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SENSITIVITY QUANTIFICATION OF AIRFIELD RIGID PAVEMENT STRESS RESPONSES

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Abstract. This study evaluated the sensitivity of airfield rigid pavement responses with respect to top-down and bottom-up cracking. The analysis was conducted by positioning an Boeing 737-800 (B737-800) aircraft at different locations (interior, corner, and edge of slab) as baseline while varying other inputs, including mechanical properties of concrete pavement, subbase materials and temperature. Sensitivity evaluations were performed using a normalized sensitivity index.

Keywords: airfield rigid pavement, concrete slab, bottom tensile stress, top tensile stress, main landing gear, top-down cracking, temperature loading, sensitivity analysis.

Introduction

In Ukraine, the conventional rigid pavement is two-layer concrete pavement on a cement treated base. The improvement of the rigid pavement design is important, especially for pavement analysis under the impact of the main landing gears of new aircrafts.

The purpose of this research is to quantify sensitivity of critical stress outputs to various inputs required in airfield rigid pavement analisys at different landing gear locations and case scenarios for a single aircraft type (B737-800).

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).

“Aerodrom 380” (in Ukrainian) program has been developed for airfield concrete pavement design. It is written in Visual C++. “Aerodrom 380” has a certificate of recognition (Avtorske svidotstvo 2014). “Aerodrom 380” uses the maximum tensile stress at the bottom and top edge of the concrete slab as the design factor (Rodchenko 2017).

A research version of the “Aerodrome” design software has been developed, in which the airfield rigid pavement is under action of combined wheel and temperature loading. There are numerous inputs to “Aerodrome” that need to be considered in developing the stress response model. It requires significant understanding of rigid pavement analysis input properties that characterize the airfield rigid pavement materials, layers, wheel load location, temperature conditions.

Sensitivity analysis

Sensitivity analysis has become a useful tool in analyzing most engineering problems that involve a large number of interacting variables. One of the most common uses of sensitivity analysis is in pavement design and analysis (Rezaei-Tarahomi *et al*. 2017).

In this research, sensitivity analysis can help to focus on those design inputs that have the most effect on airport rigid pavement thickness.

Chen *et al.* (Chen *et al*. 2012; Chen 2014) identified the critical aircraft gear (single-gear and multiple-gear) loading position that induces the critical tensile stresses. Their study evaluated the effect of elastic modulus and thickness of each airfield rigid pavement layer and the joint stiffness on the critical tensile stresses and the critical top-to-bottom tensile stress ratio. They used three-layered pavement structure (concrete slab, granular subbase, and subgrade) under the loading condition (A380 aircraft load with an assumed equivalent thermal gradient). These studies (Chen *et al*. 2012; Chen 2014) reported that the critical top-to-bottom tensile stress ratio (t/b ratio) was sensitive to the concrete slab thickness and the modulus of the subgrade variation, but it was not sensitive to the variation of subbase thickness, the modulus of concrete slab, and the modulus of subbase. Further investigations were performed by Rezaei-Tarahomi *et al.* (Rezaei-Tarahomi *et al*. 2017) and included the use of different cases including a four-layered rigid pavement structure, different loading conditions, and different load locations and case scenarios for a single aircraft type (B777-300ER). These studies (Rezaei-Tarahomi *et al*. 2017) reported that all stress responses has the highest sensitivity to concrete slab thickness. For the top tensile stress, the thicknesses of pavement structural layers are the most effective inputs. It is noteworthy that subgrade modulus has a higher effect on bottom tensile stresses and shear stresses changes. Top tensile stress is more sensitive to concrete slab thermal coefficient variations while bottom tensile stress is more sensitive to the thermal gradient changes (Rezaei-Tarahomi *et al*. 2017).

Methodology

The analysis has been done for a four-layered pavement structure by applying a B737-800 aircraft loading. A four-layered pavement structure (concrete slab, lean concrete, cement treated base and subgrade) with 7.5 m concrete slab was modelled to represent a typical and realistic airfield rigid pavement structure in Ukraine.

