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Architectural and Structural Design of Free-form Structures – Case Study

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Abstract: This article describes the conceptual design process of an equestrian centre, presenting the covered stadium of the building complex in detail, designed it as a free-form, wide-span steel structure. The main goal of this study is to present the application of the parametric design method through a case study and to examine the interoperability opportunities between architectural and structural design software.

Keywords: free-form, parametric design, wide span, steel structure

1. Introduction

Recently thanks to the development of the software aided designing and manufacturing technologies the opportunities of architects significantly increased. This makes it possible to design and accomplish double curved constructions with complex geometry. Free-form edifices exist since the '50s but in the last decades their number is increased. Architectural proceeding was a stylistic issue until the second half of the 20th century, buildings denotes the marks of the relevant architectural styles. In our days there is a considerable changing: now the presence of a building is defined by an architectural concept not by the style of the era. As a consequence architects can select from various construction tools, thus they use free forms more often nowadays.

Designing a free form edifice is a complex process demanding particular accuracy. For a satisfying consequence in the case of such an edifice a very close collaboration is indispensable from the beginning of the conceptual designing between the architect and the structural engineer. In case of these buildings the function, the structure and the form influences each other firmly, thus it is important that both professions have to do with the other in some measure. [1]

The aim of the project presented in this paper is to examine the applicability of parametric design method through a case study, including both of architectural and structural conceptual design. Furthermore, the examination of the interoperability opportunities of structural and architectural design software have a decisive role in this study. The design task was inspired by the vision of the Olympics in Budapest in 2024, which gave a chance to design a representative, great volume facility – an equestrian centre.

2. Architectural design concept

According to the feasibility study published by the Hungarian Olympic Committee [2], the equestrian sport has shown an appreciable demand for a new facility out of the Olympic sports. Additionally, the jumping competitions and dressage tests become increasingly popular in the world, however in eastern-Europe there is not any equestrian venue, that is capable for international and world competitions. Furthermore, the equestrian sport has considerable tradition in Hungary, which is worthy for revival. Based on the feasibility study the building complex was designed near the Olympic Village, on a large and calm green island of the Danube River, the so-called Csepel-Island.

2.1. Design program

The design objective was to create a representative facility, which utilizes the possibility given by the architecture of the 21st century and represents the dynamism and power of the equestrian sport by the form and used architectural tools. The main consideration of the architectural concept was the use of the free-form and parametric design method. The building complex should resuscitate the tradition with the tools of the modern architecture. The chosen area will not detain free-form designing and there is no any assimilation difficulty. In the course of design the coherent forms, emblematic appearance was a very important point, since the building complex should identify as an Olympic venue too.

The equestrian centre has functionally two objectives. On the one hand it ensures indoor and outdoor sport facilities including the theoretical and practical education both in hobby and competition level, the horse therapy and the boarding services [3]. On the other hand it offers recreation possibility for the viewers by giving place for domestic, international and world competitions and other sport and cultural events. To satisfy the defined demands the building complex consists covered and uncovered racecourses with adequate seating capacity, as well as covered and uncovered warm-up courses connected directly to the racecourses.

The main approach of the building complex is in the north, while the service road leads from the western street to the south-west side of the centre. The layout of the two stadiums is acute-angled, therefore the entrance hall between them flares out and so allures the guest. The warm-up halls are encompassed by an articular hill in order to keep coherent formatting. On the southern side of the composition the stables and storages are located following the lines of the composition and closing it. (Fig. 1.)

