Effects of Various Design Features on Rigid Airfield Pavement Design

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Problem Statement

- Current FAA Rigid Pavement Design
  - Will result in same required min. slab thickness
  - Regardless of different joint spacing, load transfer mechanism, environmental effects
- Objective
  - Investigate the effects of various design features
  - Continuous effort to expand the applicability of previously proposed design procedure (Lee & Yen 2001)

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Introduction

- Review of Rigid Airfield Pavement Design
  - Conventional FAA & LEDFAA design procedures
  - Lee and Yen's proposed alternative design procedure
- Estimation of Critical Edge Stress for Design
  - Reanalysis of Corps of Engineers full-scale test pavements data
  - Investigate the effects of finite slab sizes; a second bonded/unbonded layer; and curling & warping
- Alternative Structural Deterioration Relationship
- Implementation of the Proposed Approach

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Stress Analysis of FAA Design Procedure

- Plate Theory & Westergaard Critical Edge Stresses
- Pickett and Ray's Influence Charts

$$\sigma_e = \frac{P}{h^2}\left[RC0 + RC1\times\ln(\ell) + RC2\times\left(\ln(\ell)\right)^2\right]$$

  - Applicable to U.S. customary system / infinite slab size
- Use Multi-Layered Linear Elastic Theory (B-777)
  - LEDFAA design procedure

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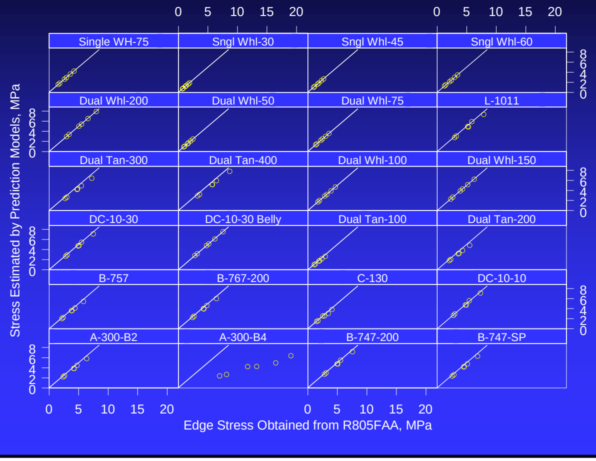
Estimation of Critical Edge Stress for Design

$$\sigma_e = \sigma_{we} \times R_1 \times R_2 \times R_5 + \sigma_c * R_T$$

σ_{we} : Westergaard edge stress
σ_c : Westergaard/Bradbury’s curling stress
R_1 : Gear configurations adjustment factor
R_2 : Finite slab size adjustment factor
R_5 : Second layer adjustment factor
R_T : Combined effect of loading plus daytime curling adjustment factor

(Ref: Lee, et al., 1997)

Verification of Stress Prediction Models



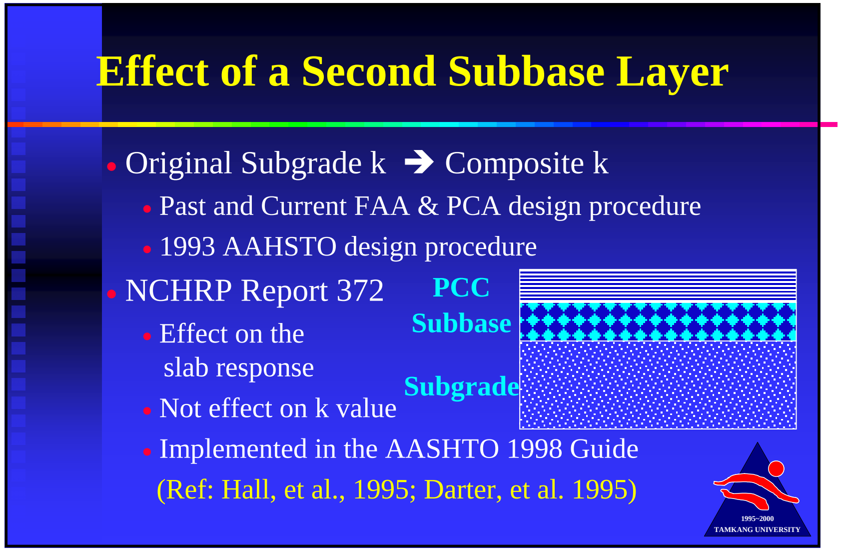
Corps of Engineers Full-Scale Test Data

- Include 8 Test Tracks (1943~1972)
  - Zone 1 – Lockbourne Air Force Base, Ohio
    - Lockbourne No.1
    - Lockbourne No.2
    - Lockbourne No.3
  - Zone 2 – Sharonville, Ohio
    - Sharonville Channelized Traffic
    - Sharonville Heavy Load
  - Zone 3 – Waterways Experiment Station, Mississippi
    - Multiple-Wheel Heavy Gear Load (MWHGL)
    - Keyed Longitudinal Joint Study (KLJS)
    - Soil Stabilization Pavement Study (SSPS)

