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IMPROVEMENT OF THE TWO-LAYER AIRFIELD RIGID PAVEMENT DESIGN

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Abstract. The State norms of Ukraine have only two values of transition factor (one value for free-edge loading case, other for joint edge) which do not allow aircraft main landing gear and number of wheels. Transition factors for calculation of edge bending moment are determined for airfield rigid pavement design. New values of transition factors account main landing gear configuration of new aircrafts. Transition factor values are obtained by using finite element modeling programs LIRA and FEAFAA.

Keywords: airfield rigid pavement, main landing gear, dowel bar, joint, transition factor, deflection, strain, joint load transfer efficiency, finite element modeling.

Introduction

In Ukraine conventional airfield rigid pavement of the international airports is two-layer concrete pavement on the stabilized base that’s why improvement of the two-layer rigid pavement design is important especially for pavement analysis under impact of the main landing gears of new wide body large aircrafts such as A350-900, A380, B747-8, B777, B787-9.

The load transfer and stress reduction effects from joints (dowel bars) in concrete pavements have not been directly simulated in structural analysis models used for one- and two-layer pavement thickness design by the State Norms of Ukraine (SNiP 2.05.08-85 Aerodromy 1985).

1. Joint Load Transfer Efficiency

Simplified free-edge (without joints) loading structural analysis is performed using single-slab models without joints and with loads placed on the center of the Portland cement concrete (PCC) infinite slab. The free-edge stress equals interior stress multiplied by transition factor $k = 1,5$. If PCC slab has joints the edge stress is equal interior stress multiplied by transition factor $k = 1,2$.

According to the analytical research of Glyshkov G. (Glyshkov 1999) reduction factor depends on main landing gear configuration and number of wheel.

USA Federal Aviation Administration (USA) uses the simplified 25 % reduction factor that has allowed the complex behavior of joints (AC 150/5320-6E 2009). Free-edge loading structural analysis is performed using single-slab model without joints and with wheel loads placed along the edge of the PCC slab. The free-edge stress that result is then adjusted using a standard 25 % stress reduction factor to account for the ability of joints to transfer load (AC 150/5320-6E 2009; Byrum 2011).

Joint load transfer is not a constant but rather is a stochastic variable changing continually as a function of temperature, and degrading over time due to repeated loading (Brill 1998; Hammons 1998; Xinhua Yu *et al.* 2010; Byrum *et al.* 2011; Guo 2013; Mehta 2013; Cunliffe 2014).

When aircraft main landing gear loading is applied near a joint of a jointed concrete pavement, both the loaded PCC slab as well as the adjoining unloaded PCC slab undergo some amount of deflection. A portion of the applied wheel load is transferred to the adjoining unloaded PCC slab through the load transfer mechanisms of a joint such as aggregate interlock and dowels. The deflections and stresses in the loaded PCC slab may be reduced relative to a slab with free edges. The degree of load transfer is commonly called load transfer efficiency (LTE) and can be defined based on stresses or deflections (Byrum *et al.* 2011; Guo 2013; Mehta 2013; Cunliffe 2014).

There are three widely-used definitions for load transfer at a pavement joint (Brill 1998; Hammons 1998; Byrum *et al.* 2011; Guo 2013; Mehta 2013; Cunliffe 2014):

$$LTE_{\delta} = LTE(\delta) = \frac{\delta_U}{\delta_L}, \tag{1}$$

$$LTE_{\sigma} = LTE(S)\frac{\sigma_U}{\sigma_L + \sigma_U}, \tag{2}$$

$$LT = \frac{\varepsilon_F - \varepsilon_L}{\varepsilon_F}, \tag{3}$$

where: LTE_{δ} or $LTE(\delta)$ – deflection-based Load Transfer Efficiency; δ_U – deflection of the unloaded side of the joint; δ_L – deflection of the loaded side of the joint; LTE_{σ} or $LTE(S)$ – stress-based Load Transfer Efficiency; σ_U – bending stress in the unloading slab; σ_L – bending stress in the loading slab; LT – percent of "Free-Edge Stress" Load Transferred; ε_F – bending strain for free-edge loading conditions; ε_L – bending strain in the loaded slab edge at the joint.

Aircraft gear configuration will significantly influence the quantitative value of *LTE* (Byrum 2011). The influence of foundation reaction modulus *k* on *LTE*(*S*) is not significant. The joint load transfer efficiency rises up gradually with increase of the load moving speed (Xinhua Yu *et al.* 2010).

Thus the State Norms of Ukraine (SNiP 2.05.08-85) uses 0,80 (1,2 /1,5) stress reduction factor or deflection-based Load Transfer Efficiency LTE_{δ}, in this case stress-based Load Transfer Efficiency LTE_{σ} equels 0,20.

