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SELECTION OF PARAMETERS OF DOWELLING CONNECTIONS IN CONCRETE AIRPORT PAVEMENT

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The article presents numerical analysis of the portion of concrete airport pavement that consists of two concrete panels connected with dowels, subjected to thermal and service loads, in terms of changes in base rigidity, plate thickness and diameters, and spacing of dowels. Modifications of the thickness of the plates, diameter and spacing of dowels, and base rigidity were considered by assessing the level of stress and displacement in the analysed concrete plate, as well as normal and tangential stresses in dowels by using finite element method. On the basis of an analysis of examples, an optimal solution of dowelling connections in concrete plates with established loads was proposed. The results of the calculations were presented as a contour level distributions and comparison tables.

Key words: dowels, concrete airport pavement, numerical modelling, service loads, thermal loads.

1. Introduction

Concrete surface pavements are widely used throughout the world. Concrete pavements are more vulnerable to various kinds of damage in areas with high intensity of traffic. One of the main causes of damage to the edge of the plates in settlement joints are sagging differences of the edges of loaded and free plates.

The main task of the airport concrete pavement is to absorb the loads from aircraft wheels by a concrete layer and distribution of loads to a lower layers of base. Inside concrete plate, in addition to the stresses resulted from the weight of the aircraft transferred by individual wheels, and the base dead weight of airport plate, a thermal stress caused by atmospheric factors is present as well [1]. Analysis of plates collaboration in concrete airport pavement shows that dowelling, i.e. connection of the plates on their length by steel elements, ensures the cooperation of neighbouring plates on the transfer of the loads. Effectiveness of dowelling connections depends on many elements of the design of surface, and in particular the diameters of the dowels, their distance, rigidity of base course and thickness of the plate. A single dowel is a steel rod of circular

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cross-section and length of 600 mm arranged in the median plane, perpendicular to the plane of the settlement joint. Half the length of a dowel is covered with a substance that allows slip. Such design of the dowel provides the moving of vertical external loads to the adjacent plates, and simultaneously allows independent horizontal displacements of adjacent plates [2]. The observation and analysis of the concrete surfaces results show that dowelled plates provide the alignment and reduce the maximum stress in the plates and contributes to the reduction of maximum sagging of the plates. In addition, they significantly improve their collaboration in settlement joints contributing to the elimination of the phenomenon of keying plates [3].

The development of the concrete pavements is largely dependent on research carried out on sample and trial sections subjected to extreme conditions of the service. In the initial period of development, concrete pavements were normally designed and constructed for the service life of 20-25 years. Nowadays the design and construction of concrete pavements for up to 60 years has been reasonable. Influence of base dead weight of airport plate construction, time alternating aircraft service loads, and thermal loads cause fatigue undermining a concrete plates as a result of recurring overlapping of service and thermal loads. In the longer term, this leads to damage of the surface in the form of scratching, and subsequently cracking and dropping off [4].

2. Research problem considerations

Based on a survey of the national technical literature, it can be noted that the problem of influence of dowelling process on concrete pavements was the subject of the very few researches [5]. The dynamic development of approximate calculation methods has increasingly been pushing builders to use models based on finite elements method (FEM). One of the means to recognize the nature of the impact of dowelling methods with service and thermal loads is the strength analysis of slabs using FEM.

The main objective of this study was to carry out numerical analysis and evaluation of the effectiveness of dowelling connections taking into account the effect of the rigidity of the base layer, thickness of the slabs and the diameter and spacing of dowels. Service loads, thermal loads, and base weight of airport concrete slab were taken into account in numerical analysis. The results, in comparison to the generalised and not very precise requirements of the design described in the standards, allow to determine the optimal design of concrete airport pavements' dowelling [6].

3. Discrete model

The study shows examples of numerical simulations using solid model using the FEM. To determine the displacement and stress in airport concrete surfaces and inside the dowels under static loads of selected type of service loads, and a range of temperatures, the MSC.NASTRAN for WINDOWS system was used [7].

Configuration of two equal square slabs, measuring 5 m × 5 m with thicknesses 0,61 m, 250 mm and 280 mm, connected with dowels along one edge, was considered in numerical analysis.

Concrete slabs were marked with following material constants:

– Longitudinal concrete spring constant E = 32 600 MPa;
– Poisson's ratio v = 0,17.

Discrete solid model of a slab was created with the eight-node CHEXA solid elements of 100 mm × 100 mm sizes. For single plate of 5 m × 5 m size, four equal layers of elements were used including a total of 10,000 solid element regardless of the thickness of the surface. Elastic base was described with two-node non-tensile GAP elements, corresponding to the stiffness of the base course with constant k = 100 MPa/m or k = 200 MPa/m. The service loads in numerical model were described assuming that the surface was statically laden with main landing gear of C-130 Hercules transport aircraft with two wheels in tandem (Fig. 1). The wheel footprint was in the form of a rectangle with length 600 mm and a width of 500 mm. Gravity force of 480 kN acting on the undercarriage, divided by the pressure field of wheels, gives the pressure on the wheel footprint equal to 1 MPa. Three typical load variants were considered: variant No I – centre of the plate, variant No II – middle of the edge, variant No III – quoin. (Fig. 2)

Fig. 1. C-130 Hercules aircraft on the apron.
Rys. 1. Widok samolotu Herkules C-130 na płycie lotniska

The calculations were made on the assumption that the ties between the slab and base course do not carry the stretch what was achieved using GAP elements. An analysis was carried out as a non-linear one for static loads derived from the pressure of aircraft wheel (without the dynamic and fatigue effects). In addition, the thermal load induced by uniform change of temperature within slab thickness (positive gradient 15/0, negative gradient 0/15) was taken into account adopted on the basis of the assumptions of work [8]. Gradient was defined as the ratio of the temperature on the upper surface of the slab to the lower surface of the slab.

