

**DEVELOPMENT OF A NEW THICKNESS DESIGN PROGRAM FOR
RIGID AIRFIELD PAVEMENTS**

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DEVELOPMENT OF A NEW THICKNESS DESIGN PROGRAM FOR RIGID AIRFIELD PAVEMENTS

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Abstract

The main objective of this study is to develop a new thickness design program for rigid airfield pavements in attempts to accommodate the new-coming Boeing 777 airplanes based on the plate theory approach. The differences of the conventional FAA design method and the newly developed LEDFAA design methodology are investigated. The original concept of pass-to-coverage ratio is reevaluated. The prediction models developed by Lee, et al. (1997) are utilized for the estimation of critical edge stresses. The problems and difficulties of the conventional method especially in the conversions of different aircraft types are identified. The concept of cumulative damage factor is used to account for the combined damages of different aircraft types and departures. Structural deterioration relationships are compared and tentative modification alternatives are investigated. Consequently, an equivalent stress factor is introduced and an alternative structural deterioration model is proposed. The proposed approach has been implemented in a user-friendly computer program (TKUAPAV) for practical trial applications.

1. Introduction

The conventional Federal Aviation Administration's (FAA, 1995a) thickness design methodology for rigid airfield pavements was based on "the plate theory" and Westergaard's analytical solution for edge loading condition. When the main gear assembly is analyzed using the conventional FAA design procedures, however, the pavement thickness requirements are considered to be "unduly conservative" (FAA, 1995b), especially noticeable for flexible pavements on weak subgrades. Thus, FAA has recently issued a new Advisory Circular which entirely utilized "the multi-layered linear elastic theory" for the design of both flexible and rigid airfield pavements to accommodate the new-coming Boeing 777 airplanes (FAA, 1995b). Computerized design procedures are coded in the LEDFAA (Layered Elastic Design – Federal Aviation Administration) program. Nevertheless, the applicability of layered elastic theory in concrete pavement design has always been questioned and debated over the decades, which warrants the need for further investigations. Consequently, the main objective of this study was to develop a new thickness design program for rigid airfield pavements, particularly based on the conventional plate theory approach (Lee, et al., 1998).

2. Reevaluation of Pass-to-Coverage Concept

The pass-to-coverage ratio concept was developed based on the assumption of normally distributed airfield traffic. It was considered that coverage represents the maximum number of tire prints applied to the pavement surface at that point where maximum accumulation occurs. The effect of the edge of a tire at 0 is assumed as detrimental as the effect of the tire centerline at 0. Thus, the accumulations at 0 may be expressed by:

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

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

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

Where, $P_t(x)$ is the frequency of aircraft centerline passes per unit width; C_x is the maximum ordinate on the normal distribution curve; W_t is the tire width; x is the lateral placement of wheel center line; u is the mean value and σ_x is the standard deviation of the normal distribution curve. The area under the normal distribution curve is equal to 1.0. Thus, the reciprocal of coverage or $(C_x)(W_t)$ is referred to the pass-to-coverage (P/C) ratio. This method was extended to aircraft having many wheels by graphical addition of any number of single-wheel traffic distribution curves. As the wheel spacing (s) becomes smaller as shown in Figure 1, the general normal distribution curve for each single-wheel overlap can be expressed by:

$$P_C(x) = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{x}{\sigma_x} \right)^2} + \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{x-s}{\sigma_x} \right)^2} \tag{2}$$

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

In this case, graphical addition of the individual single-wheel curves results in a cumulative distribution curve with a maximum ordinate (C_{xc}) greater than that of either single-wheel curve (C_x). The area under the cumulative distribution curve is equal to 2.0. Thus, the coverage per one aircraft pass can be approximated by the value of $(C_{xc})(W_t)$. (Ahlvín, et al., 1971, pp. 75-80)

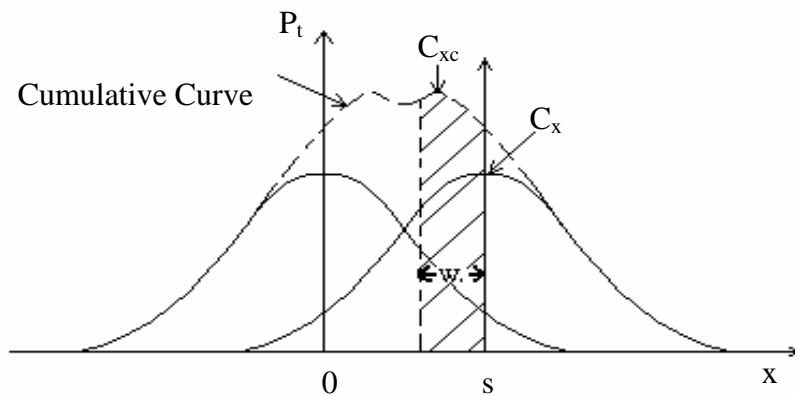


Figure 1 – General Normal Distribution for Overlapping Single Wheels

The P/C ratio concept was reexamined in this study. The P/C ratios reported in the conventional FAA design procedures for various gear assemblies and aircraft types are used for the analysis (FAA, 1995a). The wheel spacing and tire width values for specific aircraft types were not clearly specified in the conventional FAA method and thus were obtained from the LEDFAA program. The standard deviation of the lateral placement of wheel centerline was

assumed as 77.5 cm (30.5 in.) for all aircraft types. Customized functions were written using the S-PLUS statistical package (MathSoft, Inc., 1997) to conduct this analysis. The P/C ratios of Boeing 777 airplanes were also determined. As a result, the P/C concept was found in very good agreement with which described in the literature (Lee, et al., 1998).

