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THE INFLUENCE OF THERMAL LOADS ON MODERN ROAD CONCRETE PAVEMENTS IN POLAND

Summary. This article presents the opportunities for the development of road concrete pavements in Poland. The analysis of the prospects for evolving a new type of concrete pavement, based on continuous reinforcement, has been performed. The advantages and disadvantages, in terms of functionality, strength and economy, have been analysed. The evaluation of stress and displacements in the analysed continuously reinforced concrete slabs, involving the use of the finite element method (FEM), has been performed on selected temperature distributions derived from thermal loads. Based on the analysis of adopted decompositions, the use of the FEM to assess the effectiveness of the continuously reinforced pavements has been proposed.

Keywords: continuously reinforced concrete pavement; numerical modelling; thermal loads; concrete slab; temperature.

1. INTRODUCTION

The *Programme for National Road Construction 2014-2023 (with a View to 2025)* is a document that defines the objectives regarding the development of road infrastructure. It includes a schedule for the realization of investments, aimed at their accomplishment and highlighting funding sources and the amount of planned expenditures. The main aim of the programme is to build a consistent and modern system of roads in the country, which will

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provide the effective functioning of road passenger and cargo transport. The programme costs, which are estimated at PLN 107 billion, will be used to build about 3,900 km of highways and expressways, as well as 57 ring roads. Furthermore, PLN 51.8 billion will be allocated to the maintenance and modernization of existing roads. In order to achieve the above goals, missing parts of expressways and highways will be completed, while selected parts of national roads will be refurbished and ring roads constructed, which will improve the traffic flow in the urban centres that are the most affected by loaded transit traffic. The crucial aim of the above programme is to build, by 2023, over 880 km of concrete roads in the national road system [3,7,10].

On the new financial horizon, it is assumed that approximately three quarters of new roads will be built using traditional bitumen technology, whereas approximately one quarter will use concrete pavements. In 2016, upon the completion of parts of concretized expressways and highways, as well as making them available for use, their total length will be less than 580 km, which will only constitute 6% of all highways.

2. DEVELOPMENT OF CONCRETE PAVEMENTS IN POLAND

Concrete pavements date back to ancient times, when the Romans started using cement to bond the layers that roads were made of. The first contemporary concrete pavements were created at the beginning of the 20th century in the US, with the first concrete pavement comprising a concrete slab, which was 0.175 m thick, 1 mi long and 4.5 m wide, and had stretching gaps with wooden inserts positioned every 7.5 m. The first concrete highways appeared in 1939 in Germany, while Poland developed a new technology for constructing road surfaces for the first time in 1912 in Cracow [6,13].

Since the early 20th century, concrete pavements have gone through a period of significant evolution and technological revolution, including a reduction in the distance between transverse gaps up to 5 m, the implementation of a road foundation of concrete slabs, the obligatory use of aeration admixtures of concrete, and the careful use of fresh concrete.

The advantages of concrete pavements have been recognized by many countries, mainly in Western Europe. Germany is the country with the longest and the most significant tradition in Europe regarding the creation of concrete pavements. Currently, Germany has 12,000 km of highways, with as much as 40% of such a grade of roads made with the use of concrete technology. In the context of European countries, Belgium should also be mentioned, where concrete pavements constitute nearly 90% of the main road system. The main advantages of concrete pavements can be divided into three categories: technical (long-term endurance of pavements), economic (a lower overall cost of creation and maintenance) and social (the majority of the materials used are produced in the country).