Dowels were anchored in the slabs having 300 mm from each side. The width of the expansion gap between two slabs for all the examples were equal of 5 mm.

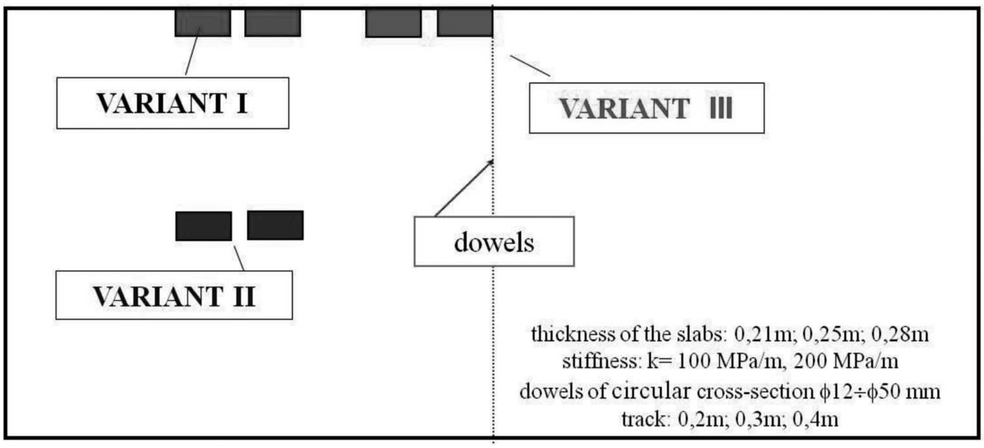

Fig. 2. Three variants of the wheel footprint on the airport apron slab.
Rys. 2. Widok rozmieszczenia śladów podwozia głównego na płycie lotniska dla trzech wariantów

4. Analysis of the results

Detailed description of the principles of surface calculation with regard to the impact of dowelling were included in [1,3,5]. Theoretical analysis of slab connecting was described as well in Polish Standards, however, the description includes only the general principles and has wide options to choose [6].

In order to assess the impact of dowelling, analysis was carried out for discrete single (non-dowelled) airport slab model of 0,210 mm thickness, resting on the foundation of stiffness k = 100 MPa/m. Calculations were made for: the three classical variants of the load distributions with one main landing gear (two wheels as a tandem) – (No I÷ III variants), for two variants of the thermal load (GRAD ±variants) and two variants of associative loads. For further analysis, Variant No III was chosen, for which the maximum principal stress σ_{max} adopted as the effort criterion, reaches the extremum (Table 1).

While analysing the deflection of a single slab, it can be noted that in the case of application of elastic ground in the numerical model, which can be described by non-tensile elements, some areas of the slab can separate from the foundation (positive displacement values along the Z axis marked as a z_{max}, negative values of displacement component along Z axis corresponding to the slab immerse into the ground marked as a -z_{min}). On the basis of the results listed in Table 1, it was found that the values of the maximum slab deflection for accepted variants of loads strongly depended on the place of application of the load and adopted gradient and change for -z_{min} 0,7÷4,3 mm, whereas for z_{max} 0,1÷3,1 mm. Taking into account that the thermal loads is of the main importance for slab deflection (Fig. 3).

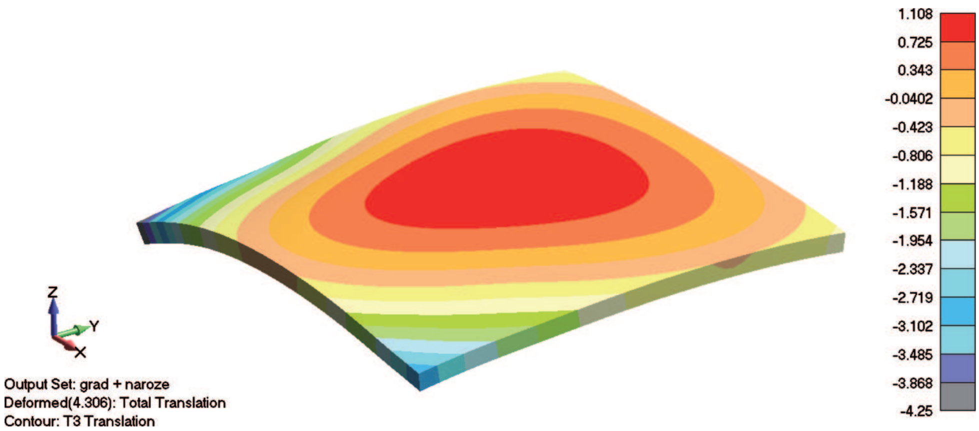

Fig. 3. Slab deflection for variant III GRAD+ (Table 1) [mm].
Rys. 3. Ugięcie płyty dla wariantu III GRAD+ (tabela 1) [mm]

For a single slab with No III variant, the load applied in quoin causes maximum main stress (Table 1). Therefore, No III variant including thermal loads will be a subject to further analysis.

