Saimaa University of Applied Sciences
Technology, Lappeenranta
Double Degree Program in Civil and Construction Engineering

Denis Shusterman

STRUCTURES OF GAS STATION IN SAINT PETERSBURG

Thesis 2017

Abstract

Denis Shusterman
Structures of gas station in Saint Petersburg, 97 pages
Saimaa University of Applied Sciences
Faculty Lappeenranta/Imatra
Double Degree Program in Civil and Construction Engineering
Bachelor’s Thesis 2017
Instructors: Lecturer Petri Himmi, Saimaa University of Applied Sciences
Managing Director Alexand Boytsov, ”Reengineering”.

The purpose of the study was to analyze and calculate different gas station structure variations. The main objective of the research was to compare total costs of all design decisions.

Data for this study were collected from Russian and European norms and from literature for designers. This study was carried out in designing and calculation programs such as LIRA-SAPR and AutoCAD. LIRA-SAPR with its steel structures modulus was used to select the most economical frame elements.The calculations are based on official Russian norms SP 26.13330.2011.

The results of the calculations show the principle of joint work of the main load-bearing structures and their connections. Further study is required to describe and design other modern steel structure variations and connections used in gas station frameworks.

Keywords: construction, gas station, steel structures, cross-section, connections, CAD program, cost estimation.

Table of contents

Terminology

LMF	Liquid motor fuel
SP	Normative rules
N	Longitudinal force
M	Bending moment
Qz /Q_y	Horizontal (shear) forced
q_d	Designed load,
q_s	Service load
ρ	Density, kg/m^3
γ_m	Material multiple coefficient
γ_f	Load multiple coefficient
c_e	Coefficient that takes into account the demolition of snow from the cover of buildings under the influence of wind or other factor
c_t	Thermal coefficient
M	The conversion factor from the weight of the snow cover of the ground to the snow load on the roof cover
Sg	Weight of snow cover on 1 m^2 of the horizontal surface of the earth
V	Average winter wind speed
W	*Service value of wind load*
W_0	*Service value of wind load average component*
c	Aerodynamic coefficient
z	Height above the ground

W_p	Service value of wind load pulsating component
$\zeta(z_e)$	Pulsating coefficient of wind pressure
v	The coefficient of spatial correlation of wind pressure pulsations
I18B1	Section made special for beams, h = 18 cm.
h	Section height
f_u M	Maximum allowable deflection
Mb1-5	Main beams
Sb 1-4	Secondary beams
Br1-8	Bracings
C1-3	Columns
ULS	Ultimate limit state
SLS	Serviceability limit state
LB	Local buckling
U_{max}	Maximum utilization percentages
W, t/m	Weight of running meter of section

1 Introduction

1.1 General information

Over the past 20 years, the number of machines has increased several times. Demand for fuel has increased, which led to the construction of a large number of gas stations. For economic reasons, in order not to pay money to third-party designers and engineers, large fuel companies began to create their own design institutes for the design of gas stations. The aim of these design institutes was to create a standardized design of a filling station in order to minimize the costs of designing and increase its speed. Especially, fuel companies are not interested in the individuality of the architecture of each filling station.

However, because of the great difference in natural and geological conditions, as well as the difference in the size and location of the construction site, it is impossible to create a standardized design that is suitable for the whole territory of Russia. Various snow and wind loads, a different composition of the ground base - all this requires an individual approach to the design of gas station structures. Certainly, it is possible to put large reserves of strength in the basic load-bearing structures, creating a more or less standardized project. Unfortunately, this is economically unprofitable because of the industrial scale of gas stations construction.

1.2 Task description

The purpose of the thesis is to design and calculate load-bearing structures of the gas station (Service building for drivers and passengers) in Saint Petersburg, using LIRA-SAPR software, taking into account natural, geological, and economic conditions. To minimize costs for materials, the most common and available metal structures are used, a comparison of their possible variants are made.

1.3 Methodology

In the work the main bearing structures of the gas station are designed and calculated by means of AutoCAD and Lira SAPR 2013. There will also be a comparison of different structures in order to choose the most efficient and economical variant. The calculations are made according to Russian design norms.

2 Theoretical background

2.1 Designing of gas stations

The projected gas station is designed for receiving, storing and issuing automobile liquid fuel for fueling cars and trucks, and for providing services to owners and passengers of vehicles.

Designing of gas stations is a complex, multi-stage process. When designing a gas station project, it is necessary to take into account the climatic, engineering-geological and socio-economic features of the territory that are developed in this particular place. Technological and auxiliary facilities should be located on the territory of gas stations. For technological connections and in fire prevention purposes, road passes might be provided. For the work of the gas station, designers have to design engineering services. Services of the gas stations are:

- Electric power supply - from the existing electricity network and from the designed diesel generator;
- Sewage;
- Drainage of household waste water;
- Water supply - from the existing water supply [1].

Designing of a gas station includes a lot of different interconnected parts and takes a lot of time to complete it. The final project should consist of the following documents:

1. Explanatory note

2. Drawings of the general plan:

- Situational plan M 1: 5000 or 1: 2000;
- General plan M 1: 500;
- Traffic management scheme;

- Arrangement of accelerating and brake bands;
- Plan for improvement of the adjacent territory;
- Plan for the organization of the relief M 1: 500;
- Alignment drawing;

3. Technology of reception, storage and delivery of liquid motor fuel:

- Technological scheme, specification for it;
- Axonometric scheme (single-line);
- The recommended scheme of equipment binding (3D);
- External piping pipelines (equipment layout plan);
- Plan for laying pipelines;
- Pipeline longitudinal profile;
- Installation dimensions of fuel dispensers, pumps (pump unit);

4. Automation of technological processes. Power supply system of equipment:

- Automation scheme, specification for it;
- Circuit diagrams of automation and power supply boards, specifications for them;
- Sketches of shields;
- Scheme of external connections;
- The plan of a lining of cables;
- Cable magazines.

5. Internal power supply system of the operator's building

- Schematic diagrams of power and distribution boards, specifications for them;
- Sketches of shields;
- Scheme of external connections;
- The plan of a lining of cables;
- Cable magazines.

6. Lightning protection and earthing

7. Electrochemical protection (if necessary)

8. Architectural and color solutions:

- General plan 1: 500;
- Alignment drawing;
- Service building for drivers and passengers
- Canopies (general view, sketches of facades, sections).

9. Architectural and construction part

- Canopy (general view, facades, structural solutions);
- Main building (general view, structural solutions);
- Foundations.

10. Environmental protection

11. Water and storm sewerage

12. Inner water supply and sewerage networks

13. Treatment facilities

14. Engineering and technical measures of the Civil Defense. Measures to prevent emergencies

15. Labor protection of workers. Production and enterprise management

16. List of measures to ensure fire safety

There should be entrances with a hard surface for all designed buildings and structures. On the site of the gas station should be a water pipe with the installation of a fire hydrant.

17. The list of measures to ensure access for disabled persons to objects of transport, trade, public catering facilities

18. Site planning and construction methodology [1].

Taking into account the complexity of the construction of gas stations it is necessary to involve qualified specialists of various profiles.

Design, construction and placement of gas stations, including roadside service facilities, should be carried out taking into account the requirements of standards, technical regulations and traffic safety standards, environmental safety. All project documentation for the construction of the gas station is subject to state expertise. Permission to build a gas station should be given by the Russian Federation authorities in the presence of approved project documentation, and a positive conclusion of the state expertise of project documentation.

2.2 The main buildings and structures located at the gas station

The main buildings and structures located at the gas station are shown on Figure 1.

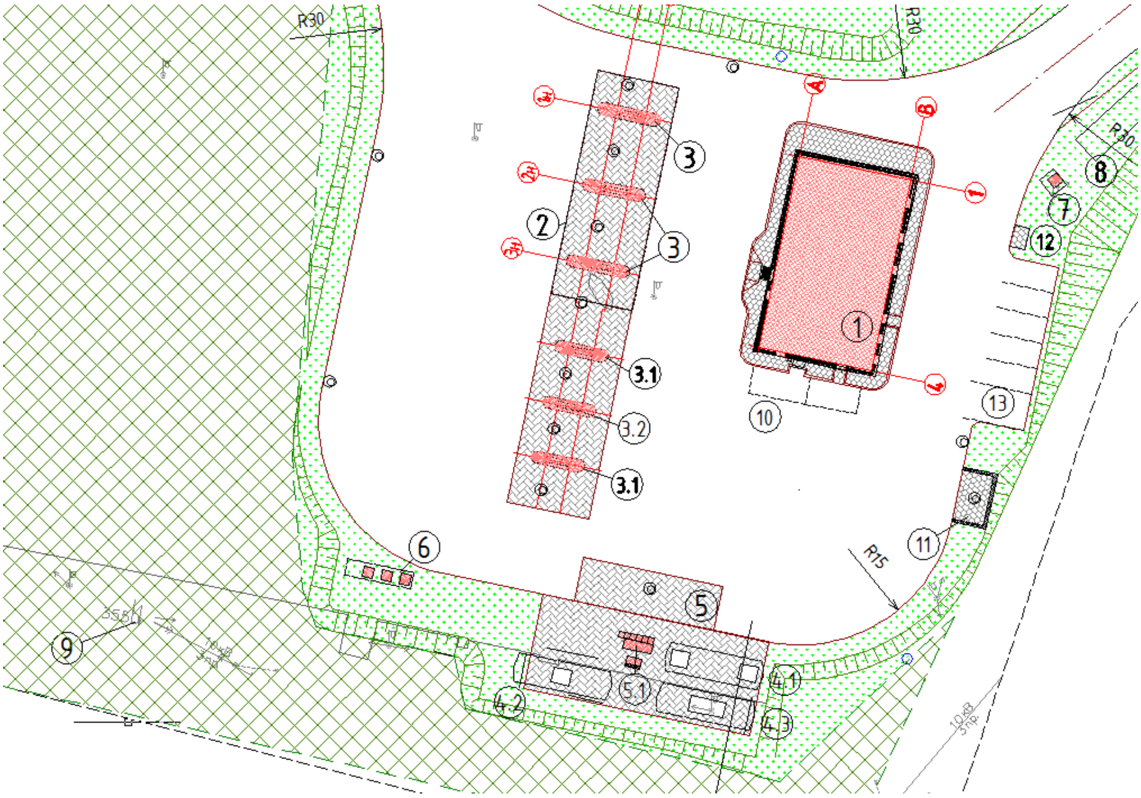


Figure 1. General plan of gas station

The main buildings and structures located at the gas station are shown at the Figure 1, listed in Table 1 below:

Table 1. List of buildings and structures located at the gas station

№ on plan	Name of building or structure
1	Service building for drivers and passengers (Main building)
2	Canopy
3	Dispenser with liquid motor fuel (LMF);
3.1	Dispenser with diesel fuel (DF);
3.2	Dispenser with 2 satellites DT
4.1	Storage tank LMF -50 m3 (10 + 40);
4.2	Storage tank LMF -50 m3 (25 + 25);
4.3	Storage tank LMF -50 m3;
5	A platform of a drain of LMF from a road tanker;
5.1	Fuel drain place
6	Storm water treatment facilities
7	Treatment facilities of domestic wastewater
8	Filtration field
9	Transformer substation
10	A platform for self-service
11	Site for installation of solid waste containers
12	A platform for the installation of a mobile diesel power plant
13	Parking lot for visitors cars.

3 Project data

3.1 Place of construction

”Gazpromneft’” gas station is planned to be located in the Kirovsky district of the Leningrad region near the R-21 Kola motorway St. Petersburg-Murmansk (45 km from the Murmansk highway). Figure 2 shows the location of the gas station.

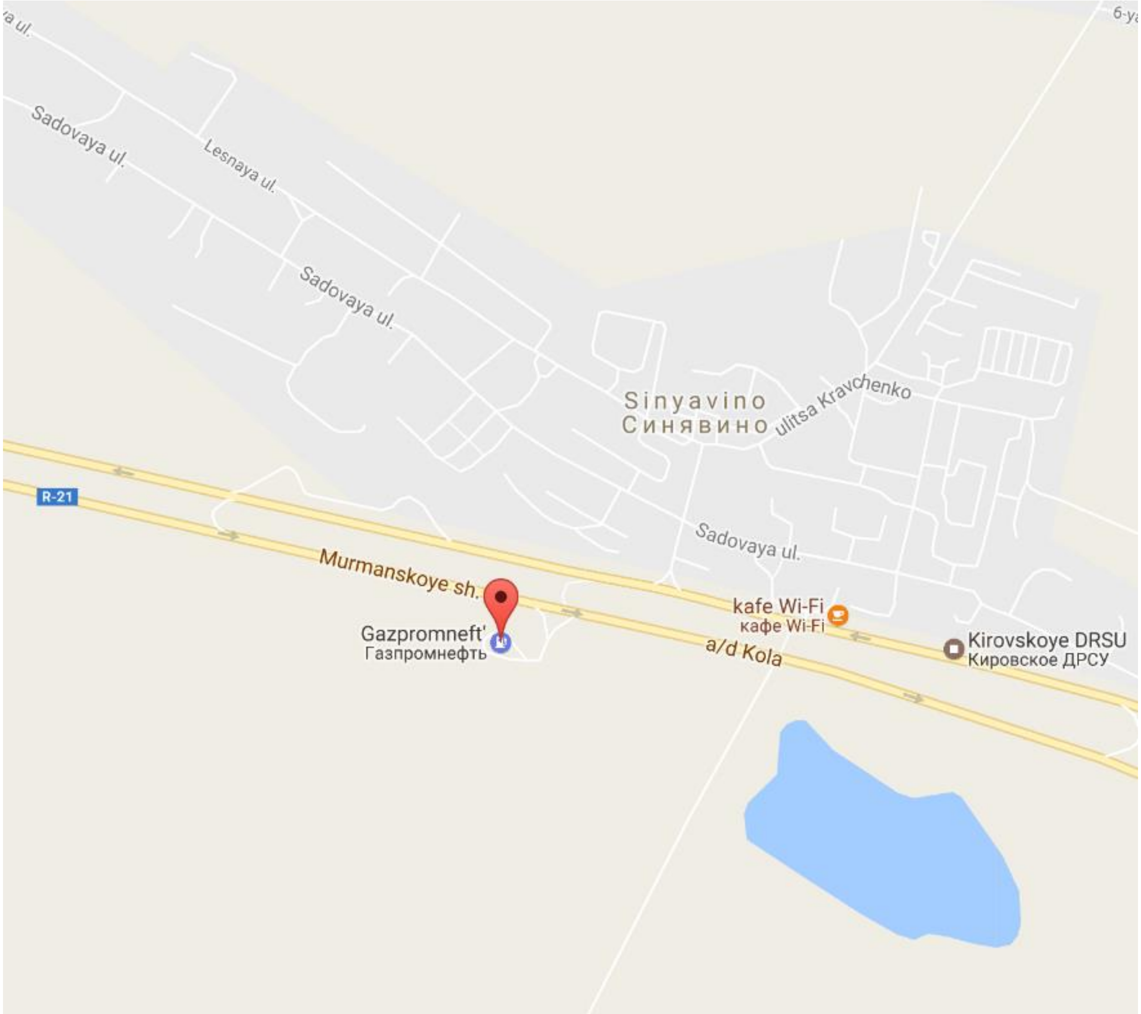


Figure 2. Location of the gas station

The nearest residential development is located 140 meters to the northern part of the gas station - the village ”Sinyavino”. This place is not densely populated, surrounded on one side by a forest, and on the other side by road.

3.2 Gas station architecture

The exterior of the service building for drivers and passengers and a canopy over dispensers includes an aesthetic architectural solution, which includes a shape, color solution, device and equipment of entrances, construction of steps, stairs and canopies. Figure 3 shows the architectural concept of the gas station.

Figure 3 Picture of the gas station made in the 3dsMax program

Gas station is a single-storey frame type building. The rectangular service building for drivers and passengers has dimensions in the axes of 18.90 x 11.00 meter. The height of the building is 4.1 meters. The main facade is directed to the dispensers, and lateral to the adjacent road.

The main facades of the building are decorated with a special facade panel with blue elements in the form of a flame. The facade of the building is finished with square 1000x1000 mm blue panels. The joints of the panels, 30 mm wide, form a visible grid with straight lines. The facings of the side and rear facades are RAL Classic 9003. The aluminum profiles of the vitrified windows and doors are painted in RAL 9004 color. The frieze is installed along the perimeter of the facades with the logo of the company name. The main facades are shown on Figure 4.

Figure 4. Main facades of the gas station

A modern gas station is a whole complex of goods and services for motorists. In addition to its main purpose, the gas station must satisfy other customer needs. At the gas station there is an opportunity to buy not only goods for cars, but also food, newspapers and magazines, and opportunity to eat fast. At the gas station, the customer service area and the service facility are combined to create additional convenience for customers.

The designed building has the following main entrances from the streets:

- For the staff;
- For loading the products of the fast-food company and the grocery store;
- For loading non-food items of the store;
- Two entrances for visitors.

Technological solutions for the interior layout of the store are taken into consideration with the sanitary and epidemiological requirements. Figure 5 shows the interior layout of the service building.

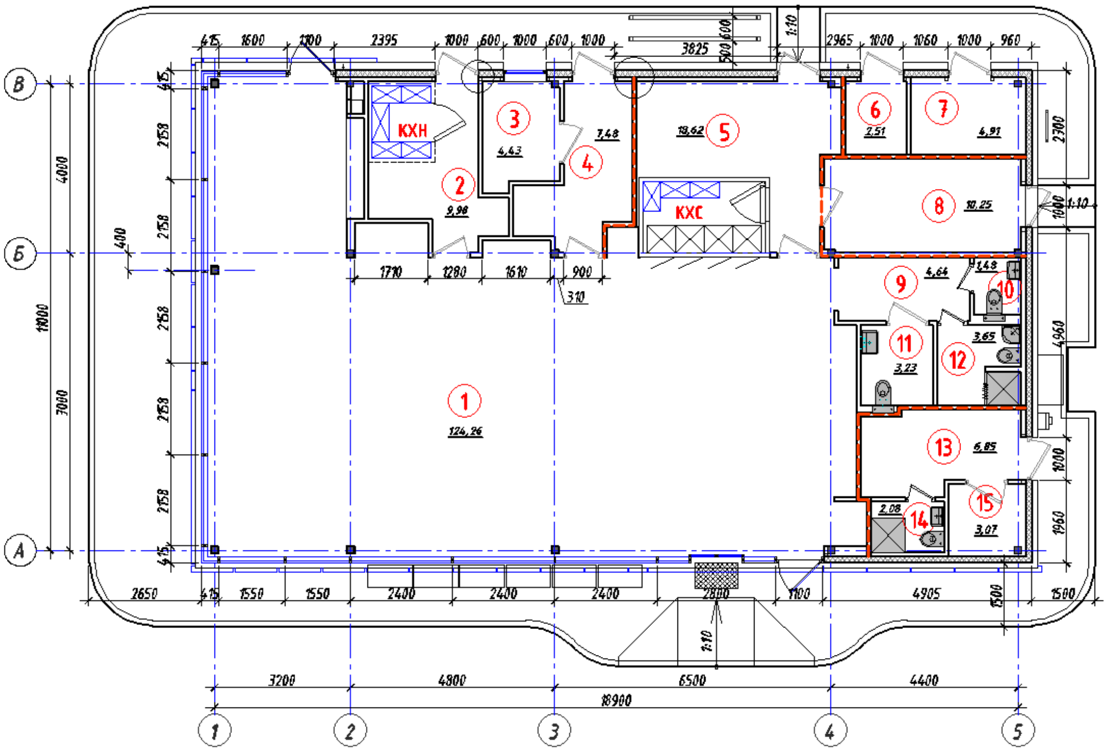


Figure 5. Interior layout of the service building. 1 - service room; 2 - auxiliary room of the fast-food factory; 3 - manager's office; 4 - personal service room; 5 - room for the reception, storage and preparation of food products; 6 - maintenance room; 7 – switchboard room; 8 - room for reception, storage and preparation of non-food items; 9 – restroom vestibule; 10 - restrooms for visitors; 11 - restroom for disabled people; 12 - restroom for staff; 13 - residential room for employees of the gas station; 14 - bathroom with shower; 15 - storage room for cleaning tools.

Planning solutions of the premises of the fast-food company and their composition provide a sequence of technological processes, exclude counter flows of semi-finished products and finished products, counter flows of visitors and staff (there are different entrances provided for visitors and staff).

The service station provides services for disabled people. The parking lot provides parking for disabled people. The distances between the equipment located in the service room allow wheelchair users to move freely. There is also a separate restroom.

The connection of the power supply to the equipment is provided in accordance with the requirements of the current rules and regulations. Electricity is supplied from the general electrical switchboard installed in the switchboard room.

The interior of the trading hall is made in dark colors: the trading equipment is painted in RAL 9004 color, the walls are painted with paint Tikkurila n487. The interiors of the shopping area are completed by modern finishing materials with high sanitary and hygienic and aesthetic properties:

- Floor - porcelain tiles “Italom Urban”, with tile dimensions 596x596 mm
- Ceilings - in the trading hall and in the restroom vestibule are made of suspended ceilings with a cube-like design

The ceiling space and communications in the trading floor are painted in matt black colour. The lighting of the trading hall is placed in the construction of a false ceiling.

Technical and economic parameters of the building:

- Estate area - 12000 m^2;
- Building area - 226.82 m^2
- Total area of the building - 215.03 m^2;
- Useful area - 207.44 m^2;
- Construction volume - 929.96 m^2;
- Number of storeys - 1 floor;
- Height of the building - 4,1 m;
- Number of seats at the fast-food factory - 19 seats;
- Number of car places - 8 places

3.3 Climatic and geological conditions of construction site

In accordance with the normative document SP 131.13330.2012 "Construction climatology", the construction area refers to the climatic zone IIB [3]. Figure 6 shows a map of climatic zones for construction in Russia.

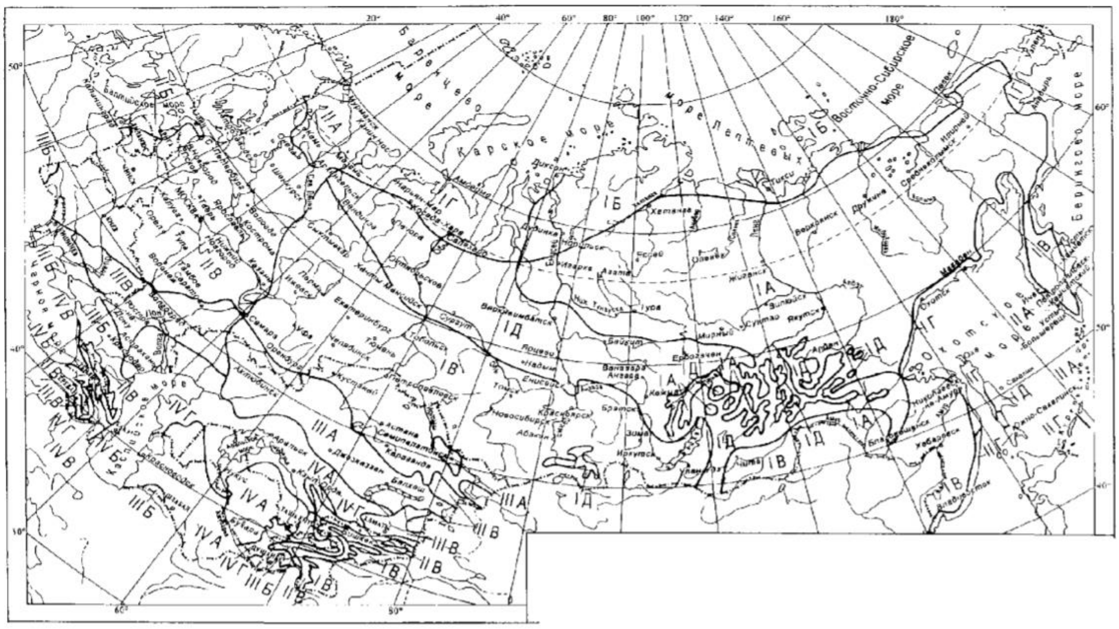


Figure 6. Climatic zones for construction in Russia

The area of the site is characterized by a mildly warm summer, a long and relatively warm winter with frequent thaws in December. The average air temperature at the nearest meteorological station of St. Petersburg is + 4.3 °. The temperature of the coldest month (February) is 7.9 °, the warmest (July) + 17.8 °. The absolute maximum + 34 ° C is in the summer, and at least -44 ° in winter.

The main direction of the wind is western. The average annual wind speed is 4.3 m / sec. The highest speed, observed every 10 and 20 years, is 24 and 26 m / sec.

The normative depth of seasonal freezing in this area, according to SP 131.13330.2012 "Construction climatology", for bulk soils and sands is 1.20 m, for peat - 0.80 m [3]. The relief of the site with small differences in height, the absolute marks of the surface is about 13.75 - 14.20 meters.

Anthropogenic deposits (t IV) and biogenic deposits (bIV), lacustrine-glacial drift deposits (lg III) and glacial drift deposits (g III) take part in the geological structure of the site within the depth of drilling (15.0 meters).

Anthropogenic deposits (t IV) - artificial ground.

Biogenic deposits (bIV) - Biogenic deposit The formation of rocks, traces or structures as a result of the activities of living organisms.

Lacustrine-glacial drift deposits (lg III) - Sediments of proglacial lakes of various genesis formed during the deposition of thin-clastic material carried out by flows of thawed glacial waters in the periglacial zone.

Glacial drift deposits (g III) - A general term applied to all rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier [2].

Figure 7 shows the results of engineering survey.

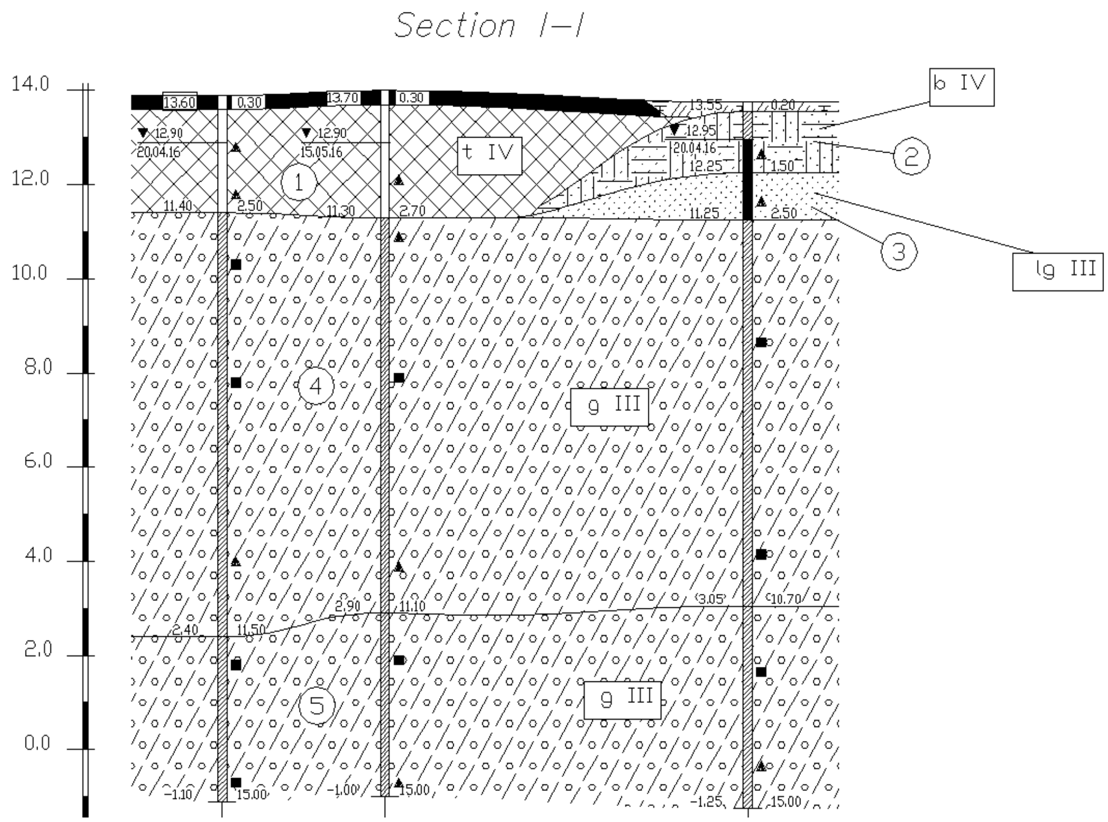


Figure 7. Geological section of the construction site

The main geological units are listed in the table below.

Table 2. List of geological units

Type of geological unit	Geological element composition
1. Anthropogenic deposits (t IV)	Fine sands with rubble, moist and saturated with water. Found at a depth of 0.30 m (abs. mark of 13.60 - 13.70 m.) with a 2.20 - 2.40 meter thickness.
2. Biogenic deposits (t IV)	Silty sands, saturated with water. Found at a depth of 0.20 - 0.30 m (abs. mark 13.45 - 14.00 m.) with a 1.30 to 1.70 meter thickness.
3. Lacustrine-glacial drift deposits (lg III)	Medium-dense fine brown sands, saturated with water. Found at a depth of 1.50 - 1.90 m (abs. mark 11.95 - 12.30 m), with a 0.50 - 1.00 meter thickness.
4. Glacial drift deposits (g III)	Plastic silty sandy loams with gravel and pebbles up to 5-10%. Found at a depth of 2.40 - 2.80 m (abs. mark 10.95 - 11.80 m), with a 5.80 - 9.00 meter thickness.

For the period of exploration (May 2016), groundwater was at a depth of 0.70 - 1.00 meter (abs. mark of 12.90 - 13.50 m). Water is non-pressure. The observed level of groundwater can be attributed to the average annual. The groundwater is quite high, which requires the installation of special drainage systems. Underground water, in relation to concrete is not aggressive.

Under the foundation of the service building for drivers and passengers at a depth of 1.0 m, there will be silt-filled sands with a 1.7 meters thickness, and fine sands under it. Anthropogenic soils, peats and fine sands, in the wetted state, belong to the strongly punched soils, which means, that basement need additional insulation.

4 Calculations

4.1 LIRA-SAPR software

As the aim of the thesis is to design and calculate load-bearing structures of the gas station (Service building for drivers and passengers) in Saint Petersburg, using LIRA-SAPR software, then it should be explained, because LIRA-SAPR is a software, made by Russian programmers and it is widely used in Russia and in countries of the former Soviet Union. LIRA-SAPR has all required licenses and certificates of compliance to building codes of RF. It allows Russian engineers to use this software. Figure 8 shows the standard interface of LIRA-SAPR.

