INTRODUCTION

The unconstrained creation of free forms in present day architecture has become a new aesthetical paradigm: architectonic requirements have stimulated the search for new types of structures. Architects, drawing complex curvilinear forms, are immediately drawn into the process of their manufacture. To execute digital free surfaces, technical mastery of the material is needed, as new geometric solutions often pave the way for exploration of new materials and vice versa [1].

Virtual free surface imposes such technical solutions and materials which question the traditional thinking about a building. This is related to the principle of combining the load bearing structure and the “skin” into one tectonic self-supporting element. The structural envelope is the integration of surface and structure into one. As can be seen, different types of materials can be used as components of structural envelope. Popular are: shotcrete shells, fibre glass reinforced concrete and fibre glass reinforced plastic.
2. ENGINEERING COMPLEX GEOMETRIES – THE HEYDAR ALIYEV CENTRE IN BAKU

The Heydar Aliyev Center is a 101,801m² building complex in Baku designed (2005) by Zaha Hadid Architects (structural engineering: Adams Kara Taylor). The complex represents a fluid form which emerges by folding of the landscape’s natural topography and wrapping of individual functions of the Center. The object was designed to host exhibitions, concerts and other cultural activities. 121,000 m³, an equivalent of 5,500 tons of structural steel were needed to construct the 40,000 m² basis area for panels made from fiberglass reinforced polyester or of concrete, a total of almost 17,000 individual panels with different geometries [2]. The building consists of two main systems that collaborate: concrete structure combined with a system of spatial structure (Fig. 1). The space frame system allows the construction of a freeform structure and saves time during the construction process, while the substructure has been developed to incorporate a flexible connection between rigid grid of the spatial structure and sheathing seams freely. The space frame system allows the construction of a freeform structure and saves time during the construction process, while the substructure has been developed to incorporate a flexible connection between rigid grid of the spatial structure and sheathing seams freely. These seams were obtained from a process of rationalization of the complex geometry, use, and aesthetics of the project. The geometric 3D modelling of the envelope’s structure was carried out in Rhino 4.0. The resulting Rhino-models were extended with additional information for the MERO – specific technical processing by means of specially developed software tools. MERO KK system are made of solid steel ball nodes and CHS members. The nodes have a diameter between 110 and 350 mm and up to 16 threaded holes in different directions. Due to double-curved geometry all nodes and members are different and individually produced. The members with a diameter from 60.3 to 273 mm are automatically (CNC) prefabricated of steel cones, CHS pipes, threaded bolts and sleeves, up to 4.5 m long. The special geometry of surfaces promotes unconventional structural solutions, such as the introduction of curves or “boot columns” for reverse shell from the ground surface to the west of the building, and the “duck tail” resulting from the narrowing of the cantilever beams that support the skin of the building on the east side [2].

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3. CURVILINEAR SURFACES WITH SHOTCRETE TECHNOLOGY

Initially, shotcrete was used mainly in repair and renovation works as well as for hardening of loose road slopes. Shotcrete is a type of concrete which is sprayed onto the face of curvilinear structures to form a protective lining and support, usually tens of millimetres thick. It is most useful in protecting soft
or weak material and can be adapted to suit varying conditions. In the 21st century, shotcrete has been used as an important component of multi-layer structural “skins” for digitally designed non-linear shaped architecture.

3.1. Structural envelop for the EMP in Seattle

The Experience Music Project (EMP) is a one-of-a-kind project that required new methods of construction – even in the application of shotcrete. The EMP building, with a 9,114 m² footprint, houses the interactive music museum in Seattle. The architectural design is by Frank O. Gehry and the construction by Hoffman Construction.

In the groundbreaking use of computer technology, the building was designed in CATIA, a software package created for the aerospace industry. CATIA allowed the project team to translate The EMP’s three-dimensional shapes into coordinated drawings and geometric data that builders and manufacturers could understand [3]. The museum consists of seven elements resembling irregular, undulating blobs which look as if they were the result of an eruption. The monorail running right through the building and the construction site is also worth noticing (Fig. 2).

As the figures show, it is a geometrically complex project that requires unique construction techniques. Each of the elements is designed as a semi-monocoque shell composed of several layers. Their structure is composed of shapes resembling cages with curved steel ribs. Each of the building’s 280 undulating structural ribs is unique. At first, the cages were covered from the outside with steel mesh “canvas” on which the liquid concrete mixture was applied with the shotcrete method. In this way, the shell made of a layer of shotcrete 7-28 cm thick was created. It is a type of a substrate integrated with steel ribs which acts in the same capacity as plywood does in conventional balloon frame residential projects. This is the layer which makes the building “real” and to which exterior cladding is fixed. From each frame a sufficient number of projections is made in order to assemble the outer layer of the skin. This layer is installed on the smart metal panel system. This massive project includes 3,300 unique panel assemblies, resulting in over 42,672 m² of metal surfacing [4]. For The EMP, a new method was developed to build complex non-linear “skins” with minimal waste and a reduced ecological footprint, eliminating the need for additional structural construction. This method can be used in the implementation of other buildings with complex geometry.

3.2. Structural “skin” for the City of Culture of Galicia in Santiago de Compostela

Shotcrete was also applied in the implementation of curvilinear forms of The City of Culture of Galicia, according to Peter Eisenman’s design. The construction is challenging and expensive as the design of the buildings involves high degree contours, meant to make the buildings look like rolling hills. Although Eisenman proposed eight buildings, the project was reduced to six. Two of the buildings, the 47,306 m² Archive of Galicia and the 56,994 m² Library of Galicia, opened in January 2011 (Fig. 3).

