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FINITE ELEMENT MODELLING OF AIRFIELD CONCRETE PAVEMENT

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Abstract. Finite element modelling of airfield concrete pavement can be provided in program *LIRA-SAPR*. Sample numerical computations were performed using the introduced finite element model in program *LIRA-SAPR*. Numerical solutions were compared to other solutions using *FEAFAA* software. Finite element model of multi-slab jointed concrete pavement for program *LIRA-SAPR* allows analyzing pavement with or without separator layer and under impact of modern aircrafts all main landing gears.

Keywords: finite element method, airfield concrete pavement, main landing gear, dowel bar, joint, separator layer, compression ratio.

Introduction

In Ukraine conventional airfield pavement is concrete pavement on the treated subbase that's why finite element modelling (FEM) is important for airfield concrete pavement design under impact of the main landing gears of modern aircrafts.

There are different programs for airfield concrete pavement finite element analysis such as *ABAQUS*, *FEAFAA*, *FAARFIELD*, *ILLI-SLAB*, *LIRA-SAPR*.

FEM software

Abaqus FEA (formerly *ABAQUS*) is the general purpose finite element software. The main feature of Abaqus FEA is using of the library concept to create different models by combining different solution procedures, element types, and material models (Brill 1998).

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 finite element analysis of multiple-slab airfield concrete pavements. It is useful for computing accurate responses of concrete pavement structures to individual aircraft landing gears (Hammons 1998).

FEAFAA's basic element type is an eight-node hexahedral solid element. The model uses only one element type for all structural layers. The 8-node hexahedral finite element has an incompatible modes formulation to improve its bending performance over standard hexahedral elements. The enhanced *FEAFAA* software uses linear elastic joints, where joint stiffness is modeled as a constant linear stiffness value (Bradley *et al.* 2000; Byrum *et al.* 2011).

FAARFIELD (Federal Aviation Administration Rigid and Flexible Iterative Elastic Layered Design) designs the concrete slab thickness based on the assumption of edge loading. The gear load is located either tangent or perpendicular to the 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).

ILLI-SLAB (Illinois Slab) is the two-dimensional finite element analysis (FEA) software. It provides nine slabs with joints. Two-dimensional shell finite elements are used to represent slab layer. Subgrade model is represented by Winkler's hypothesis (Roesler *et al.* 2007). User cannot create pavement on treated subbase.

LIRA-SAPR (it's not abbreviation) is the general purpose finite element software that is developed in Kyiv (Ukraine).

Finite element modelling of concrete pavement in *LIRA-SAPR* software

A concrete pavement system consists of a number of concrete slabs finite in length and width over one treated subbase layer. When a slab is subjected to a wheel load, it develops bending stresses and distributes the load over the subbase. However, the response of these finite slabs is controlled by joint.

Finite element modelling of airfield concrete pavement can be provided in program *LIRA-SAPR* that is the general purpose FEM software. Multiple-slab jointed concrete pavement model includes nine slabs. Longitudinal joint of pavement can include aggregate interlock or tie bars. Transverse joint include dowel bars. Joints between adjacent slabs are spring connection. The ideal spring connection would be one that provides a vertical spring force proportional to the relative vertical displacement between adjacent slab edges but does not constrain movement in any other direction.

The *LIRA-SAPR* finite element (FE) library contains spring model that is called FE 55. The stiffness of the joint for concrete pavement analysis consists of springs which have stiffness in the vertical direction Z. A shear modulus for the joint element can be calculated from the assumed joint stiffness.

For the dowel load transfer mechanism, the joint stiffness is prescribed by the parameter *k*, which defines the force transmitted per unit length along the joint per unit differential deflection across the joint (Hammons 1998).

Once *k* has been established, it is necessary to distribute the stiffness to the nodes along the concrete pavement joint.

One method of allocating the stiffness to the nodes is by using the concept of contributing area, which is commonly used in structural analysis. In this method the stiffness values assigned to each node, stiffness of FE 55, are determined based upon the length that contributes to the stiffness of the node (Rodchenko 2013).

Two-dimensional shell finite elements are used to represent the concrete slab of airfield pavement and treated subbase. Subgrade model is Winkler foundation.

The concrete slabs and subbase are unbounded layers with or without the separator layer. Thin chip seal, polyethylene sheeting or slurry seals can be used as separators.

Compression of interacting layers of multi-layer concrete pavement is described by compression ratio. If the separator layer is located between pavement layers compression ratio is defined by (Totskyi *et al.* 1982):

$$R_i = \frac{2.4 \cdot E_i E_{i+1} E}{E \cdot (t_i E_{i+1} + t_{i+1} E_i) + 2.4 \cdot E_i E_{i+1} t \nu_1}, \quad (1)$$

where: E_i, E_{i+1} are the elasticity modules of a rigid pavement layers, MPa; E is the elasticity modulus of the separator layer, MPa; t_i, t_{i+1} are the thicknesses of a rigid pavement layers, m; t is the thickness of the separator layer, m; v_1 is the reduced Poisson's ratio of the separator layer.

