Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2020.54.2269

UDC 624.041.1

Civil building frame-struts steel carcass optimization by efforts regulation

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With steel structures help it is possible to construct buildings with individual dimensions and different functions, using typical design solutions. The increase in the load-bearing building structures unification level is facilitated by the use of the same transverse frames, which are installed with an equal step. It is possible to ensure the frame stiffness in its own plane by installing struts between the column and the beam. In this case, the crossbar must be calculated as a beam on the hinged supports on the frame columns and on the intermediate elastic supports with a given predetermined stiffness on the struts. By adjusting the struts stiffness and their installation scheme, it is possible to adjust and optimize the stress along the length of the crossbar

Keywords: civil building, frame-struts steel carcass, design scheme optimization, internal forces regulation

Оптимізація регулюванням зусиль рамно-підкісного сталевого каркасу цивільної будівлі

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Сталеві конструкції дозволяють споруджувати будівлі з індивідуальними розмірами та різного функціонального призначення, використовуючи при цьому типові архітектурно-конструктивні рішення. Підвищенню рівня уніфікації несучих будівельних конструкцій сприяє використання однакових поперечних рам, що встановлюються з рівним кроком. Жорсткість рам у власній площині забезпечується або встановленням системи вертикальних і горизонтальних в'язей (при цьому вузли спирання балок на колони виконуються шарнірними), або влаштуванням жорстких вузлів між балками та колонами. Ще одним ресурсоефективним способом забезпечення жорсткості рами у власній площині є встановлення підкосів між колоною й балкою. Завдяки такому рішенню підвищується жорсткість кожної рами та збільшується робочий внутрішній простір будівлі за рахунок відсутності вертикальних в'язей між колонами у поперечному напрямку будівлі. Нерозрізний ригель перекриття у цьому випадку необхідно розраховувати як балку на шарнірних опорах на стійках рами та на проміжних пружних опорах із заданою попередньо визначеною жорсткістю на підкосах. Напруження по довжині ригеля перекриття можна регулювати та оптимізувати за рахунок зміни жорсткості підкосів і схеми їх установлення,. Показано, що нехтування різною жорсткістю стійок і підкосів завищує в декілька разів опорні моменти на підкосах. Це зі свого боку зменшує прольотні моменти, що загалом приводить до отримання хибних результатів статичного розрахунку. У цілому, використання рамно-підкісної схеми каркаса цивільної будівлі дало можливість ресурсоефективно відрегулювати внутрішні зусилля по довжині основних елементів поперечних рам будівлі – стійок і ригелів. Навіть із врахуванням додаткових витрат сталі на влаштування підкосів витрати металу на несучі рами будівлі зменшено на 6% (0,85 кг/м^2) в основному за рахунок зменшення перерізу на один номер прокатного двотавра ригелів перекриття

Ключові слова: цивільна будівля, рамно-підкісний сталевий каркас, оптимізація розрахункової схеми, регулювання внутрішніх зусиль

Introduction

Reducing typical constructions volume in Ukraine in recent decades requires reducing the cost of individual (single for one object) basic load-bearing buildings elements production or increasing the level of their formative and qualitative parameters unification (for example, structures load-bearing capacity, levels of design loads on buildings floors and roofs, etc.) [1].

Steel structures meet the above requirements as they can be used to construct buildings with individual dimensions and purposes, using standard design solutions [2]. Also, steel load-bearing structures have less weight compared to a relatively heavier reinforced concrete carcass, which reduces the laboriousness and terms of building elements production and installation both due to the lack of "wet" processes and by reducing the required load capacity of assembly and transport equipment and machines [3].

Review of the research sources and publications

The increase in the load-bearing building structures unification level is facilitated by the use of the same transverse frames, which are installed with an equal step [4]. The load-bearing capacity of steel elements in load-bearing building structures thus can be effectively used by enough free adjustment of these sections geometrical parameters, namely a wide range of rolled profiles range and ability to create profitable welded sections [5; 6].

The frames' rigidity in its own plane is provided either by the installation of vertical and horizontal knits systems (in this case, the nodes of bearing the beams on the columns are hinged), or the arrangement of rigid nodes between the beams and columns. Another solution to ensure the transverse rigidity of the frame using hinges is to install struts between the column and the beam [7]. Hinged nodes are easy to manufacture; they transmit only longitudinal and transverse forces. Rigid joints form a frame system that, in addition to linear forces, redistributes angular forces (moments) [8]. Rigid nodes also make it possible to create statically indeterminate frames, with which it is possible to redistribute internal forces between the frame elements [9].