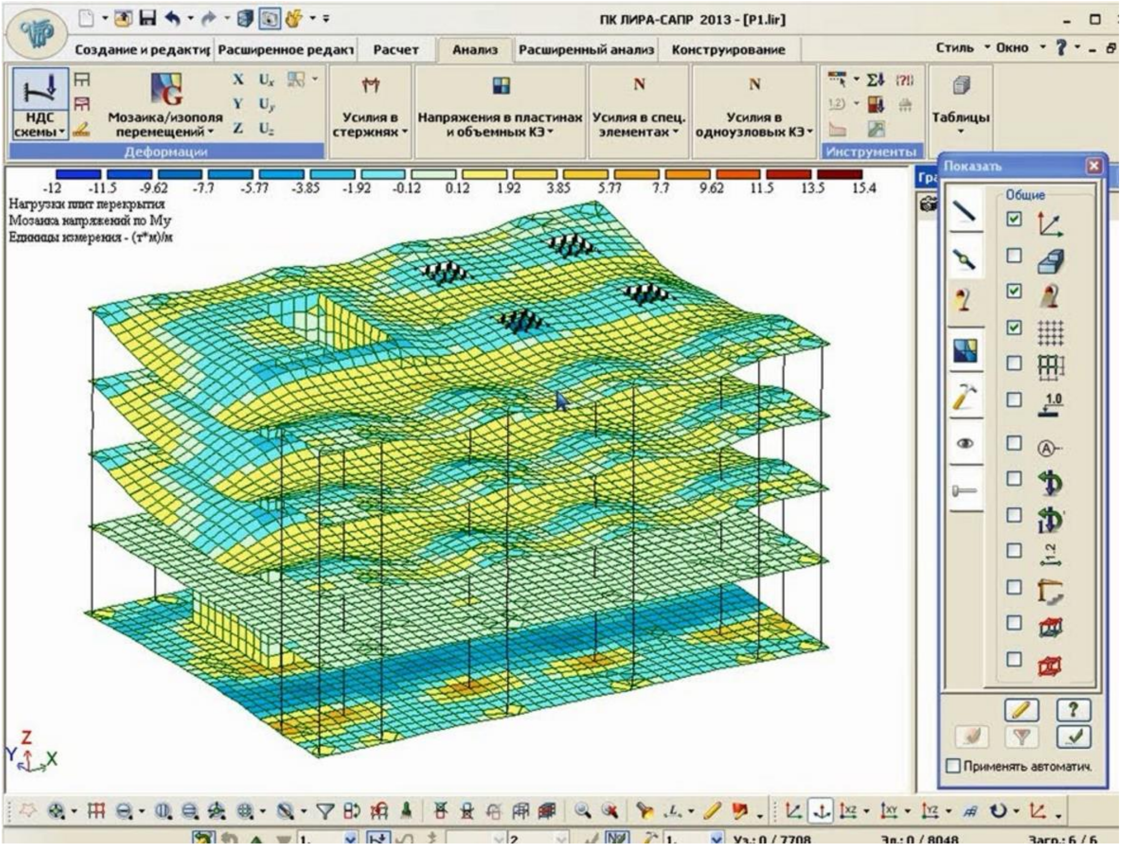


Figure 8. LIRA-SAPR interface

LIRA-SAPR is a comprehensive software package that benefits from BIM technology. The software is intended for analysis and design of building structures. BIM-technology is supported due to the interface with other architectural, analysis & design, graphical and documentary systems (SAPFIR-3D, Revit Structure, AutoCAD, ArchiCAD, Advance Steel, Tekla, BoCAD, Allplan, STARK ES, Gmsh, MS Word, MS Excel, GLAZER, etc.) through DXF, MDB, STP, SLI, MSH, STL, OBJ, IFC, and other files. [4]

The program complex LIRA-CAD is a multifunctional software complex for the calculation, research and design of structures for various purposes.

In addition to the basic calculation of the model for all possible types of static loads (power, temperature, deformation) and dynamic influences (wind with allowance for pulsation, seismic effects according to various norms), the LIRA-SAPR automates a number of design processes:

- Determination of the calculated combinations of loads and forces
- Creation of structural elements
- Selection and verification of steel and reinforced concrete sections
- Drawings creation of columns and beams

To calculate an analytic model, the corresponding calculation modulus must be selected. The LIRA-SAPR system includes several calculation modulus. All of them are created to determine the structure mode of deformation, based on the deflection method. Linear modulus is created to solve problems that describe the operation of structural material in a linearly elastic state. Modules of geometrical nonlinearity enable engineers to analyze the structures that are initially geometrically stable (slabs and beams, trusses) and structures that are initially geometrically unstable. For the analysis of the former ones, it is necessary to determine the equilibrium shape for the specified load type.

LIRA-SAPR program contains the following systems:

- VISOR-SAPR (Graphical user environment). VISOR-SAPR system is the unified graphical user interface (GUI) that includes professional tools for generating design models for different structures and evaluating analysis results.
- SAPFIR-Structures system. It enables designers to generate design model of the structure based on 3D model obtained in SAPFIR-3D program.

- Reinforced Concrete Structures (Analysis & design of reinforced concrete structures). In this system designers could determine areas of reinforcement for columns, beams, slabs and shells according to ultimate and serviceability limit states. Building codes of different countries are supported. It is possible to assign properties of concrete and reinforcement that is useful for analyses of reconstruction. In this system designers can unite several elements of the same type into one structural element and arrange reinforcement along the whole length of this element. Figure 9 shows the interface of this system.

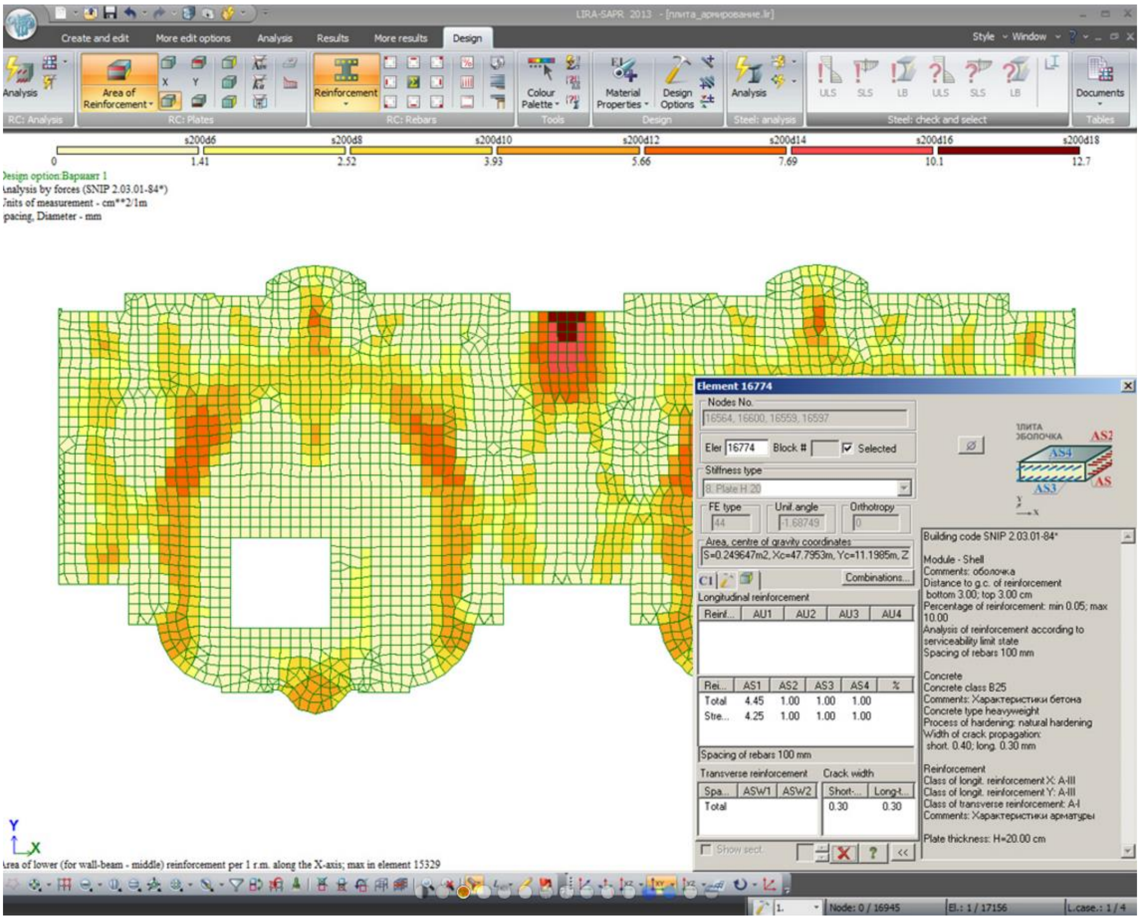


Figure 9. Analysis and design of reinforced concrete structures in LIRA-SAPR

- Steel Structures (Analysis & design of steel structures). Figure 10 shows the interface of this system.

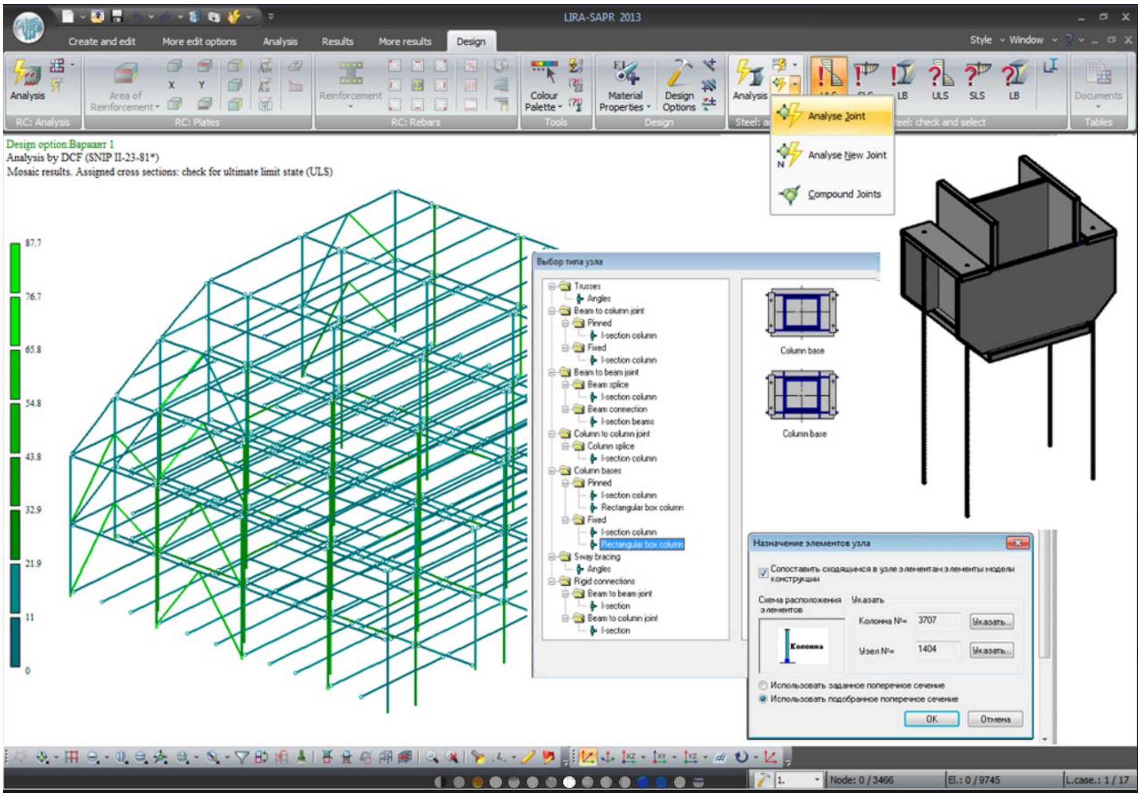


Figure 10. Analysis and design of steel structures in LIRA-SAPR

- Modules are mentioned to automatically generate the whole set of working drawings

In the "Reinforced concrete and steel structures" software developers realized the selection and verification of the elements of steel structures and their nodes for the first and second limit states. Figure 11 shows this module interface.

Figure11. Reinforced concrete and steel structures module

All elements of metal structures for calculation are divided into types: columns, beams, trusses and ropes. The columns take into account the axial force, bending moments and transverse forces in calculation (N, My, Qz, Mz, Qy); Beams - bending moments and transverse forces (My, Qz, Mz, Qy); Trusses - only axial force

(N); Ropes - only tensile axial force (N +). This allows designers to perform the following calculations:

- Load-bearing capacity calculation of the cross-section according to the 1-st limit state:
  - Strength calculation
  - Stability calculation of the bent, centrally and eccentrically-compressed elements
- Load-bearing capacity calculation of the cross-section according to the 2-nd limit state:
  - Bending deflection calculation
  - Ultimate flexibility calculation of compressed and stretched elements

4.2 Description of the service building structures

4.2.1 Columns and rafters

Structural system of the service building for drivers and passengers is a framework. The primary steel framework consists of columns and rafters, which form portal frames, and bracing. Figures 5 and 12 show the location of the main columns in accordance with the layout, made by architects.

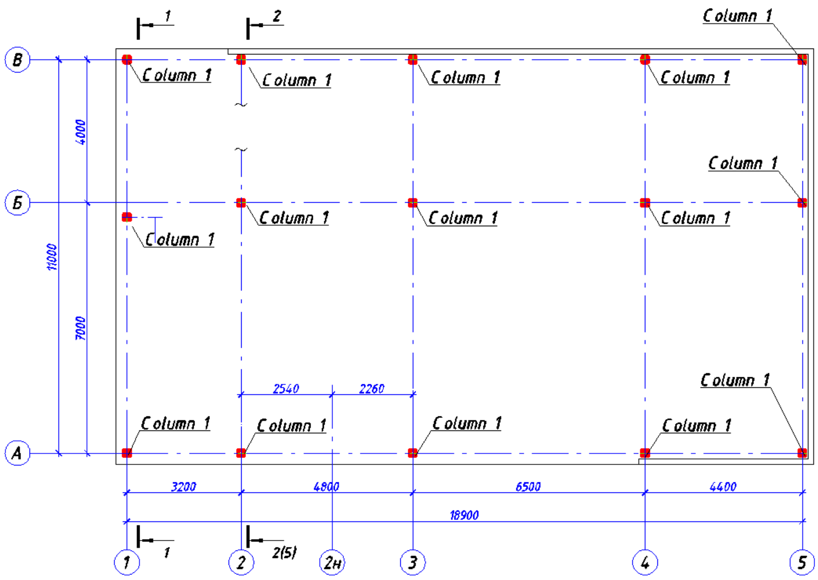


Figure 12. Location of the service building main columns

Due to small spans in both directions, it is not rational to design a complicated roofing system. In this case, the most rational scheme is frame beam and column structures. By means of different height of the columns and straight beams it is possible to organize the required slope of the pent roof. In a frame beam and column structure, the basic configuration is a series of parallel beams, each supported by columns at its ends, as shown on Figure 13 [5].

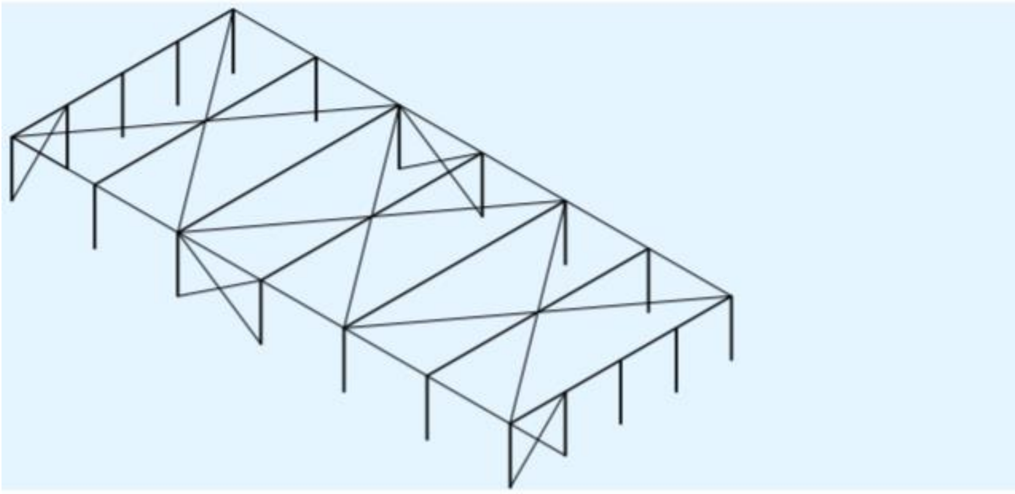


Figure 13. Typical structural configuration for a beam and column structure

The most common type of beam and column structure uses hot rolled steel I sections for both beams and columns. Deep sections with relatively narrow flanges are preferred for roof beams, as showed on Figure 14, where they primarily resist bending. Columns, which primarily resist compression, are usually thicker, shallower sections with wider flanges.

Figure 14. I section beam and column structure example

There should be plane bracings in the roofing system and additional bracings. Figures 15 and 17 show the arrangement of roof load-bearing structures.

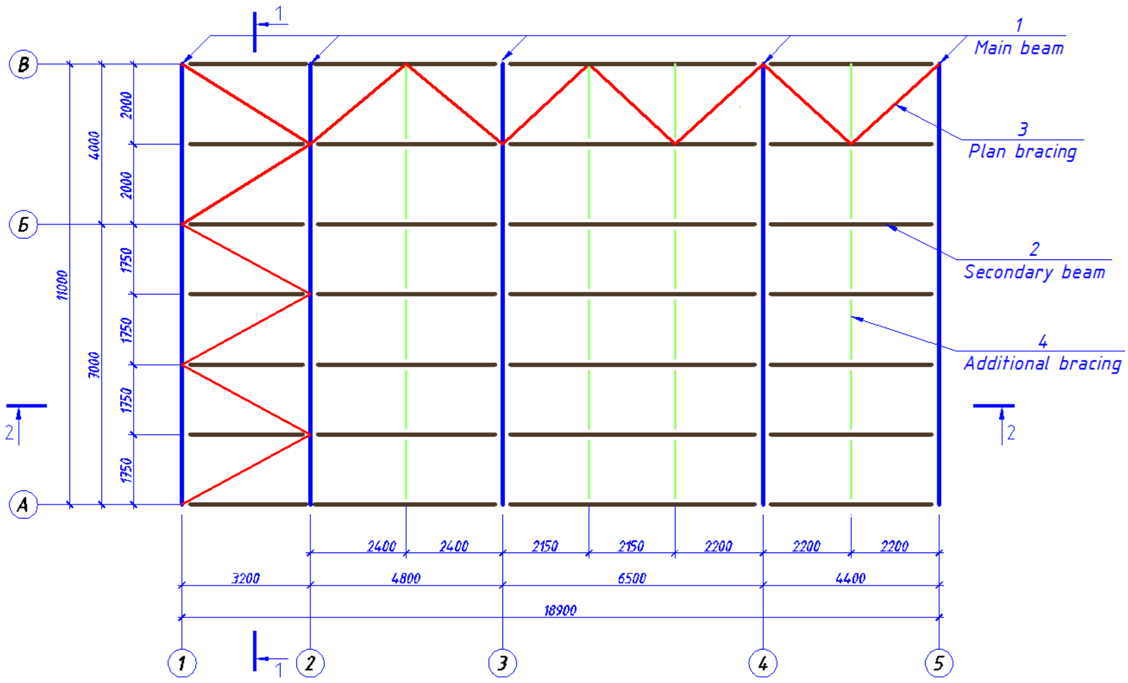


Figure 15. Simplified scheme of the service building roof load-bearing structures. 1 (blue) - Main beams (rafters); 2 (black) – Secondary beams (purlins); 3 (red) – Plane bracings, 4 (green) – Additional bracings

The roof coat is profiled sheets. Additional bracings are spaced 2-2.5 meters to provide a surface for attachment of profiled sheets. Description of plane bracings is placed in the paragraph below. The profiled sheet roof coat is shown in Figure 16.

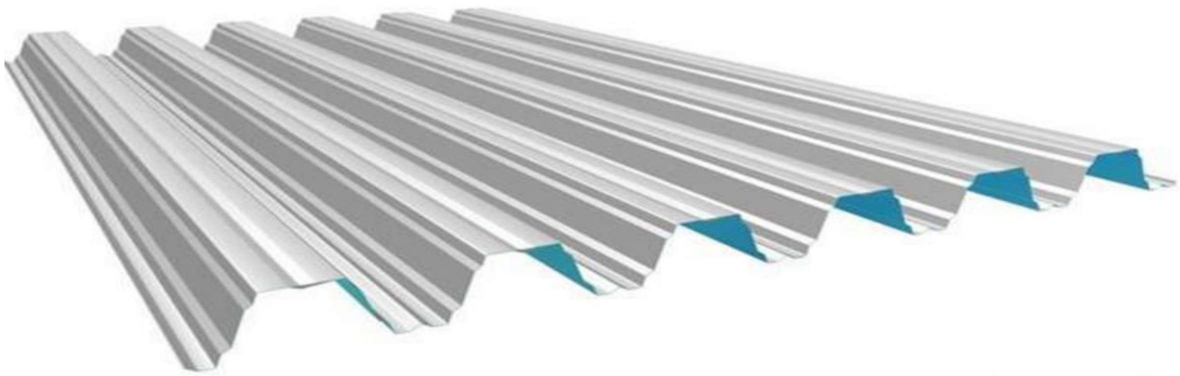


Figure 16. Profiled sheets roof coat

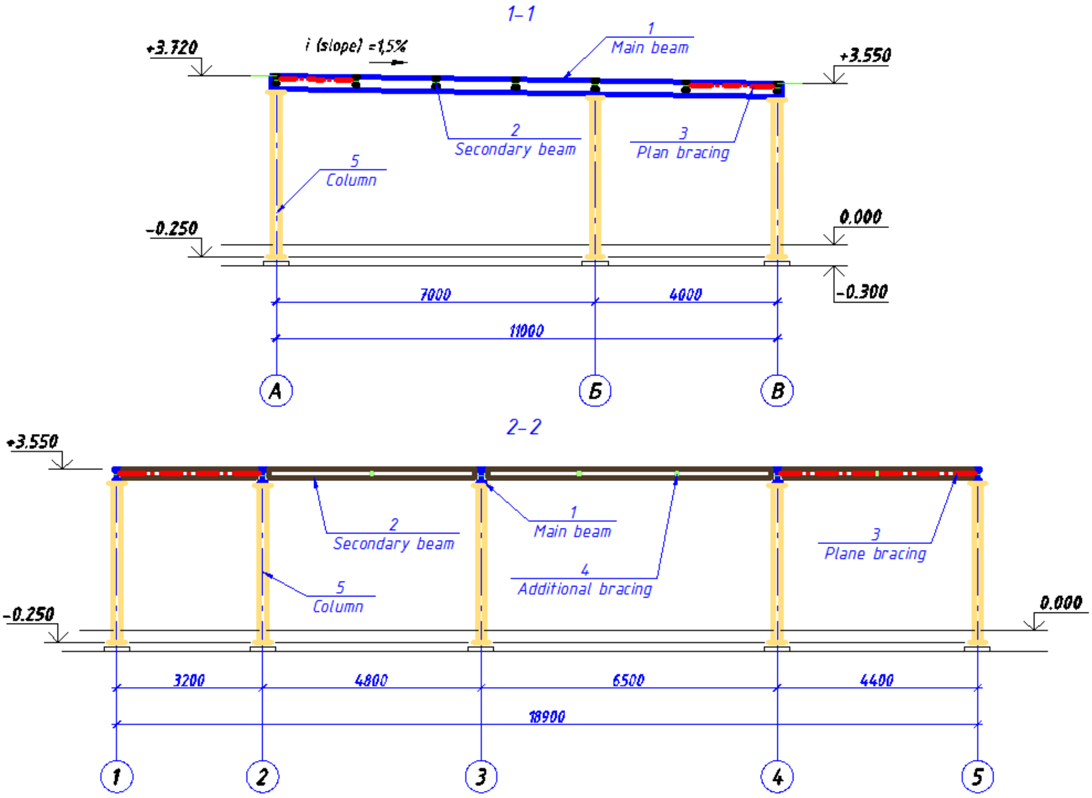


Figure 17. Service building cross and longitudinal sections 1-1 and 2-2. 1 (blue) – Main beams (rafters); 2 (black) – Secondary beams (purlins); 3 (red) – Plane bracings, 4 (green) – Additional bracings, 5 (beige) - Columns

The span for the roof beams may reach 15 – 20 meters. The span of the service building is 11 meters, divided into two spans (7 and 4 meters) by the central row of columns. It means, that there is a possibility to remove the central row of columns. On the one hand it may reduce the total price of the building by means of decreasing number of load-bearing columns, but on the other hand it will increase the bending moment in the main beams (rafters). With increasing bending moment, a larger load-bearing capacity of the beam is required, which leads to increasing of beam cross section. There is a need to compare both variations to find the cheapest one. The comparison will be carried out by the amount of metal spent and its cost in accordance with the latest prices. Figure 18 shows this variation.

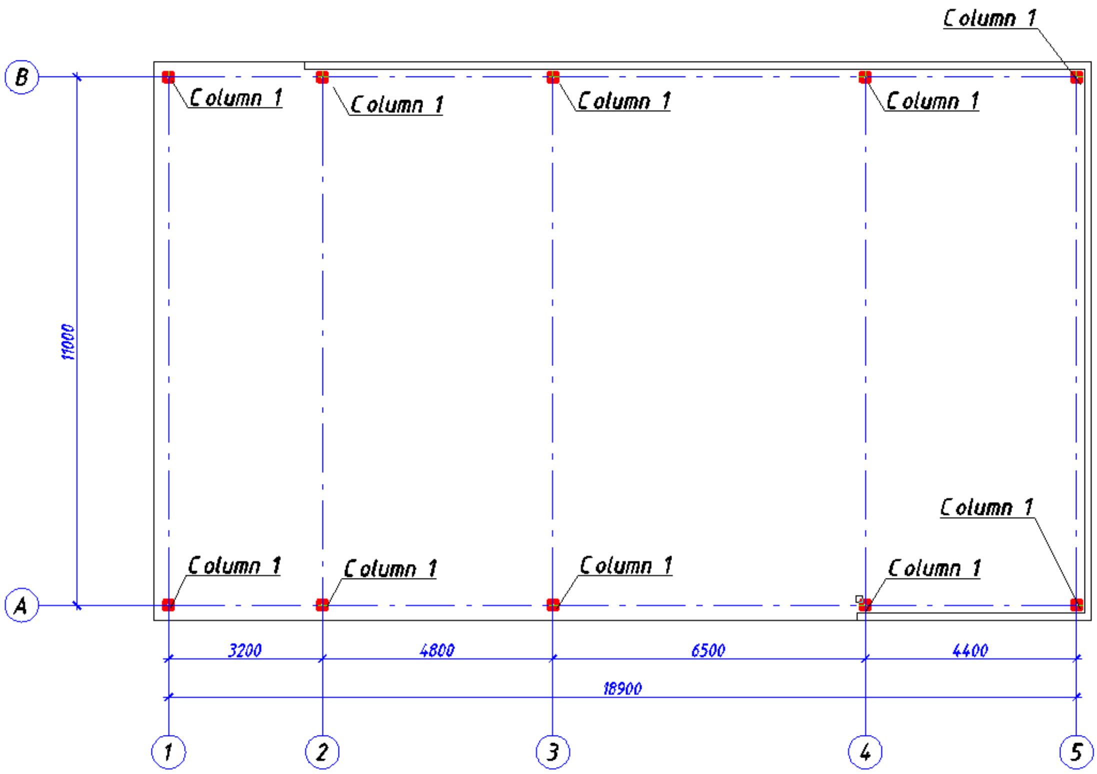


Figure 18. Location of the main columns (second variation)

4.2.2 Bracings

Bracing is required to resist longitudinal actions due to wind and cranes, and to provide restraint to members. There are two types of bracings:

- Vertical bracing. The primary functions of vertical bracing in the side walls of the frame are:
  - To transmit the horizontal loads to the ground. The horizontal forces include forces from wind and cranes
  - To provide a rigid framework to which side rails and cladding may be attached so that the rails can in turn provide stability to the columns
  - To provide temporary stability during erection.
- Plan bracing. It is located in the plane of the roof. The primary functions of the plan bracing are:
  - To transmit wind forces from the gable posts to the vertical elements

– To transmit any frictional drag forces from wind on the roof to the vertical elements
– To provide stability during erection [5]

It is common to use hollow sections as bracing members. Figure 19 shows typical bracings in portal frames.

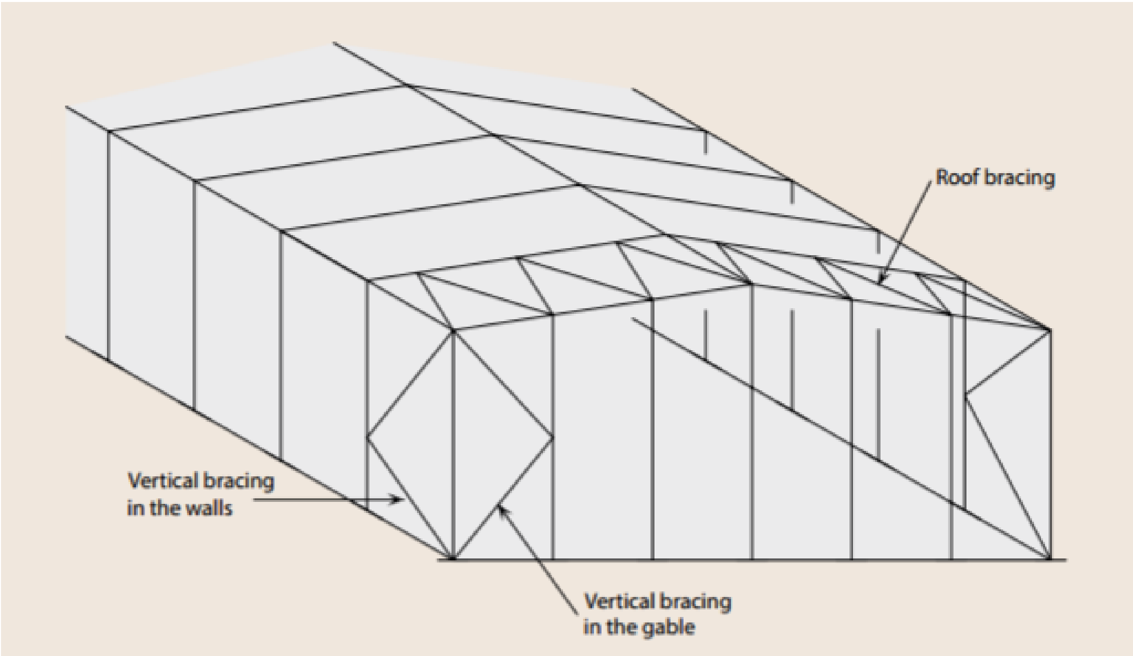


Figure 19. Typical bracings in portal frames

The arrangement of vertical bracings in all spans is impossible on the basis of the requirements of the technological process and the layout scheme of the service building, and therefore the stability of the structure must be ensured by the stiffness of the frames in the longitudinal and transverse directions. In this case, stiffness may be ensured by means of rigid connections in frames.

4.2.3 Connections

In the frame beam and column structures, there are three main connections:

- Column base connection (between column and foundation
- Beam to column connection
- Beam to beam connection

Column base connection

Column base connection may be pinned or rigid. In the majority of cases, a normally pinned base is provided, because of the difficulty and expense of providing rigid base. A rigid base may involve a more expensive steelwork details and foundation would have to resist bending moment. Figure 20 shows a typical pinned base [5].