(Ref: Guciblmez & Yuce, 1995; Parker, et al., 1979)

Effect of Finite Slab Width and Length

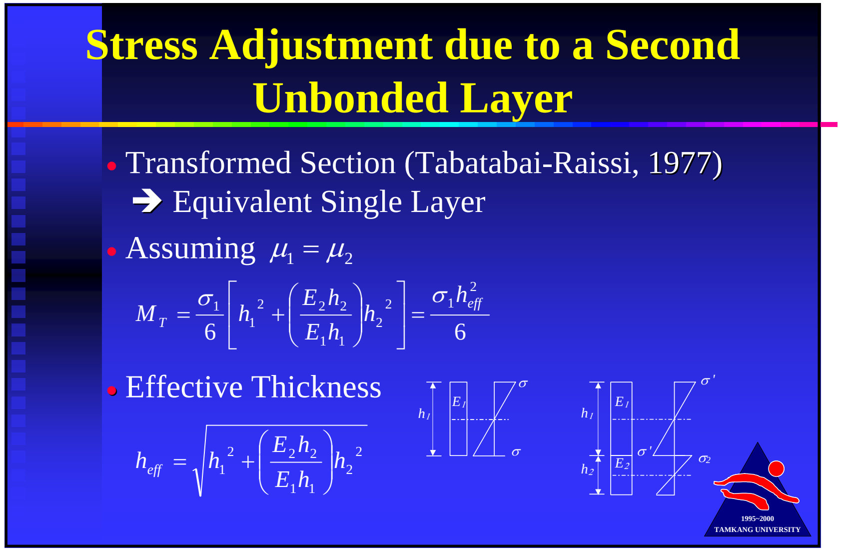
- Reanalysis of the Corps of Engineers Full-Scale Test Data (36 Test Pavements)
  - L = 6.1~15.24 m
  - W = 3.05~15.24 m
- Stress Adjustment Factor R_2
  - Corrected the main landing gear load of Item K2.100
  - R_W ranging from 0.998 to 1.0
  - R_L ranging from 0.964 to 1.0
  - ➔ Negligible



Effect of a Second Subbase Layer

- Original Subgrade k ➔ Composite k
  - Past and Current FAA & PCA design procedure
  - 1993 AAHSTO design procedure
- NCHRP Report 372
  - Effect on the slab response
  - Not effect on k value
  - Implemented in the AASHTO 1998 Guide

(Ref: Hall, et al., 1995; Darter, et al. 1995)



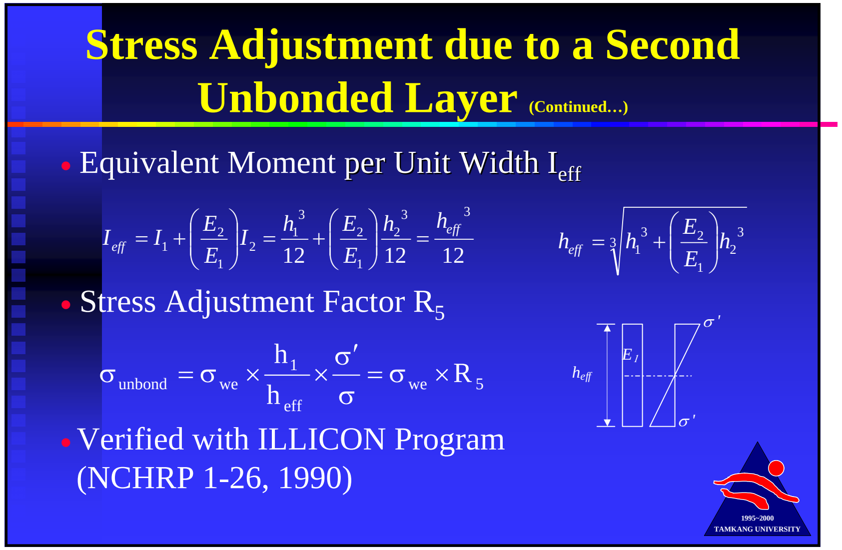
Stress Adjustment due to a Second Unbonded Layer

- Transformed Section (Tabatabai-Raissi, 1977)
  ➔ Equivalent Single Layer
- Assuming $\mu_1 = \mu_2$

$$M_T = \frac{\sigma_1}{6}\left[h_1{}^2 + \left(\frac{E_2 h_2}{E_1 h_1}\right)h_2{}^2\right] = \frac{\sigma_1 h_{eff}^2}{6}$$

- Effective Thickness

$$h_{eff} = \sqrt{h_1{}^2 + \left(\frac{E_2 h_2}{E_1 h_1}\right)h_2{}^2}$$



Stress Adjustment due to a Second Unbonded Layer (Continued…)

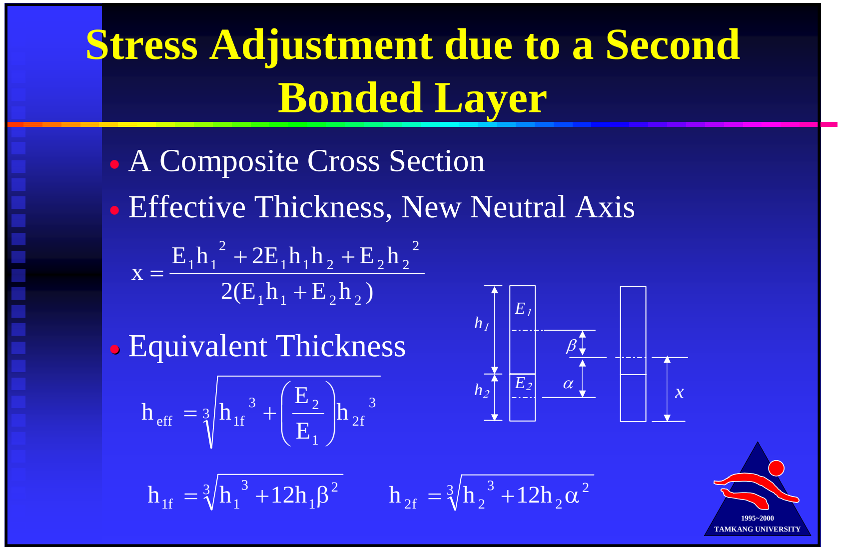
- Equivalent Moment per Unit Width I_{eff}

$$I_{eff} = I_1 + \left(\frac{E_2}{E_1}\right)I_2 = \frac{h_1{}^3}{12} + \left(\frac{E_2}{E_1}\right)\frac{h_2{}^3}{12} = \frac{h_{eff}{}^3}{12} \qquad h_{eff} = \sqrt[3]{h_1{}^3 + \left(\frac{E_2}{E_1}\right)h_2{}^3}$$

- Stress Adjustment Factor R_5

$$\sigma_{unbond} = \sigma_{we} \times \frac{h_1}{h_{eff}} \times \frac{\sigma'}{\sigma} = \sigma_{we} \times R_5$$

- Verified with ILLICON Program (NCHRP 1-26, 1990)



Stress Adjustment due to a Second Bonded Layer

- A Composite Cross Section
- Effective Thickness, New Neutral Axis

$$x = \frac{E_1 h_1{}^2 + 2E_1 h_1 h_2 + E_2 h_2{}^2}{2(E_1 h_1 + E_2 h_2)}$$

- Equivalent Thickness

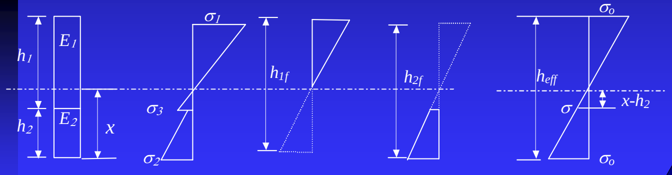
$$h_{eff} = \sqrt[3]{h_{1f}{}^3 + \left(\frac{E_2}{E_1}\right)h_{2f}{}^3}$$

$$h_{1f} = \sqrt[3]{h_1{}^3 + 12h_1\beta^2} \qquad h_{2f} = \sqrt[3]{h_2{}^3 + 12h_2\alpha^2}$$

Stress Adjustment due to a Second Bonded Layer (Continued…)

