Challenges in structural designing of egg-shaped steel structure

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Challenges in structural designing of egg-shaped steel structure

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Abstract

This paper presents the evolution and challenges of structural designing of a highly unusual three-storey steel structure. The construction will operate as an office building, having an egg-shaped form and it will tower in between the existing reconverted single-storey buildings. In addition, includes the structural design of the additional necessary objects for reconversion process, such as skylights and connecting greenhouse. The article provides detailed examples, methods and results of structural design, accomplishing the challenges of multi-criteria decision making through structural efficiency, building implementation, environmental issues and project costs.

Keywords: multi storey steel structure, steel detailing, joint design, buckling analysis

1 Introduction

In Romania, many of the buildings have reached the service life stage, when retrofit is unavoidable. The majority of old buildings are not part of a maintenance program; therefore, their level of degradation is quite high. Usually, unused industrial spaces are demolished, creating a significant amount of environmentally harmful construction debris. Reason why a mixed reconversion solution was applied in the case of our project: the middle concrete tower was demolished and the two remaining longitudinal concrete halls, having 105 m length each, were refurbished and reconverted to office buildings.

The architectural design process started in March 2015, however numerous cladding and partitioning details were modified during the structural detailing and erection work. These changes presented an additional challenge, also provided significant time pressure for the design team. The structural design process of the structure started in June 2015 and was completed in November 2015 (see evolution on Fig. 1).

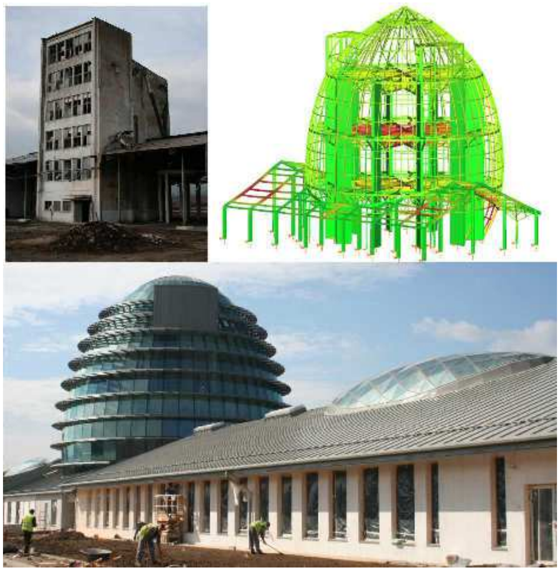

Fig. 1: Structural walkthrough

The client's main requirements were the followings:
- achieving the required egg-shape of the three storey office building (hereinafter C1) at a sophisticated level, from both structural and architectural perspective;
- to establish an interior space, rich in natural light, which initial destination was agricultural building with no requirement of natural light;
- to retain and refurbish the original prefabricated concrete structure (hereinafter C2 and C3) in order to maximize the usable office area.

Under these conditions, the design team had the following main requirements:
- full design of C1 building, which provides the gorgeous esthetical view of the whole facility;
- to bring natural light, placing skylights on the roof of C2 and C3 buildings;
- to join the non-conventional form of C1 new building with the existing C2 and C3 buildings, breaking straight lines and following the architectural conception with curved surfaces.

The article describes the applied structural solutions, the detailing procedure of the nonconventional joints and presents the erection process of the steel structure. Furthermore, discusses some environmental and cost issues of the project.

2 Building description

2.1 Architectural facts

Transavia, the client's company, is one of Romania's leader in preparation and processing of poultry meat. The company celebrates 25 years in 2016, hence the initiative to develop an ultramodern administrative headquarter. The project consists in functional reconversion of a set of existing agricultural buildings, which included a mill unit, a grain sorting station and two grain storage halls. As conceptual level, the ovoid shape of C1 (Fig. 2) links to the essential business premises with poultry. The 'egg' symbol is definitely the starting point, the genesis for any living being. Furthermore, this design is the perfect solution to interconnect the two existing buildings.

The cumulative area of C1 is 1350 m^2, while C2 and C3 are 2050 m^2 each.