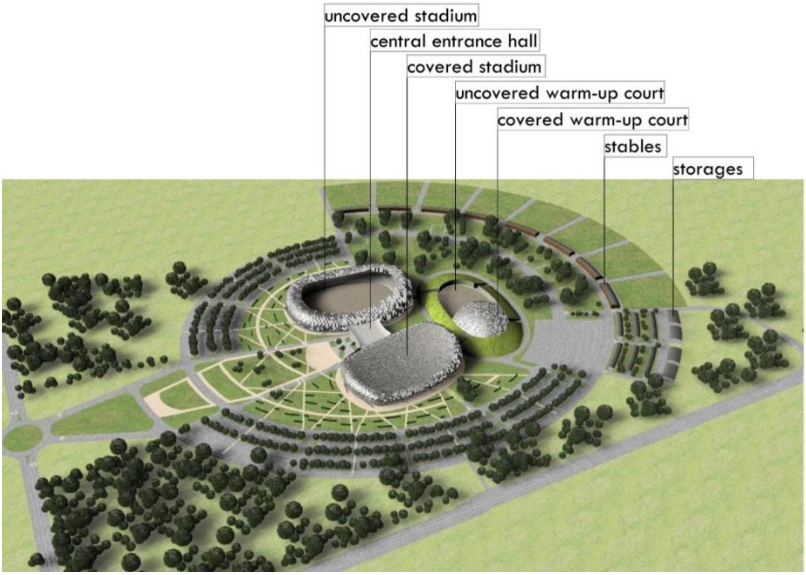

Figure 1. The building complex

2.2. Design of the covered stadium

The size of the racecourse in the covered stadium meets the requirements of the International Federation of Equestrian Sports [4, 5] and exceeds it (40x80 m) in order to use it multifunctional. Therefore the overall dimension of the building is 136x100 m and has a seating capacity of 4500 guests. In the building there are private spaces – viewing area, buffet, and restaurant – for the umpires, the rooms for the media and the VIP guests, offices, general engineering room and changing rooms for the equestrians. These rooms may locate centred, in one compact mass paying attention to adequate visibility of the racecourse.

2.3. Form finding

In the case of the covered stadium the form came mainly from the function. A significant mass – a four-storey reinforced concrete building part – will be resulted by locating the above mentioned centred. According to larger height demand of the auditorium a translation surface, the hyperbolic paraboloid was used for the main form of the stadium. Because of the higher reinforced concrete building part the parabola was deformed on the southern side. The building form as an emblematic saddle is in accordance with the demands described in design program (Fig.2).

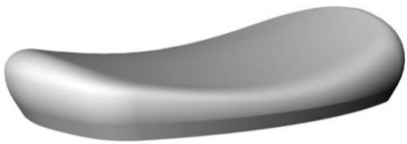

Figure 2. The form of the stadium

3. Parametric design process

For modelling this double-curved surface, parametric design method was used. The main advantage of this method is that the form and dimensions can be easily modified later on. Additionally, it is also easier to create and join organic shapes. This flexibility is a fundamental aspect in any design activity, where the designer is constantly going forward and backwards, in order to develop the optimal solution. Using this powerful method, the architectural forms and structural solutions can be designed in an easy and interactive way. [6] In this study the Rhinoceros 3D design software [7] was used with a plug in called Grasshopper. [8] The modelling method is demonstrated here through the implementation of the saddle-shaped surface of the covering shell. The curve of the cross-section was run over the hyperbolic cosine function according to the curve of the longitudinal section. (Fig.3)

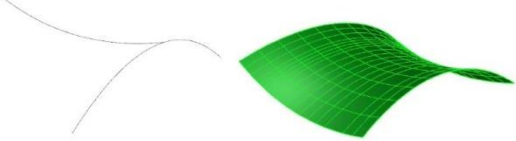

Figure 3. Constructing the saddle-surface [9]

The position of the points of this curve is variable with a help of each parameters, therefore the whole surface is flexible (Fig. 4.).

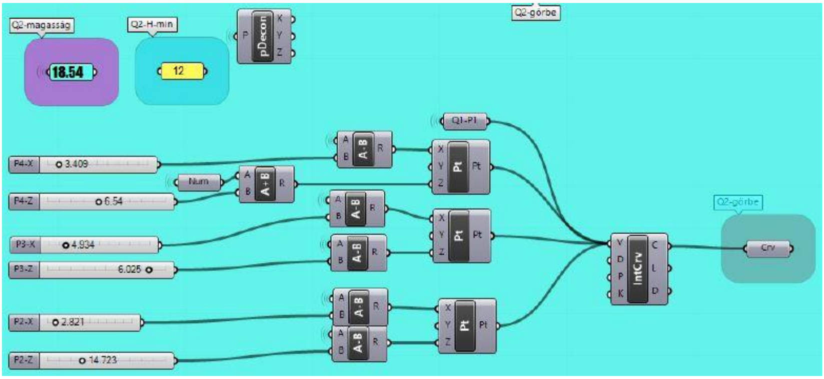

Figure 4. The command box of a main curve of the sidewall surface (Grasshopper) [9]

The whole building structure – including the steel grid and other structural elements – was elaborated using this method. During the conceptual design process it has seen to be an effective tool; the height and dimensions of the structural elements had to be constantly modified in order to reach an optimal solution in both of architectural and structural point of view.