3. Estimation of Critical Edge Stress for Design

The conventional FAA pavement design curves were developed using Westergaard edge loading analysis for rigid pavements. The edge loading stress was reduced by 25 percent to account for the effect of load transfer across the joints. This factor was chosen from test results and experience and continues in use today. As coded in the R805FAA program, the following equation was adopted to determine the critical edge stress (σ_e) of the slab using Pickett and Ray's influence charts and the concept of equivalent single wheel load (ESWL). The ratio of the concrete flexural strength (S_c) to the allowable slab tensile stress ($\sigma_a = 0.75 * \sigma_e$) is called a design factor (DF) or analogous to a safety factor.

$$\sigma_e = \frac{P}{h^2} \left[RC0 + RC1 \times \ln(\ell) + RC2 \times (\ln(\ell))^2 \right] \quad (3)$$

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

Where RC0, RC1 and RC2 are coefficients obtained using influence charts for various aircraft types and are provided along with the R805FAA program. P is the main landing gear load, lbs; σ_e is the critical edge tensile stress, psi; $\ell = (E * h^3 / (12 * (1 - \mu^2) * k))^{0.25}$ is the radius of relative stiffness, in.; E is the elastic modulus of the slab, psi; k is the modulus of subgrade reaction, psi/in; μ is the Poisson's Ratio, and h or h_1 is the slab thickness, in. Note that the above equation is only applicable to the U.S. customary system (English system) unless proper adjustments to the coefficients are made for metric system.

To expand the applicability of the Portland Cement Association's equivalent stress for different material properties, finite slab sizes, gear configurations, environmental effects (e.g., temperature differentials), and different unit systems, Lee, et al. (1997b) have developed prediction models for various stress adjustment factors using the well-known ILLI-SLAB FE program (Korovesis, 1990). The ILLI-SLAB program's applicability for stress estimation was further verified by reproducing very favorable results to the test sections of the Taiwan's second northern highway, the AASHO Road Test, and the Arlington Road Test (Lee, et al., 1997a). Thus, the following equations may be used for the estimation of critical edge stresses:

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

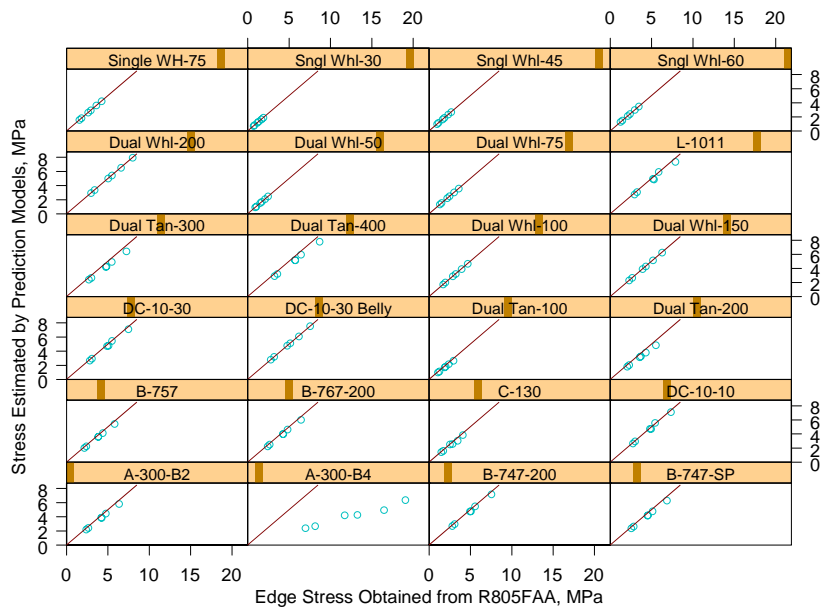
$$\sigma_{we} = \frac{3(1 + \mu)P}{\pi(3 + \mu)h^2} \left[\ln \frac{Eh^3}{100ka^4} + 1.84 - \frac{4}{3}\mu + \frac{1 - \mu}{2} + 1.18(1 + 2\mu) \frac{a}{\ell} \right] \quad (4)$$

$$\sigma_{ce} = \frac{CE\alpha\Delta T}{2} = \frac{E\alpha\Delta T}{2} \left\{ 1 - \frac{2 \cos \lambda \cosh \lambda}{\sin 2\lambda \sinh 2\lambda} (\tan \lambda + \tanh \lambda) \right\}$$

Where, σ_e is the predicted critical edge stress, $[FL^{-2}]$; σ_{we} is the Westergaard's (1948) closed-form edge stress solution, $[FL^{-2}]$; σ_{ce} is the Westergaard/Bradbury's edge curling stress, $[FL^{-2}]$ (Bradbury, 1938); C is the curling stress coefficient ($\lambda = B / ((8^{0.5}) * \ell)$); B is the finite slab length or width. P is main landing gear load, [F]; a is the applied load radius, [L]; α is the thermal expansion coefficient, $[T^{-1}]$; and ΔT is the temperature differential through the slab

thickness. R_1 is an adjustment (or multiplication) factor, which represents the combined effect of several prediction models for different gear configurations including dual-wheel, tandem axle, and tridem axle. R_2 , R_3 , R_4 , and R_5 are adjustment factors for finite slab length and width, a tied concrete shoulder; a widened outer lane, and a bonded / unbonded second layer, respectively. R_T is the adjustment factor for the combined effect of loading plus daytime curling. Since the proposed models were developed based on the principles of dimensional analysis, all the mechanistic variables involved in the prediction models are dimensionally correct or dimensionless. Thus, the above equation is applicable to the U.S. customary system and the metric system. More detailed descriptions of the proposed models for edge stress adjustments can be found elsewhere (Lee, et al., 1997b).