Figure 2. Architectural rendered view

2.2 Design loads of the structure

In order to evaluate the structural response, in the design process were considered the following loads (characteristic values):
- Curtain walls (security glass) self-weight: q_k = 0,65 kN/m^2;
- Composite slab dead load: q_k = 4 kN/m^2;
- Composite slab live load: q_l = 4 kN/m^2;
- Partition walls dead load: q_k = 5 kN/ml;
- Technological load on the roof of technical spaces: q_t = 1,5 kN/m^2;
- Temperature variation effects between interior (18 degrees) and outer surface (40 degrees during summer days) on the skylights;
- Snow loads with corresponding roof shape coefficients according to CR 1-1-3-2012 [1] (EN1991-1-3), $s_{0,k}$ =1,5 kN/m^2;
- Wind loads on building envelope according to CR 1-1-4-2012 [2] (EN1991-1-4), $v_{b,o}$=27 m/s, q_{ref} = 0,4 kN/m^2, calculated with Reynolds number;
- Seismic action according to P100-2013 [3] (EN1998-1), with peak ground acceleration a_g=0,10g, control period of seismic motion Tc=0,7 sec and behavior factor q=2;
– Load combination for ultimate limit state (ULS) and serviceability limit state (SLS) according to CR-0-2005 [4] (EN 1990).

2.3 Structural solution and conceptual design of steel structure

2.3.1 C1 building

The major issue regarding the structural configuration of C1 was to maintain the initial ovoid shape with the adequate structural rigidity

(Fig. 3). To address this issue, building information modelling (BIM) was used with continuous consultation with the steel manufacturer and architectural team in order to obtain the best solution both structural and execution point of view. Selection of the most appropriate structural solution has been driven by a number of factors including the span, building geometry, load to be carried, aesthetics and the use of sustainable construction materials.

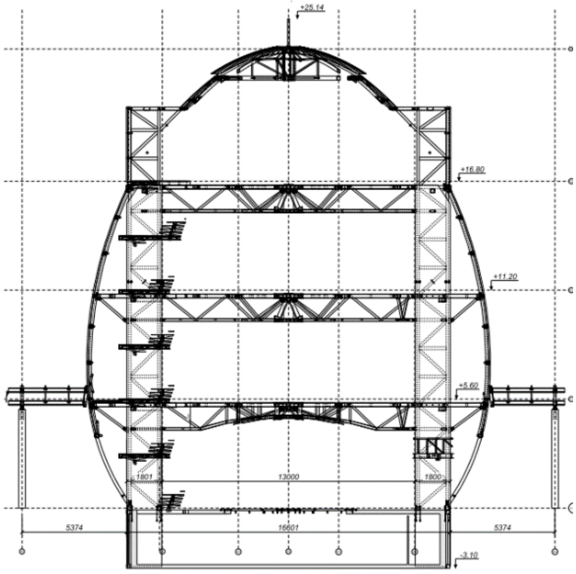

Figure 3. Transverse section through C1

The C1 static scheme's main concept features 10 radially positioned RHS truss columns whit a height of 16,6 m each, between these being positioned the composite RHS truss girders with a span of 13 m. The columns are fixed through anchor rods in the diaphragms of the basement, and are embedded in on-site poured reinforced concrete (180 cm x 30 cm final dimensions) to increase their stiffness and fire resistance. For the composite interaction between steel and concrete, welded shear studs have been used on the floor beams, which are simply supported through pin-ended joints using D45 mm round bars. On the junction of the truss girders a massive connection joint has been designed using a CHS508*12 mm middle pipe. To increase the global rigidity of the structure, respectively to provide support for the composite floor, HEA truss beams were positioned radially between the columns.

The selection of the curtain wall bearing structure (structural ribs) had to address the previously mentioned aesthetical issue. RHS160x80x5 profile has been used, although the initially required welded segmentation of the structural ribs would have resulted in a disadvantageous look. Ultimately, the ribs were curved/rolled in Poland, as the expenses would have been too high in Romania. Since the utilization of wind bracings was forbidden on the ground-, 1st- and 2nd floors, horizontal circular pipes were placed to link and stabilizing the structural ribs at every 1,80 m.