3.1. Grid generation

After implementation of the main architectural form, the next step was the grid generation. In the case of the equestrian centre basically a triangular grid was applied in accordance with the aesthetic and economical aspects. Quadrangle-meshed nets can also be used on double-curved surfaces, but usually the quadrangles of the surface are not planar, which can enhance the costs of the facing material. [10] Two types of triangular meshes were constructed for the surface. (Fig.5) The parametric design method provides facilities for examination of these nets: the number of nodes, the distribution of the elements in certain range of length may be demonstrated, minimal and maximal lengths of elements can be examined. Based on these examinations the second grid was shown more favourable because of the less number of elements and less number of elements of different-lengths, which is advantageous from the point of view of production. Additionally, the aesthetic appearance of the second mesh was an influential factor. Using this variant of net the composition and the rhythm of the covered and glassed triangles may be various, and the architectural formatting may be exciting.

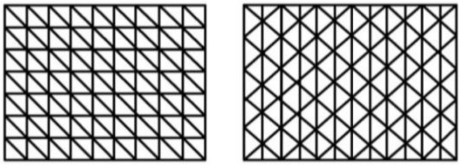

Figure 5. Examined triangular meshes [9]

The generation method of the grid consists of two parts in the case of the stadium: the mesh of the sidewall surface and the saddle surface. First the sidewall surface is described. Dividing the ground-plan curve into defined (and variable) number of equal parts, curves of the triangular mesh located in the vertical plane – with the main curves parallel – can be obtained. After that, dividing these "vertical" curves further, the diagonal curves can be also created. (Fig. 6)

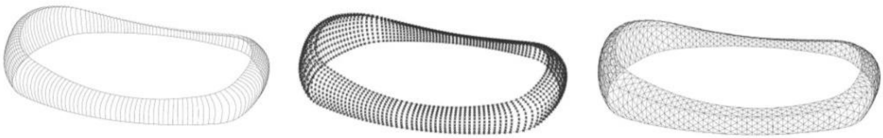

Figure 6. Generation of the mesh of the sidewall surface

The generation method of the mesh of the saddle surface is the projection method, which is a commonly used way in the case of domes. [11] The saddle-surface, in accordance with the sidewall surface was given lamella structured net (Fig.7. a). The basic points of the grid were given by the curves of the sidewall grid joined to the connection line between the sidewall and the saddle-surface. Running the lines into the centre of the surface (Fig.7. b) and dividing into equal parts the concentric curves to the contour of the surface may be obtained. The intersection points of the concentric curves and radial lines were resulted in the nodes. Because of the dimension of the surface the number of the dividing points was halved twice (Fig.7. c) in order to creating elements of ideal lengths. Grouping the concentric curves into three segments the lamella grid can be created (Fig.7. d), by using connective rings, which transmit the forces.

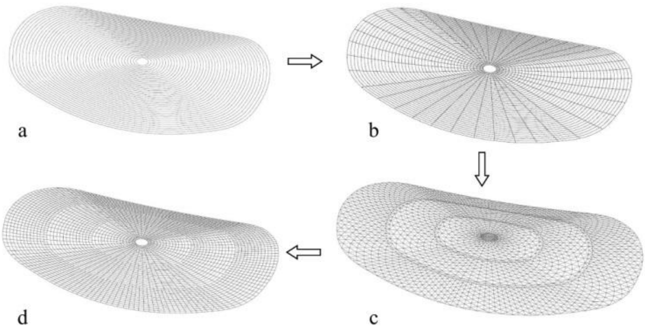

Figure 7. Generation of the grid of the saddle-surface

4. Structural design concept

4.1. Variations

The covering structure is a single-layer triangle meshed steel grid. Because of the function, the building cannot be supported by internal columns however the clearly membrane behaviour is impossible in consequence of the form. Two concepts were invented for the structural performance. The first variety is a hierarchical structural system which consists of a grid surface covering the barrier and a frame-system based on main beams [9]. (Fig. 8) This frame supports the shape of the structural form and bears the reaction forces of the grid surface. Transmission of the forces is ensured by an edge beam between the two elements of the hierarchical system. The second variety owns a similar hierarchy, nevertheless the frame based on main beams is connected directly with the continuous mesh of sidewall and saddle-shaped surface.