The applicability of the above prediction models for critical edge stress estimations is also reexamined in this study. The default characteristics of all aircraft types used in the analysis were obtained from the LEDFAA program. The corresponding RC0, RC1 and RC2 values for each aircraft type were obtained from the R805FAA program, except the B-777 airplanes. A wide variety of different pavement designs including $h = 30.5\sim 50.8$ cm (12~20 in.), $E = 27.6\sim 41.3$ GPa (4~6 million psi), and $k = 27\sim 108$ MN/m³ (100~400 pci) was chosen for the analysis. Critical edge stresses resulted from the main landing gear loads of different aircraft types on a very long slab were estimated using equation (3) and (4). In such a comparison, equation (4) was reduced to $\sigma_e = \sigma_{we} * R_1$, since the effects of R_2 , R_3 , R_4 , and R_5 are neglected and should have the same value of unity. Furthermore, the combined effect of loading plus curling was not considered here and thus R_T is equal to zero. As shown in Figure 2, the critical edge stresses obtained from the proposed prediction models (4) are indeed in very good agreement with those determined using equation (3) with the only exception of A-300-B4 aircraft type. It is believed, however, that the corresponding coefficients of RC0=2.24009, RC1=-1.18694 and RC2=0.314165 for A-300-B4 aircraft type were mistakenly recorded in the R805FAA program. Thus, equation (4) will be used as a supplemental equation to the original FAA's equation (3) for the estimation of critical edge stresses of A-300-B4 and B-777 aircraft types in the subsequent



analyses.

Figure 2 - Verification of the Proposed Stress Prediction Models

4. Conversion of Different Aircraft Types and Departures

Since the traffic forecast is a mixture of a variety of aircraft having different landing gear types and weights, the “design aircraft” concept was introduced to account for the effects of all traffic in the conventional FAA design methodology. Each aircraft type in the forecast should be checked in order to determine the required pavement thickness using the corresponding design curve with the forecasted annual departures. The design aircraft is the one that produces the greatest pavement thickness and is not necessarily the heaviest aircraft in the forecast. All aircraft must be converted to the same landing gear type as the design aircraft. Conversion factors, which represent “an approximation of the relative fatigue effects of different gear types,” have been established for both flexible and rigid pavements (FAA, 1995a, p. 25). After the aircraft have been grouped into the same landing gear configuration, the conversion to equivalent annual departures of the design aircraft is determined by:

$$\log R_1 = \log R_2 \times \sqrt{\frac{W_2}{W_1}} \quad (5)$$

Where, R_1 is the equivalent annual departures by the design aircraft; R_2 is the annual departures expressed in design aircraft landing gear; W_1 is the wheel load of the design aircraft; and W_2 is the wheel load of the aircraft in question. Wheel loads for wide body aircraft is taken as the wheel load for a 300,000-pound (136,100 kg) dual tandem aircraft for equivalent annual departure calculations.

Commonly, these equivalencies for the relative fatigue effects of different gear types are defined by a simple ratio of the evaluated total repetitions for the two loadings being compared for a selected pavement structure. However, it is noted that the load equivalencies, presently determined by the aforementioned conversion factors and equation (5), are not single valued and may vary widely for different levels of aircraft departures in this study. This conclusion is similar to the statement by Ahlvin (1991, p. 10-9) that “any simple ratio will be different for different magnitudes of load repetitions so that the adopted practice is arbitrary and unverified.” Thus, FAA (1995a, p.25) has also indicated that “much more precise and theoretically rigorous factors could be developed for different types and thickness of pavements.”

Consequently, the conventional “design aircraft” concept, conversion factors for different landing gear types, and equation (5) have been replaced by the concept of cumulative damage factor (CDF) in the new LEDFAA design methodology (FAA, 1995b). The cumulative damage effects of multiple aircraft types and departures are accounted for by using Miner’s hypothesis. This approach is more mechanistically based and will result in a single valued factor to represent the relative fatigue effects of different aircraft types for a given pavement structure. This single valued factor will vary widely for different aircraft loads, gear configurations and properties of pavement structure but not the magnitude of load repetitions. Several practical examples, showing such a conversion is more theoretically rigorous than the conventional FAA approach, were conducted (Lee, et al., 1998). Nevertheless, the conversion of different aircraft types and departures to equivalent annual departures of a specific aircraft type is no longer necessary and thus will not be further discussed hereafter.

