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SELECTED ASPECTS OF THE STRUCTURAL ANALYSIS OF THE NORTH DOME IN THE "FOUR DOMES PAVILION"

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Abstract

The subject of the paper is north dome of the Four Domes Pavilion in Wroclaw, which was erected according to the project by architect Hans Poelzig in 1913. The geometry of the dome (plan, rise, thickness) has an essential influence on the stress distribution in the structure and may be a crucial factor determining the cracking pattern. The results of the study of archival documents and numerical analysis indicate that there is a need for increasing the bearing capacity of the structure. After carrying out 3D FEM analysis, it was decided to apply strengthening technology based on the FRCM system with carbon and P.B.O. fibers on the surface and on the external ring of the dome.

Keywords: Four Domes Pavilion, dome, strengthening, FEM

1. INTRODUCTION

The dome is a commonly occurring form of historic rooftops, which can be constructed, among others, on a circular, elliptical or octagonal structure. A brick or stone wall is the most common building material, with reinforced concrete also used since a given period of time. The geometry of the dome

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(plan, rise and thickness) influences the stress distribution in the construction and can be a deciding factor influencing the cracking pattern.

1.1. "Four Dome Pavillion"

In 1912, Hans Poelzig designed a set of objects on the fairgrounds in the eastern part of Wroclaw, in the direct proximity of the Centennial Hall (HalaStulecia), Pergola and Japanese Garden. In August 1912, the construction project was accepted and the company *SchlesischeBetonBaugesellschaft* initiated construction works. In October 1912, the architect was asked to make changes in the design of the main dome hall in the north wing. The reason for this was to enlarge the hall without altering the shape and size of the dome itself. In December 1912, construction works were nearing completion and in the middle of February 1913, the building was opened for use. A historical and architectural study [1] shows that all changes which occurred during the realization of the works resulted from: a lack of time, delays in carrying out static assessment, project blueprints being handed over in an inappropriate scale, or construction being carried out in the winter. The Historical Exhibition Pavilion (Pawilon Wystawy Historycznej), currently the Four Dome Pavilion was designed as an untypical museum building as it was intended for basically for one exhibition. The pavilion was entered into the register of historical objects in 1977, and in 2006 added to the UNESCO World Heritage List along with the Centennial Hall. Currently, the object is in the process being adapted to serve for exhibition purposes of the national Museum in Wroclaw (Fig. 1).

Fig. 1. View of north dome after renovation (2014)

1.2. Architecture of the building

The building was planned on a layout similar to that of a square, with a courtyard on the inside (originally containing a fountain). A dome was situated on the axis of each wing. The biggest of them is found in the northern part and is the subject of this work. Below is a fragment of the blueprint from Hans Poelzig's project, containing the plan of the exhibition from 1913; the analyzed dome has been marked (Fig. 2).

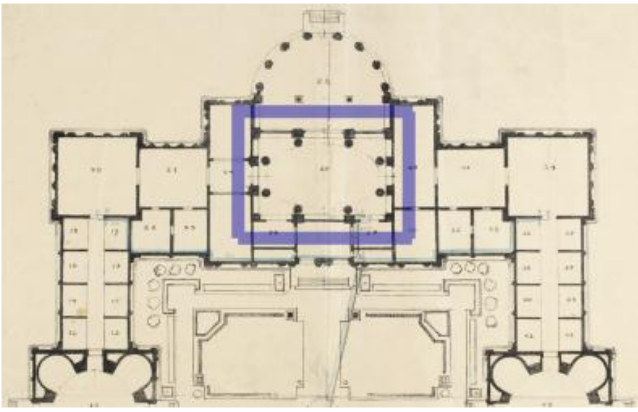

Fig. 2. Layout of the ground floor. The scope of the study is marked by a frame [5].