2. Improvement of the Transition Factor by Using program LIRA and FEAFAA

Finite element modeling of the two-layer rigid pavement can be provided in program LIRA that is the general purpose finite element method software. LIRA (it is not abbreviation) was developed in Kyiv (Ukraine).

Aircraft main landing gear interior load is modeled by using one PCC slab. Edge loading for joint transition factor k_{joint} determination is modeled by using multiple-slab (9 slabs) jointed rigid pavement. Joints between adjacent slabs are represented by FE 55 that allows the user more control over the line of action of the spring by acting only a user-specified direction. Edge loading for free-edge transition factor k_{fe} determination is modeled by using one slab rigid pavement. Wheel load was modeled as square load that has the same magnitude as the nominal tire contact area (Rodchenko 2013).

Two-dimensional shell finite elements are used to represent the upper and lower concrete slab of two-layer rigid pavement and stabilized base. Subgrade model is Winkler foundation. The upper and lower concrete slabs are unbounded layers with or without the separator layer. Polyethylene sheeting, thin chip seal or slurry seals can be used as separators. The separator layer is modeled by FE 262 of the program LIRA finite element library. Finite elements FE 262 model the separate layer as independent axial springs which have stiffness in the vertical direction Z only. The stiffness of FE 262 is determined based upon the area that contributes to the stiffness of the node (Rodchenko 2013).

FEAFAA (Finite Element Analysis – Federal Aviation Administration) was developed by the FAA Airport Technology R&D Branch as a stand-alone tool for three-dimensional (3D) finite element analysis of multiple-slab airfield rigid pavements. It is useful for computing accurate responses (stresses, strains and deflections) of rigid pavement structures to individual aircraft landing gear loads. The major features of FEAFAA are: from single- to nine-slab jointed rigid pavement model, infinite subgrade model and arbitrary gear loading capability.

The major features of FEAFAA are up to 9-slab jointed rigid pavement models, up to 6 structural layers, infinite subgrade models, arbitrary gear loading capability, explicit modeling of individual wheels in multiple-wheel aircraft gears, edge or interior aircraft loading, overlay modeling capability, user-defined slab size, customizable aircraft library, sliding interface between the PCC slab and the subbase layer, automatic generation of 3D finite element meshes.

The model had the following components the 3D FE automatic mesh generation program (AUTOMESH), that gives instructions to the finite element pre-processor (INGRID); before AUTOMESH, the model preparation required significant time and implied learning an extensive set of INGRID programming commands to generate the model mesh; the finite element preprocessor INGRID which was called from AUTOMESH to generate the model mesh; the finite element program NIKE3D.

FEAFAA's basic element type is an eight-node hexahedral (brick) solid element. The model uses only one element type for all structural layers. The 8-node hexahedral element has an incompatible modes formulation to improve its bending performance over standard hexahedral elements. The stresses in the incompatible elements are computed at the element's eight integration points. For incompatible elements, the NIKE3D original developers recommended using the average of stresses calculated at the 8 element integration points, which corresponds to the element center.

The enhanced FEAFAA software uses linear elastic joints, where joint stiffness is modeled as a constant linear stiffness value (Byrum *et al.* 2011).

Interior and edge loading of dual wheel, two dual wheels and three dual wheels main gears (table 1–3) are analyzed for the following case: 450-mm upper PCC slab (7,5- by 7,5-m. slab dimensions, E = 35 300 MPa), 300-mm lower lean concrete slab (E = 17 000 MPa), stabilized base (E = 7800 MPa), and Winkler foundation (K = 60 MN/m^3), subgrade modulus 34 MPa.

The bending moment is determined on the upper PCC slab of rigid pavement. The finite element modeling (FEM) results obtained in LIRA for joint transition factor are summarized in table 4. The transition factor values are determined as bending moment ratio

$$k_{fe} = \frac{M_{edge}}{M_{\text{int}}}, \tag{4}$$

$$k_{jo\text{int}} = \frac{M_{ejo\text{int}}}{M_{\text{int}}}, \tag{5}$$

where: M_{edge} – edge bending moment, kN•m/m; M_{int} – interior bending moment, kN•m/m; M_{ejoint} – edge bending moment in slab of jointed rigid pavement, kN•m/m.

