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PREFABRICATED ELEMENTS IN WACLAW ZALEWSKI DESIGN

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ABSTRACT: The research achievements of Waclaw Zalewski are an example of stimulating the creativity of designers in the field of shaping the structures of buildings. The methods of shaping the structures developed by Zalewski were based on the current achievements of world researches in this field and always led to their practical use. Prefabrication of elements has been carried out from the beginning of the history of concrete construction. The use of prefabricated elements in the construction of multi-storey buildings requires, on the one hand, the development of a system of repetitive elements, and on the other hand, conducting thorough analyzes of the spatial rigidity of the entire structure of the building. In the work of Wacław Zalewski, we find numerous examples of the use of precast concrete elements. Systems created by him are characterized by the complexity of applying many areas of engineering knowledge and excellent knowledge of material technology.

Keywords: pc elements, flow of forces, grids space stiffness.

1. INTRODUCTION

Waclaw Zalewski designed his structures in accordance with profound ideas, free from simplification and schematic approach. His in-depth familiarity with physical properties of structural materials enabled him a great freedom in realising his construction ideas. On a basis of his comprehensive knowledge and as the results of his research, Waclaw Zalewski created his own models of mechanics of rigid body, which he employed when shaping structure spaces. Owing to his exhaustive knowledge of mechanic principles earned at an early stage of his career, he was able to conduct thorough analyses of structures in order to solve design and research problems. Additionally, when applying calculation models to predictions of structure behaviour, he frequently relied on his intuition rather than complex calculations. The most significant example of this is his development of the method called Flow of Forces, based on the Boussinesq–Flamant problem, which he found particularly fascinating, as his drawings of geometric structure models demonstrate. In studies carried out by Zalewski, cantilever structures played a significant role in the structures used in buildings. The purpose of these analyzes was both the use of these systems for individual components as well as for the entire structure of tall buildings. In the theoretical basis, Zalewski referred to his scientific works in the field of optimization of structures carried out, among others, by W. S. Hemp and H.S.Y. Chan also W. W. Prager. From these works he drew the problems described as 'Michell's structural continua'. The analyzes conducted by Zalewski were based on the classical foundations of structural mechanics, with particular emphasis on graphical methods for determining forces in static models. He applied these graphs, which substantially diverged from the standard network of load flow in construction supports, to the analyses of material behaviour within a structure. Having a relevant experience in structure realisations gained in the first years of his career, he was immediately able to implement conceptual theoretical analyses to specific material solutions. As an ingenious designer, he never treated the optimum of a construction as an obvious simplification or banalisation resulting from the need to diminish construction costs. He also understood very well the aesthetic needs of users and recipients of this works. His independence was often criticized by his colleagues and authorities, who had a decisive voice in choosing which of his ideas would be realised. Nevertheless, his clear and logical way of explaining his projects proved persuasive in most cases.

Prefabrication of concrete structures, which constitutes a large part of his work, is an interesting example of application of creative construction methods in accordance with rigid technological principles characteristic of the 50. of the 20th century. Among the most impressive design achievement, one should recall the structures of multi-storey warehouse buildings. They were designed out of a need for building in winter, a season whose atmospheric conditions prevent an on site production of concrete. In the same period (post-war years), saving materials, especially steel, was a common practice. Waclaw Zalewski found a solution, which accommodated all these seemingly contradictory prerequisites.

2. FORCE STREAMS IN IDEAL MATERIAL

The basic scheme that Zalewski was interested in was a triangular system consisting of two bars based on a substrate with pivot nodes spaced at a distance of 1/6 of the length of the cantilever. This minimal in its number of bars the truss is not useful in structures due to the buckling phenomenon in the compression bar. Hence, it was necessary to analyze the division of the truss in the space of the cantilever. In order to consider the arrangement of the intersections of the bars, a strip of elastic material was adopted, in which the triangular arrangement described above is in a perpendicular position to its edge. The force loading the top of the cantilever and the reactions on the supports are treated as external forces applied at the points on the edge of the strip. Under their influence the fans of forces develop there, according to the Bussinesq-Flamant principle.