To create a completely column free interior space on the 3rd floor, a self-supporting dome structure was provided. The upper end of the structural ribs is pinned with a bolt connection to a circular horizontal truss beam system, which forms the top of the dome. To provide lateral stability, rigidly connected wind bracing system was used (Fig. 4). Due to the limited space between the ribs, on-site welding was necessary to position the bracings. The structural steel with S235 steel grade (f_y=235 N/mm^2) was used.

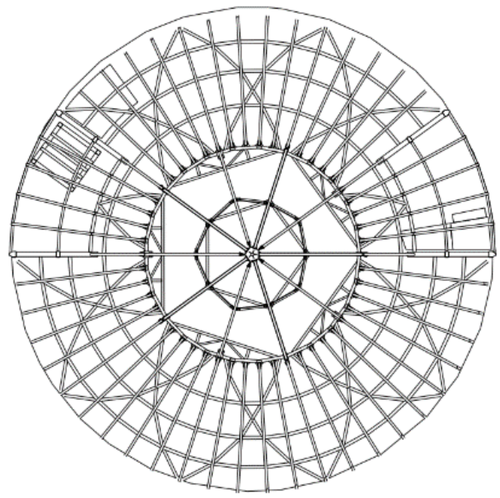

Figure 4. Wind bracing system of C1

Since the diameter of the cross section of C1 is continuously decreasing towards the top of the building, the staircase and the lift's punching the 3rd floor glazing surface, by forming two symmetric trapezoidal segments.

The lift's main structure is designed as an individual one, and it is formed by four square hollow sections (SHS 140x8), which are connected and stiffened by horizontal beams.

2.3.2 Connection greenhouse

To link C1 with C2 and C3, an independent connecting structure has been designed. The major issue in the case of the greenhouse's structure was the limited interior space which excluded the possibility of an ordinary steel or concrete column in the lobby. Hence a tree inspired steel space column has been designed in order to withstand the accumulated snow load on the roof (Fig. 5).

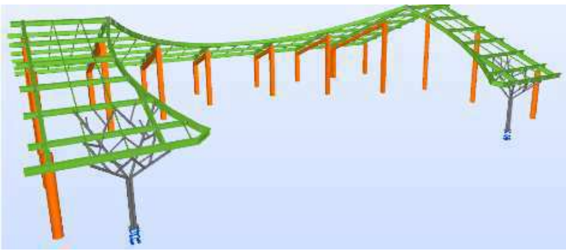

Fig. 5: Connecting building

The cladding of this building is the similar curtain wall detail as in the case of C1 in the front half, at the back half folded steel sheeting is used because of the increased technological loads (150 kg/m^2). Furthermore, the roof's shape constantly follows the outlines of C1, which needed a curved perimeter beam. IPE270 was used as primary and curved beam, respectively secondary IPE220 beams provided for the support of the curtain walls.

2.3.3 Skylight

The skylights positioned on the middle of C2' and C3's roofs convey the image of a precious diamond jewelry and interconnects the ovoid shape of C1 to the existing buildings. Shaped like turtle shells, these objects ensure the required aesthetical view and the necessary glass surface to bring natural light for the access and office area. On the other hand, this conceptual design avoids the collision with longitudinal purlins, positioned at the ridge of the roof (Fig. 6) and ensures an elegant support without damaging the integrity of the existing concrete structure. The supporting details realized through handcuff-like rod systems secure the necessary assembly tolerances (imperfections in concrete elements were in the means of centimeters) and assured a quick and easy installation. The assembling process of the structure which included the glass supporting rib system (RHS 80x60x4 welded with CHS48.3x3.2) and the perimeter caisson beams (two IPE270 welded profiles) with a total size of 7.5x15 m, was made by welding under factory conditions. Ultimately, the transport and on-site mounting was conducted as one completely independent element. Figure 6 shows the act of placing the elliptical skylight on the existing structure.