There are additional advantages of concrete pavements, which were taken into account while planning future road investments in Poland:

- Resistance to deformation, especially rutting: it is planned to build concrete roads where heavy traffic load occurs, in particular, where the ratio of passenger traffic is similar to truck traffic (truck traffic equates to approximately 5,000 vehicles per day)
- A much longer period of using concrete pavements (over 30 years) compared to asphalt pavements (about 20 years of use)
- Concrete pavements after applying surface treatment do not require additional funding, even over a period of up to 20 years (or up to nine years in the case of asphalt pavements)

- Increasing the number of contractors, both domestic and international, with experience regarding the possibility of realizing new tasks using concrete technology

Currently, concrete pavements compete with asphalt ones at the executive stage, as the former are poorer in terms of endurance. While comparing other aspects of both types of the surface, concrete pavements are characterized by greater durability over a long period of their use (they do not require repairs or replacements for up to 50 years). Concrete pavements are appreciated by drivers, as they are properly designed and textured, as well as lesser deformation (lack of rutting), thus guaranteeing greater safety, driving comfort and decreased fuel need. In turn, brighter-coloured concrete pavements and increased reflexivity improve visibility, especially at night. Regarding concrete mixtures used for surfaces, industrial by-products and waste products can be used (cement with fly ash, open-hearth slag), which not only eliminate the need for their storage, but also reduce the need for new materials, thereby saving natural resources [5,13,14].

According to the Board of the Generalna Dyrekcja Dróg Krajowych i Autostrad (GDDKiA), or the General Directorate for National Roads and Motorways, once the *Programme for National Road Construction* has been implemented after 2023, there will be over 22,000 km of roads in total, including 4,611 km of highways and expressways. Regarding the national road system, there will be 20,660 km of asphalt roads (94%) and 1,350 km of concrete roads (over 6%) (Fig. 1). The decision of the GDDKiA regarding the construction of 810 km of roads using concrete technology is surprising in the context of historical data; within the last 20 years, only 600 km of roads of this type have been built. The current change in attitude is the result of observing experienced road managers in other countries and the similarity of costs in the construction of both concrete and asphalt roads. Meanwhile, the development of concrete roads involves searching for new and improved construction techniques, implementing new technologies, and conducting related research.

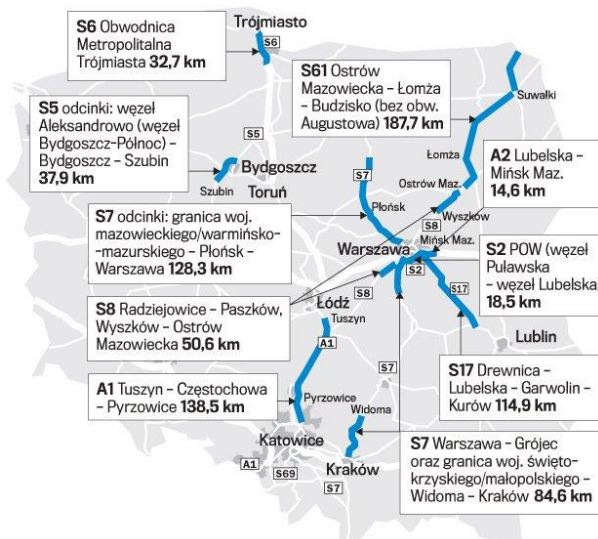


Fig. 1. Expressways and highways to be built with the use of concrete surface technology. S6: Tri-city metropolis ring road, 32.7 km; S5 sections: Aleksandrowo junction (Bydgoszcz-North), Bydgoszcz-Szubin, 37.9 km; S7 sections: Mazovian/Mazurian border-Warmia Provinces-Płońsk-Warsaw, 128.3 km; S2: POW (Puławska junction-Lubelska junction), 18.5 km; S7: Warsaw-Grójec and the border of Świętokrzyskie/Lesser Province of Widoma-Cracow, 84.6 km

3. CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

After more than century of experience regarding the use of road concrete pavements, the following types of pavements are available:

- Unreinforced and non-interconnected pavements
- Unreinforced interconnected surface and anchored pavements
- Reinforced pavements with interconnected gaps
- Prestressed concrete pavements
- Prefabricated pavements
- Complex pavements (mixed): concrete foundation upon which a thin layer of a mineral is placed; asphalt mixture or a concrete layer placed on existing asphalt pavement (white topping)
- Continuously reinforced pavements without transverse gaps [13,14]