Table 1. Dual wheel main landing gears

Aircraft	Magnitude of the main gear static load	Main gear tire pressure	Magnitude of the wheel load with dynamic ratio (SNiP)
A320-200	364,00 kN	1,44 MPa	227,50
B737-900ER	403,67 kN	1,52 MPa	262,39 kN

Table 2. Two dual wheels in tandem main gears

Aircraft	Magnitude of the main gear static load	Main gear tire pressure	Magnitude of the wheel load with dynamic ratio (SNiP)
A350-900	1259,60 kN	1,66 MPa	409,37 kN
A380-800	1069,20 kN	1,50 MPa	334,13 kN
B-747-8	1062,99 kN	1,52 MPa	345,47 kN
B-787-9	1177,4 kN	1,54 MPa	382,66 kN

Table 3. Three dual wheels in tandem main gears

Aircraft	Magnitude of the main gear static load	Main gear tire pressure	Magnitude of the wheel load with dynamic ratio (SNiP)
A380-800	1603,80 kN	1,50 MPa	334,13 kN
B777-300ER	1629,34 kN	1,52 MPa	353,02 kN

Table 4. Results of finite element modeling (LIRA 9.6) for joint transition factor

Aircraft	M_{ejoint}	M_{int}	k_{joint}
A320-200	69,451 kN•m/m	58,362 kN•m/m	1,19
A380-800 two dual wheels in tandem main gear	92,671 kN•m/m	77,135 kN•m/m	1,20
B737-900ER	73,025 kN•m/m	61,886 kN•m/m	1,18
B747-8	103,54 kN•m/m	87,078 kN•m/m	1,19
B777-300ER gear perpendicular location to the slab edge	115,386 kN•m/m	103,187 kN•m/m	1,12
B777-300ER gear tangent location to the slab edge	105,665 kN•m/m	103,187 kN•m/m	1,02
B787-9	103,06 kN•m/m	79,664 kN•m/m	1,29

Nine-slab FEM of jointed two-layer rigid pavement model for B747-8 problem is shown in fig. 1.

The FEM results obtained in FEAFAA for joint and free-edge transition factor are summarized in table 5, 6.

So long as FEAFAA uses imperial unit of measure the following expressions may be helpful here:

$$h_{inch} = \frac{h}{25{,}4}, \tag{6}$$

$$E_{pci} = \frac{E}{145{,}04}, \tag{7}$$

$$\sigma = \frac{\sigma_{pci}}{145{,}04}, \tag{8}$$

where: h_{inch} – slab thickness, inch; h – slab thickness, m; E_{pci} – elastic modulus, pci (pressure per square inch); E – elastic modulus, Mpa; σ_{pci} – stress, pci; σ – stress, MPa.

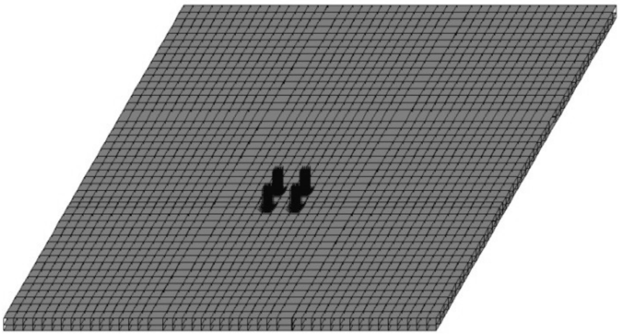

Fig. 1. Finite element model of the two-layer rigid pavement under impact of B747-8 main landing gear

Table 5. Results of finite element modeling (FEAFAA 2.04) for joint transition factor

Aircraft	M_{ejoint}	M_{int}	k_{joint}
A320-200	69,464 kN•m/m	57,992 kN•m/m	1,20
A350-900	92,526 kN•m/m	74,527 kN•m/m	1,24
A380-800 two dual wheels in tandem main gear	91,498 kN•m/m	77,455 kN•m/m	1,18
A380-800 3 dual wheels in tandem body gear (perpendicular location to the slab edge)	112,543 kN•m/m	87,423 kN•m/m	1,29
A380-800 three dual wheels in tandem body gear (tangent location to the slab edge)	85,999 kN•m/m	87,423 kN•m/m	0,98
B737-900ER	74,369 kN•m/m	63,056 kN•m/m	1,18
B747-8	99,845 kN•m/m	86,118 kN•m/m	1,16
B777-300ER gear perpendicular location to the slab edge	117,843 kN•m/m	103,167 kN•m/m	1,14
B777-300ER gear tangent location to the slab edge	101,269 kN•m/m	103,167 kN•m/m	0,98
B787-9 gear tangent location to the slab edge	100,913 kN•m/m	78,325 kN•m/m	1,29
B787-9 gear perpendicular location to the slab edge	100,557 kN•m/m	78,325 kN•m/m	1,28

FEAFAA calculates tensile stress that can be converted to bending moment M by using FAA formula (AC 150/5320-6E 2009):

$$M = 1{,}7\frac{\sigma \cdot I_g}{c}, \qquad (9)$$

where: 1,7 – live load factor; σ – stress, Mpa; I_g – the gross moment of inertia calculated for a 1-meter strip of the concrete slab, m^4; c – the distance from the neutral axis to the extreme fibre, assumed to be one-half of the slab thickness, m.