- Stress Adjustment Factor R_5

$$\sigma_{bond} = \sigma_{we} \times \frac{2(x - h_2)}{h_{eff}} \times \frac{\sigma'}{\sigma} = \sigma_{we} \times R_5$$



- Verified with ILLICON Program

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Reanalysis Results: Effect of a Second Unbonded Layer

- Corps of Engineers Full-Scale Test Data
  - Assuming the second subbase layer as unbonded
- $R_k = \sigma_1/\sigma_2$
  - σ_1 : use composite k-value from Yuce's paper
  - σ_2 : use original k-value from the test data
  - R_k ranging from 1.00 to 1.248
- Stress Adjustment Factor $R_5 = \frac{2(x-h_2)}{h_{eff}} \times \frac{\sigma'}{\sigma}$
  - $R_5 = 0.987 \sim 1.0$

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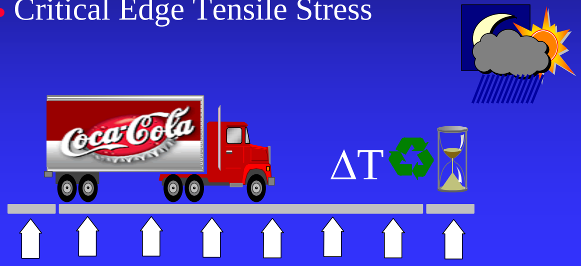
Effect of Thermal Curling and Moisture Warping

- Daytime Positive Temperature Differential
  - Additional tensile stress at the bottom of slab
- Critical Edge Tensile Stress



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Effective Temperature Differential vs. Other Climatic Factors

- 1998 AASHTO Supplemental Guide

$$TD = 0.962 - \frac{52.181}{h} + 0.341 * WIND$$
$$+ 0.184 * TEMP - 0.00836 * PREC$$

TD = effective positive temperature differential , ºF
h = slab thickness, in.
WIND = mean annual wind speed, mph
TEMP = mean annual temperature, ºF
PREC = mean annual precipitation, in.

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Climatic Data Search

- Application of the LTPP DataPave Program
- Search Test Tracks Locations from the Map
- Search SHRP IDs Nearest to Test Tracks
- Link to Virtual Weather Station's Data
  - Mean Annual Wind speed
  - Mean Annual Temperature
  - Mean Annual Precipitation

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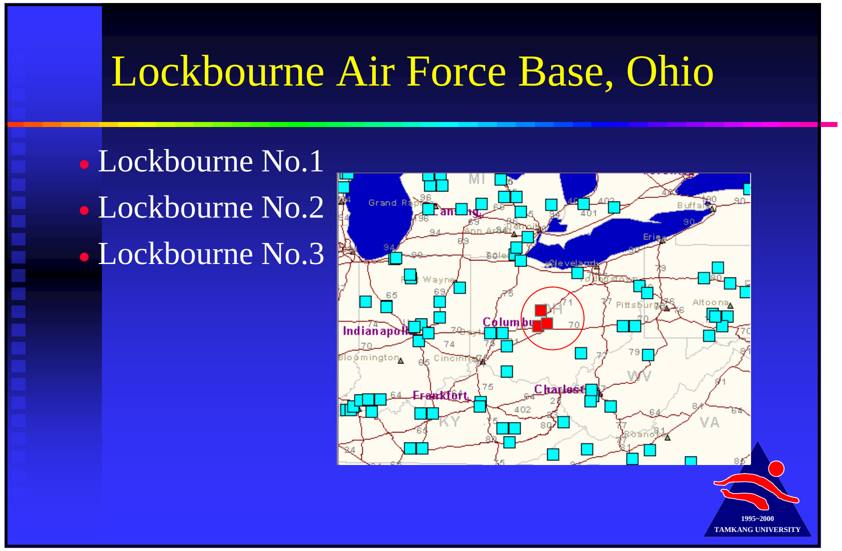