With the computer equipment spread with high technical capabilities availability, investigating the stress-strain state of the building frame elements is advantageous with computer programs of finite element analysis using [10; 11].

Definition of unsolved aspects of the problem

When developing architectural and structural design solutions for any building, the designer can use many possible standard solutions for the installation of both load-bearing and enclosing structures. [12]. Architectural and structural solutions of civil buildings elements can be classified by material, manufacturing and installation technology, etc. Therefore, when designing a building, the designer must necessarily determine the technical and economic indicators and optimize the made decisions. During the design of load-bearing structures, particular attention should be paid to the point loads location [13]. In addition, as mentioned above, the type of node arrangement affects the forces redistribution in the carcass linear elements [7].

Problem statement

The purpose of this work is to determine the feasibility of building frame-struts steel carcass placing, which allows due to the struts arrangement between the columns and beams in the building transverse frames to regulate their internal efforts.

Basic material and results

The analyzed building consists of two parts, which from a structural point of view have the same solution. The building two parts designs were developed independently of each other, so each of the parts has a symmetrical relative to the longitudinal axis transverse section with its own gable roof. During two project coordination in one, there was a necessity of a drainage arrangement longitudinal end (see fig. 1). It was decided to abandon the option of installing one common gable roof with one ridge between the two parts, so as not to rework the finished individual projects.

The left part is four-, and the right – three-span building with a carcass constructive scheme (see fig. 1). The spans' width is 6 meters. The exception is the span of the two parts connected in the axes E-F, the width of which is 1.5 m; in this span, there is end drainage. The step of transverse frames is 6 m. The grid of columns are designed with a step 6×6 m.

The height of the external columns along the axes A, E, F, and K is 3 m. The roof slope is equal to $i = 0,1$ (5,70).

The ridge of the left four-span part of the building is arranged on the middle column along the C axis.

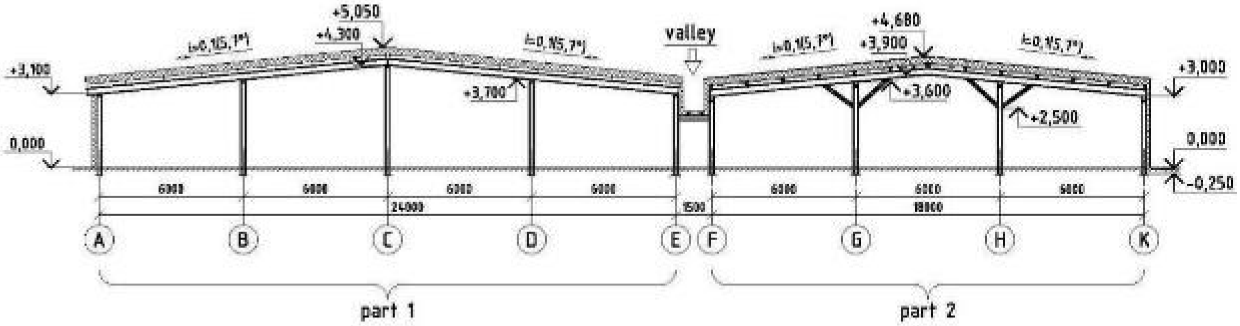


Figure 1 – General transverse section of the analyzed building two parts

The beams' bottom mark in the ridge in this building part is 4.2 m. The ridge of the building's right three-span part is arranged in the middle of the span G-H. The mark of the bottom of the beams in the ridge in this part of the building is 3.9 m. The wall and roof fencing is made of three-layer light sandwich panels. Light mineral wool insulation is provided between the two profiled flooring sheets. The vertical load-bearing structures of the building frames are steel columns with rectangular transverse sections, made of two rolled channels welded into a "box". Foundations under columns – monolithic reinforced concrete separate shallow foundations of hemp step type are arranged on crushed stone-sand preparation.

Rolled beams of the I-beam cross-section serve as beams. In the left part of the building, the beams are arranged according to a four-span split scheme. In the right part of the building, the beams are arranged according to a three-way continuous scheme.