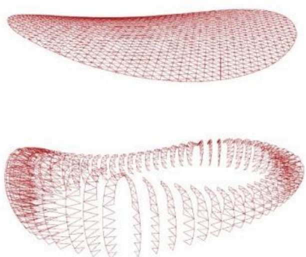

Figure 8. Hierarchical structural concept [9,12]

It was an important goal of the project evolving a concept which is optimal in architectural and also in structural aspect. For this reason several variety of main beamed system was designed and analysed. Essentially two ways of performance were worked out: a clear and simple form and an organic one (Fig.12). Finally, the organic form was applied in the aspect of aesthetics attentive to the influencing factors of the structure. As a consequence of the covering saddle-shaped surface's deflection, a damaging amount of moments and tension forces may be transmitted. To preclude this phenomenon it is recommended to attach the main beams to the covering mesh in the more points and the more orientations as it possible. Furthermore the lever arm can be increased by placing the main beam farther from the joining line of the saddle-shaped surface and the sidewall. Hence to guarantee the structural form the two kind of main beams should be combined. The result of the combination is shown on Fig. 10. It is a frame based on main beams which connect each other and to the mesh around the barrier.

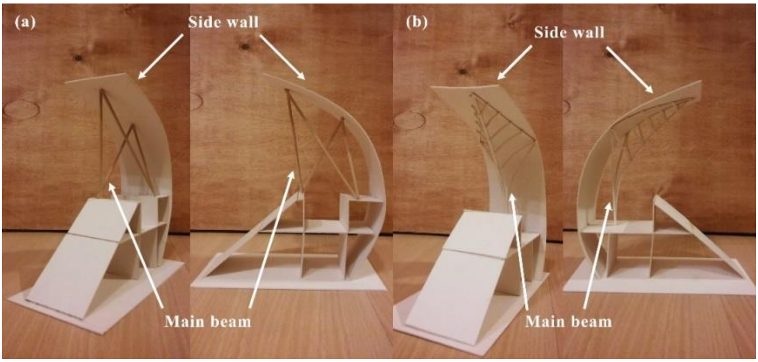

Figure 9. Variations for the main beams

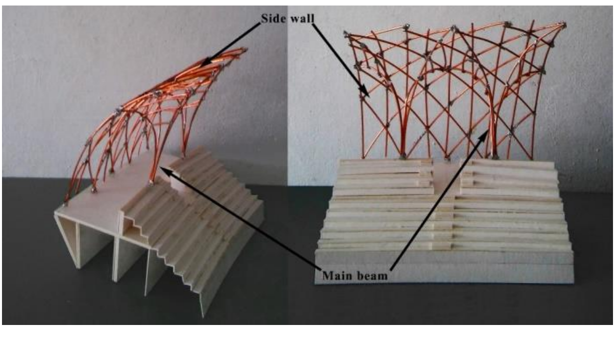

Figure 10. Final version of main beam

4.2. The global structural model

Fig. 11 shows the structural model of the steel construction. Concerning the architectural concept, all bars are made of hot-rolled CHS segments. The bars joined directly with the covering shell are straight and the column members are curved. The conceptual model do not consists the elements of the reinforced concrete substructure, the effect of it is replaced by rigid supports.

Figure 11. Global structural model of the construction: (i) complete model; (ii) supporting columns [12].

The conceptual design of the structure is accomplished for dead load (self weight + sheet: 0,3 kN/m^2) and for the Hungarian one-sided snow load (1,0 kN/m^2) for the sake of simplicity and in the lack of wind-tunnel examination. The global structural behaviour may be approximated by a tensioned chain along the longitudinal axis and a compressed arch along the cross axis of the building (Fig.12).