The reduced Poisson's ratio of the separator layer is defined by the relationship (Totskyi *et al.* 1982):

$$\nu_1 = 1 - \frac{2\nu^2}{1-\nu}, \quad (2)$$

where: μ is Poisson's ratio of the separator layer.

Compression ratio of the separator layer between concrete slab and treated subbase is defined as:

$$R = \frac{2.4 \cdot E_c E_s E}{E \cdot (t_c E_s + t_s E_c) + 2.4 \cdot E_c E_s t \nu_1}, \quad (3)$$

where: E_c is the elasticity modulus of concrete, MPa; t_c is the thickness of concrete slab, m; E_s is the elasticity modulus of stabilized base, MPa; t_s is the thickness of treated subbase, m.

The separator layer between concrete slab and treated subbase is proposed to model by FE 262 of the program *LIRA-SAPR* finite element library. FE 262 models the separate layer as independent axial springs which have stiffness in the vertical direction *Z*.

The stiffness values assigned to each node, *S* (stiffness of FE 262 of the program *LIRA-SAPR* finite element library), are determined based upon the area that contributes to the stiffness of the node. Based upon the concepts of contributing area, the stiffness of the interior nodes *S* must be twice that of the edge nodes S_e; the stiffness of the edge nodes S_e must be twice that of the corner nodes S_c.

If the separator layer is not located between pavement layers compression ratio is defined by (Totskyi *et al.* 1982):

$$R'_i = \frac{2.4 \cdot E_i E_{i+1}}{t_i E_{i+1} + t_{i+1} E_i}, \quad (4)$$

where: E_i, E_{i+1}, t_i, t_{i+1} are the same as in equation (1).

Thus compression ratio between concrete slab and treated subbase is defined as:

$$R' = \frac{2.4 \cdot E_c E_s}{t_c E_s + t_s E_c}, \quad (5)$$

where: E_c, h_c, E_s, h_s are the same as in equation (3).

Finite element modelling results

This part presents typical results from the finite element concrete pavement model. All of the solutions presented in the following part were computed by using *LIRA-SAPR* and *FEAFAA* software.

Interior and edge loading of modern aircraft main landing gears (Table 1–3) are analyzed for the following case: 450-mm concrete slab (7.5- by 7.5-m. slab dimensions, E = 35300 MPa), treated subbase (E = 7800 MPa), and Winkler foundation (K = 70 MN/m^3), subgrade modulus 39 MPa. The separator layer is located between pavement layers.

The FEM results obtained in *FEAFAA* and *LIRA-SAPR* are summarized in table 2, 3.

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

$$p_{a,psi} = p_a \cdot 145.04, \quad (6)$$

$$h_{inch} = \frac{h}{25.4}, \quad (7)$$

$$E_{pci} = \frac{E}{145.04}, \quad (8)$$

$$\sigma = \frac{\sigma_{pci}}{145.04}, \quad (9)$$

where: $p_{a,psi}$ – tire pressure, psi; p_a – tire pressure, MPa; 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.

Table 1. Aircraft main landing gears parameters

Aircraft	Magnitude of the main gear static load, kN	Main gear tire pressure, MPa	Magnitude of the wheel load with dynamic ratio (SNiP), kN
A320-200	364.00	1.44	227.50
B737-900ER	403.67	1.52	262.39
A350-900	1259.60	1.66	409.37
A380-800	1069.20	1.50	334.13
B747-8	1062.99	1.52	345.47
B787-9	1177.4	1.54	382.66
A380-800	1603.80	1.50	334.13
B777-300ER	1629.34	1.52	353.02

Table 2. Comparative results of finite element modelling (interior loading case)

Aircraft	$M_{interior}$ *LIRA-SAPR*	$M_{interior}$ *FEAFAA*	Δ, %
A320-200	58.362 kN·m/m	57.992 kN·m/m	0.6
A350-900	76.903 kN·m/m	74.527 kN·m/m	3.2
A380-800 2 dual wheels in tandem main gear	77.135 kN·m/m	77.455 kN·m/m	–0.4
A380-800 3 dual wheels in tandem body gear	87.96 kN·m/m	87.423 kN·m/m	0.6
B737-900ER	68.361 kN·m/m	69.056 kN·m/m	–1.0
B747-8	87.078 kN·m/m	86.118 kN·m/m	1.1
B777-300ER	103.187 kN·m/m	103.167 kN·m/m	0.02
B787-9	81.984 kN·m/m	78.325 kN·m/m	4.7

FEAFAA calculates tensile stress that can be converted to bending moment *M* by using FAA formula (AC 150/5320-6F 2016):

$$M = 1.7 \frac{\sigma \cdot I_g}{c}, \quad (10)$$

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.

Nine-slab FEM of jointed two-layer rigid pavement models for A350-900 and B747-8 problem are shown in Fig. 1 and 2.