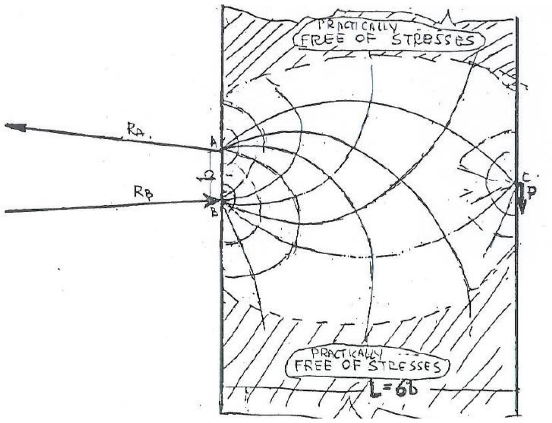

Fig. 1 Trajectories of force streams (Ref.1)

Based on the existing results of elasto-optical tests, Zalewski used the hypothesis of attracting mutual forces of the same nature (compression-compression, tension-tension). The directions of action of antagonistic forces are mutually perpendicular. The trajectory of force streams created by this method he treated as the directions of resultant forces for the areas of structural material. Graphs with high densities of streams are not practically useful for shaping bar systems. Therefore, for the practical application of the obtained schemes in shaping the structure, the system should be discretized by replacing the arches with straight sections. As a result of this action, a geometric grid of bars similar to the Michell's framework is obtained. In this network, the meshes have the shape of quadrangles completed by triangles in the support zone. The most far-reaching simplification leads to a truss scheme consisting of 8 bars, which describe one quadrangle and three support triangles. The obtained shape is similar to the initial scheme of a high triangle, but internal struts give the structure greater stiffness that protects the bars from buckling. At the same time, according to the diagram, maximum forces in the final diagram are much smaller than in the initial scheme. A striking effect of the process is the appearance of compressed bars bent in the supporting structure zone.

Such distribution of forces in the supporting bars of the structure is very advantageous for reducing their material cross-sections. Since the practical use of trusses with non-parallel bar bars is limited in design practice, Zalewski also analyzed systems with parallel stripes.

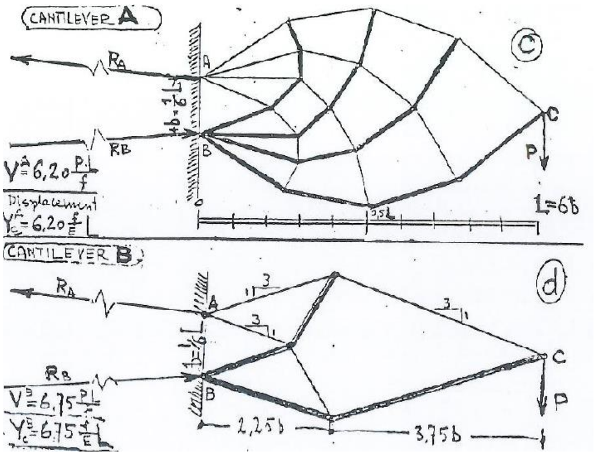

Fig. 2 Cantilevers based on Michell's framework (Ref.1)

In static analyzes of cantilever elements W. Zalewski paid attention to the material consumption and its distribution along the construction element. In reinforced concrete elements, he conducted a search on how to adjust the reinforcement systems for the distribution of internal forces. The dependencies thus formulated have a significant impact on the rigidity of the element and the optimization of the design solution. In cross-sections of cantilevers with a constant cross-section shape, he justified the existence of transversal reinforcement with diagrams of forces with an oblique position and their tensile action. At the same time Zalewski highlighted compression forces in concrete, whose mechanical properties allow their free transfer. In addition to prismatic cantilever elements, he analyzed elements with a variable cross-section.