5. Fatigue Relationship and Thickness Design Criteria

The conventional FAA thickness design methodology was based on an earlier fatigue curve developed by the Corps of Engineers from test track data and observation of full-scale test

pavements. The fatigue curve originally adopted a bilinear relationship between a design factor (DF) and the number of load repetitions (in terms of coverages, C) at the specified failure criteria. However, no explicit fatigue relationship is available elsewhere in the literature (FAA, 1995a). The method presently adopted for the determination of minimum required slab thickness for design is based on the basic thickness concept. A design factor of 1.3 was chosen to determine the allowable slab tensile stress for 5000 coverages. The thickness of pavement required to sustain 5,000 coverages of the design loading is considered to be the basic thickness (or 100 percent thickness). The required design thickness for the expected 20-year coverage levels is determined by the product of the basic thickness (h_1) and the percent thickness (or relative thickness, RH). The pertinent equations are summarized as follows:

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

$$h_1 = \left[\left(RC0 + RC1 \times \ln(\ell) + RC2 \times (\ln(\ell))^2 \right) \times \left(\frac{P}{\sigma_e} \right) \right]^{0.5} \tag{6}$$

$$RH = \begin{cases} 1 + 0.15603 * (\log(C) - 3.69897) & \text{if } C > 5000 \\ 1 + 0.07058 * (\log(C) - 3.69897) & \text{if } C < 5000 \end{cases} \tag{7}$$

Equation (7) was identified under this study by finally checking into the source code of the R805FAA program, since it was often presented in a graphical form elsewhere (FAA, 1995a). For any given pavement structure with known slab thickness, concrete modulus of rupture, elastic modulus of the slab and subgrade modulus, the allowable number of load repetitions (in terms of coverages) of a specific aircraft and wheel load may be determined through a very simple backcalculation process. Thus, the above equations are analogous to a fatigue relationship. However, it is worth of mentioning that the relationship between a design factor (DF) and coverages (C) derived from the above equations is not a unique curve any longer. As shown in Figure 3 (a), the fatigue curves showing a bilinear relationship and coincided at the point of DF=1.3 and C=5,000 are obtained for different sets of P, E, h, k, and S_c values for example.

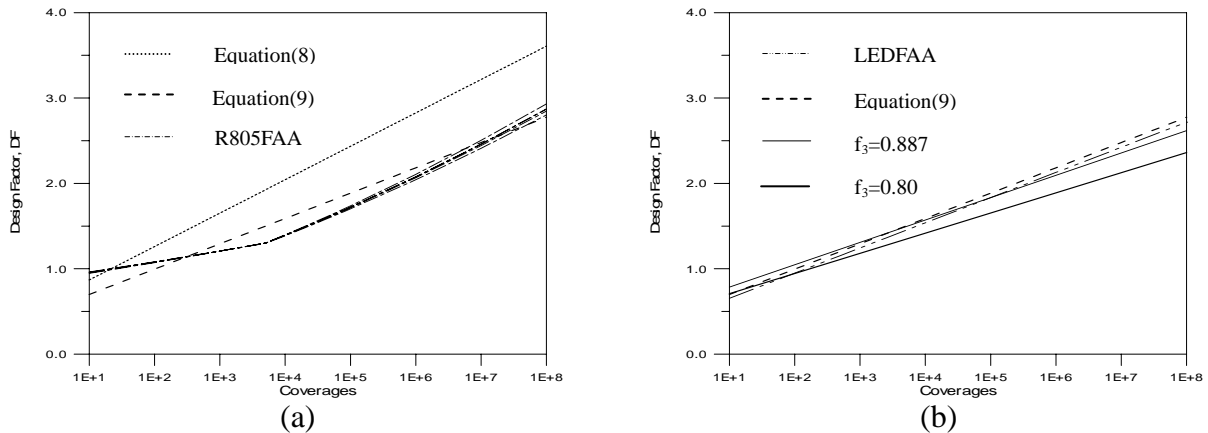


Figure 3 – Comparison of Fatigue Relationships for Rigid Airfield Pavement Design

Rollings and Witczak (1990) developed a structural deterioration model for rigid airfield pavements that predicts performance in terms of a structural condition index (SCI), a design factor (DF), the coverages at the onset of structural deterioration (CO) and the coverages at absolute failure (CF). The SCI is derived from the pavement condition index (PCI) considering

the distresses associated with tensile fatigue loading only and is on a scale from 0 to 100. The DF is defined as the ratio of flexural strength of concrete (S_c) and the critical tensile stresses (σ) calculated using the layered elastic pavement model. The basic fatigue relationship used to find the number of coverages (C) to failure in the LEDFAA program (FAA, 1995b; Rollings and Witczak, 1990) is as follows. Failure is defined as the number of coverages (C_{80}) to reduce the pavement SCI to 80 at any given value of DF or S_c/σ .

$$SCI = \frac{DF - 0.2967 - (0.3881 + 0.000039 * SCI) \log(C)}{0.002269} \quad (8)$$

$$DF = 0.4782 + 0.3912 * \log(C_{80})$$

Gucbilmez and Yuce (1995) reanalyzed the Corps of Engineers accelerated traffic data and provided an alternative rigid airfield pavement deterioration relationship using stresses calculated by the Westergaard edge loading idealization, i.e., plate on Winkler foundation. This relationship can be used to determine the expected structural condition of the pavement at a specified level of coverages or vice versa for pavements with joints capable of load transfer. The design factor is defined as $DF = S_c / (0.75 * \sigma_e)$ and the fatigue equation is given by:

$$SCI = \frac{100 * \log(C) - 320.61558DF + 56.4417}{0.20903DF - 0.99336} \quad (9)$$

$$DF = 0.40289 + 0.29644 * \log(C_{80})$$

Figure 3 (a) shows a comparison of the conventional FAA and the basic LEDFAA fatigue equations with the fatigue curve given in equation (9). It is noted that the fatigue curve obtained by Guccilmez and Yuce (1995) performs similarly with the conventional FAA fatigue curve given by equations (6) and (7), even though the specified failure criteria may be different. Generally speaking, the fatigue equation (9) requires a thicker pavement than the conventional FAA curve for a given coverage level above 1,000.