Lockbourne Air Force Base, Ohio

- Lockbourne No.1
- Lockbourne No.2
- Lockbourne No.3

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Sharonville, Ohio

- Sharonville Channelized Traffic
- Sharonville Heavy Load

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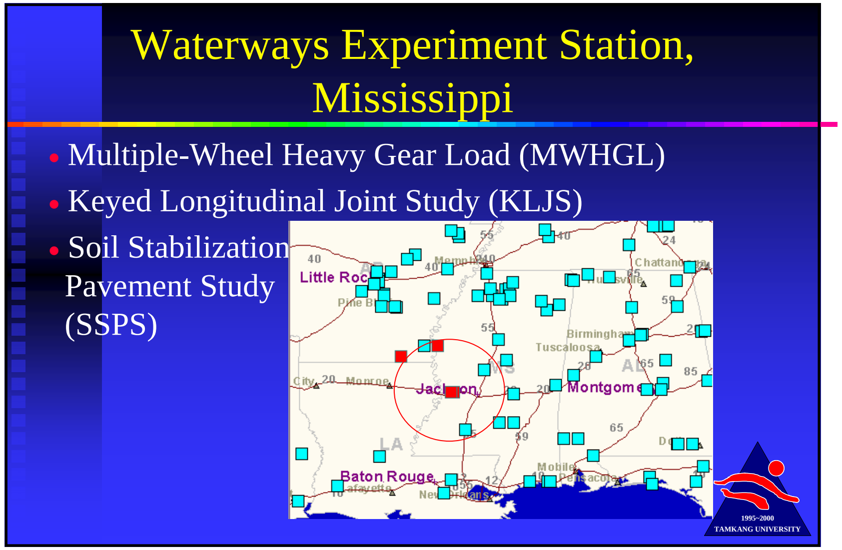

Waterways Experiment Station, Mississippi

- Multiple-Wheel Heavy Gear Load (MWHGL)
- Keyed Longitudinal Joint Study (KLJS)
- Soil Stabilization Pavement Study (SSPS)

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Reanalysis Results: Effect of Curling & Warping

- Full-Scale Test Data / LTPP Climatic Data
  - h = 14.0 ~ 71.1 cm PREC = 983 ~ 1441.9 mm
  - TEMP = 11.2 ~ 17.6 ºC WIND = 3.08 ~ 4.05 m/s
- Results:
  - TD ranging from 1.79 ~ 6.35 ºC
  - Stress adjustment factor $R_{TD} = \sigma_e / \underline{\sigma_L} = 1.023 \sim 1.241$

$$\sigma_e = \underline{\sigma_{we} \times R_1 \times R_2 \times R_5} + \sigma_c * R_T$$

$$\sigma_L \,//$$

Fatigue Relationship and Thickness Design Criteria (1)

- Conventional FAA Design Procedure
- Basic Thickness
- Design Factor = 1.3 $\sigma_e = \frac{S_c}{1.3*0.75}$
- Fatigue Relationship $h_1 = \left[\left(RC0 + RC1 \times \ln(\ell) + RC2 \times (\ln(\ell))^2 \right) \times \left(\frac{P}{\sigma_e} \right) \right]^{0.5}$

$$RH = \begin{cases} 1 + 0.15603 * (\log(\mathrm{C}) - 3.69897) & \mathit{if}\ \mathrm{C} > 5000 \\ 1 + 0.07058 * (\log(\mathrm{C}) - 3.69897) & \mathit{if}\ \mathrm{C} < 5000 \end{cases}$$

(Ref: Lee & Yen, 2001)

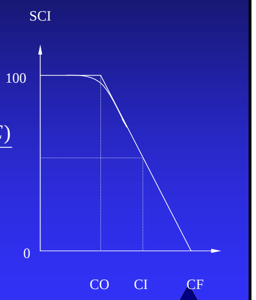
Fatigue Relationship and Thickness Design Criteria (2)

- LEDFAA's Fatigue Relationship
- Rollings and Witczak(1990)
  - Structural Condition Index (SCI, 0~100)

$$SCI = \frac{DF - 0.2967 - (0.3881 + 0.000039 * SCI) * \log(C)}{0.002269}$$

$$DF = 0.4782 + 0.3912 * \log(\mathrm{C80})$$

- Select the higher of the two
  - Interior Stress of Layered Elastic Theory
  - 75% Westergaard's Edge Stress
  - Arbitrary & Unsupported



(Ref: Lee & Yen, 2001)