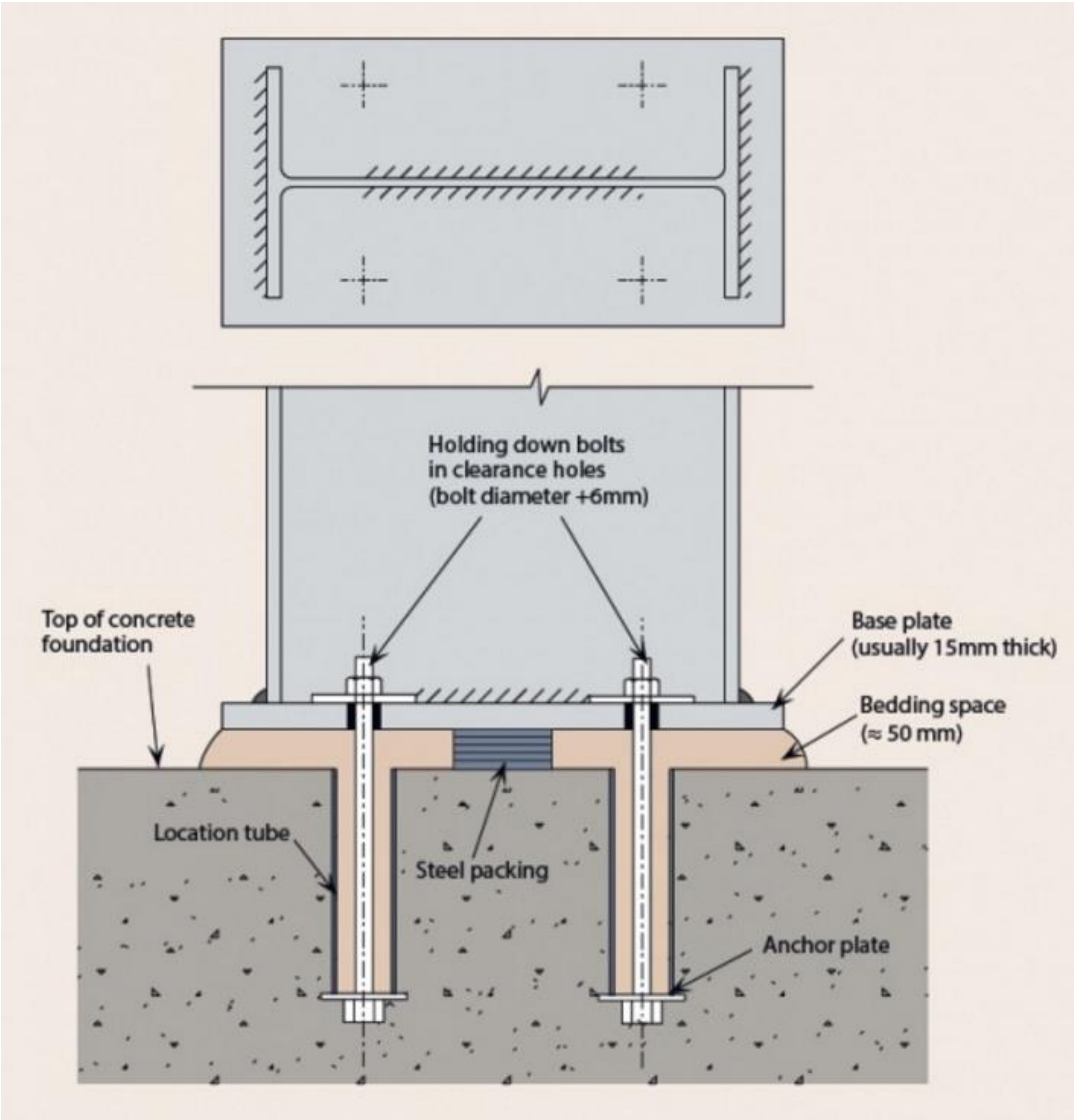


Figure 20. Typical pinned base.

A rigid base is usually carried out by providing a bigger level arm for the bolts and by increasing the plate thickness. Additional gusset plates may be required for bases subject to large bending moment. In spite of the big price of the rigid base, in Russia it is widely used. Figure 21 shows a typical rigid base.

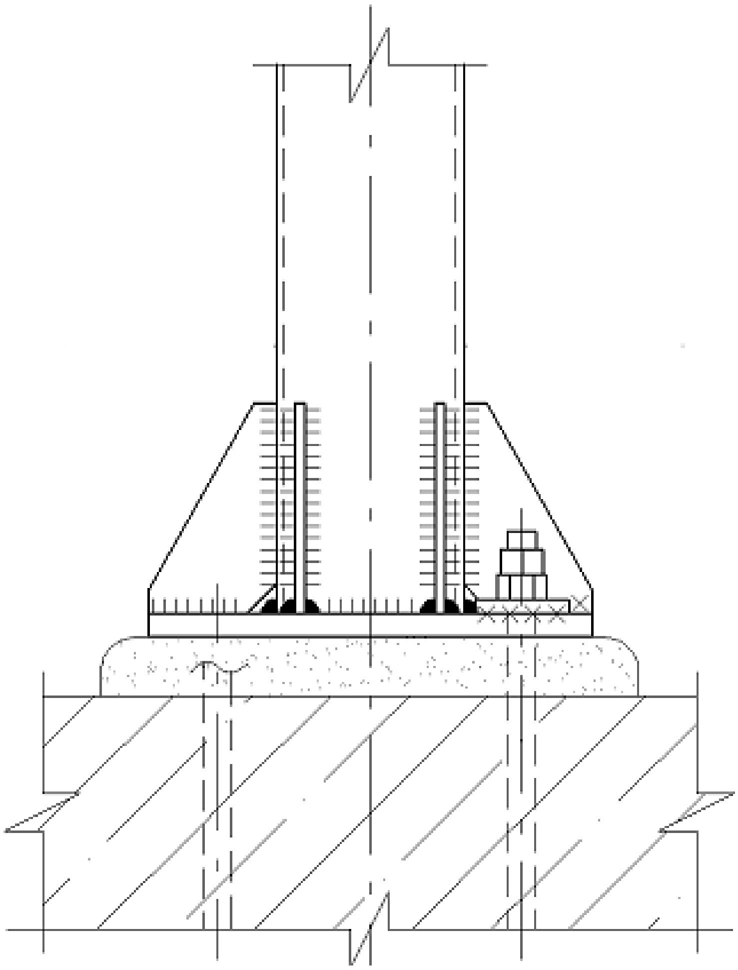


Figure 21. Typical rigid base.

Beam to column connection

In a beam and column structure, the connections are nominally pinned and are not assumed to transfer any moments between the connected members. Pinned connections are relatively easy (and cheap) to fabricate. Figure 22 shows a typical beam to column pinned connection in Russia.

This connection may be rigid as well. Rigid connection is more complicated, because it requires much more expensive steelwork details and welding. Figure 23 shows this type of a connection.

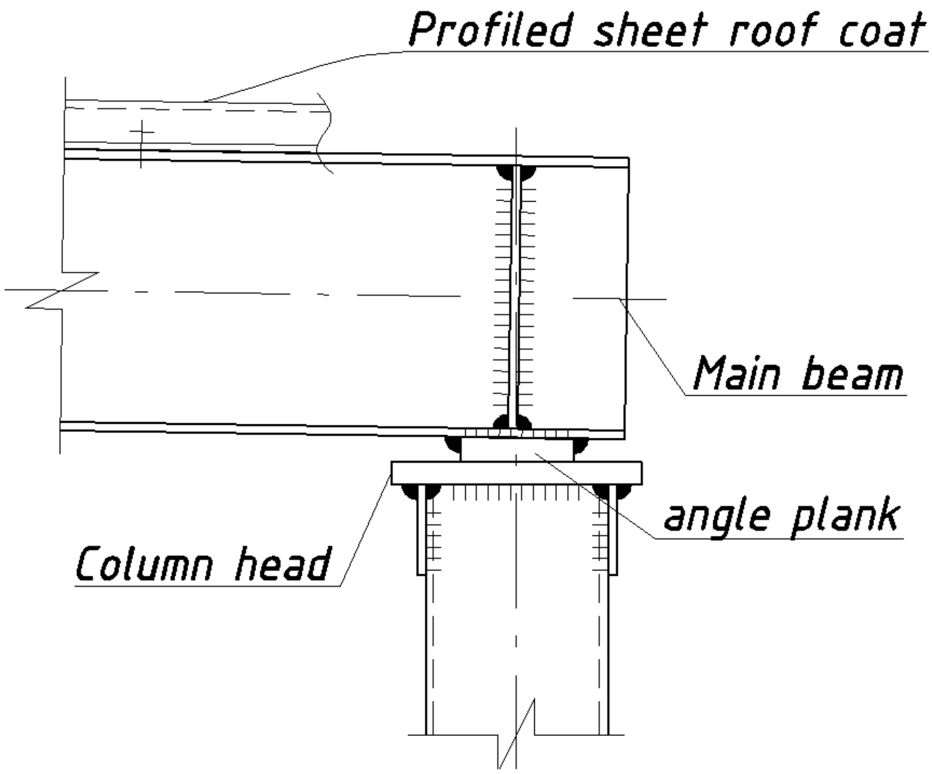


Figure 22. Beam to column pinned connection

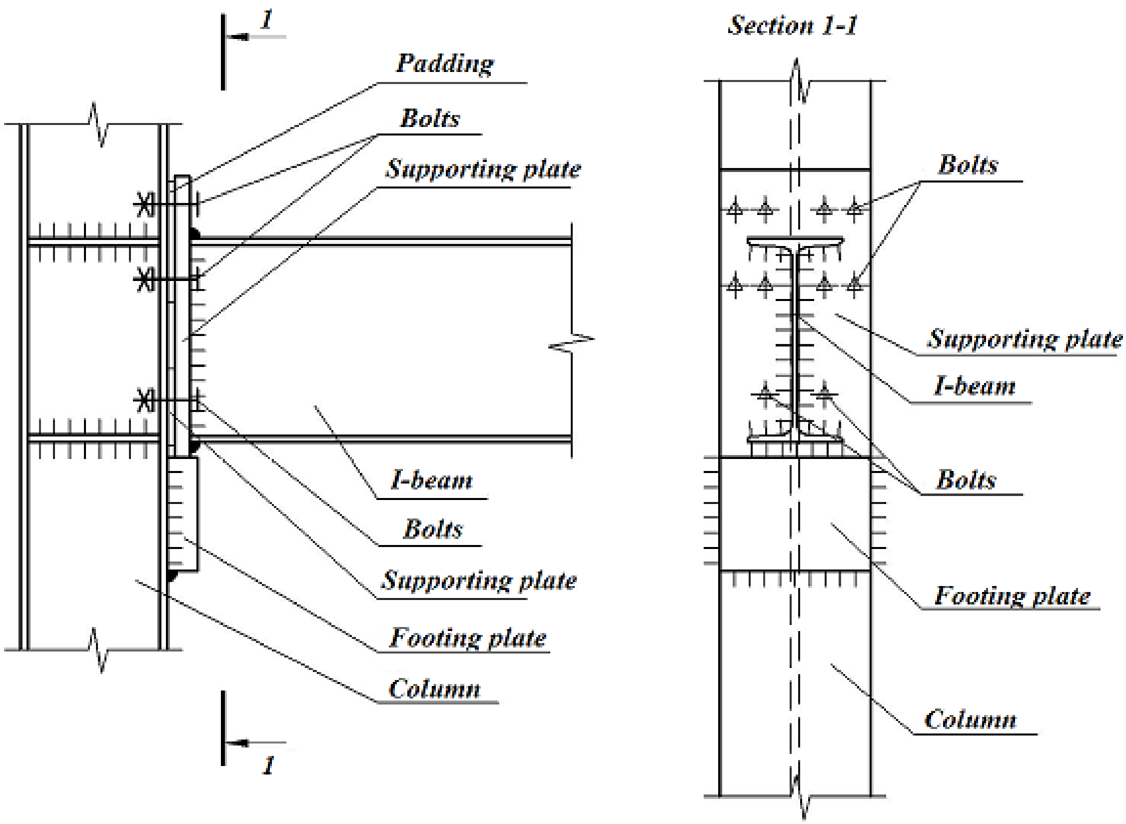


Figure 23. Beam to column rigid connection

Beam to beam connection

Secondary beam (purlin) to main beam (rafter) connection is usually pinned, as well as additional bracing to secondary beam connection. Bracing to main beam connection should be pinned as well. Their main purpose is to transmit loads to main beams and columns, not to redistribute efforts. Figure 24 and Figure 25 show connections between main beam, secondary beams and bracings.

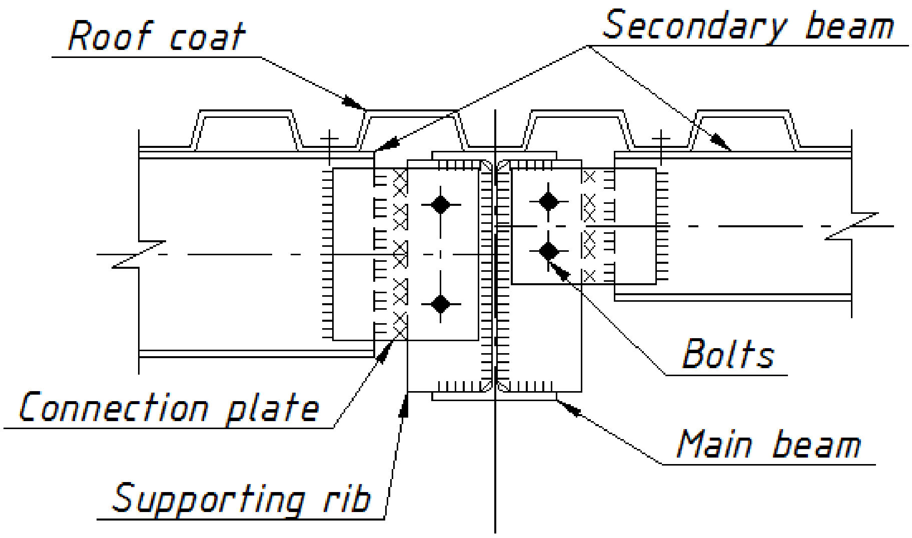


Figure 24. Typical secondary beam to main beam connection

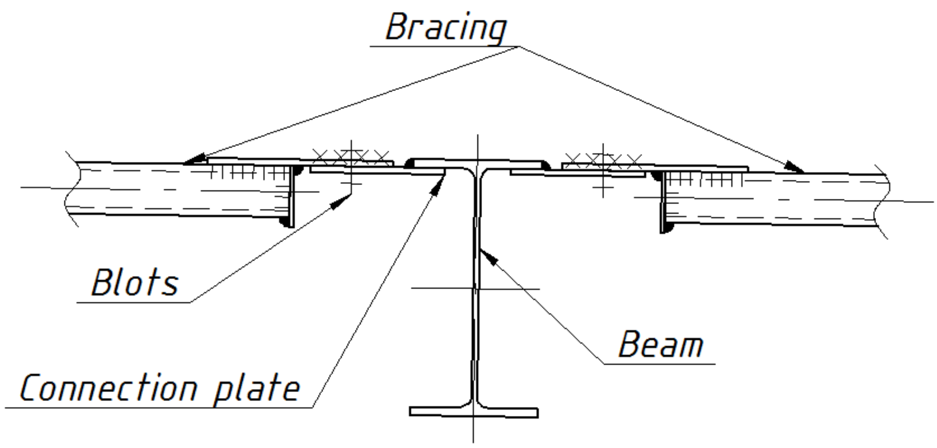


Figure 25. Bracing to beam (main or secondary) connection

4.3 Possible design variations

Based on the results of the previous paragraphs, it is required to calculate two principal cases:

1. Roofing system rest on three columns rows
2. Roofing system rest on two columns rows

Additionally, for each case different design diagrams must be calculated. The design diagram for the service building is a frame consisting of columns and main beam, interconnected by secondary beams and bracings. There are two main design diagrams for these frames:

- With rigid column base connection and pinned beam to column connection
- With pinned column base connection and rigid beam to column connection

These diagrams are shown on Figure 26.

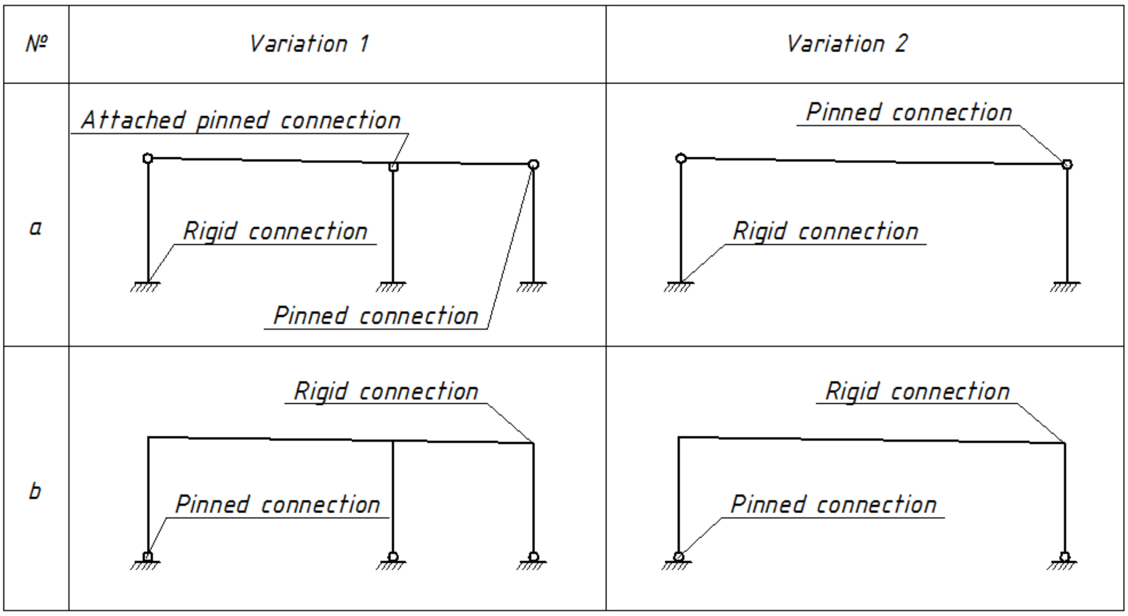


Figure 26. Frame diagrams for different design variations

For the first variation, the scheme in which the central pinned connection divides the main beam into two parts is not considered, because through beam is more economical. In the main beam above the attached pinned connection of the middle row column appears a support moment, which reduces the bending moment in the middle of the span. Moreover pinned connection scheme (pinned base connection and pinned beam to column connection) is not considered, because it makes substatic system, that brakes without vertical bracings.

To sum up, it is required to calculate four variants of design schemes and choose the most economical option, comparing them.

4.4 Load collection

Collection of loads was provided according to Russian set of rules SP 20.13330.2011 «Loads and actions». In this paragraph, the design loads on the service building frame (kg/m^2) are indicated.

<u>Permanent actions:</u>

1. Self-weight of metal structures (weight of the main beams, secondary beams, bracings)
   Self-weight of metal structures calculates automatically by LIRA-SAPR after choosing supposed sections and their properties.
2. Roof weight
   Figure 27 shows all roof components.

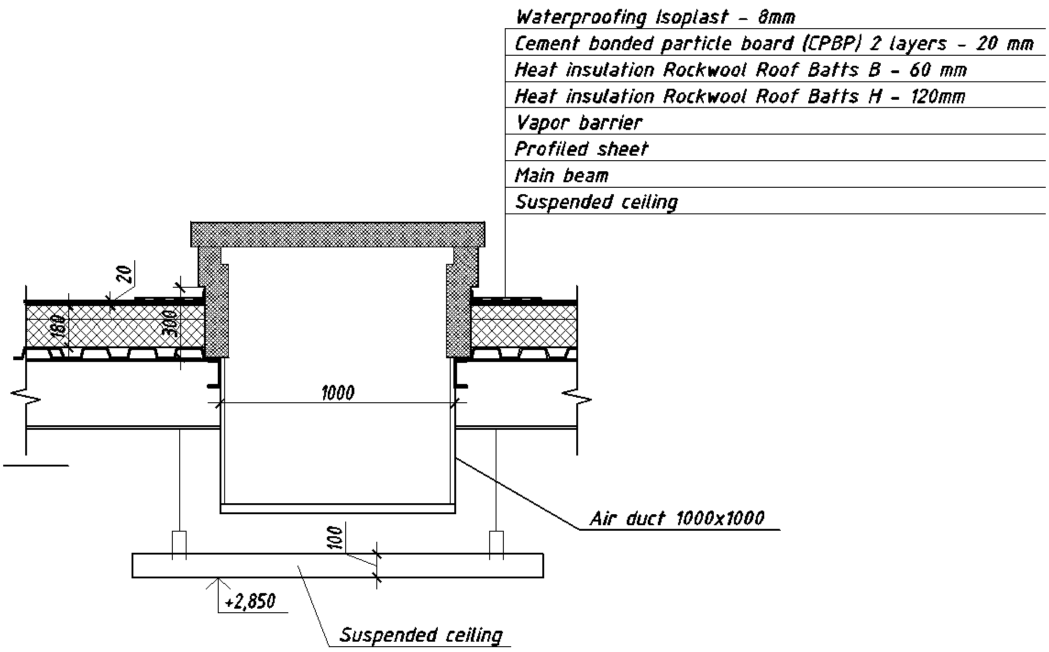


Figure 27. Roof components

- Waterproofing Isoplast, 8 mm thickness:

Density: p = 1250 kg / m^3

$$q_d = t \cdot \rho \cdot \gamma_m = 1250 \cdot 0.008 \cdot 1.3 = 13\frac{kg}{m^2} \tag{1}$$

- Cement bonded particle board (2 layers), 20 mm thickness:

Density: p = 1300 kg / m^3

$$q_d = t \cdot \rho \cdot \gamma_m = 1300 \cdot 0.02 \cdot 1.2 = 32\frac{kg}{m^2} \tag{2}$$

- Heat insulation Rockwool Roof Batts B, 60 mm thickness:

Density: p = 190 kg / m^3

$$q_d = t \cdot \rho \cdot \gamma_m = 190 \cdot 0.06 \cdot 1.3 = 15\frac{kg}{m^2} \tag{3}$$

- Heat insulation Rockwool Roof Batts H, 120 mm thickness:

Density: p = 115 kg / m^3

$$q_d = t \cdot \rho \cdot \gamma_m = 115 \cdot 0.12 \cdot 1.3 = 18\frac{kg}{m^2} \tag{4}$$

- Vapor barrier, PVC film

$$q_d = q_s \cdot \gamma_m = 3 \cdot 1.3 = 3.9\frac{kg}{m^2} \tag{5}$$

- Profiled sheet

$$q_d = q_s \cdot \gamma_m = 8 \cdot 1.05 = 8.4\frac{kg}{m^2} \tag{6}$$

- Suspended ceiling

$$q_d = q_s \cdot \gamma_m = 15 \cdot 1.3 = 19.5\frac{kg}{m^2} \tag{7}$$

Summary roof weight: q_d = 109.8 kg

Variable actions

3. People load when cleaning snow from the roof:

$$q_d = q_s \cdot \gamma_f = 50 \cdot 1.3 = 65 \frac{kg}{m^2} \quad (8)$$

4. Snow load (according to SP 20.13330.2011 «Loads and actions»):

Service value of snow load:

$$S^s = 0,7 \cdot c_e \cdot c_t \cdot \mu \cdot S_g = 0,7 \cdot 0.77 \cdot 1 \cdot 1 \cdot 180 = 97 \frac{kg}{m^2} \quad (9)$$

c_e – coefficient that takes into account the demolition of snow from the cover of buildings under the influence of wind or other factors;

c_t – thermal coefficient;

μ – the conversion factor from the weight of the snow cover of the ground to the snow load on the roof cover;

Sg – Weight of snow cover on 1 m^2 of the horizontal surface of the earth

Sg = 180 kg/m^2 (III snow region) – Table 10.1 to SP 20.13330.2011 «Loads and actions» [6].

$$c_e = \left(1,2 - 0,1 \cdot V\sqrt{k}\right) \cdot (0.8 + 0.002b)$$
$$= \left(1,2 - 0,1 \cdot 4\sqrt{0,5}\right) \cdot (0.8 + 0.002 * 18,9) = 0.77 \quad (10)$$

V - average winter wind speed (for Saint Petersburg V = 4 m/s)

k = 0.5 (At a height of <5 meters and type of terrain B) – table 11.2 SP 20.13330.2011 «Loads and actions» [6].

c_t = 1

μ = 1 – ($\alpha = 0^0 \leq 30^0$)

Design value of snow load:

$$S^d = S^s \cdot \gamma_f = 97 \cdot 1.4 = 136 \frac{kg}{m^2} \quad (11)$$

5. Wind load:

Service value of wind load formula:

$$W = W_m + W_p \tag{12}$$

Service value of wind load averege component formula:

$$W_m = W_0 \cdot k(z_e) \cdot c \tag{13}$$

Service value of wind pressure:

W_0 = 0,30 кПа (II wind region)

The coefficient that takes into account the change in wind pressure for building height z_e:

k (z_e) = 0.5 (At a height of <5 meters and type of terrain B) – table 11.2 SP 20.13330.2011 «Loads and actions» [6].

Equivalent height: z_e = h = 4.1 meters

Aerodynamic coefficients:

- For the windward side: c = 0,8
- For the leeward side: c = – 0,5

Service value of the wind load averege component:

- For the windward side
$$W_m = W_0 \cdot k(z_e) \cdot c = 0.3 \cdot 0.5 \cdot 0.8 = 0.12\ kPa \tag{14}$$
- For the leeward side
$$W_m = W_0 \cdot k(z_e) \cdot c = 0.3 \cdot 0.5 \cdot (-0.5) = 0.075\ kPa \tag{15}$$

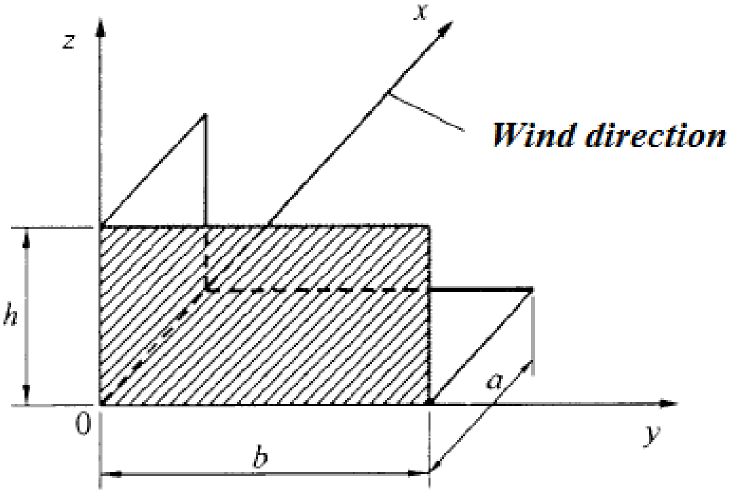
Service value of the wind load pulsating component formula:

$$W_p = W_m \cdot \zeta(z_e) \cdot v \tag{16}$$

Pulsating coeffitient of wind pressure for heigh z_e = h = 4.1 meters and type of terrain B: ζ(z_e) = 1,22

The coefficient of spatial correlation of wind pressure pulsations is determined for the design surface of the structure parallel to the coordinate plane ZoY (ρ = b = 18,9 meters, χ = h = 4,1 meters). Figure 28 shows surfaces of the structure

v = 0,845



Main coordinate plane, design surface parallel to	ρ	χ
zoy	*b*	*h*
zox	0,4*a*	*h*
xoy	*b*	*a*

Figure 28. Surfaces of the structure and table of coefficients

Service value of the wind load pulsating component:

- For the windward side

$$W_p = W_m \cdot \zeta(z_e) \cdot v = 0{,}12 \cdot 1.22 \cdot 0{,}845 \;=\; 0{,}124 \text{ kPa} \qquad (17)$$

- For the leeward side

$$W_p = W_m \cdot \zeta(z_e) \cdot v =-0{,}075 \cdot 1.22 \cdot 0{,}845 \;=-\; 0{,}077 \text{ kPa} \qquad (18)$$

Service value of the wind load:

- For the windward side

$$W^s = W_m + W_p = 0{,}12 \;+\; 0{,}124 \;=\; 0{,}244 \text{ kPa} \qquad (19)$$

- For the leeward side

$$W^s = W_m + W_p = -0{,}075 - 0{,}077 = -0{,}152 \text{ kPa} \tag{20}$$

Design value of the wind load:

- For the windward side

$$W^d = W^s \cdot \gamma_f = 0.244 \cdot 1.4 = 0{,}342 \text{ kPa} \tag{21}$$

- For the leeward side

$$W^d = W^s \cdot \gamma_f = -0.152 \cdot 1.4 = 0{,}213 \text{ kPa} \tag{22}$$

4.5 First variation calculations

The first variation of the frame is a design diagram with a central row of columns. Two options are considered:

- With rigid column base connection and pinned beam to column connection
- With pinned column base connection and rigid beam to column connection. Figure 29 shows these design diagrams.

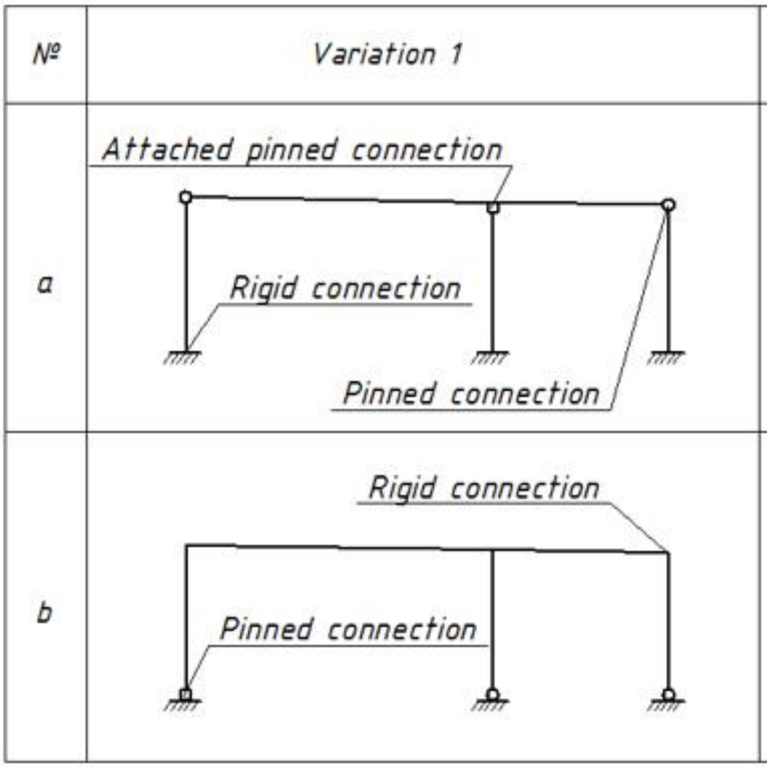


Figure 29. First variation design diagram options

4.5.1 Rrigid column base connection and pinned beam to column connection

Spatial design diagram, created in LIRA-SAPR, is shown on Figure 30.

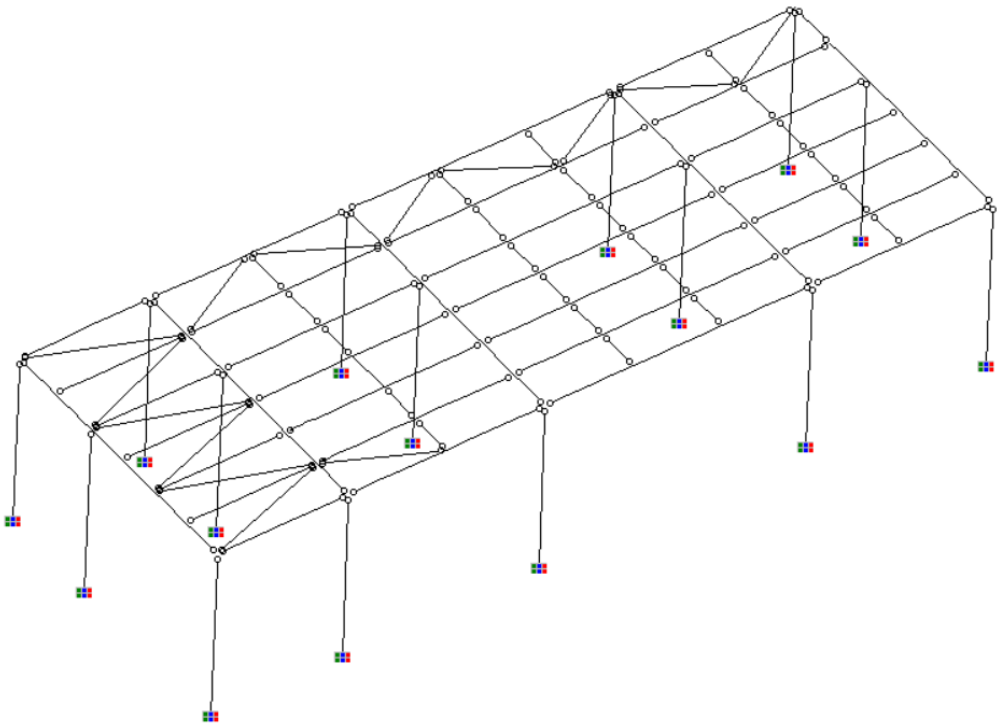


Figure 30. Spatial design diagram

Restraints (column bases) have a fastening from three displacements and three angles of rotation, which makes them rigid. There are hinges between beams and columns, main beams and secondary beams, bracings and beams that makes connections pinned.

For the selection of sections in LIRA-CAD for each element of the calculation scheme, it is required to determine such parameters as:

- Calculated length coefficient for buckling calculations (for compressed elements)
- Maximum allowed deflection
- Class of steel
- Cross section

For steel structures buckling coefficients are chosen according to table 30 SP 16.13330.2011 «Steel structures» [7]. Figure 31 shows those coefficients for different types of fastenings.