A One-at-a-time sensitivity analysis was implemented using a baseline limit normalized sensitivity index (NSI) to provide quantitative sensitivity information. The sensitivity of the input parameters has been evaluated by considering their effects on the critical responses corresponding to the top-down and bottom-up cracking (Rezaei-Tarahomi *et al*. 2017). The One-at-a-time sensitivity analysis has been carried out by varying one parameter at a time while holding the others fixed. This analysis helps to identify the most significant inputs in the airfield rigid pavement structural analysis.

Inputs that are needed can be categorized as:

- pavement structure inputs;
- subgrade inputs;
- airplane inputs.

The goal is to evaluate the sensitivity of those input parameters which are more important for analyzing and designing airfield rigid pavements. A detailed summary of the input parameters to be varied as well as constant inputs are shown in Table 1.

Table 1. Ranges of inputs for sensitivity analysis.

Inputs category	Inputs	Min	Baseline	Max	Base case
Pavement structure inputs	Concrete slab modulus, MPa	32,400	35,300	35,300	32,400
	Concrete slab thickness, m	0.35	0.4	0.45	0.4
	Concrete slab Poisson ratio	0,15	0,15	0,15	0,15
	Lean concrete modulus, MPa	13,000	17,000	26,000	17,000
	Lean concrete thickness, m	0.20	0.25	0.30	0.25
	Lean concrete Poisson ratio	0.15	0.15	0.15	0.15
	Cement treated base modulus, MPa	1,950	4,810	7,800	7,800
	Cement treated base thickness, m	0.15	0.20	0.25	0.15
	Cement treated base Poisson ratio	0.15	0.15	0.15	0.15
Subgrade inputs	Subgrade ratio, MN/m^3	40	50	60	40
Airplane B737-800 inputs	Ramp weight, t	79.242			
	Number of main gears	2			
	Maximum vertical wing gear ground load, t	37.06			
	Tire pressure, MPa	1.41			
Loading inputs	Loading position	Interior/Mid Slab Edge/Corner			
	Daily average amplitude of temperature (July), ˚C (DSTU-N B V.1.-27:2010)	9.4	10.2	11.2	9.4

Each evaluated input was varied within its recommended range to study its effect on critical responses (maximum tensile stress at top/bottom of the concrete slab) while assigning base case values to all other input parameters.

To present the sensitivity of each parameter, a normalized sensitivity index (NSI) has been adopted as a quantitative metric

$$NSI = \frac{\Delta Y_j}{\Delta X_k}\frac{X_k}{Y_k}, \tag{1}$$

where: X_k – baseline value of input k; ΔX_k – change in input k about the baseline; Y_j – change in output j corresponding to ΔX_k; Y_k – baseline value of output j (Rezaei-Tarahomi *et al*. 2017).

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 (Lapenko *et al*. 2017):

$$M_{\text{int}} = \left[0{,}1164 - 0{,}0902 ln\left(\frac{\sqrt{\frac{F_n k_d \gamma_f}{2\pi p_{\text{a}}}}}{l}\right)\right] - \\ - 0{,}0873\frac{F_n k_d \gamma_f}{2} ln\frac{0{,}86}{l}, \tag{2}$$

where: F_n – maximum vertical wing gear ground load, kN (Boeing 2013); 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 interior stress at the bottom of the slab is determined using a formula:

$$\sigma_{\text{int}} = \frac{6M_{\text{int}}}{1000h_{cs}^2}, \quad (3)$$

where: h_{cs} – concrete slab thickness, m.

The maximum tensile stress at the bottom edge of the concrete slab can be determined by using the following expression:

$$\sigma_1 = \frac{B_{cs}}{B_{tot}} \cdot \sigma_{\text{int}} k \left[1 - 0{,}167 \left(0{,}791 - 0{,}141 \ln \frac{B_{cs} + B_{lc}}{B_f} \right) \right], \quad (4)$$

where: B_{cs} – concrete slab stiffness, MPa·m^4/m; B_{tot} – the total concrete, lean concrete and cement treated base layers stiffness, MPa·m^4/m; B_f – cement treated base stiffness, MPa·m^4/m.