In the context of construction technology at a global level, the practical use of concrete pavements concerns the following types: dowel and anchored, unreinforced and non-interconnected, complex pavements (mixed) and continuously reinforced. The latter type is undoubtedly the most popular in the US and EU countries (namely, England, Belgium and France). The main disadvantage of this method is the higher cost of construction (about 5 to 8%), which has been a significant barrier to its use in Poland. In terms of road concrete pavements in Poland, however, it can be observed that continuously reinforced pavements include the following advantages:

- High levels of driving comfort: a lack of dilatation means that there is no prevalence of curling
- Lower maintenance and operation costs in relation to other types of pavements, with regard to the limitation of dilatation gaps
- The lack of the adverse phenomenon known as so-called “pumping water in gaps” (penetration of water into the subsoil does not occur)
- The significantly long period of their usage

The general rules for constructing continuously reinforced pavements are based on the transverse reinforcement disposed at between 0.1 and up to 0.23 m, situated in the middle of the concrete slabs' thickness. Reinforcement bars are usually placed on props (Fig. 2) or by means of specialized machines designed for this purpose. During the operation, capillary fractures appear, which are 0.2 mm wide, reaching to a depth of 1 to 2 cm from the surface of the concrete. According to repair technology, it is assumed that such pavements may be covered with a thin layer of a new bituminous surface in the future (in approximately 30 years' time) without the need to incur expenses for its repair.

One of the first experimental parts of a continuously reinforced road concrete pavement was constructed at the section of the A4 highway near Kały Wrocławskie. The contractor was a consortium comprising Joint Venture Kirchner/Bogl/Berger, which is the main contractor of the A4 highway, and the GDDKiA department in Wrocław. While testing a new pavement, a new continuously reinforced section, which was 1 km long and 11 m wide, with only two oblong gaps, was made. This section was built as a “testing ground” before a more comprehensive implementation of a new type of surface in Poland [4].



Fig. 2. The works conducted during the construction of a continuously reinforced concrete highway

4. THERMAL LOADS OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

Concrete pavements are affected, apart from the external forces caused by movement on them, by internal forces generated in the pavements themselves, due to changes in atmospheric temperature referred to as thermal forces. Apart from stresses coming from wheels, thermal stresses, caused by a change in temperature on the pavement and the bottom of a concrete slab, can be distinguished. There are several methods for calculating the rigid surface, in which the criterion may be, for instance, allowable deflection, allowable deformation of the subsoil or an allowable load of the subsoil [1]. The theoretical studies on concrete pavements are mainly based on the Westergaard method. The following point is an attempt to present the possibilities of supporting classical methods for designing modern concrete pavements with the use of numerical methods. Such support can be used to verify the main construction parameters of a pavement, e.g., the thickness of a pavement, the type and grade of the used concrete, the types of gaps, or the type of road foundation. On the basis of the knowledge about temperature distribution in concrete pavements, an idea has been proposed whereby it is used in calculating the strength of the continuously reinforced concrete pavements by taking a numerical approach.

The values of stresses in continuously reinforced concrete pavements, caused by a change in temperatures, should be maintained with such limitations in order to avoid uncontrolled cracking of concrete slabs. Searching for optimal solutions for a proper functioning of concrete pavements is a difficult task to perform, due to the fact that fulfilling all the criteria must involve a compromise between economy, durability and safety. Below, an example is given in terms of how reinforced slabs, which are thermally loaded, can be tested (modelled) in such a way where all the decisive factors affecting surface durability can be properly selected.

Due to a large number of factors affecting the durability of concrete constructions, it is necessary to develop a numerical model with the most optimal assumptions and solutions

related to the actual ones. Previous strength analyses of concrete pavements were based on the assumptions, whereby a concrete slab rests on an elastic foundation with specified rigidity, while there is a lack of friction between the foundation and the slab resting on it [2]. The current state of knowledge regarding the impact of thermal loads on the durability of concrete pavements has inspired research on the role of friction between the slab and the road foundation [6,8]. The current empirical and theoretical considerations on rigid slabs, subjected to thermal load, have shown that, regardless of the accepted gradient of temperatures, a free slab made of concrete takes a characteristic shape, which resembles a bowl. The theoretical flexion of the slab, in the case of a positive gradient, is presented in Fig. 3.

