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Airfield Pavements Made of Reinforced Concrete: Dimensioning According to the Theory of Limit States and Eurocode

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***Abstract*—**In the previous airfield construction industry, pavements made of reinforced concrete have been used very rarely; however, the necessity to use this type of pavements in an emergency situations justifies the need reference to this issue. The paper concerns the problem of airfield pavement dimensioning made of reinforced concrete and the evaluation of selected dimensioning methods of reinforced concrete slabs intended for airfield pavements. Analysis of slabs dimensioning, according to classical method of limit states has been performed and it has been compared to results obtained in case of methods complying with Eurocode 2 guidelines. Basis of an analysis was a concrete slab of class C35/45 with reinforcement, located in tension zone. Steel bars of 16.0 mm have been used as slab reinforcement. According to comparative analysis of obtained results, conclusions were reached regarding application legitimacy of the discussed methods and their design advantages.

***Keywords*—**Reinforced concrete, cement concrete, airport pavements.

I. Introduction

AIRFIELD pavement structure consists of diversified arrangement of layers. In which the roadway is made of cement concrete. The whole arrangement takes over the load of the moving aircraft and transfers it safely to the soil subbase. Reinforced concrete pavements are one of many structure types. They are developed by incorporating reinforcement into concrete. Reinforcement applied to pavement structure is usually in the form of bar grid arranged lengthwise and crosswise. Reinforcement bars are located at the bottom and at the top of concrete cross-section at the distance of approx. 15-35 cm [1].

Depending on requirements, it is advised that in case of sections loaded more intensively (final sections of runways, runway crossroads and crossroads of a runway and taxiway, technical plates) the distance between reinforcements bars is max. 20 cm. Reinforcement preventing from shrinkage stress at slab surface should be applied every 25-30 cm [4]. Diameters of reinforcement bars should be 12-16 mm. The main purpose of airfield structure reinforcement is to equalize the distribution of internal forces in the surface in the case of changes in bearing capacity. As a result, the possibility of the formation of random cracks in slabs due to sudden thermal changes or overloading the structure is limited. Application of this type of structural solution allows to reduce pavement cross-section and number of expansion gaps, provides improvement of structure technical condition and high air traffic safety. Incorporating steel to the concrete slab changes concrete slab structure and directly influences service life extension, even in intensive traffic and repeated loading conditions. Basic criterion justifying the necessity of using reinforced concrete pavements is landing gear load exceeding 1.40 MPa [4].

Reinforcement in case of reinforced concrete pavements provided in formwork - is arranged two-plies on the bottom layer, so that it would reach slab edge at the distance of 15-35 mm. In case of longitudinal joints, overlaps are not used, whereas in case of crosswise joints, the overlap is approx. 40-45 cm [5]. The aim of using these overlaps is to enable splicing of reinforcement meshes crosswise. Each time, optimum amount of reinforcement should be selected according to calculations. In practice, in case of airfield pavements made of reinforced concrete, the percentage of pavement reinforcement is dependent on the cross-section area of reinforcement and concrete element and it is determined according to (1):

$$\mu = \frac{F_z}{F_b} \text{ [2]} \quad (1)$$

where: F_z - cross-section area of reinforcement; F_b - concrete cross-section area.

National research published in [2] proved that the suitable percentage of reinforcement in case of steel reinforced pavements is between 0.25 and 0.40%.

II. Calculation of Reinforced Concrete Pavements: Design Assumptions

The theory of elastic slabs resting on the deformable surface was used in calculating of multilayer airport pavement. In the course of design process, interaction of slab and subgrade was considered, assuming the most popular model: Slab on elastic subgrade according to Winkler's model. Airfield pavement design, as individual solution, includes several stages. Preliminary stage refers to the selection of initial issues related to the choice of the design aircraft and its typical parameters, which include traffic flow, the amount of transmitted load and the method of its distribution on the pavement (number of

