Reevaluation of the FAA Thickness Design Procedures for Rigid Airfield Pavements

Dr. Ying-Haur Lee
Mr. Ping-Kung Cheng
Mr. Shao-Tang Yen

Department of Civil Engineering
Tamkang University
Taiwan, Republic of China

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Ying-Haur Lee, Ping-Kung Cheng, and Shao-Tang Yen
Department of Civil Engineering, Tamkang University
Taiwan, Republic of China

Summary

The main objective of this study is to reevaluate the current design methodology 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 for design. The problems and difficulties of the conventional method especially in the conversions of different aircraft types are identified. The concept of cumulative damage factor should be used to account for the combined damages of different aircraft types and departures. Structural deterioration relationships are compared and tentative modification alternatives are explored. Consequently, the concept of an equivalent stress factor is introduced and an alternative structural deterioration model is proposed for trial design 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, the pavement thickness requirements are considered to be unduly conservative (FAA, 1995b), especially noticeable for flexible pavements. 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 Association) 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 reevaluate the current design methodology 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:

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

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

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

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 of the normal distribution curve; and σ_x is the standard deviation of the normal distribution curve. Thus, the reciprocal of coverage or $(C_i)(W_t)$ is referred to as 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, the general normal distribution curve for each single-wheel overlap can be expressed by:

$$P_C(x) = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x}{\sigma_x}\right)^2} + \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{X-S}{\sigma_X}\right)^2} \qquad (2)$$

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

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). Thus, the coverage per one aircraft pass can be approximated by the value of $(C_{xc})(W_t)$. (Ahlvin, et al., 1971, pp. 75-80)

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 not clearly specified and 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. 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.

$$\sigma_e = \frac{P}{h^2}\left[RC0 + RC1 \times \ln(\ell) + RC2 \times (\ln(\ell))^2\right]$$
$$DF = \frac{S_c}{0.75 * \sigma_e} \tag{3}$$

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 in the U.S. customary system (English system). Proper adjustments to the coefficients should be made in order to use the equation with pertinent input variables in metric system.

To expand the applicability of the PCA'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 equation 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 closed-form edge stress solution, $[FL^{-2}]$; σ_{ce} is the Westergaard/Bradbury's edge curling stress, $[FL^{-2}]$; 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.

It should be emphasized that the proposed models were developed on the basis of 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 prediction models for edge stress adjustments can be found in the literature (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 = 30.5~50.8 cm (12~20 in.), E = 27.6~41.3 Gpa (4~6 Mpsi), and k = 27~108 MN/m^3 (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 equations (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 1, 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.

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:

$$\log R_1 = \log R_2 \times \sqrt{\frac{W_2}{W_1}} \tag{5}$$

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 in this paper.

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:

$$\sigma_e = \frac{S_c}{1.3 * 0.75}$$
$$h_1 = \left[\left(RC0 + RC1 \times \ln(\ell) + RC2 \times (\ln(\ell))^2 \right) \times \left(\frac{P}{\sigma_e} \right) \right]^{0.5} \tag{6}$$

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

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 2, 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.

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 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 (C80) to reduce the pavement SCI to 80 at any given value of DF or S_c/σ.

$$SCI = \frac{DF - 0.2967 - \left(0.3881 + 0.000039 * SCI\right)\log(\mathrm{C})}{0.002269} \tag{8}$$
$$DF = 0.4782 + 0.3912 * \log(\mathrm{C80})$$

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). The program converts k to E by using the following logarithmic relationship: log E = 1.415 + 1.284 log k. The complete procedure is to compute the interior layered elastic stress, compute 75 percent of the Westergaard edge stress, and then select the higher of the two as the working stress for design (σ) (FAA, 1995b). 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.