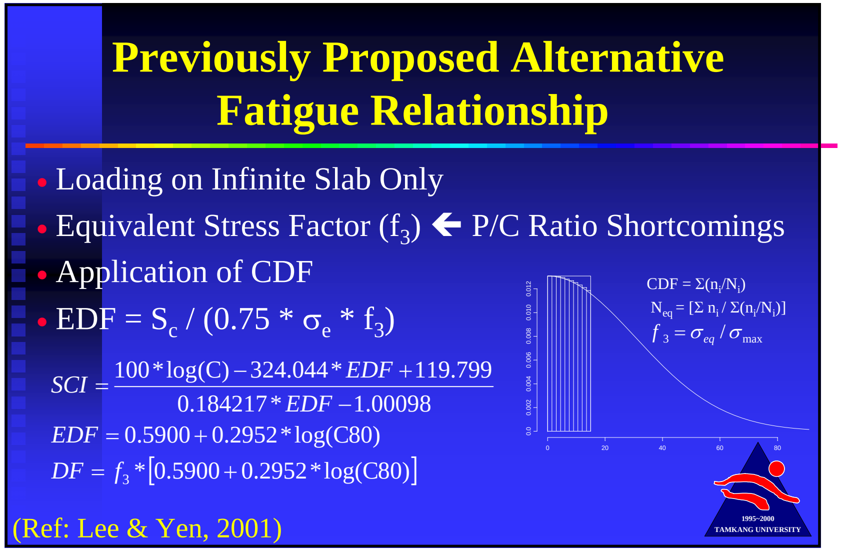
Fatigue Relationship and Thickness Design Criteria (3)

- Gucbilmez and Yuce's Fatigue Relationship
- Re-analyzed Corps of Engineers Full-size Test Data
- Westergaard edge stress
- DF = S_c / (0.75 * σ_e)

$$SCI = \frac{100 * \log(\mathrm{C}) - 320.61558 DF + 56.4417}{0.20903 DF - 0.99336}$$

$$DF = 0.40289 + 0.29644 * \log(\mathrm{C80})$$

(Ref: Lee & Yen, 2001)



Previously Proposed Alternative Fatigue Relationship

- Loading on Infinite Slab Only
- Equivalent Stress Factor (f_3) 🡐 P/C Ratio Shortcomings
- Application of CDF
- EDF = $S_c / (0.75 * \sigma_e * f_3)$

$$SCI = \frac{100 * \log(C) - 324.044 * EDF + 119.799}{0.184217 * EDF - 1.00098}$$

$$EDF = 0.5900 + 0.2952 * \log(C80)$$

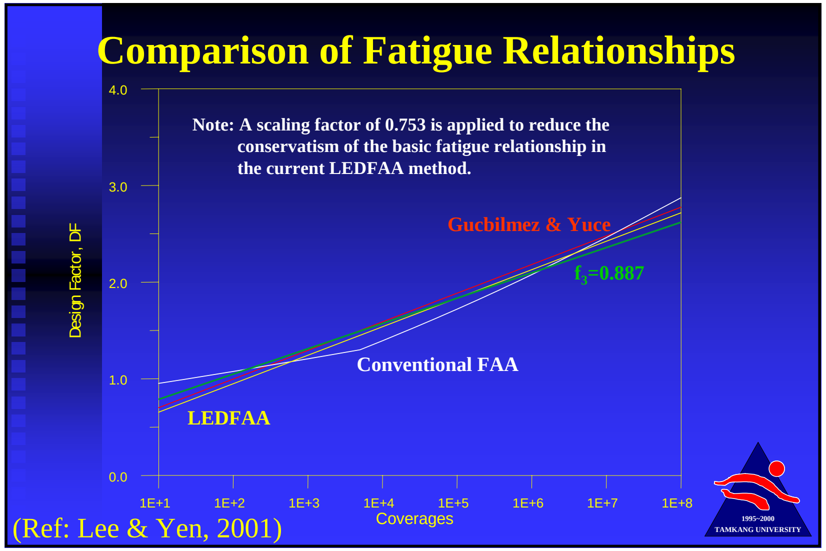
$$DF = f_3 * [0.5900 + 0.2952 * \log(C80)]$$

$CDF = \Sigma(n_i/N_i)$

$N_{eq} = [\Sigma\, n_i / \Sigma(n_i/N_i)]$

$f_3 = \sigma_{eq} / \sigma_{max}$

(Ref: Lee & Yen, 2001)



Comparison of Fatigue Relationships

Note: A scaling factor of 0.753 is applied to reduce the conservatism of the basic fatigue relationship in the current LEDFAA method.

(Ref: Lee & Yen, 2001)

Alternative Deterioration Relationships

- Consider Additional Design Features & Curling
- Equivalent Design Factor (EDF) = $S_c / (0.75 * \sigma_e * f_3)$

Tentative Fatigue Equations	SEE	R^2	N
EDF = 0.6040 + 0.2467*log(CO)	0.115	0.742	24
EDF = 0.5082 + 0.2493*log(CI)	0.113	0.788	36
EDF = 0.3520 + 0.2685*log(CF)	0.118	0.730	24
EDF = 0.4910 + 0.2422*log(PO)	0.121	0.716	24
EDF = 0.3975 + 0.2441*log(PI)	0.118	0.769	36
EDF = 0.2354 + 0.2629*log(PF)	0.124	0.701	24

Treatment of Possible Outlying Items

- Item K2.100
  - Corrected the main landing gear load of Item K2.100
  - Considered throughout this paper
- Item 59, If Removed (But Not Used)

Tentative Fatigue Equations	SEE	R^2	N
EDF = 0.4719 + 0.2680*log(CI)	0.101	0.838	35
EDF = 0.3542 + 0.2619*log(PI)	0.107	0.816	35

Newly Proposed Fatigue Relationship

- Consider Additional Design Features & Curling

$$SCI = \frac{100 * \log(C) - 372.439(EDF) + 131.099}{0.3291(EDF) - 1.1373}$$

$$EDF = 0.5569 + 0.2508 * \log(C_{80})$$

$$DF = f_3 * [0.5569 + 0.2508 * \log(C_{80})]$$

- C80 is the coverages to reduce the SCI from 100 to 80
- C is the coverage level for the SCI to be calculated

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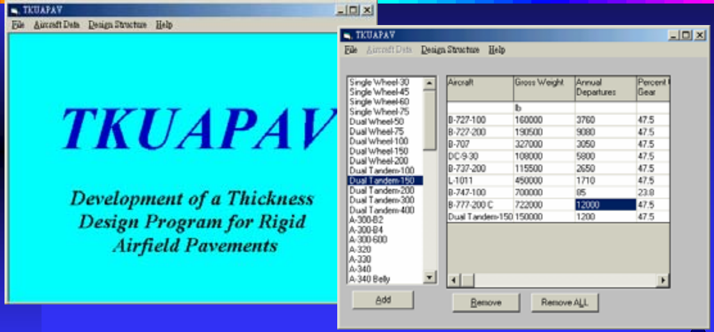
TKUAPAV Example Input (1)



Aircraft	Gross Weight	Annual Departures	Percent Gear
	lb		
B-727-100	160000	3760	47.5
B-727-200	190500	9080	47.5
B-707	327000	3050	47.5
DC-9-30	108000	5800	47.5
B-737-200	115500	2650	47.5
L-1011	450000	1710	47.5
B-747-100	700000	85	23.8
B-777-200 C	722000	12000	47.5
Dual Tandem-150	150000	1200	47.5

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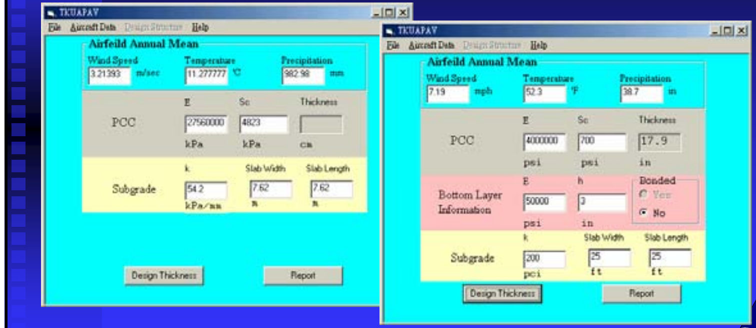
TKUAPAV Example Input (2)



Airfeild Annual Mean
Wind Speed 3.21393 m/sec
Temperature 11.277777 ℃
Precipitation 982.98 mm
PCC E 27560000 kPa
PCC Sc 4823 kPa
PCC Thickness cm
Subgrade k 54.2 kPa/mm
Subgrade Slab Width 7.62 m
Subgrade Slab Length 7.62 m

Airfeild Annual Mean
Wind Speed 7.19 mph
Temperature 52.3 °F
Precipitation 38.7 in
PCC E 4000000 psi
PCC Sc 700 psi
PCC Thickness 17.9 in
Bottom Layer Information E 50000 psi
Bottom Layer Information h 3 in
Bonded ○ Yes ● No
Subgrade k 200 pci
Subgrade Slab Width 25 ft
Subgrade Slab Length 25 ft