Table 1

Result for a single slab.
Zestawienie wyników dla pojedynczej płyty

	Variant		z_{max} / - z_{min} [mm]	σ_{max} [MPa]
k =100 MPa/m gr. 21 cm				
1	Service loads	VARIANT I	0,15 / - 0,7	3,0
2		VARIANT II	0,5 / - 2,0	3,6
3		VARIANT III	0,08 /- 3,3	4,1
4	Thermal loads	GRAD +	1,08/- 1,02	1,44
5		GRAD -	1,2/ - 0,69	1,46
6	Combined loads	VARIANT III GRAD +	1,1 /- 4,3	4,9
7		VARIANT III GRAD -	3,1 /- 2,5	3,49

It should be noted that in case of quoin stress and thermal load with positive gradient σ_{max} it reached values close to 5 MPa, which for an assumed concrete class exceeded the limit of stress. On the basis of further analysis of the three variants, the cases in which the stress in slabs and/or dowels exceeds the limit values could be defined.

The above mentioned generalized assumptions led to the adoption of a further analysis of the four major factors that determine the quality of the dowelling connection:

– effect of diameter of dowels: dowels of circular cross-section $\varphi 12$ mm ÷ $\varphi 50$ mm ($\varphi 12$, $\varphi 16$, $\varphi 30$, $\varphi 40$, $\varphi 50$);
– effect of stiffness of ground plate: stiffness k = 100 MPa/m and k = 200 MPa/m;
– effect of the thickness of the slab: thickness of the slabs h = 0,21 m, h = 0,25 m, h = 0,28 m;
– effect of dowels' track: even track distributed along the edge of the plate from 0,2 m to 0,4 m (distance 0,2 m, 0,3 m, 0,4 m);

As a result of the conducted calculations for each of the analysed samples, two groups of results were obtained:

– for slabs: maximum main stress σ_{max} and extreme slab deflections $z_{max}/-z_{min}$;
– for dowels: normal stress σ_g induced by bending of dowels and tangent stress τ_{max} induced by transverse force calculated from the known formula τ_{max} = T/A, where T is the shearing force,
  A – dowel cross-section area.

In order to assess the impact of the individual construction parameters for the value of the maximum main stresses, as well as the maximum slab deflections, an analysis was made using the model consisting of two plates connected by dowels.

Dowel diameter analysis

The value of the maximum deflection of dowelled slabs computed for C-130 Hercules aircraft for the analysed load variants showed significant reduction in relation to non-dowelled ones. As in the case of a single slab, maximum deflection value depends on the place of load application, but dowelling results in a significant reduction of the maximum deflection value of the slab, with a tendency to achieve extreme values for No III variant and the negative gradient.

Comparative summary of the results for different dowel diameters (Table 2) showed that the change in diameter of dowels in insignificant way affects the change of the maximum main stress and the maximum deflection in the slab, although this analysis provides a number of information about stress in the dowels, confirming a significant influence on their diameter.

With the reduction of the dowels' diameter, the maximum values of the normal stresses were increasing in dowels $\sigma_g \approx 39 \div 431$ MPa (Fig. 4) and calculated on the basis of shearing force distribution values in $\tau_{max} \approx 43 \div 450$ MPa. For the five analysed examples it was observed in two cases that the normal stress values σ_g exceeded the value of the stress limit k_g while for τ_{max} in three cases exceeded the value of maximum stress k_t (Table 2). According to the literature, [9] the bending stress limit

k_g for dowels with a diameter between 16÷40 mm is 145 MPa and maximum shear stress k_t is 90 MPa. On the basis of the obtained results (for the assumptions made) it could be assumed that the structure of the pavement, due to the stress tangent, required the use of dowels with diameter >32 mm (Fig. 5). Based on a detailed analysis of the results for each pavement it could be seen that further increase of the diameter of the dowels became pointless, because no noticeable effect was seen on the stress and displacement in the pavement. The results for several examples showed that in most cases too small diameter adopted, although complying with the applicable standards for the thickness of the slab, gave the considerable value of the normal and tangential stress in dowels that exceeded the value of maximum stress (Fig. 4).

Table 2

Summary of results for different diameters of dowels and base rigidity.
Zestawienie wyników dla różnych średnic dybli i sztywności podłoża

