Construction of a fountain in the form of a concave-convex concrete shell

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Abstract

The paper describes the construction of a concrete shell of a fountain with a unique concave-convex mathematically generated form. The fountain, which is 9.5 m long, 4 m wide and 2 meters high, was erected in September 2001 in the main square of the historic city of Solkan in Slovenia. The architecture of the fountain, the studies of water flow, the static analysis and realization of the project were performed by various experts from corresponding fields from Slovenia. The paper describes the process of conceptual design and the main phases of water flow study, static analysis and erection, as well as unique and expensive cladding of the shell with 3D formed marble tiles (made by computer driven CNC machines). All the phases of construction are well documented with pictures and films.

1. Introduction

The form of the fountain of Solkan is an interesting computer generated concave-convex concrete shell which is approximately 9.5 m long, 4 m wide and 2 m high (Figure 1). The conceptual form of the shell and material selection were carefully matched with the surrounding architecture (Slovene Kras region is historically known for its massive stone buildings) and hilly landscape of Kras region. The fountain was erected on the main square of the city of Solkan near Nova Gorica in Slovenia in September 2001. The investor was local community of Solkan. The architecture is the work of Sadar in Vuga architects from Ljubljana. The modeling of the water flow and hydraulics of the fountain was made by Hydro department of the Faculty of Civil Engineering and Geodesy in Ljubljana (by prof. Primož Banovec). The structural concept, static analysis and building plans were performed by Structural department of the Faculty of Architecture in
Ljubljana and its co-workers. The site work was operated by Cestno podjetje Nova Gorica and Marmor Hotavlje. The paper describes the main phases of water flow study, static analysis and erection of the fountain.

Figures 1 and 2: Fountain in the main square of the historical city of Solkan.

2. Studies of the water flow

The water flow on the innovative fountain forms can be rather complex and it is of course also a challenge for the hydraulics engineers. The basic idea of Solkan fountain was to rise the water for the height of 1 m on the distance of 6 m and than to split it in the form fan shaped curtain. It was soon recognized that at least the following important parameters influence the idea: a) fountain shape, b) water capacity, c) water speed, d) pout shape, e) roughness of the surface. The main parameters of water flow (water capacity, minimal dimensions of the pout) were determined by simple one-dimensional mathematical model. It was soon recognized that the proposed form of the fountain should be modified in order to achieve the desired flow of water. The height difference was reduced and the shape of the saddle was adjusted to the needs of smooth water flow. The other parameters were examined by 1:1 model of the fountain. The task of the model was to verify the new geometry of the fountain, to determine the right direction of the pout and to determine the form for channel shaped surface needed to rise water at the top of convex part of the shell. It was also used to verify the water capacity and water speed obtained by simplified mathematical model. The erection of the model of the fountain (a strip with the width of approximately 2 m) and the tests of water flow are presented in the Figures 3, 4, 5 and 6.

Based on the model tests the final form of the fountain and the positions of upper and lower rectifiers as well as the final parameters of the water flow (water capacity, direction and pressures of the water pout) were obtained. The obtained final water flow on the erected fountain is shown in Figures 7 and 8. The effect of fan shaped curtain split of the water seems to be less effective as planned. It seems the hydraulic engineers have reached the limits given by suggested shape. It would be therefore needed to include them in earlier design phases.
Figure 3: Erection of the 1:1 model of the fountain (2 m wide strip).

Figure 4: First tests on the model

Figures 5 and 6: Tests on the physical 1:1 model.

Figures 7 and 8: Obtained final water flow shape and foundations of the fountain.
3. Static model and selected results of static analysis

The fountain basically consists of two elliptical paraboloids (one turned upside-down) that are connected with the saddle that connects the two. The fountain is supported in the central part of concave part (foundation 1, see Figure 8) and partially as a console at the side of convex part (foundation 2). Statically the fountain presents a thick shell, which is subjected to axial deformations as well as bending deformations (especially in the console part) and torsional deformations (especially in the saddle).

