

Stress Analysis of Hexagonal Element for Precast Concrete Pavements

J. Novak, A. Kohoutkova, V. Kristek, J. Vodicka, M. Sramek

Abstract—While the use of cast-in-place concrete for an airfield and highway pavement overlay is very common, the application of precast concrete elements is very limited today. The main reasons consist of high production costs and complex structural behavior. Despite that, several precast concrete systems have been developed and tested with the aim to provide a system with rapid construction. The contribution deals with the reinforcement design of a hexagonal element developed for a proposed airfield pavement system. The sub-base course of the system is composed of compacted recycled concrete aggregates and fiber reinforced concrete with recycled aggregates place on top of it. The selected element belongs to a group of precast concrete elements which are being considered for the construction of a surface course. Both high costs of full-scale experiments and the need to investigate various elements force to simulate their behavior in a numerical analysis software by using finite element method instead of performing expensive experiments. The simulation of the selected element was conducted on a nonlinear model in order to obtain such results which could fully compensate results from experiments. The main objective was to design reinforcement of the precast concrete element subject to quasi-static loading from airplanes with respect to geometrical imperfections, manufacturing imperfections, tensile stress in reinforcement, compressive stress in concrete and crack width. The obtained findings demonstrate that the position and the presence of imperfection in a pavement highly affect the stress distribution in the precast concrete element. The precast concrete element should be heavily reinforced to fulfill all the demands. Using under-reinforced concrete elements would lead to the formation of wide cracks and cracks permanently open.

Keywords—Imperfection, numerical simulation, pavement, precast concrete element, reinforcement design, stress analysis

I. INTRODUCTION

THE current state of infrastructure development demonstrates that monolithic paving systems are used over precast concrete pavement (PCP) systems due to low production costs [1], simple manufacturing technology and structural design [2]. On the contrary, using PCP systems might achieve construction time savings in highway and airfield pavement applications where rapid construction is needed. Up to date, several PCP systems have been developed. Mostly, it concerns systems invented for rapid repair and rehabilitation of existing pavements in USA and systems particularly developed for entirely new construction of airfield pavements in the Soviet Union [3].

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The proposed PCP system (Fig. 1) is being developed with the aim to provide a unique pavement system with rapid construction which involves the utilization of recycled concrete aggregate for a sub-base. The proposed system is classified as a rigid pavement which is composed of a two-layer sub-base and a surface course of hexagonal precast concrete elements. The sub-base is designed as high permeable in order to enable rainwater to seep down through the pavement. It consists of 300-mm thick layer of compacted recycled concrete aggregate 0-64 mm installed on subsoil (existing soil) and 300 mm layer of recycled aggregate polypropylene fiber reinforced concrete (PFRC) placed on top of it. The fiber reinforced concrete is made of four fundamental components (Table I) - cement, recycled concrete aggregate 0-32 mm, water and polypropylene fibers 110 mm long to strengthen the concrete matrix as well as to improve fracture toughness.

TABLE I
COMPOSITION OF RECYCLED AGGREGATE POLYPROPYLENE FIBRE
REINFORCED CONCRETE

Component	Content (kg/m ³)
Cement CEM I 42,5	260
Recycled concrete aggregate 0-32 mm	1650
Water	150
Polypropylene fibers BENSteel 110 mm	0.5