Lp.	Variant	Offset [mm]	z_{max} /-z_{max} [mm]	σ_{max} [MPa]	τ_{max} [MPa]	σ_g [MPa]
φ12, k =100 MPa/m 21 cm thickness, 0,2 m spacing						
1	VARIANT III	$\approx 0,4$	0,02/-2	3,35	440	384
2	VARIANT III GRAD +		0,9/-2,55	4,4	433	431
3	VARIANT III GRAD -		2,3/-1,6	3,3	450	399
φ16, k =100 MPa/m 21 cm thickness, 0,2 m spacing						
4	VARIANT III	$\approx 0,3$	0,02/-1,91	3,31	325	332
5	VARIANT III GRAD +		0,9/-2,52	4,35	316	362
6	VARIANT III GRAD -		2,29/-1,6	3,24	328	327
φ30, k =100 MPa/m 21 cm thickness, 0,2 m spacing						
7	VARIANT III	$\approx 0,3$	0,02/-1,9	3,32	99	83
8	VARIANT III GRAD +		0,9/-2,48	4,3	96	143
9	VARIANT III GRAD -		2,28/-1,59	3,23	100	68
φ40, k =100 MPa/m 21 cm thickness, 0,2 m spacing						
10	VARIANT III	$\approx 0,3$	0,01/-1,89	3,3	56	58
11	VARIANT III GRAD +		0,9/2,44	4,3	54	124
12	VARIANT III GRAD -		2,27/-1,59	3,2	57	62
φ50, k =100 MPa/m 21 cm thickness, 0,2 m spacing						
13	VARIANT III	$\approx 0,2$	0,02/-1,9	3,32	34	36
14	VARIANT III GRAD +		0,9/-2,48	4,3	36	99
15	VARIANT III GRAD -		2,28/-1,59	3,23	38	39
φ30, k =200 MPa/m 21 cm thickness, 0,2 m spacing						
16	VARIANT III	$\approx 0,2$	0,02/-1,21	2,75	86	65
17	VARIANT III GRAD +		0,71/-1,62	3,91	84	115
18	VARIANT III GRAD -		1,81/-1,01	2,94	87	66

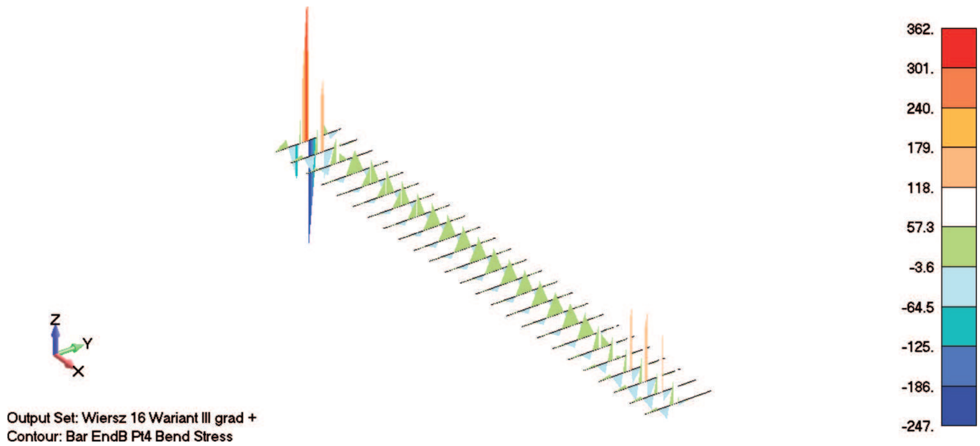

Fig. 4. Distribution of normal stress in dowels for variant III GRAD + (Table 2, position 5) [MPa].
Rys. 4. Rozkład naprężeń normalnych w dyblach dla wariantu III GRAD+ (tabela 2, Lp.5) [MPa]

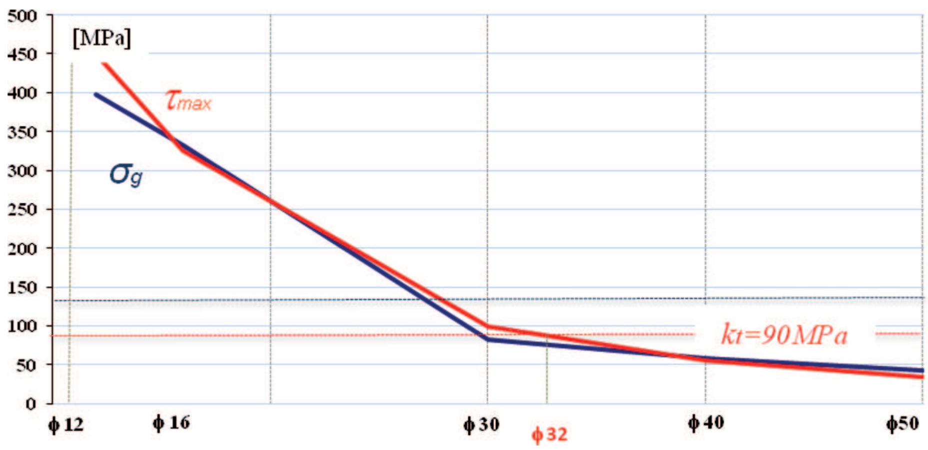

Fig. 5. Effect of changes in the diameter of the dowels on stress in dowels [MPa].
Rys. 5. Wpływ zmian średnicy dybli na naprężenia w dyblach [MPa]

It should be noted that the cases presented here are only an attempt to show opportunities for FEM to perform stress and displacement analysis in slabs and dowels with selected loads. Sample analysis can also specify an ”offset” which is the maximum difference in height between adjacent edges of slabs (Fig. 6). Among the five variants the ”offset” is within the limits from 0,2 mm to 0,45 mm. The phenomenon of keying of lateral connections, which is the result of the offset, has a very significant impact on the quality of taxiing and safety and stability of the pavement.