These are the largest structures of the complex. The challenge was to create curved roofs with pitches ranging from 30 to 70 degrees. Another difficult task was to prepare the right concrete mixture, the composition of which would prevent the concrete from running off the steep plane of the roof. The mixture was tested on the model of the steel structure of the roof. A new formula was developed, which had never been used before. However, the first tests on the model did not produce the expected results – the mixture, instead of solidifying on a steel reinforcement,
ran off the structure completely. The contractor was forced to treat the mixture directly on the site. As a result, the application of the concrete was performed by spraying, applying subsequent layers of concrete, until the desired thickness was obtained. A difficult climate of Galicia posed another challenge. Frequent and heavy storms intensified the concrete running off the sloping roof. At the next stage of work, the concrete layer of the roof was covered with thermal and water insulation [5].

Cut into 60 cm² blocks of stone (with blocks specially trimmed at the edges), it was mounted on a steel armature of curved box beams (or steel girders in the archive) with steel cross-bracing. The ventilated chunky roof surges over an under layer of concrete deck, waterproofing and protective insulation. The interstitial space between the two layers also houses mechanical equipment. The side walls of mortarless quartzite panels with stainless steel reveal stand out from the buildings like a rainscreen against galvanized aluminum. While the steel and stone are widely used, the actual structure of the buildings is reinforced concrete [6].

3.3. Inner curvilinear walls for The Museum of the History of Polish Jews in Warsaw

An innovative use of shotcrete technology is presented in the design of the three-dimensional (3-D), curvilinear wall symbolizing the Red Sea parting for the Hebrews’ exodus from Egypt. It forms the main spatial element for the interior of The Museum of the History of Polish Jews. The architectural design is by Rainer Mahlamäki and Ilmar Lahdelma (Helsinki), the winner of architectural competition in 2005. The SPB Torkret LTD was subcontracted by the main contractor (Polimex – Mostostal SA) responsible for the completion of the curvilinear wall. Włodzimierz Czajka, the Technical Manager of SPB Torkret LTD was the creator of the wall structure design. The Poznan University of Technology team led by Professor Józef Jasiczak carried out static calculations and tested the load-bearing capacity of structural elements (Fig. 4).

The 50 mm thin envelope of the curvilinear walls is made of a reinforced concrete structure with mesh reinforcement (Ø 4.5 mm stainless steel ribbed bars). The walls are suspended using a system of anchors embedded in a substructure resting on steel columns. The steel columns forming the structure’s framework are located in both walls of the hall and run along the entire building’s height. Vertical elements are made of Ø 273 mm pipes, composed of sections, bent in one plane, horizontally braced, and formed into a grid by means of pipe profiles. Horizontal elements are made of Ø 100 mm pipes. The thin-walled, curvilinear dry-mix shotcrete wall is mounted through a system of rigid anchors to the pipes as the substructure [7].

The way stresses were distributed at the point of anchorage and dispersed in the wall surface section was an innovative approach. This distribution of stress was obtained by mounting a strap with radial bars onto the anchor. The solution allowed avoiding possible scratching and cracking of the wall at the points of contact with the substructure. For static calculation model purposes, the wall envelope was considered as multiple point-of-anchorage plates loaded with dead weight. By introducing expansion joints, dimensions of a single plate were limited to approximately 16 to 20 m². Each of the wall elements underwent destructive testing, including a cut-out of the finished wall with the anchorage. Another innovative element was specially designed plastic strips embedded both in expansion joints and control joints. The structure of the plastic strips facilitated maintaining a constant shotcrete application layer thickness and delineated the outer surface. This also enabled installation of a membrane preventing humidity loss and
protecting the surface against dust when applying shotcrete onto the adjacent element. The expansion joint strips were removed and replaced with fireproof silicone material. The control joint strips were left in the structure reflecting the so-called wall pattern assumed by the architect. Strips were mounted on a special plate serving as a stay-in-place form. The plate had to meet the elasticity (multi-directional bending) and non flammability conditions. Once the plate with joint-defining strips was formed and fastened, two layers of concrete were applied [7].

The unique combination of shotcrete application technology to form the wall’s curvature and the selection of materials resulted in exceptional quality of the structure and durability that exceeds the standard life span of a building.

4. CONCLUSIONS

The presented examples show how the explorations in constructability of geometrically complex envelopes in the digital avant-garde projects have led to rethinking of surface and building tectonics. At present, the digital tectonics appears as an evolving methodology that integrates the use of design software with traditional construction methods [8]. A space construction system should follow a geometry of a free form structure. The implementation of geometrically complex structures and building systems with different components is a viable proposition. It is important, therefore, to consider the relationship between non-digital skills and tools and digital techniques as well as technology.

Designing (CAD) and manufacturing (CAM) integrated the practice of erecting buildings with their designing. Increasingly strong historical relationship between architecture and the means of production is becoming a challenge for the new digital design, manufacturing and construction processes. Varied computer linked manufacturing techniques have become an integral part of the design process, while new digital tools allow engineers and architects to understand in a more precise way the performance of load bearing surfaces, and to generate new architectural forms.

By adopting digital techniques CAD/CAM, architects are again resolving the problems of the relationship between geometrical order, materiality and structural complexity of forms.

A challenge is a structural envelope with the desired dynamic behaviour and conditioned by the strength of the material. It is expected that these new materials will be extremely durable and thin, dynamic and variable, adjusted with the composition of their components to the function, and the scope of their application will be extremely extensive. Material Engineering stands today before a new task, which is to develop and provide to the construction industry new materials so that new buildings were becoming lighter, easy to install and environment friendly.

The curvilinear parametric architecture of free geometry is implemented in various places in the world and is becoming increasingly popular due to the rapid development of robotics and CAD/CAM technology.
REFERENCE