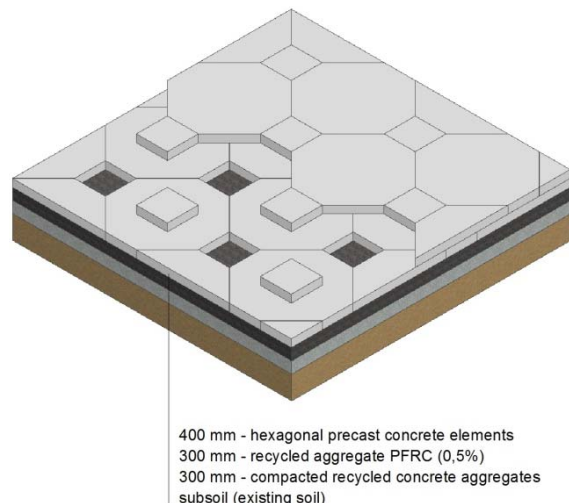


Fig. 1 Section of proposed precast concrete pavement system

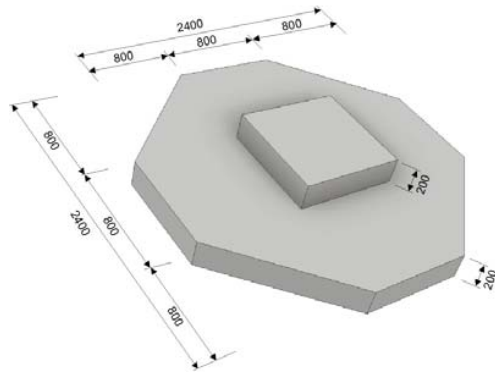


Fig. 2 Geometry of hexagonal precast concrete element

The surface course is placed on the sub-base. It is composed of hexagonal precast concrete elements installed in a basic position and the other way round. The panels are supposed to be placed into fresh recycled aggregate PFRC to limit flatness deviations and consequently to ensure full interface contact. The interaction between the elements is ensured by overlapped parts of each element which rest directly on adjacent elements without using any bedding layer. Therefore, some imperfections are expected at the interface and should be considered when designing reinforcement.

The paper outlines the reinforcement design of the precast concrete element for the proposed system which is being developed recently at Czech Technical University in Prague. This type of element belongs to a group of precast concrete elements which are being considered for the construction of a surface course. The obtained findings about the structural behavior of all considered elements will serve for the suitability evaluation in terms of the use for the surface course of the proposed system. First, the theoretical thinking of the precast concrete element behavior is presented with respect to the geometrical imperfections presumed to occur in the proposed PCP system. Then, the findings from the numerical simulation on a non-linear model are provided to show stress distribution and crack formation on the element subject to quasi-static loading. As an outcome, the design of reinforcement required to fulfill assumed conditions such as crack width, tensile stress limitation in reinforcement and compressive stress limitation in concrete are evaluated and presented.

II. FEM ANALYSIS

A. Theoretical Study of Precast Concrete Element Behavior

The structure behavior is more or less affected by the presence of various type of imperfections which are impossible to avoid. Therefore, theoretically it is impossible to reach the full interface contact between the precast concrete elements due to several factors. Namely, it concerns deviations caused by inadequate flatness of the sub-base and moulds for the elements, thermal contraction and expansion, drying shrinkage and creep. Considering such circumstances, the precast concrete element should have either high flexural

stiffness to withstand full loading, while its deformation is smaller than imperfection or high deformation capacity to withstand load until the element lands on structure underneath and subsequently the rest of applied load is transferred to the sub-base through the contact area. In both cases, the precast element, particularly its reinforcement, should be designed to fulfill selected criteria such as crack width limitation, compressive stress limitation in concrete and tensile stress limitation in reinforcement.

B. Imperfections

While cast-in-situ concrete pavements are mostly subject to out of plane compression and contains conventional amount of reinforcement to withstand internal stress caused by shrinkage, creep and temperature loading, the stress distribution in PCP systems is more complex due to imperfections which are impossible to avoid. There are several publications and standards which deal with maximum dimensional tolerances. In accordance with EN 13 369 [4], the permitted geometrical deviation of cross-section depth for precast elements 200 mm thick equals to $+11/-6$ mm and $+6/-6$ mm when common quality control and high-quality control, respectively, are considered. Czech national standards even recommend to fulfill 4 mm deviation which is commonly accepted by precast concrete suppliers. In case of the proposed PCP system, the flatness deviations of the sub-base and deviations resulted from drying, shrinkage and creep should be also taken into account. However, to determine the total value of imperfection in the proposed pavement system is a difficult task as each type of imperfection occurs in different region and have either negative or positive effect on the element behavior. As a consequence, the total permitted tolerance is assumed to be 9 mm.

