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Myron Hohol[1], Dmytro Sydorak[1], Marko Hohol[2]

SYNTHESIS OF RATIONAL CONSTRUCTIVE SOLUTION OF STEEL ROOF TRUSSES

[1] Department of Building Production,
[2] Department of Highways and Bridges,
Lviv Polytechnic National University
dmytro.p.sydorak@lpnu.ua

The article examines the issue of the occurrence and influence of bending moments on the bearing capacity of a combined steel truss made of rectangular bent-welded profiles. A comparative analysis of technical and economic indicators in terms of material intensity, labor intensity, and cost of traditional-typical and lightweight combined steel trusses was carried out. The paper examines steel trusses of long-span buildings with a span of 30 m. The force graphs (bending moments and axial forces) for various calculation schemes of the combined steel truss are shown. An analysis of the forces in the combined truss for different ways of connecting the lattice to the chords was carried out. The plot of normal stresses along the middle line of the stiffening girder of the combined truss for various calculation schemes is presented. The load-bearing capacity of compressed rods with different connection methods was calculated. According to the research results, an engineering method of taking into account the influence of bending moments is proposed.

Key words: steel combined trusses; rational design; rational structure; metal consumption and labor intensity of production; numerical studies; comparative analysis.

Introduction

In world designing practice, many universal public and industrial structures have been created. One of them is steel truss roofing systems, distinguished by original architectural forms and progressive design solutions (Hohol, 2018).

Currently, the leading direction of effective metal construction is the use of light metal structures in industrial, civil and agricultural buildings. In recent years, the development of construction in Ukraine has a tendency to grow and goes in the direction of increasing the use of new efficient light domestic and foreign industrial structures, in particular metal ones (Gogol, Zygun, Maksiuta, 2018). The modern market of building metal structures poses an acute problem in justifying the adopted constructive decisions and requires the improvement of theoretical foundations for engineers during design. Today, the industry of construction metal structures is experiencing a second renaissance, the growth in demand for the products of metal construction plants contributes to the expansion of the market and the growth of competition.

Scientific and technical progress in the field of construction is closely related to the problems of development and improvement of steel metal structures. One of the main tasks of designers when designing buildings from metal structures is, in addition to ensuring the overall stability of the building and its elements, is to reduce the metal consumption, the labor intensity of manufacturing and, as a result, the cost of expenses. Truss metal structures are effective and most satisfying architectural and construction requirements for strength, stability and architectural and structural expressiveness when designing building roofing. Metal trusses are widely used in industrial and public buildings. The main element of building roofing is a steel truss, the contour of which is determined mainly by the architectural and planning decision of the building and is necessarily related to the roofing material.

In the practice of designing metal structures for the roofing of long-span buildings, trusses from closed profiles (bent-welded, tubular) have been widely used, which is reflected in the current standards (Achtziger, 2007; Brütting, Desruelle, Senatore and Fivet, 2019). Further improvement of the process of designing, manufacturing, complex supply and installation of light metal structures of industrial buildings requires a combination of optimal mass indicators with minimal labor intensity of mechanized flow manufacturing (Gogol, Kropyvnytska, Galinska, Hajiyev, 2020).

Traditional trusses are distinguished by a significant consumption of metal for shapes and gaskets, increased labor intensity of production, inconvenience of painting rods during operation (protection of metal structures from corrosion) (Chilton, 2000; Gasii, 2020; Romaswamy, Eekhout and Suresh, 2002). The second disadvantage of the solutions of the slatted lattices of traditional trusses is the significant unevenness of the rods in relation to their axes. Today, it has been proven that the most economical are trusses with the lowest self-weight, less metal consumption, with maximum unification and typification of truss elements, which is the basis for the development of new and improvement of existing types of trusses, aimed at eliminating structural deficiencies (Hohol, 2018). The creation of rational constructive solutions of steel trusses, aimed at reducing the labor intensity of manufacturing, steel consumption and manufacturing cost, is becoming relevant (Hohol, Marushchak, Peleshko and Sydorak, 2022).

