program



$$D_f = \sum_{i=1}^{m} \frac{n_i}{N_i}$$

PCA Equivalent Stress Calculation

$$\pm_{eq} = \frac{6M_e}{h^2} \bullet f_1 \bullet f_2 \bullet f_3 \bullet f_4$$

$Me = f(a, k)$ (in English System)

SA/NS , TA/NS , SA/WS , TA/WS

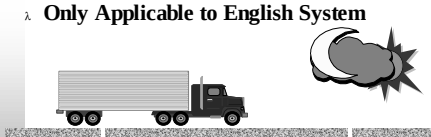
PCA Fatigue Analysis

$$\begin{cases} \log N_f = 11.737 - 12.077 \times SR & SR \geq 0.55 \\ N_f = \left(\frac{4.2577}{SR - 0.4325}\right)^{3.268} & 0.45 < SR < 0.55 \\ N_f = \text{Unlimited} & SR \leq 0.45 \end{cases}$$

$SR = \pm / S_c$, N_f = Allowable Load Repetitions

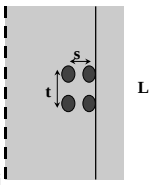
LIMITATIONS OF PCA THICKNESS DESIGN PROCEDURE

- Did NOT Consider Curling Stresses
- Limited to Fixed Gear Configurations
- Only Applicable to English System



PCA Simplifications & Limitations

- Fixed Slab Size: L=180 in., W=144 in.
- Fixed Gear Configurations: a=4.72 in., t=50 in., s=12 in. (Axle Width D=72 in.)
- Fixed Material Properties: E=4 Mpsi, «=0.15, AGG=25,000 psi



Modified Equivalent Stress Calculation (I)

$$\pm_{eq} = \left(\pm_W \cdot R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 + R_T \cdot \pm_c\right) \cdot f_3 \cdot f_4$$

Modified Equivalent Stress Calculation (II)

$$\pm_w = \frac{P}{h^2} \times f_1\left(\frac{a}{a}\right)$$

$$\pm_c = \frac{1}{2} E \sim \Delta T \times f_2\left(\frac{W}{a}\right)$$

$R_1 \sim R_5$, R_T = Prediction Models

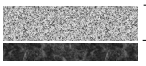
Modified PCA Stress Analysis & Thickness Design Procedures (I)

- Calculate Expected Load Repetitions (ni)
- Calculate Modified Equivalent Stress (σ_{eq})

  $\sigma_{eq} = \sigma_{cr} * f_3 * f_4$
  - Loading Only
  - Loading + Curling ($\Delta T>0$)
- Calculate Stress Ratio (σ_{eq} / Sc)

Modified PCA Stress Analysis & Thickness Design Procedures (II)

- Determine Max. Allowable Load Repetitions (Ni)
- Check Cumulated Fatigue Damage Σ (ni / Ni) < 100%
- Repeat Previous Steps, If Necessary

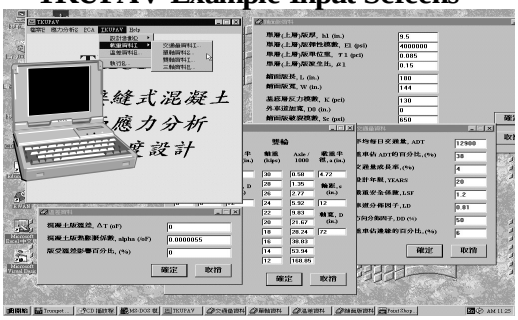


$$D_r = \sum_{i=1}^{m} \frac{n_i}{N_i}$$

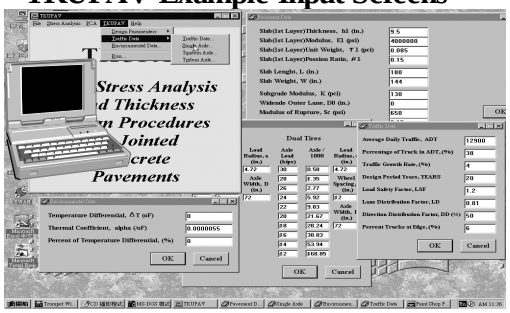
DEVELOPMENT OF TKUPAV PROGRAM

- **Using Visual Basic Program (Ver. 4.0)**
- **Highly User-Friendly Interfaces**
- **Basic Features of TKUPAV Program**
  - **Different Slab Size, Axle Configurations, Material Properties, Temperature Differentials**
  - **Metric and English Systems**
  - **English & Chinese Versions**

TKUPAV Example Input Screens

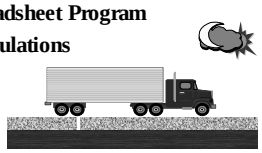


TKUPAV Example Input Screens



TKUPAV PROGRAM VALIDATION

- **Comparing the Results of PCAPAV, TKUPAV, and a Spreadsheet Program**
- **Equivalent Stress Calculations**
  - **TKUPAV / PCAPAV**
- **Fatigue Analysis**
  - **Loading Only**
  - **Loading + Day-time Curling**

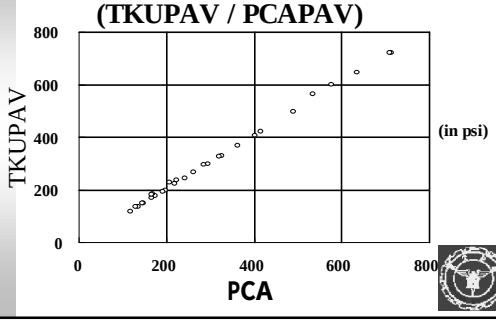


A Case Study for Validation

Single Axle		Tandem Axle	
Load, kips	Axles/1000 Trucks	Load, kips	Axles/1000 Trucks
30	0.58	52	1.96
12	168.85	16	124.69

Basic Assumptions: Same as PCA Method

Comparison of Equivalent Stress (TKUPAV / PCAPAV)



Fatigue Analysis for Loading Only

Axle Load	Fatigue (%)	
	PCAPAV	TKUPAV
Single	61.4	70.5
Tandem	2.0	0.9
Sum =	63.4	71.4

Fatigue Analysis for Loading + Day-time Curling

Axle Load	TKUPAV Fatigue (%)		
	90% Load Only	10% Load + Curling	Total
Single	63.4	128.9	192.3
Tandem	0.8	9.8	10.7
Sum =	64.2	138.8	203.0

DISCUSSIONS

- Followed Similar Approach Adopted by NCHRP 1-26 Project
  - ILLI-CONC Program for Edge Stress Only
- Resolved the Dimensional Analysis Issue for Loading + Curling Condition
- Provided More Complete Treatment
  - Edge, Corner, and Interior Stress Analysis
- ESAR Concept Was Replaced by Stress Reduction Adjustment Factors (R =0~1)

CONCLUSIONS AND RECOMMENDATIONS (I)

- Validated ILLI- SLAB Applicability
- Developed an Alternative Procedure for Critical Stress Estimation
  - Edge, Corner, & Interior L+C Stress
- Modified PCA Equivalent Stress Calculation & Fatigue Analysis
- Developed a Highly User-Friendly TKUPAV Program

CONCLUSIONS AND RECOMMENDATIONS (II)

- Expanded PCA Thickness Design for:
  - Different Slab Size, Axle Configurations, Material Properties, Temperature Differentials
  - Metric and English Systems
- Validated the TKUPAV Program
- Illustrated the Effect of Loading + Curling Should be Considered
- Further Verifications & Trial Applications

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  - NSC85-2211-E032-010

THANKS FOR YOUR ATTENTION!

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