Fig. 6: Skylight BIM and erection

The design of the steel structure was performed following the European standards. For strength, stability and stiffness requirements of the structural elements the prescription of SR-EN1992-1-1 [5], EN1993-1-1 [6], SR-EN1993-1-8 [7], Cidect manuals [8], and P100/2013 [3] were used. For the design of the structural elements, linear elastic structural analysis was performed. The design checks of the structural elements for ULS include persistent or transient design situations (fundamental combinations), where snow loads in combination with live loads play the key role. Also, as the results of seismic analysis, additional stiffener truss beams were positioned between the concrete columns.

For global stability checks Consteel V9 [9] software was used, which calculation procedure is based on the general method of EN1993-1-1 [6]. For individual member checks, both method A and B of EN1993-1-1 [6] was also performed.

3 Particular problems in the design process

Due to the non-conventional shape of the building and the intersection with the greenhouse, completely unique joint details resulted. The main challenges in the detailing process were the configuration of connection of radial elements and to include the curved staircase in the existing limits. With the help of BIM, then design team was able to devise the erection phases of the steel structure, also to observe and prevent the possible clash problems which would cause delay later in the erection process.

During the design process a list of problems and constrains had to be handled, like:
- the central joining of 10 radial truss beams;
- the configuration of the intersection of ribs with the perimeter and floor beams on each level;
- the round connection of ribs on the top of the dome structure on the 3rd floor;
- the elimination of ribs at the intersection of the gangway in the ground floor;
- the intersection of the connection greenhouse with building C1;
- the substitution of a regular column with a tree inspired column which helps the structure to sustain the snow pocket on the greenhouse roof;
- the binding of the staircase landings to the structure and the curved radial ramp configuration.

3.1 Central connection of radial floor beams

The radial arrangement of columns required the conceiving of a central detail, which allows the joining of the 10 beams competing in the center of the circular floor (Fig. 7). The core of the central assembly is a 508 x 12 mm circular pipe with a height of 1400 mm, which interconnects two discs at extremities and 2 intermediate rings, while gusset plates are radially welded between the discs and rings. In order to provide a continuous detail of the upper (2 x UPN200) and lower (2 x UPN140) chords, each profiles flanges and webs are bolted with M16 and M20 bolts (10.9 grade). The lower disk is subjected to tension from the action of lower chords, respectively the upper disc is subjected to compression, and it is stabilized by the presence of concrete floor. The connections subassemblies were sized to resist the efforts resulted from second order elastic global analysis.

Fig. 7: Central floor detail

The resulted connection has been designed in a way to facilitate the required structural integrity and rigidity of the floor which was essential in the progress of maintaining the fundamental vibration period over the critical limit of 5 Hz.

3.2 The round connection of ribs on the top of the dome structure on the 3rd floor

The stereotomy of 50 radially positioned ribs which shape the building C1, geometrically intersect at the top of the egg (Fig. 8). To ensure the physically needed space for the connections, it was necessary to keep just those main ribs which were positioned right next to the pillars (10 in total), meanwhile the remaining 40 ribs connection had to be cut and ensured. The configuration of ending subassemblies resulted in ten trussed hemispheres, which connected in a bolted central pentagon through the means of end plates.

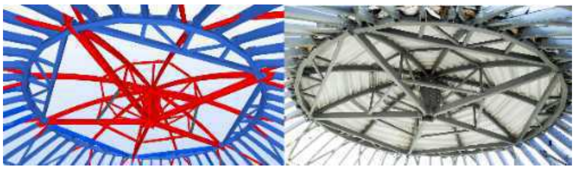

Fig. 8 Rib connections at the top of C1

On the other hand, the remaining interrupted ribs also form a larger pentagonal shape, by defining a horizontal truss system, which provides the required diaphragm effect. This horizontal trussed pentagon also means the disruption of the glazing surface, starting from this point trapezoidal sheeting, rigid insulation board and seamed flat sheeting has been used for the sealing of the roof.