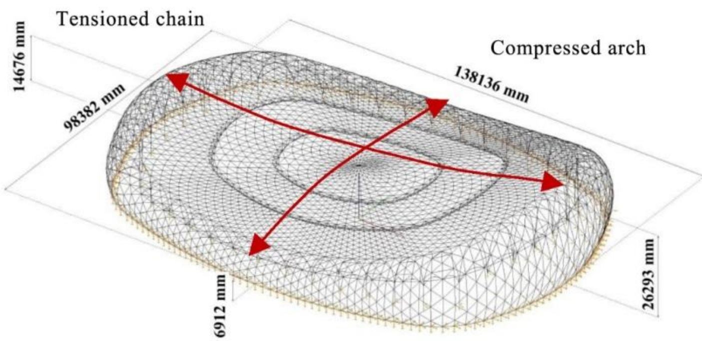

Figure 12. The global force behaviour of the construction [12]

Due to the building's interior design the performance of the grid cannot follow the global force behaviour of the construction. The "frames" constituted by the internal columns and arches and the external central planar bars cannot be rigid enough to strain the surface along or to insure the compressed-arch-like behaviour. At this point, considering the effect of the reinforced concrete substructure became a key-question in the designing. In Fig. 13 the global deformation of the structure is shown with the substructure's supporting effect. The maximum deflection is 313 mm, which value may be accepted.

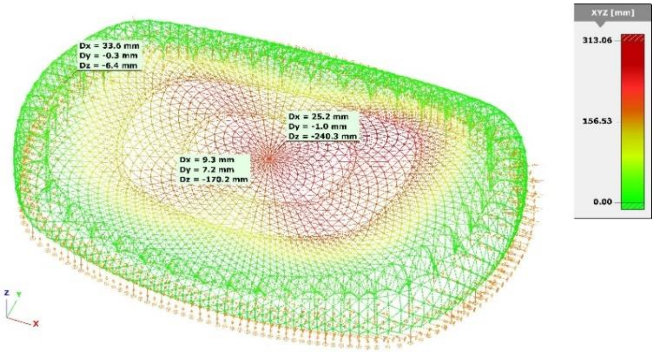

Figure 13. Global deformation of the structure with the supporting effect of the reinforced concrete substructure [12]

4.3. Design of the cross sections

The entire model is divided to ten groups based on by the initial stresses. Bars in each group have identical diameter and thickness of CHS cross-section. Sizes of sections are ranged from CHS 139.7x4 up to CHS 508x20. The largest sections are needed for the vertical bars of the lateral-wall and the bars of the internal columns. Minor sections are used for the internal zones of the saddle-shaped surface. The utilization of cross-sectional resistances according to the EN 1993-1-1 [13] is shown in Fig. 14. The specific structural steel usage of 128 kg/m^2 can be decreased by virtue of particular designing.

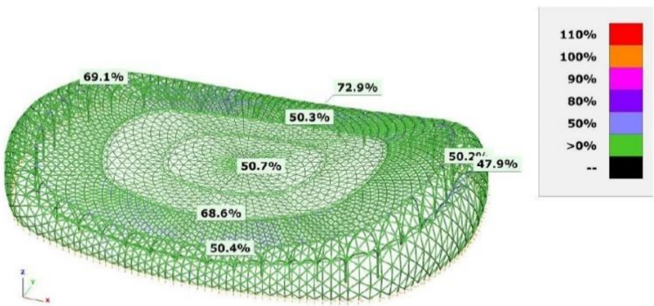

Figure 14. Utilization of resistances of the structure selected in ten groups of sections according to EN 1993-1-1 [12, 13]

4.4. Global stability analysis

The global stability analysis begins with determining the elastic stability loss ways. Typical elastic global buckling modes and critical load multipliers of the structure are shown in Fig. 15. According to the stability loss modes and the critical load multipliers the consequences are the followings:

- the value of the first critical load multiplier (α_{cr}=1.61) is too low
- the buckling shape fluctuates along two concentric rings.