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. 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 * σ_e) and the equation is given by:

$$SCI = \frac{100 * \log(\mathrm{C}) - 320.61558DF + 56.4417}{0.20903DF - 0.99336} \qquad (9)$$
$$DF = 0.40289 + 0.29644 * \log(\mathrm{C80})$$

Figure 2 shows a comparison of the conventional FAA and the new LEDFAA fatigue equations with the fatigue curve given in equation (9). It is interesting to note that the fatigue equation (9) performs similarly with the conventional FAA fatigue curve given by equations (6) and (7), even though the specified failure criteria may be different. In general, the fatigue equation (9) requires a thicker pavement than the conventional FAA curve for a given coverage level above 1,000. The new LEDFAA fatigue curve given by equation (8) requires the greatest thickness overall under the same circumstances.

Both equations (8) and (9) were derived based on the same full-scale accelerated traffic tests and same failure criteria, i.e., SCI=80. But, why the fatigue curves change so much in terms of coverages at failure (C80) or a design factor (DF)? The answer to this speculation should be because of the means by which critical tensile stresses were calculated differently. Equation (8) was originally derived based on the interior layered elastic stress, whereas equation (9) was based on the Westergaard edge load stress. The coverages at failure (C80) obtained from both fatigue curves were implicitly tied to the manner in which critical tensile stress, or consequently the design factor, was determined. Preliminary analysis on critical stress estimation under this study has also found that 75 percent of Westergaard edge stress using the ILLI-SLAB model is often higher than the interior stress determined based on layered elastic theory using the BISAR computer code. Thus, the fatigue curves in Figure 2 are evident.

The new LEDFAA design methodology (FAA, 1995b) was adopted for the B-777 airplane and was intended to reduce some of the conservatism experienced with the conventional FAA design procedures. The new procedures may work well for the design of flexible pavements. However, it is unfortunately to know that this new methodology is biased by the means by which the working stress for design (σ) is determined for rigid airfield pavement design. The selection of the higher of the two stresses, determined by both the interior layered elastic model and 75 percent of the Westergaard edge stress, as the working stress for design is arbitrary and unsupported. The combination of the working stress and the fatigue curve given by equation (8) may result in even more conservative design thickness for B-777 airplanes, since the value of 75 percent of Westergaard edge stress is often higher than the other one. The use of equation (8) should be strictly limited to interior layered elastic stress only.

6. Investigation of Tentative Modification Alternatives

It is also 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 3 for example. 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.

To help formulate a unified approach for the design of rigid airfield pavements, tentative modification alternatives are further investigated as follows. The beneficial 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 3 is equivalent to D_0 in equation (10).

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

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

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

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

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

$$Limits: 0.1 \le \frac{a}{\ell} \le 0.4\ ,\ 0 \le \frac{D_0}{\ell} \le 2$$

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 $\sigma_e = \sigma_{we} * R_1$ and 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 using the relation $1.273(\pi a^2) = 1.6 (W_t)^2$, 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 equations (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. These three models are identical to those reported in Gucbilmez and Yuce's paper and are the basic fatigue relationships used to develop equation (9). In an attempt to investigate the possibility of the dismissal of the P/C concept, models #4 to #6 are developed for the passes at the onset of structural deterioration (PO), at initial failure (PI), and at absolute failure (PF) as functions of DF. Comparison between models #1 to #3 and models #4 to #6 respectively indicates that the inclusion of P/C concept slightly improves the fatigue relationships and corresponding regression statistics. It is still worth the effort to continuously use the P/C concept, even though the slopes are approximately the same and the mean difference of the intercepts in these models is about 0.14, which may be represented by 0.3*log(average P/C) approximately.

Thus, research efforts are focused on the determination of "equivalent stress factor" (f3) when the centerline location of the lateral wheel load placement (L_c) falls within the full tire print as shown in Figure 3, which is also compatible with the P/C concept. The equivalent stress factor (f3) is often referred to be a value of 0.894 throughout in the PCA thickness design procedures for the determination of equivalent stress (Lee, et al., 1997b). The f3 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 computerized 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 3.
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.
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 (f3) 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 (f3) determined in such a manner is more mechanistically based in attempts to represent an approximation of equivalent cumulative fatigue damages. The f3 factor may vary widely for different aircraft types, gear configurations, lateral distributions, and other pertinent design parameters. This proposed procedure has been further verified by producing an f3 value of 0.88 to 0.89, which is very close to 0.894 used by the PCA method, based on PCA's fatigue relationship and simplifications of other pertinent design parameters (Lee, et al., 1998).

