# APPLICATION OF STATISTICAL APPROACH FOR THE CONCRETE AERODROME PAVEMENT DESIGN AND EVALUATION

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***Abstract:*** *The paper covers procedure for predicting of concrete airport pavements functional life reflecting statistical properties of design variables. Existing procedure do ignores stochastic nature of other main variables: aircraft takeoff weight, airplane traffic wander, in situ slab thickness, elastic modulus of concrete, modulus of subgrade reaction and climatic inputs causing thermal bending moments in the concrete and probability of its combined effect with bending moment in slab under traffic loadings expected from specific volume of mixed traffic and its distribution pattern. It is shown that functional life of concrete pavements depends on statistical variability of mechanical properties of materials, aircraft traffic mix loads and environmental condition.*

***Keywords:*** *airfield pavement, plate, elastic foundation, concrete pavement, airports, wheel load, repetitions, flexural strength, modulus of elasticity, slab, thickness, modulus of subgrade reaction, temperature, variability, probability, reliability.*

## I. INTRODUCTION

This report describes the analysis of current practice used in the Russian Federation for new concrete pavements design and evaluation. According to the Specification [1] concrete pavements are designed to serve a predicted number of load applications for twenty years at the lowest possible initial and maintenance costs. The main criteria for design of concrete slabs thickness is cracking initiated by aircraft wheel gears and thermal stresses. Repeated loading from the traffic mixture is converted into a single design aircraft. The design aircraft is determined as the most damaging heavy airplane. All annual departures of the traffic mixture are converted to equivalent number of annual departures of the design aircraft. Thickness design Specification [1] reflect only a realistic degree of variation in flexural strength of concrete applying 95% confidence level and thermal stress about 0,05-0,07 MPa considering its different signs during daily and night period and decrease due to subbase restraint stress. Existing procedure do ignores stochastic nature of other main variables: aircraft takeoff weight, airplane traffic wander, in situ slab thickness, elastic modulus of concrete, modulus of subgrade reaction and climatic inputs causing thermal bending moments in the concrete and probability of its combined effect with bending moment in slab under traffic loadings expected from specific volume of mixed traffic and its distribution pattern.

Analysis of concrete pavements performance life show that real serviceability age at civilian airports of Russian Federation differ from 3 to 30 years. One of the reasons of such deviation in the concrete performance life may be ignoring of the stochastic nature of the design inputs in the previous deterministic design guides.

## II. MAIN CONTENTS

### CURRENT PRACTICE

Deterministic design procedure include comparison of bending moments caused by aircraft loads at the outside edge of a concrete pavement and ultimate bending moment for given slab thickness using the following equation

$$m_d \le m_u , \tag{1}$$

where $m_d$ - bending moment in concrete slab caused by the design aircraft main gear arrangement at the outside edge of slab

$$m_d = m_c \cdot k , \tag{2}$$

$m_c$ - bending moment in concrete slab caused by design aircraft main gear wheels at the interior of the slab; k - factor to convert bending moment increase at the outside edge; $m_u$ - ultimate bending moment for given slab thickness, flexural strength of concrete at design age and number of load repetitions

$$m_u = \gamma_c \cdot R_{btb} \cdot \frac{h^2}{6} \cdot k_u , \tag{3}$$

$\gamma_c$ - factor to convert concrete strength increase with age and warping stresses which was not changed since 1960 year till nowadays, table 1.

***Table 1.***

| Pavement Sections | Meanings for $\gamma_c$ according to Specifications | | | |
|---|---|---|---|---|
| | СН-120-60 | СН-120-70 | СНиП 11- 47-80 | СНиП 2.05.08-85 СП 121.133.2012 |
| Taxiways | 0,8 | 0,8 | 0,8 | 0,8 |
| The ends of runways L= 150 m | 0,9 | 0,8 | 0,8 | 0,8 |
| Subdivisions of runway pavements $L_{RUNWAY}$/4 - 150 m, connecting to the runway ends | 0,9 | 0,9 | 0,9 | 0,9 |
| Runway middle pavement section | 0,9 | 0,9 | 0,9 | 0,9 |
| Edge parts of the runway middle pavement section | 1,1 | 1,1 | 1,1 | 1,1 |
| Exits, aprons and other special sections | 0,9 | 0,9 | 0,9 | 0,9 |

$R_{btb}$ - design modulus of rupture;

$K_u$ - load repetition factor to reflect fatigue effect in the concrete under repeated loading.