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

$$\sigma_2 = \sigma_1 \left(0{,}453 - \frac{1}{30h_{cs}} \right). \quad (5)$$

Results

Analysis was carried out for mechanical and thermal loading. Two stress types were considered as critical stresses for wheel load of all main landing gears and used as outputs for the NSI calculation:

- maximum tensile stress at the top of the concrete slab (top tensile stress);
- maximum tensile stress at the bottom of the concrete slab (bottom tensile stress);
- critical top-to-bottom tensile stress ratio (t/b ratio).

The bottom tensile stress is more sensitive to concrete slab thickness than the other inputs for the case in which interior wheel loading is applied to the concrete pavement. The higher sensitivity index of concrete slab thickness to tensile stress at the bottom of the slab shows the importance of this input for studying bottom-up cracking in concrete pavement.

Bottom tensile stress exhibits higher sensitivity to concrete slab thickness than other inputs when the wheel load is centered on one edge of the concrete slab (Fig. 1).

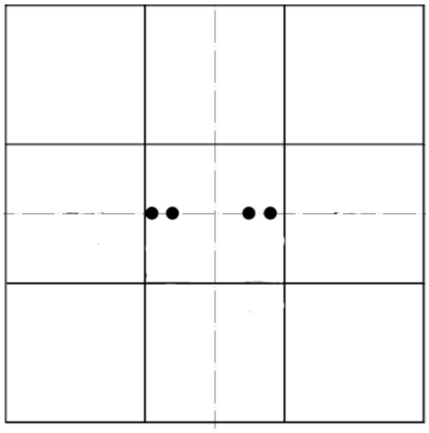

Fig. 1. B737-800 main landing gear located on one edge of the concrete slab.

Concrete slab thickness has been identified as the most effective input for top and bottom tensile stresses in case when pavement is under action of mechanical loading only. Variations in modulus of concrete, lean concrete and cement treated base show less sensitivity index for bottom tensile stress. The stress responses are not sensitive to lean concrete and cement treated base modulus.

Temperature loading related input (daily average amplitude of temperature) exhibits sensitivity for top tensile stress. Bottom tensile stress shows sensitivity to subgrade ratio and concrete slab modulus. The concrete slab thickness and modulus, daily average amplitude of temperature, subgrade ratio, lean concrete thickness are all effective inputs for bottom stress.

Concrete slab thickness exhibited the highest NSI for top and bottom tensile stresses in mechanical loading only case for the B737-800 wing landing gear located at the corner of the concrete slab (Fig. 2). Lean concrete and cement treated base thicknesses have high NSI for top tensile stresses but low NSI for bottom tensile stresses, while concrete modulus is effective input for both types of tensile stresses. Lean concrete modulus, treated subbase modulus have the lowest NSI for all stress responses.

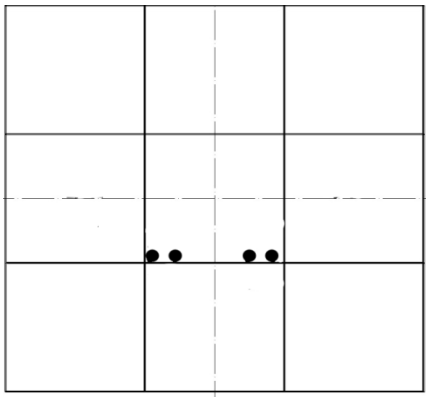

Fig. 2. B737-800 main landing gear located at the corner of the concrete slab.

Higher NSI values of concrete slab thickness were observed for bottom tensile stress than for top tensile stress. Daily average amplitude of temperature and concrete slab modulus are the most effective inputs for top tensile stress. Lean concrete thickness forms the next lower tier of effective inputs. Top tensile stress has low sensitivity to subgrade ratio.

Table 2 and 3 show the sensitivity analysis results for different inputs.

Table 2. Inputs ranking for top tensile stress responses.