C. Loading

The proposed pavement system could be used for various types of structure such as car parking, pedestrian pavement, airport pavement and highways. The reinforcement of the precast concrete element has to be only adjusted with respect to intended load. The presented numerical simulation deals with the structural behaviour of the precast concrete element under quasi-static loading from an aeroplane. Such type of loading is significantly affected by a type of an aeroplane, in particular by its weight, number and position of gears, a number and size of wheels the gears have. For the numerical simulation, it was selected the aeroplane Airbus A380-800F which belongs to the biggest planes in terms of a size and weight. The contact patch between a wheel and a pavement is determined using the equation (1), where A is the contact patch, F_w is concentrated load from one wheel and p_t is tire pressure. Assuming 1.6 MPa high tire pressure, typical of such aeroplane, and concentrated load almost 300 kN/wheel, the contact patch is equal to 187 500 mm². Subsequently, the shape of the contact patch was determined. Generally, it has a complex shape composed of a rectangular and an ellipse, but in order to simplify the numerical analysis, only the rectangular shape 235 x 800 mm was used.

$$A = \frac{F_w}{P_t} \quad (1)$$

D. Numerical Simulation

Numerical analysis software belongs to the main tools for simulating the real behavior of various concrete-based structures [5], [6]. In comparison with experimental tests, they offer an affordable way to study the mechanical behavior of structures under various conditions. The non-linear simulation was carried out on a non-linear finite element model in the software Atena. It was conducted with the aim to design and optimize reinforcement for the selected precast concrete element with respect to crack width, tensile stress limitation in reinforcement and compressive stress limitation in concrete. Totally, two static schemes of the hexagonal element were analyzed. They reflect the possible placement of the element in a real structure. The simply supported element as well as the overhanging element was subject to uniform load from a gear wheel of Airbus A380-800F. The load was applied to the area 0,235 m x 0,800 m in 100 kN/m² steps until the failure of the panel occurred. In each step, the selected parameters (vertical deformation, crack width, tensile stress in reinforcement, compressive stress in concrete) were monitored in the position of a deflection monitor. In case of the simply supported panel, due to the symmetry, only the half of the element was modeled in order to reduce computational demands.

The computational model was composed of two materials - concrete C35/45 and reinforcement B500B. The mean values of mechanical properties of both materials were considered and taken over from EN 1992-1-1 [7]. As the object of the numerical simulation was to observe the effect of the reinforcement used on the hexagonal element behavior, several simulations with different bar diameter were performed; particularly 14 mm, 16 mm, 18 mm and 20 mm bars were considered. The panel contained reinforcement at 100 centers both ways top and bottom with 50 mm concrete cover. The middle square part 400 mm thick also contained a reinforcement cage which ensures the interaction with the rest of the element.

To slow down reinforced concrete degradation by carbonation, the crack width is limited to 0.3 mm which is recommended for elements exposed to cyclic wet and dry environment in accordance with EN 1992-1-1 [7]. The compressive stress in concrete is also limited to 60% of the mean value of cylinder compressive strength ($f_{cm}=43$ MPa) to avoid longitudinal cracks which might lead to a reduction of durability. Moreover, the tensile stress in reinforcement is limited to 80% of mean yield strength of reinforcement B500B ($f_{ym}=550$ MPa) to avoid inelastic strain, unacceptable cracking or deformation.

E. Study of Numerical Simulation

The obtained data from the numerical simulation served for generating diagrams which describe the relation between the uniform load, vertical deformation, crack width, tensile stress in reinforcement and compressive stress in concrete. The results of the numerical simulations on the overhanging

element model (Fig. 4) show that the element with all considered reinforcement has flexural stiffness high enough to withstand full load from the aeroplane before overcoming the maximum allowable imperfection. The deformation at the level of the full load decreases from 8.8 mm to 4.4 mm with increasing bar diameter used. The crack limitation is also fulfilled except the element reinforced by 14 mm bars which exhibits cracks wider than 0.3 mm. In such a case, the service life of the element might become shorter especially in environments where chemical attack and chloride attack are possible. On the other hand, as the element is expected to be subject to the intended load temporary, cracks open only when the load is applied and remains closed in the unloaded state depending on the history of tensile stress in reinforcement. High tensile stress in reinforcement results in inelastic strain which prevents cracks to be fully close in the unloading state. When full load applied, the elements reinforced with either 14 mm bars or 16 mm bars show excessive tensile stress in reinforcement (circles) far beyond the limit (450 MPa). The reinforcement starts yielding and as a consequence are not adequate for the intended use. Considering the compressive stress in concrete, none of considered elements fulfill the selected criteria. The compressive stress slightly exceeds the allowable stress and as consequence minor cracks on the element surface may occur. However, as the values obtained from the numerical simulation are very close to the limit and the element is exposed to the load temporary, these criteria are neglected. Considering the obtained findings, only the elements reinforced with either 18 mm bars or 20 mm bars are structurally adequate for the intended use.

