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TKUAPAV: A New Thickness Design Program for Rigid Airfield Pavements

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ASCE

1995~2000 TAMKANG UNIVERSITY

Introduction

- Conventional FAA Design Procedure
  - Plate theory
  - Westergaard edge stress
- LEDFAA Design Procedure
  - Multi-Layered Linear Elastic Theory
- Question of B-777 Airplanes
  - Unduly Conservative
- Reevaluate Rigid Airfield Pavements Design Procedure

Research Approach

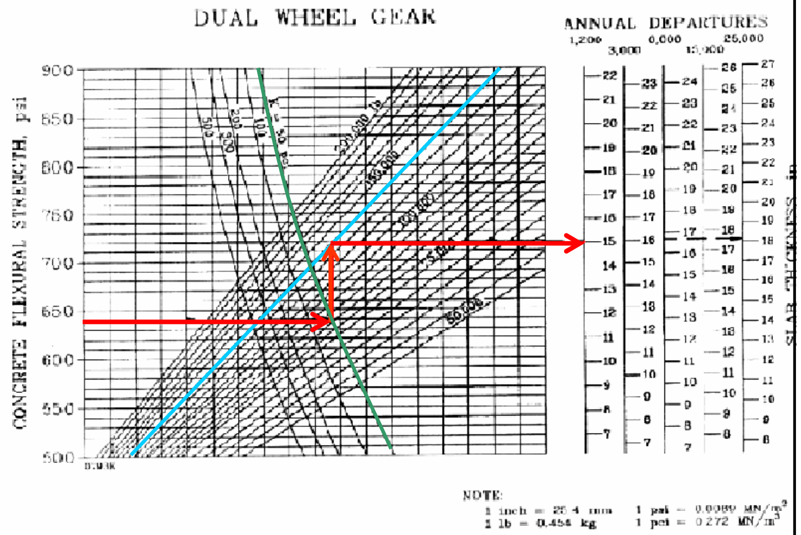
- Reevaluate Pass-to-Coverage Ratio Concept
- Estimation of Edge Stress for Design
- Conversion of Different Aircraft Types and Departures
- Fatigue Relationship and Thickness Design Criteria
- Investigation of Tentative Modification Alternatives
- Determination of Equivalent Stress Factor
- Alternative Structural Deterioration Relationship

Conventional FAA Design Method

- The Plate Theory & Westergaard Edge Stresses
- Pass-to-Coverage Ratio (P/C)
- Design Aircraft & Conversion Factors
- Fatigue Relationship
  - Coverages & Basic Thickness

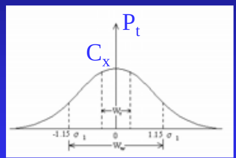
Design Aircraft & Conversion Factors

To Convert From	To	Multiply Departures by
single wheel	dual wheel	0.8
single wheel	dual tandem	0.5
dual wheel	dual tandem	0.6
double dual tandem	dual tandem	1.0
dual tandem	single wheel	2.0
dual tandem	dual wheel	1.7
dual wheel	single wheel	1.3
double dual tandem	dual wheel	1.7



Reevaluate P/C Ratio Concept

- Effect: Edge of a tire at 0 = Tire centerline at 0
- Extended to Multi-Wheels
- Reevaluated the P/C Concept



$$Coverages = \int_{-\frac{W_t}{2}}^{\frac{W_t}{2}} P_t(x)dx \approx (C_x)(W_t)$$

$$P_t(x) = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-u}{\sigma_x}\right)^2}$$

$$P/C = \frac{1}{(C_x)(W_t)}$$

Aircraft Type	FAA P/C Ratio	Calculated P/C Ratio	Aircraft Type	FAA P/C Ratio	Calculated P/C Ratio
SINGLE WH-30	5.18	6.22	C-130	4.15	4.58
SINGLE WH-45		5.56	L-1011	3.62	3.40
SINGLE WH-60		5.20	A-300-B2	3.51	3.45
SINGLE WH-75		4.97	A-300-B4	3.45	3.57
DUAL WH-50	3.48	3.71	B-757	3.88	3.90
DUAL WH-75		3.57	B-767	3.9	3.89
DUAL WH-100		3.53	DC-10-10	3.64	3.80
DUAL WH-150		3.24	DC-10-30	3.38	3.54
DUAL WH-200		3.25	DC-10-30Belly		2.88
DUAL TAN-100	3.68	4.55	B-747-200	3.7	3.53
DUAL TAN-200		3.73	B-747-SP		3.66
DUAL TAN-300		3.34	B-777-200A	N/A	4.21
DUAL TAN-400		3.14	B-777-200B		4.21
			B-777-200C		3.97

- Wheel spacing and tire width obtained from LEDFAA
- The standard deviation is assumed as 77.5 cm.