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wheels of an undercarriage leg and their mutual configuration, tire pressure and wheel and pavement contact surface). Airfield pavement loading depends on aircrafts which are diversified in terms of their size and weight. Particular attention was focused on issues related to static loads generated as a result of weight of the selected design aircraft, which influences airfield pavement. Design aircraft is the one which is assumed as basic mean of air transport for a given airport. Design aircraft, Boeing 747-400, of the total take-off weight of 394625 kg was an external load, taken into consideration during slab dimensioning. Aircraft load is transmitted to the roadway of airfield pavement by means of undercarriage leg wheels. Fig. 1 presents wheel track in front and main undercarriage legs of the design aircraft, assumed in the course of analysis, also basic parameters of the analysed aircraft assumed in the course of dimensioning process.

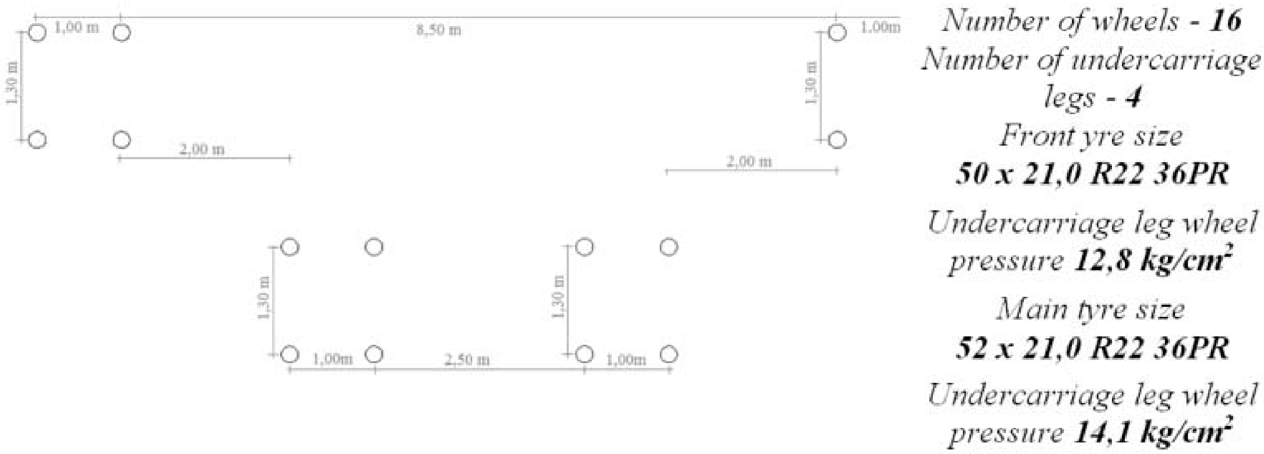

Fig. 1 Wheel plan in main hydraulic springs of the subject Boeing 747-400 [3] aircraft and assumed basic aircraft parameters

III. Calculation of Reinforced Concrete Pavements: According to Traditional Method

Design load was determined assuming 90% of the main undercarriage leg load of the design aircraft. Load transmitted by the main undercarriage leg is 85-90%, and by the front undercarriage leg 10-15%. The value of the design load of the main undercarriage leg is 88790.63 kg in case of the design aircraft, equipped with four main undercarriage legs, the weight of which is 394625 kg. The load, in case of one wheel of undercarriage leg was determined assuming dynamic factor equal to the pressure in design aircraft tire of 1.25 and overload factor of 1.00. Therefore, the value of the load for the analyzed plane amounts to 27747.07 kg. For calculated theoretically the contact area with the road wheels equal 1967.88 cm^2 ($\frac{27747.07}{14.10} = 1967.88$), determined the basic parameters depending on the assumed shape. In case of the assumed square shape of tire-pavement interface, contact radius is a = 44.36 cm, circle shape r = 25.03 cm, ellipse a_1 = 35.40 cm and b_1 = 17.70 cm, and in case of rounded ellipse a_2 = 35.07 cm and b_2 = 21.04 cm.