2. DIAGNOSTICS OF TECHNICAL STATE

2.1. Construction and geometry of the building

The reinforced concrete dome which forms the roof of the object is a surface girder with a thickness of 12 – 20 cm. In the support zone, a layer of concrete overlay with a maximal thickness of 50 cm was applied in order to camber the shape of the top surface to channel rainwater. The reinforcement of the concrete shell is composed of steel profiles in the form of angle bars measuring 25x50x7mm (dimensions determined based on an uncovering in the western part of the dome). A reinforcement mesh of steel bars Ø10mm spaced 15–20 cm apart was placed over the L-bars. An elliptical base shell is supported by the top reinforced concrete ring. The top ring is supported by 22 reinforced concrete columns (S1 – S22) characterized by a polygonal cross-section. Beneath the columns is the middle ring, supported by eight columns and eight brick pillars located on the ground floor. The pillars and columns are placed on pad foundations. The dome was constructed in monolithic technology.

2.2. Archival documentation

The analysis of archival documentation containing blueprint solutions as well as the original static-strength calculations made by the author of the project is an important stage in the construction analysis of a building. According to archival documentation, the original static calculations assumed permissible stress in the concrete at a level of 36 to 40 kg/cm^2. The design strength of steel was accepted at a level of f_y = 1000kg/cm^2 [5]. Original construction drawings show project solutions which were compared to the actual state.

2.3. Identification of damage

During on-site visits to the building, a cracking pattern that is typical of dome-type roofs was identified in the longitudinal and latitudinal direction [2]. The shell of the dome is cracked from the inside as well as from the outside. On the outside, a horizontal (latitudinal) distribution of cracks is visible, running down approx. ¼ of the circumference of the dome in its north-western section. On the inside, the most severe cracking was observed around the whole circumference in the direct zone of support. Additionally, longitudinal cracking (densely distributed) was localized, as well as latitudinal cracking in the lower sections and at half the dome height. Latitudinal cracking at a height of 50-100 cm above the supporting point coincide with cracking on the inside (Fig. 3).

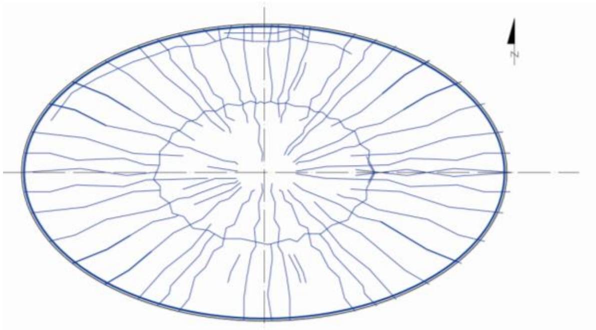

Fig. 3. Bottom view of dome roof with a schematic depiction of the cracking pattern.

The top ring is characterized by vertical cracking as well as cracking over the supports (columns) as well as in the bay (in the middle of the window opening). These cracks are densely distributed and, in the majority of cases, their width does not exceed 0.1 mm. Triangular ceiling structures under the middle ring and above the columns and pillars indicate cracks which coincide with yield line patterns of ceiling structures of a triangular geometry. The uncovering of foundations available during the on-site visit under column K7 and pillar F did not reveal damage to them.

3. CONSTRUCTION ANALYSIS

3.1. Assumption made for analysis

1) The geometry of the construction system was accepted on the basis of the available technical documentation.
2) The following construction elements were taken into account: the dome shell, support ring and columns supporting the ring. Due to the increased stiffness of the lower ring, it can be treated as a support for the construction located above.
3) The design values of a fixed load (self-weight of the dome and roof cover) as well as the live load (weight of snow). Loads were accepted in accordance with PN-EN-1991.
4) The analysis was conducted in a simplified manner in a flexible scope in order to determine the distribution of stresses and the shape of deformation, not accounting for the state of cracking of the dome.
5) A homogenous material was used for all construction elements. Young's modulus and Poisson's ratio for concrete C16/20 (according to the standards: PN-EN 1992-1-1:2008) were the applied parameters of the material. The materials were characterized using pull-off tests conducted in July of 2013, as well as sclerometric studies carried out in 2008 [4]:
   - Characteristic compressive strength: $f_{ck} = 20MPa$,
   - Design compressive strength: $f_{cd} = 13.3MPa$,
   - Tensile strength according to EC2$f_{ctm} = 1.9MPa$,
   - Tensile strength based on pull-off tests: $f_{ct} = 1.5MPa$,
   - Young's modulus $E = 29GPa$, Poisson's ratio $\nu = 0.20$.