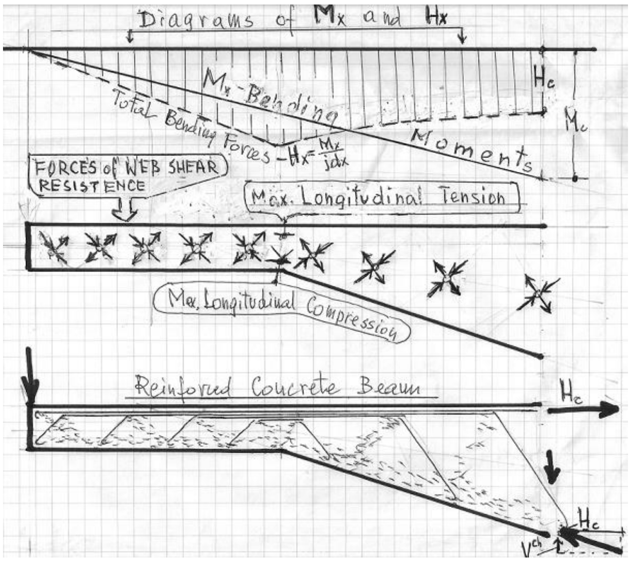

Fig. 3 Statics analysis for cantilever beam (Ref.1)

In these considerations, he described the directions of internal forces and looked for places of concentration of stress that should be taken into account when designing reinforcement for concrete. The interpretation of the support zone in these diagrams is particularly interesting, where Zalewski replaces the bending moment by the action of axial forces in the beam support points. This approach makes it easier for the designer to provide a concrete solution for concrete reinforcement and gives the opportunity to properly assess the impact of the support element on the building structure in the place of supporting the element.

3. CAPITAL SYSTEM

The main technological challenge in prefabricated structures is assembling the prefabricated elements. In order to maintain a continuity of materials of which reinforced concrete is made, it is required that the steel reinforcement frame is continuously concreted. From the very start, this problem was solved in two ways. One of them made use of joints, which were parallel to steel structures, bolted with screws on the construction site. This solution, however, created weak points of the structure in the places of high corrosion risk. Additionally, the transfer of forces from the complex concrete structure to single screw joints was difficult to implement. The second solution involved monolithic joints, whereby monolithic meant that a reinforced joint protruding from two elements was submerged in plastic concrete composite directly on the construction site. A drawback of this method was merging two types of concrete, the prefabricated and the monolithic one, as the interaction of the two was limited to the transfer of compression tension. Fully aware of these processes, Waclaw Zalewski employed new methods of prefabricate assemblage in accordance with the magnitude of forces flowing in the structure. The structure layout has a diagonal orientation, in contrast to more common orthogonal systems. This grants the structure a greater rigidity and resistance to horizontal forces, as the surface of walls remains at 45^o angle to the supports in the column heads. Such a configuration of column rows enables a proper support of prefabricated elements in external curtain walls, whose points of support are to be found at a distance of half a space between the columns. Another unusual feature of the system is the arrangement of plate layout, which fills in the ceiling surface. The middle square plate of orthogonal edges constitutes a continuation of the diagonal system over the beams of the ribbed bottom. A variable height of these beams has a character of both an arch and a support, and at the same time grants the whole structure a simplified discrete form of a flat spherical shell with a square keystone, which helps maintain rigidity of the principal diagonal directions of the layout. The hexagonal enhanced plates supplementing the ceiling infill conform to the principles of shell approximation, but their ribs do not form a diagonal extension of the construction system, forming a local diagonal system between the supports in the column heads instead. Such a structure of the ribs lending rigidity to the columns was contrived in accordance with the results of Zalewski's static analyses with regard to the supports of a variable height in a section.