The results of flexural fatigue research show that under continued repetitions of loads failure of concrete beams occurs at stresses ratios of less than unity. Flexural fatigue of concrete is reflected in specification [1] by selection of load repetition factor Ku based on number of the heaviest aircraft undercarriage wheel passes expected during the pavement design life which is supposed to be equal 20 yeas

$$K_u = 2 - \frac{\lg(U_d)}{6}, \tag{4}$$

where $U_d$ - expected number of the heaviest aircraft main gear wheel load applications for design age of the pavement.

It should be noted that equation (4) corresponds with PCA fatigue model results published in 1973 [2, 3, 4, 5, 6] and may be expressed as follow

$$K_u = \frac{\gamma(N)}{\gamma\left(N = 1\cdot 10^6\right)} = \frac{\gamma(N)}{0,5}, \tag{5}$$

where $\gamma(N)$ - stress repetition ratio for $N_i$

$$\gamma(N) = \frac{\sigma_{N_i}}{R} = 1 - \frac{\lg(N)}{12}, \tag{6}$$

$\sigma_{N_i}$ - repetitive stress; $R$ - mean flexural strength of concrete; $N$ - number of repetitions to cause concrete flexural fatigue failure.

$\gamma(N = 1\cdot 10^6) = 0,5$ - stress ratio permitting $1\cdot 10^6$ load repetitions without loss of fatigue resistance of plain cement concrete in flexure test.

From equation (6) one can calculate number of repetitions $N_i$ to cause flexural rupture under stress $\sigma_{N_i}$

$$N_{\sigma_{Ni}} = 10^{12\cdot[1-\gamma(N_i)]}. \tag{7}$$

Under real pavement performance conditions stress ratio $\gamma(N_i)$ of concrete depends on stochastic nature of design variables which effect on the bending moments in the slab.

## SUGGESTIONS FOR THE CONCRETE PAVEMENTS THICKNESS DESIGN

Suggestions proposed here was developed from a study and correlation of the existing design procedures [1], statistical analysis of aircraft centerline deviations on runway and taxiway that were collected in reports [9-15, 17, 20-22], plate theory [2-6, 16, 18, 19], Miner fatigue law and theory of stochastic functions.

The equation (1) may be rewritten in the next form

$$(\overline{m}_F + \overline{m}_t) \cdot P_{Ft} \le k_p \cdot \overline{m}_u , \qquad (8)$$

where $\overline{m}_F$ - mean of the bending moment under main gear wheels loading calculated by formula (2); $\overline{m}_t$ - mean of the bending moment caused temperature calculated by the following equation [7]

$$\overline{m}_t = 0,0437\alpha \cdot h^2 \cdot E_b \cdot A , \qquad (9)$$

where $\alpha$ - coefficient of thermal expansion of concrete: $\alpha = 0,00001$; $h$ - slab thickness, $m$; $E_b$ - modulus of elasticity of concrete, Pa; $A$ - average difference of temperature between the bottom and upper surfaces of the slab during design period (spring or autumn); $P_{Ft}$ - probability to reflect the combined effect of the functions $\overline{m}_F$ и $\overline{m}_t$ on the summary bending moment in the slab under consideration

$$P_{Ft} = P(\overline{m}_F + \overline{m}_t) - P(\overline{m}_F) \cdot P(\overline{m}_t) \qquad (10)$$

$P(\overline{m}_F)$ - probability of the mean bending moment under main gear wheels; $P(\overline{m}_t)$ - probability of the mean thermal bending moment

$P(\overline{m}_F) = P(\overline{m}_t) = 0,5$, so by (9) $P_{Ft} = (0,5 + 0,5) - 0,5 \cdot 0,5 = 0,75$;

$\overline{m}_u$ - mean ultimate bending moment for slab thickness, flexural strength of concrete at design age and number of load repetitions calculated by equation (3); $K_p$ - parameter to adjust stochastic nature of the design inputs and design reliability of the concrete pavement [7]

$$K_p = \frac{1 - \sqrt{1 - \left\{ \left[ 1 - z_p^2 \cdot \frac{D_{Mf} + D_{Mt}}{(\overline{M}_f + \overline{M}_t)^2} \right] \cdot \left[ 1 - z_p^2 \cdot V_{Mu} \right] \right\}}}{1 - z_p^2 \cdot V_{Mu}}, \qquad (11)$$