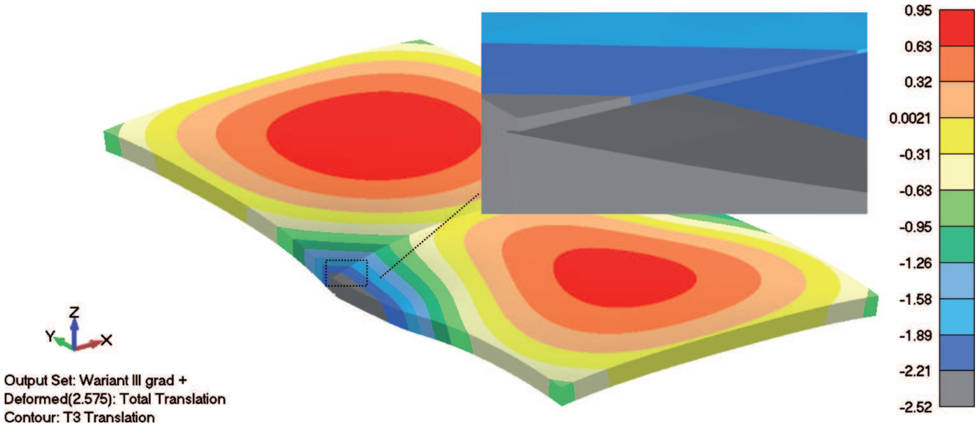

Fig. 6. Deformation of slabs for Variant III GRAD +, the difference in height of the ”offset” (Table 2; position 5) [mm].
Rys. 6. Deformacja płyt dla Wariantu III, różnica wysokości krawędzi ”uskok” (tabela 2; Lp.5) [mm]

Influence of stiffness analysis

The achieved results of the influence of base course stiffness analysis shown in Table 2 (pos. 16-18) confirmed the very significant impact of this factor on the displacement and stress in slabs and dowels. Double increase of stiffness caused a significant drop in the value of negative vertical movements, corresponding to the immerse of the slab quoins with positive gradient of temperature (Fig. 7), and immersed of the central part of the slab with a negative gradient. The reduction of the maximum main stress in the slabs and the decrease of the maximum values of normal and tangential stress in dowels is particularly important. If this reduction causes the stress values to decrease below the stress limit in dowels, the value of the maximum main stress in slab for variant III GRAD + still varies within the limits of 4 MPa (Fig. 8). Reduction of this value is possible by increasing the thickness of the slab.

Influence of analysis of slab thickness

The following example allows to track the stress state of dowelled surface in case of use of different slab thicknesses, namely: 210 mm, 250 mm and 280 mm. While

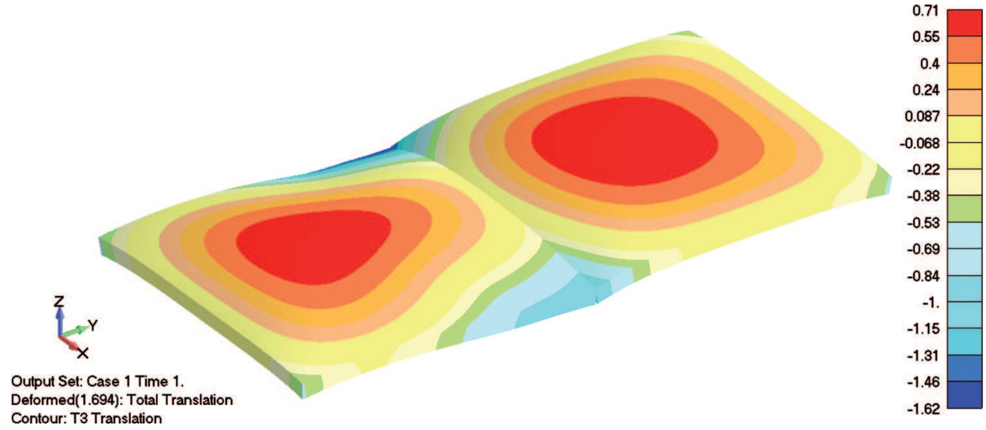

Fig. 7. Deformation of the plate for the variant III GRAD + (Table 2, position 17) [mm].
Rys. 7. Deformacja płyty dla Wariantu III GRAD + (tabela 2, Lp.17) [mm]

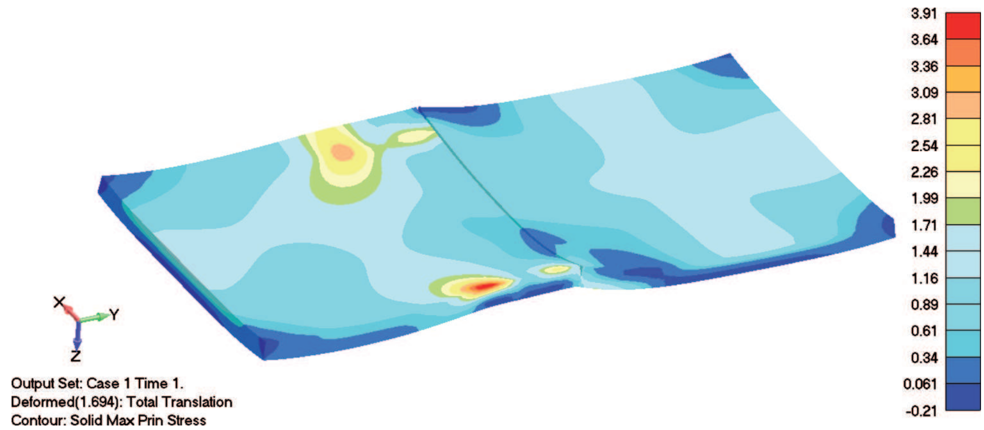

Fig. 8. Distribution of σ_{max} on the lower surface of the slab for the variant III GRAD + (Table 2, position 17) [MPa].
Rys. 8. Rozkład σ_{max} na dolnej powierzchni płyty dla Wariantu III GRAD + (tabela 2, Lp.17) [MPa]