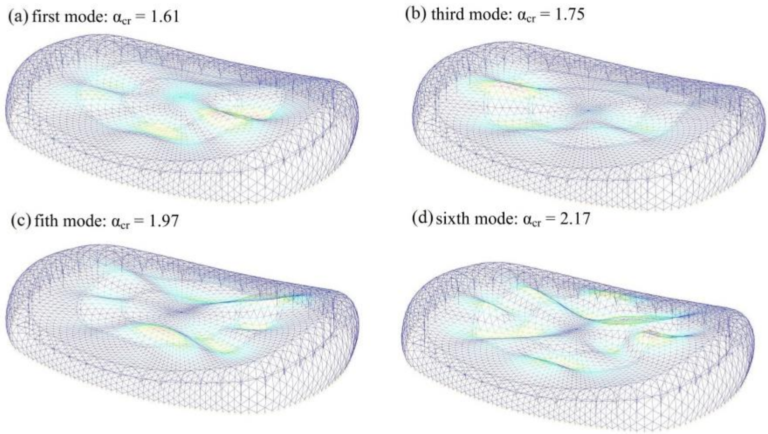

Figure 15. Typical modes of global stability loss and critical load multipliers of the structure [12]

The previous consequences are lead to the modification of the structure: the first critical load multiplier is increasable by placing a spatial truss as a stiffener beam along the two rings. This stiffener truss can block the fluctuant buckling modes. The stiffeners can be configured expediently as a triangular spatial truss. The truss itself consists of an isosceles triangle's sides, a flange which connects the isosceles triangles, and stiffener bars on the sides of the triangle truss (Fig.16.).

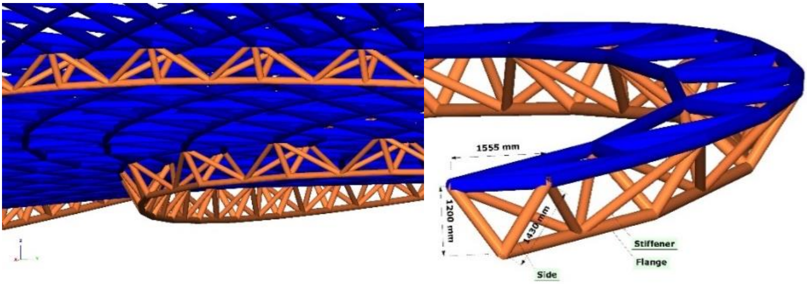

Figure 16. The performance of one triangular spatial truss [12]

The triangle's three different heights were examined: a height of 900 mm, 1200 mm and 1500 mm, in order to find an optimal α_{cr} value by iteration. It should be mentioned, that here the parametric design was an effective tool to vary the dimensions of the triangles. The variations were exported from Rhinoceros in .dxf format and directly imported to ConSteel, where the analysis was performed. The effect of the height of these triangles on α_{cr} value can be seen in Fig. 17.

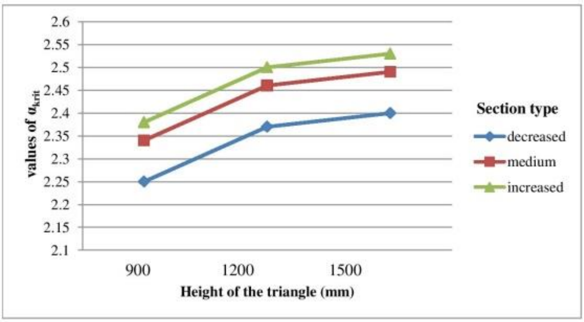

Figure 17. The effect of the height of the stiffener on critical load multiplier

The regulation EN 1993-1-1 [12] of overall imperfection method of compressed bars was used to accomplish the global stability analysis. According to the regulation the first buckling shape may be placed onto the initial perfect structural geometry (Fig. 18) with initial amplitude ($L_0/150 \cong 73$ mm) defined in favour of safety.

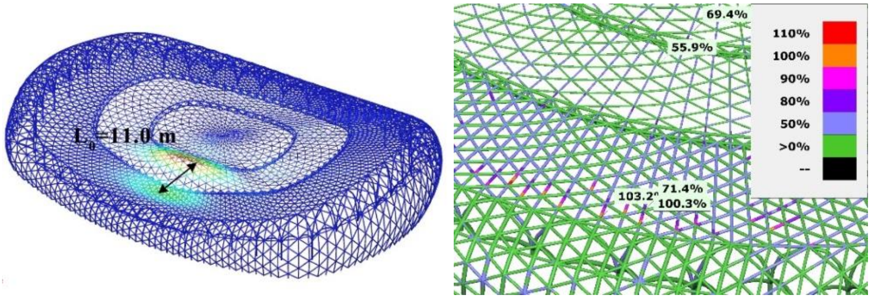

Figure 18. (i) First mode of global stability loss of the modified structure (stiffener rings) (α_{cr}=2.50), (ii) Results of the global stability analysis [12]

The dynamic behaviour of the structure is well defined by the self-oscillation's number. On Fig. 19 the first and the fourth mode of self-oscillations is shown. The lowest value of self-oscillation is 0.848 which value is high enough to preclude the excitation of the structure caused by repeating blows [19]. Irrespective of this conclusion a more precise dynamical calculation is needed by virtue of detailed analysis and designing.