The coverages at failure (C_{80}) obtained from both fatigue equations (8) and (9) were implicitly tied to the manner in which critical tensile stress, or consequently the design factor, was determined. To make the layered elastic design procedure compatible with the conventional FAA thickness design procedure, an adjustment is made to the calculated layered elastic interior stress to provide an equivalent edge stress. The subgrade is assumed to be infinite in thickness and is characterized by either an elastic modulus (E) or modulus of subgrade reaction (k -value) in the current LEDFAA program. If a k -value is specified, it is converted to an equivalent E -value using a logarithmic relationship.

Fatigue failure expressed in terms of a "cumulative damage factor" (CDF) using Miner's hypothesis is adopted in the new LEDFAA thickness design approach. CDF is the amount of the consumed structural fatigue life and is expressed as the summation of the ratio of applied load repetitions to allowable load repetitions to failure. The LEDFAA program automatically calculates the damaging effects of each aircraft in the traffic mix. When the damaging effects of all aircraft sums to a value of 1.0, the design conditions have been satisfied and the required slab thickness is determined.

These comparisons show that a scaling factor is required to reduce the conservatism of the basic LEDFAA fatigue relationship. It is also noted that in the current LEDFAA method, a scaling factor of 0.753 is applied to stresses used to compute the design factor. As shown in Figure 3 (b), the resulting fatigue curve is similar to the conventional FAA curves and slightly less conservative than the relationship based on the Guccilmez and Yuce study.

6. Tentative Modification Alternatives

It is noted that the coverages at failure obtained from the fatigue curves were implicitly tied to the manner in which critical tensile stress was determined. The load magnitude and load repetitions to failure are certainly interrelated with the material properties of a given pavement structure. However, the use of P/C concept is in fact a rather crude application of cumulative damage concept. In addition, the location of the centerline of the lateral wheel load placement of each aircraft is considered to be coincident. This is not necessarily true and a further refinement is warranted. (Ahlvin, et al., 1971, p. 75; Ahlvin, 1991, p. 10-9; Parker, et al., 1979, p. 82)

The P/C concept is based on the assumption that the effect of the edge of a tire at 0 is as detrimental as the effect of the tire centerline at 0. In other words, the P/C concept also implies that 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 as shown in Figure 4. Thus, the well recognized effect of stress reduction due to the wandering of the L_c , moving away from the maximum tensile stress location, is totally neglected by the P/C concept. The P/C concept is indeed embedded with a very conservative means in estimating the cumulative fatigue damages of each aircraft type. In fact, when the concept of cumulative damage factor (CDF) is precisely used to evaluate pavement remaining life, the P/C concept becomes useless and may be given up.

To help formulate a unified approach for the design of rigid airfield pavements, tentative modification alternatives are further investigated. The effect of edge stress reduction due to the wandering of the L_c is often recognized as the effect of a widened outer lane in the literature. As a supplement to equation (4), the following prediction model was proposed by Lee, et al. (1997a) to account for the stress reduction due to the width of a widened outer lane (D_0). The L_c as previously defined in Figure 4 is equivalent to D_0 in equation (10).

$$R_4 = 0.61711 + 0.15373\Phi_1 + 0.02504\Phi_2$$

$$\Phi_1 = \begin{cases} 0.693 + 1.279(A1) + 0.369(A1)^2 + 0.037(A1)^3 & \text{if } A1 \leq -2.5 \\ 2.839 + 8.234(A1) + 8.158(A1)^2 + 3.608(A1)^3 + 0.576(A1)^4 & \text{if } A1 > -2.5 \end{cases}$$

$$\Phi_2 = \begin{cases} -2.285 + 5.921(A2) - 6.001(A2)^2 + 7.743(A2)^3 & \text{if } A2 \leq 0.5 \\ -3.008 + 4.693(A2) + 4.334(A2)^2 - 2.167(A2)^3 & \text{if } A2 > 0.5 \end{cases}$$

$$A1 = -0.98868\left(\frac{D_0}{\ell}\right) - 0.12214\left(\frac{a}{\ell}\right) - 0.08717\left(\frac{D_0}{a}\right) \quad (10)$$

$$A2 = 0.19802\left(\frac{D_0}{\ell}\right) + 0.98019\left(\frac{a}{\ell}\right) + 0.00305\left(\frac{D_0}{a}\right)$$

$$\text{Limits: } 0.1 \leq \frac{a}{\ell} \leq 0.4, \quad 0 \leq \frac{D_0}{\ell} \leq 2$$

6.1 Determination of Equivalent Stress Factor

The Corps of Engineers accelerated traffic data provided by Gucbilmez and Yuce (1995) was reanalyzed in this study. As given in Table 1, the coverages at the onset of structural deterioration (CO), the coverages at initial failure (CI), the coverages at absolute failure (CF), and the design factor (DF) are obtained. Critical edge stresses can also be determined by the proposed model given by equation (4) or by $\sigma_e = \sigma_{we} * R_1$. Very favorable agreements with those reported in that paper are observed. The radius of the wheel load (a) and the tire width (W_t) are obtained