3.2. FEM Model

Elastic analysis was carried out using the COSMOS/M program. During the modeling, spatial elements of the SOLID type were used. The model contains 187,272 finished elements, 249,824 knots, and 742,932 degrees of freedom. It was accepted that columns located between windows are mounted rigidly to the ring at their base. Support was modeled at surfaces constituting the column heads. All degrees of freedom in the lower surfaces of poles were fixed.

3.3. Results of calculations

The following symbols were accepted for use:

σ_x normal stresses of a vertical direction (for the roof – longitudinal direction)

σ_y normal stresses of a horizontal direction (for the roof – latitudinal direction)

The elliptical geometry of a dome determines the distribution of stresses concentrated at the base of the dome shell (Fig. 4).

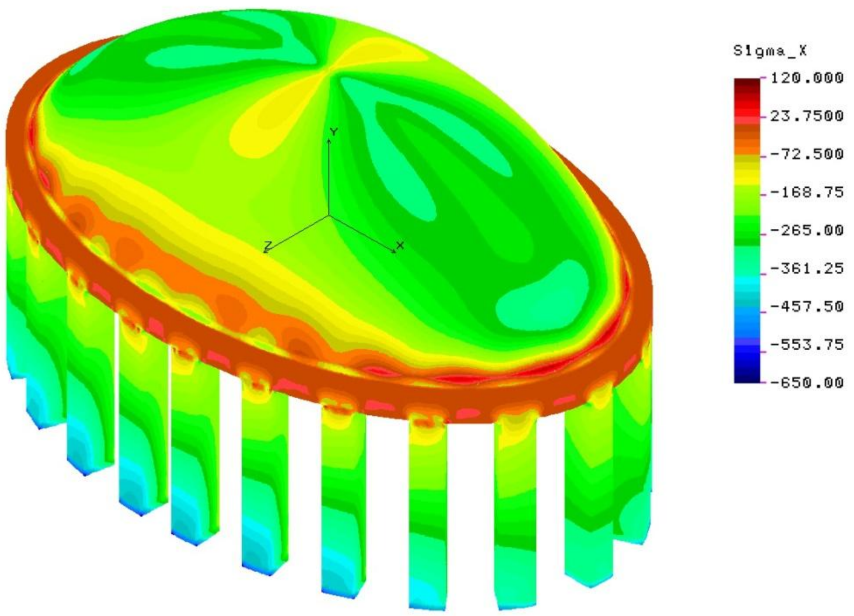

Fig. 4. Distribution of σ_x stresses [kPa]

3.4. Analysis

Historical documentation shows that the author of the project changed the construction of the support of the northern dome during the realization of the works as requested by the investor, which may have influenced changes in the initial static-strength assumptions. What is more, historical analysis indicates that the object was constructed in a hurry, which may have resulted in mistakes in the project design and their realization. When comparing the cross-section of the dome according to the original project with the actual state, it can be stated that it was constructed differently from the blueprints. The band around the dome shell is actually found above the top ring (in the project it is located beneath it). It is highly probable that the dome shell was not sufficiently reinforced in the support area, as is also indicated by the damage present.

3.5. Reinforcing method

Reinforcing the northern dome involved applying carbon fiber mesh in the FRCM system [6] (Ruredil X Mesh C10), in the longitudinal and latitudinal direction, on the outer and inner side of the cover. The meshes on both sides of the shell were connected using connectors made of carbon mesh at locations where the given strips of mesh intersected. Up to a level of approximately 2 m from the support, the meshes were laid in two layers. Moreover, the top ring was reinforced peripherally using P.B.O. fiber mesh (Fig. 5).