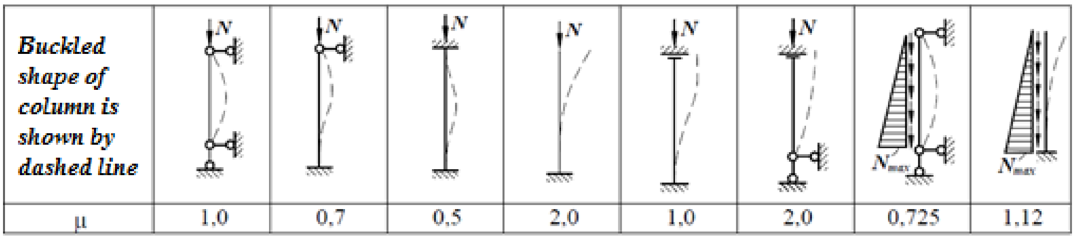


Figure 31. Buckling coefficients

The maximum allowable deflection is determined according to table E1 SP 20.13330.2011 «Loads and actions» [6]. For beams, trusses, purlins and girders, the aesthetic-psychological requirements for maximum allowed deflections are as follows:

- For 1-meter span: $f_u = \frac{1}{120} \cdot l$ (23)
- For 3-meter span: $f_u = \frac{1}{150} \cdot l$ (24)
- For 6-meter span: $f_u = \frac{1}{200} \cdot l$ (25)
- For 12-meter span: $f_u = \frac{1}{250} \cdot l$ (26)

In the previous paragraph (paragraph 4.2), the following types of sections are chosen:

- I-beam section
- Hollow structural section

Selection of sections is carried out in accordance with GOST 26020-83 «Hot-rolled steel I-sections with parallel shelfs, set», GOST 30245-2003 «Hollow structural sections, set».

The designations of the basic structures are shown on figures 32, 33.

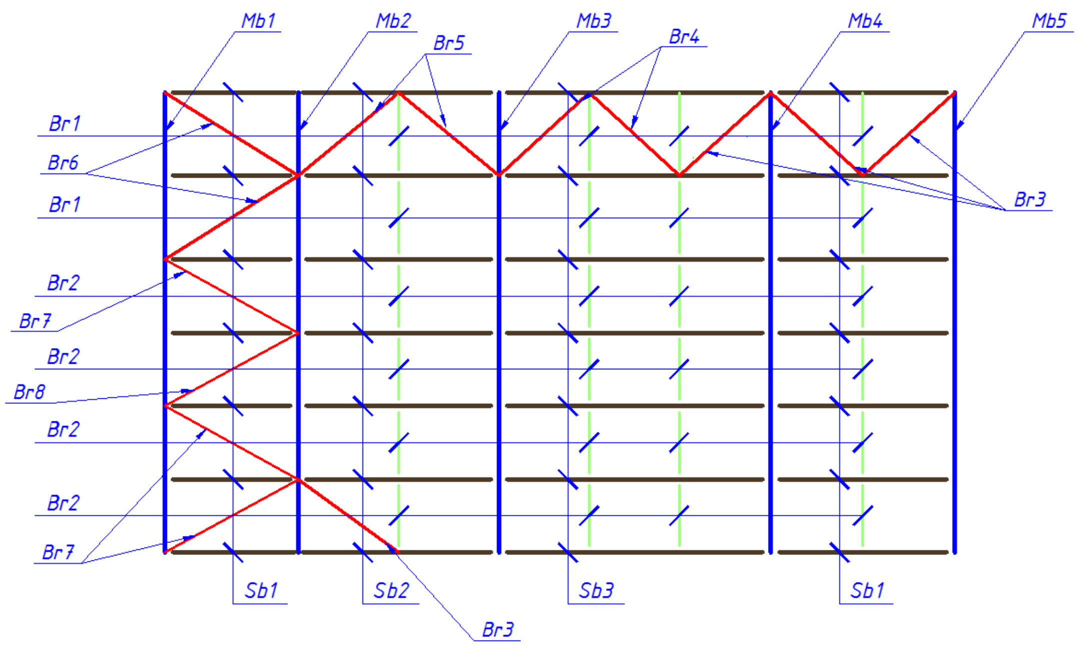


Figure 32. Roof structures designations

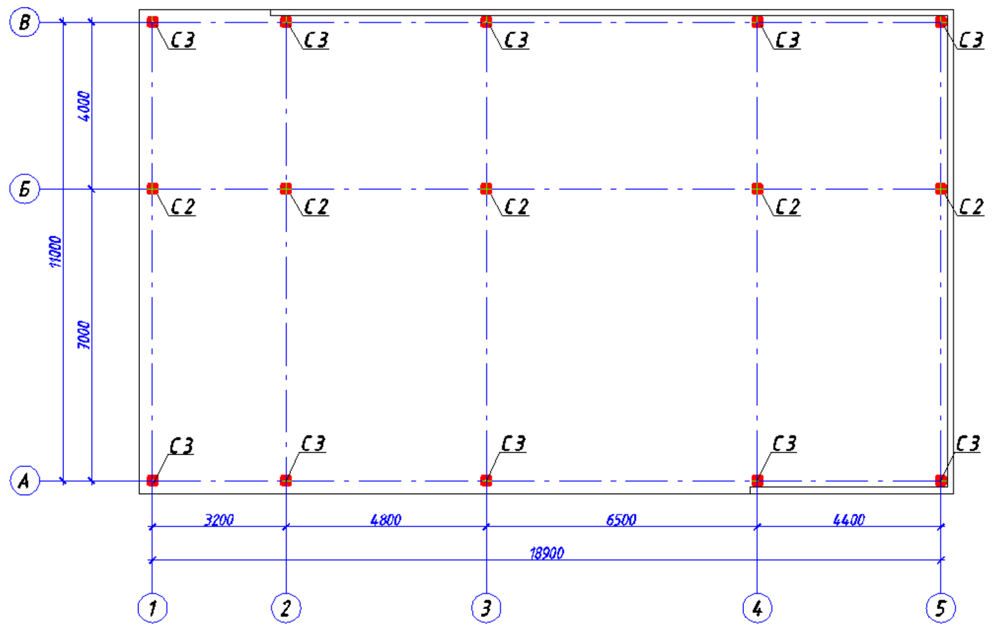


Figure 33. Columns designations

Primarily stiffnesses for the application of self-weight design loads, selected in accordance with similar projects for other regions (for all sections steel S235 is used):

- Main beams Mb1, Mb5 – I-section 26 B-1 (Mb1 and Mb5 beams have approximately the same spans, less than Mb2, Mb3, Mb4 beams).
- Main beams Mb2, Mb3, Mb4 – I-section 30 B-2
- Secondary beams: Sb1 - Sb4 – I-section 30 B-2
- Column C1, C2, C3 – I-section 20 K-1 (special sections for columns. Columns, which primarily resist compression, are usually thicker, shallower sections with wider flanges)
- Horizontal bracings Br1 - Br8 – hollow structural section 50x4 mm.

All loads calculated in the previous paragraph are applied in the form of linear loads. Vertical loads are applied to the columns. Horizontal loads are applied to the secondary beams. Secondary beams transfer them to the main beams. Main beams transmit them to the columns. Figure 34 shows load application to the service building structures.

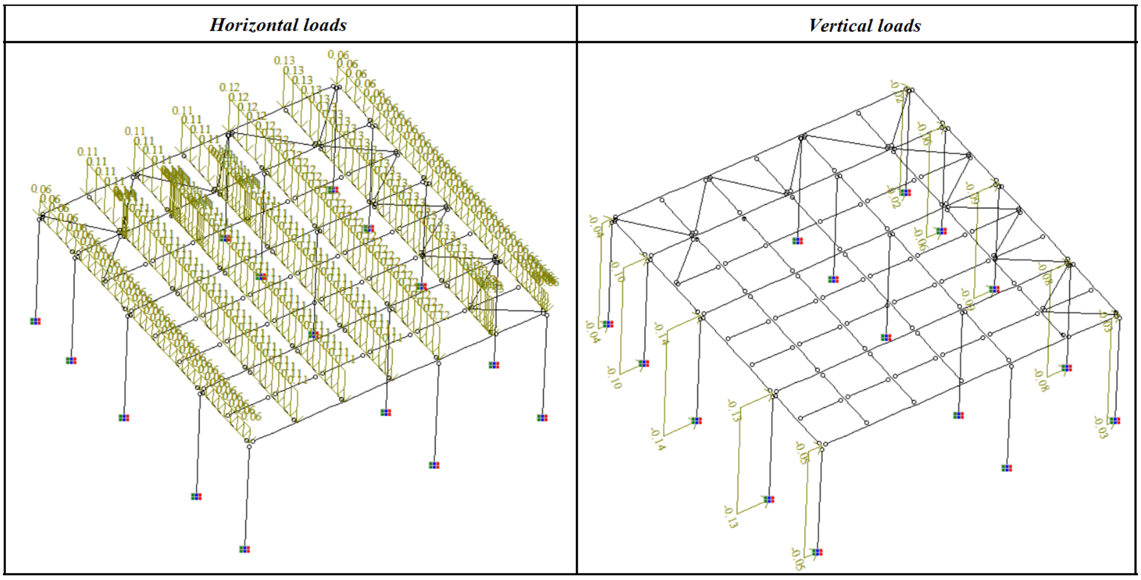
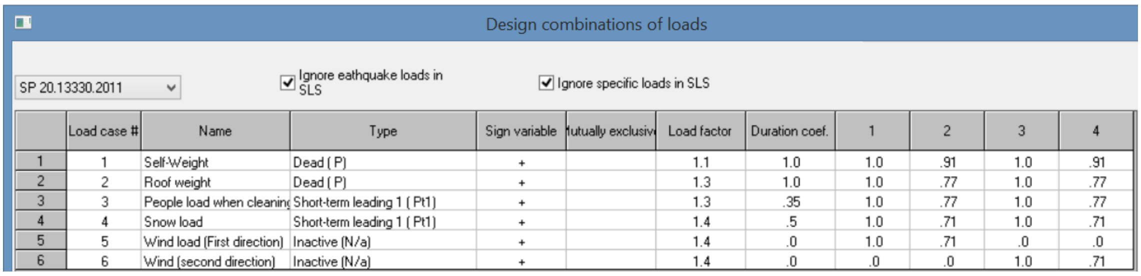


Figure 34. Load application to the service building structures.

The LIRA-SAPR calculates the forces in the elements by combinations of loads. Loads are specified as designed loads. To calculate the second group of limit states, an additional combination of loads is created, the combination coefficients of which are divided by the reliability coefficients. Figure 35 shows the main load combinations (two design load combinations with different wind directions –1,3; two service load combinations – 2,4).



Design combinations of loads

SP 20.13330.2011

☑ Ignore eathquake loads in SLS

☑ Ignore specific loads in SLS

	Load case #	Name	Type	Sign variable	lutually exclusiv	Load factor	Duration coef.	1	2	3	4
1	1	Self-Weight	Dead (P)	+		1.1	1.0	1.0	.91	1.0	.91
2	2	Roof weight	Dead (P)	+		1.3	1.0	1.0	.77	1.0	.77
3	3	People load when cleanin	Short-term leading 1 (Pt1)	+		1.3	.35	1.0	.77	1.0	.77
4	4	Snow load	Short-term leading 1 (Pt1)	+		1.4	.5	1.0	.71	1.0	.71
5	5	Wind load (First direction)	Inactive (N/a)	+		1.4	.0	1.0	.71	.0	.0
6	6	Wind (second direction)	Inactive (N/a)	+		1.4	.0	.0	.0	1.0	.71

Figure 35. Main load combinations

By load combinations, LIRA-SAPR calculates efforts and deflections in load-bearing structures. Figures 36-41 show the deformed model with mosaic of displacement along the vertical axis and effort diagrams.

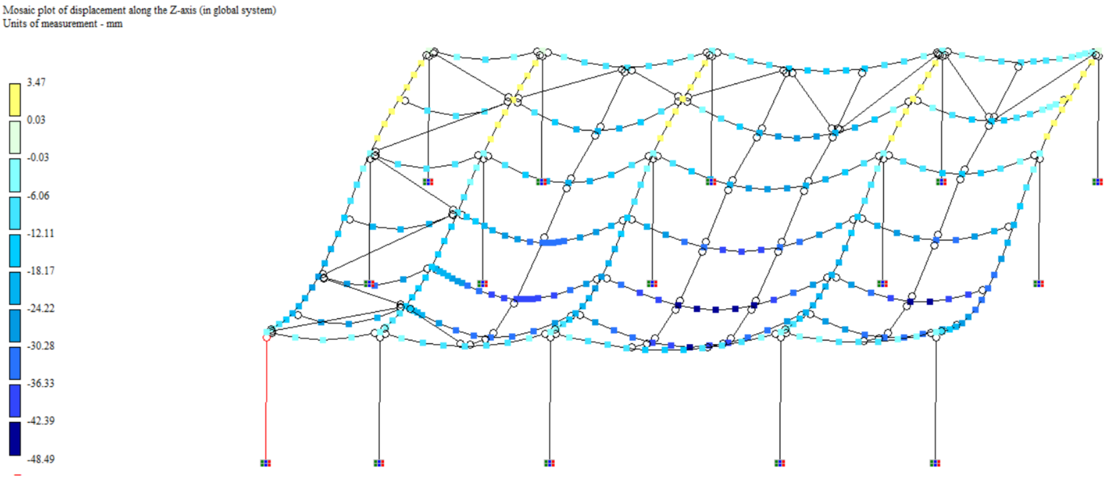


Figure 36. Deformed model with mosaic of displacement along the vertical axis

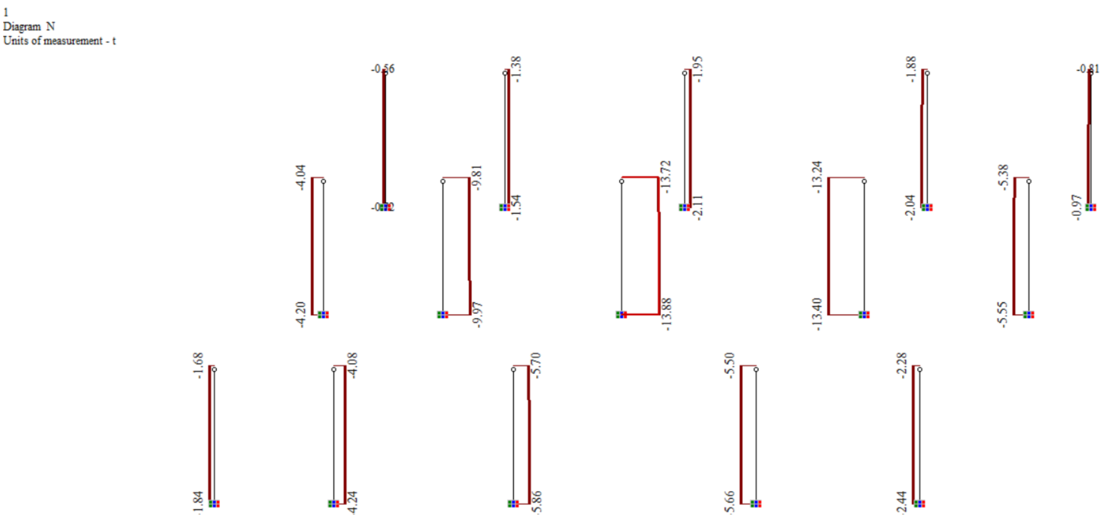


Figure 37. Diagram of longitudinal forces in columns N, t

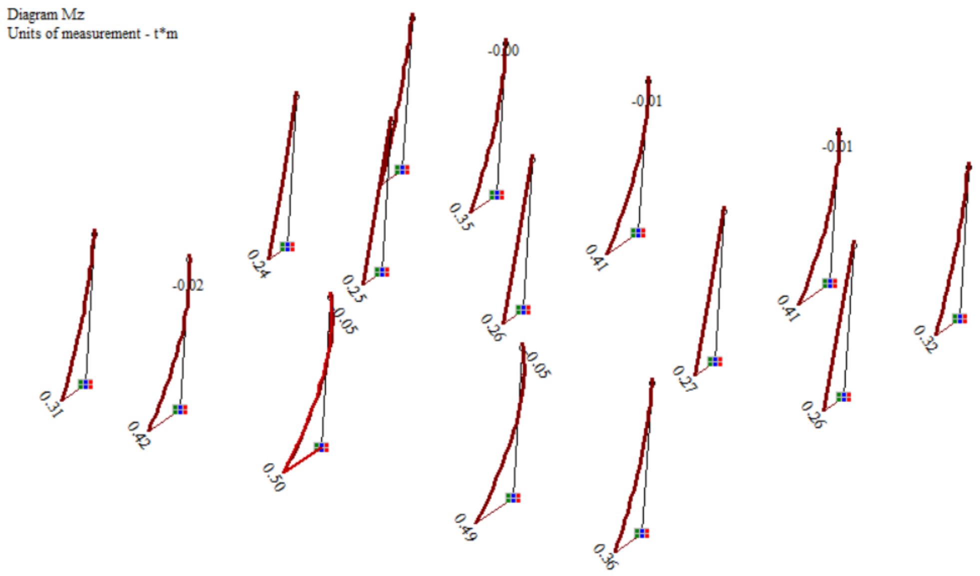


Figure 38. Diagram of bending moments in columns M_z, $t \cdot m^2$

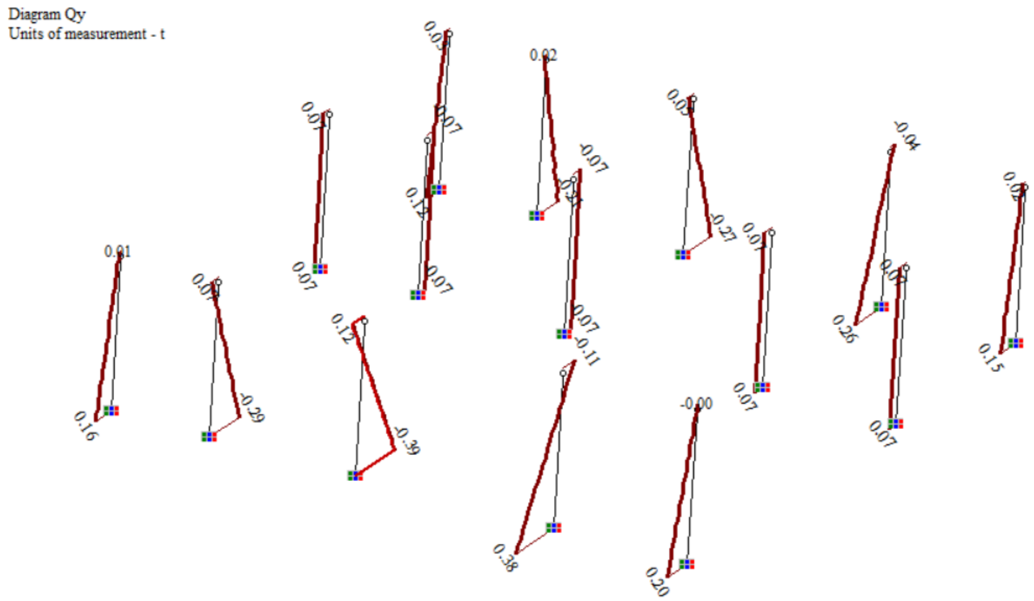


Figure 39. Diagram of horizontal forces in columns Q_y, t

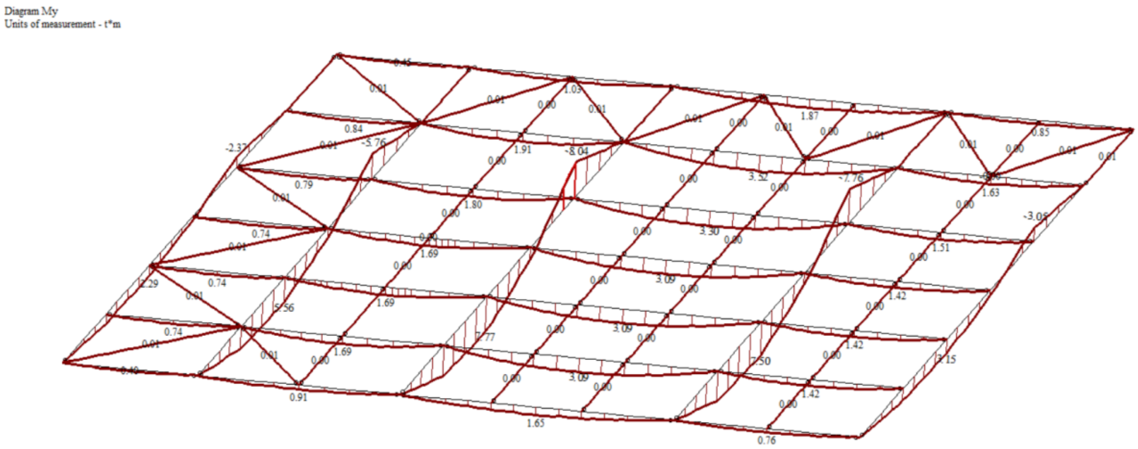


Figure 40. Diagram of bending moments in roof structures M_y, t·m

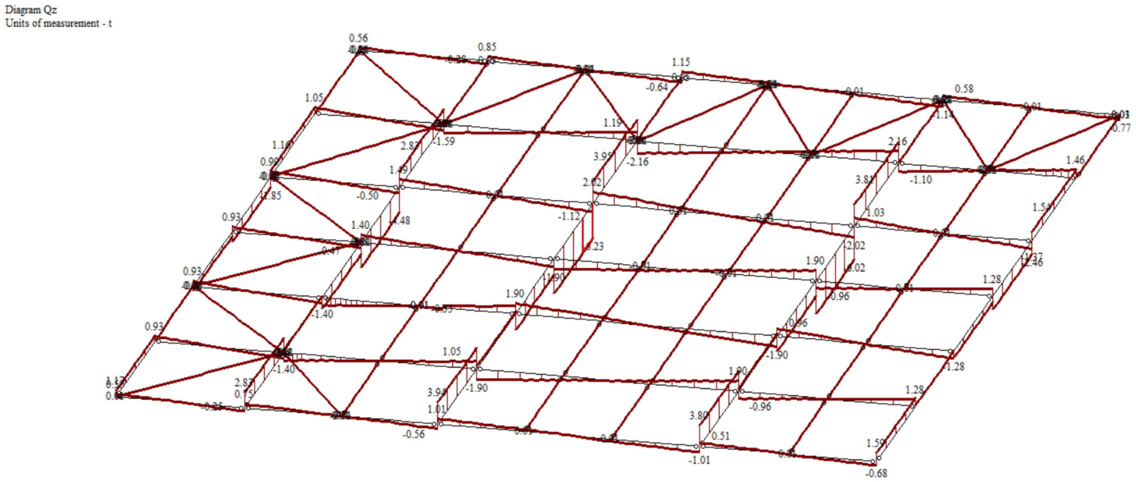


Figure 41. Diagram of horizontal forces roof structures Q_z, t

Maximum efforts and deflections in structures:

- Columns:
  - Longitudinal force N = 13.88 t (in the middle row column);
  - Bending moment M_y = 0.5 t·m;
  - Horizontal force Q = 0.38 t
- Main beam
  - Bending moment M_y = 8.04 t·m;
  - Horizontal force Q_z = 4.48 t
- Secondary beam
  - Bending moment M_y = 3.52 t·m;
  - Horizontal force Q_z = 2.16 t.

- Bracings set constructively.
- Diagram deflection is f_u = 48 mm.

In LIRA-SAPR, all analyzed sections of elements the following data is presented: results of checks for strength and buckling (by ultimate limit state), slenderness and deflection (serviceability limit state). Results are presented as utilization percentage of the section in comparison with ultimate bearing capacity by a certain check. That is, the result is always equal to:

$$Utilization\ percentage = \frac{100\% \cdot Maximum\ value}{Ultimate\ bearing\ capacity} \tag{27}$$

When generating analysis results, the concept 'utilization percentage' for ultimate limit state and for serviceability limit state is used.

Utilization percentage by ultimate limit state (ULS) — the greatest from percentages by checks for strength and buckling, taken from all design combinations of loads.

Utilization percentage by serviceability limit state (SLS) — the greatest from percentages by checks for ultimate slenderness or deflection, taken from all design combinations of forces.

Utilization percentage of section by local buckling (LB) — the greatest from percentages for buckling of web and flange, taken from all design combinations of forces.

Figures 42 – 44 show the utilization percentages of pre-selected sections (selected sections checking).

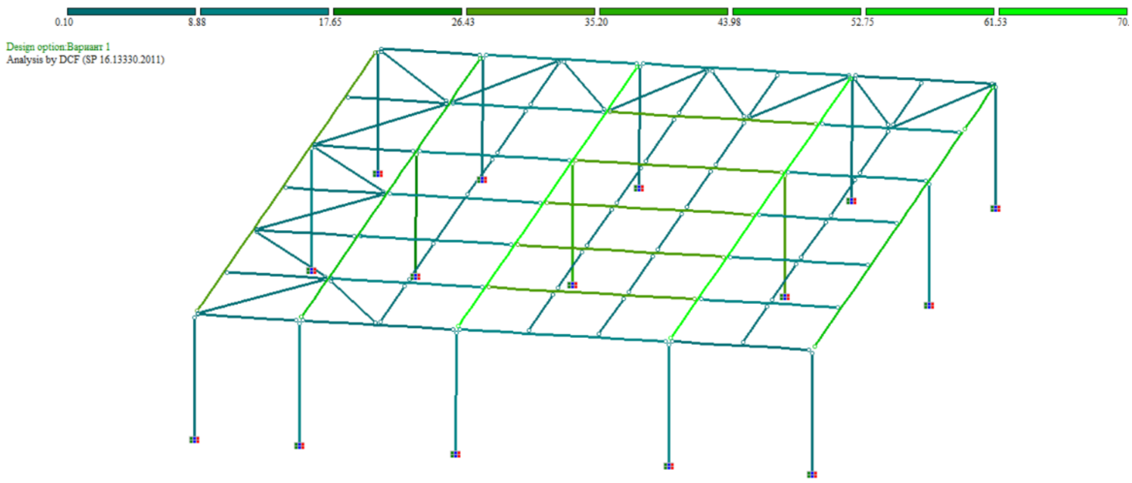


Figure 42. Utilization percentage of section by ultimate limit state, %

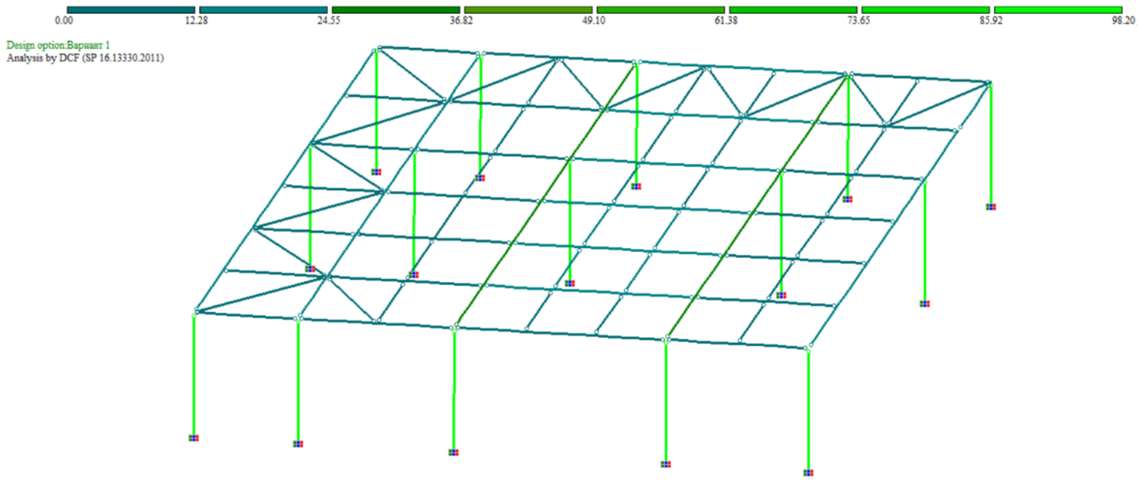


Figure 43. Utilization percentage of section by serviceability limit state,%

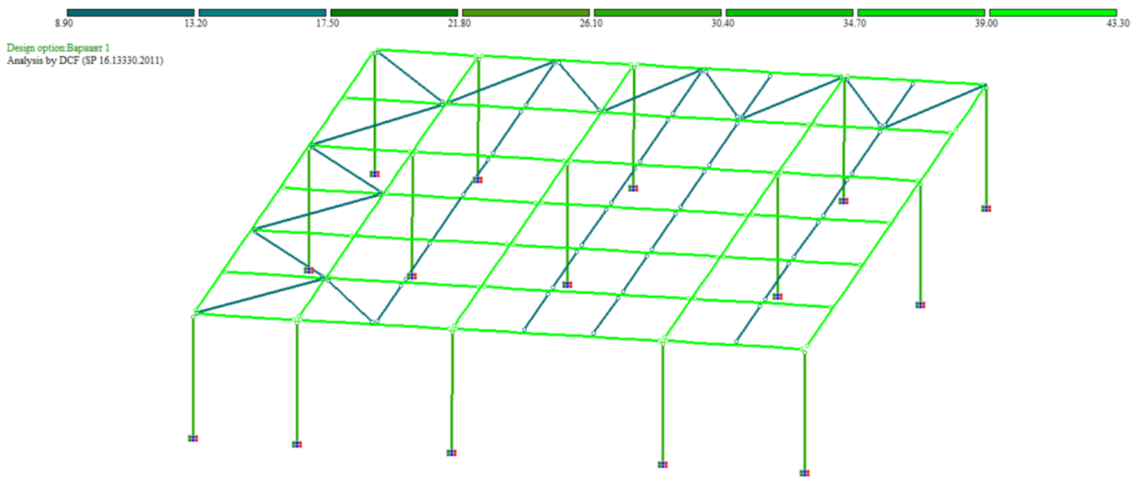


Figure 44. Utilization percentage of section by local buckling, %

The maximum utilization percentages for the main types of structures:

- Columns: U_{max} = 98.2% (by serviceability limit state)
- Main beams: U_{max} = 70% (by ultimate limit state)
- Secondary beams: U_{max} = 52.8% (by ultimate limit state)
- Horizontal bracings: U_{max} = 24.55% (by serviceability limit state)

According to the results of the section checking, we have large reserves in cross-sections, therefore, in order to reduce the total price of the framework more economical sections might be selected. Sections, offered by LIRA-SAPR have the biggest utilization percentage of section with the minimum margin of safety (within the range of the selected section type). Figure 45 shows these sections.

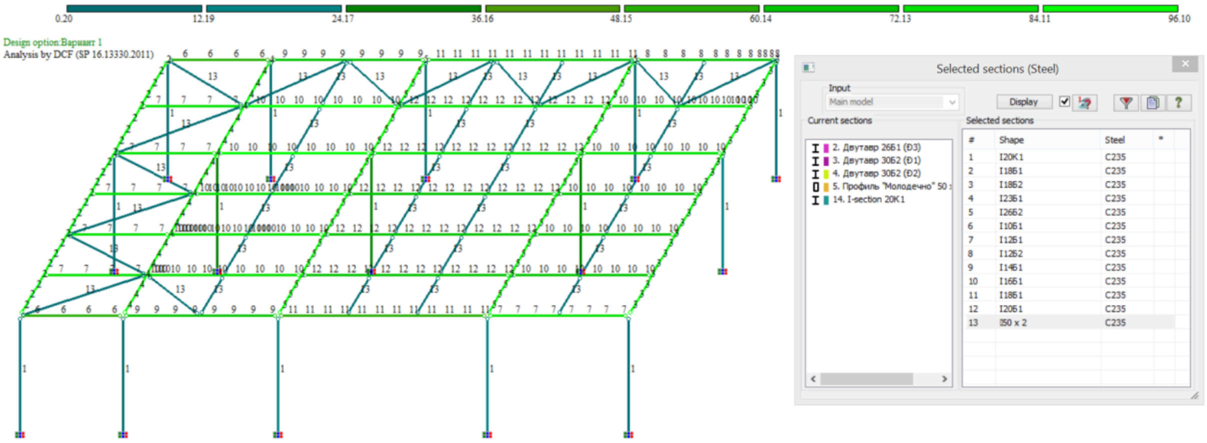


Figure 45. LIRA's proposed cross sections

For the convenience of transportation and installation, it makes sense to unify the following positions:

- Mb1,5 and Mb 2,3,4 – it has approximately the same bending moment
- Sb – Unify by spans (Sb1,Sb2,Sb3,Sb4)
- Columns – Unification of all columns. Columns have a different type, compare with other sections

According to the LIRA-SAPR results and unification, the following sections are selected:

- Main beams:
  - Mb1,5 – I-section for beams 18B1 (pre-selected section – I-section 26B1);
  - Mb2,3,4 – I-section for beams 26B2 (pre-selected section – I-section 30B2);
- Columns:
  - C1,2,3 – I-section for columns 20C1 (pre-selected section – I-section for columns 20C1 as well);
- Secondary beams
  - Sb1 – I-section for beams 12B1 (pre-selected section – I-section 30B2);
  - Sb2, Sb4 – I-section for beams 16B1 (pre-selected section – I-section 30B2);
  - Sb3 – I-section for beams 20B1 (pre-selected section – I-section 30B2);
- Bracings
  - Ab 1-8 – hollow structural section 50x4 (pre-selected section – hollow structural section 50x4)

When sections of elements are changed, the stiffness matrix of the main model is also changed and, as a result, forces in elements are changed. Therefore, the problem should be analysed again in LIRA with new stiffnesses.

Checking the accepted LIRA-SAPR section is shown in Figure 46.

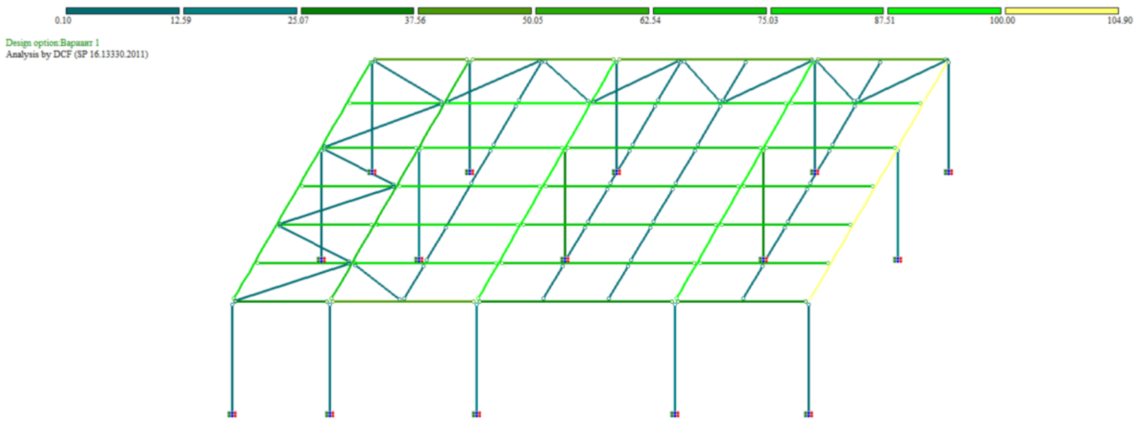


Figure 46. Utilization percentage of section by ultimate limit state, %. Checking the accepted sections

Main beam Mb5 has 104.9% utilization percentage. It means, that cross section might be increased. New I-section for beams 18B2 is selected. Figures 47-49 show checking selected sections after changing.

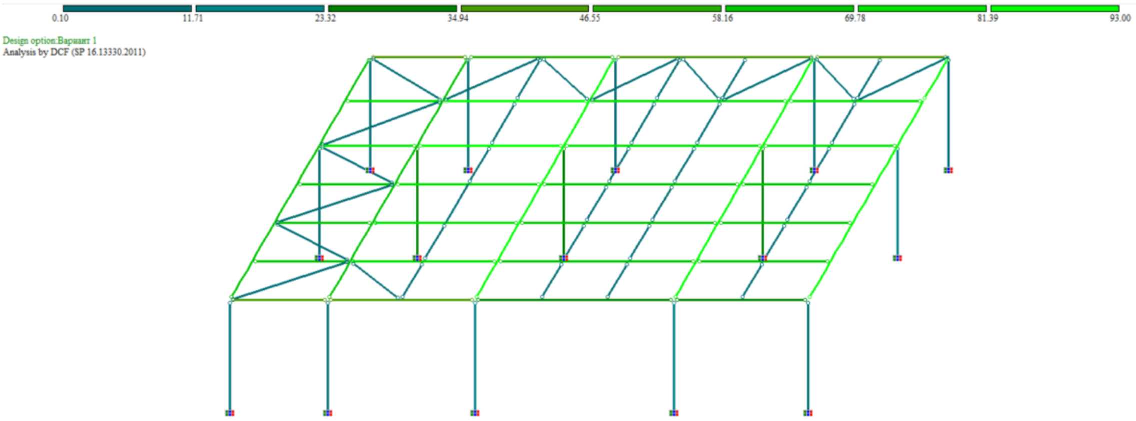


Figure 47. Utilization percentage of section by ultimate limit state, %. Checking selected sections after changing Mb5

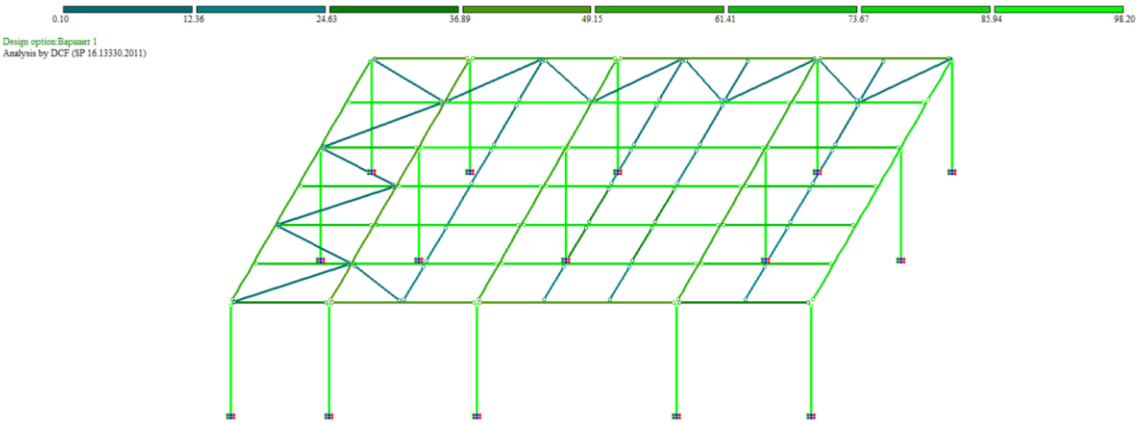


Figure 48. Utilization percentage of section by serviceability limit state, %. Checking selected sections after changing Mb5

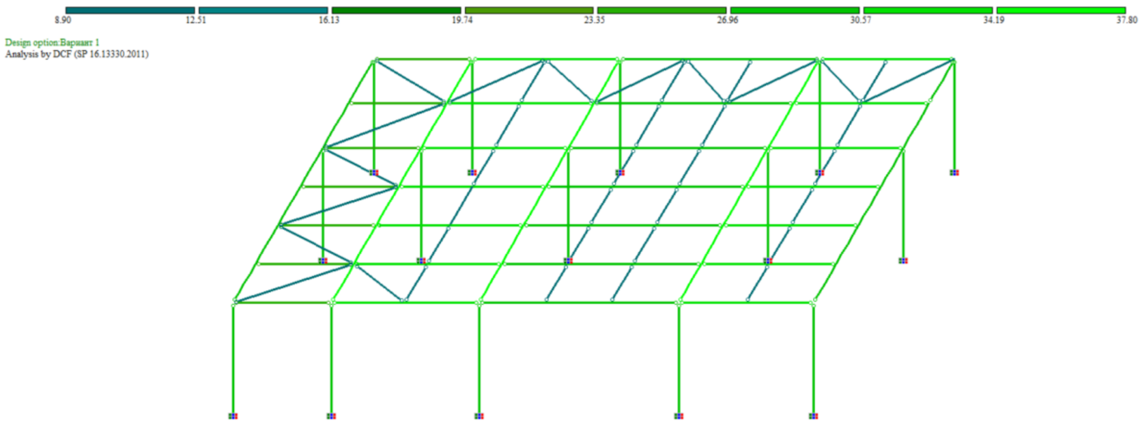


Figure 49. Utilization percentage of section by local buckling, %. Checking selected sections after changing Mb5

All sections have been checked, the variation is ready.

Also, one of the most common sections for a columns is a hollow structural section. It might be checked as well. In accordance with similar projects for other regions hollow structural section column 180x8 is chosen.

Figure 50 shows the chosen and LIRA-SAPR selected cross sections utilization percentages.

Figure 50. Chosen and LIRA-SAPR selected cross sections utilization percentages

LIRA offers a hollow structural cross-section 140x4. Hollow section 140x4 is accepted.

Table 2 shows the cost comparison of hollow section and I-section columns according to current prices for rolling steel products in Saint Petersburg.

Table 2. Cost comparison of hollow section and I-section columns

<table>
<tr><th>Mark</th><th>heigh, m</th><th>Quantity</th><th>Σ length, m</th><th>Section</th><th>W, t/m</th><th>Price rub/t</th><th>Column price, rub</th><th>Total price, rub</th></tr>
<tr><td colspan="9">I-section for columns</td></tr>
<tr><td>C1</td><td>3.65</td><td>5</td><td>18.25</td><td rowspan="3">I-20C1</td><td rowspan="3">0.042</td><td rowspan="3">53850</td><td>40785</td><td rowspan="3">119337</td></tr>
<tr><td>C2</td><td>3.55</td><td>5</td><td>17.75</td><td>39667</td></tr>
<tr><td>C3</td><td>3.48</td><td>5</td><td>17.4</td><td>38885</td></tr>
<tr><td colspan="9">Hollow structural section</td></tr>
<tr><td>C1</td><td>3.65</td><td>5</td><td>18.25</td><td rowspan="3">□140x4</td><td rowspan="3">0.017</td><td rowspan="3">44790</td><td>13700</td><td rowspan="3">40086</td></tr>
<tr><td>C2</td><td>3.55</td><td>5</td><td>17.75</td><td>13325</td></tr>
<tr><td>C3</td><td>3.48</td><td>5</td><td>17.4</td><td>13062</td></tr>
</table>

W – Weight of running meter of section

Based on the results of the cost comparison, it is obvious that the version with hollow section columns is 3 times cheaper. In the next variations calculations only hollow sections are selected for columns.

4.5.2 Pinned column base connection and rigid beam to column connection

Figure 51 shows spatial design diagram for this variation.

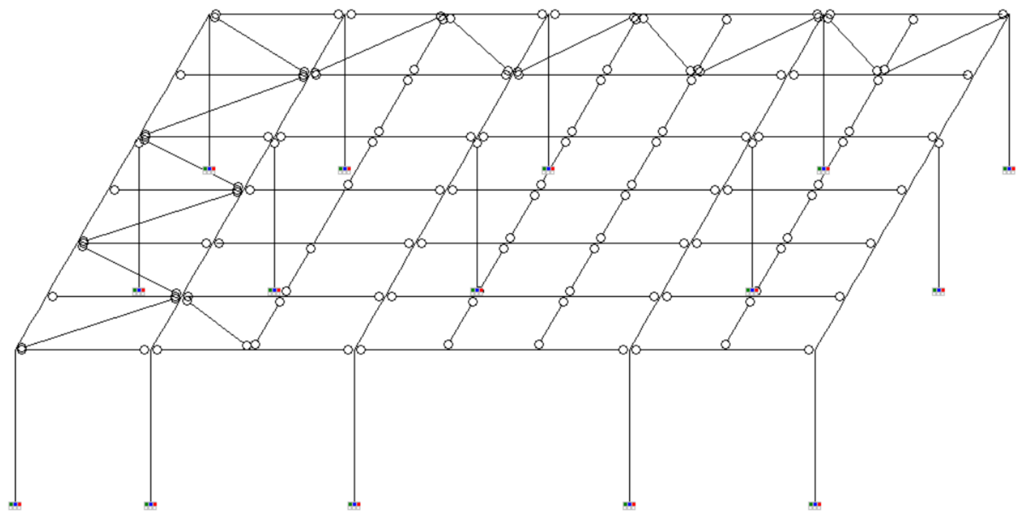


Figure 51. Spatial design diagram

Restraints (column bases) have a fastening from three displacements only, which makes them pinned. There are hinges between main beams and secondary beams, bracings and beams that makes connections pinned. Column to main beam connections are rigid.

For pinned column base connection and rigid beam to column connection diagram, the sections are preliminarily taken from the previous variation calculations. Loads and load combinations remained the same.

Figure 52 shows the deformed model with mosaic of displacement along the horizontal X-axis.

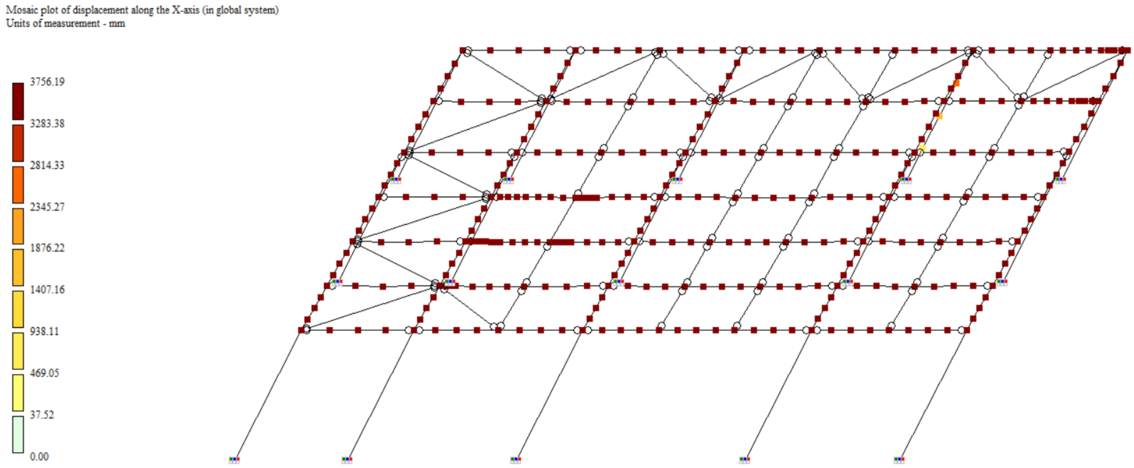


Figure 52. Deformed model with mosaic of displacement along the horizontal X axis

The horizontal displacements of the design diagram are enormous. This means that it is geometrically changeable and requires additional hardness bracings. Figures 53 and 54 show the new design diagram with bracings. Vertical bracings have the same cross section as all bracings in this project – 50x50x4 hollow section.

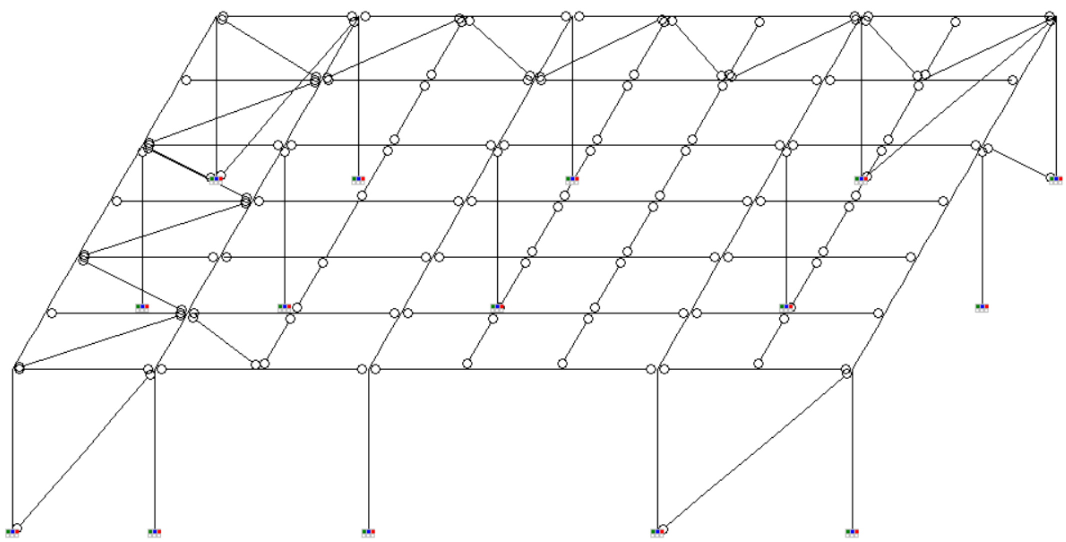


Figure 53. New spatial design diagram

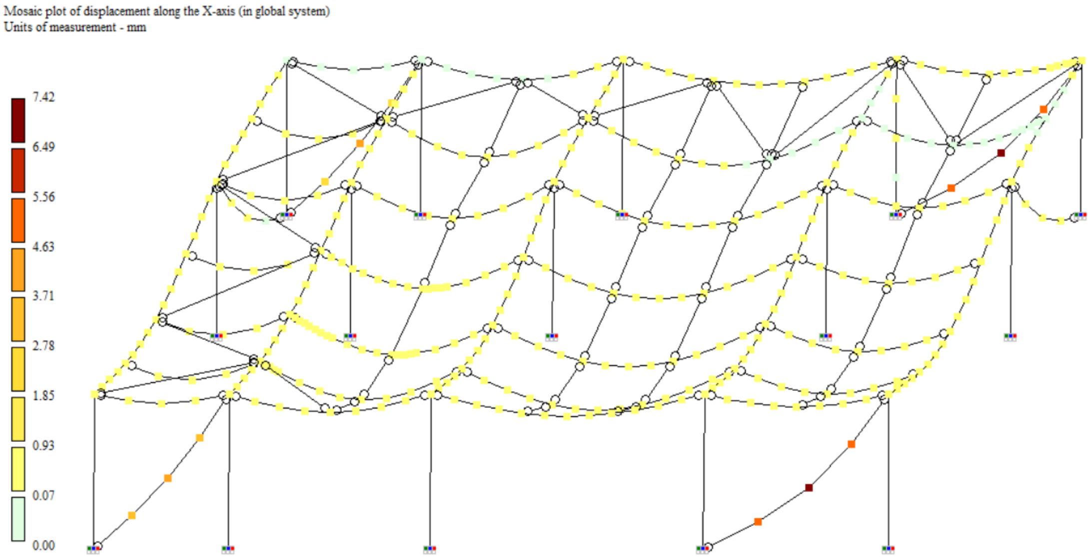


Figure 54. Deformed model with mosaic of displacement along the horizontal X-axis

New diagram with vertical bracings does not create large horizontal displacement. Vertical bracings do not allow the diagram to change geometrically.

Secondary beams are connected to the main beams hinged, and transfer the load to them. With the same loads and load combinations in the secondary beams the same bending moments and horizontal forces occur. Figures 54-60 show displacements and efforts in columns, main beams and vertical bracings

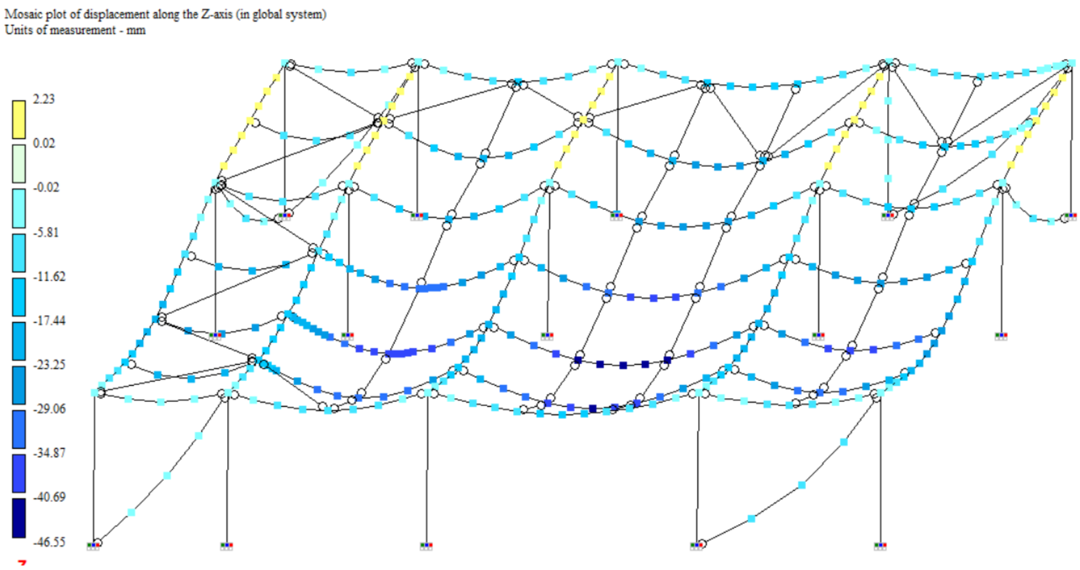


Figure 54. Deformed model with mosaic of displacement along the vertical Z-axis

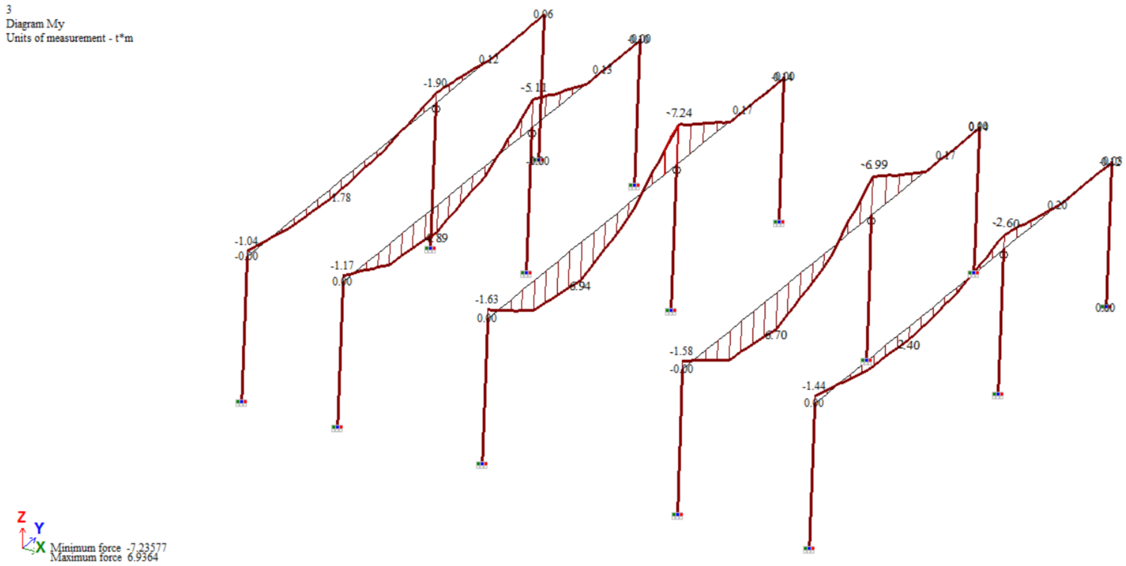


Figure 55. Diagram of bending moments in main beams M_y, t·m

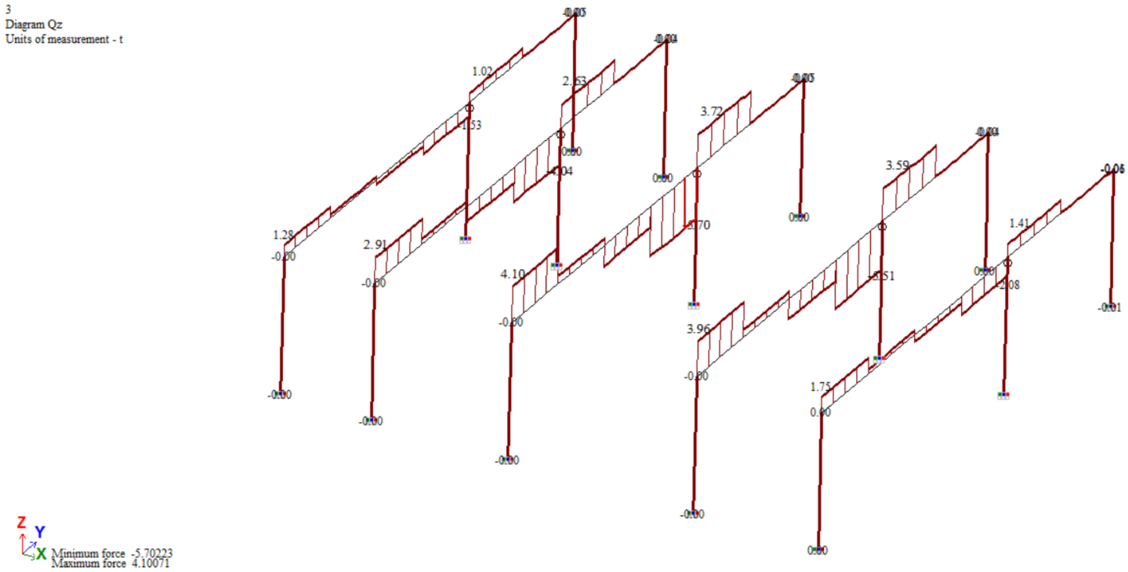


Figure 56. Diagram of horizontal forces in main beams Q_z, t

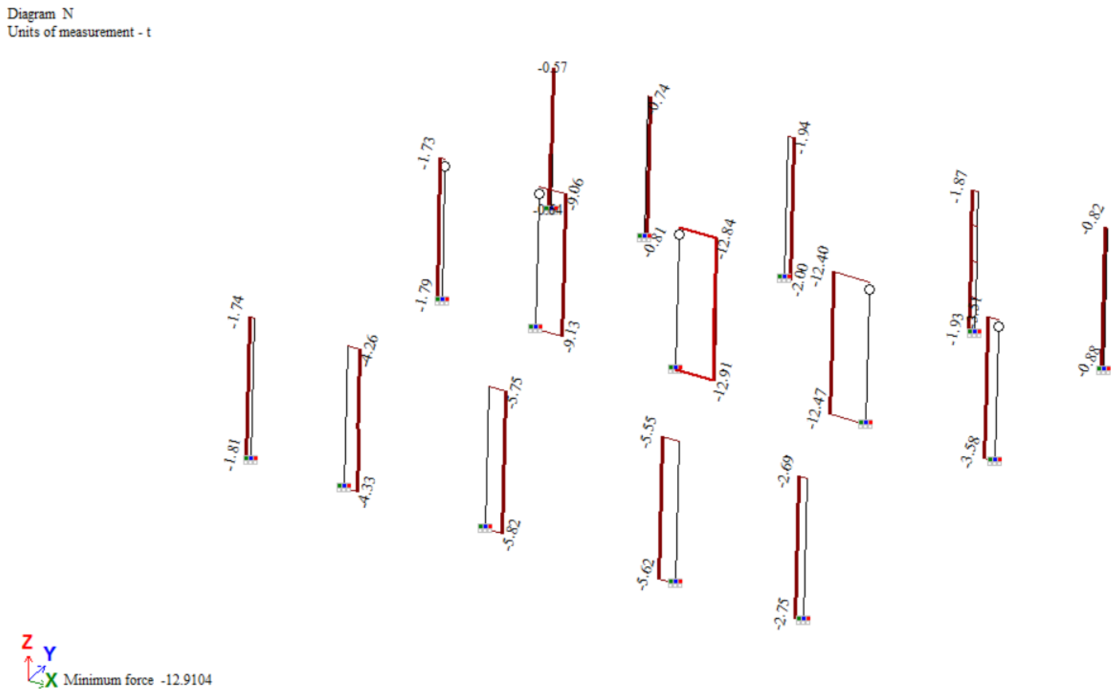


Figure 57. Diagram of longitudinal forces in columns N, t

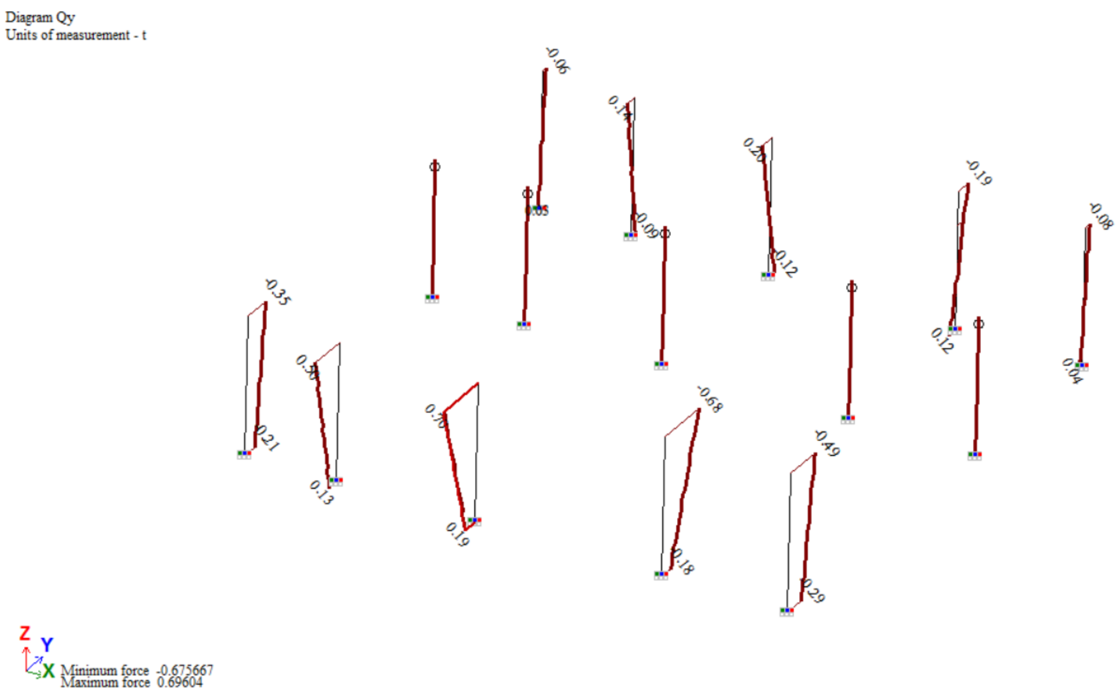


Figure 58. Diagram of horizontal forces in columns Q_y, t

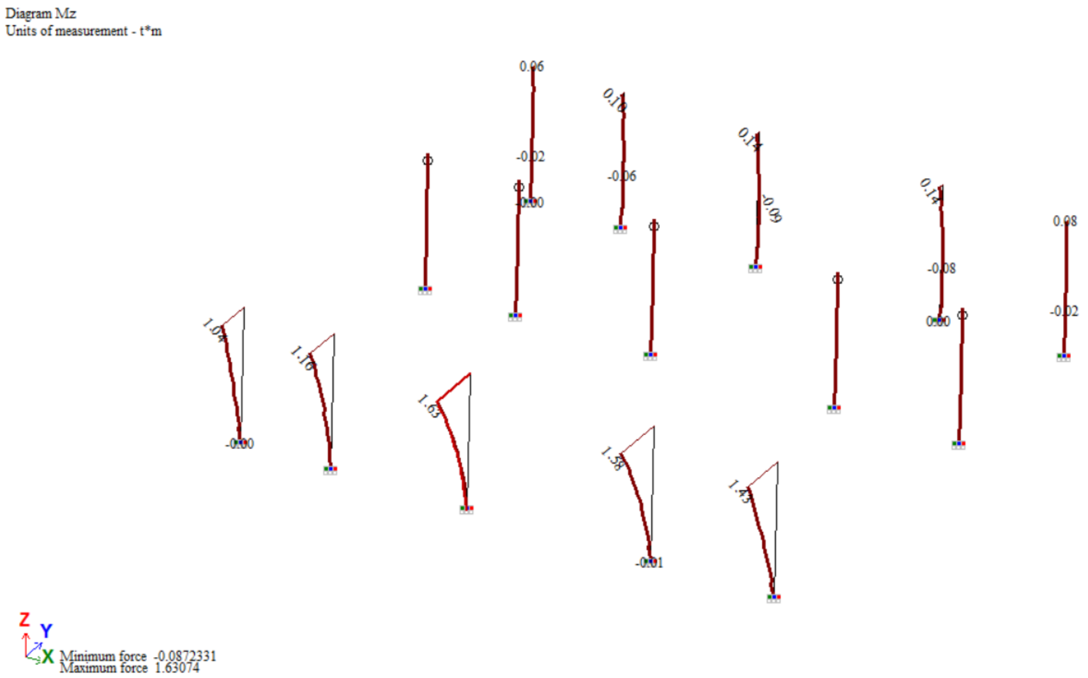


Figure 59. Diagram of bending moments in columns M_z, t·m

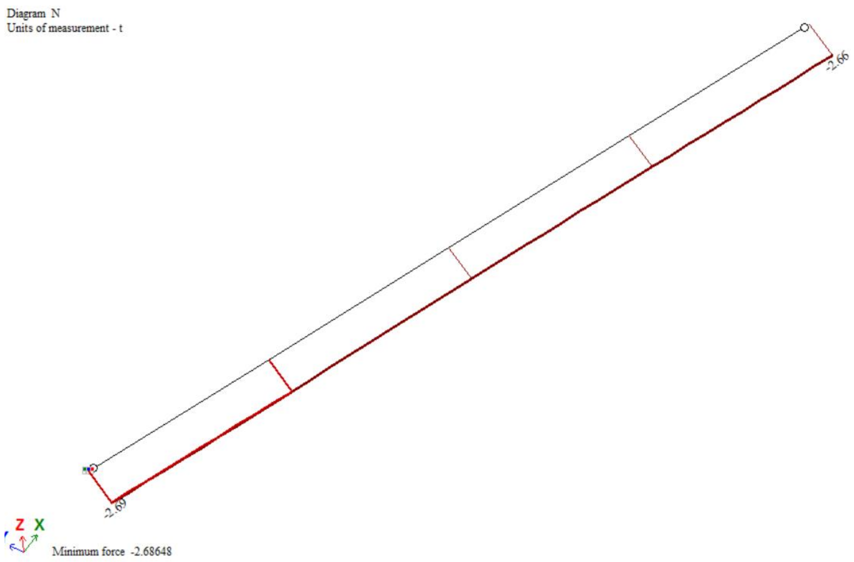


Figure 60. Diagram of maximum longitudinal force in vertical bracings N, t

Vertical bracings are perceived only longitudinal forces.

Maximum efforts and deflections in structures:

- Columns:
  - Longitudinal force N = 12.91 t

  - Bending moment M_y = 1.63 t·m; (3 times larger than in first variation)
  - Horizontal force Q = 0.7 t
- Main beam
  - Bending moment M_y = 7.24 t·m;
  - Horizontal force Q_z = 5.7 t
- Secondary beam (the same)
  - Bending moment M_y = 3.52 t·m;
  - Horizontal force Q_z = 2.16 t.
- Vertical bracings
  - Longitudinal force N = 2.69 t
- Horizontal bracings set constructively.
- Diagram deflection f_u = 46.55 mm.

Figures 61 – 63 show utilization percentages of pre-selected sections (selected sections checking).

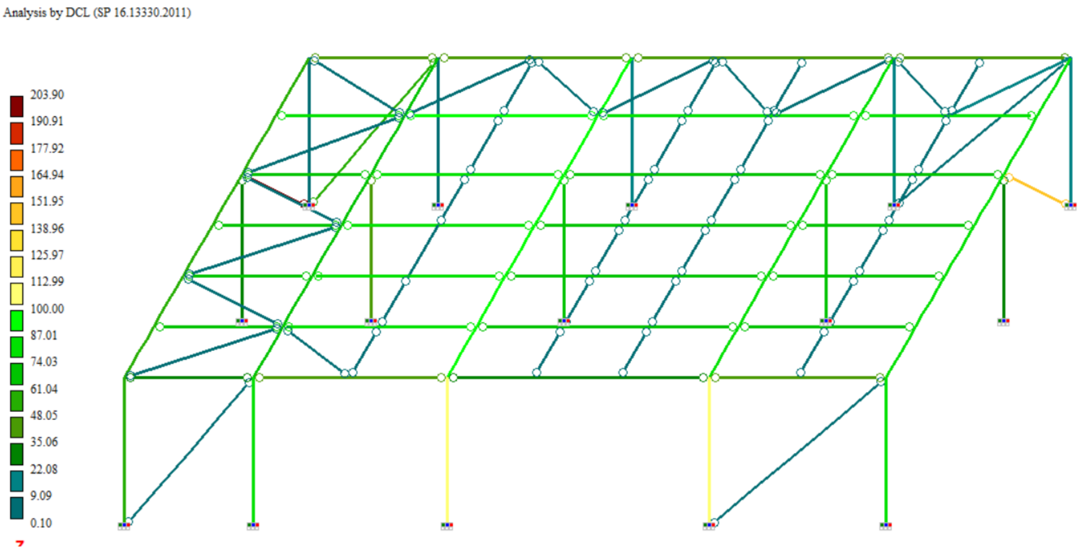


Figure 61. Utilization percentage of section by ultimate limit state, %

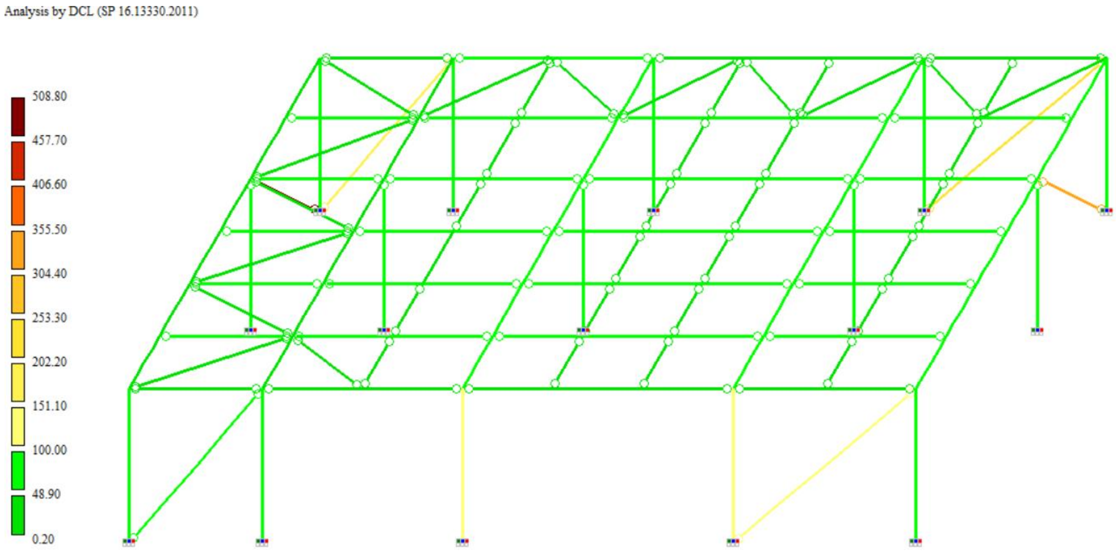


Figure 62. Utilization percentage of section by serviceability limit state,%

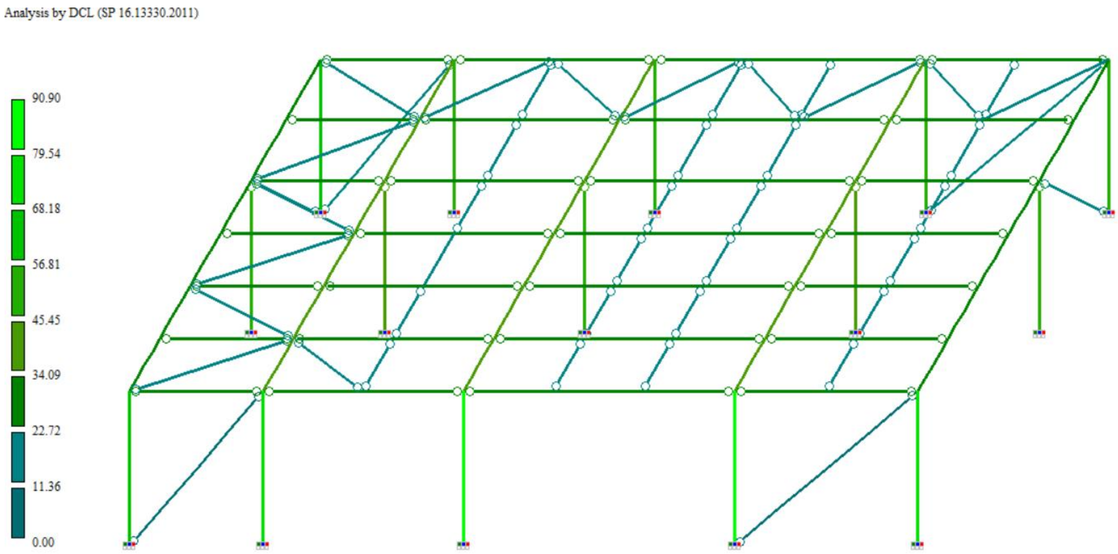


Figure 63. Utilization percentage of section by local buckling, %

Maximum utilization percentages for the main types of structures:

- Columns: U_{max} = 151% (by serviceability limit state)
- Main beams: U_{max} = 87% (by ultimate limit state)
- Secondary beams: U_{max} = 52.8% (by ultimate limit state)
- Horizontal bracings: U_{max} = 24.55% (by serviceability limit state)
- Vertical bracings: U_{max} = 508 % (by serviceability limit state)

According to the results of the section checking, we have to increase vertical bracings and columns cross-sections. The remaining sections in accordance with the results of LIRA-SPAR work as efficiently as possible. Figure 64 shows LIRA-SAPR proposed cross sections.

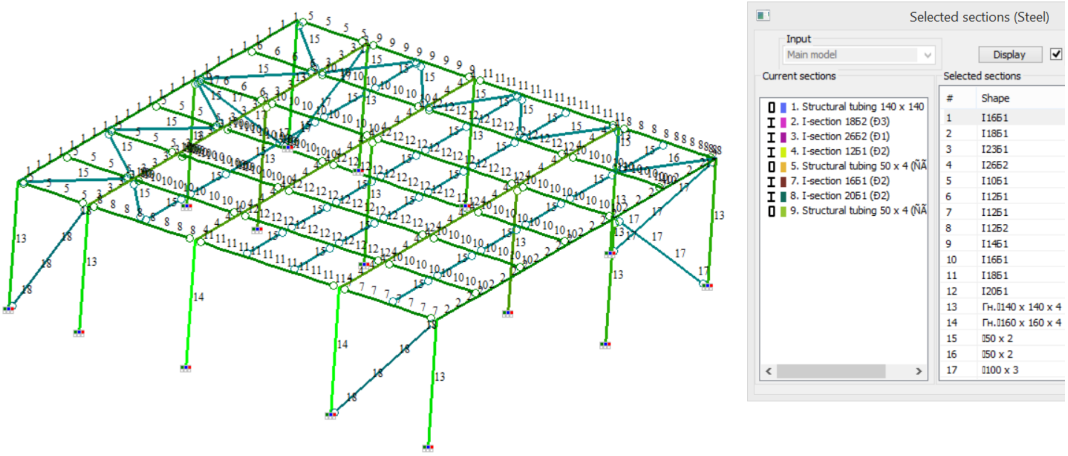


Figure 64. LIRA's proposed cross sections

According to the LIRA-SAPR results and unification, the following sections are selected:

- Main beams:
  - Mb1,5 – I-section for beams 18B2 (pre-selected section – I-section 18B2);
  - Mb2,3,4 – I-section for beams 26B1 (pre-selected section – I-section 26B2);
- Columns:
  - C1,2,3 – hollow section 160x5 (pre-selected section – hollow section 140x4);
- Secondary beams – the same.
- Bracings
  - Horizontal Ab 1-8 – hollow structural section 50x4 (pre-selected section – hollow structural section 50x4)
  - Vertical Vb 1-3 – hollow structural section 100x3 (pre-selected section – hollow structural section 50x4)

The task should be analysed again in LIRA with new stiffnesses.

Checking the accepted LIRA-SAPR section is shown in Figures 65-67.

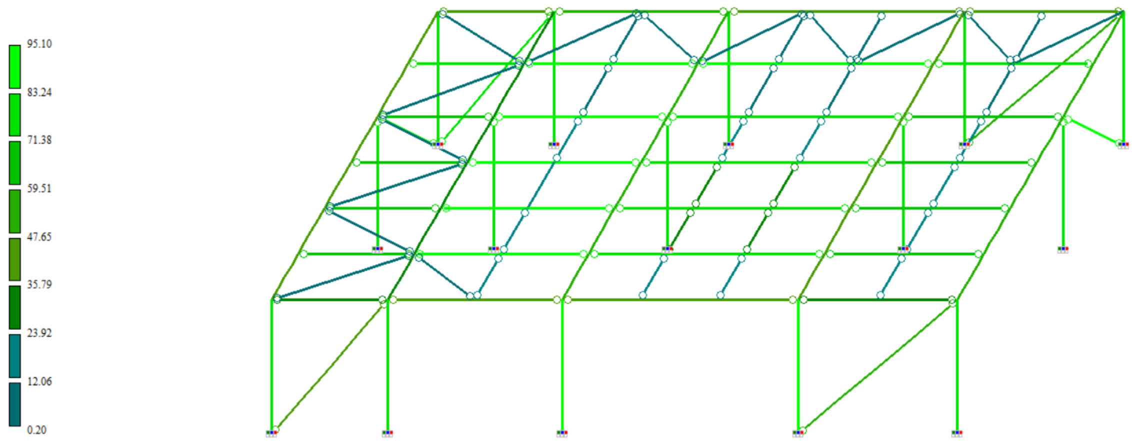


Figure 65. Utilization percentage of section by ultimate limit state, %. Checking the accepted sections

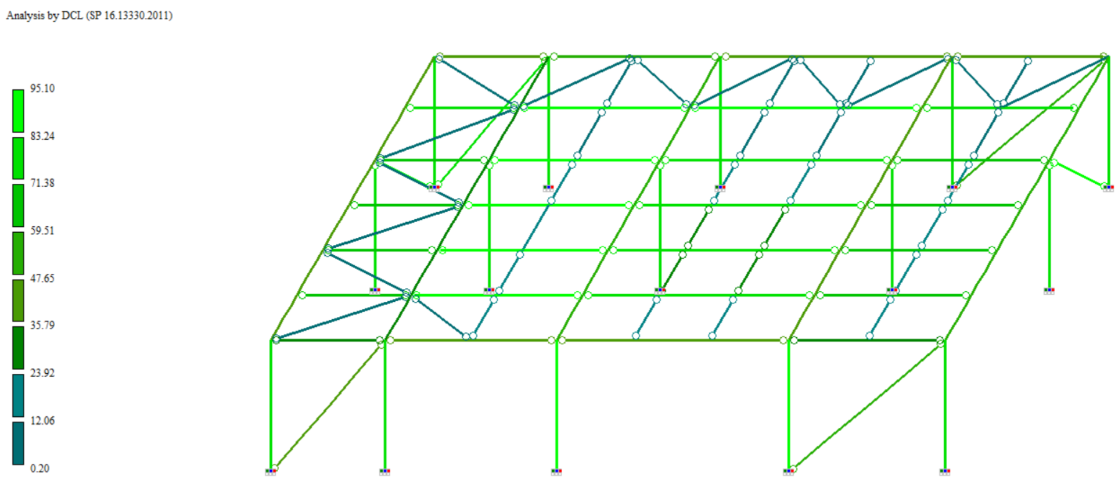


Figure 66. Utilization percentage of section by serviceability limit state, %. Checking the accepted sections

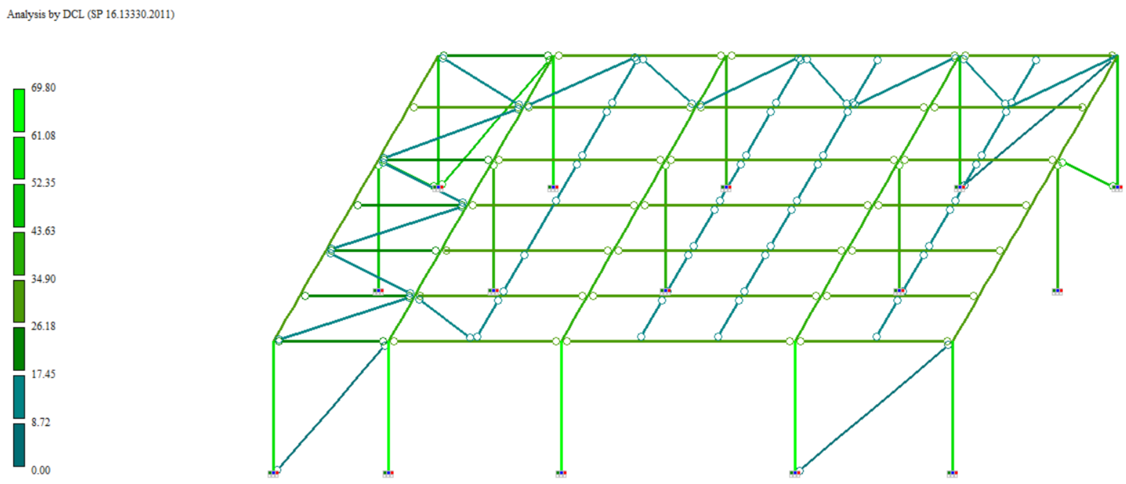


Figure 67. Utilization percentage of section by local buckling, %. Checking the accepted sections

All cross-sections have been checked, the variation is ready.

4.6 Second variation calculations

The second variation of the frame is a design diagram without central row of columns. Two options are considered:

- With rigid column base connection and pinned beam to column connection
- With pinned column base connection and rigid beam to column connection. Figure 68 shows these design diagrams.

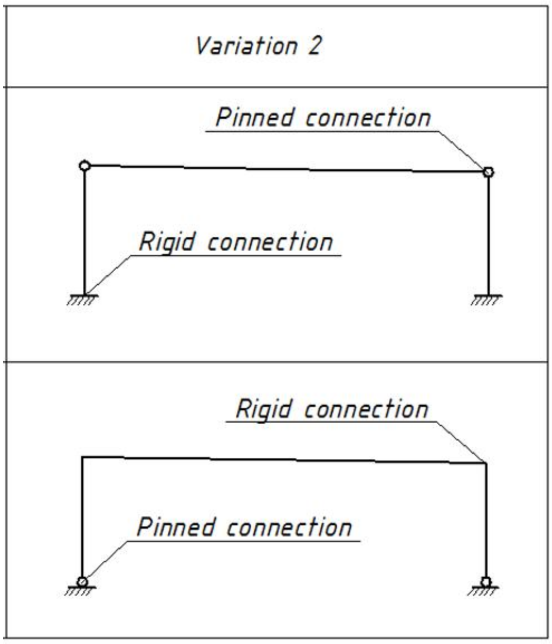


Figure 68. Second variation design diagram options

4.6.1 Rrigid column base connection and pinned beam to column connection

Figure 69 shows the spatial design diagram for this variation

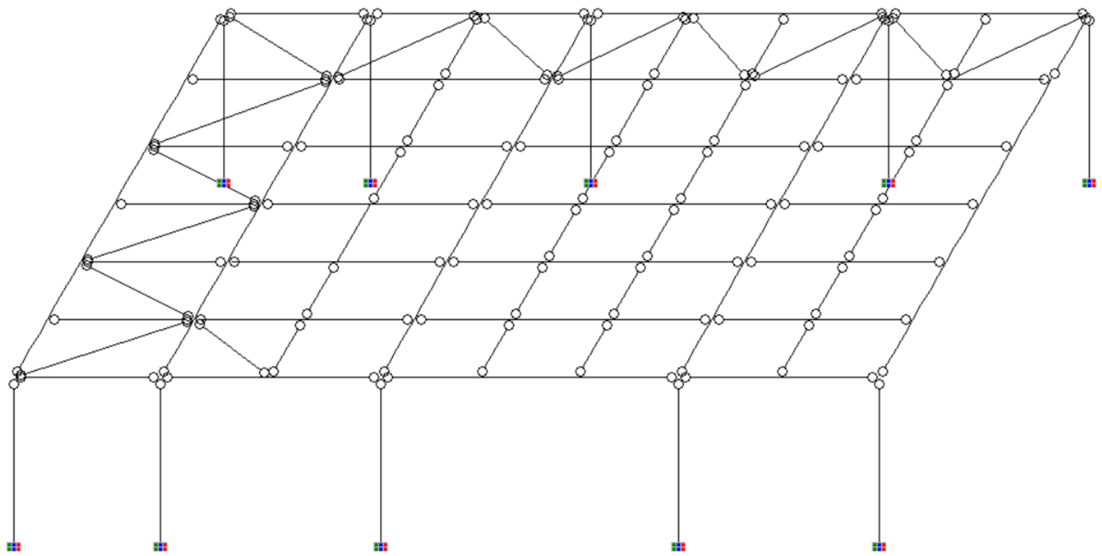


Figure 69. Spatial design diagram

For this variation, the sections are preliminarily taken from the first variation (rigid column base connection and pinned beam to column connection with central row of columns) calculations. Loads and load combinations remained the same.

With the same loads and load combinations in the secondary beams the same bending moments and horizontal forces occur. Figures 70-75 show the deformed model with mosaic of displacement along the vertical axis and effort diagrams for main beams and columns.

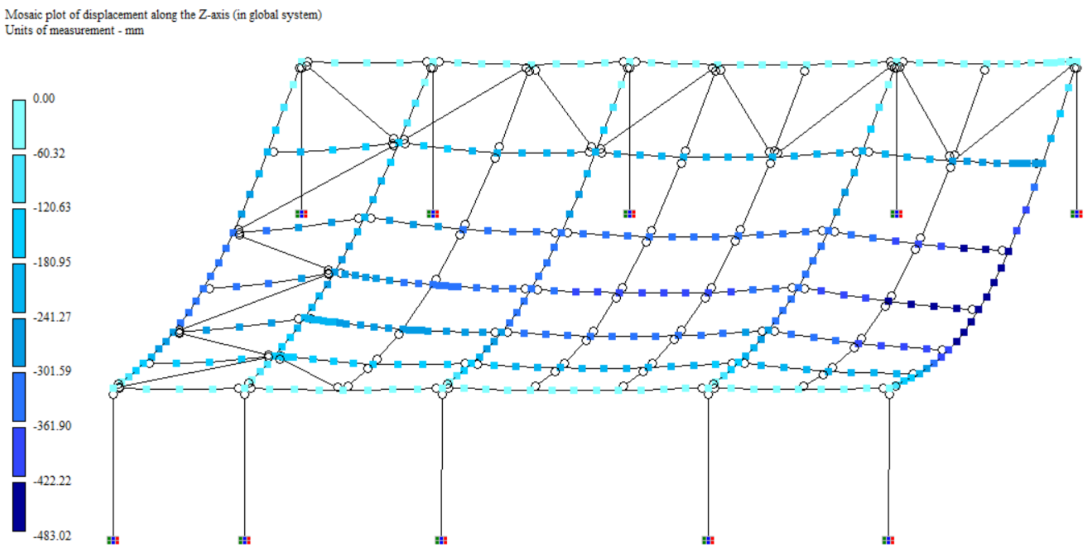


Figure 70. Deformed model with mosaic of displacement along the vertical axis

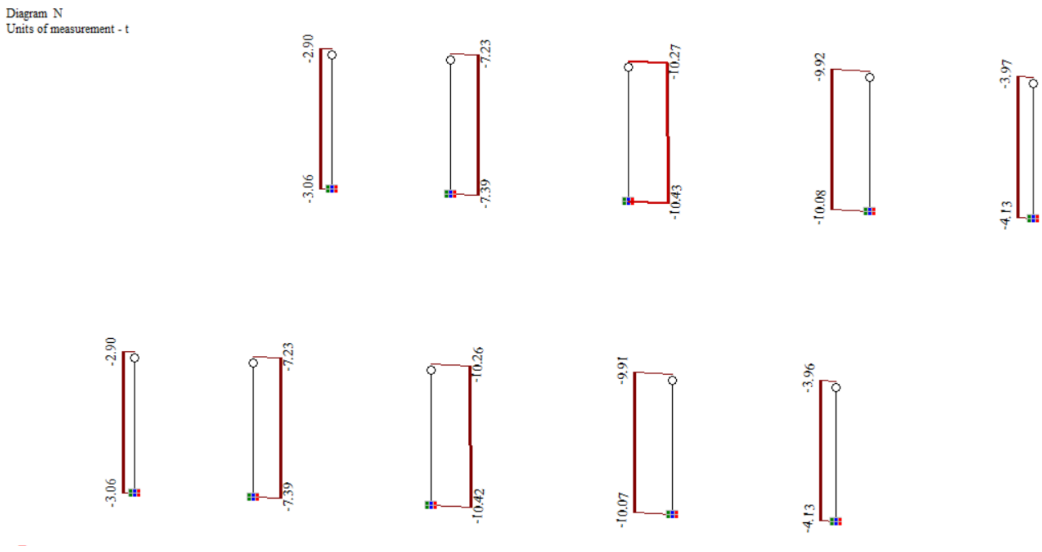


Figure 71. Diagram of longitudinal forces in columns N, t

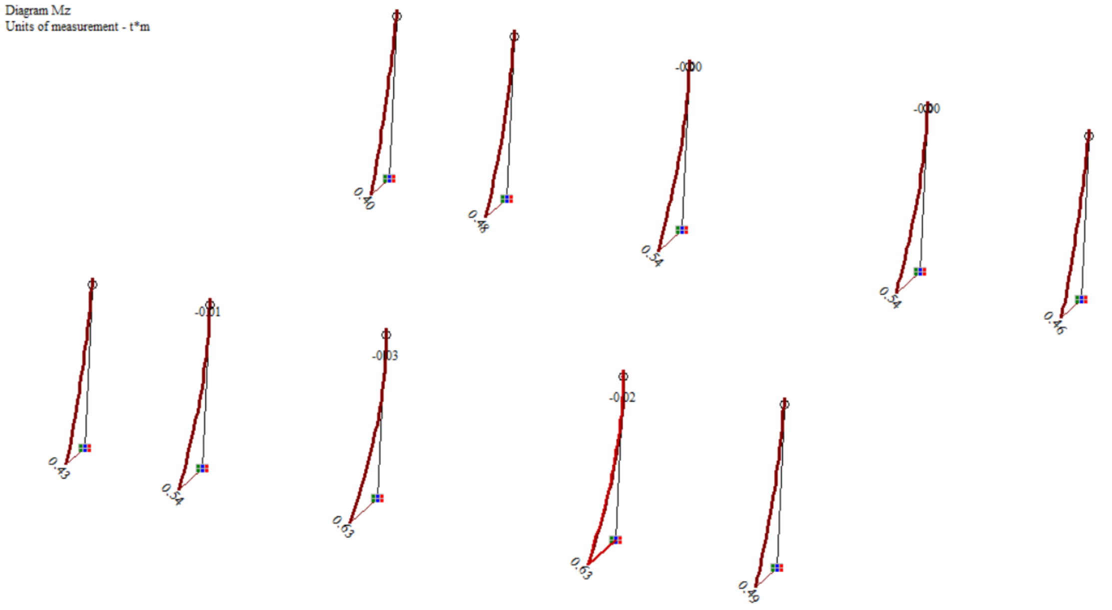


Figure 72. Diagram of bending moments in columns M_z, $t \cdot m^2$

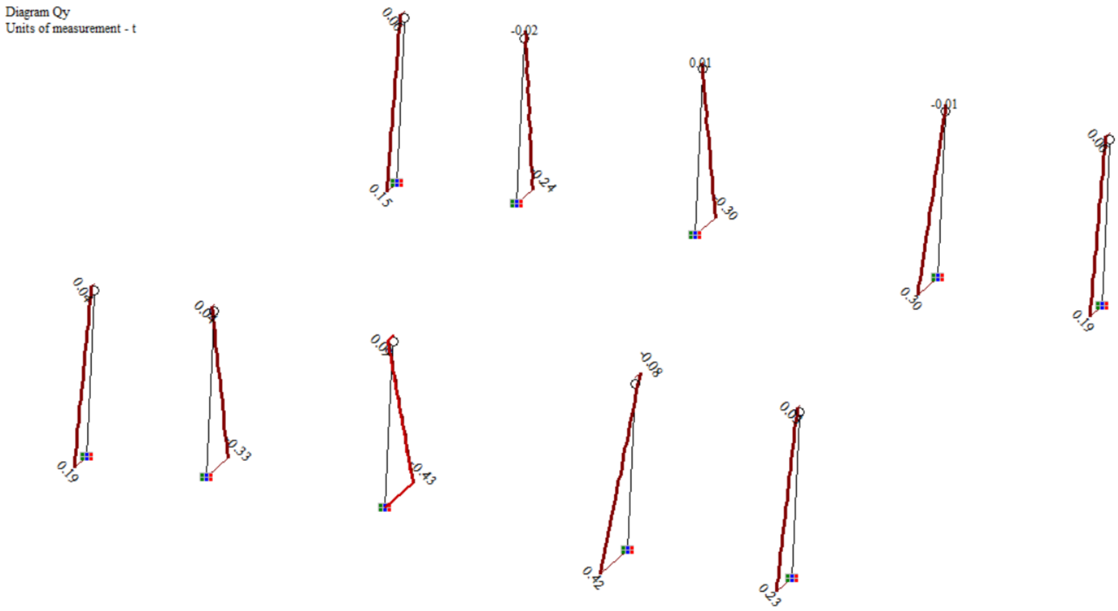


Figure 73. Diagram of horizontal forces in columns Q_y, t

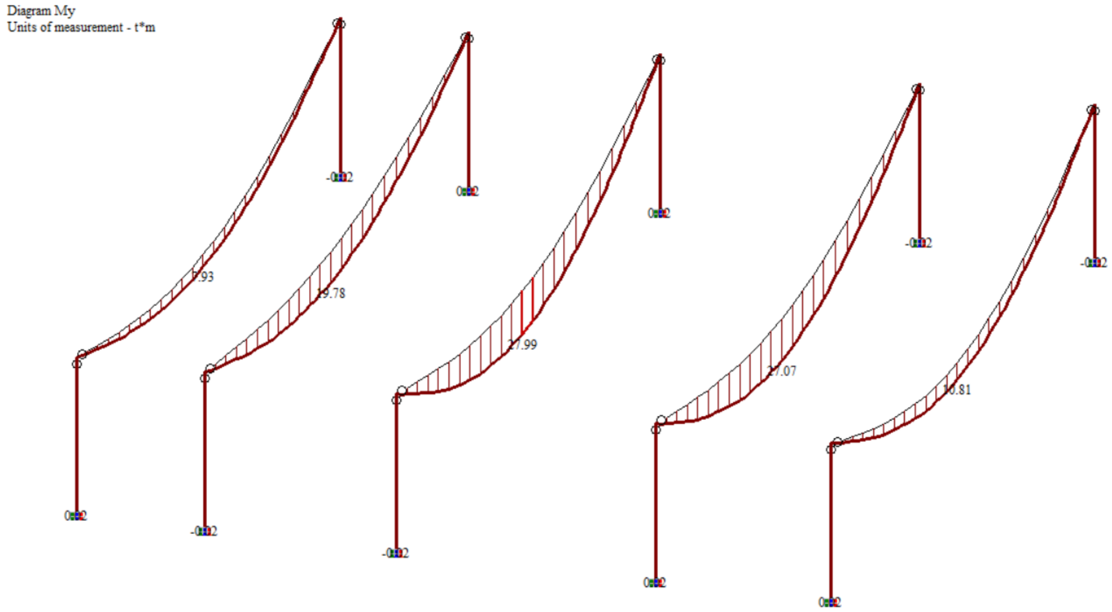


Figure 74. Diagram of bending moments in main beams M_y, t·m

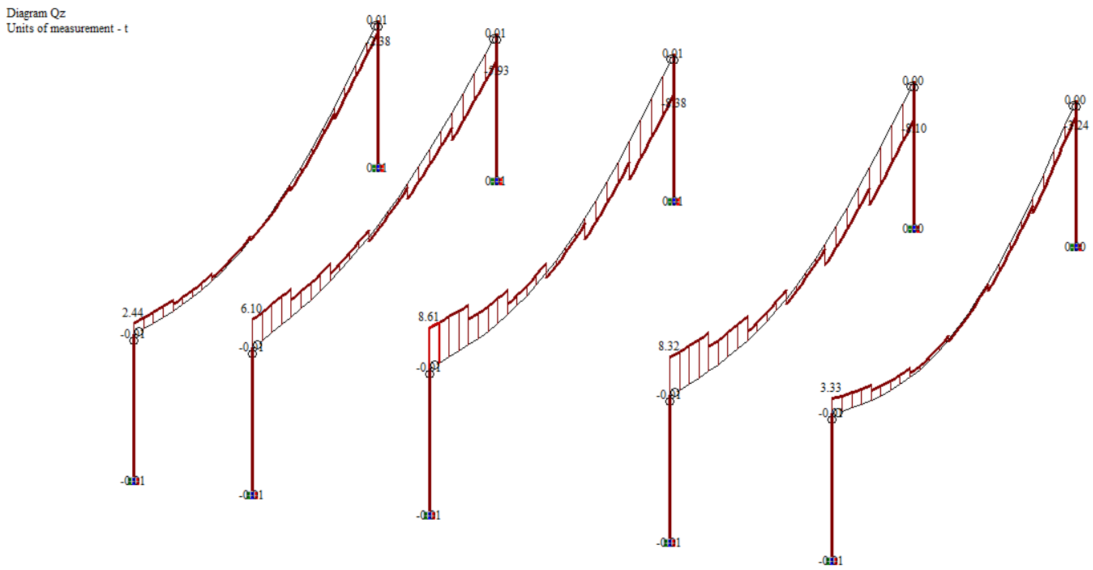


Figure 75. Diagram of horizontal forces in main beams Q_z, t

Maximum efforts and deflections in structures:

- Columns:
  - Longitudinal force N = 10.42 t;
  - Bending moment M_y = 0.63 t·m;
  - Horizontal force Q = 0.43 t
- Main beam
  - Bending moment M_y = 27.99 t·m;

– Horizontal force Q_z = 8.61 t

- Secondary beam – the same
- Bracings set constructively.
- Diagram deflection is f_u = 483 mm.