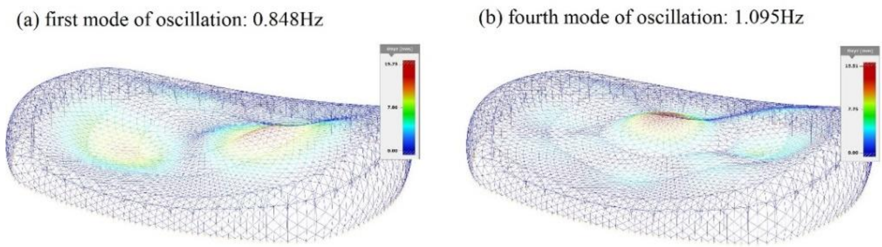

Figure 19. Modes of global self-oscillations [12]

4.5. Conceptual design of joints

As a part of the structural concept the designing of one type of joint was proposed. The selection of the joint was based on the fact which type is the commonest in the contsrtuction. Thus the chosen joint is a general intermediate joint, in which 6 beams are connected. The proportion of this kind of joint is about 80% of the construction's joints. From among these joints the most stressed had been chosen to design.

The general intermediate surface joint consist of a central joint (central element + 6 beam ends) and 6 constructional beams. Economically the most advatageous if the beams are connected to each other with clear interaction. Thus in this case every second beam is connected to the central element with clear interaction. Thereafter the remained 3 beams only could be connected with 3-3 interactions (1 with the central element, 1-1 with the adjacent beams). The connection between the incoming beams and the central element is welded. Yet the constructional beams are connected with the obtained central joint with bolted connections. To increase the flexural rigidity and to avoid the local yieldings, cross-shaped stiffeners are welded into the headplates of the connecting constructional beams.

To model the joints a model-based on finite element method, finite strip method and shell element was used. To reduce the complexity of the model the component method was used for determining the strains of the joint elements. The 3D geometry of the joint was came from the parametric model. The input data used for modeling the joints were also parametrized. A linearly elastic and perfectly plastic material model was used to accomplish the examinations. The most important input parameters were the material behavior and the properties of the connecting elements (bolts and welds). The bolted connections were replaced by springs connected in sequence. Bolts work for tensile and shear forces, while the welded contacts transmit only compression. In case of the joints' calculation their effect for the global structural behaviour have to be examined continuously. In Fig. 20 the finite element model of the central joint is shown.

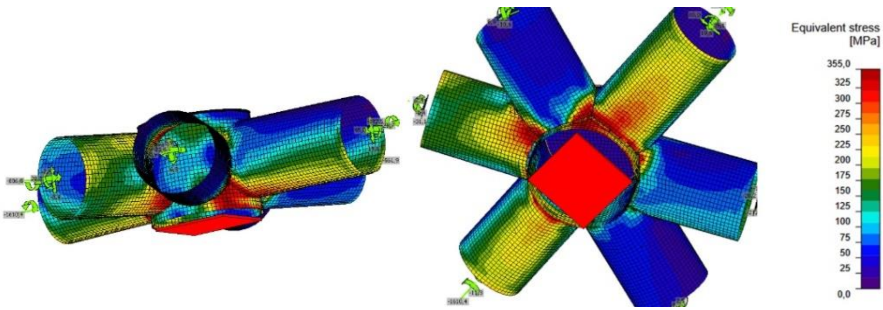

Figure 20. Equivalent stress of central joint [14]

5. Interoperability of the used architectural and structural design software

The modelling of the main form (including the structural elements and the grid) was performed in Rhinoceros 3D [7] using the Grasshopper [8] module for parametric design. For the conceptual structural design the ConSteel software [12] was used, while for design of the joints the IDEA StatiCa software was applied [14]. The model was exported in .dxf format from Rhinoceros, which is found to be an efficient method for further processing of the model. The applied software aided design method also enabled the 3D print of the structure in a scale of 1:200. The model was exported from the Rhinoceros 3D in .stl format and after checking the model adequacy, it was printed with the technology of Selective Laser Sintering (SLS). (Fig. 21)