3.3 Connection between the steel and concrete structure

Since the composite truss beam provides support for the concrete floor just until the pinned joints on the column's face, the support of the additional distance until the margin of the floor was obtained with the help of a 3,4 m cantilever fixed on both sides of the column (Fig. 9).

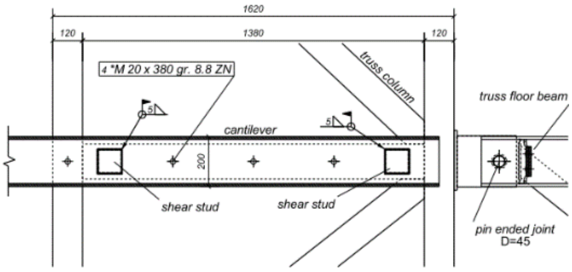

Fig. 9 Shear stud connection of cantilever

Considering the fact that the columns were embedded in concrete just after the erection of the steel elements of the floor structure, the 2 x UPN200 cantilevers were bolted to the trussed column using 4 x M20 threaded rods. In order to prevent the punching of the concrete and to resist the vertical shear force, an additional shear stud was used in the connection: the cantilevers were disposed with two mounting holes, and fixed to the studs of the column with on-site welding. The same detail was used in the case of landing connections of the staircase.

3.4 Tree inspired column

As a result of the height difference between C1 and the greenhouse (16,5 m), there is a significant snow pocket which leads an increased load next to the already high permanent and technological loads acting on the roof.

Due to architectural requirements, a regular steel or reinforced concrete column was excluded in the front part of the greenhouse, leaving a span of 4,5 m without support. A tree inspired polygonal column has been configured to overcome these disadvantages, which is convenient both structurally and aesthetically (Fig. 10). The so-called tree (umbel) column is subjected to compression, the fundamental thinking behind this structural system is to direct a group of distributed point loads to one point and from there transmit the total load via a single member to a support point, the point of application of the reaction force providing total equilibrium [10].

The column base is fixed through anchor rods in an independent foundation. Four subassemblies form the main branches of the column, using CHS 101x6 profiles. To provide necessary support for the welding of the elements, interior pipes with smaller diameter has been used at the shape interruptions. The secondary branches (CHS 89x5) were connected using on-site welding. In the interest of a seamless erection, pinned connections to the roof has been designed, using one M24 or M20 8.8 grade bolt with double shear plates.

Fig. 10 Steel tree

The intersection points of the circular hollow pipes resulted in irregular shaped cross sections, therefore single part drawings with wrap around details were provided to the steel manufacturer.

3.5 Global stability checks of the structure

The global stability checks of the structure was performed using Consteel software [9]. To have an overview about the global behavior of the structure, building C1 was calculated and checked using the full 3D model of the structure, including also the concrete columns. According to the buckling analysis, a critical load multiplication factor of α_{cr} =8.63 was computed for the truss composite beam under the action of permanent and live loads. The truss columns (in erection phase) presented a result of α_{cr} =3.21, the ribs α_{cr} =11.47, while the skylight's high rigidity (Fig. 11 a) assured a critical load multiplication factor of α_{cr} =29.62.

The seismic analysis resulted a 1^{st} vibration mode at a frequency of 0.97 Hz with a torsional response from the structure (Fig. 11 b).

Fig. 11 Global analysis results

4 Erection process and follow up

Due to a very tight deadline, the erection and designing proceeded nearly side by side. In the first step, the truss columns were positioned, followed by the first, second and third floor. The assembling of the intermediate floors was done on the ground: the truss beams were connected to the central joint then lifted to position by an 80 tonne capacity crane. Due to the expensive transportation of the ribs (total length of 22.5 m), the elements where cut in the shop into two pieces, then erected as the following third step. Because of the limited available space, the concrete works have been started gradually: parallel with the positioning of the ribs, the columns were poured starting from the ground with stops at each floor, where the composite slab works have been done. For all these intermediate phases, the position of the ribs was continuously checked (Fig. 12). Also, another important component of the whole process was the site follow up: during the execution process, each connection detail was carefully checked. Once the structure was erected, all other speciality works were possible to perform.