comparing the results from table No 3 it can be noted that by increasing the thickness of the slabs by around 20%. i.e. 40 mm the maximum deflection on average of around 20% is reduced. The values of the maximum main strain are smaller, the higher is the thickness of slabs. For variant III GRAD + the σ_{max} for slabs with 0,21 thickness has a value close to 4 MPa, with increased thickness of the slabs by 0,07m does not exceed 2,8 MPa (Fig. 9). This is the confirmation of the relationship that for the reduction of the maximum stress in slabs, the adopted thickness of the pavement plays decisive role.

The analysis of stress in dowels is of particular importance of this example. The dominant component of the interior forces in dowel is the bending moment on the vertical plane and the vertical component of the cutting force. The stress caused by other components of internal forces is low enough to be omitted.

Extreme values of normal stress in dowels, regardless of the thickness of the slabs, are always present for the variant III GRAD + and have the value of 110÷115 MPa, not exceeding the value of maximum stress. Figure 10 shows the distribution of the normal stress in the set of dowels for variant III GRAD +. Distribution of cutting forces in the set of dowels for variant III GRAD− is shown in the Fig. 11. Maximum values of the normal stress in far left slabside dowel are caused by load from aircraft wheels. The graph of changes of the normal stress in dowel presented in Fig. 10 is given in Fig. 12, and the distribution of cutting force in Fig. 13. Characteristic pile of values of normal stresses and cutting forces can be seen in parts of dowels adjacent to the settlement joint.

Table 3

Summary of results for different slab thickness.
Zestawienie wyników dla różnych grubości płyt

	Variant	Offset [mm]	z_{max} / $-z_{max}$ [mm]	σ_{max} [MPa]	τ_{max} [MPa]	σ_g [MPa]
φ30, k =200 MPa/m thickness 21 cm, 0,2 m spacing						
1	VARIANT III	$\approx 0,2$	0,02/-1,21	2,75	86	65
2	VARIANT III GRAD +		0,71/-1,61	3,91	84	115
3	VARIANT III GRAD -		1,81/-1,01	2,94	87	66
φ30, k =200 MPa/m thickness 25 cm, 0,2 m spacing						
4	VARIANT III	$\approx 0,2$	0,0/-1,01	2,18	89	63
5	VARIANT III GRAD +		0,78/-1,5	3,17	85	112
6	VARIANT III GRAD -		1,83/-0,79	2,55	90	69
φ30, k =200 MPa/m thickness. 28 cm, 0,2 m spacing						
7	VARIANT III	$\approx 0,15$	0,0/-0,9	1,9	91	61
8	VARIANT III GRAD +		0,7/-1,48	2,78	86	111
9	VARIANT III GRAD -		1,91/-0,6	2,39	91	70

Influence of the dowels spacing analysis

The analysis of the influence of changes in dowels spacing, performed for slab thickness of mm 0,25 m, laid on the foundation of stiffness k = 200 MPa/m. The analysis assumes the usage of dowels with a diameter of 30 mm with 0,2, 0,3 and 0,4 m spacing. Load of the C-130 main landing gear at slab quoin is again considered. The results of the analysis are presented in table 4. Double increase of dowel spacing gives minimal, percentage growth in deflection and maximum main stress in the slab. The

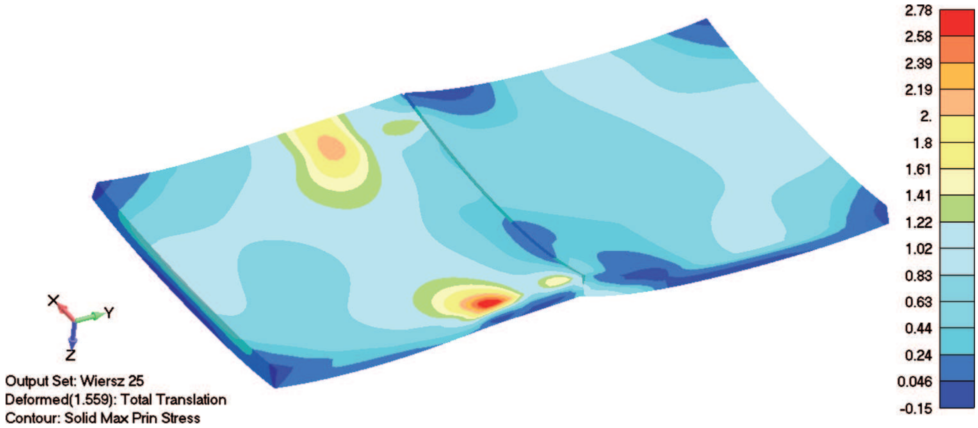

Fig. 9. Distribution of σ_{max} on the lower surface of the slab for the variant III GRAD + (Table 3, pos. 8) [MPa].
Rys. 9. Rozkład σ_{max} na dolnej powierzchni płyty dla Wariantu III GRAD + (tabela 3, Lp.8) [MPa]