6.2 Alternative Structural Deterioration Relationship

The f3 value of each of the test item was calculated based on the proposed procedure and is given in Table 1. An equivalent design factor (EDF) is defined by EDF = S_c / (0.75 * σ_e * f3) to account for the reduction of critical edge stress. Similarly, fatigue relationships are developed for CO, CI and CF as functions of EDF and are listed as models #7 to #9 in Table 2. Models #10 to #12 are developed for PO, PI, and PF as functions of EDF in a similar fashion.

Models #7 to #9 are proposed for subsequent analyses in this study. The structural deterioration of a pavement slab at a given coverage level defined by Gucbilmez and Yuce (1995) is as follows:

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

Where, C is the coverage level at which the SCI is to be calculated. The following fatigue relationship is obtained by solving models #7 and #9 for CO and CF and then replacing them in the above equation. The C80 is the coverages to reduce the pavement SCI from 100 to 80.

$$\begin{aligned} SCI &= \frac{100*\log(\mathrm{C}) - 324.044(EDF) + 119.799}{0.184217(EDF) - 1.00098} \\ EDF &= 0.5900 + 0.2952*\log(\mathrm{C80}) \qquad (12) \\ DF &= f3*[0.5900 + 0.2952*\log(\mathrm{C80})] \end{aligned}$$

The sensitivity analysis of f3 factor was conducted. Generally speaking, the f3 factor increases when slab thickness (h), subgrade modulus (k), and/or concrete modulus of rupture (S_c) increases. The f3 factor is not very sensitive to the increase in slab modulus (E); however, the f3 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 2, the fatigue curve labeled as f3 = 0.887, which is the average value obtained from the analysis, performs similarly to that defined by equation (9). A relative low value of f3 = 0.80 was chosen and the corresponding fatigue curve is plotted in Figure 2 just to show how differently the proposed model will perform. The fatigue curve labeled as f3=0.80 requires the least slab thickness overall. Since the f3 factor always has a value less than 1.0, the proposed deterioration relationship will also help to resolve the "unduly conservative" issue of the conventional FAA design methodology.

Currently, all the analyses were conducted using the S-PLUS statistical analysis software. Continuous research effort is still underway to implement the proposed approach into a highly user-friendly computer program using Microsoft Visual Basic software package (Microsoft Taiwan Corp., 1997) for trial applications.

7. Conclusions

Many research findings and conclusions can be 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) should be used instead.

Comparison of the conventional FAA and the new LEDFAA fatigue relationships with the fatigue curve obtained by Gucbilmez and Yuce was conducted. The new LEDFAA design methodology was intended to reduce some of the conservatism experienced with the conventional FAA design procedures. However, it is unfortunately to know that this new methodology is biased by the means by which the working stress for design (σ) is determined for the design of rigid airfield pavements. The selection of the higher of the two stresses, determined by both the interior layered elastic model and 75 percent of the Westergaard edge stress, as the working stress for design is arbitrary and unsupported. The combination of the working stress and the LEDFAA fatigue curve may result in even more conservative design thickness for B-777 airplanes. The use of LEDFAA fatigue relationship should be strictly limited to interior layered elastic stress only.

The "unduly conservative" aspect of the present design methodology when analyzing the main gear assembly of B-777 airplanes is probably tied to the manner in which critical tensile stress was determined. 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) are reanalyzed in this study. An equivalent stress factor (f3) 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 in this study. 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 and very reasonably agreement with the performance trend of the existing fatigue curves.

The f3 factor may vary widely for different aircraft types, gear configurations, lateral distributions, and other pertinent design parameters. The sensitivity analysis of f3 factor has indicated that it generally decreases when the tire width (W_t) increases. Since the f3 factor always has a value less than 1.0, the proposed deterioration relationship will also help to resolve the “unduly conservative” issue of conventional FAA design approach. Continuous research effort is still underway to implement the proposed approach into a user-friendly computer program for trial design applications.

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