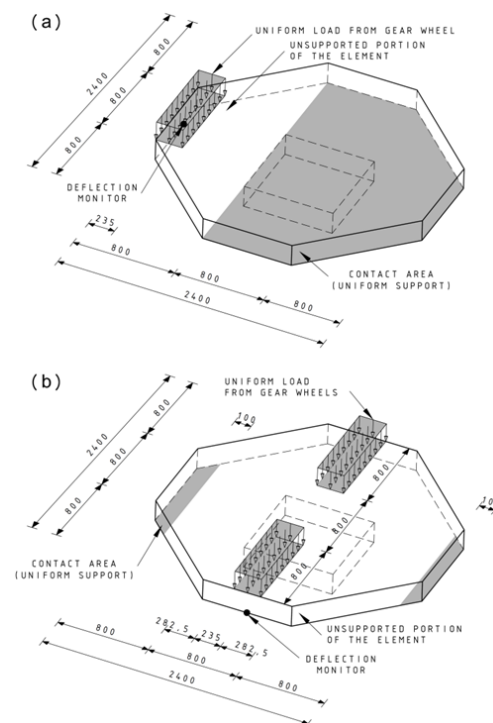


Fig. 3 Static schemes: overhanging element (a) and simply supported element (b)

The mechanical behavior of simply supported element (Fig. 5) is more complex. While the element reinforced with 20 mm bars is capable of withstanding the full load due to the high flexural stiffness, the elements with the other types of reinforcement overcome the maximum allowable imperfection before the full load is applied and lands on structure underneath. However, due to the high cross-sectional curvature the crack width observed from the simulations exceeds the limit 0.3 mm in most cases. Only the precast element with 20 mm bars fulfills the requirements related to the crack width. Considering tensile stress in reinforcement, the performance of the precast elements is identical. In most cases, the tensile stress in reinforcement exceeds the allowable limit and as a consequence inelastic strains might be expected. Only the element reinforced with 20 mm bars shows such tensile stress which fulfills the selected requirements. The compressive stress in concrete is beyond the limit as before in the case of the overhanging panel. However, the values obtained from the simulation are close to the limit again, and therefore, this criterion is neglected. Considering all the criteria, only the element reinforced with 20 bars satisfies the selected requirements.

III. CONCLUSION

The contribution is focused on the study of the hexagonal precast concrete element developed for the innovative precast concrete pavement system. The element belongs to a group of precast concrete elements which are being considered for the construction of a surface course of the system. Within the scope of work, the numerical simulations were conducted with the aim to design and optimize reinforcement of the element subject to quasi-static load from Airbus A380-800F with respect to permitted imperfection, crack width limitation, tensile stress limitation in reinforcement and compressive stress limitation in reinforcement. In accordance with recommendations listed in technical publications and European standards, the limit values 9 mm, 0.3 mm, 450 MPa and 26 MPa were considered for the imperfection, crack width, tensile stress in reinforcement and compressive stress in concrete, respectively.

