21-osios jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis“ teminės konferencijos
TRANSPORTO INŽINERIJA IR VADYBA,
vykusios 2018 m. gegužės 4-5 d. Vilniuje, straipsnių rinkinys

Proceedings of the 21th Conference for Junior Researchers ‘Science – Future of Lithuania’
TRANSPORT ENGINEERING AND MANAGEMENT, 4-5 May 2018, Vilnius, Lithuania

Сборник статей 21-й конференции молодых ученых «Наука – будущее Литвы»
ИНЖЕНЕРИЯ ТРАНСПОРТА И ОРГАНИЗАЦИЯ ПЕРЕВОЗОК, 4-5 мая 2018 г., Вильнюс, Литва

AIRFIELD RIGID PAVEMENT THICKNESS DESIGN ACCOUNTING FOR TOP-DOWN CRACKING

Oleksandr Rodchenko

National Aviation University,
E–mail: rodchenko@nau.edu.ua

Abstract. The top-down cracking in concrete slabs has not been directly simulated in structural analysis models used for airfield rigid pavement design by the Ukrainian Standard. Empirical formulas for the calculation of top tensile stress and the coverages to failure using the criterion of top tensile stress are obtained. Computer program “Aerodrom 380” has been developed for the design of airfield rigid pavement. It provides the required thickness of a concrete slab needed to support an Airbus 380 over a particular subgrade, determines pavement anticipated life and uses the bottom and top tensile stresses as design factors.

Keywords: airfield rigid pavement, bottom tensile stress, fatigue failure, main landing gear, new large aircraft, top tensile stress, top-down cracking.

Introduction

In Ukraine, the conventional rigid pavement is a concrete pavement on a stabilized base. The improvement of the rigid pavement design is important, especially for pavement analysis under the impact of the main landing gears of new large aircraft Airbus 380 (A380-800).

The purpose of this research is to develop the formulas, and a computer program for airfield rigid pavement design under the impact of the A380–800 main landing gears.

The top-down cracking in concrete slabs has not been directly simulated in structural analysis models used for airfield rigid pavement design by the Ukrainian Standard (SNiP 2.05.08–85).

Top-down cracking

Full-scale rigid pavement tests at the National Airport Pavement Test Facility (NAPTF) of the Federal Aviation Administration (FAA) and the Airbus Pavement Experimental

Program (PEP) have shown that top-down cracking can occur under the loading of aircraft all main landing gears (Airbus 2005; Ricalde 2007). Guo (Guo, Pecht 2007) analysed the results of the NAPTF tests and observed that top-down cracks occurred in the longitudinal direction when the main landing gears moved near transverse joints. The strength at the top of the concrete slab could be 35 percent lower than at the bottom. The generalized longitudinal median crack (top to bottom) observed at the surface of the slabs trafficked by the two A380 bogies during the fatigue campaign of PEP should be related to high tensile stresses at the top of the concrete slab (Airbus 2005).

The effects of aircraft main landing gear configurations and the locations of airfield rigid pavement slabs are analyzed by Guo and Pecht. They focus on analyzing pavement behavior based on test data and finite element analysis (Guo, Pecht 2006). Roesler obtained the key slab loading locations on an airfield rigid pavement which alter the critical tensile stress at the top of the concrete slab (Roesler *et al.* 2007; Evangelista, Roesler 2008).

The ratio of top to bottom tensile stress is significantly higher for the full main landing gear analysis relative to the individual gear analysis (Roesler, Evangelista 2010).

The top tensile stress is more sensitive to thermal coefficient variation than equivalent temperature gradient variation. The bottom tensile stress shows higher sensitivity to equivalent temperature gradient variation. Portland cement concrete (PCC) slab thickness has the highest effect on top and bottom tensile stresses followed by PCC modulus and thermal coefficient for top tensile stresses and thermal coefficient for the bottom tensile stresses (Rezaei-Tarahomi *et al.* 2017).