Nodes leaning on the columns' bases and foundations and nodes contiguity beams to the columns taken hinge (see fig. 2).

The building rigidity in vertical and horizontal planes is ensured by the system of cross or portal ties installation in one step of the frames. In addition, the rigidity in the frames transverse direction is provided by partial concreting of the bases of the columns and for the second part of the building in the F-K axes by installing struts between the columns and the beams (see fig. 4).

It is the study of the beams' continuity and struts installation influence on the internal efforts in the optimization of the beam, the subject of research in this paper.

The figures 3 and 4 show separate transverse building sections in two parts. Under each transverse section of buildings, the design schemes for which static calculation and definition of internal efforts in frame elements were carried out are given. In this case, the concentrated load on the crossbar from the girders to simplify the calculations is replaced by evenly distributed. This simplification will not make significant changes to the following materials.

The building covering is made of steel profiled flooring sheets concluded on the girders from rolled channels. Due to the attachment of each wave of the profiled flooring to the upper shelf of the girders with self-tapping screws is provided additional rigidity of the coating disk and performed the perception of the pitched roof horizontal component by a hard disk of profiled flooring and girders, which allowed to reduce the cross-section of the latter.

For the two analyzed variants of building transverse section design schemes, which are shown in figures 2b and 3b depending on the variant of rigidity ensuring for the transverse frame (with vertical ties or struts), it is possible to sketch the "game of internal efforts" - the bending moment *M* and the longitudinal force *N* - along the beam length [14]. Herewith for factors of influence on internal efforts value in beam reduction, in both variants, continuous schemes of only 18-meter beams work are accepted. The change in the transverse force *V* is neglected since the stresses from it are many times less than from *M* and *N*.

a) b)

c) d)

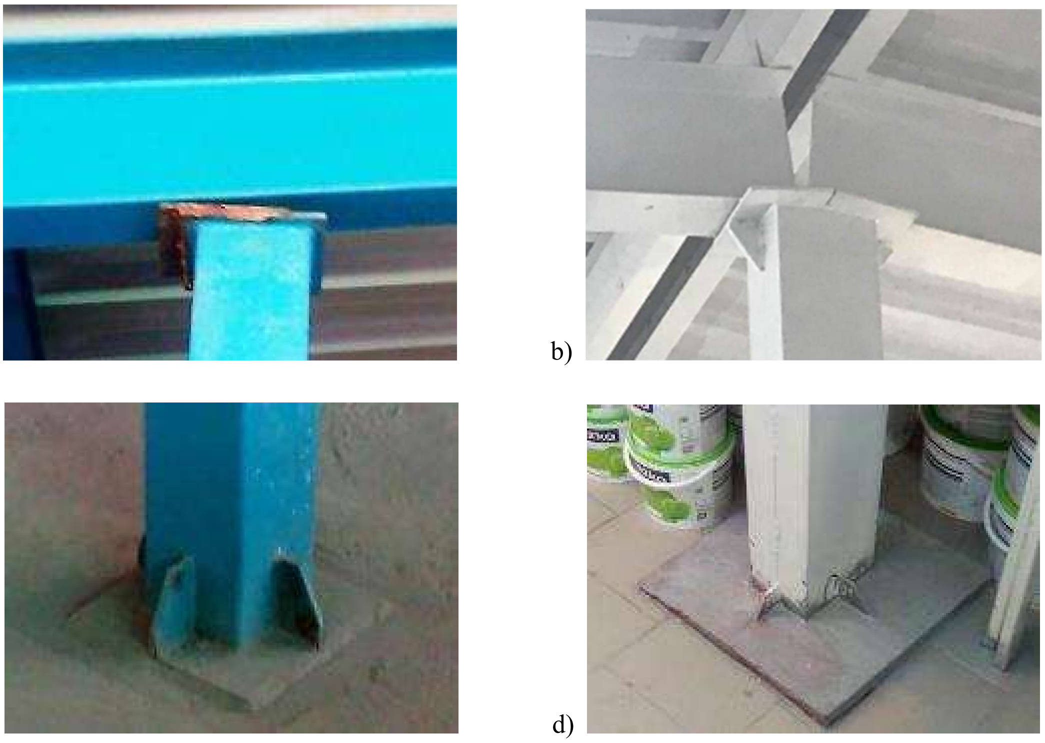
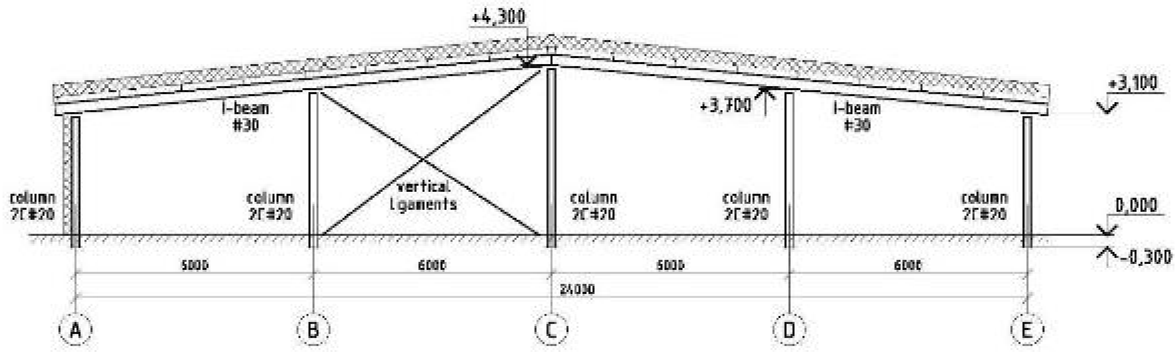
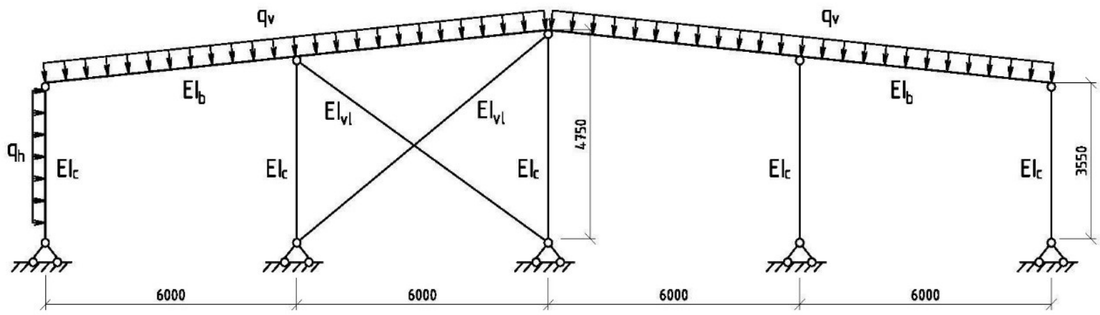


Figure 2 – Placing hinged nodes of beams of connection to heads of external columns (a), middle columns (b) and the hinged column bases (c; d)

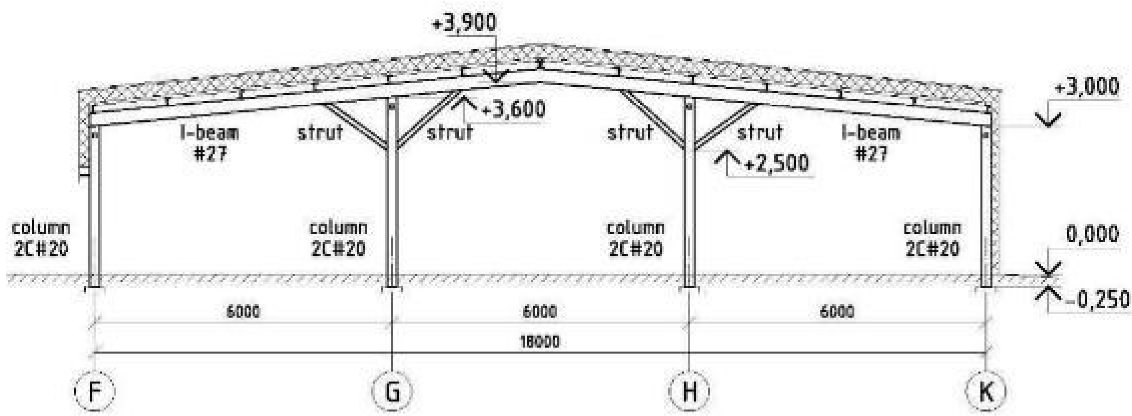


a)