Table 6. Results of finite element modeling (FEAFAA 2.04) for free-edge transition factor

Aircraft	M_{ejoint}	M_{int}	k_{fe}
A320-200	80,303 kN•m/m	57,992 kN•m/m	1,39
A350-900	119,030 kN•m/m	74,527 kN•m/m	1,60
A380-800 two dual wheels in tandem main gear	116,934 kN•m/m	77,455 kN•m/m	1,51
A380-800 three dual wheels in tandem body gear (perpendicular location to the slab edge)	131,966 kN•m/m	87,423 kN•m/m	1,51
B737-900ER	87,858 kN•m/m	63,056 kN•m/m	1,39
B747-8	127,931 kN•m/m	86,118 kN•m/m	1,49
B777-300ER gear perpendicular location to the slab edge	140,906 kN•m/m	103,167 kN•m/m	1,37
B777-300ER gear tangent location to the slab edge	130,818 kN•m/m	103,167 kN•m/m	1,27
B787-9 gear tangent location to the slab edge	135,328 kN•m/m	78,325 kN•m/m	1,73
B787-9 gear perpendicular location to the slab edge	128,841 kN•m/m	78,325 kN•m/m	1,64

Bending moment has maximum value for three dual wheels in tandem main gear when it has perpendicular location to the slab edge. Bending moment has maximum value for two dual wheels in tandem main gear when it has tangent location to the slab edge. This conclusion coincides with results of FAA NAPTF (National Airport Pavement Test Facility) CC2 (Khazanovich 2004; Guo, Pecht 2007; Ricalde 2007).

3. Adjusted Transition Factor Values

According to FEM analysis joint and free-edge transition factor have values more than standard values for modern aircrafts. Its recommended values are represented in table 7. So long as aircraft B737-900ER has the same gear geometry as lower models (B737-400, -500, -600, -700, -800) transition factor is shown for aircraft B737.

Aircraft B747-8 has freight version (B747-8F) that has the same taxi weight and landing gear geometry that’s why table 7 includes factor values for freighter.

Aircraft B777-300ER also has lower models (B777F, B777-200LR) with the same main landing gears.

LTE(S) values are also determined by using proposed formula:

$$LTE(S) = \frac{k_{joint}}{k_{fe}}. \qquad (10)$$

Table 7. Recommended joint transition factor

Aircraft	k_{joint}	k_{fe}
A320-200	1,20	1,40
A350-900	1,24	1,60
A380-800 (2 dual wheels in tandem main gear)	1,20	1,50
A380-800 (3 dual wheels in tandem body gear)	1,29	1,50
B737	1,18	1,40
B747-8 (B747-8F)	1,18	1,50
B777-300ER, B777-200LR, B777F	1,15	1,37
B787-9	1,29	1,73

Determined LTE(S) values are shown in table 8.

Table 8. Recommended LTE(S) values for airfield two-layer rigid pavement on stabilized base

Aircraft	$LTE(S)$
A320-200	0,86
A350-900	0,78
A380-800 (two dual wheels in tandem main gear)	0,80
A380-800 (three dual wheels in tandem body gear)	0,86
B737	0,84
B747-8 (B747-8F)	0,79
B777-300ER, B777-200LR, B777F	0,83
B787-9	0,75

The two-layer rigid pavement with joints in upper PCC slab is calculated by using the State norms of Ukraine (SNiP 2.05.08-85) with accounting standard transition factor and adjusted joint transition factor. The bending moment is determined on the upper and lower slab. The maximum bending moment of upper slab is labeled as M. The results obtained in the analysis are summarized in table 9.

Table 9. Comparative results of accounting standard and adjusted transition factor

Aircraft	Upper PCC slab bending moment			
	SNiP $K = 1{,}2$	SNiP k_{joint}	FEAFAA	LIRA
A350-900	90,171 kN•m/m	93,177 kN•m/m	92,526 kN•m/m	–
B777-300ER	122,900 kN•m/m	117,779 kN•m/m	117,843 kN•m/m	115,386 kN•m/m
B787-9	98,261 kN•m/m	105,630 kN•m/m	100,913 kN•m/m	103,06 kN•m/m

Conclusions

New transition factor values for two-layer rigid pavement on stabilized base were determined by using FEM programs LIRA and FEAFAA.

Transition factor values depend on aircraft main landing gears configuration.

For dual wheel main landing gears joint transition factor is the same as standard (SNiP 2.05.08-85).

For dual wheel gears free-edge transition factor equals 1,40.

For two dual wheels in tandem gears joint transition factor is equal from 1,18 to 1,29.

For three dual wheels in tandem gears joint transition factor is equal from 1,15 to 1,29.

For two dual wheels in tandem gears free-edge transition factor is equal from 1,50 to 1,73.

For three dual wheels in tandem gears free-edge transition factor is equal from 1,37 to 1,50.

The using of research results will have to improve airfield rigid pavement design.

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