In the initial phase of the design several different construction materials were taken into account. One of the possibilities would be to build a fountain only from stone marble pieces connected with anchors and epoxy glue or additionally with epoxy ribbons. Due to rather large console part this option was soon rejected by the marble producing company. Other option would be to build the shell with a plastic with glass wool, similar to producing of plastic boats. In this way a very light weight structure could be obtained, however the appearance requirements for final surface did not favor this solution. Finally, the reinforced concrete shell was selected to be the most appropriate solution which satisfies the price requirements as well as it gives the required noble massive marble view of the fountain.

The main loading case (apart of self weight) turned to be the gravity load of marble cladding that covers the fountain at the top as well as at the bottom side. It was foreseen that the thickness of the cladding would vary from 2 up to 4 cm, but during the realization phase it was find out, that the cladding thickness should be up to 8 cm at the parts with the biggest curvatures. As additional loading the weight of twenty people on the console part was taken into account. Other loading cases (wind, snow) did not contribute significantly to the proportioning of the shell.

The shell was modeled with 3D mathematical model and shell type finite elements. The model is shown in Figure 9. The selected thickness of the shell follows the loading demand as well as the requirements for mounting of the concrete. Too thin concrete shell would also not allow the appropriate positioning of reinforcement. The overall thickness of the shell is 12 cm, except near the foundations where the thickness rises up to 30 cm. All thickness changes are gradual and adjusted to the demands of the architecture. The concrete with the compression strength \(\sigma_c=4\ \text{kN/cm}^2\) with the size of maximal grain of aggregate limited to 8 mm was used. The main reinforcement of the shell runs in to two orthogonal directions. The main steel reinforcement bars are ribbed \(\Phi 10/8\) cm on the upper and lower side of the shell (see Figure 11). The parts of the shell near the foundations are additionally reinforced with the ribbed bars \(\Phi 14/8\) cm (which are added between main reinforcement). The strength of the shell was additionally increased by the strengthening edge which runs all around the shell.
The task of the edge is to strengthen the shell and to minimize the eventual buckling phenomena in the shell edges. The strengthening edge has the dimensions 18 cm by 16.4 cm and it is reinforced by 4RΦ14 and stirrups Φ8/10 cm.

The static analysis proves that the selected reinforcement is able to accommodate all stress concentrations which appear in the saddle and in the convex part of the shell. The displacements due to maximal vertical loading are shown in the Figure 10. It can be seen that the maximum displacement does not exceed 5 mm. The reinforcement of characteristic shell sections is schematically presented in the Figure 11. During the finalization of the shell we decided to reduce the thickness and increase the width of reinforcing edge in order to simplify the positioning of the reinforcement. The actual reinforcement of the convex and concave part is shown in Figures 12 and 13.

The shell lays on the concrete square basin which serves as a foundation as well as to collect the water running over the fountain. The basin is covered with stainless steel net that enables the reception of the water and the walking around the fountain. The visual effect of slenderness of the shell was additionally achieved by marble conically shaped finishing elements mounted on the reinforcing edge.

Figures 9 and 10: 3D mathematical model of the shell and displacement of the shell under maximum vertical loading ($\Delta_{\text{max}}=0.41$ cm).

Figure 11: Shell thickness and reinforcement.
4. Building of the fountain

The fountain shell has to be built very precisely according to building plans, since even small discrepancies in the form of 3D surface could change the water flow. For this purpose two types of wooden profiles were used: a) lower profiles which supported the lower marble cladding and served also as concrete formwork and b) upper profiles which defining the position of the top of the concrete shell. The main phases of the building of the fountain are briefly shown next.

4.1 Foundations

Figure 14: Foundation plate, basin walls and prepared foundations for the shell with already built in reinforcement. It can be seen also the formwork of the engine room.

Figure 15: Preparation of the foundation under the concave part of the shell. The lower profiles for supporting of marble cladding can be also seen.
The foundations of the shell are connected with the concrete foundation plate with a thickness of 25 cm. This plate serves also as a bottom of square water basin that is maid of water-proof concrete with specially prepared concrete mixture. The width of the basin walls is 20 cm. The whole basin was made in one piece.