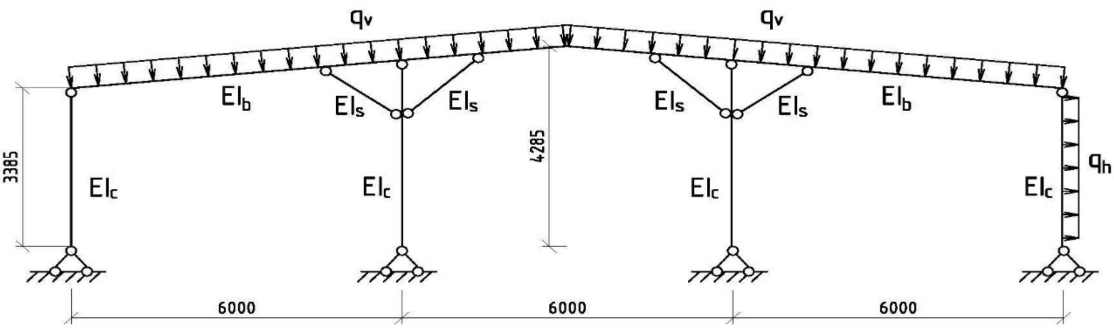


b)

**Figure 3 – Transverse section (a) and design scheme (b)
of the left part of the building in the axes A-E**



a)



b)

**Figure 4 – Transverse section (a) and design scheme (b)
of the right part of the building in the axes F-K**

It is known [2] that the normal stresses in the cross-sections beams, working on compression with bending, are determined by the formula

$$\sigma_{\max} = \left| -\frac{N}{\varphi \cdot A_n} \pm \frac{M_x}{c_x \cdot W_{xn.\min}} \right| \le \gamma_c \cdot R_y . \qquad (1)$$

In the case of providing frame transverse rigidity with vertical ties (see fig. 3), the crossbar occurs predominantly at a bending moment, and the longitudinal force is negligible and occurs only due to the beam slope (see fig. 5). The moments along the crossbar length diagram are two-extreme. The first extreme M_{sp} occurs in the extreme spans in the lower fibers of the beam (in this area the lower fibers of the beam are stretched). The second extreme M_{sup} occurs in the upper fibers of the beam on the middle columns of the frame (in this area the upper fibers of the beam are stretched). Extreme bending moment values in extreme spans M_{sp} and on the middle support M_{sup} are different, the largest of which is M_{sup}. That is, we have two design cross-sections along the continuous 18-meter crossbar length only on the middle supports.

For the first design scheme, in addition to the design cross-sections occurring on the middle supports, we will have another problematic issue from constructive considerations. Since the floor beams are arranged on top of the beams, we will have on the middle supports not unfastened from the frame plane the lower compressed fibers of the floor beams [15]. To solve this problem, it is necessary to either arrange additional ties between the frames in the specified places or weld additional steel plates on the lower shelves of the I-beams.

The design moments M_{sup} on the middle supports of the floor beam can be reduced by using a frame-struts scheme of the transverse building frame (see fig. 4). In this case, it is possible to achieve a diagram of M along the beam length with four calculated sections instead of two. That is to align the values of the span and support moments by aligning the steps of the crossbar supports "rack-strut-rack" installation. In [7] it is proved that the optimal angle of the struts inclination relative to the vertical in terms of internal forces in the strut is equal to 40…50°. This angle of the struts inclination to the uniform supports step "rack-strut-rack" lowers the point of the attachment of the struts to the rack too low in the working space of the room, which is impractical for internal space of premises free planning. Therefore, the point of the attachment of the struts to the rack is performed at a mark close to the mark of the extreme columns head (usually not less than 2.5 m – see fig. 4, a). With such a design scheme, the value of the bending moment M_{sup} on the middle support decreases by 2-3 times, and the design cross-section becomes the span moment M_{sp}, as shown in fig. 6. That is, in this case, we will also have two design cross-sections along the continuous18-meter crossbar length, but no longer on the middle supports but in the extreme spans. The design values of the span moments will be lower than in the first case (see fig. 5) by ~ 42%.