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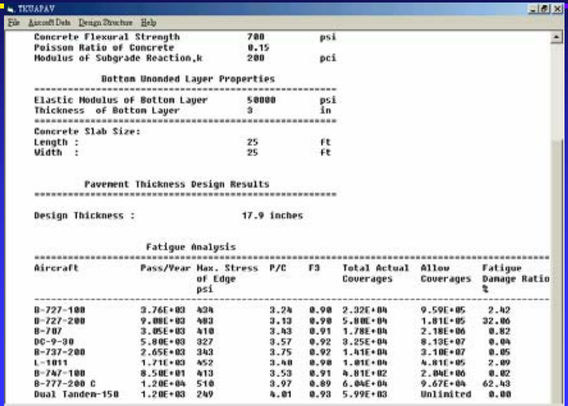
TKUAPAV Example Output



```
Concrete Flexural Strength          700          psi
Poisson Ratio of Concrete           0.15
Modulus of Subgrade Reaction,k      200          pci

            Bottom Unonded Layer Properties
=======================================================
Elastic Modulus of Bottom Layer     50000        psi
Thickness  of Bottom Layer          3            in
=======================================================
Concrete Slab Size:
Length :                            25           ft
Width  :                            25           ft


         Pavement Thickness Design Results
=======================================================

Design Thickness :                 17.9 inches


                  Fatigue Analysis
===============================================================================================
Aircraft            Pass/Year Max. Stress P/C    F3    Total Actual  Allow       Fatigue
                              of Edge                  Coverages     Coverages   Damage Ratio
                              psi                                                %
-----------------------------------------------------------------------------------------------
B-727-100           3.76E+03  434         3.24   0.90  2.32E+04      9.59E+05      2.42
B-727-200           9.08E+03  403         3.13   0.90  5.80E+04      1.81E+05     32.06
B-707               3.05E+03  410         3.43   0.91  1.78E+04      2.18E+06      0.82
DC-9-30             5.80E+03  327         3.57   0.92  3.25E+04      8.13E+07      0.04
B-737-200           2.65E+03  343         3.75   0.92  1.41E+04      3.10E+07      0.05
L-1011              1.71E+03  452         3.40   0.90  1.01E+04      4.81E+05      2.09
B-747-100           8.50E+01  413         3.53   0.91  4.81E+02      2.04E+06      0.02
B-777-200 C         1.20E+04  510         3.97   0.89  6.04E+04      9.67E+04     62.43
Dual Tandem-150     1.20E+03  249         4.01   0.93  5.99E+03      Unlimited     0.00
```

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Sensitivity Analysis of the Effect of a Second Layer

Bonded			
E_2=13.78 GPa		h_2 =15.2 cm	
h_2 (cm)	R_5	E_2 (GPa)	R_5
5.1	0.650	1.72	0.737
7.6	0.510	3.45	0.579
10.2	0.395	6.89	0.398
12.7	0.303	13.78	0.229
15.2	0.229	20.67	0.149

Unbonded			
E_2 = 0.17 GPa		h_2 =15.2 cm	
h_2 (cm)	R_5	E_2 (GPa)	R_5
0	1	0.17	0.999
15.2	0.999	0.34	0.997
30.5	0.989	0.69	0.995
		1.38	0.989
		2.07	0.984

Unbonded			
E_2 =13.78 GPa		h_2 =15.2 cm	
h_2 (cm)	R_5	E_2 (GPa)	R_5
0.0	1	1.72	0.987
7.6	0.987	3.45	0.973
15.2	0.902	6.89	0.948
22.9	0.734	13.78	0.902
30.5	0.544	20.67	0.860

- Unbonded Layer with Low Modulus ➔ Negligible
- Bonded Layer with High Modulus ➔ More Pronounced

Conclusions

- Reanalyzed the Corps of Engineers Test Data
- Utilized Prediction Models (Lee, et al., 1997) for Critical Edge Stress Estimation

$$\sigma_e = \sigma_{we} \times R_1 \times R_2 \times R_5 + \sigma_c * R_T$$

- Effect of a Subbase Layer (NCHRP Report 372)
  - Effect on the slab response (Adopted)
  - Not effect on k value
- Re-investigated Transformed Section Concept
  - Verified with ILLICON Program

Conclusions (Continued…)

- Climatic Data Obtained from the LTPP Database
- Resulting Stress Adjustment Factors
  - Finite slab length (0.964~1.0) and width (0.998~1.0)
  - Second unbonded layer (0.987~1.0)
  - Curling & warping (1.023~1.241)
- Proposed New Fatigue Relationship
  - Allow various new design features & curling
- Implemented in the TKUAPAV program
- http://teg.ce.tku.edu.tw/

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