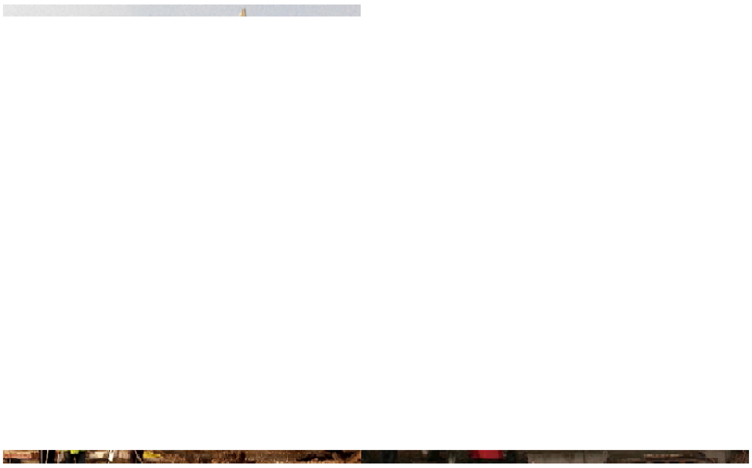

Fig. 12 Erection phases of C1

5 Environmental issues and sustainability costs

The successful reconversion of an existing building is something to be celebrated. The example presented here creates an ultramodern office facility with a total estimated cost of 5,5 million euro, by transforming two unused, old agricultural halls without demolition. In this way, roughly 2050 tonne (855 m^3) of construction waste was prevented from environmental pollution and additional 300,000 Euro cost savings was achieved, keeping the old concrete structure and foundations instead of build a new one. Furthermore, the use of steel for additional constructional objects (such as C1 structure, skylights and greenhouse) provides a long-lasting solution which is almost 100 percent recyclable.

As an unfavourable factor, the glazing surface of C1 causes an excessive energy cost to provide the necessary cooling and heating: the ventilation requirements of the 3^{rd} floor, has a total energy consume as the ground-, first and second floor together. In order to improve the efficiency of the ventilation costs, a system of sunshades was provided on the entire perimeter and height of the glass façade. These sunshades also ensure the possibility of cleaning and maintenance of the glass façade.

As a positive fact, the new reconverted facility transforms not only the old building, but the previously unfriendly industrial platform into an attractive working place for the employees. Additionally, the rural landscape gets new opportunities and opens new development possibilities.

6 Discussion and conclusions

This paper presents a number of issues regarding the design and execution process of a highly unusual egg-shaped structure, which represented the main extension work to a reconversion process of an old agricultural building into an ultramodern office facility, highlighting the most significant particularities that characterize this work.

Each reconversion project is unique. The experience accumulated with this project, especially relating the structural solutions, cannot be transferred and applied directly to another building, due to some specific details which are deriving from particular architecture, applicable only in case of this building. It seems though, that the mixing of reconversion works with new-build building presents a number of advantages relating to choice of materials or construction methods and technologies.

Designing the ovoid shaped central building covered entirely in glass, the 13 m free span of the floor with ten radial truss beams intersecting in the centre, the configuration of 16 meter opening dome structure formed exclusively by structural ribs, or the skylights that transmit the image of a precious diamond jewellery shaped like turtle shells were only some of the challenges encountered during the design process. The above mentioned issues were addressed and handled with creative and innovative solutions by the project team, formed of architects and engineers. The authors successfully applied a set of particular structural solutions regarding unusual situations, demonstrated by complex structural calculations and modelling. These solutions were applied on-site in the manner described in the paper.

This work is another example of the holistic role that must be faced and assumed by structural design engineers in today's changing world. It highlights the fusion of different specialties, when it is required to exceed the designer's limits. Besides the professional satisfaction, it was also a good opportunity to share knowledge, to build interpersonal relationships with wonderful people, as well as to show the power of creativity brought by the collaboration between architects and engineers.

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