UDC 625.717.02

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Sensitivity quantification of airport concrete pavement stress responses under impact of Airbus 321NEO

This study evaluated the sensitivity of airport concrete pavement responses with respect to bottom-up cracking. The analysis was conducted by positioning an Airbus 321NEO (A321NEO) aircraft at different locations (interior and edge of slab) as baseline while varying other inputs, including mechanical properties of airport concrete pavement, subbase and base materials and temperature. Sensitivity evaluations were performed using a normalized sensitivity index.

In Ukraine, the conventional concrete pavement is two-layer pavement on a cement treated subbase. The improvement of the concrete 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 airport concrete pavement analisys at different aircraft main landing gear locations and case scenarios for a single aircraft type (A321NEO).

"Aerodrom 380" program has been developed for airfield concrete pavement design. It is written in Visual C++. "Aerodrom 380" has a certificate of recognition [1]. The maximum tensile stress at the bottom edge of the concrete slab (free-edge stress) equals the interior tensile stress multiplied by transition factor k [2]. "Aerodrom 380" uses a 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. The damage ratio is thus determined by using the FAA's CDF (cumulative damage factor) formula [3].

A research version of the "Aerodrome 380" design software has been developed, in which the airport concrete pavement is under action of combined wheel and temperature loading. There are numerous inputs to "Aerodrome" that need to be considered in developing the tensile stress response model. It requires significant understanding of concrete pavement analysis input properties that characterize the airport concrete pavement materials, layers, main landing gear wheel load location, temperature conditions.

A research version of the "Aerodrom 380" uses the maximum tensile stress at the bottom and top edge of the concrete slab as the design factor [4].

Sensitivity analysis has become a useful tool in analyzing most engineering problems that involve a large number of interacting variables [5].

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

Chen et al. [6,7] 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 airport concrete 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 [6,7] 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 A. Rezaei-Tarahomi et al. [5] 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 [5] reported that all stress responses has the highest sensitivity to concrete slab thickness.

The objective of this paper is to quantify sensitivity of critical stress outputs to various inputs required in a research version of the "Aerodrom 380" software for different load values and case scenarios for a single aircraft type A321NEO.

The analysis has been done for a four-layered pavement structure by applying a A321NEO [8] aircraft loading. A four-layered pavement structure (concrete slab, lean concrete, cement treated base and subgrade) with 7,5 m concrete slab was modeled to represent a typical and realistic airport concrete 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 bottom-up cracking. 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 airport concrete pavement structural analysis [5].

Inputs that are needed for research version of the "Aerodrom 380" can be categorized as:

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

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

Each evaluated input was varied within its recommended range to study its effect on critical responses (maximum tensile stress at the 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

$$NSI = \frac{\Delta Y_j}{\Delta X_k}\frac{X_k}{Y_k}, \qquad (1)$$

where X_k – baseline value of input k, ΔX_k – change in input k about the base line, Y_j – change in output J corresponding to ΔX_k, Y_K – baseline value of output J [5].

Analysis was carried out for mechanical and thermal loading. One stress type was considered as critical stress for wheel load of all main landing gears and used as outputs for the NSI calculation.

Table 1.

Ranges of inputs for sensitivity analysis of “Aerodrom 380” software

inputs category	inputs		min	baseline	max	base case
pavement structure inputs	concrete slab	modulus, MPa	32400	35300	35300	32400
		thickness, m	0,35	0,4	0,45	0,4
		Poisson ratio	0,15	0,15	0,15	0,15
	lean concrete	modulus, MPa	13000	17000	26000	17000
		thickness, m	0,20	0,25	0,30	0,25
		Poisson ratio	0,15	0,15	0,15	0,15
	treated subbase	modulus, MPa	1950	4810	7800	7800
		thickness, m	0,15	0,20	0,25	0,15
		Poisson ratio	0,15	0,15	0,15	0,15
subgrade inputs	subgrade	subgrade ratio, MN/m^3	40	50	60	40
airplane inputs	airplane A321NEO parameters	ramp weight, t	95,4			
		number of main gears	2			
		maximum vertical wing gear ground load, t	45,39			
		tire pressure, MPa	1,57			
loading inputs	loading	loading position	Interior/ Slab Edge			
		daily average amplitude of temperature (July), ˚C (DSTU-N B V.1.-27:2010)	9,4	10,2	11,2	9,4

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 airport 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).

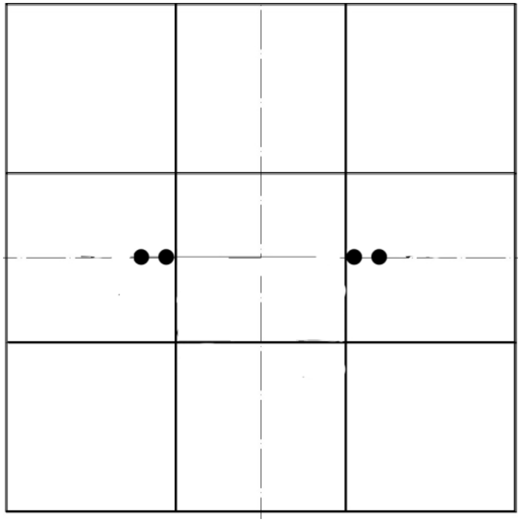

Fig. 1. A321NEO main landing gear located on one edge of the concrete slab

Concrete slab thickness has been identified as the most effective input for bottom tensile stress 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 thickness.

Bottom tensile stress shows sensitivity to concrete slab modulus. The concrete slab thickness and modulus, daily average amplitude of temperature, lean concrete thickness are all effective inputs for bottom stress when pavement is under action of mechanical and thermal loading.

Table 2 shows the sensitivity analysis results for different inputs.

Table 2.

Inputs ranking for stress responses

inputs	NSI bottom tensile stress
slab thickness	2,009
slab modulus	0,588
daily average amplitude of temperature	0,333
lean concrete thickness	0,325
subgrade ratio	0,165
subbase thickness	0,164
lean concrete modulus	0,107
cement treated base modulus	0,016

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 A321NEO aircraft. A four-layered pavement structure (concrete slab, lean concrete slab, cement treated base, and subgrade) was modelled to represent typical airport concrete 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.

In the mechanical loading 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, bottom tensile stress is sensitive to daily average amplitude of temperature and concrete clab modulus in addition to concrete slab thickness.

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

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