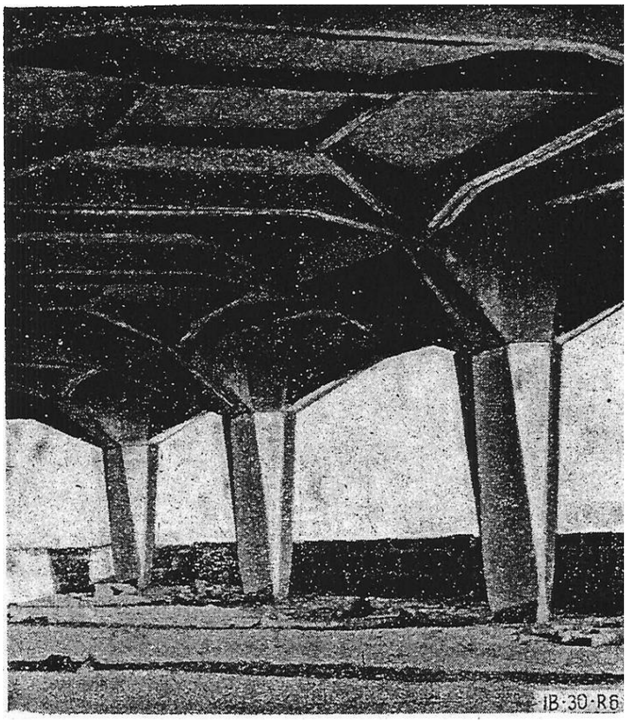

Fig. 4 Inner view of the Capital System (Ref. 2)

The main static effect is an increase in the involvement of compression forces in comparison to forces bending the concrete sections. In the case of such a layout, cross struts of column heads constitute an integral element of ceiling plates as well as of the column, despite not being directly linked to it, as they have been separately prefabricated.

The head support leaning on the column stem are a very effective solution. The stem expands towards the top of the prism of a square bottom base and octagonal top base. The edge of the base of the head support leads to the edge of the stem bottom through a trapezoidal wall, while a wall in the head between the supports leans on the edge of a triangle placed in the column stem. Such a transfer of load from the head to the column stem diminishes the influence of bending on the stem and helps maintain a rigidity of the connection between the column and the ceiling plates. Since the compression forces are dominant in the bottom part of the column, a decrease of its section appears justified. Additionally, a narrower square section enables implementing a simpler socket, in which the stem is planted. Moreover, when the column base is narrow, it is easier to mount the column on a head one floor level.

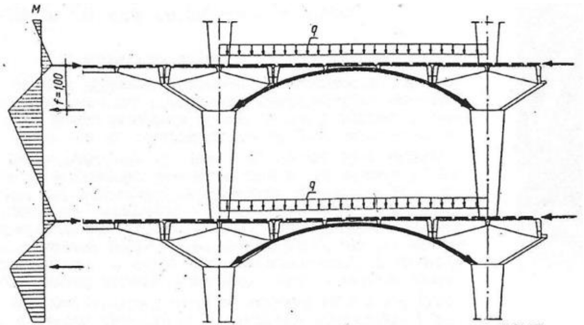

Fig. 5 Scheme for combining the effort of pc elements (Ref.2)

Spatial rigidity of multi-storey storehouses constructed by means of this technology was strengthened with the help of retracting cables arranged in the orthogonal system. The cables were placed along both sides of the square column base and pulled tight by screws fixed in building facades. Such a placement of strained ties results in an increased compression of hexagonal plates, which may decrease their deadweight in the local arch systems between the ends of column head supports. It appears that it would be better to place the ties on the column stems below the column heads. This position, however, would limit the useable height of rooms and increase a risk of corrosion. Diagonal ties of head supports could serve as an alternative solution. Unfortunately, this solution has got some limitations, resulting from differences in retracting forces in each area between the column structures. Research conducted on the construction load during its erecting confirmed a significant deadweight of the structure at an evenly distributed load. A long-term usage of buildings constructed by means of this technology attested their durability and resistance to external factors and corrosion.

4. EXPERIMENTAL PRESTRESSED SHELL

The experimental structure designed by Waclaw Zalewski at the University of Merida (Venezuela) drew significantly on the research models by Honoracio Caminos, devised as rubber membranes stretched over an artificial ring and upthrust by different configurations of internal support system distorting the flat rubber membrane.

Inspired by these shapes, Waclaw Zalewski proposed to cover an exposition space at the University campus by a structure of a circular projection 36m in diameter. According to the design the shell was supported by a system of six steel arches forming a regular hexagon. The external perimeter ring was situated 3m above the ground level. In order to remove the ring away from the support arches in the lines of their topmost point, a circle in the horizontal projection was deformed by a system of six arches ending in the circle line, whose radius was smaller than the circle.