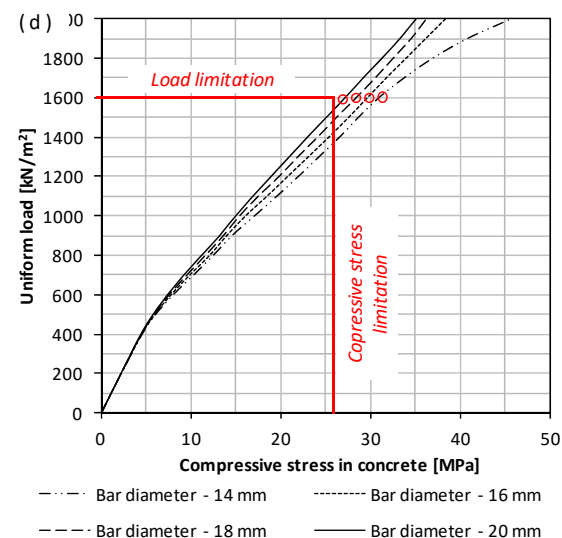
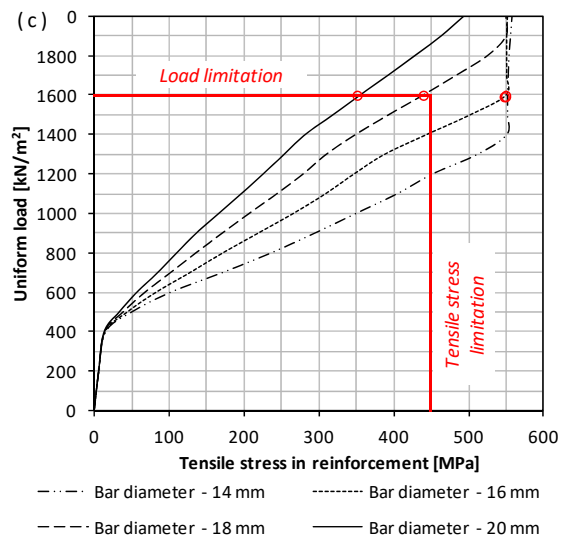
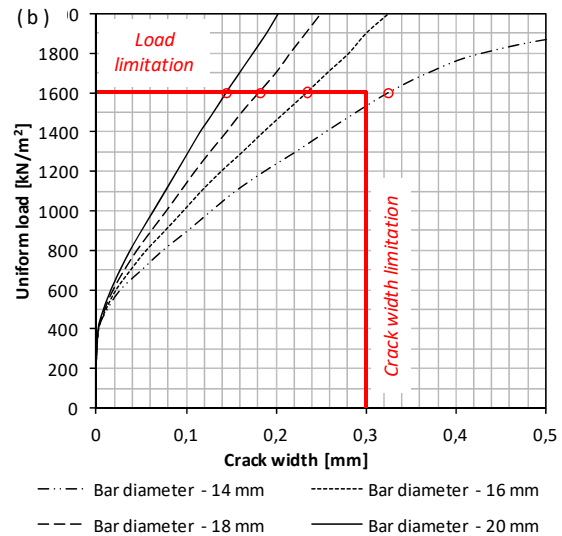
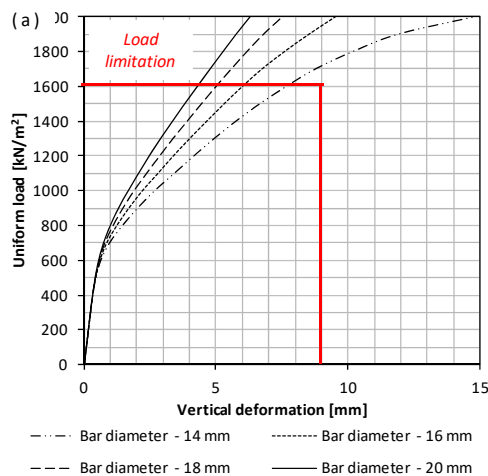