$M_f$ - average bending moment in concrete stab caused by the design aircraft main gearwheels; $M_t$ - average bending moment due to temperature gradient between top and the bottom surfaces of slab; $M_u$ - average ultimate bending moment computed for given slab thickness and design modulus of rupture of the concrete; $K_p$ - statistical coefficient to account cumulative effects of variability of the takeoff weights of the airplanes, number of the full-load applications, flexural strength and modulus of elasticity of concrete, modulus of subgrade reaction, in situ pavement slabs thicknesses, surface pavement temperature amplitude and design reliability; $Z_p$ - standardized normal variant for $P$ level of pavement reliability; $D_{Mf}$ - variance of bending moment caused by designed gear load; $D_{Mt}$ - variance of bending moment due to temperature gradient between top and the bottom surfaces of slab

$$D_{M_f} = \left(\frac{\partial M_f}{\partial F_d}\right)^2 \cdot S_{F_d}^2 + \left(\frac{\partial M_f}{\partial E_B}\right)^2 \cdot S_{E_B}^2 + \left(\frac{\partial M_f}{\partial h}\right)^2 \cdot S_h^2 + \left(\frac{\partial M_f}{\partial K_s}\right)^2 \cdot S_{K_s}^2 ; \tag{12}$$

$$D_{M_t} = \left(\frac{\partial M_t}{\partial h}\right)^2 \cdot S_h^2 + \left(\frac{\partial M_t}{\partial E_B}\right) \cdot S_{E_B}^2 + \left(\frac{\partial M_t}{\partial A}\right)^2 \cdot S_A^2 ; \tag{13}$$

$$V_{M_u} = \frac{\sqrt{D_{M_u}}}{\bar{M}_u} ; \tag{14}$$

$$D_{M_u} = \left(\frac{\partial M_u}{\partial R}\right)^2 \cdot S_R^2 + \left(\frac{\partial M_u}{\partial h}\right)^2 \cdot S_h^2 + \left(\frac{\partial M_u}{\partial u}\right)^2 \cdot S_u^2 , \tag{15}$$

$S_{Fd}, S_{Eb}, S_h, S_{Ks}, S_A, S_R, S_u$ - standard deviations of wheel load, modulus elasticity of concrete, slab thickness, modulus of subgrade reaction, amplitude of temperature, flexural strength of concrete and number of loading; $\frac{\partial M}{\partial}$ - first partial derivative of stochastic function of bending moments with respect to the means of random variables: wheel load $F_d$ modulus of elasticity of concrete $E_b$ thickness of slab $h$, modulus of subgrade $K_s$, amplitude of pavement surface temperature $A$, flexural strength of concrete $R$ and number of load applications $U$

$$\frac{\partial M_f}{\partial F_d} = 0{,}018306\sqrt{P_a / \bar{F}_d^{3}} \cdot \sqrt[4]{\bar{E}_b \bar{h}^3 / \bar{k}_s} ; \tag{16}$$

$$\frac{\partial M_f}{\partial E_b} = 0{,}001749\sqrt{\bar{h}^3 / \bar{k}_s \cdot \bar{E}_b^{3}} - 0{,}013745\sqrt[4]{\bar{h}^3 / \bar{k}_s \bar{E}_b^{7}} ; \tag{17}$$

$$\frac{\partial M_f}{\partial h} = 0{,}013745\sqrt{P_a \cdot \bar{F}_d} \cdot \sqrt[4]{\bar{E}_b / \bar{h}^5 \bar{k}_s} + 0{,}005248 P_a \sqrt{\bar{E}_b / \bar{h} \cdot \bar{k}_s} ; \tag{18}$$

$$\frac{\partial M_f}{\partial k_s} = 0{,}022908\sqrt{P_a \cdot \bar{F}_d} \cdot \sqrt[4]{\bar{E}_b t^3 / \bar{k}_s^{9}} - 0{,}005247 P_a \sqrt{\bar{E}_b \bar{h}^3 / \bar{k}_s^{5}} ; \tag{19}$$

$$\frac{\partial M_t}{\partial h} = 0{,}0874\alpha \bar{h}\bar{E}_b\bar{A} ; \tag{20}$$

$$\frac{\partial M_t}{\partial E_b} = 0,0437\alpha \bar{h}^{-2} \cdot \bar{A} ; \quad (21)$$

$$\frac{\partial M_t}{\partial A} = 0,0437\alpha \bar{h}^{-2} \cdot \bar{E}_b ; \quad (22)$$

$$\frac{\partial M_u}{\partial R} = \alpha_1 \bar{h}^{-2} \left(2 - \lg \bar{U} / 6\right) ; \quad (23)$$

$$\frac{\partial M_u}{\partial h} = 2\alpha_1 \bar{R} \cdot \bar{h} \left(2 - \lg \bar{U} / 6\right) ; \quad (24)$$

$$\frac{\partial M_u}{\partial U} = -0,0724\alpha_1 \bar{R} \cdot \bar{h}^{-2} / \bar{U} ; \quad (25)$$

$\alpha_1$ - parameter to convert concrete flexural strength increase with age.