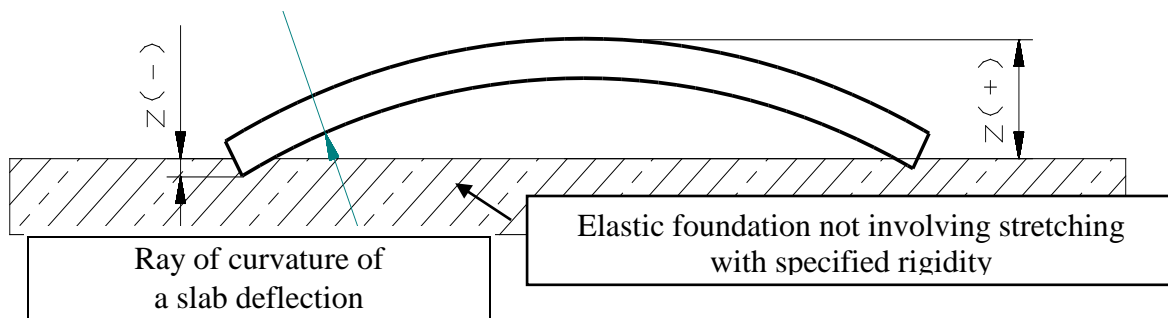


Fig. 3. Free slab with specified weight and temperature distribution

Temperature fluctuations cause a change in volume in slab pavements. In the case of steady temperature influences on the whole thickness of a slab, axial deformations are created, while, in the case of unsteady temperature distribution, flexion of the slab occurs. In theoretical terms, a homogenous isotropic body, supported in a statistically determined way, is subjected to a temperature field, which is a linear function of the Cartesian coordinates that are deformed during a state of stresses equal to zero [12]. In actual cases, when a slab cannot be easily deformed because of its own weight, the friction and reaction of subsoil or the limitations presented by other slabs, temperature stresses appear in the slab. Combining such stresses with those coming from other additional loads, e.g., wheel pressure can lead to a situation in which the presenting maximum stresses exceed the values of allowable stresses, which in turn leads to damage to the slabs, such as scratches or cracks.

The current state of knowledge on the temperature distribution in concrete pavements, although relatively poor, confirms the legitimacy of the above use of simplifications in a significant way. The results of the research on temperature distributions in airport slabs, under different climate conditions in Poland, as well as research conducted on national road or airport concrete pavements [1,9], reveal that the climate and its changeability, as opposed to the thickness of the slab, particularly determine the distributions and occurring temperature gradients. The significant changeability climate within Poland means that, from the point of view of durability analyses, knowledge about the occurrence of actual temperature distributions is necessary for measuring cycles in the long run.

If it is assumed that the difference in temperature fluctuations in summer and winter on two following consecutive days is as high as 30°C , it is necessary to perform a daily analysis of the occurring stresses and deformations of the slab. The perfect tools for conducting such analyses are programs based on the FEM, which additionally allows for a detailed analysis of not only the influence of the size of the gradient, but also the nature of temperature distributions in terms of slab thickness.

5. ANALYSIS OF THE DISCRETE MODEL

This study presents an example of numerical simulation with the use of a solid model using the FEM. The MSC Nastran for Windows system was used to determine the movements and stresses in continuously reinforced concrete pavements with static loads for a chosen field of temperatures.