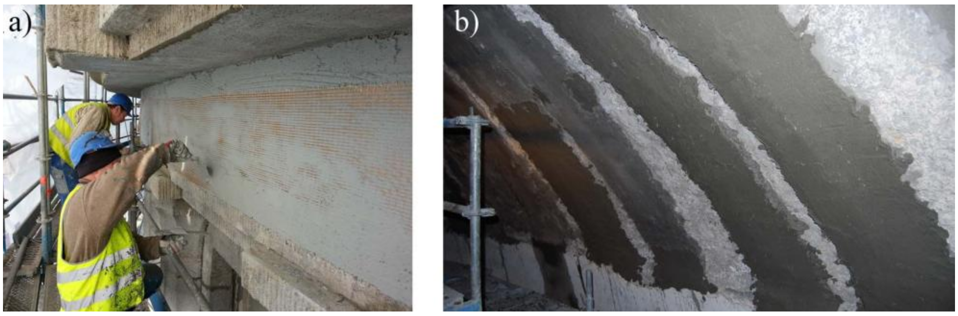

Fig. 1. a) Reinforcing the support ring using P.B.O. fiber mesh; b) Reinforcing the shell from the inside using carbon mesh

4. CONCLUSIONS

1) The basic source of knowledge regarding the construction of the object is archival documentation.
2) The cracking pattern of the north dome corresponds to cracking patterns typical of comparable structures.
3) Latitudinal and longitudinal cracking over 1mm in width result from insufficient reinforcement of the dome shell, especially in the support zone.
4) Some of the narrower cracks (0.1-0.3mm) are of a thermal nature.
5) The map of tensile stresses coincides with the state of cracking on the inside surface of the dome. Tensile stresses are highest at a level of approximately 50cm above support ring of the dome shell.
6) The causes of damage to buildings may result from load-bearing capacity being decreasing as a result of redesigning the building immediately prior to its construction, without carrying out a detailed analysis of the influence the changes will make to the structural solutions.
7) One of the means of consolidating and increasing the stiffness of the structure is applying carbon and P.B.O fiber mesh.

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WYBRANE ASPEKTY ANALIZY KONSTRUKCYJNEJ KOPUŁY PÓŁNOCNEJ W PAWILONIE CZTERECH KOPUŁ

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

Powszechnie występującą na całym świecie formą przekryć historycznych jest kopuła, która może być realizowana m.in. na rzucie koła, elipsy czy ośmioboku. Geometria kopuły (rzut, wyniesienie oraz grubość) wpływa na rozkład naprężeń w konstrukcji i może być decydującym czynnikiem wpływającym na propagację rys. Przedmiotem pracy jest Pawilon Czterech Kopuł we Wrocławiu, który powstał wg projektu Hansa Poelziga w 1913r. Analiza dokumentacji archiwalnej wykazuje, iż wszelkie zmiany jakich się podejmowano w trakcie realizacji prac były wynikiem: braku czasu, opóźnień w wykonaniu oceny statycznej, przekazaniu rysunków projektowych w nieodpowiedniej skali oraz prowadzenia prac budowlanych w zimie. Efektem powyższych działań jest niedostateczne zbrojenie kopuły, która uległa uszkodzeniom w formie pęknięć południkowych i równoleżnikowych od strony zewnętrznej i wewnętrznej. W wyniku przeprowadzonej analizy konstrukcyjnej przy użyciu Metody Elementów Skończonych (MES) podjęto decyzję o wzmocnieniu przekrycia przy użyciu siatek z włókien węglowych w systemie FRCM oraz wzmocnienie pierścienia górnego przy użyciu siatek z włókien P.B.O. w matrycy mineralnej.

Słowa kluczowe: Pawilon Czterech Kopuł, kopuła, wzmacnianie, MES

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