Stress Analysis of Conventional FAA Design Method

- Westergaard Critical Edge Stresses
- Pickett and Ray's Influence Charts
- Analysis of B-777 Airplanes
  - Unduly Conservative

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

- Only Applicable to U.S. Customary System

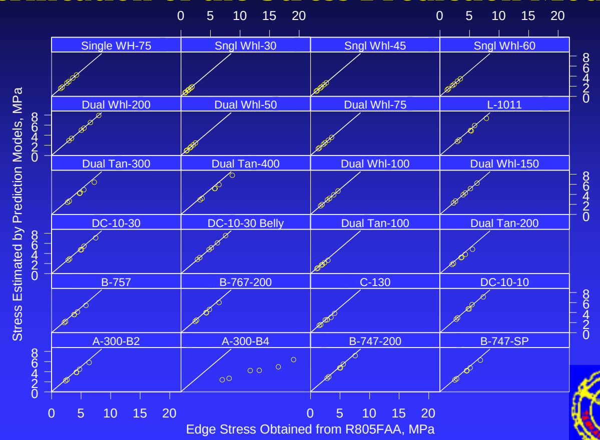
Estimation of Critical Edge Stress

$$\sigma_e = \sigma_{we} * R_1 * R_2 * R_3 * R_4 * R_5 + \sigma_{ce} * R_T$$

- σ_{we} : Westergaard edge stress
- R_1 : Gear configurations adjustment factor
- R_2 : Finite slab size adjustment factor
- R_3 : Concrete shoulder adjustment factor
- R_4 : Widened outer lane adjustment factor
- R_5 : Second layer adjustment factor

(Ref: Lee, et al., 1997)

Verification of the Stress Prediction Models



Conversion of Different Aircraft Types and Departures

- **Conversion Factors**
  - Conversion to equivalent annual departures of the design aircraft
  - "Arbitrary and Unverified" (Ahlvin 1991, p. 10-9) $\log R_1 = \log R_2 \times \sqrt{\frac{W_2}{W_1}}$
- Cumulative Damage Factor (CDF) in LEDFAA
  - Conversion is no longer necessary

Fatigue Relationship and Thickness Design Criteria (1)

- **Conventional FAA Design Procedure**
- Basic Thickness
- Design Factor = 1.3
- Fatigue Relationship

$$\sigma_e = \frac{S_c}{1.3 * 0.75}$$

$$h_1 = \left[\left(RC0 + RC1 \times \ln(\ell) + RC2 \times (\ln(\ell))^2 \right) \times \left(\frac{P}{\sigma_e} \right) \right]^{0.5}$$

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

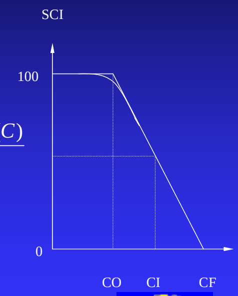
Fatigue Relationship and Thickness Design Criteria (2)

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

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

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

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



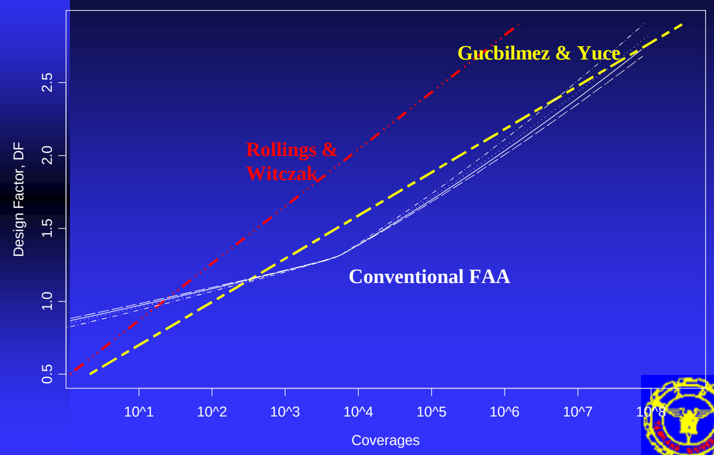
Fatigue Relationship and Thickness Design Criteria (3)

- **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)