Modelling reinforced concrete poses a significant number of problems caused mainly by the structure and properties of the material. Reinforced concrete constructions combine two materials of a different quality, namely, concrete and steel. Steel is a relatively homogenous and well-tested material, while concrete is a composite of aggregate, sand, cement and water, which reveals microvoids. Even for small deformations, there is physical non-linearity. Concrete indicates high levels of endurance in terms of compression and minimum levels for stretching in relative terms. In the stretched areas, concrete has tendencies to become scratched and, when compressed, to be crushed, which changes the properties of the material. In general, the reaction of reinforced concrete is non-linear involving complex laws of behaviour. The procedures for calculating the FEM in reinforced concrete are based on incremental iterative methods.

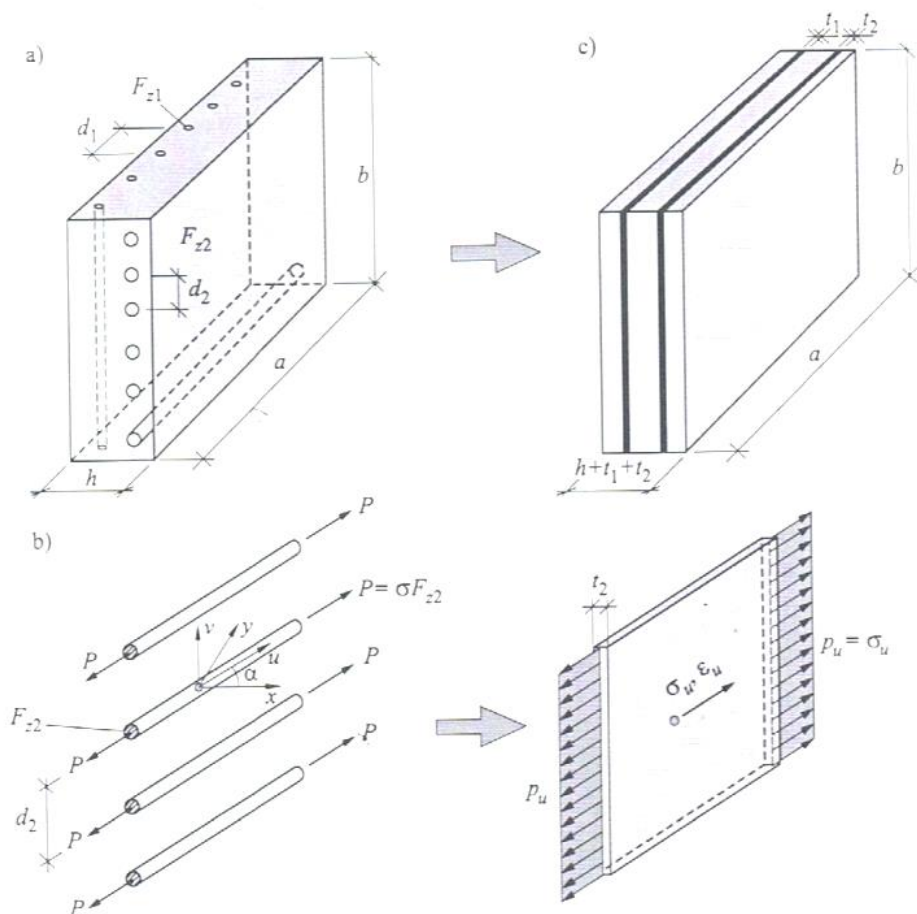


Fig. 4. The replacement model of a reinforced concrete shield [12]

In the analysed model of the reinforced concrete shield, as shown in Fig. 4, the arrangement of reinforcement bars is replaced by a slab element of thickness. As a result, the reinforced concrete shield converts to a layer shield, with a layer of concrete, which is h thick, and steel, which is t_1 , t_2 thick, assuming that there is full cooperation between the two materials, which means that the compatibility of movements and deformations on their touching takes place. The model of a reinforced concrete airport slab was made using the Femap program. The particular stages of construction of the model are:

- Creating a square plane sized 10x10 [m] and providing the material properties for steel and concrete (Table 1) [4].