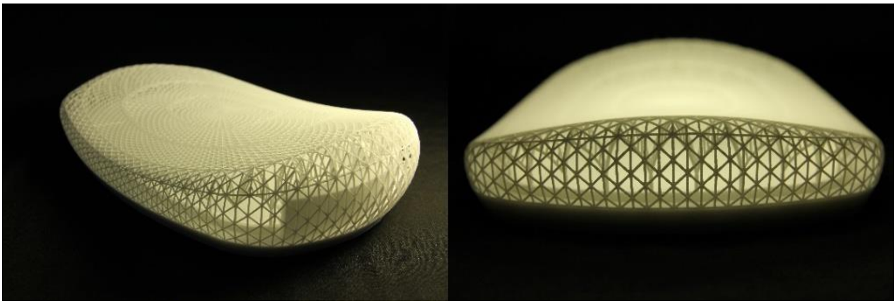

Figure 21. 3D printed model of the structure

Conclusions

With this case study the authors would like to demonstrate the advantages of the use of parametric design method in architectural and structural design projects. This method was an effective tool during the whole design process. It enabled to try different forms of the building, to vary the main dimensions of the final form in order to reach the optimal solution both functionally and architecturally. It was also used to generate and analyse different grid variations. Furthermore, the modification needed based on the structural analysis was made easier by this method. The communication between the software used was mostly quick and appropriate. As a consequence, in the course of the cooperation with structural designer the parametric design method can be a powerful tool, which made it possible to handle the effect of structural behaviour of the building on the architectural design.

References

[1] F. R. Khan, Structural aesthetics in architecture and its social and technological relevance, IABSE Congress Report Vol. 11, 1980.

[2] PriceWaterhouseCoopers, Budapest 2024: Summer Olympic and Paralympic Games – Feasibility Study, Budapest, (2015) [cited 2016-02-26] URL http://olimpia.hu/images/bp2024/PwC_Olimpiai%20Megvalosithatosagi%20tanulmany_2015_junius_vegleges.pdf, in Hungarian.

[3] Ernst Neufert, Peter Neufert: Architects' Data, 4th Edition, Wiley-Blackwell, 2012.

[4] Fédération Equestre Internationale, Dressage Rules, 25th edition, effective 1st January 2014, Including updates effective 1st January 2015, (2015) [cited 2016-03-30]. URL https://inside.fei.org/sites/default/files/DRE-Rules_2016_GA-approved_mark-up.pdf

[5] Fédération Equestre Internationale, Jumping Rules, 25th edition, 1 January 2014, Updates effective 1 January 2016, (2016) [cited 2016-03-30]. URL https://inside.fei.org/sites/default/files/JumpRules_25thEd_modifs-2016_approved_2015GA_mark-up.pdf

[6] Javier Monedero: Parametric design: a review and some experiences, Automation in Construction 9, (2000) pp. 369-377.

[7] Robert McNeel & Associates, Rhinceros 3D, [cited 2016-03-30]. URL https://www.rhino3d.com/

[8] S. Davidson, Grasshopper – Algorithmic Modeling for Rhino, [cited 2016-03-30]. URL http://www.grasshopper3d.com/

[9] G. Kiss, Integrated numerical design methods for designing of „free-form" buildings, Diploma thesis, Budapest University of Technology and Economics, Department of Structural Engineering, Budapest, 2016, in Hungarian.

[10] H. Schober, Freeform Glass Structures, (2006) [cited 2016-12-10]. URL http://www.formpig.com/pdf/formpig_freeform%20glass%20structures_schober.pdf

[11] L. Mészáros, Large-spain roof structures – steel dome structures, Magész Acélszerkezetek, 7 (2) (2010) pp. 46-51, in Hungarian.

[12] ConSteel Advanced Building Analysis Solution for Structural Engineers, ConSteel Soltutions Ltd., URL www.consteelsoftware.com

[13] MSZ EN 1993-1-1:2005/A1:2015, Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings

[14] IDEA StatiCa 2009-2018, [cited 2016-03-30]. URL https://www.ideastatica.com/steel/