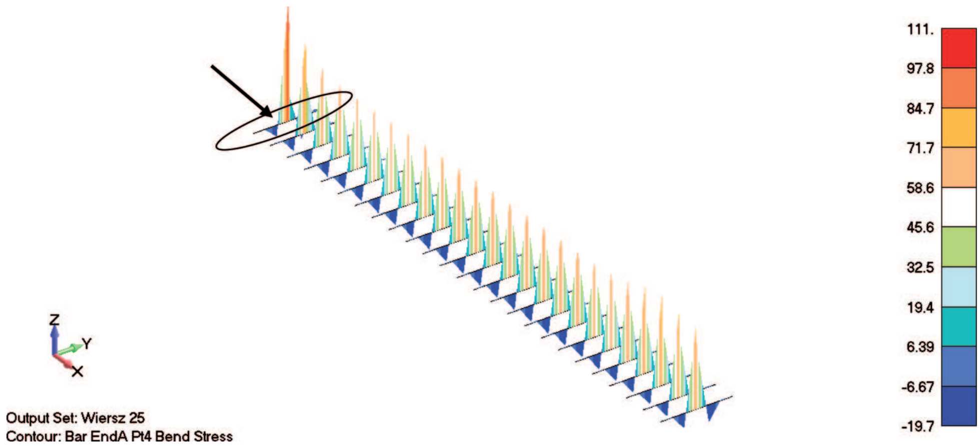

Fig. 10. Distribution of normal stress for variant III GRAD + (Table 3, pos. 8) [MPa].
Rys. 10. Rozkład naprężeń normalnych dla wariantu III GRAD+ (tabela 3, Lp.8) [MPa]

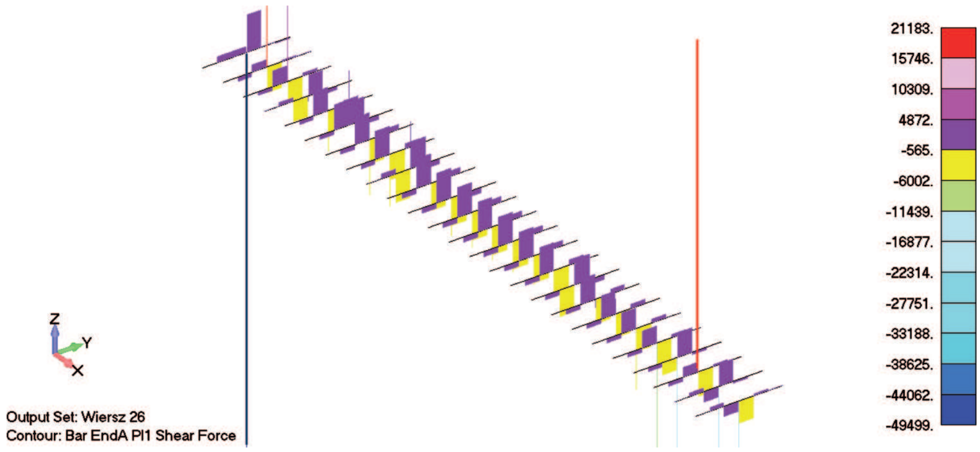

Fig. 11. Distribution of lateral force in dowels for variant III GRAD – (Table 3, pos. 9) [N].
Rys. 11. Rozkład sił poprzecznych w dyblach dla Wariantu III GRAD – (tabela 3, Lp.9) [N]

stress in dowels is more noticeable. This applies particularly to tangent stress. Increase of dowels spacing from 0,2 m to 0,4 m produces 20% increment of tangent stress ? the tangents with the exceeding of the maximum stress. The increase of normal stress does not exceed 10%.

Table 4

Summary of results for different dowels spacing.
. Zestawienie wyników dla różnych rozstawów dybli

	Variant	Offset [mm]	z_{max} -z_{max} [mm]	σ_{max} [MPa]	τ_{max} [MPa]	σ_g [MPa]
φ30, k =200 MPa/m, thickness 0,25 m, 0,2m spacing						
1	VARIANT III		0,0/-1,01	2,18	89	63
2	VARIANT III GRAD +	$\approx 0,2$	0,78/-1,5	3,17	85	111
3	VARIANT III GRAD -		1,83/-0,79	2,55	90	69
φ30, k =200 MPa/m, thickness 0,25 m, 0,3m spacing						
4	VARIANT III		0,0/-1,1	2,2	96	67
5	VARIANT III GRAD +	$\approx 0,3$	0,8/-1,55	3,2	93	117
6	VARIANT III GRAD -		1,9/-0,8	2,6	98	74
φ30, k =200 MPa/m, thickness 0,25 m, 0,4m spacing						
7	VARIANT III		0,0/-1,2	2,3	105	71
8	VARIANT III GRAD +	$\approx 0,4$	0,9/-1,6	3,3	103	126
9	VARIANT III GRAD -		1,93/-0,88	2,71	108	79