Table 1. Material properties of concrete and steel

Material	Concrete	Steel
Young module [MPa]	32,000	210,000
Poisson ratio [-]	0.7	0.3
Density [g/mm ³]	2.4E-9	7.85E-9

- Dividing a plane into 10,000 finite elements and providing the third dimension of a slab by drawing, at the height of 0.3 m, a solid consisting of 60,000 elements.
- Removing nodes placed at the bottom part of the solid to a distance of 0.1 m in order to create elements of the GAP type in order to replicate the reaction of the subsoil to the reinforced concrete. The created geometric model, sizeD 10x10x0.3 [m], is the only slab of a continuously reinforced concrete pavement that is surrounded by all four sides by the other slabs.
- Two layers of fabric, composed of steel rods with a diameter of 10 mm, were placed in a model of concrete. In order to make trusses, rod-type elements were used. Rods are used in the analysis of truss constructions, which include axial stresses (compression, stretching), apart from bending.

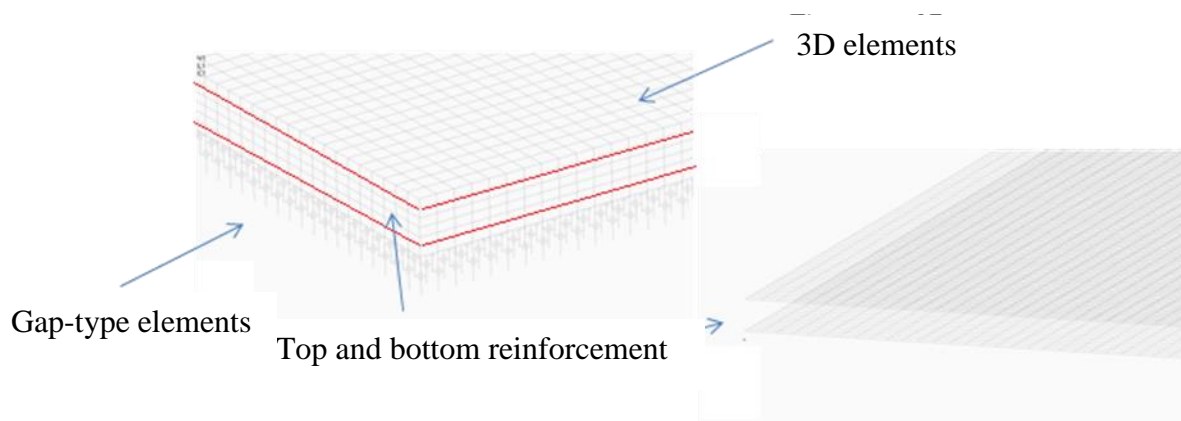


Fig. 5. Solid model of a slab with marked reinforcement

The present example is only part of the entire analysis of thermal loads with regard to the impact of daily temperature fluctuations on displacements and stresses in continuously reinforced concrete pavements with the use of numerical analyses. To simulate the operation of reinforced concrete at negative temperatures, a load in the form of a positive gradient of temperature of $-16/0^{\circ}\text{C}$ was used, where the lowest temperature occurs at the bottom of a slab. According to the map of displacements below, it is shown that the negative temperature at the bottom part of the plate causes its shrinkage, whereas higher temperatures in the upper layers cause its stretching. Maximum displacements occur at the free corner of the slab. The greatest maximum stresses mainly occur at the bottom of the slab, within a layer in which the lowest temperature and the subsoil are affected (Fig. 6).

