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## **FREE-FORM SHELL STRUCTURES AS ART OBJECTS IN THE URBAN ENVIRONMENT**

**Abstract:** *City environment is a complicated system, where individual buildings interact with streets, squares, public spaces. The comfort of the urban environment and the quality of life are determined not only by the absence of dirt and dust, noise and unpleasant odors, the presence of lawns, trees, rest areas with convenient equipment, information organization, etc., but also the unity of the visual appearance of all components of this environment: design and landscape, their harmony with the nature of human. The most striking components of visual perception, close to a person, are elements of art and art objects. The present article analyses how shell structures can influence the organization of successful public spaces as art objects. Shell structures play a special, singular role for architects and engineers in the urban environment. Their shape directly derives from their flow of forces, and defines their load-bearing behavior and lightness, saving material by creating local employment, their social aspect. This is especially true for thin concrete shells with different types of curvatures, such as a single curvature, synclastic (domelike), anticlastic (saddle-like) or even free (experimental). There are a lot of methods and approaches to create a shell structure, from physical hanging modeling to a complicated analysis using modern software. One of them is the Force Density Method, which was introduced by Linkwitz and Schek during their work with Frei Otto on the cable net structures of the Olympic stadium in Munich. A number of shell structures with different esthetic and structural characteristics have been created using this method. These shells are created on a human scale, organizing urban spaces. A successful place has to combine such attributes as physical space, the sensory experience, and activity. The created objects are environment dominants, which fill the space with a semantic content in social, psychological and cultural dimensions.*

**Keywords:** *shell structures, art objects, urban environment, form finding, force density method.*

### **Introduction**

The notion of urban quality incorporates social, psychological and cultural aspects. In other words, in successful city environment physical elements are combined properly with the psychology of a place. Art objects, elements of visual communication and small architectural forms contribute a lot to the urban environment, to both open and enclosed landscape spaces. They are placed in exteriors and interiors, varied in function and spatial characteristics. Kurochkin (2013) defines an art-object as an environment dominant, which fills the space with a semantic content. It is created not only for material but also artistic value. The main features characterizing art objects are integrativity, self-sufficiency, functionality, the possibility of transformation, environmental friendliness and human orientation. The objects of art design are usually created using following approaches and methods: harmonious combination of functions (polyfunctionality), application of innovative materials and technologies, use of interactivity elements in equipment, etc. Art objects are more complex from a visual and content point of view than the objects of monumental art. They can motivate people, cause positive emotions, contribute to a sense of comfort.

In all these aspects shell structures are significantly valuable for the urban environment. Since ancient times, such shapes as vaults and domes played an outstanding part in architecture and urban design. Nowadays a broad variety of shell structures designed of various materials,

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such as steel or timber grid-shells, cable nets, reinforced concrete or masonry exist. The variability of unique spatial structures reveals numerous opportunities for architects and engineers.

In general, form finding methods can be divided into two groups: when the form of a shell surface is based on mathematically defined geometries, and when it is found based on the laws of equilibrium. Both approaches are widely used in the architectural and construction industries. The first approach is used by the brilliant architects and engineers Pier Luigi Nervi, Felix Candela, Eduardo Torroja, Anton Tedesko and Vladimir Shukhov. It is based on analytical or “geometric” forms and has reached its blooming period in the 1930’s. The present article pays more attention to the structures created through the second approach.

The main principle of form finding of all structures in equilibrium is a law of a hanging chain, which was formulated by Robert Hooke in the second of his ten ‘Inventions’ in 1676, and transcribed by Richard Waller in 1705:

*Ut pendet continuum flexile, sic stabit contiguum rigidum inversum.*

(As a flexible line hangs, so inverted a rigid arch will stand.)

The idea is genius in its simplicity: if you invert the shape of the hanging chain, which by definition is in pure tension and free of bending, you will obtain the equivalent rigid arch that will work in pure compression (Adriaenssens, Block, Veenendaal, Williams, 2014).

The analysis of the 6th Century AD arch of Taq-i Kisra (Hernández Montes et al, 2017) showed that this law was known from the ancient times and used for creating the most effective arches and vaults. The arch of Taq-i Kisra is the largest single-span vault of unreinforced brickwork remaining in the world, and its shape is significantly close to the catenary shape, which was mathematically described more than eleven centuries after its construction.