Fig. 4 Numerical simulation of overhanging element

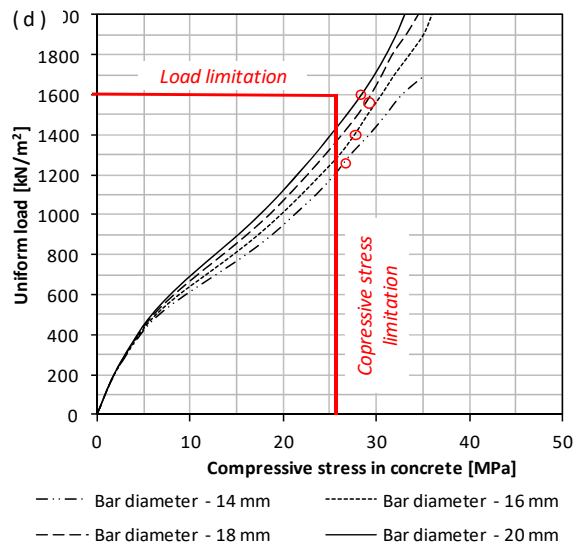
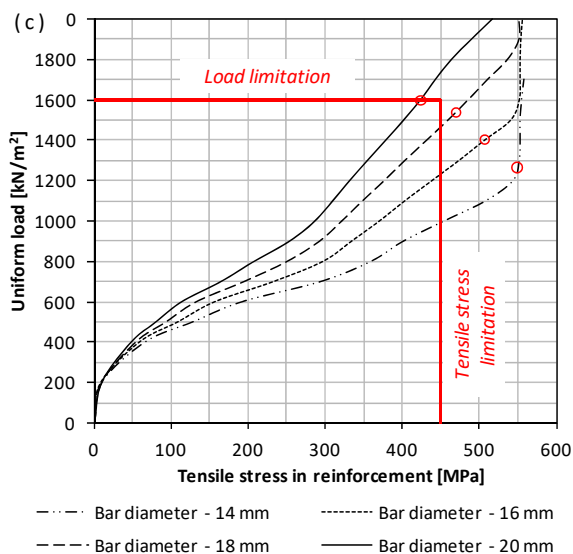
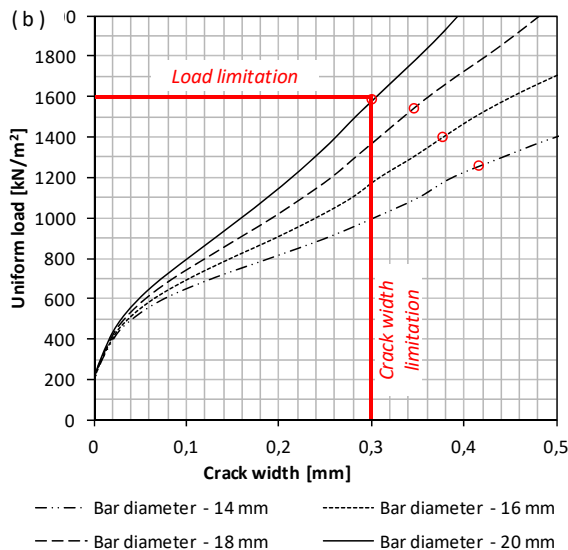
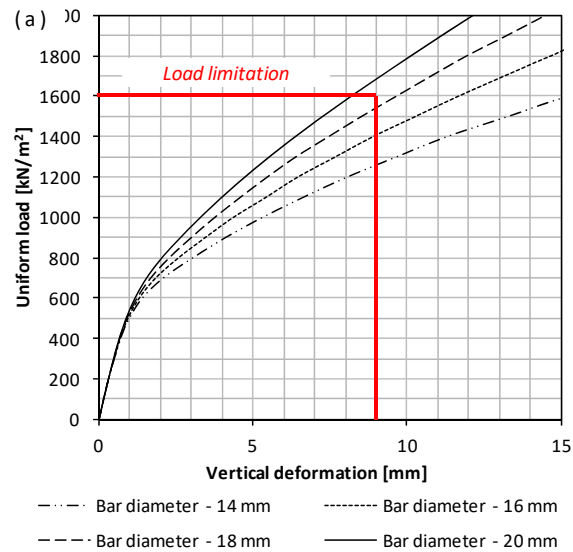


Fig. 5 Numerical simulation of simply supported element

The numerical simulation conducted on the models of the simply supported element and the overhanging element show that the tensile stress in reinforcement might be considered as the most decisive factor. From four types of reinforcement tested the precast concrete element reinforced with 20 mm bars fulfill all the selected requirements and consequently is structurally adequate for the intended use. Using the other types of reinforcement considered within the numerical simulation would lead to wide cracks or cracks permanently open resulted from excessive tensile stress in reinforcement. To reduce such high amount of reinforcement used, the maximum allowable imperfection should be reduced at a minimum by either improving manufacturing quality or using a flexible bedding material at the interface of elements. In the next phase of the project, the fatigue resistance of the precast concrete element should be analyzed.

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