Deflection is high because of the small main beam section. After new sections selection deflection should be recalculated.

Figures 76 – 78 show the utilization percentages of pre-selected sections (selected sections checking).

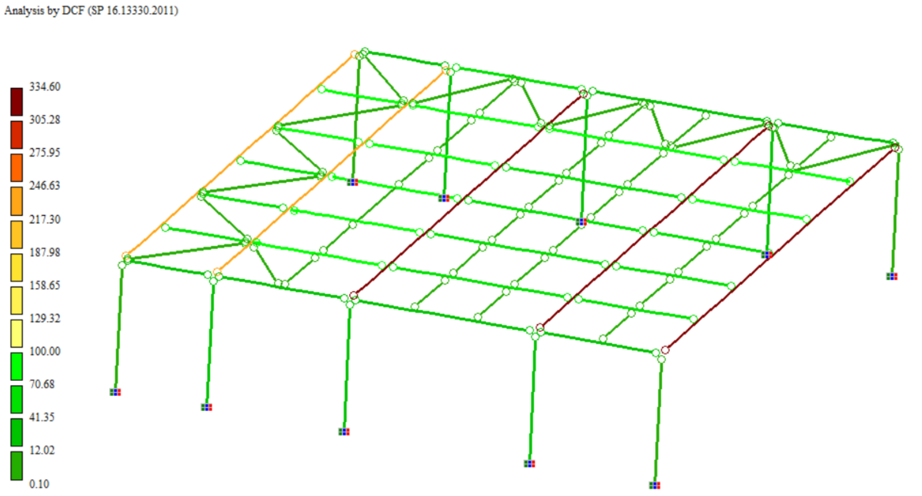


Figure 76. Utilization percentage of section by ultimate limit state, %

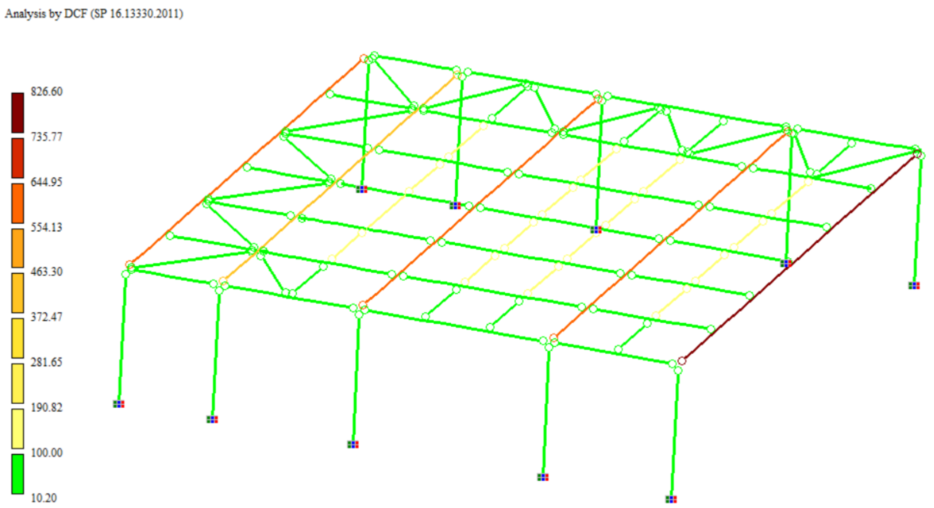


Figure 77. Utilization percentage of section by serviceability limit state,%

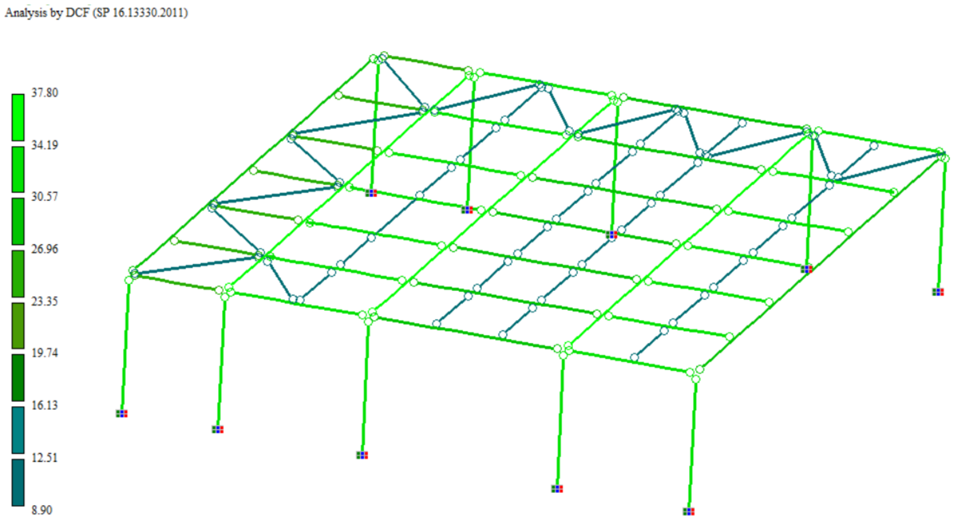


Figure 78. Utilization percentage of section by local buckling, %

Maximum utilization percentages for the main types of structures:

- Columns: U_{max} = 78.4% (by serviceability limit state)
- Main beams: U_{max} = 826% (by serviceability limit state)
- Secondary beams: U_{max} = 52.8% (by ultimate limit state)
- Horizontal bracings: U_{max} = 24.55% (by serviceability limit state)

Figure 79 shows LIRA-SAPR proposed cross sections.

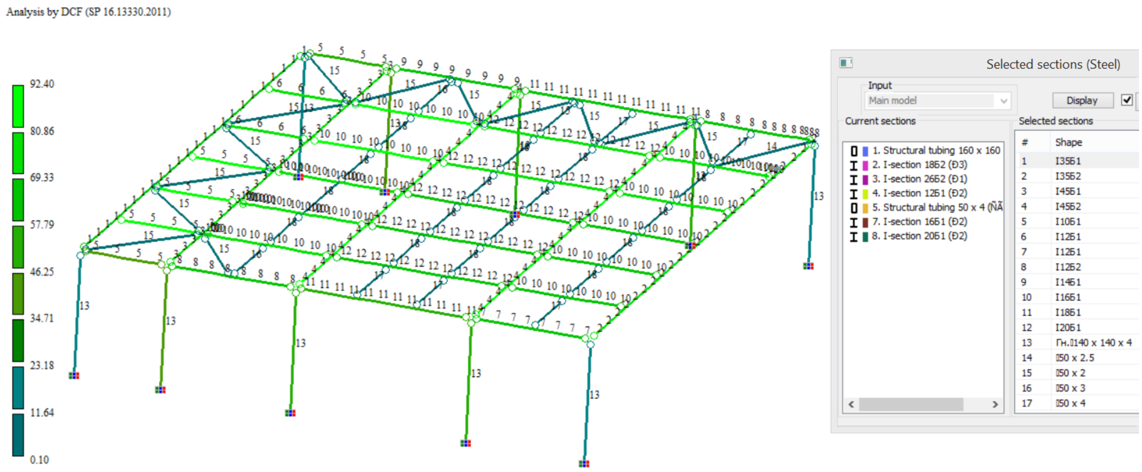


Figure 79. LIRA's proposed cross sections

According to the LIRA-SAPR results and unification, the following sections are selected:

- Main beams:
  - Mb1,5 – I-section for beams 35B1 (pre-selected section – I-section 18B2);
  - Mb2,3,4 – I-section for beams 45B2 (pre-selected section – I-section 26B2);
- Columns:
  - C1,2,3 – hollow section 140x4 (pre-selected section – hollow section 160x5);
- Secondary beams – the same.
- Bracings
  - Horizontal Ab 1-8 – hollow structural section 50x4 (pre-selected section – hollow structural section 50x4)

The task should be analysed again in LIRA with new stiffnesses.

Checking the accepted LIRA-SAPR section is shown in Figures 80-81.

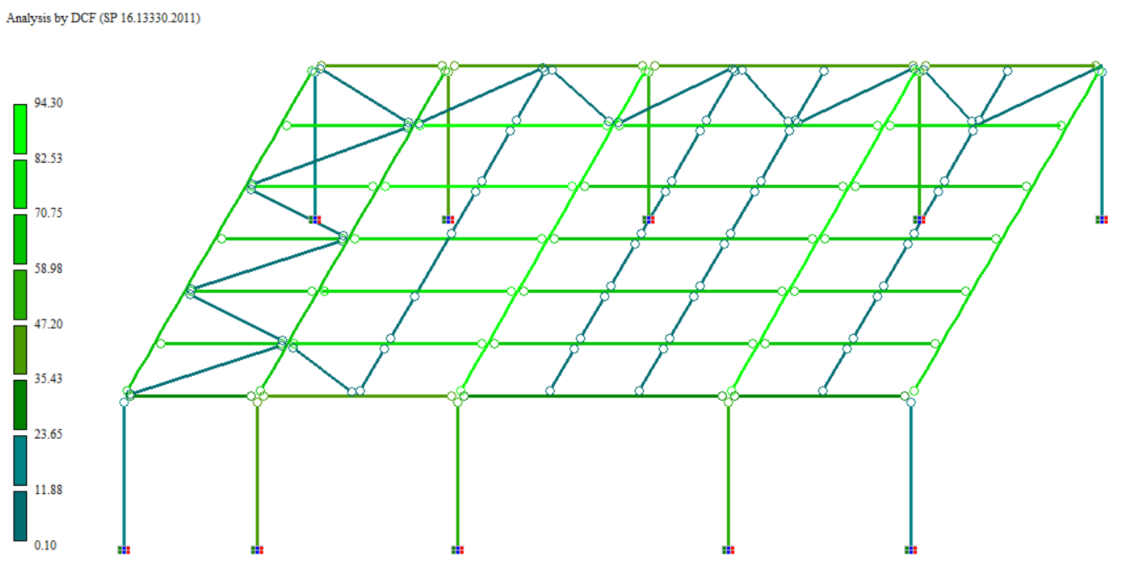


Figure 80. Utilization percentage of section by ultimate limit state, %. Checking the accepted sections

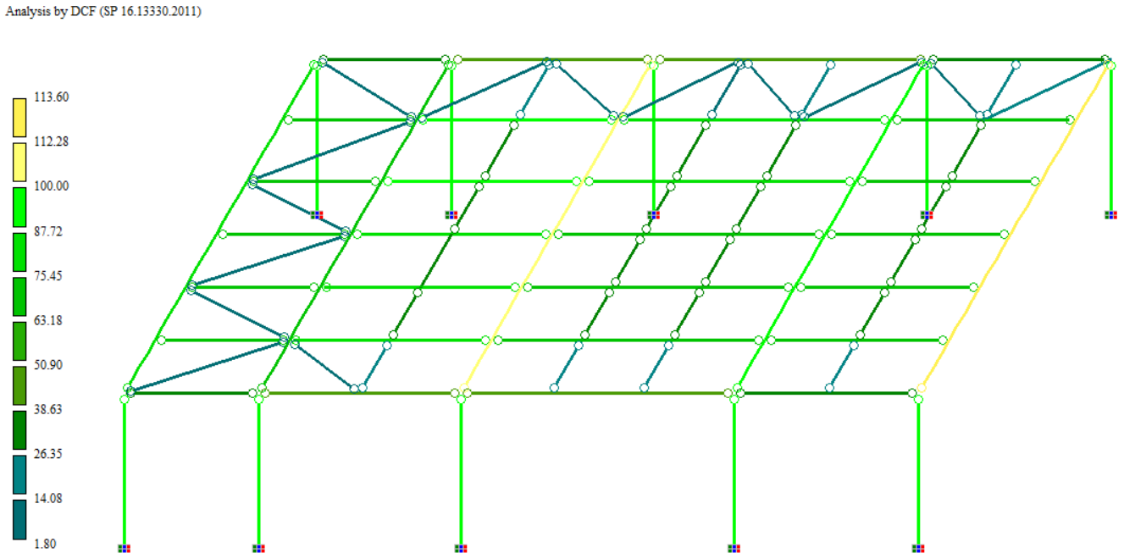


Figure 81. Utilization percentage of section by serviceability limit state, %. Checking the accepted sections

The beams Mb5 and Mb3 did not pass. It is necessary to increase the section. Mb5 might be increased from 35B1 to 35B2, Mb3 from 45B2 to 50B1 (the next position in the assortment). Checking the accepted LIRA-SAPR section with re-selected main beams is shown in Figures 82-84.

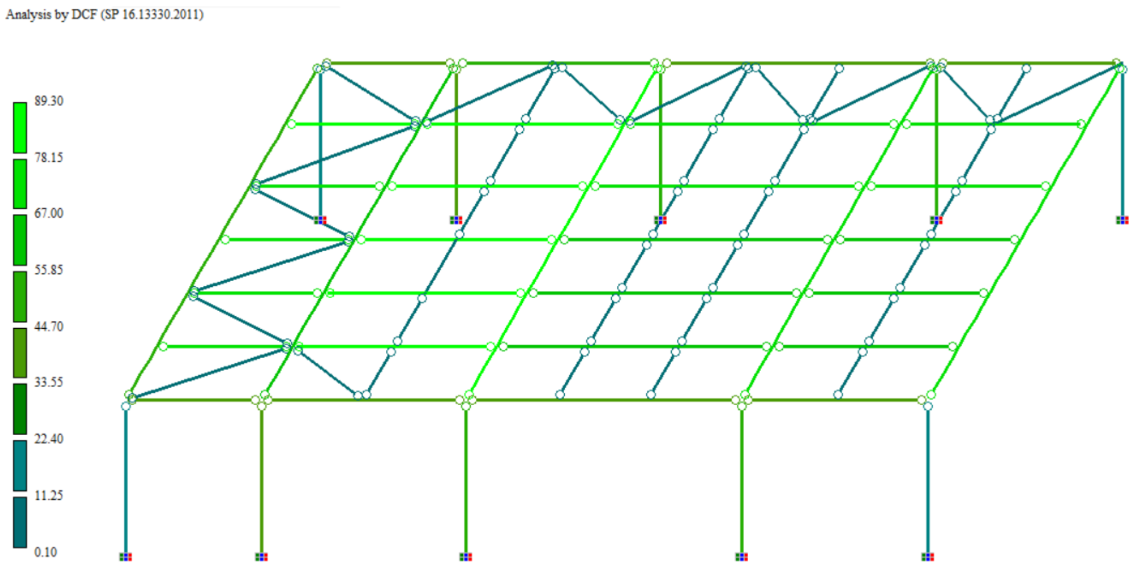


Figure 82. Utilization percentage of section by ultimate limit state, %. Checking the accepted sections

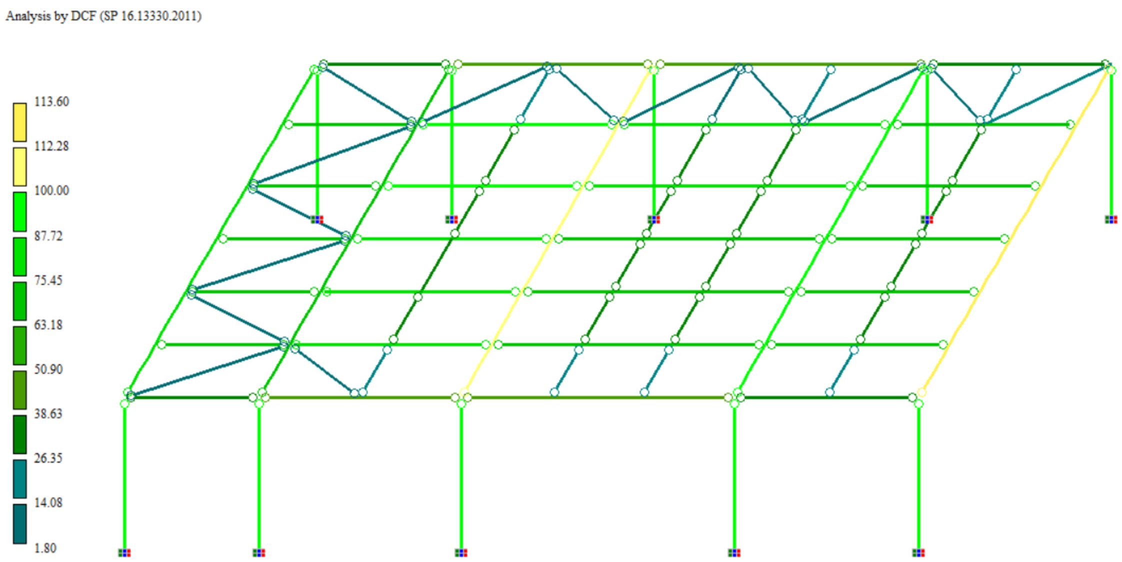


Figure 83. Utilization percentage of section by serviceability limit state, %. Checking the accepted sections

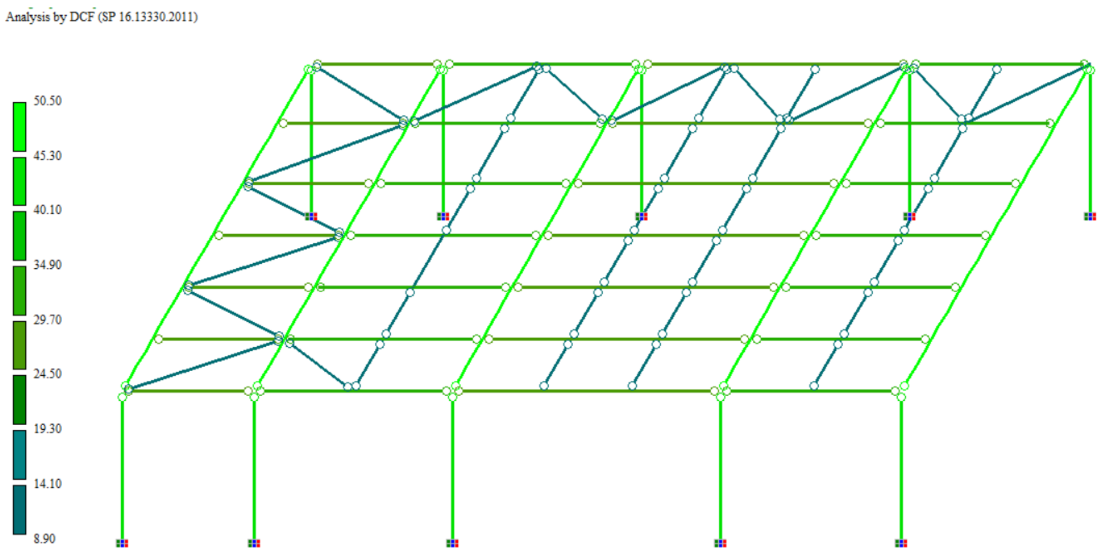


Figure 84. Utilization percentage of section by local buckling, %. Checking the accepted sections

All cross-sections have been checked, the variation is ready.

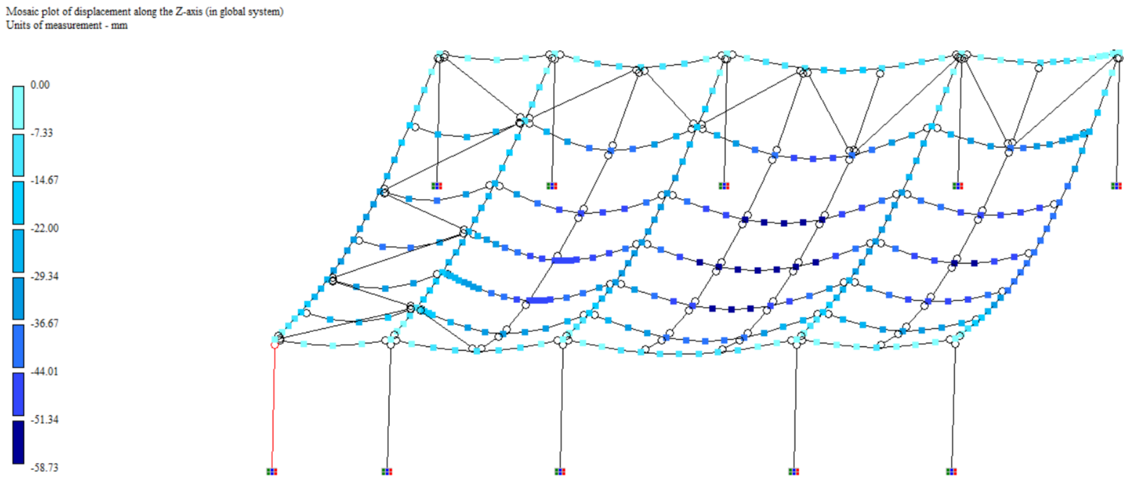


Figure 85. New deformed model with mosaic of displacement along the vertical axis

4.6.2 Pinned column base connection and rigid beam to column connection

In order to put vertical bracings into the last spans, it is required to put the central columns there. Figure 86 shows the spatial design diagram for this variation.

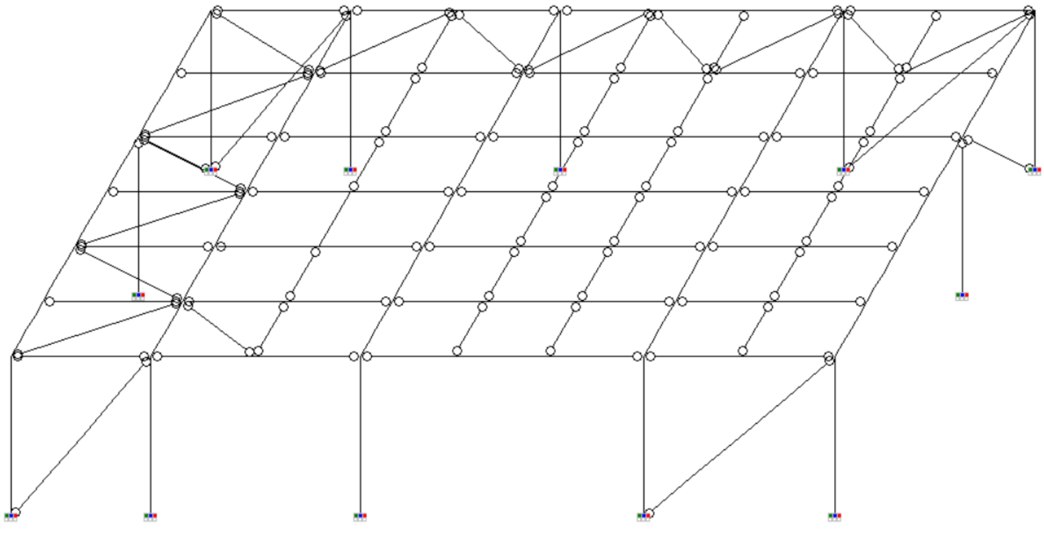


Figure 86. Spatial design diagram

For pinned column base connection and rigid beam to column connection diagram, the sections are preliminarily taken from the previous variation calculations. Loads and load combinations remained the same.

Figures 87-93 show displacements and efforts in columns, main beams and vertical bracings