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

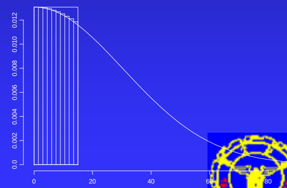
$$DF = 0.40289 + 0.29644 * \log(C80)$$

Comparison of Fatigue Relationships



Investigation of Tentative Modification Alternatives

- P/C Concept Assumed:
  - Effect: the edge of a tire at 0 = the tire centerline at 0
  - Maximum tensile stress should be used throughout when the centerline location of the lateral wheel load placement (L_c) falls within this tire print area
- Very crude & conservative application of CDF
- Prediction model for stress reduction due to D_o effect



Re-analyze Corps of Engineers Full-size Test Data

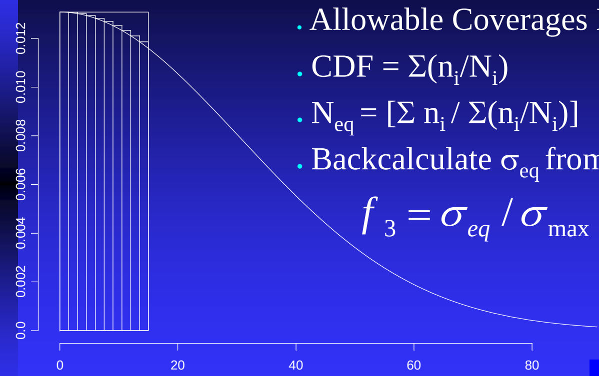
- Fatigue Relationships developed for CO, CI & CF

Tentative Fatigue Equations	SSE	R^2	N
DF = 0.4561 + 0.2928*log(CO)	0.108	0.822	24
DF = 0.3470 + 0.3013*log(CI)	0.125	0.818	36
DF = 0.1760 + 0.3119*log(CF)	0.122	0.775	24
DF = 0.3171 + 0.2894*log(PO)	0.114	0.804	24
DF = 0.2124 + 0.2953*log(PI)	0.131	0.800	36
DF = 0.0338 + 0.3074*log(PF)	0.127	0.755	24

- Similar to Gucbilmez and Yuce's Equation

Determination of Equivalent Stress Factor

- **Equivalent Stress Factor (f_3)**
- Equivalent Damage Effect
- Cumulative Fatigue Damage $\Sigma(n_i/N_i)$
- Stress Prediction Models $\sigma_e = \sigma_{we} * R_1 * R_4$
  - σ_{we} : Westergaard edge stress
  - R_1 : Gear configurations adjustment factor
  - R_4 : Widened outer lane adjustment factor
- DF = $S_c / (0.75 * \sigma_e)$



- Assumed aircraft pass n_i
- Allowable Coverages N_i
- CDF = $\Sigma(n_i/N_i)$
- $N_{eq} = [\Sigma n_i / \Sigma(n_i/N_i)]$
- Backcalculate σ_{eq} from N_{eq}

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

Item	f_3	Item	f_3	Item	f_3	Item	f_3
A1.60	0.808	K2.100	0.859	U1.60	0.819	72	0.912
B2.66L	0.826	N1.86	0.840	E-6	0.872	73	0.901
B1.66L	0.796	N2.86	0.809	M-1	0.873	1-C5	0.833
C2.66S	0.826	O1.106	0.862	M-2	0.892	2-DT	0.873
C1.66S	0.795	O2.106	0.830	-	0.810	3-DT	0.883
D1.66	0.796	P1.812	0.835	59	0.887	2-C5	0.834
E2.66M	0.835	P2.812	0.806	60	0.856	4-DT	0.865
E1.66M	0.806	Q1.102	0.865	61	0.873	3-200	0.892
F1.80	0.835	Q2.102	0.833	62	0.888	4-200	0.891

- Gucbilmez and Yuce (1995)
- Assuming $1.273(\pi a^2) = 1.6 (W_t)^2$

Alternative Deterioration Relationship

- Equivalent Design Factor (EDF) = $S_c / (0.75 * \sigma_e * f_3)$

Tentative Fatigue Equations	SSE	R^2	N
EDF = 0.6421 + 0.2920*log(CO)	0.119	0.793	24
EDF = 0.5266 + 0.3037*log(CI)	0.136	0.792	36
EDF = 0.3697 + 0.3086*log(CF)	0.134	0.735	24
EDF = 0.5056 + 0.2879*log(PO)	0.125	0.771	24
EDF = 0.3911 + 0.2976*log(PI)	0.142	0.774	36
EDF = 0.2319 + 0.3032*log(PF)	0.140	0.712	24