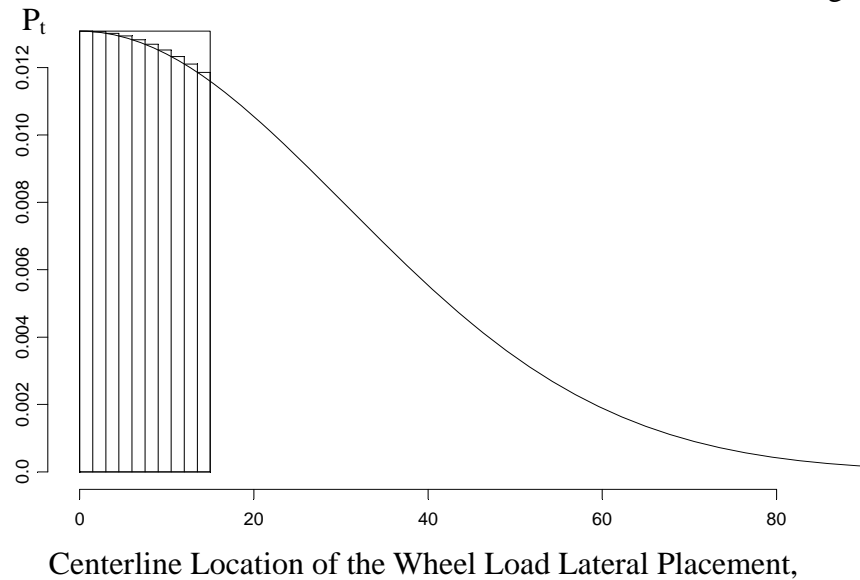


Figure 4 – Lateral Placement of the Centerline Location of the Wheel Load

using the relationship: $1.273(\pi a^2) = 1.6 (W_t)^2$, similar to that used in the LEDFAA program. More detailed descriptions of the data and original development of equation (9) can be found in the literature (Gucbilmez and Yuce, 1995).

The traffic at failure in terms of coverages assigned to each of the test pavements was for one type load and is implicitly tied to the manner in which the traffic was applied (Parker, et al., 1979, p. 80). The P/C ratio of each original test item was calculated using equation (1) and (2). The fatigue relationships developed for CO, CI and CF as functions of DF are labeled as models #1 to #3 in Table 2. Where, SSE is the standard error of estimate, R^2 is the coefficient of determination, and N is the number of observations. These three models are identical to those reported in Guccilmez and Yuce's paper and are the basic fatigue relationships used to develop equation (9).

Thus, research efforts are focused on the determination of "equivalent stress factor" (f_3) when the centerline location of the lateral wheel load placement (L_c) falls within the full tire print as shown in Figure 4, which is also compatible with the P/C concept. The equivalent stress factor (f_3) is often referred to be a value of 0.894 throughout in the Portland Cement Association's thickness design procedures for the determination of equivalent stress (Lee, et al., 1997b). The f_3 factor is defined in this study as the stress adjustment factor (or reduction factor) based on the equivalency of the cumulative fatigue damages to account for the lateral wandering effect of the L_c within the full tire print area and may be determined by the following procedures:

1. Select each test item or aircraft type, gear configurations and a standard deviation of the lateral distribution; input other pertinent design parameters such as slab modulus, subgrade modulus, concrete flexural strength, and slab thickness.
2. Assume a normally distributed aircraft pass data set (n_i) in smaller intervals, say 10 intervals, of the specified wheel width (W_t) as shown in Figure 4.
3. Calculate the critical edge stress using equations (4) and (10) for each interval, i.e., $\sigma_e = \sigma_{we} * R_1 * R_4$.
4. Calculate the corresponding allowable number of load repetitions (N_i) in terms of coverages for each interval using the fatigue relationship given by equation (9).
5. Calculate the cumulative fatigue damage $\Sigma(n_i/N_i)$ for the given aircraft pass data within the full tire print.
6. Determine the maximum edge stress (σ_{max}) or the critical edge stress of the first interval.