4.2 Producing of 3D marble cladding

The fountain is covered with marble cladding from both sides. The cladding was made of individual pieces that fit exactly to prescribed 3D shape of the shell. The size of marble pieces was chosen as big as technology allowed in order to minimize the number of figures that would hinder the flow of water. At the places of large curvatures the pieces have rather complicated space form. With the aid of computer generated model we were to produce necessary input data for computer controlled machines for cutting of granite. The producing of marble pieces is shown in Figures 16 to 19.

Figure 16: Machine for cutting up the granite blocks in pieces.

Figure 17: Cutting of granite block into pieces and their preparation for further treatment.

Figure 18: Computer driven shaping machine for final fabrication of granite pieces.

Figure 19: Fabrication of conically shaped cladding pieces (decoration of reinforcing edge).
The producer of marble cladding pieces was the company Marmor Hotavlje from Slovenia that prepared all marble claddings for the fountain. More than 300 different pieces were cut from bigger blocks and transported to the building site.

4.3 Lower marble cladding as formwork for concrete shell

Larger concrete shells need corresponding formwork which substantially increases the price of concrete shells. In our case it was possible to avoid the expensive formwork by using the lower marble cladding pieces as a formwork for the concrete shell. The pieces of cladding were cut exactly into prescribed shapes and positioned on the braced wooden profiles spaced at a distance of approximately 20-30 cm (Figure 20). The purpose of the wooden profiles was to support the weight of the shell during concreting phase. The profiles were positioned on the already prepared basin base plate. The pieces of lower cladding were equipped with stainless steel anchors in order to achieve necessary bond between cladding and concrete shell (Figure 21). The individual pieces of marble cladding are connected with stainless steel bolts.

4.4 Concreting of the shell

During concreting of the shell the upper profiles were also needed. Their task was to give the exact position of the top surface of the concrete shell. The concreting of the shell and the usage of upper and lower profiles is shown in Figures 22 and 23.

4.5 Upper marble cladding and final treatment of the surface

The upper cladding was mounted on already prepared anchors. The pieces of marble cladding are also interconnected with bolts. At the end also conically shaped edge marble pieces were added to increase the visual effect of the slenderness of the fountain (Figure 24). The width of fugues is less than 1 mm.
Where necessary the fugues were filled with elastic putty. The edges of marble pieces were polished where necessary to achieve the sufficient smoothness of upper surface (Figure 25).

Figure 22: Upper wooden profiles and concreting of the shell.

Figure 23: Leveling of the top surface of the concrete shell.

Figure 24: Mounting of upper marble cladding and conically shaped edge pieces.

Figure 25: Polishing of the final surface of the fountain.

4.6 View on the finished fountain

Figure 26: Finished fountain and water flow.

Figure 27: Opening of the fountain in September 2001.
5. Conclusions

The paper describes the main phases of erecting and building of the concrete shell of the fountain in the city Solkan in Slovenia. The following main technical phases are briefly presented: a) hydraulics of the fountain, b) structural concept, c) static analysis and reinforcement, d) marble cladding and e) technology and building of the fountain. For a successful realization of the project in given minimal time frame a good and constant cooperation among all parties involved in the building process was extremely important. In this way a rather unique (and expensive) and fairly complicated project of the fountain was realized in less than 6 months.

The most problematic phase of the whole project was to develop the hydraulic measures to assure the water would flow on previously prescribed form. Since this was not completely possible, few design cycles and improvements of the final form were needed. Even in the final solution the flow of water is not exactly the same as it was foreseen by initial architectural design. It was soon realized that the projects which include a more elaborate flow of water, should involve the hydraulic engineer in as early stage as possible. The water flow can be formed even in unfavorable boundary conditions, however in such a case the solution can be much more expensive and un-rational as in normal case.

Acknowledgements

The author expresses his gratitude to all co-workers and companies involved in the project for contributing knowledge, data and slides that make possible the presentation of this paper (Hydraulics: Asst Prof. Dr. Primož Banovec - Faculty of Civil and Geodetic Engineering from Ljubljana; Architecture: Sadar in Vuga arhitekti, Ljubljana; Marble cladding and consulting: Marmor Hotavlje, Hotavlje; Executant of works: Čestno podjetje Nova Gorica, Nova Gorica; Technical documentation: Uniarih and Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia).