Centrum Rzeczoznawstwa Budowlanego

Open Access Journal
Modern Engineering 2 (2020) 50-61
journal homepage: https://mengineering.eu

MODERN ENGINEERING

Performance-based Design and Construction of the "World Class" Gym in Minsk using Innovative Structural Solutions

Andrei V. TUR[1], Viktar V. TUR*[1,2], and Tsimafei A. TSYMBAREVICH[3]

[1]Department of Building Structures, Brest State Technical University, Belarus
[2]Bialystok University of Technology, Białystok, Poland
[3]Deputy Director for Design AZSINDUSTRIYA LTD, Belarus

Abstract

The article presents the result of the implementation of innovative design solutions techniques during the construction of the building of the "WORLD CLASS" Fitness Club in Minsk with usage of the performance-based approach. Proposed design solution of building include the composite structures (plane frames consists of steel-concrete columns and delta-beam), prestressed hollow core slabs. The cantilever parts of the building were designed as a complex post-tensioned monolitic structure, including cantilever beams and slabs with a maximum length of 12 m, monolitic walls and pylons. The example of performance criteria verification (structural serviceability) with usage different methods presents.

Keywords: performance-based design, post-tension, composite structures, cantilever beam.

1 Introduction

Currently, in the world practice of designing and constructing of the structural systems buildings, more and more diverse and complex structural solutions are used, as well as an innovative materials themselves. Such innovative solutions often come into conflict with applicable codes and standard, which based on prescriptive design criteria. Unlike most current building codes and standards, which have use prescriptive (or compliance) criteria, in recent years, there has been strong interest worldwide in developing codes and regulations that are more performance-based. According to [2] a prescriptive approach describes an acceptable solution while a performance approach describes the required performance. Traditional prescriptive criteria are straightforward for a builder or designer to follow, easy for a third party to check, and relatively easy for building regulators to enforce. It should be pointed that there are some fundamental difficulties associated with the use of prescriptive criteria in case of innovative solution and these problems have increased the interest in development of performance-based codes and standards [2]. Among them, the most serious problem with prescriptive approach is that it serves as a barrier to innovation. For example, improved and/or cheaper products may be developed by prescriptive codes and standards [2]. Another problem with prescriptive approach is that it makes it very difficult to cost-optimize building construction. The third problem is related to international trade in building products. If two trading countries each use their own prescriptive criteria, it is often difficult to establish the equivalence between the two set, of criteria and to show that one country's accepted solution would equal the implead performance level required in the other country (mainly, for innovative materials and structural solutions). According to ISO 6241-1984 [5] performance is defined as "behaviour of product related to use". Here, the product might mean an entire building as well as a part of it. Preiser et al. [7] suggest that the concept of performance in buildings was developed by Eberhard [1] in the 1960s, and was first introduced into the profession of architecture at the end of 1970s. The report titled "Performance-Based Study of Buildings" prepared for CIB provides the most basic definition of performance-based approach as follows: "The performance approach is, first and foremost, the practice of thinking and working in terms of end rather than the means. It is concerned with that a building or building product is required to do, and not prescribing how it is to be constructed" [4]. As was shown in [8] this definition is the very first and the most basic definition of the performance-based approach to buildings and main its validity, as it is still being used in many resent studies. As a basic example of the performance-based approach,

*Corresponding author: E-mail address: profturvic@gmail.com (Viktar V. TUR)

Received 04 March 2020
Available online 15 June 2020
ISSN 2450-5501
Published by Centrum Rzeczoznawstwa Budowlanego

the first record that mentioned building performance was made in the Code of Laws up by King Hammurabi (Article 229: “The builder has built a house for a man and his work is not strong and if the house he has built falls and kill a house holder, that builder shall be slain”).

In this article nothing about construction technique, materials, thickness, size, etc., but clearly states that the building is expected to provide the desired performance. As was shown in [6], most design briefs agreed between building owners/clients and designers are a mixture of prescriptive and performance specification (see Figure 1). A lower-level specification is more prescriptive and constraining. But the higher the level of specification in term of performance, the more difficult it is to find a universally accepted method for the verification of performance [8].

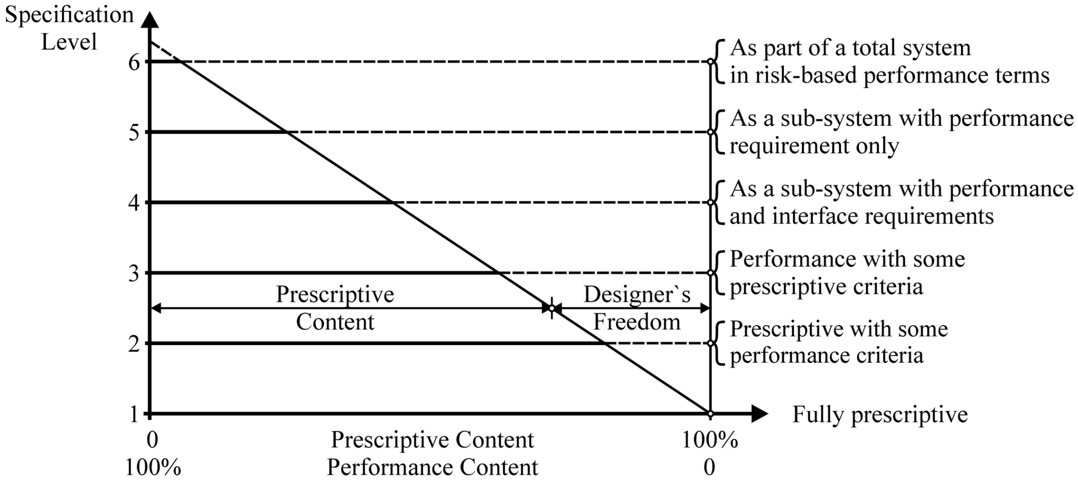

Figure 1. Level of specification with a different performance-prescriptive mixes [6]

2 Description of the structural system and their performance indicators

The design solution of the building was formed based on the assignment of the customer (performance requirements). The following tasks were set:

- fullycomply with the solutions of the exterior design;
- minimize construction time;
- optimize and minimize the cost of construction (cost-optimization);
- ensure maximum quality of the finished property.

For each of the listed items, appropriate measures were identified to solve the tasks. The maximum compliance with the performance requirements of the exterior design project was carried out using the BIM-design technology. Reduction of terms was achieved by dividing the building into the maximum number of independent sections(sub-structures) for construction (see Figure 2). As it can be seen from Figure 2, the building is divided into 4 sections (sub-structures): *section 1*– a swimming pool zone of 900 sq. m.; *section 2, 3* - cantilever sections of 400 sq. m.; *section 4* - a training zone of 1700 sq. m., made in an A-kit from VDS.

The design solution of *section 1* (Figure 3) includes a monolithic technical floor under a swimming pool, a monolithic slab and a pool bowl, steel trusses of the Molodechno type, supported by monolithic columns in fixed steel formwork. Enclosing structures - reinforced concrete panels with clinker tiles. The height of the floor to the bottom of the trusses is 6 m with a span of 25 m.

Sections 2, 3 (Figure 4) – monolithic post-tensioned concrete cantilever sections. The height of the console from the top of the foundation edge to the top of the second floor on the console is 5.9 meters. The maximum length of the console is 12 meters.

Section 4 (Figure 5) is made in the VDS A-kit using steel-concrete composite structures of columns, delta beams and a hollow-core prestressed slab of 220 mm. The columns spacing is 8x8 meters, the floor thickness is 320 mm, the height of the first floor is 6 meters and the height of the second floor is variable - from 3 to 6 meters.

Figure 2. Dividing a building into sections

The most labor-intensive sections were *sections 1* of the pool zone and *sections 2, 3* of consoles with a total labor intensity of 16,000 man*h. and a total area of 1300 square meters. In comparison with an area of 1700 square meters of section 4 and total labor intensity of 1000 man*h.

Section 4 was built in parallel with technological breaks in the construction of *sections 1, 2, 3.* As a result, the total construction period of the building was 3 months. Of these, *section 1* - 0.5 months; *sections 2, 3* - 2.5 months; *section 4* - 3 weeks.

When determining the cost of the building, three variants of the design solution were calculated: a steel frame with hinged panels, a monolithic version with small-sized filling and an implemented version. The steel frame has a high metal consumption of 100 kg/m. sq. when performing building with cantilever sections; the need for fire protection of metal structures - all of the above led to a 25% increase in price relative to the implemented option. The monolithic variant due to the wide column spacing, complex architecture and high floors required complex formwork and large labor costs. Therefore, at a comparable cost, the construction period exceeded two times the realized option. The total cost of the monolithic version is 5-10% higher than the realized one.

Figure 3. Section 1 – A swimming pool zone

The quality of reinforced concrete panels is very high; the front surface has high aesthetic characteristics. In addition, hidden connection nodes have improved the appearance of structures. VDS metal structures developed using Tekla-based BIM technology and manufactured on CNC-controlled machines made it possible to assemble metal structures of machine-building precision.

Figure 4. Sections 2, 3 – Post-tensioned monolitic cantilever sections

Figure 5. Section 4 – Composite steel-concrete structure

3 The use of BIM in the design and construction of the "WORLD CLASS" GYM

Six design teams participated in the development of the design solutions (design team of VDS; general designer consisting of the chief architect and engineering sections; development team A-kit from VDS; factory manufacturing panels; metalwork factory VDS; cantilever sections design and scientific support of the project were released by Brest State Technical University. It was required to communicate with each other with minimal errors and high speed. To accomplish such a task without completing a project without BIM technology is a difficult task. If we take into account the complexity of the geometry and the maximum geometric uniqueness of all structural elements, this task is not possible without BIM. To maximize the design-project, all work on the framework of the above teams carried out with the continue monitoring of architects in Revit and 3Dmax, which means that the models in Tekla, Revit and 3Dmax constantly checked for compliance (Figure 6).

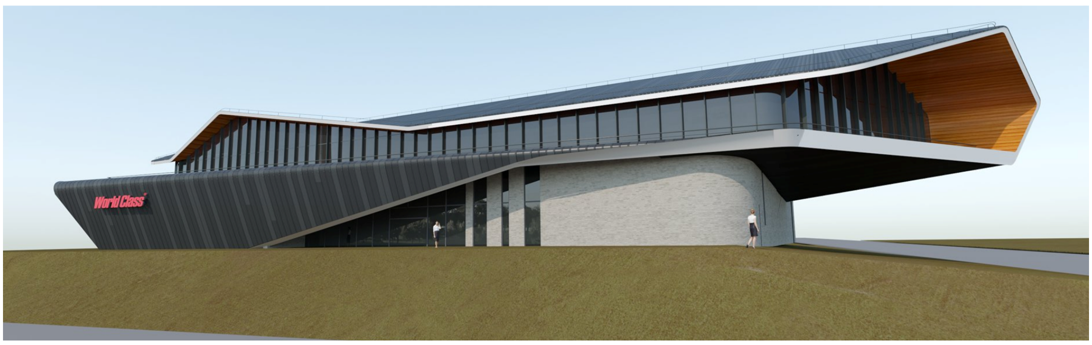

Figure 6. General view (3DMAX)

The use of BIM technology not only reduced labor costs for the development of the project, but also at the construction site there were no stops due to poor design decisions or errors in the project. That is, not only increased the speed of design and increased the manageability of the project with a large number of participants, but also the risks of making mistakes in the project reduced to zero.

4 Performance-based regulatory framework

Most performance-based regulatory frameworks used in analysed object are variations of what is known as NFLS-(Nordic Five Level System) [3]. In this system:

Level 1: (GOAL) addresses the essential interests of the community at large and/or the needs of the user-consumer.

Level 2: (Functional Requirement) addresses one specific aspect of the building element to achieve the stated goal;

Level 3: (Operative or performance requirements) specifies the actual requirements to be satisfied;

Level 4: (Verification) and *Level 5* (Examples of acceptable solutions) deal with the specifics of meeting the goal.

In general case, the last two level can be combined because compliance to a given prescriptive solution *(Level 5)* is just one of the several possible methods of verification as shown in Figure 7.

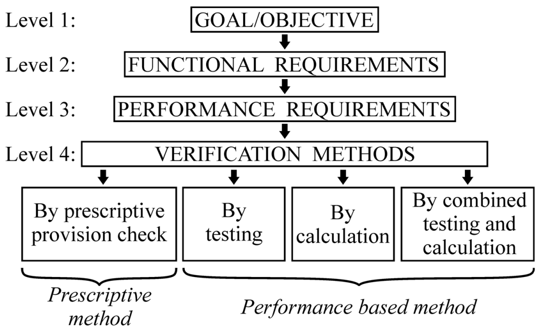

Figure 7. General four-level regulatory framework [3]

Proposed innovative and complex solution consists of combination of the post-tensioned concrete structures, steel-concrete composite frames (so called, delta-beams, composite columns), hollow-core slabs, new type of thermal insulations and finishing materials. The application of these innovative design solutions at one facility with usage of the performance-based design approach and BIM-techniques at one facility ("World Class" GYM in Minsk) are presented in the article.

5 Example of verification of performance criteria (structural serviceability) for post-tensioned cantilever parts (section 2, 3 of the building)

As shown in [2, 3] the higher the level of specification in term of performance (see Figure 8 – performance matrix), the more it is to find a universally acceptable method for the verification of performance. In general case verification of performance is an important component of the performance-based approach because it will be necessary to demonstrate that particular building solution will meet a given performance criteria.

According to [2] performance criteria means a statement of the operative or performance requirement. The performance criteria for analyzed monolithic post-tension floor system will include following:

a) in will have sufficient resistance to support the applied load combination in Ultimate Limit States (ULS) in the lifetime of structure (i.e. structural safety, marked X in Figure 8);

b) it will not sag or vibrate so much that it annoys or bring discomfort to occupants (i.e., structural serviceability, marked by Y, in Figure 8);

c) other performance statements related to fire safety, the bending and shear resistance of the floor joists should be larger (or equal) than applied load, and for serviceability, there could be limits set on the deflection of individual joists or whole structural system, and on the acceptable vibration of floor system.

PRODUCTS/PARTS \ ATTRIBUTES	SAFETY	Structural	Fire	Accident (Safety in Use)	HABITABILITY	Structural Serviceability	Thermal Comfort	Tightness (Water and Air)	Air Quality	Acoustic	Lighting	Access	Security	Condensation	Health and Hygiene	Functionality	Adaptibility	Aesthetic	SUSTAINABILITY – LCP	Maintainability	Durability	Economic	Decommission	Environmental Friendliness
WHOLE BUILDING																								
SPACE																								
Functional Space																								
Building Envelope Space																								
STRUCTURE																								
Super-structure		X		X		Y																		
Sub-structure																								
Composite frame		X	X			Y																		
Post-tension part		X				Y																		
Swimming pool		X																						
SERVICES																								
Plumbing (Water and waste)																								
Heating, Ventilation and AirCon																								
Electrical system																								
Communication system																								
Security and protection																								
Fittings																								

Figure 8. Example of building performance matrix (structural requirements)

According to [3] verification can be through (1) actual testing; (2) calculation (e.g., use of a computational procedure or mathematical model to show that the required performance will be achieved); or (3) a combination of testing and calculation (see Figure 7).

The structural system of the cantilever parts of the building is a complex post-tensioned monolithic structure (see Figure 9), including cantilever beams and slabs connected inextricably with them, monolithic walls and pylons. Beams and pylons designed using a post-tensioned system allow to eliminate shrinkage strains and control the deformations of system nodes.

The pylon designed with dimensions of 1700x700 mm. The pylons made post-tensioned to absorb tensile forces from shrinkage in concrete and compensate for part of the deformation. Tendons arranged vertically from the bottom up, with a bend at the upper point to the centre of gravity of the upper section. The cantilever beam designed with a variable section: height from 300 mm to 1500 mm and a width of 700 mm (see Figure 9). The beams made post-tensioned in order to reduce deformations at the end sections of the cantilever beams and at key nodes. Post-tensioned tendons anchored in the c.g.c. from the side of a smaller section to prevent the occurrence of bending moment at the end of the cantilever beam and located horizontally to the opposite end of the beam with bending down to the centre of gravity of the larger section (see Figure 12). Slabs are designed with a thickness of 160 mm. Monolithic walls are designed with a thickness of 200 mm. Loads for developing design solutions for the cantilever parts of the building adopted in accordance with the data provided by the customer and the general design organization:

- self-weight of structure;
- weight of the floor structure (design value) – 2,53 kPa;
- imposed load (design value) – 7,5 kPa;
- the design value of the load from the board and the stained-glass window 2,53 kN/m and 8,1 kN/m, respectively.
- concentrated loads (see Figure 10): loads are transferred to the beams in the cantilever part through columns supported by them from their self-weight, the design value of the roof structure based on the columns, and the variable climatic loads acting on the roof.

As a result of the analysis of various options for the execution of the cantilever parts of the structure, the most

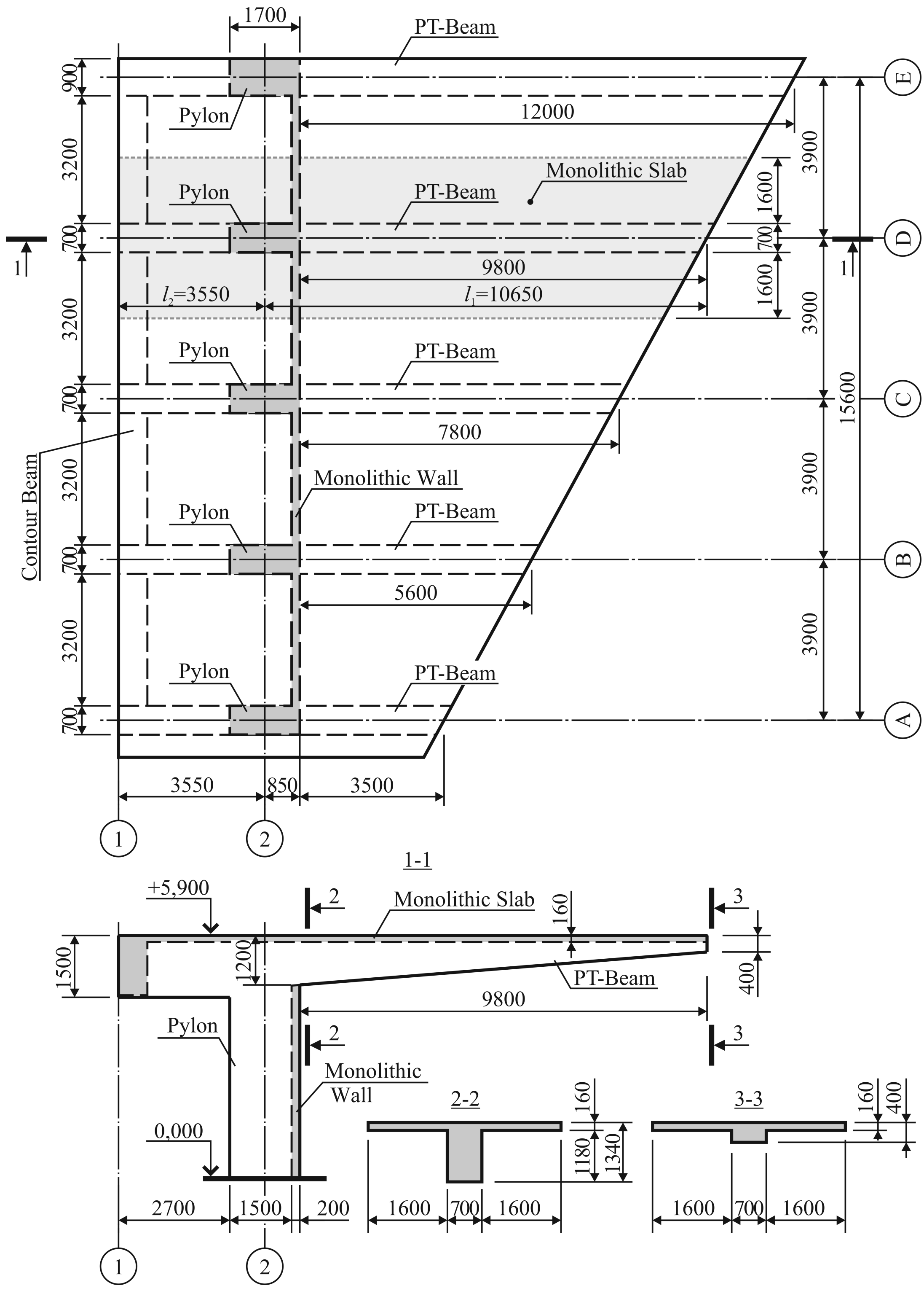

Figure 9. Section 2,3 – Post-tensioned cantilever parts of the buildings blueprints

optimal one was determined, for which the following stages procedure for its construction was established (see Figure 11):

Stage 1. The construction of the cantilever parts to the level of +5.900. At this stage, in-situ concreting of monolithic walls, pylons, beams, and slabs performed. After concreting, the tendons tensioned to compensate for the deflection of the structure from its self-weight.

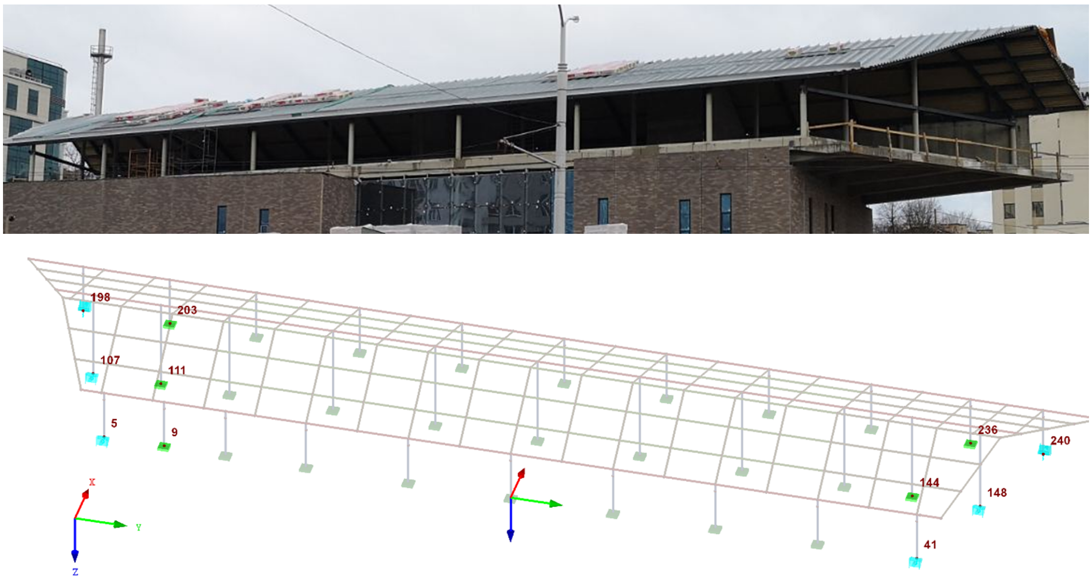

Figure 10. Location of the concentrated loads supported by the beams

Stage 2. At this stage, concrete walls concreted in-situ to the level of +9.750 to increase the overall rigidity of the building. Then columns and a roof structure are mounted.

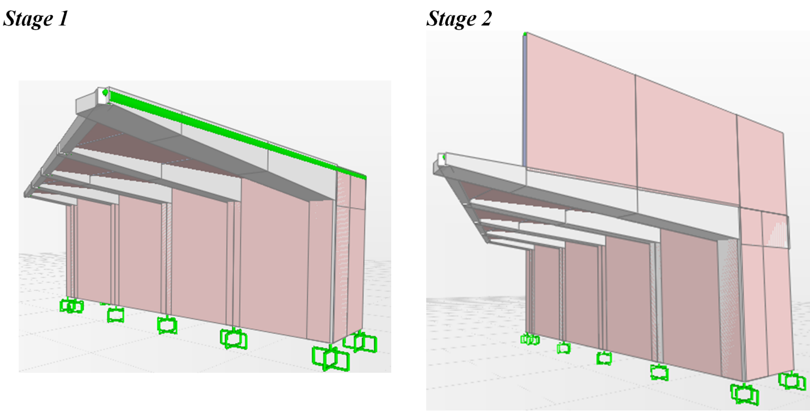

Figure 11. The staged construction of the cantilever parts

In this solution, it is possible to adjust the overall rigidity of the structure at both stages. The first stage (post-tension) used to increase rigidity in relation to the perception of the self-weight of the structure. The second stage (erection of a wall connected with the rest of the structure) allows increasing rigidity in terms of perception of the remaining loads (floor construction, variable loads, imposed loads, self-weight of the roof, columns, glazing and boards).

5.1 Verification of the deflection

5.1.1 Analytical solution

Main geometrical sizes of cantilever section of the building shown in Figure 12, and key sections properties listed in Table 1. According to Figure 13, equilibrium conditions can be written as:

$$\sum F = 0 \tag{1}$$

Using small angle theory:

$$tan\Theta_1 = \frac{a}{L_1} \approx \Theta_1 \approx sin\Theta_1; cos\Theta_2 \approx 1 \Rightarrow L_2 \approx L_2^{'} \tag{2}$$

$$F_{z1} = F \cdot sin\Theta_1 = F \cdot \left(\frac{a}{L_1}\right) = P_{equiv} \tag{3}$$

$$F_{z_1} = P_{equiv} \tag{4}$$

$$F_{z_2} = F \cdot sin\Theta_2 = F \cdot \Theta_2 = F \cdot \left(\frac{a}{L_2}\right) \tag{5}$$

$$\sum M_0 = 0 : M_{left} = P_{equiv} \cdot L_1 = F \cdot \left(\frac{a}{L_1}\right) \cdot L_1 = F \cdot a; M_{right} = F_{z2} \cdot L_2 = F \cdot \left(\frac{a}{L_2}\right) \cdot L_2 = F \cdot a \tag{6}$$

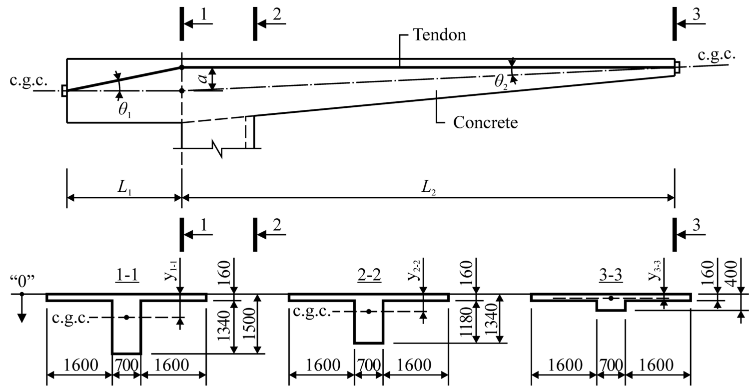

Figure 12. For analytical analysis of cantilever section of the building

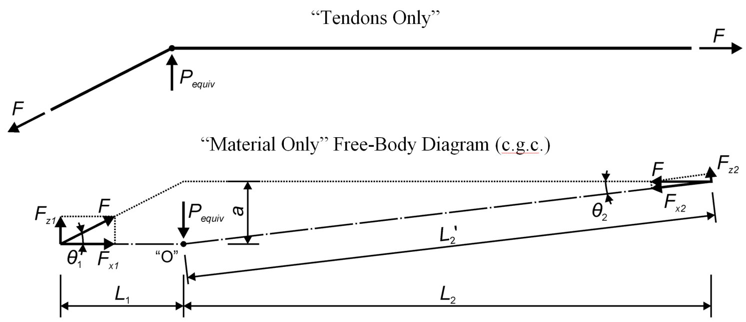

Figure 13. Free-body diagram for theoretical analysis

Table 1. Key section properties

Section (see Figure)	Section area, mm^2	The centre of gravity (c.g.c.), mm	Moment of inertia, mm^4
1-1	1.562x10^6	530.4	3.525x10^{11}
2-2	1.450x10^6	461.7	2.567x10^{11}
3-3	0.792x10^6	122.4	7.432x10^9

Results of calculation (analytical solution) are listed in Table 2.

Table 2. Classes of Data Center objects according to ASHRAE classification

Type of deflection	a $[mm]$	M_{PT} $[N \cdot mm]$	$M_{tot,2-2}$ $[N \cdot mm]$	$1/r$ $[1/mm]$	Δ_{PT} $[mm]$	Δ_{SW} $[mm]$	$\sum \Delta$ $[mm]$
Upward deflection by post-tension (see Figure 14)	339.3	1967.9x10^6	-	2.555x10^{-7}	8.17	-	-
Deflection due to self-weight (see Figure 14)	-	-	1213.95x10^6	1.576x10^{-7}	-	3.78	-
Upward deflection by post-tension taking into account self-weight:							4.39

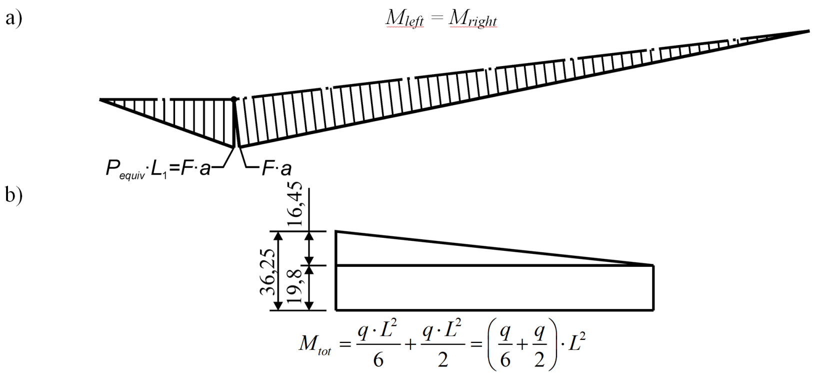

Figure 14. Moment distribution along cantilever beam due to post-tension (a); and self-weight (b)

5.1.2 FE-modelling

Figure 15 shows the distribution of vertical deformations in the cantilever *section 2* and *section3* for the case of loading by its self-weight and post-tension forces, obtained using a FE software SAP2000. The design values of the deflections for *section 2* and *section 3* were obtained 5.6 mm and 6.2 mm, respectively. According to the executive survey, after the tension of the tendons, the actual values of the upward deflections of 7 mm and 12 mm, respectively, were obtained.

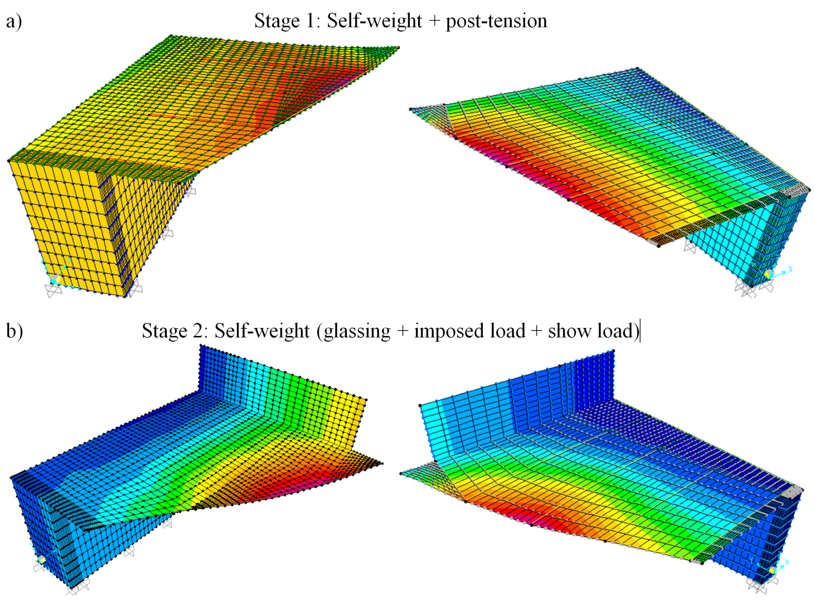

Figure 15. The value of the deformations in the cantilever sections 2, 3 for a) stage 1 and for b) stage 2

Figure 15 shows the distribution of deformations in the cantilever sections for stage 2. The design value of the deflections is 13.1 mm and 20 mm, respectively.

5.1.3 Testing by imposed load

After stage 1, control tests of cantilever sections with a characteristic value of the imposed load of 5kPa were carried out. The full value of the deflection of its self-weight, post-tension and 5 kPa was 3 mm (right console) and 4 mm (left console). Comparison of the obtained result of verification performance criteria for structural serviceability (deflections) shown in Table 3.

Table 3. Classes of Data Center objects according to ASHRAE classification

	Verification approach	Deflection Δ_{max}, mm	Comments
1	Analytical solution	-4.39	self-weight + post-tension
2	FE-modelling	-1	self-weight + post-tension + imposed load
3	Testing by imposed load P=5 kPa	-3	self-weight + post-tension + imposed load
4	FE-modelling	-5.6	self-weight + post-tension
5	Testing	-7	self-weight + post-tension

As it can be seen from Table3 proposed structural post-tensioned system satisfied to performance requirement formulated by client.

6 Conclusion

Summarizing the research contained in the article, two basic conclusions can be distinguished:

1. Proposed performance-based approach to design allows to eliminate the known disadvantages of the prescriptive codes and standards (barrier to innovation, cost-optimization, international trade in building products). In case of presented building very different innovative materials, products structures were used, produced in few countries ("Betonica", "Peiko"-Finland, "Diwidag SI"-Germany). All formulated performance criteria were satisfied.
2. Using BIM technique for performance-based design allowed:
   - to reduce the time of engineering preparation when studying project documentation by two times, since the three-dimensional model gives a greater idea of the work, which also reduces errors in the performance;
   - the time for building construction schedules was halved due to the rapid exchange of data;
   - reduce the influence of the human errors to zero, which allowed increasing the speed of the project and its manageability.

For this building, it was possible to implement a design solution of unique post-tensioned concrete cantilever parts (sections 2, 3) 12 m long and to fully use the dualism of post-tension: unloading effect and initial compression.

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