When using the frame-struts design scheme of the transverse frame in cross-sections of crossbar between points of struts fastening to middle columns we will have sites of a local increase in longitudinal force (see fig. 6). That is, with a significant decrease in the value of M on the middle supports, we will have a jump on the diagram N. The stresses in the beam cross-sections, determined by the formula (1), will change not only in proportion to the change in bending moment but abruptly in places of abrupt change in the diagram N.

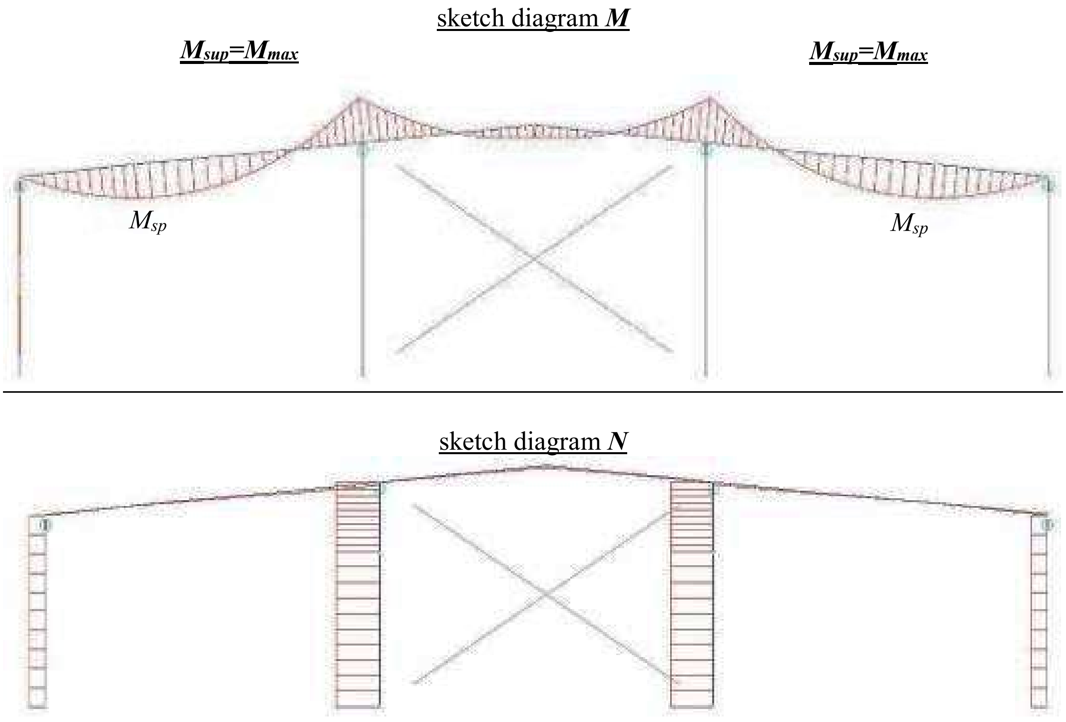


Figure 5 – Sketch diagrams of internal efforts for the transverse frame with vertical ties

Also, when using struts, you need to keep in mind the concentration of bending moment in the frame columns at the points of struts attachment (see fig. 6), as well as the growth of the longitudinal force in the middle columns by increasing the load width of the distribution over the area weight. It is possible to provide the local bearing capacity of a rack in a place of struts adjunction either by the device of a cross-cutting gusset or (see fig. 7, a) or by the device of additional vertical plates (see fig. 7, b).