Tensile stress at the bottom and top edge of the concrete slab as design factors

Computer program "Aerodrom 380" (in Ukrainian) is developed for airfield rigid pavement design and it has certificate of recognition (*Avtorske svidotstvo*… 2014). "Aerodrom 380" uses the maximum tensile stress at the bottom and top edge of the concrete slab as design factors. The maximum tensile stress at the bottom edge of the concrete slab (free-edge stress) equals interior stress multiplied by transition factor k = 1,5 (SNiP 2.05.08-85). If the concrete slab has joints the edge stress is equalled interior stress multiplied by transition factor k = 1,2 (SNiP 2.05.08-85). The interior stress at the bottom of the slab is determined using an interior loading condition.

The interior bending moment can be determined by using the following expression:

$$M_{\text{int}} = \frac{F_n k_d \gamma_f}{4}\left[0{,}1154 - 0{,}0902 \cdot \ln\left(\frac{\sqrt{\dfrac{F_n k_d \gamma_f}{10 \cdot \pi p_a}}}{20l}\right)\right] - \frac{F_n k_d \gamma_f}{4}\left[0{,}1506 \cdot \ln\frac{1{,}35}{l} + 0{,}0873 \cdot \ln\frac{1{,}7}{l}\right] + 0{,}00045 F_n k_d \gamma_f e^{\frac{1{,}7}{l}}, \quad (1)$$

where: F_n – maximum vertical wing gear ground load, kN (Airbus 2014); k_d – dynamic ratio, its value must be applied according to the Ukrainian Standard (SNiP 2.05.08-85); γ_f – derating factor, its value must be applied according to the Ukrainian Standard; p_a – tire pressure, MPa; l – radius of relative stiffness, m.

Radius of relative stiffness of two-layer concrete pavement on the stabilized base is determined according to the Ukrainian Standard (SNiP 2.05.08-85).

The maximum tensile stress at the top edge of the upper concrete slab is determined as follow:

$$\sigma_2 = \sigma_1(0{,}048\ln K + 0{,}457), \quad (2)$$

where: σ_1 – maximum tensile stress at the bottom edge of the upper concrete slab, MPa; K – subgrade ratio, MN/m^3.

The maximum tensile stress at the top edge of the lower lean concrete slab is determined as follow:

$$\sigma_4 = \sigma_3(0{,}088\ln K + 0{,}439), \quad (3)$$

where: σ_3 – maximum tensile stress at the bottom edge of the lower lean concrete slab, MPa; K – subgrade ratio, MN/m^3.

Computer program "Aerodrom 380" uses fatigue failure concept that is expressed in terms of a damage ratio (D). It is expressed as the ratio of applied load repetitions to allowable load repetitions. Thus damage ratio is determined by using FAA CDF (cumulative damage factor) formula (AC 150/5320-6F) but computer program "Aerodrom 380" determines two damage ratios for every structural layer:

$$D_1 = \frac{N \cdot T}{C_1 \cdot P}, \quad D_2 = \frac{N \cdot T}{C_2 \cdot P_T}, \quad (4)$$

$$D_3 = \frac{N \cdot T}{C_3 \cdot P}, \quad D_4 = \frac{N \cdot T}{C_4 \cdot P_T}, \quad (5)$$

where: D_1 – damage ratio for design factor expressed as the maximum tensile stress at the bottom edge of the upper concrete slab; D_2 – damage ratio for design factor expressed as the maximum tensile stress at the top edge of the upper concrete slab; D_3 – damage ratio for design factor expressed as the maximum tensile stress at the bottom edge of the lower lean concrete slab; D_4 – damage ratio for design factor expressed as the maximum tensile stress at the top edge of the lower lean concrete slab; N – annual departures; T – design life (20 years); C_1 – number of admissible cycles of loads for design factor expressed as the maximum tensile stress at the bottom edge of the upper concrete slab; C_2 – number of admissible cycles of loads for design factor expressed as the maximum top tensile stress; C_3 – number of admissible cycles of loads for design factor expressed as the maximum tensile stress at the bottom edge of the lower lean concrete slab; C_4 – number of admissible cycles of loads for design factor expressed as the maximum tensile stress at the top edge of the lower lean concrete slab; P – probability factor, it is the similarity of FAA pass to coverage ratio (PCR), it is determined by using HoSang method (HoSang 1975); P_T – probability factor for the top edge, it is equaled 4,15.