Proposed Fatigue Relationship

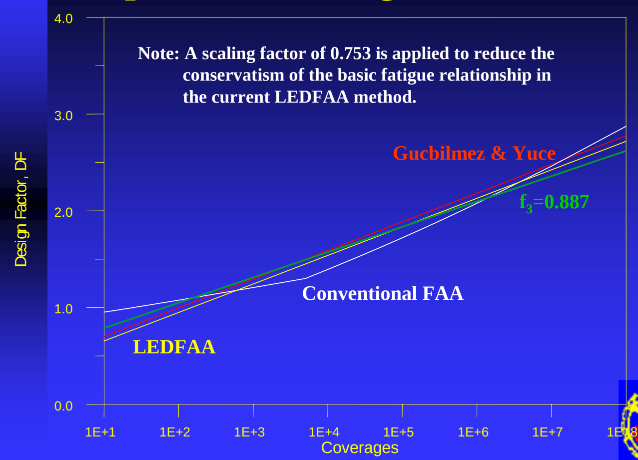
$$SCI = \frac{100 * \log(C) - 324.044 * EDF + 119.799}{0.184217 * EDF - 1.00098}$$

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

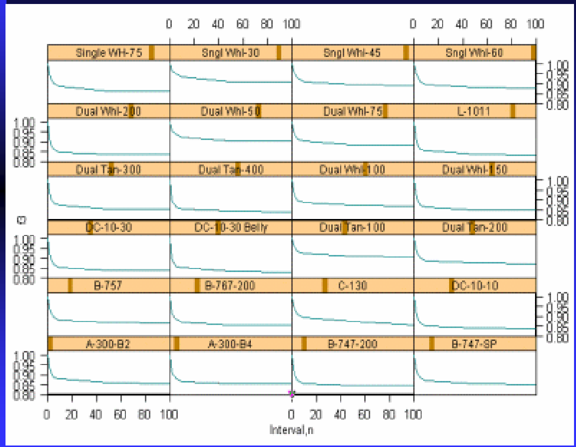
$$DF = f_3 * [0.5900 + 0.2952 * \log(C80)]$$

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

Comparison of Fatigue Relationships



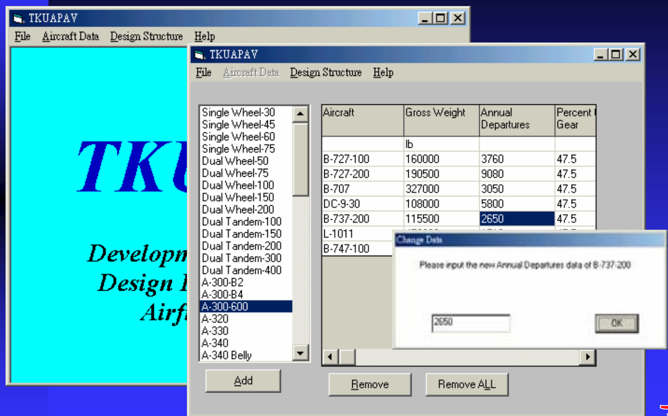
Sensitivity Analysis : f_3 - interval, n



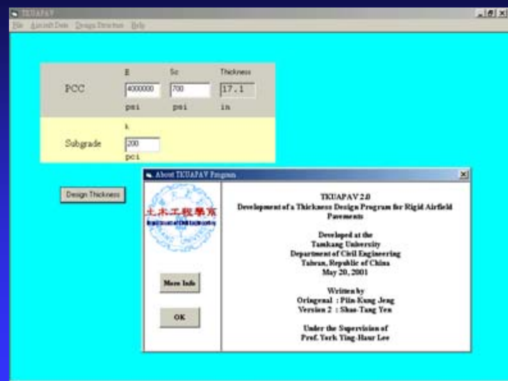
Implementation of the Proposed Approach

- Application of the P/C & CDF Concept
- Prediction Models for Critical Edge Stress
- Application of Equivalent Stress Factor (f_3)
- Alternative Fatigue Relationship
- Development of a User-friendly Computer Program (TKUAPAV) Using VB5.0

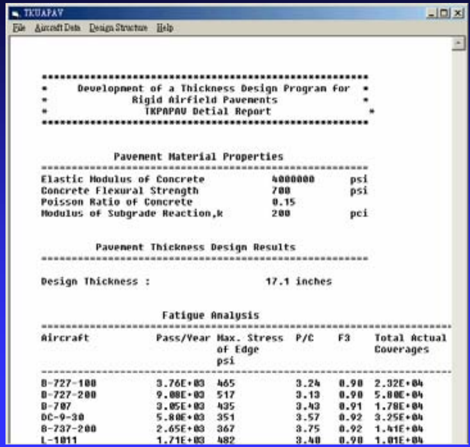
TKUAPAV Example Input (1)