## NUMERICAL ANALYSIS

To investigate the influence of statistical variability of design parameters and given probability level on the concrete pavement functional life numerical analysis was performed under following conditions:

concrete slab thickness $\bar{h} = 0,3$ m ; coefficient of variation of slab thickness $V_h = 0,10$; average flexural strength of concrete $\bar{R} = 5,13 MPa$; coefficient of variation of concrete flexural strength $V_R = 0,135$; average modulus elasticity of concrete $\bar{E}_b = 3,24 \cdot 10^4$ MPa ; coefficient of variation of modulus of elasticity of concrete $V_E = 0,135$; average coefficient of subgrade reaction $\bar{K}_s = 51,6 MH / m^3$; coefficient of subgrade reaction $V_{K_S} = 0,30$; average amplitude of concrete surface pavement temperature $\bar{A} = 7,55^0 C$; coefficient of variation of amplitude $V_A = 0,33$; aircraft average take-off mass $\bar{M} = 206 \cdot t$; coefficient of take-off mass variation $V_M = 0,55$; average daily departures $\bar{U_i} = 60$; coefficient of daily take off number variation $V_u = 0,10$; number of tandem axes - 2; probability of main wheels passes $P_i(x) = 0,83$.

Values of parameter $K_p$ calculated by formulas (11) - (25) are given in the table 2.

***Table 2.*** *The results of numerical analysis*

| Design reliability level | 0,5 | 0,6 | 0,7 | 0,8 | 0,9 | 0,95 |
|---|---|---|---|---|---|---|
| Parameter $K_p$ | 1,0 | 0,95 | 0,90 | 0,84 | 0,77 | 0,72 |

## STATISTICAL APPROACH TO ESTIMATE THE FUNCTIONAL LIFE OF CONCRETE PAVEMENT

To account the stochastic nature of the design inputs and considering (8) the equation (7) may rewritten as follows

$$N_{\sigma_{N_i}} = 10^{12\left[1 - P_{Ft} \cdot \frac{(\overline{M_f} + \overline{M_t})}{K_p \overline{M_u}}\right]} \quad (26)$$

$\overline{M_f}$ - mean of bending moment in concrete stab caused by the wheels of main gear arrangement; $\overline{M_t}$ - mean of bending moment due to temperature gradient between the top and the bottom surfaces of slab; $\overline{M_u}$ - mean of ultimate bending moment computed for given slab thickness and design modulus of rupture of concrete; $K_p$ - statistical coefficient to account combined effect of variability of wheel loads, number of load repetitions, flexural strength and modulus of elasticity of concrete, modulus of subgrade reaction, thickness of slab and surface pavement temperature amplitude (11).

Detrimental effect $D$ caused by load applications $N_i$ may be calculated by formula

$$D = \frac{1}{N_{\sigma_{N_i}}} = \frac{1}{10^{12\left(1 - P_{Ft} \cdot \frac{(\overline{M_f} + \overline{M_t})}{k_p \overline{M_u}}\right)}} . \quad (27)$$

In common summary detrimental effect $D$ under repetition cycles of special aircraft traffic mix pattern is expressed by Miner's law [17, 18]

$$\sum_{i=1}^{k} \frac{N_{\sigma_i}}{N_{\sigma_{N_i}}} = 1 \ , \quad (28)$$

where $N_{\sigma i}$ - number of stress repetitions at outside edge of slab for $i$-th aircraft main undercarriage wheels for the design life may be calculated as follow

$$N_{\sigma_i} = n \cdot \left(365 - T_f\right) \cdot \Sigma k_{n_i} \cdot n_o \cdot U_i \cdot P_i\left(x\right), \quad (29)$$