Probability factor P values are calculated for all current Airbus 380 weight variants (Table 1).

Table 1. Probability factor P

A380-800 Weight Variant (WV)	Maximum Ramp Weight, t	P
WV000	562	4,08
WV001	512	4,13
WV002	571	4,07
WV003	512	4,13
WV004	562	4,08
WV005	562	4,08
WV006	575	4,05
WV007	492	4,21
WV008	577	4,05
WV009	512	4,13

The number of admissible cycles of loads can be determined by using Stepushyn's expression (Stepushin 2001)

$$C = 10^{12[1-f]}, \quad f = \frac{\sigma_{\max}}{\gamma_c R}, \quad (6)$$

where: f – degree of relative mechanical stress level; σ_{max}– maximum tensile stress, MPa; γ_c – service factor; R –

standard concrete flexural strength measured at 28 days, MPa.

Stepushyn's expression (6) provides a fatigue function for determining the number of admissible cycles of loads permissible by concrete slab before it cracks.

Thus the number of admissible cycles of loads C_1, C_2, C_3 and C_4 are determined by using the following formulas:

$$C_1 = 10^{12[1-f_1]}, \quad f_1 = \frac{\sigma_1}{\gamma_c R_1}, \tag{7}$$

$$C_2 = 10^{12[1-f_2]}, \quad f_2 = \frac{\sigma_2}{0{,}65\gamma_c R_1}, \tag{8}$$

$$C_3 = 10^{12[1-f_3]}, \quad f_3 = \frac{\sigma_3}{1{,}28\gamma_c R_2}, \tag{9}$$

$$C_4 = 10^{12[1-f_4]}, \quad f_4 = \frac{\sigma_4}{0{,}832\gamma_c R_2}, \tag{10}$$

where: σ_1 – maximum tensile stress at the bottom edge of the upper concrete slab, MPa; σ_2 – maximum tensile stress at the top edge of the upper concrete slab, MPa; σ_3 – maximum tensile stress at the bottom edge of the lower lean concrete slab, MPa; σ_4 – maximum tensile stress at the top edge of the lower lean concrete slab, MPa; γ_c – service factor; R_1 – standard concrete flexural strength measured at 28 days of the upper concrete slab, MPa; R_2 – standard concrete flexural strength of the lower lean concrete slab, MPa.

The damage ratios must be equalled 1. Computer program "Aerodrom 380" determines the maximum damage ratio for desired conditions then it performs concrete slab thickness design. If damage ratio is less than one computer program decreases upper concrete slab thickness. If damage ratio is more than 1 "Aerodrom 380" increases upper concrete slab thickness. Computer program "Aerodrom 380" uses upper concrete slab thickness in the range 0,31-0,45 m. If upper concrete slab thickness tops 0,45 m program calculates pavement anticipated life T_a:

$$T_a = U/N, \tag{11}$$

where: U – number of allowable load repetitions for the maximum damage ratio, $U=C \cdot P$.

Comparing the results of airfield rigid pavement design using "Aerodrom 380" and FAARFIELD

FAARFIELD (Federal Aviation Administration Rigid and Flexible Iterative Elastic Layered Design) designs the concrete slab thickness based on the assumption of edge wheel loading. The gear load is located either tangent or perpendicular to the concrete slab edge, and the larger of the two stresses, reduced by 25 percent to account for load transfer through the joint, is taken as the design stress for determining the concrete slab thickness (Brill 2014; *AC 150/5320-6F* 2016; Doug 2016; Guo 2013).

"Aerodrom 380" and FAARFIELD pavement anticipated life analysis (Table 2) is performed for rigid pavements:

1. a 450-mm upper concrete slab (R_1=5,76 MPa, E_1=35300 MPa), service factor equals 0,75 (for parallel taxiway); 300-mm lower lean concrete slab (R_2=2,09 MPa, E_2=17000 MPa); 250-mm stabilized base (E_{sb}=4810 MPa), and Winkler foundation (60 MN/m^3); design aircraft A380-800 WV002 with maximum ramp weight of 571 t, 3650 annual departures;
2. a 420-mm upper concrete slab (R_1=5,76 MPa, E_{up}=35300 MPa), service factor equals 0,75 (for runway); 300-mm lower lean concrete slab (R_2=2,09 MPa, E_2=17000 MPa); 250-mm stabilized base (E_{sb}=3700 MPa), and Winkler foundation (60 MN/m^3); design aircraft A380-800 WV003 with maximum ramp weight of 512 t, 5000 annual departures;
3. a 420-mm upper concrete slab (R_1=5,24 MPa, E_1=32400 MPa), service factor equals 0,85 (apron); 200-mm lower lean concrete slab (R_2=2,09 MPa, E_2=17000 MPa); 150-mm stabilized base (E_{sb}=1950 MPa), and Winkler foundation (60 MN/m^3); design aircraft A380-800 WV003 with maximum ramp weight of 512 t, 10000 annual departures;
4. a 450-mm upper concrete slab (R_1=5,76 MPa, E_1=35300 MPa),service factor equals 0,75 (for runway); 300-mm lower lean concrete slab (R_2=2,09 MPa, E_2=17000 MPa); 200-mm stabilized base (E_{sb}=4810 MPa), and Winkler foundation (50 MN/m^3); design aircraft A380-800 WV003 with maximum ramp weight of 512 t, 5000 annual departures;
5. a 390-mm upper concrete slab (R_1=5,24 MPa, E_1=32400 MPa),service factor equals 0,90 (for apron); 250-mm lower lean concrete slab (R_2=2,09 MPa, E_2=17000 MPa); 200-mm stabilized base (E_{sb}=1950 MPa), and Winkler foundation (40 MN/m^3); design aircraft A380-800 WV007 with maximum ramp weight of 492 t, 2000 annual departures.

In the FAARFIELD computer program upper concrete slab is modeled as PCC overlay fully unbounded (its strength equals standard concrete flexural strength measured at 28 days multiplied by service factor); lower lean concrete slab is modeled as PCC slab (strength value of 3,45 MPa); stabilized base is modeled as variable stabilized base (rigid).

The airfield rigid pavement anticipated life calculated by "Aerodrom 380" is 47-93% of FAARFIELD pavement life (see Table 2).

In Table 3, the main features of computer program "Aerodrom 380" are shown in comparison with the Ukrainian Standard (SNiP 2.05.08-85) and the FAAR-

FIELD computer program. The fatigue model of the FAARFIELD computer program is two-staged (Bin, Balbo 2014).

Table 2. Pavement anticipated life

Design case	FAARFIELD Pavement Anticipated Life, Years	"Aerodrom 380" Pavement Anticipated Life, Years
1	23,9	11,1
2	31,7	17,0
3	16,1	11,3
4	27,8	15,0
5	24,7	23,0

Table 3. Airfield rigid pavement design methods

Feature	SNiP 2.05.08-85	FAARFIELD	Aerodrom 380
Design factor − maximum bottom tensile stress	+	+	+
Design factor − maximum top tensile stress	–	–	+
Design aircraft	+	–	+
Traffic mixture	–	+	–
Fatigue model	–	two-staged	one-staged

Thus the benefit of the "Aerodrom 380" computer program is two design factors which allow maximum bottom and top tensile stresses.

Conclusions

The "Aerodrom 380" computer program contains one-staged concept and lateral wander of the aircraft traffic (probability factor *P* or *PCR*). It uses different *PCR* values for every A380-800 weight variant (WV). The FAARFIELD computer program operates with one *PCR* value and changes tire pressure automatically when user increases or decreases A380-800 maximum ramp weight. FAARFIELD aircraft database does not include all A380-800 weight variants and engineer should set required maximum ramp weight manually.

The airfield rigid pavement anticipated life calculated by computer program "Aerodrom 380" is 47-93% of FAARFIELD pavement life. The using of research results and computer program "Aerodrom 380" will have to improve airfield rigid pavement thickness design.

References

Advisory Circular 150/5320-6F. 2016. *Airport Pavement Design and Evaluation*, US Department of Transportation, Federal Aviation Administration, USA Standard.

Airbus. 2005. *A380 Pavement Experimental Programme. Rigid phase*.Rigid P.E.P Brochure. Airbus, Toulouse.