Table 1 – Reanalysis of the Corps of Engineers Accelerated Traffic Test Data

item	quality	CO	CF	CI	DF	a (cm)	Wt (cm)	P/C	f ₃
A1.60	A	13	59	45	0.855	36.16	57.17	3.31	0.808
B2.66L	B			187	0.948	28.06	44.37	4.11	0.826
B1.66L	A	3	96	35	0.679	36.16	57.17	3.31	0.796
C2.66S	A	48	636	200	0.934	28.06	44.37	4.11	0.826
C1.66S	A	13	92	44	0.667	36.16	57.17	3.31	0.795
D1.66	A	6	104	33	0.679	36.16	57.17	3.31	0.796
E2.66M	B			430	1.081	28.06	44.37	4.11	0.835
E1.66M	A	50	212	77	0.779	36.16	57.17	3.31	0.806
F1.80	B			111	0.967	36.16	57.17	3.31	0.835
K2.100	B			72	1.004	36.16	57.17	3.31	0.859
N1.86	A	105	285	150	1.096	36.16	57.17	3.31	0.840
N2.86	A	6	32	9	0.782	46.46	73.45	2.58	0.809
O1.106	A	347	1605	573	1.367	36.16	57.17	3.31	0.862
O2.106	A	41	155	72	0.959	46.46	73.45	2.58	0.830
P1.812	A	244	1148	262	1.078	36.16	57.17	3.31	0.835
P2.812	B			6	0.782	46.46	73.45	2.58	0.806
Q1.102	B			1390	1.484	36.16	57.17	3.31	0.865
Q2.102	A	36	237	57	1.055	46.46	73.45	2.58	0.833
U1.60	A	85	529	88	0.951	36.16	57.17	3.31	0.819
E-6	A	1343	13083	2204	1.383	54.65	86.40	2.25	0.872
M-1	A	68	379	134	1.005	23.52	37.19	2.98	0.873
M-2	A	1693	6781	2204	1.330	23.52	37.19	2.98	0.892
-	B			18	0.596	26.13	41.32	2.82	0.810
59	B			7600	1.246	23.42	37.02	3.17	0.887
60	B			1674	1.114	23.42	37.02	3.17	0.856
61	B			3867	1.355	23.42	37.02	3.17	0.873
62	B			10082	1.705	23.42	37.02	3.17	0.888
72	B			9680	1.714	23.41	37.01	2.99	0.912
73	A	662	7078	2115	1.365	23.41	37.01	2.99	0.901
1-C5	A	150	939	221	0.880	24.09	38.08	2.98	0.833
2-DT	A	128	477	95	0.896	20.63	32.61	3.86	0.873
3-DT	A	177	959	205	1.033	20.63	32.61	3.86	0.883
2-C5	A	292	783	344	1.133	24.09	38.08	2.98	0.834
4-DT	A	227	1092	320	1.208	20.63	32.61	3.86	0.865
3-200	A	939	4269	3215	1.443	23.42	37.02	3.40	0.892
4-200	A	1188	5741	4660	1.474	23.42	37.02	3.40	0.891

Note: Item name is the same item designation used by Gucbilmez and Yuce (1995). If the test item is suitable for use in the analysis of CO, CF, and CI, that item is referred to as “quality” class A. Class B is suitable for use in the analysis of CI only. Assuming $1.273(\pi a^2) = 1.6 (W_t)^2$.

Table2 – Alternative Structural Deterioration Relationships

Model No.	Tentative Fatigue Equations	SSE	R ²	N
#1	DF = 0.4561 + 0.2928*log(CO)	0.108	0.822	24
#2	DF = 0.3470 + 0.3013*log(CI)	0.1253	0.818	36
#3	DF = 0.1760 + 0.3119*log(CF)	0.122	0.775	24
#4	EDF = 0.6421 + 0.2920*log(CO)	0.119	0.793	24
#5	EDF = 0.5266 + 0.3037*log(CI)	0.136	0.792	36
#6	EDF = 0.3697 + 0.3086*log(CF)	0.134	0.735	24

7. Determine the equivalent allowable number of load repetitions (N_{eq}) by calculating the ratio of $\Sigma(n_i)$ and $\Sigma(n_i/N_i)$ assuming all aircraft passes applied on the maximum edge stress location.
8. Backcalculate the equivalent edge stress (σ_{eq}) using the obtained N_{eq} value and equation (9).
9. The equivalent stress factor (f_3) is determined by the ratio of σ_{eq} and σ_{max} .
10. Repeat steps (1) - (9) for each test item or aircraft type.

The equivalent stress factor (f_3) determined in such a manner is more mechanistically based in attempts to represent an approximation of equivalent cumulative fatigue damages. The f_3 factor may vary widely for different aircraft types, gear configurations, lateral distributions, and other pertinent design parameters.

6.2 Alternative Structural Deterioration Relationship

The f_3 value of each of the test item calculated based on the proposed procedure is given in Table 1. An equivalent design factor (EDF) is defined by $EDF = S_c / (0.75 * \sigma_e * f_3)$ to account for the reduction of critical edge stress. Similarly, fatigue relationships developed for CO, CI and CF as functions of EDF are listed as models #4 to #6 in Table 2. The structural deterioration of a pavement slab at a given coverage level defined by Gucbilmaz and Yuce (1995) is as follows:

$$SCI = 100 \left(\frac{\log(CF / C)}{\log(CF / CO)} \right) \quad (11)$$

Where, C is the coverage level at which the SCI is to be calculated. The following fatigue relationship is obtained by solving models #4 and #6 for CO and CF and then replacing them in the above equation. The C_{80} is the coverages to reduce the pavement SCI from 100 to 80.

$$SCI = \frac{100 * \log(C) - 324.044(EDF) + 119.799}{0.184217(EDF) - 1.00098} \quad (12)$$

$$EDF = 0.5900 + 0.2952 * \log(C_{80})$$

$$DF = f_3 * [0.5900 + 0.2952 * \log(C_{80})]$$

The sensitivity analysis of f_3 factor was conducted. Generally speaking, the f_3 factor increases when slab thickness (h), subgrade modulus (k), and/or concrete modulus of rupture (S_c) increases. The f_3 factor is not very sensitive to the increase in slab modulus (E); however, the f_3 value decreases when the tire width (W_t) increases. The structural deterioration relationship

given by equation (12) is also compared to the fatigue curves discussed earlier. As shown in Figure 3 (b), the fatigue curve labeled as $f_3 = 0.887$, which is the average value obtained from the analysis, performs similarly to that defined by equation (9). A relative low value of $f_3 = 0.80$ was chosen and the corresponding fatigue curve is plotted in Figure 3 (b) just to show how differently the proposed model will perform. The fatigue curve labeled as $f_3 = 0.80$ requires the least slab thickness overall.