The Spanish architect Antonio Gaudí (1852–1926) was not the first who used hanging models in his work, but the one who brought them to a new level. He applied them to unite the process of design and structural analysis from the very beginning, using both two- and three-dimensional hanging models made with strings and bags of sand to help establish the forms of his arches and vaults.



Figure 1. Reproduction of Gaudí’s hanging model for the crypt of Colònia Güell, Barcelona

Heinz Isler (1926–2009) was one of the innovative architects of the 20th century, who created concrete shell structures. As Antonio Gaudi, he used the Hooke's law for creating his hanging shell structures, bringing into three dimensions the idea of a hanging chain (Fig. 2).

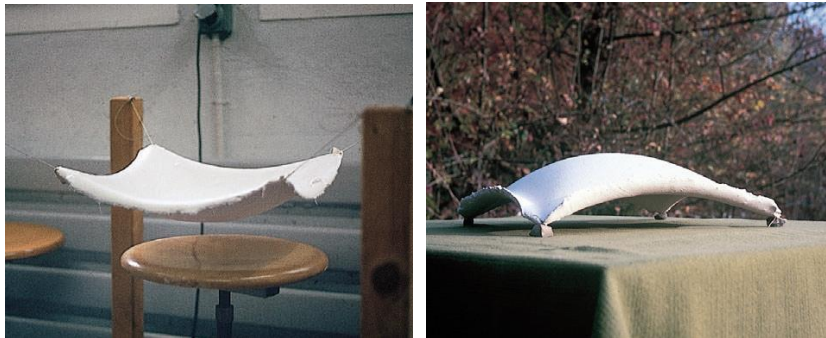


Figure 2. The hanging membrane, once hardened, is inverted to create a shell form in pure compression

Frei Otto (1925-2015), the founder of the famous Institute of lightweight structures at the University of Stuttgart, is one of the largest authorities in the field of tension structures and lightweight membranes. His team's work has spearheaded advances in structural mathematics and civil engineering. Moreover, he explored a great number of physical form-finding techniques, from hanging models to soap models. His professional path was far from the traditional methods of calculating forces. Another field of Frei Otto's research interests was form-finding of light-weight shells which could be formed using the Hookean principle of inverting a hanging net (Fig. 3).

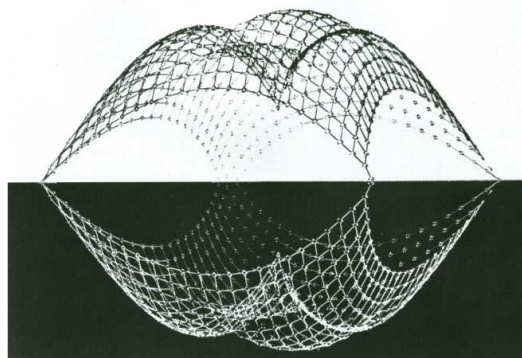


Figure 3. A form-finding experiment by Frei Otto illustrates Hooke's principle of inversion

### Methodology

The methodology of this article is based on the method of form-finding called the force-density method, firstly implemented by Linkwitz and Shek (1971).

As it was mentioned, in the Institut für Leichte Flachtragwerke (directed by F. Otto) at the University of Stuttgart a great research work in experimental methods of form-finding was done. The results of this work were applied in the construction of the cable net structures in the Olympic stadium in Munich, and many others. While working on the project 'Olympic Roofs' it became more and more evident that experimental methods had a number of limitations, and design of large-spanned structures required new tools for analytical computation of equilibrium shapes. That project had a lot of challenges, and to solve them, a number of breakthrough solutions were found. Linkwitz and Shek introduced the concept of force-densities, which was a starting point for the discovery and formulation of the force density method (Linkwitz, 1999).