Airbus. 2014. *A380. Aircraft characteristics – airport and maintenance planning*. Airbus S.A.S., France.

Avtorske svidotstvo Ukraine. *Computerna programa «Aerodrom 380»* / Rodchenko O. V. (Ukraine). – № 57948 ; data reestratsiy. 30.12.14.

Bin, C; Balbo, J. 2014. Comparing Results of Airport Pavement Concrete Slab Design Using Damage Models of FAARFIELD to MEPDG Concrete Fatigue Model [online], in *2014 FAA Worldwide Airport Technology Transfer Conference*, 5–7 August2014, Atlantic City, USA. Available at: http://www.airtech.tc.faa.gov/ATT2014/ Papers/P10049%20-%20Bin%20&%20Balbo.pdf.

Brill, D. R. 2014. FAARFIELD 1.4. Updates, Improvements and New Capabilities, in *XI ALACPA Seminar on Airport Pavements and IX FAA Workshop*, 3d of September, 2014, Santiago, Chile. 24 p.

Doug, J. 2016. Airport Pavement Design and Evaluation. Draft AC 150/5320-6F. FAARFIELD Software, in *ACC Summer Workshop*, 10th of August, 2016, Washington, USA. 24 p.

Evangelista, F.; Roesler, J. 2008. Is Top-Down Cracking Critical on Airfield Rigid Pavements? in *9th International Conference on Concrete Pavements*,17–21 August 2008, San Francisco, California, USA.

Fabre, C.; Balay, JM. 2008. The Airbus Pavement Experimental Programme and High Tire Pressure Test, in *3rd International Conference APT 2008*, 30 September – 3 October 2008, Madrid, Spain.

Guo, E.; Pecht, F. 2006. Critical Gear Configurations and Positions for Rigid Airport Pavements – Observations and Analysis, *Pavement Mechanics and Performance*: 7-14. http://dx.doi.org/10.1061/40866(198)2.

Guo, E.; Pecht, F. 2007. Application of Surface Strain Gages at the FAA NAPTF[online], in *2007 FAA Airport Technology Transfer Conference*, April 2007, Atlantic City, USA.

Guo, E. 2013. PCC Pavement Models in FAARFIELD Today and Tomorrow [online], in *Federal Aviation Administration Airport Pavement Working Group Meeting*, 15–17 April 2013, Atlantic City, USA.

HoSang, V. 1975. *Field Survey and Analysis of Aircraft Distribution on Airport Pavements* [online]. Report No. FAA-RD-74-36, Systems Research and Development Service Airport Division, Washington, USA.

Rezaei-Tarahomi, A.; Kaya, O.; Ceylan, H.; Gopalakrishnan, K.; Kim, S.; Brill D. 2017. Sensitivity Quantification of Airport Concrete Pavement Stress Responses Associated with Top-Down and Bottom-up Cracking – *International Journal of Pavement Research and Technology* 10 (2017): 410–420. http://dx.doi.org/10.1016/j.ijprt.2017.07.001.

Ricalde, L. 2007. Analysis of HWD Data from CC2 Traffic Tests at the National Airport Pavement Test Facility[online], in*2007 FAA Airport Technology Transfer Conference*, April 2007, Atlantic City, USA.

Roesler, J.; Evangelista, F.; Domingues M. 2007. Effect of Gear Positions on Airfield Rigid Pavement Critical Stress Locations [online], in *2007 FAA Airport Technology Transfer Conference*,April, 2007, Atlantic City, New Jersey, USA.

Roesler, J.; Evangelista, F. 2010. Top-down Cracking Predictions for Airfield Rigid Pavements[online], in *2010 FAA Worldwide Airport Technology Transfer Conference*, 20–22 April, 2010, Atlantic City, New Jersey, USA.

SNiP 2.05.08-85. *Aerodromy* [Airfields]. Ukrainian Standard.

Stepushin, A. 2001. K obosnovaniyu srokov slyzhby zestkih aerodromnyh pokrytiyizt sementobetona, *Proectirovanie, stroitelsvo i ekspluatatsiya sooruzheniy aeroportov*: 12–18 (in Russian).