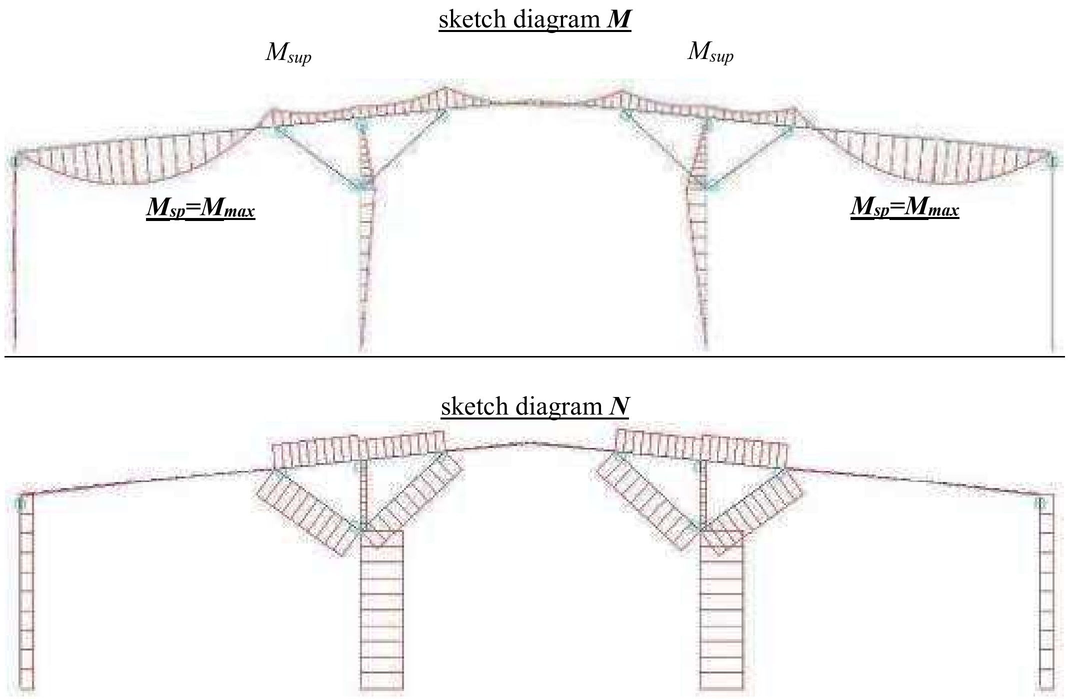


Figure 6 – Sketch diagrams of internal efforts for the transverse frame with struts

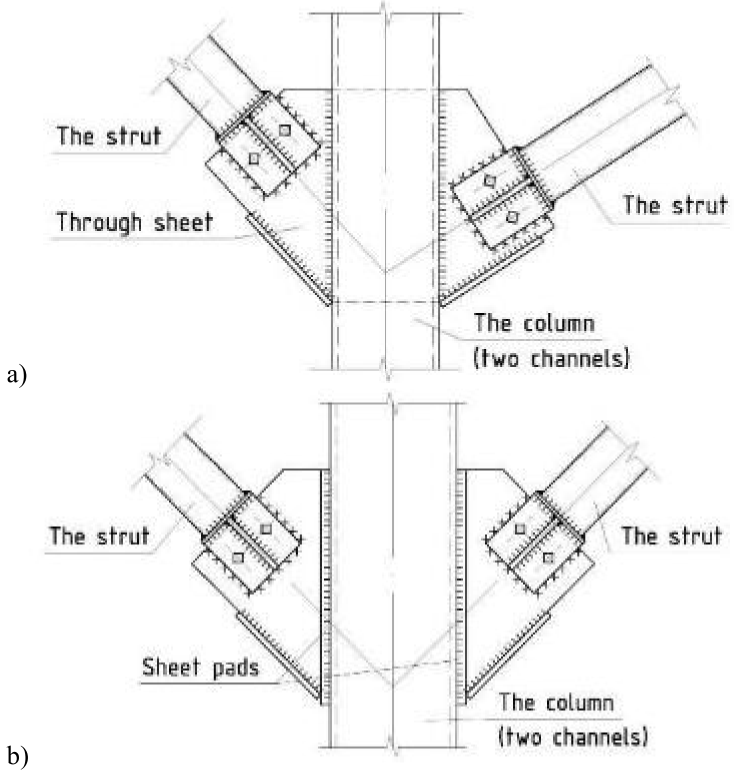


Figure 7 – Nodes of struts to columns connection:
a) using cross-cutting gusset; b) using additional vertical plates

Also on change of internal efforts in beam cross-sections will be influenced not only by the geometrical scheme of struts installation but also struts rigidity (cross-sectional dimensions). Usually, the struts have a smaller cross-section than the frame columns. Therefore subsidence (vertical displacements) of beam supports in places of frame columns and struts will not be identical, which will affect the distribution of the bending moment along the beam length. In this case, the design scheme of the beam will be shown more correctly as proved in [4] in the form of a beam on hinged supports on the frame struts and on intermediate elastic supports with a given predetermined stiffness on the struts (see fig. 8).