7. Implementation of the Proposed Approach

In brief, the following procedures are proposed to determine the required minimum slab thickness for rigid airfield pavement design:

1. Assume a trial slab thickness; input other pertinent design factors, material properties and the expected departures of different aircraft types.
2. Determine the P/C ratio for each aircraft type using the aforementioned procedures.
3. Determine the equivalent stress factor (f_3) for each aircraft type based on the procedures described in Section 6.1.
4. Convert the expected aircraft departures (or passes) to coverages (n_i).
5. Calculate the critical edge stress for each aircraft type using equation (4).
6. Determine the allowable number of load repetitions in terms of coverages (C80) for each aircraft type (N_i) according to the proposed fatigue relationship, i.e. equation (12).
7. Check if the cumulative damage factor, $CDF = \sum(n_i/N_i) < 100\%$.
8. If not, assume a different slab thickness and repeat previous steps (1) - (7) again to obtain the minimum required slab thickness.

Specially customized S-PLUS functions were written to conduct the analysis in a very consistent manner. The proposed approach has also been implemented in a highly user-friendly computer program (TKUAPAV) using Microsoft Visual Basic software package (Microsoft Taiwan Corp., 1997). Example input and output screens of the TKUAPAV program are shown in Figure 5.

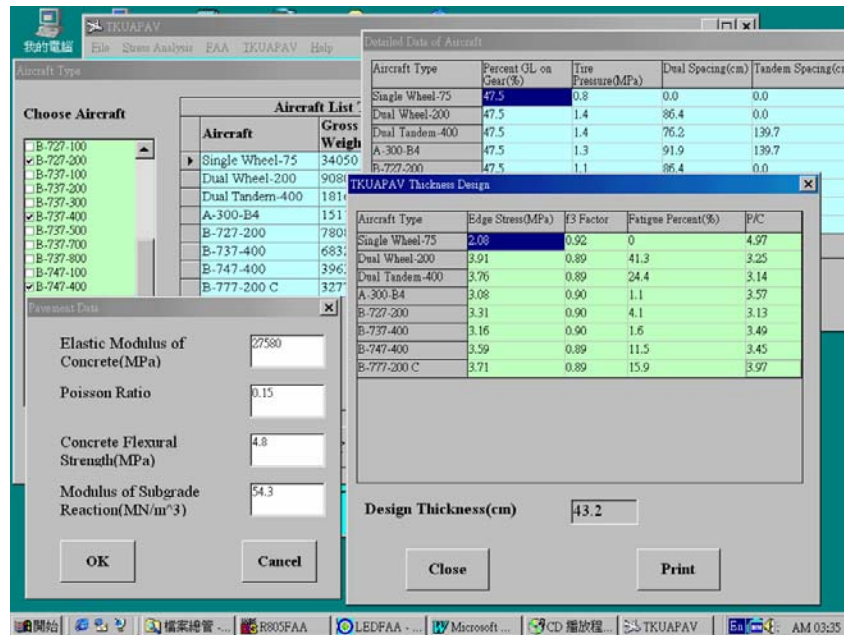


Figure 5 – Example Input and Output Screens of the TKUAPAV Program

8. Conclusions and Recommendations

Many research findings and conclusions are obtained from this study. Firstly, the original P/C concept was reexamined and the P/C ratio of B-777 airplane was determined. Prediction models for the estimation of critical edge stresses are proposed and verified. The proposed models were developed on the basis of the principles of dimensional analysis and thus are applicable to both of the U.S. customary system and the metric system. The problems and difficulties of the conventional FAA method in the conversions of different aircraft types and departures are identified. The concept of cumulative damage factor (CDF) is used to account for the combined damage effects of different aircraft types and departures. In fact, when the CDF concept is precisely employed to evaluate pavement remaining life, the P/C concept may be given up.

Comparison of the conventional FAA and the basic LEDFAA fatigue relationships with the fatigue curve obtained by Gucbilmez and Yuce (1995) was conducted. These comparisons show that a scaling factor is required to reduce the conservatism of the basic LEDFAA fatigue relationship. It is noted that in the current LEDFAA method, a scaling factor of 0.753 is applied to stresses used to compute the design factor. The resulting fatigue curve is similar to the conventional FAA curves and slightly less conservative than the relationship based on the Gucbilmez and Yuce study.

The well recognized effect of stress reduction due to the wandering of the centerline location of the lateral wheel load placement (L_c), moving away from the maximum tensile stress location, is totally neglected by the use of P/C concept. Thus, the Corps of Engineers accelerated traffic data provided by Gucbilmez and Yuce (1995) is reanalyzed. An equivalent stress factor (f_3) based on the equivalency of the cumulative fatigue damages to account for the lateral wandering effect of the L_c within the full tire print area is introduced. An equivalent design factor (EDF) is also defined to account for the reduction of critical edge stress. Alternative structural deterioration relationship given by equation (12) is obtained. This fatigue relationship is in very good agreement with the performance trend of the existing fatigue curves.

The f_3 factor may vary widely for different aircraft types, gear configurations, lateral distributions, and other pertinent design parameters. Generally speaking, the f_3 factor decreases when the tire width (W_t) increases. The proposed approach has been implemented in a user-friendly computer program (TKUAPAV) for practical trial applications.

It is also noted that the effects of finite slab sizes, temperature differentials, and a bonded/unbonded second layer may be analyzed using the proposed edge stress prediction models. However, further investigations in this respect are warranted in attempts to provide a more economic and maintenance-free design of rigid airfield pavements. A slightly thicker pavement is recommended until damaging potential of B-777 aircraft has been well defined by full scale testing.

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