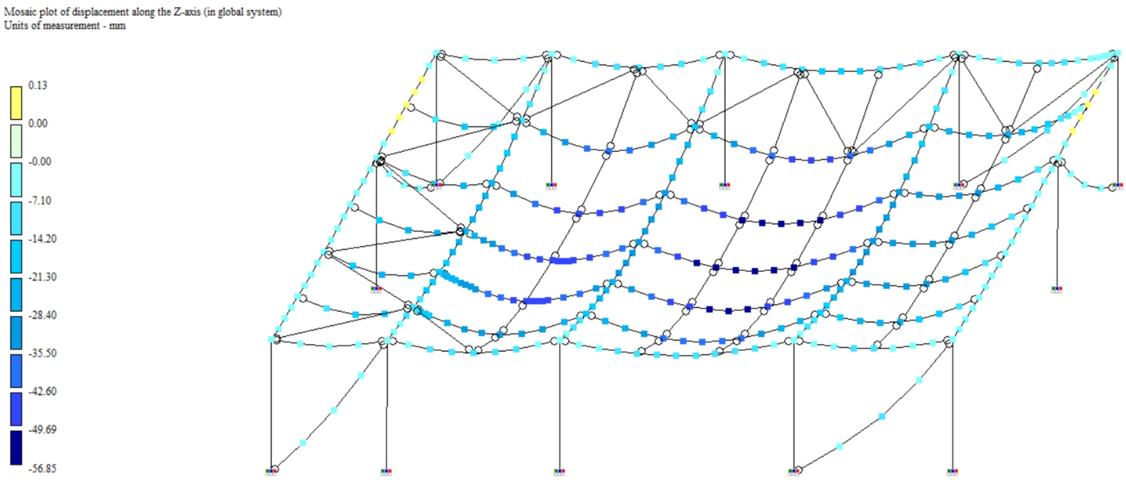


Figure 87. Deformed model with mosaic of displacement along the vertical Z-axis

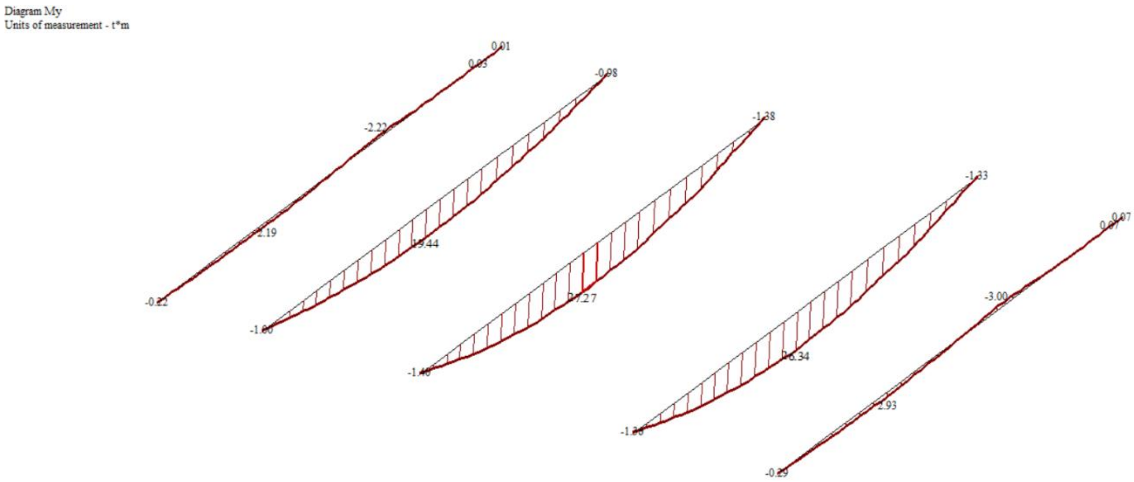


Figure 88. Diagram of bending moments in main beams M_y, t·m

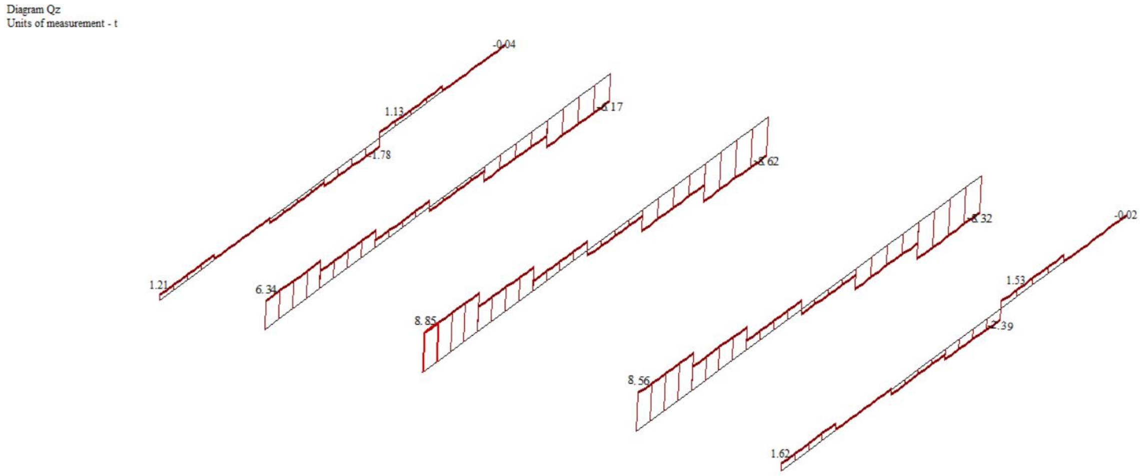


Figure 89. Diagram of horizontal forces in main beams Q_z, t

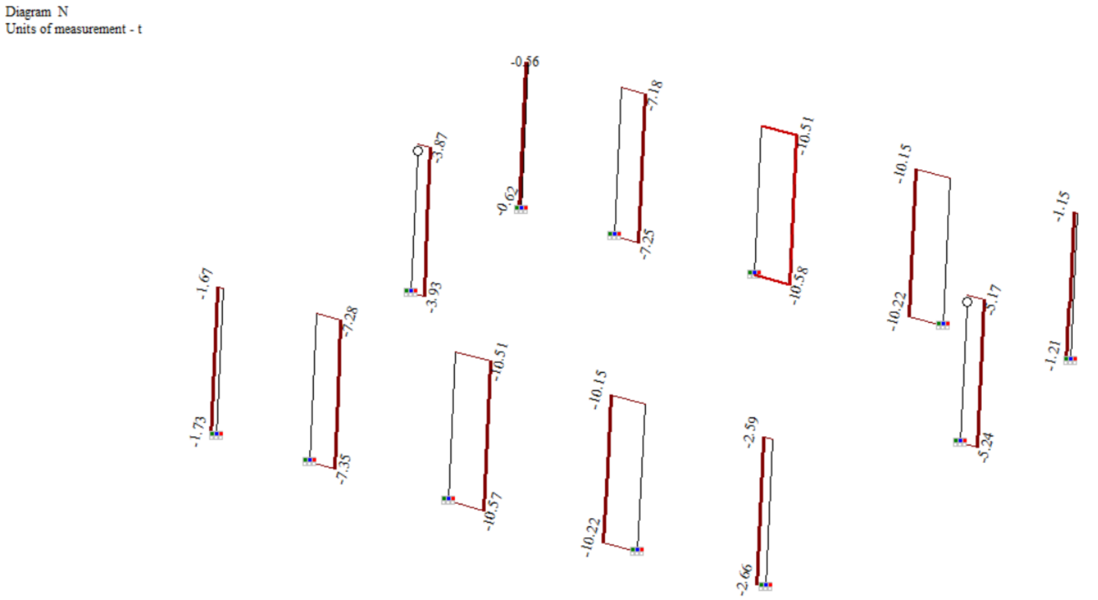


Figure 90. Diagram of longitudinal forces in columns N, t

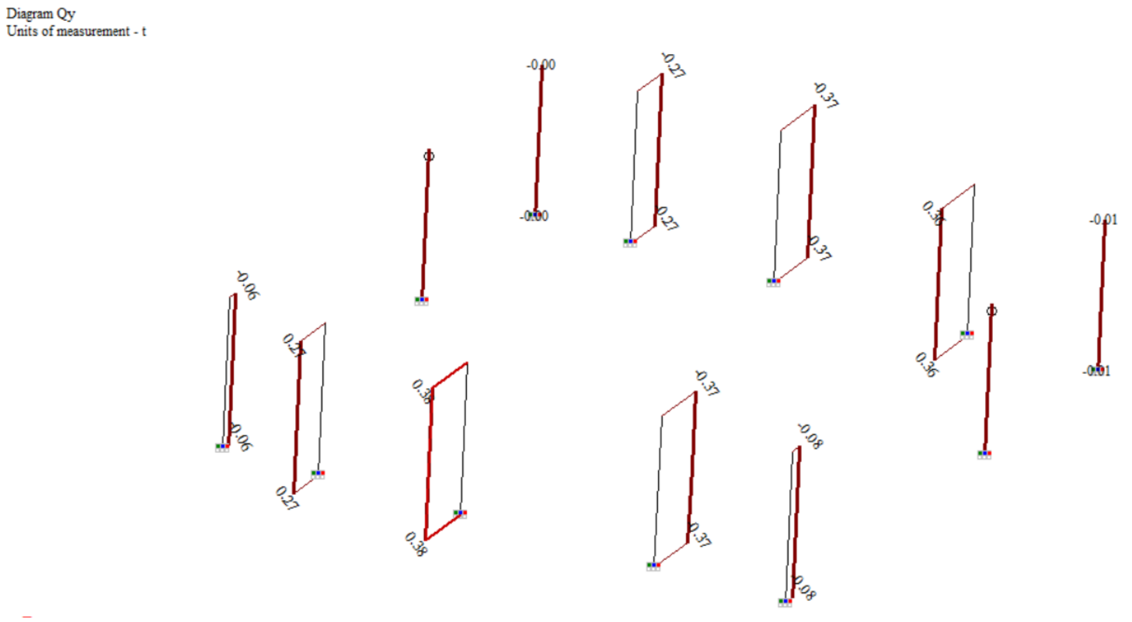


Figure 91. Diagram of horizontal forces in columns Q_y, t

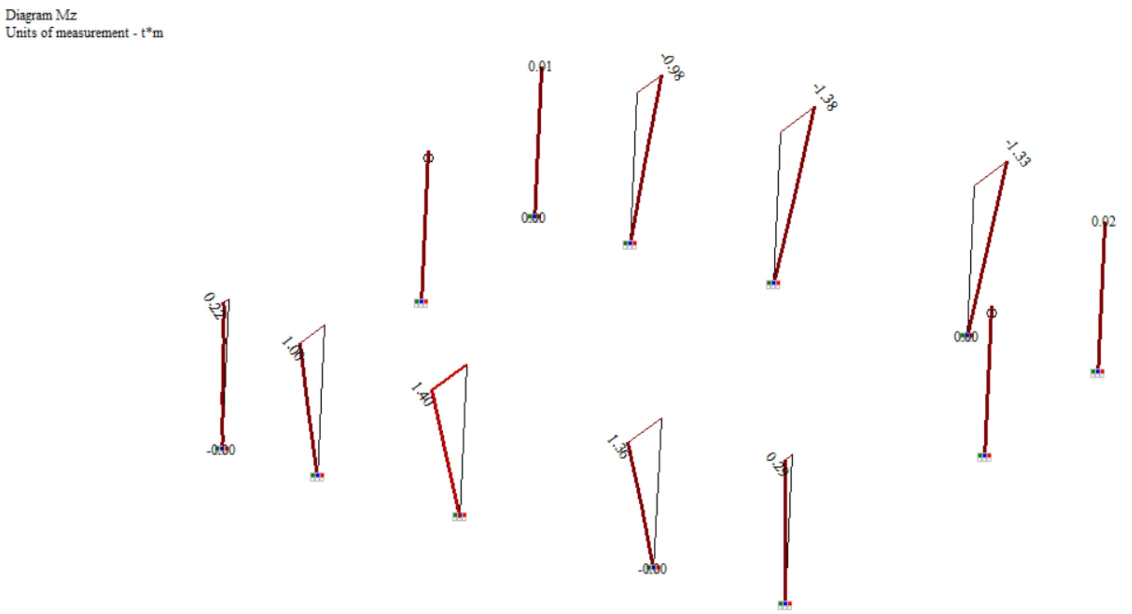


Figure 92. Diagram of bending moments in columns M_z, t·m

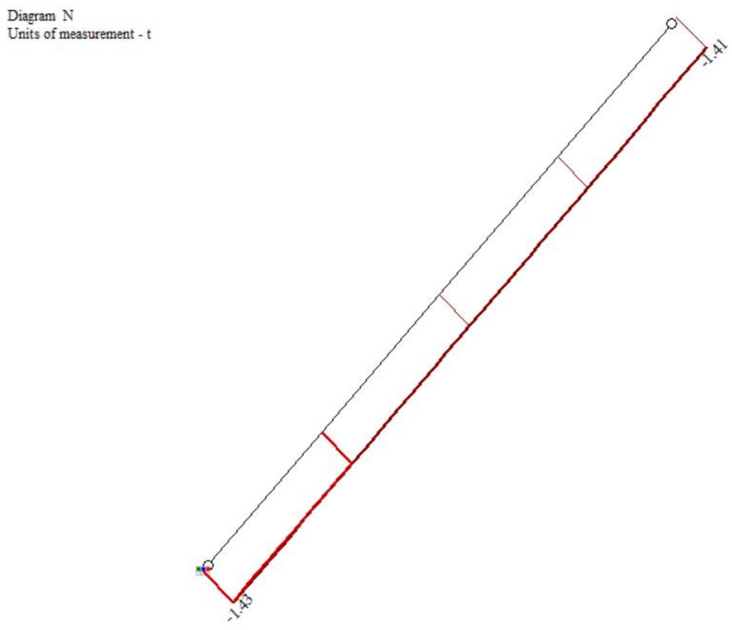


Figure 93. Diagram of maximum longitudinal force in vertical bracings N, t

Vertical bracings are perceived only longitudinal forces.

Maximum efforts and deflections in structures:

- Columns:
  - Longitudinal force N = 10.58 t
  - Bending moment M_y = 1.4 t·m;
  - Horizontal force Q = 0.37 t
- Main beam
  - Bending moment M_y = 27.27 t·m;
  - Horizontal force Q_z = 8.85 t
- Secondary beam (the same)
  - Bending moment M_y = 3.52 t·m;
  - Horizontal force Q_z = 2.16 t.
- Vertical bracings
  - Longitudinal force N = 1.43 t
- Horizontal bracings set constructively.
- Diagram deflection f_u = 56.85 mm.

Figures 94 – 96 show utilization percentages of pre-selected sections (selected sections checking).

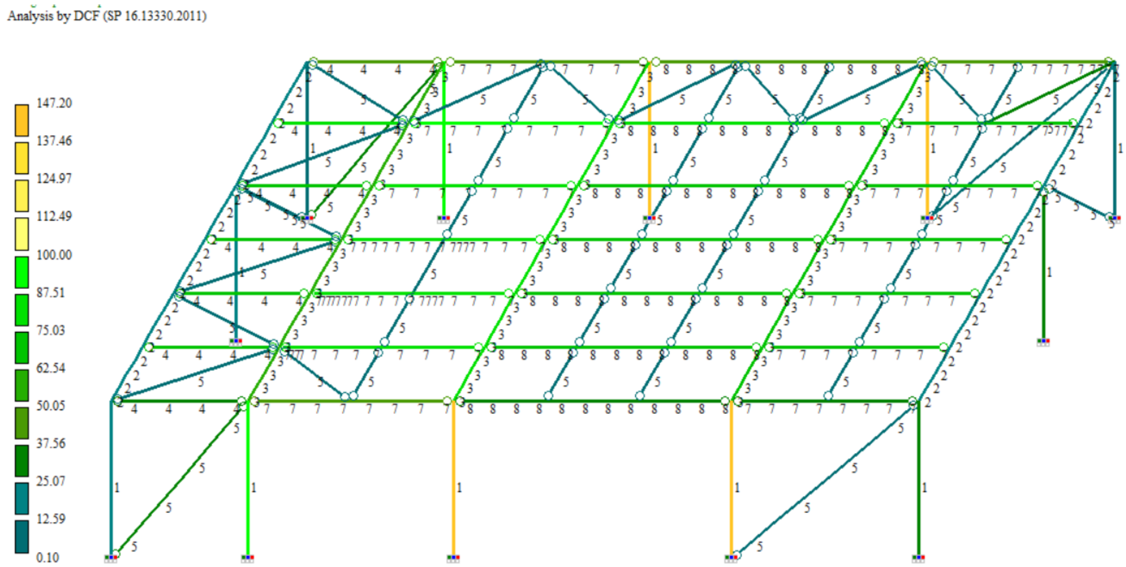


Figure 94. Utilization percentage of section by ultimate limit state, %

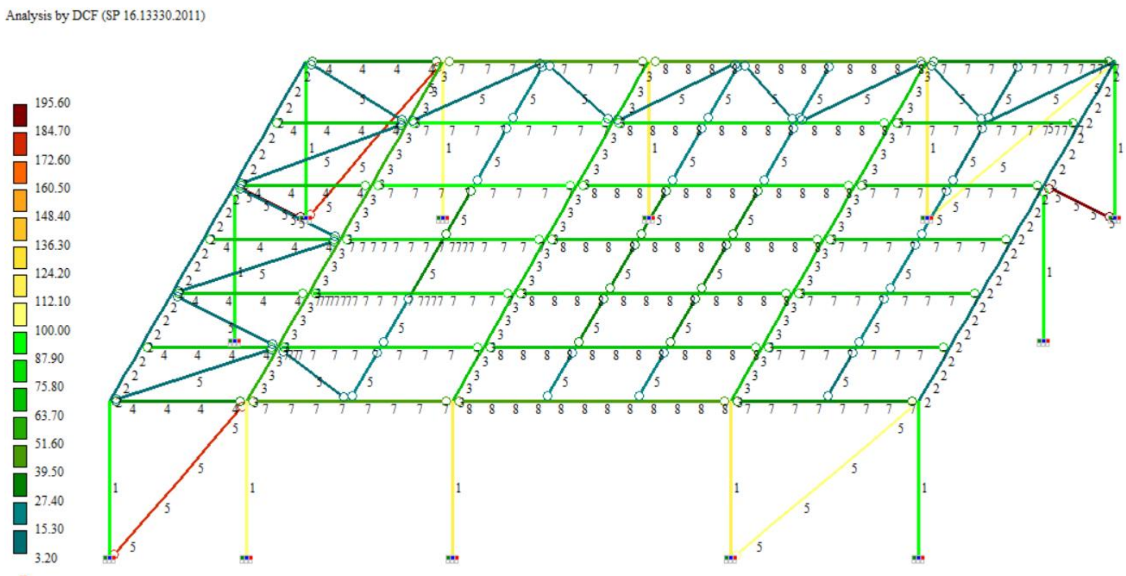


Figure 95. Utilization percentage of section by serviceability limit state,%

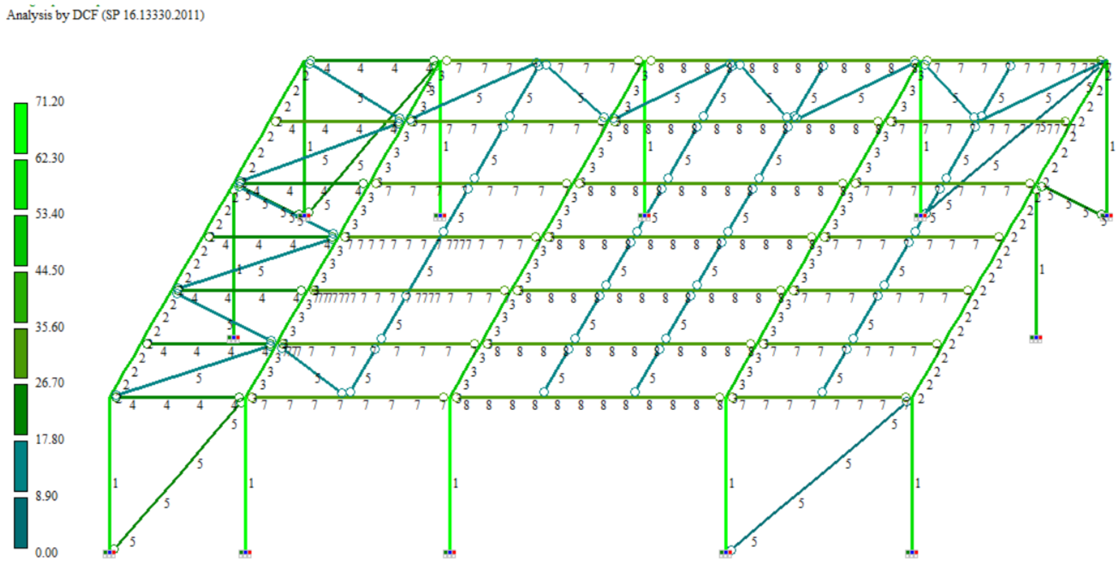


Figure 96. Utilization percentage of section by local buckling, %

Maximum utilization percentages for main types of structures:

- Columns: U_{max} = 147% (by ultimate limit state)
- Main beams Mb1,5: U_{max} = 19.4% (by ultimate limit state) – because of two supporting additional columns for bracings
- Main beams Mb2,3,4: U_{max} = 75% (by serviceability limit state)
- Secondary beams: U_{max} = 52.8% (by ultimate limit state)
- Horizontal bracings: U_{max} = 24.55% (by serviceability limit state)
- Vertical bracings: U_{max} = 195.6 % (by serviceability limit state)

According to the results of the section checking, vertical bracings and columns cross-sections should be increased. Main beam sections should be reduced. The remaining sections in accordance with the results of LIRA-SPAR work as efficiently as possible. Figure 97 shows LIRA-SAPR proposed cross sections.

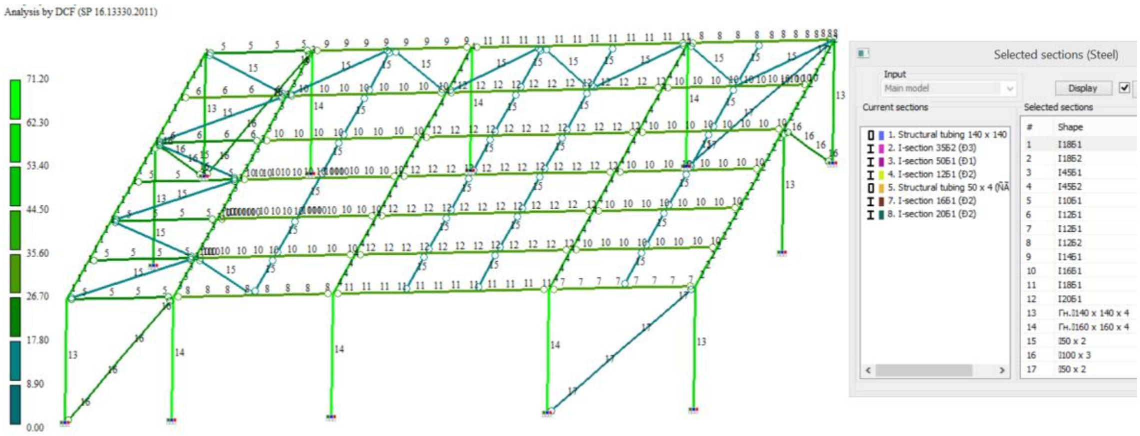


Figure 97. LIRA's proposed cross sections

According to the LIRA-SAPR results and unification, following sections are selected:

- Main beams:
  - Mb1,5 – I-section for beams 18B2 (pre-selected section – I-section 35B2);
  - Mb2,3,4 – I-section for beams 45B2 (pre-selected section – I-section 50B1);
- Columns:
  - C1,2,3 – hollow section 180x8 (pre-selected section – hollow section 160x4);
- Secondary beams – the same.
- Bracings
  - Horizontal Ab 1-8 – hollow structural section 50x4 (pre-selected section – hollow structural section 50x4)
  - Vertical Vb 1-3 – hollow structural section 100x3 (pre-selected section – hollow structural section 50x4)

The task should be analysed again in LIRA with new stiffnesses.

Checking the accepted LIRA-SAPR section is shown in Figures 98-100.

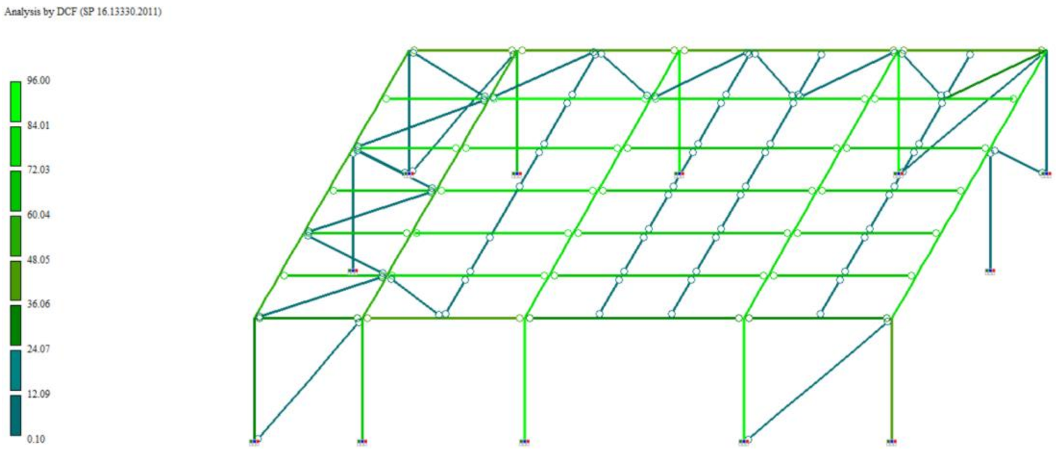


Figure 98. Utilization percentage of section by ultimate limit state, %. Checking the accepted sections

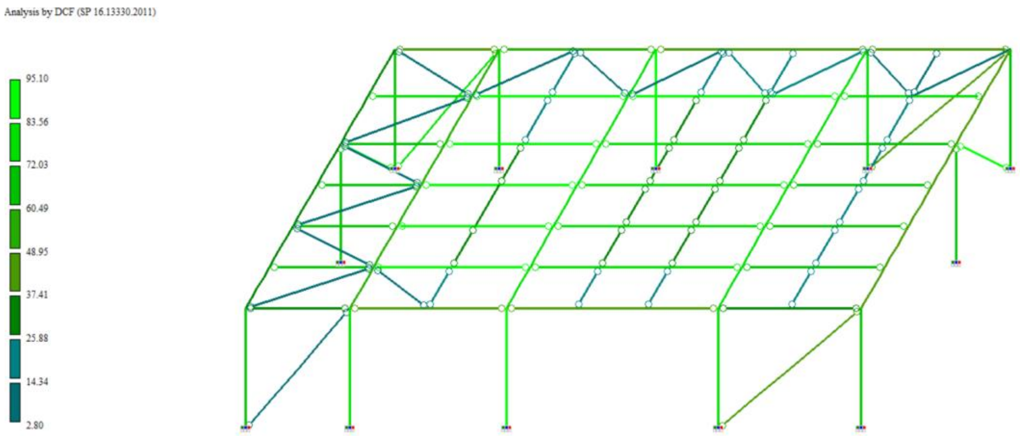


Figure 99. Utilization percentage of section by serviceability limit state, %. Checking the accepted sections

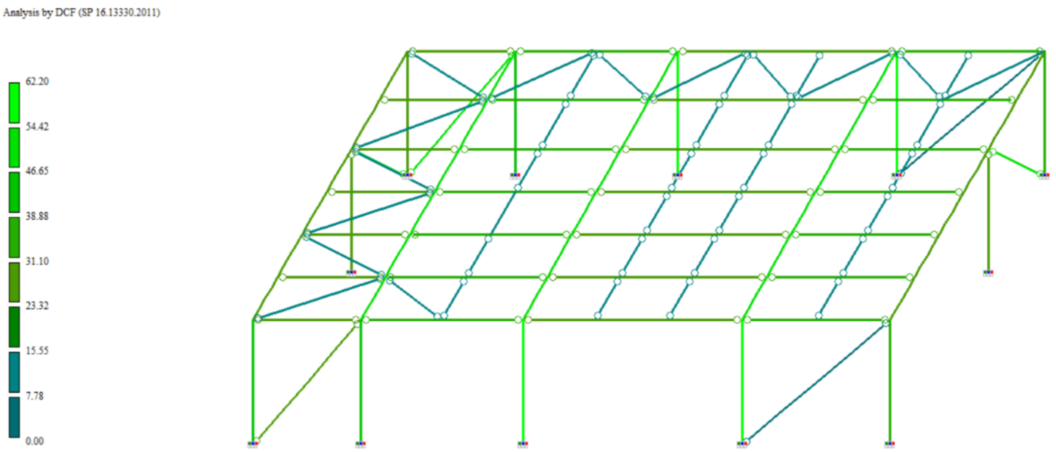


Figure 100. Utilization percentage of section by local buckling, %. Checking the accepted sections

All cross-sections have been checked, the variation is ready.

4.7 Steel costs comparison

In the previous paragraph, 4 design options were considered. For each variant, the cross sections of the elements were selected. The framework was divided into separate components:

- Main beams
- Secondary beams
- Columns
- Bracings

Tables 3 – 6 show a steel cost comparison of each element type for each variation. For each element type, the mass in tones is calculated. The ton costs of particular sections are taken from factories producing metal structures.

Table 3. Columns costs

Columns									
Name	Heigh, m	Quantity	Σ length, m	Section	W, t/m	Steel grade	Price rub/t	Column price, rub	Total price, rub
Variation 1a. Rrigid column base connection and pinned beam to column connection, I									
C1	3.65	5	18.25					40785	
C2	3.55	5	17.75	I20К1	0.042	S235	53850	39667	119337
C3	3.48	5	17.4					38885	
Variation 1a. Rrigid column base connection and pinned beam to column connection, □									
C1	3.65	5	18.25					13700	
C2	3.55	5	17.75	□140x4	0.017	S235	44790	13325	40086
C3	3.48	5	17.4					13062	
Variation 1b. Pinned column base connection and rigid beam to column connection									
C1	3.65	5	18.25					20180	
C2	3.55	5	17.75	□180x5	0.027	S235	41000	19627	59048
C3	3.48	5	17.4					19240	
Variation 2a. Rrigid column base connection and pinned beam to column connection									
C1	3.65	5	18.25	□140x4	0.017	S235	44790	13700	26762
C3	3.48	5	17.4					13062	
Variation 2b. Pinned column base connection and rigid beam to column connection									
C1	3.65	5	18.25					32268	
C2	3.55	2	7.1	□180x8	0.042	S235	41760	12554	75587
C3	3.48	5	17.4					30765	

Table 4. Main beams costs

Main beams									
Desig nation	heigh, m	Quantity	Σ length, m	Section	W, t/m	Steel grade	Price rub/t	Column price, rub	Total price, rub
Variation 1a. Rrigid column base connection and pinned beam to column connection									
Mb1	11.2	1	22.4	I18B2	0.019	S235	43500	18319	62704
Mb5	11.2	1							
Mb2	11.2	1	33.6	I26B2	0.026		51400	44385	
Mb3	11.2	1							
Mb4	11.2	1							
Variation 1b. Pinned column base connection and rigid beam to column connection									
Mb1	11.2	1	22.4	I18B2	0.019	S235	43500	18319	64700
Mb5	11.2	1							
Mb2	11.2	1	33.6	I26B1	0.028		49300	46381	
Mb3	11.2	1							
Mb4	11.2	1							
Variation 2a. Rrigid column base connection and pinned beam to column connection									
Mb1	11.2	1	22.4	I35B2	0.043	S235	58600	56837	175062
Mb5	11.2	1							
Mb2	11.2	1	33.6	I50B1	0.073		48200	118225	
Mb3	11.2	1							
Mb4	11.2	1							
Variation 2b. Pinned column base connection and rigid beam to column connection									
Mb1	11.2	1	22.4	I18Б2	0.019	S235	43500	18319	132853
Mb5	11.2	1							
Mb2	11.2	1	33.6	I45Б2	0.068		50500	114534	
Mb3	11.2	1							
Mb4	11.2	1							

Table 5. Secondary beams costs

Secondary beams									
Desig nation	heigh, m	Quantity	Σ length, m	Section	W, t/m	Steel grade	Price rub/t	Column price, rub	Total price, rub
Sb1	3.2	7	22.4	I12B1	0.009	S235	39000	7600	88426
Sb2	4.8	7	33.6	I16B1	0.013		41500	17709	
Sb3	6.5	7	45.5	I20B1	0.022		46000	46883	
Sb4	4.4	7	30.8	I16B1	0.013		41500	16233	
Sb1	3.2	7	22.4	I12B1	0.009	S235	39000	7600	88426
Sb2	4.8	7	33.6	I16B1	0.013		41500	17709	
Sb3	6.5	7	45.5	I20B1	0.022		46000	46883	
Sb4	4.4	7	30.8	I16B1	0.013		41500	16233	
Sb1	3.2	7	22.4	I12B1	0.009	S235	39000	7600	88426
Sb2	4.8	7	33.6	I16B1	0.013		41500	17709	
Sb3	6.5	7	45.5	I20B1	0.022		46000	46883	
Sb4	4.4	7	30.8	I16B1	0.013		41500	16233	
Sb1	3.2	7	22.4	I12B1	0.009	S235	39000	7600	88426
Sb2	4.8	7	33.6	I16B1	0.013		41500	17709	
Sb3	6.5	7	45.5	I20B1	0.022		46000	46883	
Sb4	4.4	7	30.8	I16B1	0.013		41500	16233	

Table 6. Bracings costs

Bracings									
Designation	heigh, m	Quantity	Σ length, m	Section	W, t/m	Steel grade	Price rub/t	Column price, rub	Total price, rub
Ab1	1.75	16	28	□ 50x4	0.005	S235	45800	6989	21721
Ab2	2	8	16					3994	
Ab3	2.97	3	8.91					2224	
Ab4	2.94	2	5.88					1468	
Ab5	3.12	2	6.24					1558	
Ab6	3.77	2	7.54					1882	
Ab7	3.65	3	10.95					2733	
Ab8	3.5	1	3.5					874	
Ab1	1.75	16	28	□ 50x4	0.005	S235	45800	6989	34646
Ab2	2	8	16					3994	
Ab3	2.97	3	8.91					2224	
Ab4	2.94	2	5.88					1468	
Ab5	3.12	2	6.24					1558	
Ab6	3.77	2	7.54					1882	
Ab7	3.65	3	10.95					2733	
Ab8	3.5	1	3.5					874	
Vb1	4.89	2	9.78	□ 100x3	0.009		44800	3926	
Vb2	5.45	2	10.9					4375	
Vb3	5.76	2	11.52					4624	
Ab1	1.75	16	28	□ 50x4	0.005	S235	45800	6989	21721
Ab2	2	8	16					3994	
Ab3	2.97	3	8.91					2224	
Ab4	2.94	2	5.88					1468	
Ab5	3.12	2	6.24					1558	
Ab6	3.77	2	7.54					1882	
Ab7	3.65	3	10.95					2733	
Ab8	3.5	1	3.5					874	
Ab1	1.75	16	28	□ 50x4	0.005	S235	45800	6989	34646
Ab2	2	8	16					3994	
Ab3	2.97	3	8.91					2224	
Ab4	2.94	2	5.88					1468	
Ab5	3.12	2	6.24					1558	
Ab6	3.77	2	7.54					1882	
Ab7	3.65	3	10.95					2733	
Ab8	3.5	1	3.5					874	
Vb1	4.89	2	9.78	□ 100x3	0.009		44800	3926	
Vb2	5.45	2	10.9					4375	
Vb3	5.76	2	11.52					4624	

Total price:

- Variation 1a with I-section column

$$P_{1aI} = 119337 + 62704 + 88426 + 21721 = 292188\,rub \tag{28}$$

- Variation 1a with hollow structural section

$$P_{1ah} = 40086 + 62704 + 88426 + 21721 = 212937\,rub \tag{29}$$

- Variation 1b

$$P_{1b} = 59048 + 64700 + 88426 + 34646 = 246820\,rub \tag{30}$$

- Variation 2a

$$P_{2a} = 26762 + 175062 + 88426 + 21721 = 311971\,rub \tag{31}$$

- Variation 2b

$$P_{2b} = 75587 + 132583 + 88426 + 34646 = 333512\,rub \tag{32}$$

As expected, the cheapest variation for constructing the framework is an option in which the base of the columns is rigidly attached to the foundation, and the main beams are attached to the columns hinged. This variation is “Variation 1a with hollow structural section” The central row is present in this variation, creating an adhering hinge in the design scheme that reducing the bending moment. In addition, beam to column connection is much simpler and more technologically then rigid connection.

5 Conclusion

There are many steel frame variations. The various combinations of the chosen basic load-bearing structures and their connections between each other give designers the opportunity to carry out variant design and find the best option suitable for the defined situation.

Modern technologies give us new design possibilities. When calculating in LIRA-SAPR, it is much easier to take into account the largest number of factors that affect the design, evaluate tha factors and find a solution how to remove or correctly perceive them.

During this study, many variations for the load-bearing framework designing were considered, but only one of them proved to be the most efficient according to current steel costs. The results of this study show that calculations and decisions were made correctly, it is possible to save about 30 percent of the total cost on building materials, which may become a huge figure in the construction of large objects.

Structures of the most advantageous variant developed during the thesis work were applied for the construction of real gas station in the ”Sinyavino” village. Figure 101 shows the service building of the gas station under construction.

Figure 101. Gas station under construction

Figures

Tables

References

1. SP 156.13130.2014 «Car refueling stations» (rus)

2. Information project USGV.gov. https://mrdata.usgs.gov/geology/state/sgmc-lith.php?text=glacial+drift Assessed on 07 December 2016.

3. SP 131.13330.2012 «Construction climatology». Updated version of SNiP 23-01-99 *(rus)

4. LIRA-SAPR official website https://www.liraland.com/lira/ - Assessed on 25 October 2016

5. D. Koschmidder, D. Brown 2013. Elastic design of single span steel portal frame buildings to Eurocode 3, Ascot, Steel Construction Institute, 196p.

6. SP 20.13330.2011 «Loads and actions». Updated version of SNiP 2.01.07-85*(rus)

7. SP 20.13330.2011 «Loads and actions». Updated version of SNiP II.23-81*(rus)