TKUAPAV Example Input (2)



TKUAPAV Example Output



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TKUAPAV
File  Aircraft Data  Design Structure  Help

**********************************************************
*     Development of a Thickness Design Program for    *
*               Rigid Airfield Pavements               *
*                 TKPAPAV Detial Report                 *
**********************************************************

            Pavement Material Properties
==========================================================
Elastic Modulus of Concrete            4000000      psi
Concrete Flexural Strength             700          psi
Poisson Ratio of Concrete              0.15
Modulus of Subgrade Reaction,k         200          pci

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

Design Thickness :                    17.1 inches

                   Fatigue Analysis
=======================================================================
Aircraft            Pass/Year Max. Stress  P/C    F3    Total Actual
                              of Edge                   Coverages
                              psi
-----------------------------------------------------------------------
B-727-100           3.76E+03  465          3.24   0.90  2.32E+04
B-727-200           9.08E+03  517          3.13   0.90  5.80E+04
B-707               3.05E+03  435          3.43   0.91  1.78E+04
DC-9-30             5.80E+03  351          3.57   0.92  3.25E+04
B-737-200           2.65E+03  367          3.75   0.92  1.41E+04
L-1011              1.71E+03  482          3.40   0.90  1.01E+04
```

Case Study I

Aircraft Type	Gear Type	Annual Departures	Takeoff Weight lbs
B-727-100	Dual	5,000	45000
A-300-B2	D-Tandem	2,000	304,000
B-747-100	D-D-Tandem	85	700,000
A-300-B4	D-Tandem	Case I~IV	333,000

Case	A-300-B4 Departures	R805FAA in.	LEDFAA in.	TKUAPAV in.
I	0	14.5	14.6	14.8
II	100	28.5	14.8	14.9
III	1,000	29.5	15.4	15.6
IV	5,000	31.8	16.6	16.7

- 20 Years Design Life
- k = 130 pci
- Sc= 650 psi

Case Study II

Aircraft Type	Gear Type	Annual Departures	Takeoff Weight lbs
B-727-100	Dual	3,760	160,000
B-727-200	Dual	9,080	190,500
B-707-320B	D-Tandem	3,050	327,000
DC-9-30	Dual	5,800	108,000
B-737-200	Dual	2,650	115,500
L-1011-100	D-Tandem	1,710	450,000
B-747-100	D-D-Tandem	85	700,000
B-777-200C	D-Tridem	Case I~III	722,000

Case	Departures	R805FAA	LEDFAA	TKUAPAV
I	0	16.9″	17.6″	17.1″
II	1,200	--	17.6″	17.3″
III	12,000	--	17.6″	17.9″

- 20 Years Design Life
- k = 200 pci
- Sc= 700 psi

Case Study III

Aircraft Type	Gear Type	Annual Departures	Takeoff Weight lbs
D-T-300	Dual-Tandem	2,015	300,000
D-T-400	Dual-Tandem	445	400,000
B-747-400	D-D-Tandem	2,700	873,000
B-767-300ER	D-Tandem	1,200	405,000
B-777-200C	D-Tridem	Case I~IV	722,500

Case	Departures	LEDFAA in.	TKUAPAV in.
I	0	18.5	19.0
II	500	18.7	19.4
III	2,000	19.4	20.1
IV	5,000	20.2	20.8

- 20 Years Design Life
- k = 130 pci
- Sc= 650 psi

Conclusions (1)

- Reexamined the P/C Concept
- Proposed and Verified the Stress Prediction Models
  - Dimensionally Correct: Metric and English Systems
  - Other features: finite slab size, second layer, curling, etc.
- Identified the Problems and Difficulties for the Conversions of Aircraft Types and Departures
- The CDF Concept Should Be Used
- Investigated Various Fatigue Relationships & Thickness Design Criteria

Conclusions (2)

- A scaling factor of 0.753 is applied to reduce the conservatism of the basic fatigue relationship in the current LEDFAA method
- Reanalyzed the Corps of Engineers traffic data
- Introduced an equivalent stress factor (f_3) & EDF
  - f_3 factor decreases when tire width (W_t) increases
- Proposed an alternative fatigue relationship
- Developed a user-friendly PC program (TKUAPAV)
- Further investigations are warranted

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