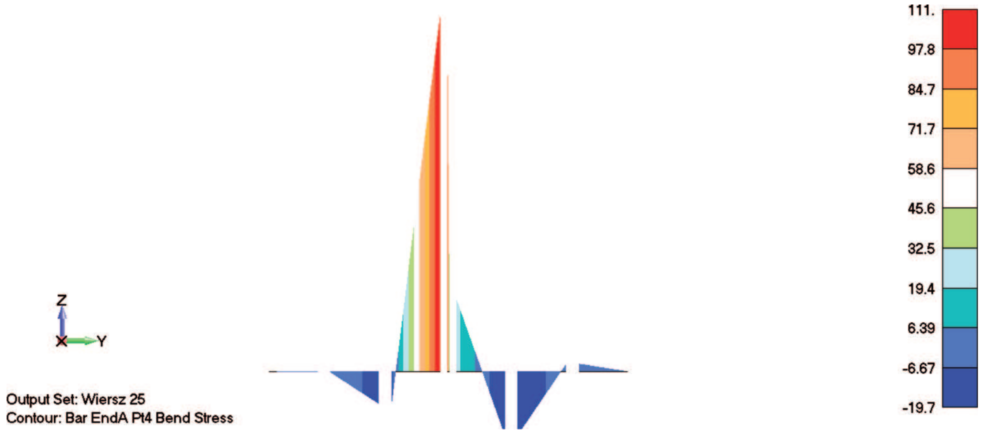

Fig. 12. Distribution of normal stress in a single dowel for variant III GRAD – shown in Fig. 10 (Table 4, pos.2) [MPa].
Rys. 12. Rozkład naprężeń normalnych w pojedynczym dyblu dla wariantu III GRAD – wskazanym na rysunku 10 (tabela 4, Lp.2) [MPa]

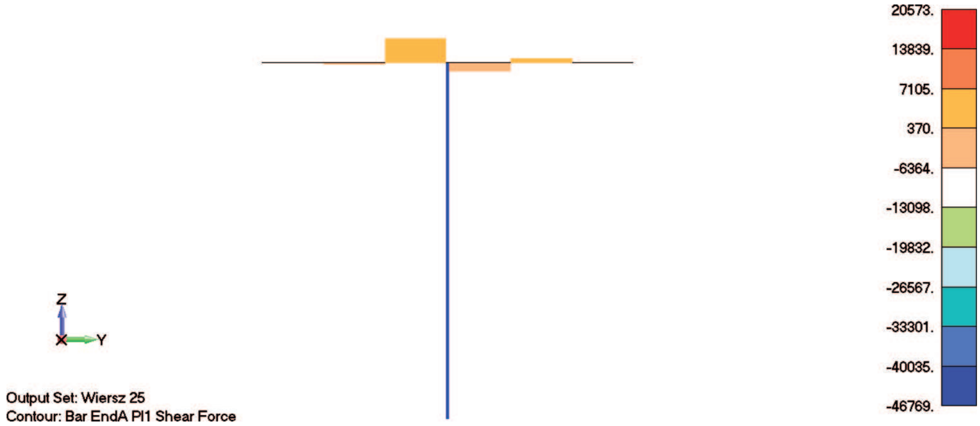

Fig. 13. Distribution of lateral forces in a single dowel for variant III GRAD – (Table 4, pos. 2) [N].
Rys. 13. Rozkład sił poprzecznych w pojedynczym dyblu dla wariantu III GRAD – (tabela 4, Lp.2) [N]

5. Summary

– The analyses presented in this study shows the ability of the use of professional FEM software for full analysis of displacement and stress status in plates and dowels.
– The analysis carried out herein allows to select the best examples taking into account the stress and safety reasons.
– The analyses indicate that the adopted dowelling schema in terms of dowel spacing and dowel diameter changes affects in particular the volume of the maximum stress in dowels while changes of the foundation stiffness and slab thicknesses - on the volume of the main maximum stress in slabs.
– The connection of tri-dimensional slab elements with single-dimension dowel elements does not allow to assess the clamp stress between concrete and dowels. For the purpose of the analysis of this effect, the more precise model is required. The model adopted here is rather simplified.

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WPŁYW DYBLOWANIA NA PRZEMIESZCZENIA I NAPRĘŻENIA W BETONOWYCH NAWIERZCHNIACH LOTNISKOWYCH

S t r e s z c z e n i e

W artykule przedstawiono numeryczną analizę fragmentu betonowej nawierzchni lotniskowej składającej się z dwóch betonowych płyt połączonych dyblami, poddanych obciążeniom termicznym i użytkowym, w aspekcie zmian sztywności podłoża, grubości płyt oraz średnicy i rozstawu dybli. Stosując modyfikacje grubości płyt, średnic dybli i ich rozstawu oraz sztywnością podłoża dokonano oceny stanu naprężeń i przemieszczeń w analizowanych płytach betonowych oraz naprężeń normalnych i stycznych w dyblach przy wykorzystaniu metody elementów skończonych. Na podstawie analizy przyjętych przykładów zaproponowano optymalne rozwiązanie połączeń dyblowych w płytach betonowych przy założonych obciążeniach. Wyniki obliczeń przedstawiono w postaci przykładowych rozkładów warstwicowych oraz tabel z zestawieniem porównawczym.

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