Based on the force-density method and topological mapping, GAUDI software was developed by Carbonell-Márquez, Gil-Martín, Hernández-Montes, Jurado-Piña (2012) as a new form-finding tool. It is based on constant values of the force: length ratios that give endless opportunities for creativity to architects and engineers. FDM itself is a method where processes of design and structural analysis are integrated. New software allows linearization of the process of form-finding by solving it linearly by iterations. It allows finding an equilibrium shape of a structure initially desired by the artist by iteratively changing input parameters. With this tool, forces follow any well conceived form of structure. This new conception changes the traditional notion of “form follows forces” to “forces follow a well conceived form”.

### Measurement and analysis

The described method opens various opportunities for creativity in the process of form finding, and the main advantage of it is that the result is an effective structure, which provides the best work of material. To demonstrate the work of the GAUDI software with different input parameters, a catalog of compression structures was created (Moskaleva, Šćepanović, Carbonell-Marquez, Fernández-Ruiz, Hernández-Montes, 2017). A number of free-form compression-only structures in different materials were generated, and in each of them the shape is presenting the real flow of forces (Fig. 4).

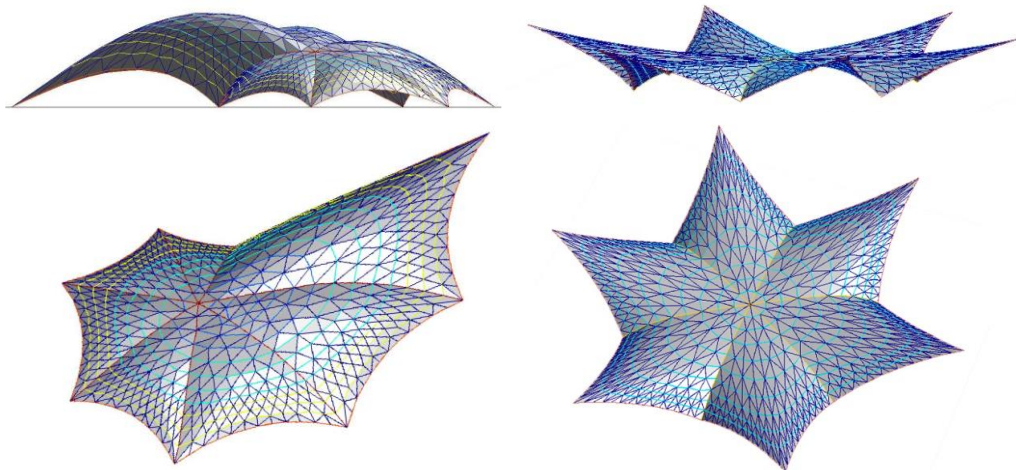


Figure 4. Form-found shells in compression, generated by GAUDI software

To apply on practice this powerful tool, the shell structure was created as an art object to mark the roundabout at the entrance to the city of Granada, Spain (Fig. 5). This place is significant for the citizens and the visitors of the town, because it is one of the first places you see when entering it. The structure was designed using the GAUDI software, based on the application of the Force density method and Topology mapping for compression structures, offered by Hernández-Montes at al. (2016).



Figure 5. Topography scheme of the roundabout on the entrance to the city of Granada

The first step of the design process is defining the initial shape in the ground plan and the coordinates of anchor points (supports) (Table 1). The next step is to define the material and the own weight of the structure. The structure is designed in the technique of a Catalan vault with ribs of the strength. Then the network is defined, by such parameters as a number of rings in the net, a number of nodes in the initial ring and type of topology for each ring (Table 1 and Fig. 6). Adding inner and outer ribs is an important advantage of the method, which can be achieved by assigning a higher value of force: the length ratio to the certain branches of the network (Fernández-Ruiz et al, 2017).