$$M_0 = Sq\left(0.096\,a - 0.012\,S\right) \tag{1}$$

$$M_0 = Sq\left(0.17r - 0.012S\right) \tag{2}$$

$$M_0 = -0.558(1+\nu)qSrU \tag{3}$$

It was assumed that the value of deformation of subsoil is equal to the value of slab deflection, assuming that the whole bottom slab surface touches the subsoil surface [4]. Maximum moment based on hypothesis of subsoil reaction factor was determined using the Koroniew method [4], taking into consideration subsoil reaction and slab deflection located on subsoil typical for the Winkler's model. Calculations were conducted for a slab of limit load-bearing capacity. Initial stage was calculating slab rigidity 38 cm thick (Fig. 2), made of cement concrete of class C35/45, which was 152.72 cm.

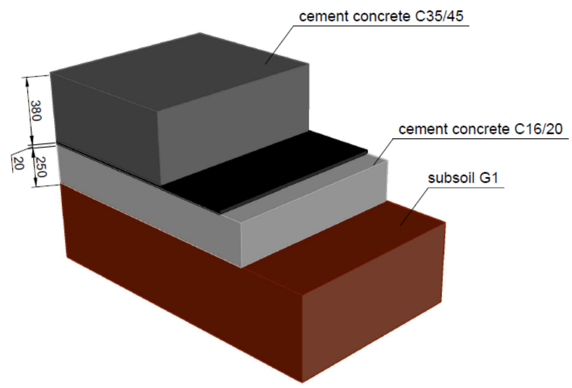

Fig. 2 A cross-section of pavement structure

Bending moment of vertical section under the tire contact centre of the most loaded wheel, located over design cross-section was calculated according to (2) for $\frac{a}{s} \in <0.3; 1.0)$, (3) for $\frac{r}{s} \in <0.17; 0.56)$, (4) for $\eta = 1.41\,\frac{r}{s}$ and numerical values were included in Table I-case a.

TABLE I
DETERMINED VALUES OF BENDING MOMENTS IN CASE OF WHEEL K_1

Boundary condition	Numerical value		M_0 [kNcm]	
	a	b	a	b
$\frac{a}{s}$	0.30	0.317	52.81	50.90
$\frac{r}{s}$	0.17	0.179	52.73	50.83
$\eta = 1{,}41\,\frac{r}{s}$	0.23	0.25	55.74	50.63

After accepting maximum value of calculated moment in the slab centre, in case of the most loaded wheel - K_1 total moments for the remaining wheels K_2, K_3 and K4 were determined. Table II includes determined values, based on calculation of radial moments M_r - (5) and contact moments M_v - (6) and rectangular coordinates – (7) and (8).

$$M_r = -\frac{p^i}{h}\left(V - \frac{1-\nu}{\xi^i}U\right) \tag{5}$$

$$M_\nu = -\frac{P^i}{h}\left(\nu V + \frac{1-\nu}{\xi^i}U\right) \tag{6}$$

where: P – single undercarriage wheel load, h – assumed slab thickness, V, U – functions selected depending on ξ value, determined on the basis of $\xi = 1{,}41\,\frac{r'}{s}$ (r' – distance between considered point and tyre contact centre)

$$M_x = P\overline{M}_x \tag{7}$$

$$My = P\overline{M}_y \tag{8}$$

where: P – single undercarriage wheel load, $\overline{M_x}$, $\overline{M_y}$ – moments selected depending on application of force point P and ξ value, determined on the basis of $\xi = 1.41\,\frac{x}{s}$ and $\eta = 1.41\,\frac{y}{s}$ (x, y - coordinates of force application)

$$S_b = \frac{M_{obl}}{mR_b} \tag{9}$$

Next stage, steel reinforcement of elasticity coefficient of 210 GPa was assumed for 0.4% and slab rigidity according to [4] assuming more disadvantageous situation to dimension the structure at rigidity of $5.28x10^8\ \frac{kN\,cm^2}{m}$. Thickness of verified reinforced concrete slab of 27.79 cm, operating after crack occurrence and elastic characteristics of the slab of 154.70 cm were determined. Bending moments presented in Table II – case b, were determined in case of reinforced slab.

Assuming operating conditions coefficient of m=0.9 and concrete compression strength during bending of 34.5 MPa, contact moment of compression zone was determined and then bottom reinforcement cross-section and distance between cracks were determined, at compression zone height of $6.10*10^{-3}$ cm, l_t - Table II, case b. Assuming that k_1 = 2.8; ratio of steel and concrete elasticity coefficient n= 52.50, and the value of steel cross-section to circumference is u=0.65 cm the following distance between cracks **l_t= 48.07 cm** and crack opening width **a_t = 0.0357 mm ≈ 0.04mm** were determined.

TABLE II
DETERMINED VALUES OF BENDING MOMENTS IN CASE OF WHEEL K_2, K_3 AND K_4

Wheels	Case a			Case b		
	K_2	K_3	K_4	K_2	K_3	K_4
ξ	0.876	1.437	1.139	0.911	1.495	1.185
U	-0.227	-0.187	-0.213	-0.221	-0.174	-0.205
V	-0.219	-0.031	-0.108	-0.154	-0.009	-0.076
M_r [kNcm]	0.012	-0.736	-0.300	-0.480	-0.829	-0.652
M_v [kNcm]	-1.733	-0.979	-1.246	-1.692	-0.901	-1.252
M_x [kNcm]	0.012	-0.878	-1.246	-0.480	-0.561	-1.252
M_y [kNcm]	-1.733	-0.878	-0.300	-1.692	-0.859	-0.652
$M_x^{śr}$ [kNcm]		53.60			53.66	
$M_y^{śr}$ [kNcm]		52.78			52.75	
Rectangular coordinates method				Static moment S_b		
ξ	0.876	0.876	0	16.46 [cm^2]		
η	0	1.139	1.139			
$\overline{M_x}$ [kNcm]	0.009	0.016	0.045	Cracks distance l_t		
$\overline{M_y}$ [kNcm]	0.064	0.032	-0.005	$l_t = 0.5\,k_1\,n\,u$		48,07 [cm]
M_x [kNcm]	2.386	4.439	12.49			
M_y [kNcm]	7.730	0.888	-1.387			
$M_x^{śr}$ [kNcm]		50.09		Crack spacing width a_t		
$M_y^{śr}$ [kNcm]		51.12		a_t	0.035 ≈ 0.04 [mm]	

TABLE III
DETERMINED VALUES AT DIRECTION X AND Y DURING ULS MEASURING AND PHASES I AND II DURING SLS MEASURING

parameters	ULS		SLS	
	Direction y	Direction x	Phase I	Phase II
μ_{eff}	0.052	0.062	$E_{c,eff}$[MPa]	x_{II} [m]
ξ_{eff}	0.974	0.968	$13.6*10^3$	0.071
$A_{s1}\left[\frac{cm^2}{m}\right]$	7.35	8.06	α	I_{II} [m^4]
Load - bearing capacity verification			14.71	$3.86*10^{-4}$
$A_{s1}^{min}\left[\frac{cm^2}{m}\right]$	3.94	3.68	x_I [m]	σs [kN/m^2]
μ_{eff}	0.053	0.062	0.153	$4.29*10^5$
ξ_{eff}	0.051	0.064	I_I [m^4]	$A_{s1}^{min}\left[\frac{cm^2}{m}\right]$
ζ_{eff}	0.975	0.968	3.06	$4.39*10^{-4}$
$A_{s1}\left[\frac{cm^2}{m}\right]$	7.47	8.06	M_{cr} [kNm]	w_k [mm]
x_{eff}[m]	0.11	0.014	66.59	0.66
M_{Rd} [kNm]	74.91	74.9	M_{max} [kNm]	$S_{r,max}$ [cm]
M_{Ed} [kNm]	74.025		75.02	43.43

IV. DIMENSIONING OF REINFORCED CONCRETE PAVEMENT ACCORDING TO EUROCODE

First of all, it should be emphasised that dimensioning method in compliance with PN-EN [7]-[9] is primarily intended to design building facilities and bridge structures, as well as geotechnical structures, due to the fact that proceedings do not include dynamic load generated by aircraft traffic. Assumptions of preliminary design were concurrent with those presented in sec. III. Analyses were based on limiting conditions (Ultimate Limit State - ULS and Serviceability Limit State - SLS), in which structure fails to comply with design requirements. In case of reinforced concrete structure, as a result of external loads, shrinkage or thermal factors, cracks may occur, when concrete tensile strength is exceeded. Scratches occur as a result of bending, distribution of tensile stresses is variable at heights and certain part of cross-section is compressed [6]. Calculations were conducted for cross-section in phase I, i.e. non-scratched or scratched in phase II, and obtained results were included in Table III, symbols in accordance with [7]-[9].

V. Conclusions

Presented comparison of reinforced concrete slab designed according to two methods allowed to reach the following conclusions:

1. Reinforcement was designed in tensile section using bars of 16 mm diameter distributed every 20 cm (Fig. 3) and obtaining the required load-bearing capacity of cross-section with the slab thickness of 30 cm (Fig. 4). Application of reinforcement prevented the occurrence of accidental slab cracks resulting from structure overloading or rapid ambient temperature changes. The main objective of the applied reinforced bars was to take over concrete tension forces, improvement of operation of scratched cross-section and maintaining crack opening in constant, not exceeding allowable crack width. Additional advantage is limiting the height of concrete slab cross-section.
2. Using older limit state method in the design process, due to the fact that it is intended and adapted to airfield pavements made of reinforced concrete, provided more advantageous results. This method considers statics and support nature of concrete slab located on subbase in Winkler's method.
3. Applying higher value of reinforcement cover according to EC method than according to limit states had direct influence on internal force and distance between cracks and their width. Crack width (0.66 mm), calculated according to EC is wider by order of magnitude in comparison to the one determined according to the traditional method (0.04 mm). Distance between cracks differs by more than 4 cm. Distance calculated according to Eurocode is 43.4 cm, whereas the distance calculated by means of the traditional method 48.1 cm.

According to obtained parameters characteristics, regarding airfield pavement made of reinforced concrete, it was proved that at this stage of dimensioning, traditional method is more advantageous. Dimensioning of reinforced concrete pavements using Eurocodes method will be the subject of further analyses conducted by the design team.

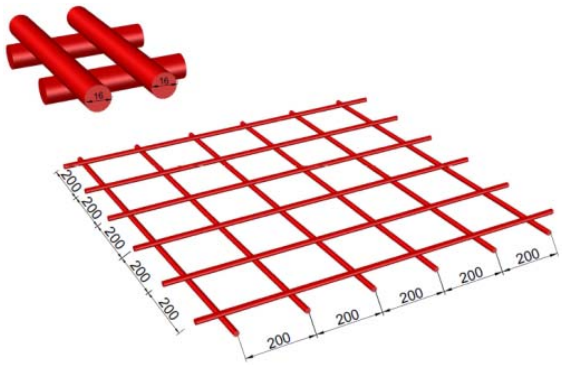

Fig. 3 Distribution of reinforcement bars

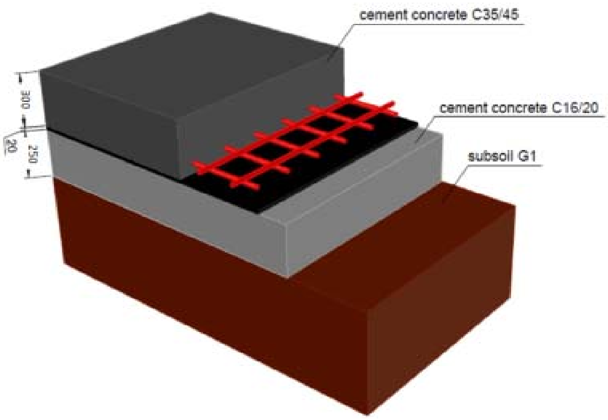

Fig. 4 Reduced cross-section of reinforced concrete pavement

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