Inputs	NSI top tensile stress
Concrete slab thickness	1.783
Daily average amplitude of temperature	0.946
Concrete slab modulus	0.606
Lean concrete thickness	0.562
Cement treated base thickness	0.291
Lean concrete modulus	0.102
Subgrade ratio	0.070
Cement treated base modulus	0.027

Table 3. Inputs ranking for bottom tensile stress responses.

Inputs	NSI bottom tensile stress
Concrete slab thickness	1.999
Concrete slab modulus	0.620
Daily average amplitude of temperature	0.369
Lean concrete thickness	0.301
Subgrade ratio	0.277
Cement treated base thickness	0.151
Lean concrete modulus	0.100
Cement treated base modulus	0.015

Top tensile stress, unlike the bottom tensile stress, exhibits sensitivity to the lean concrete and cement treated base thickness. Variations in modulus of lean concrete and cement treated base show less sensitivity index for bottom tensile stress.

The top tensile stress exhibits considerable sensitivity to most inputs, but the bottom tensile stress has considerable sensitivity to just two inputs (concrete slab thickness and concrete modulus). The stress responses are not sensitive to cement treated base modulus (lowest NSI) that coincide with conclusions of Rezaei-Tarahomi et al. (2017).

Discussion and interpretation of sensitivity results

All stress responses has the highest sensitivity to concrete slab thickness (see Table 2, 3). For the top tensile stress, the thickness of pavement structural layers are the most effective inputs. It is noteworthy that subgrade modulus has a higher effect on bottom tensile stresses.

Inputs ranking for critical top-to-bottom tensile stress ratio (t/b ratio) is follows: concrete slab thickness (2.117); daily average amplitude of temperature (0.577); subgrade ratio (0.076); cement treated base modulus (0.019); concrete slab modulus (0.014); lean concrete thickness (0.007); cement treated base thickness (0.006); lean concrete modulus (0.002). Thus the critical top-to-bottom tensile stress ratio (t/b ratio) is sensitive to the concrete slab thickness and the daily average amplitude of temperature, but it is not sensitive to the variation of lean concrete modulus, and cement treated base thickness that coincide with conclusions of Chen et al. (Chen *et al*. 2012; Chen 2014).

Conclusions

The primary objective of this research was to quantify sensitivity of stress responses to various inputs required in the research version of the “Aerodrom 380” software for critical tensile stress outputs at different main gear locations and load case scenarios for a B737-800 aircraft. A four-layered pavement structure (concrete slab, lean concrete slab, cement treated base, and subgrade) was modeled to represent typical airfield rigid pavement structure. The One-at-a-time sensitivity analysis was implemented using a baseline limit normalized sensitivity index (NSI) to provide quantitative sensitivity information on top and bottom stress responses output for mechanical loading case, mechanical and thermal loading case.

All stress responses are most sensitive to concrete slab thickness, followed by slab modulus and daily average amplitude of temperature.

Top tensile stress is more sensitive to daily average amplitude of temperature then bottom tensile stress.

For the top tensile stress, the thickness of concrete slab is effective input. Subgrade ratio has a higher effect on bottom tensile stress.

Bottom tensile stress is more sensitive to subgrade ratio than top tensile stress. In the mechanical loading only case under interior loading condition, concrete slab thickness and subgrade ratio are the most effective input parameters for bottom stress response.

In the simultaneous mechanical and thermal loading case under edge loading condition, top and bottom tensile stresses are sensitive to daily average amplitude of temperature in addition to concrete slab thickness. Especially, higher NSI of concrete slab thickness for the bottom tensile stress was observed than for the top tensile stress.

In the modelling of mechanical and thermal loading case under corner wheel load condition, concrete slab thickness, among all other inputs, has the highest effect on top tensile stress followed by daily average amplitude of temperature and concrete modulus.

The inputs categorized as insensitive for all stress responses under mechanical and thermal loading are lean concrete modulus and cement treated base modulus.

The critical top-to-bottom tensile stress ratio (t/b ratio) is sensitive to the concrete slab thickness and the daily average amplitude of temperature.

The inputs categorized as insensitive for critical top-to-bottom tensile stress ratio (t/b ratio) are concrete slab modulus, lean concrete thickness, cement treated base modulus and lean concrete modulus.

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