where $n$ - design life of the concrete pavement; $T_f$ - number of days in the year when subgrade is in frozen condition; $K_{ni}$ - coefficient to convert the effect of particular aircraft to the effect of undercarriage assembly of the design aircraft; $n_0$ - number of tandem gears in undercarriage assembly of the particular aircraft; $U_i$ - number of daily departures of particular aircraft; $P_i(x)$ - probability to account lateral movement (airplane wander) and particular airplanes main gear and configurations on the transverse distribution of load applications on the pavement at the anticipated facility;

$$P_i\left(x\right) = P\left(x_1 \le x \le x_2\right) = \int_{x_1}^{x_2} f\left(x, \overline{x_i}, S_{x_i}\right) \ ; \quad (30)$$

$$f\left(x,\overline{x_i},S_{x_i}\right)=\frac{1}{S_{x_i}\sqrt{2n}}e^{-\frac{x-\overline{x_i}^{2}}{2S_{x_i}^{2}}}\,; \tag{31}$$

$$\left.\begin{aligned} x_1 &= x-\frac{b}{2} \\ x_2 &= x+\frac{b}{2} \end{aligned}\right\}, \tag{32}$$

where $f\left(x,\overline{x_i},S_{x_i}\right)$ - normal distribution function; $x_i$ and $S_{xi}$ - mean and standard deviation of aircraft wheel paths from pavement centerline or guideline marking; x - distance from longitudinal axis (centerline or guideline marking) of pavement to design section of slab, where load repetitions are determined; b - design traffic width

$$b=d+2R_i \tag{33}$$

d - distance between centers of contact areas of dual wheels;

$R_i$ - radius of main undercarriage wheel contact area for specific aircraft

$$R_i=\sqrt{\frac{F_{d_i}}{\pi\cdot P_a}} \tag{34}$$

$$F_{d_i}=\frac{\overline{M}_i\cdot g\cdot k_m}{n_m\cdot n_w}\cdot k_d\cdot\gamma_f \tag{35}$$

$F_{di}$ - wheel load, $N$; M - take-off mass for specific aircraft, t; g - acceleration of gravity; $K_m$ - percent of the maximum anticipated takeoff weight of the airplane on the main landing gears; $K_d$ - parameter to account dynamic impact of the airplane main gears wheels on the pavement; $\gamma_f$ - parameter to reflect wings lift; $n_m$ - number of main undercarriage assemblies; $n_w$ - number of wheels in undercarriage assembly.

Substitution formula (29) to (26) gives following equation to determine anticipated life of concrete pavement

$$n=10^{12\left[1-P_{Ft}\cdot\frac{(\bar{M}_f+\bar{M}_t)}{K_pM_u}\right]}\Big/(365-T_f)\cdot\sum_{i=1}^{k}k_{n_i}n_{o_i}u_i\cdot P_i\left(x\right) \tag{33}$$

Proposed equation allows more precisely evaluate number of load applications expected during pavement life from specific volume of mixed traffic, its distribution pattern, variability of flexural strength and elastic modulus of concrete, modulus of subgrade reaction, slab thickness, mean amplitude of surface pavement temperature, number of stress repetitions and design reliability level of pavement structure.

## III. CONCLUSION

It is shown that functional life of concrete pavements depends on statistical variability of mechanical properties of materials, aircraft traffic mix loads and environmental condition. That is why to predict pavement service life till cracking of concrete due to fatigue consumption will take place can be implemented only with certain probability. Procedure proposed in this paper may be considered as first step towards statistical approach in that direction. The results of that approach also underline the significance of quality control and statistical evaluations of test data of construction materials used for a particular airport pavement's project in situ. The use of statistical approach provides more realistic data to the cost estimator for a new particular project or pavement overlay design [19]. Probability distribution pattern for different traffic mix and statistical coefficient values, calculated for various regions of Russian Federation are proposed for adjustment to aerodrome's construction rules and to modify existing deterministic method [1].

It is important to note that functional pavement life define the moment of initial process of cracking caused by stress repetitions in a critical traffic width where the probability of design aircraft main leg wheels passes is maximum. That is why procedure proposed here requires modification to reflect cracking propagation in concrete slabs after initial cracks have developed. Also it is of interest to compare numerical value of functional life received by statistical approach to real serviceability age of concrete pavements designed by conventional deterministic methodology. Statistical analysis have shown that mean serviceability age of concrete pavements in Russian Federation airports is 11 years. That result has a good compromise with statistical approach using suggested form (33) at desired probability level $P = 0{,}95$.

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