Fig. 6 Supporting on steel arches (Ref.1)

The external ring lacked any secondary support and was elevated in its entirety to the sling system of the hanging shell. The internal ring was designed in the circular projection of approx. 3m in diameter. The load bearing slings of the shell were attached to the rim of this ring. The shape of the shell was adjusted to the sling system attached to the hexagon framed by the steel arches connecting the two rings: the external and internal.

In order to balance the internal ring, the breaklines between the rings of of the shell were run along the diagonals of the hexagon, so that rainwater could flow down the breaklines.

The upper parts of the steel arches in the hexagonal system served at the same time as the breaking edge of the hang slings. Sectional roofing bent parallel to the curvature of the arches was added in order to shield this edge from the atmospheric conditions. The lower sections of the steel arches projecting in an open space beneath the surface of the shell formed a hexagonal system of V-shaped columns supported in the corners of the hexagon. The arches of the hexagonal system were constructed from two bifurcating steel arches connected by steel elements assembled in a truss system. From the outside the structure formed a hanging shell, flowing down from the upper sections of the six arches towards the internal and external ring. The spacing between the load bearing slings influenced the shape of the shell, which was not continuous in terms of bicurvature of geometrical surface, but flattened between the lines of load-bearing slings.

Concrete blocks situated in support points of the steel arches in the apexes of the hexagon served as the foundations of the experimental structure. While the horizontal forces of support reactions between the adjacent arches were to a large extent counterbalanced, only the vertical component of this reaction force needed to be transferred to the ground. Parabolic arches in the hexagonal system were double arches composed of C-shaped steel profiles. The parabolic shape was also rendered by the straight sections of steel beams welded together. The middle walls of C-profiles were situated on the external surface of the arches. The arches bifurcating upwards were connected by a spatial truss of steel bars, on whose lower rim the load-bearing slings were hung. The points of sling attachment were adjusted to the nodes of the truss structure. The roofing of the upper section of the steel arches was made by laying out concrete on the truss branches of the arches supplemented by a margin placed outside of the arches. The external perimetral ring of the shell was made as a concrete trough. The sections of the ring between the steel arches were prefabricated. The sections facing the arches were cast in situ.

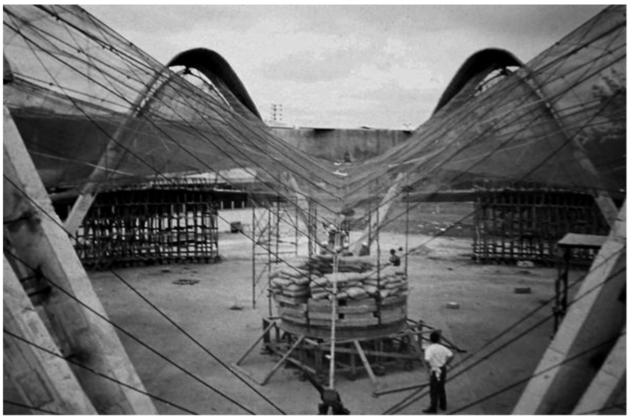

Fig. 7 Configuration of cable net (Ref.1)

Steel load-bearing slings of a profile diameter of approx. 4cm were hung with an initial bent against the string length of the overhang. While the adopted length of a bent vertically measured inside the structure was 1m long, for the internal bent of the sling 0,75m was assumed.

Spanning slings were placed perpendicularly to the load-bearing slings, forming fields of linear system resembling regular quadrangles. In the system of slings, it was possible to distinguish radial directions convergent to the middle ring of the shell. The connectors of the obtained sling mesh were made with the help of steel clamps joined together by screws. In order to position the concrete shell, a steel mesh of small openings was unfolded on the sling system. Since the concrete mass had been hand-laid, its layer varied in terms of thickness on each of its sections. A crucial role in preserving the form of the structure was played by dynamic changes of weight of both the external and internal perimetral ring, which helped to maintain a force balance in the whole structure. After concrete had solidified, the shell functioned as a rigid load-bearing surface. Bicurvate form of the shell had a positive influence on the compensation of deformations caused by wind-load or thermal load resulting from insolation of the external surface. The influence of insolation was minimized by covering the shell with silver paint.

It was assumed the an optimized and modernized version of the solution from Merida will be an appropriate structure for the auditorium commemoration professor Waclaw Zalewski.