Table 3. Comparative results of finite element modelling (edge loading case)

Aircraft	M_{edge} *LIRA-SAPR*	M_{edge} *FEAFAA*	Δ, %
A320-200	69.451 kN·m/m	69.464 kN·m/m	–0.02
A350-900	101.021 kN·m/m	98.302 kN·m/m	2.8
A380-800 two dual wheels in tandem main gear	94.264 kN·m/m	93.99 kN·m/m	0.3
A380-800 3 dual wheels in tandem body gear	101.8 kN·m/m	102.543 kN·m/m	–0.7
B737-900ER	82.165 kN·m/m	82.867 kN·m/m	–0.9
B747-8	103.54 kN·m/m	103.207 kN·m/m	0.3
B777-300ER three dual wheels in tandem main gear perpendicular location to the slab edge	115,386 kN·m/m	117,843 kN·m/m	–2.1
B777-300ER three dual wheels in tandem main gear tangent location to the slab edge	105.665 kN·m/m	101.269 kN·m/m	4.3
B787-9	105.411 kN·m/m	100.913 kN·m/m	4.5

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 *et al.* 2002; Guo, Pecht 2007; Ricalde 2007).

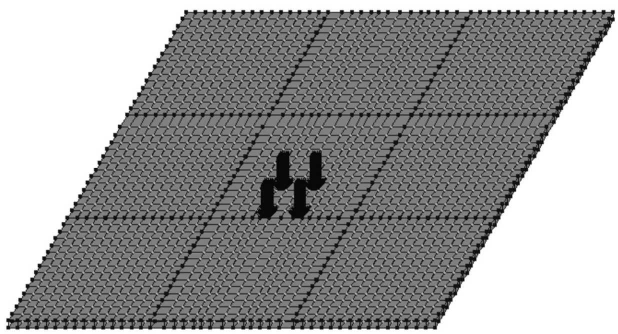

Fig. 1. Finite element model of concrete pavement under impact of A350-900 main landing gear

Multi-slab jointed concrete pavement model allows analyzing the impact of multi-wheel landing gears of new large aircrafts such as B777-300ER (Fig. 3).

Multi-slab pavement model also allows analyzing the impact of all landing gears of aircraft such as A320-

200. The finite element mesh for the A320-200 problem is shown in Fig. 4. Impact of aircraft all main landing gears is not supported by the State norms (SNiP) method.

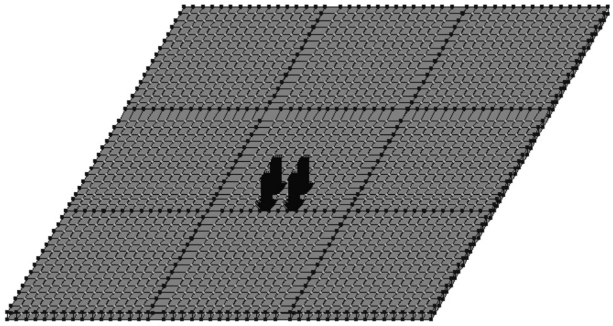

Fig. 2. Finite element model of concrete pavement under impact of B747-8 main landing gear

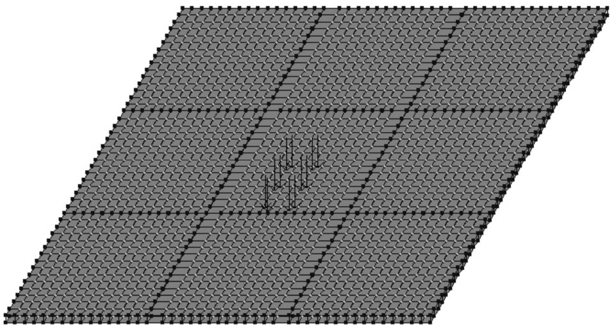

Fig. 3. Finite element model of the airfield concrete pavement under impact of B777-300ER multi-wheel main landing gear

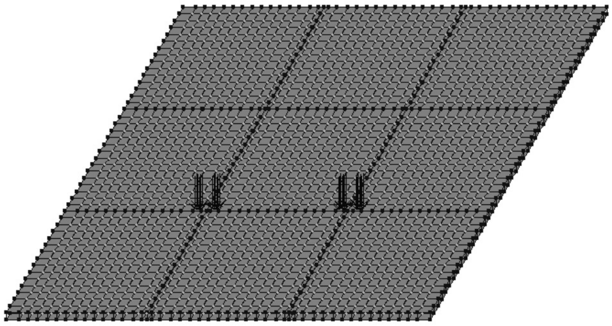

Fig. 4. Finite element model of the airfield concrete pavement under impact of A320-200 all main landing gears

Conclusions

Finite element model of multi-slab jointed concrete pavement was developed for program *LIRA-SAPR* by authors. Compression ratio relationships of Totskyi were applied to the *LIRA-SAPR* finite element FE 262 stiffness calculation.

Sample numerical computations were performed using the introduced finite element model in program *LIRA-SAPR*. Numerical solutions were compared to other solutions using *FEAFAA* software.

The introduced finite element model provides a practical approach of computing multi-slab jointed concrete pavement in the general purpose program *LIRA-SAPR* and takes into account such factors as multiple-wheel interaction, finite slab size, multiple-layer construction, variable joint stiffness and separator layer between concrete slab and treated subbase. The using of research results should have to improve airfield concrete pavement design and evaluation.

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