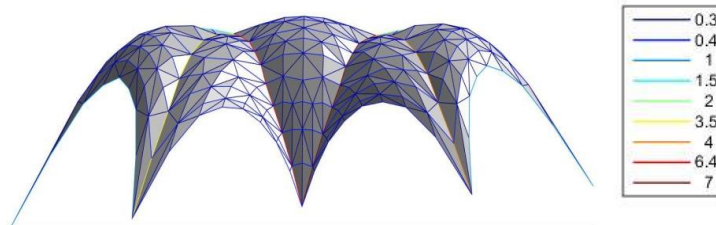


Figure 5. The equilibrium shape of the roundabout structure, generated by GAUDI software

Table

Input data		Coordinates of anchor points		
Number of rings	10	$X_i$	$Y_i$	$Z_i$
Number of nodes in the initial ring	6	0,0	4,0	0,0
Number of contour anchor points	8	2,5	0,5	0,15
Weight of the ribs (kN/m)	0,23	6,0	2,0	0,36
Self-weight (kN/m <sup>2</sup> )	1,0	9,5	0,5	0,57
		12,0	4,0	0,72
		9,5	7,5	0,57
		6,0	6,0	0,36
		2,5	7,5	0,15

This process of finding the proper shape of the structure is iterative, depending on the boundary conditions and the initial idea of the designer. It is described in detail by Hernández-Montes et al (2016). Fig. 6 and 7 show the 3d-visualisation of the structure in the environment.



Figure 6. The 3D-visualisation of the designed structure

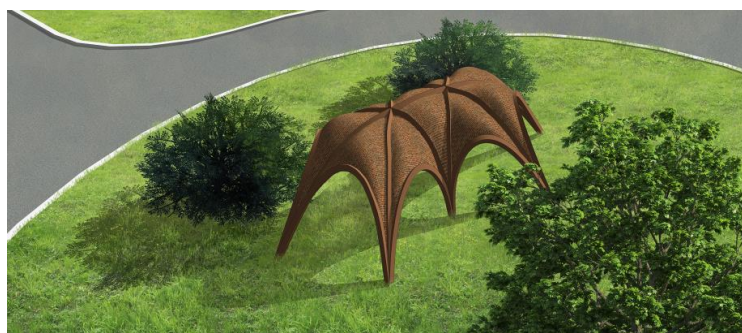


Figure 7. The 3D-visualisation of the designed structure

Two types of bricks are used for the construction: Rasilla (23 X 10 X 2.5 cm) is used for the shell, Macizo-taco (23X 11 X 4 cm) is used for the ribs (Fig. 8).

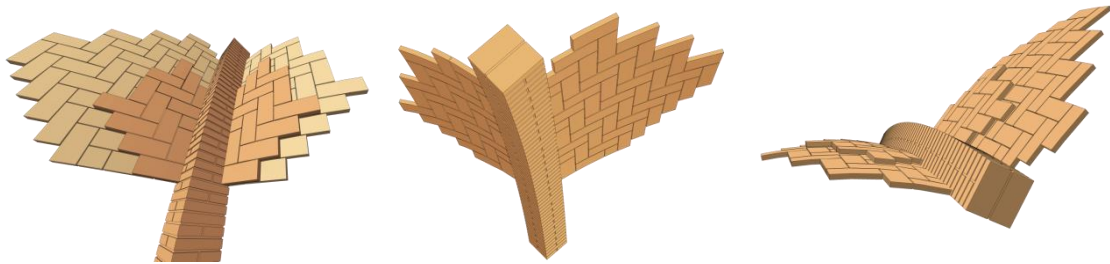


Figure 8. Details of the construction

The shells created using FDM can be used in any creative way, to increase attractiveness of appearance of any city or town. Fig. 9 shows how such shell structures can be used in Krasnoyarsk city, Russia. The Universiade is going to take place in Krasnoyarsk in 2019, so these shells, used as arbors, pavilions, bus-stops and art-objects can contribute a lot to its environment.



Figure 9. The 3D-visualisation of the structure in Krasnoyarsk city, Russia

## Conclusion

In conclusion, it can be noted that there are different principles of shell structure form finding. Architects and engineers determine the method which is the most suitable for the particular case by a number of parameters, such as material of the structure, the main idea of design, boundary conditions, etc. The article describes some practical applications of a tool for design of free-form shell structures in equilibrium, which is based on previous works related to the topological mapping (TM) and the force density method (FDM). The GAUDI software allows creating various structures of different materials, and the main advantage that the resulting shape is a shell with minimal bending moments. This means that these structures are cost-effective, although each of them can have its own unique form. Therefore, including them to the city environment as art objects can contribute a lot to the attractiveness of the place, with not very high investment and labor costs.

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