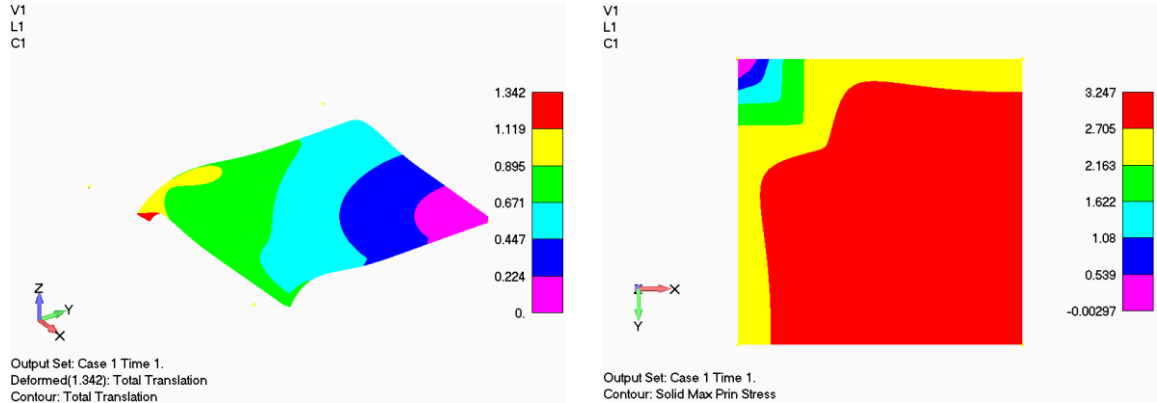


Fig. 6. Finite displacements and deformations [mm] and maximum main stresses at the bottom of the slab [MPa]

In the case of loads with a positive gradient of temperature within a range $0/-16^{\circ}\text{C}$, the lowest temperature occurs mainly in the upper layer of a slab, which causes the shape of deformation to be reversed (Fig. 7).

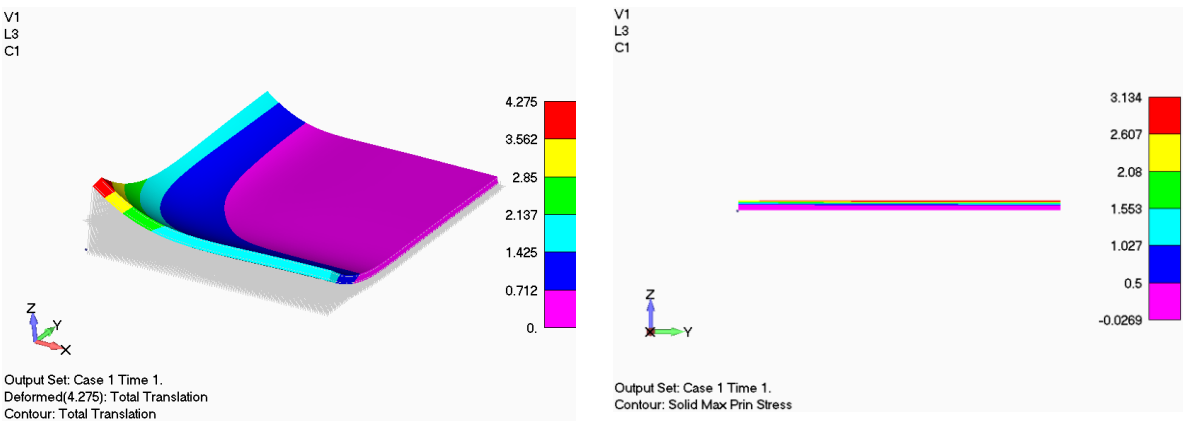


Fig. 7. Entire displacements and deformations [mm] and maximum main stresses at the intersection of a slab [MPa]

6. CONCLUSION

The overall analysis of the results and their comparison with other concrete pavements, including unreinforced and interconnected [1,2] types, in terms of the implementation of higher usable loads and increased traffic, highlights the need to use new, stronger and safer surfaces and, in turn, modern calculation methods for determining optimal constructions. According to the previous numerical analysis, it can be concluded that:

- The presented analysis performed in the study indicated the possibility of using professional FEM programs for the entire analysis of the state of displacements and stresses in slabs and dowels.
- The use of reinforced concrete slabs provides the possibility for avoiding the use of dilatation in slabs, which prompts the need to use dowel joints in the weakest places within surface constructions.
- Greater analysis enables a selection of examples, which, due to strength and safety reasons, are the most beneficial
- The complex nature of the occurring stresses in the vicinity of reinforcement requires additional analyses with the use of models on a different scale.

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