Figure 9 shows a comparison of the determining the bending moment values results for the 18-meter beam on the hinged supports on the frame columns and the intermediate elastic supports on the struts and all hinged supports. From the presented diagrams it is clear that the type of supports significantly affects the distribution of internal efforts along the beam length. As expected, the replacement of elastic supports with hinged ones up to twice the bearing moments in these places. This in turn reduces the span moments that generally lead to obtaining false results of the static calculation. Therefore, when determining the internal efforts in the continuous crossbar, it is necessary to take into account the actual stiffness of all supports.

Thus, by adjusting the struts stiffness and their installation scheme, it is possible to adjust the stress in the beam. This is the skill of obtaining a cost-effective construction. For this variant of the transverse frame, the use of the frame-struts scheme allowed to reduce by one number the cross-section of the beam from the rolled I-beam #30 to the I-beam #27.

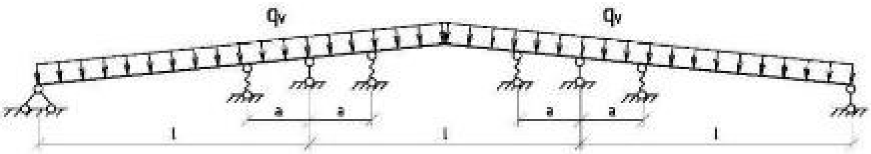


Figure 8 – The design scheme of the crossbar with intermediate spring support (struts)

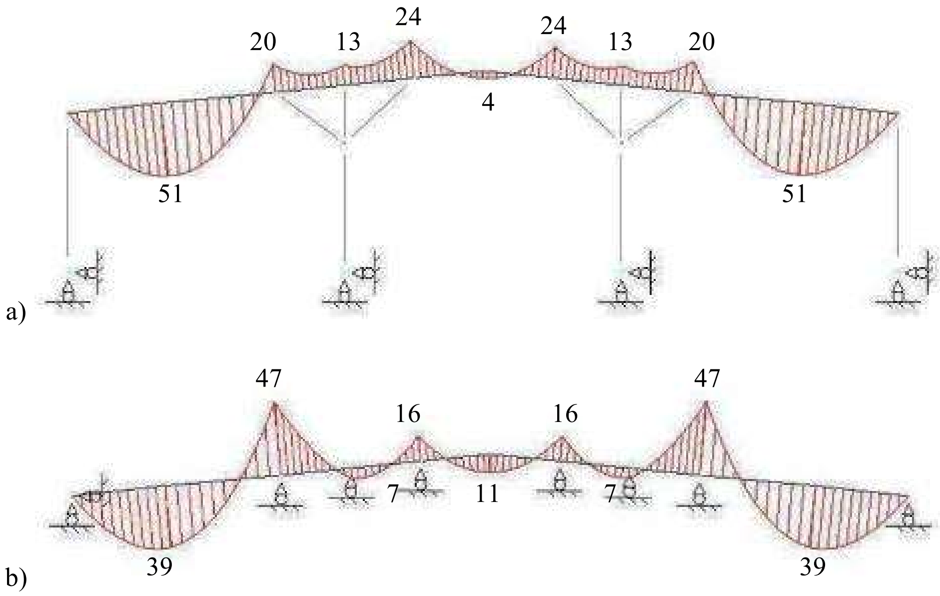


Figure 9 – Diagrams of bending moments in the 18-meter crossbar, kNm:
a) on hinged supports on frame columns and intermediate elastic supports on struts;
b) on all hinged supports

Conclusions

The use of a civil building frame-struts carcass scheme made it possible to efficiently adjust the internal efforts along with columns and beams, namely:

– even taking into account the additional costs of steel for struts installation, are reduced metal costs for the building load-bearing frames by 6% (0.85 kg/m^2) mainly by reducing the cross-section of the beam of rolled I-beam by one number;

– the rigidity of the frame in the transverse direction is increased due to the struts installation;

– is increased working space of the building due to the absence of vertical ties between the columns in the transverse direction of the building.

In further research, it is planned to carry out the mathematical description of beam work on hinged support on columns and on intermediate elastic supports with the set predetermined rigidity on struts.

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