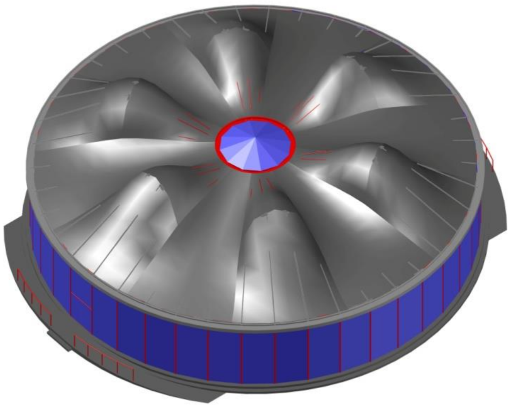

Fig. 8 Axonometry of the auditorium built on six arches.

The structure will consist of the foundation, an auditorium plate, an arch support, a ring of internal skylight, an external ring, ties holding the rings, lines and steel nets forming the final shape of the building. Steel lines, ties and nets will also be a reinforcement of thin walled reinforced concrete covering of the structure. Using the properties of the thin walled coverings erected based on the elements mentioned above a few architectonically different variants of such structures which are possible to realize can be imagined. It is possible to base the covering on two, three or a bigger number of arch supports. It changes not only the architectonic expression of the building but also influences the way of forces distribution in the elements and their value. It can facilitate or complicate the assembling and exploitation of the new object.The presented version of the auditorium of the 20m diameter is supported on three slanted arches placed also on six foundation feet. In this variant the arches eventually work independently and are not connected with one another by means of horizontal struts. The remaining construction elements work and cooperate with one another as in the 30m solution.

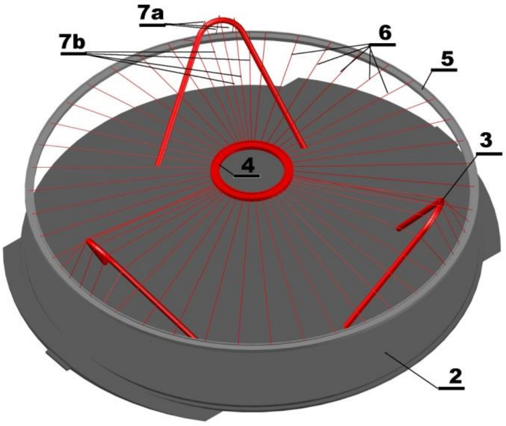

Fig. 9 Elements of the auditorium built on three arches

5. CONCLUSIONS

The achievements of Wacław Zalewski in creating concrete structures from prefabricated elements are still valid in contemporary architectural design. In the last 50 years there has been a significant change in the technology of fabrication of structures with the participation of precast concrete elements, first of all it is a change in the standard class of concrete strength of the prefabricated element from 20 MPa to 90 MPa. This causes the necessity to introduce technological changes, mainly in the field of production and assembly of concrete elements. The use of very high strength cement requires the use of more sophisticated additives in order to obtain the minimum amount of water in the concrete mix, while maintaining the possibility of mechanical mixing and tightness of the concrete mix. The expected effect of introducing these technological changes is to reduce the cross-section of the structural element and the amount of structural reinforcement. In an ecological aspect, the production of prefabricated elements becomes less energy-intensive, and thus also reduces the emission of carbon dioxide. The introduction of new solutions for concrete architecture increases its aesthetic attractiveness while further utilizing positive mechanical features. Architects can use a more durable and at the same time more and more delicate construction structure. An important element in the design are new types of hidden connections with the participation of steel elements that are embedded in concrete elements. The connectors should transfer larger internal forces on the reduced contact surfaces of the pc elements, at the same time the characteristics of the forces transferred in combination should be maintained, which result from the need to protect the stiffness of the whole structure. Progress in precast concrete construction technology is currently taking place after a certain spiral of development, in which the achievement of the next level opens opportunities for further growth. Certainly in the coming decades we will be witnessing another technological revolution in the field of prefabricated constructions using composite constructions from many different structural materials. This situation requires taking up new challenges and carrying out new experimental research and implementation of new types of elements in modern architectural structures.

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