The goal of developing rational structural solutions for steel trusses of long-span buildings, taking into account the increase in functional and structural safety of the building, fire resistance and durability of the structures, was to obtain by combining the advantages and removing the disadvantages of the closest analogues of new competitive solutions for roofing buildings and structures (Hultman, 2010).

The research methodology is based on a comparative analysis of technical and economic indicators in terms of material intensity, labor intensity and cost of traditional-typical and lightweight combined steel trusses. The paper examines steel trusses of long-span buildings with a span of 30 m. During the analysis, a truss with parallel belts, with a V-shaped lattice, also with a span of 30 m, was chosen as a reference truss (Hohol, Gasii, Pents and Sydorak, 2022; Hohol, Peleshko, Petrenko and Sydorak, 2021), Fig. 1.

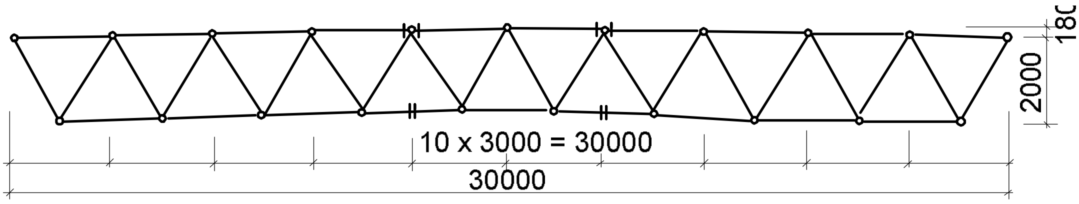


Fig. 1. Scheme of reference typical truss

Materials and methods

The appearance of rational combined trusses, as the main element of the roofing, as structures of a new class, determined the next stage of development of the construction industry (Hohol, 2018; Hohol et al., 2020; Oehlers and Bradford, 2013). Rational combined trusses have advanced among progressive designs due to the development and use of calculation methods for multiple statically indeterminate systems, which are combined trusses designed with the help of computers.

The advantages of such systems, along with aesthetic and architectural expressiveness, include the possibility of arranging a roofing with any configuration of the plan, reducing the specific mass of the structure, while not reducing the efficiency of work on payloads. A high degree of automation creates favorable conditions for the industrialization of the factory production process, reducing the work on the construction site only to bulk assembly and direct installation. Thanks to the regular placement of the elements, the design of the combined formless truss is well aware of the action of moving and unevenly acting loads (Cazacu, Grama, 2014).

Recently, in European countries – Switzerland, Germany and England, new scientific research is being conducted for the possibility of implementing an extremely lightweight design using adaptive structures (Reksowardojo, Senatore and Smith, 2020; Senatore, Duffour and Winslow, 2019), which optimally adjust their geometry to current and changing conditions through active movement. Such adaptive structures (including trusses) instead of increasing rigidity with the help of material mass, additionally use strategically located active elements – electric linear actuators that manipulate the internal flow of forces and change the shape of the structure, as well as passive steel elements. The use of adaptive structures is carried out with the help of sensors, intelligent control and executive mechanisms. Research is at an early stage. They have the following disadvantages: their implementation causes great technological difficulties; such structures require a control and management system during operation, etc., which limits their use (Weldeyesus et al., 2020).

Unlike adaptive structures, rational combined steel structures during their design and implementation do not require any additional material costs without the need for their control during operation (Cavallaro, Demasi, 2016).

The presence of redundant connections, which form the static uncertainty of combined trusses, increases the reliability of the structure in general due to the possibility of redistributing stresses after the possible exclusion of individual elements from work. Such systems, taking into account their multiple static uncertainty, have greater rigidity compared to typical trusses, which allows designing structures of lower height (He and Gilbert, 2015; Ruiz-Teran and Aparicio, 2010).

The synthesis (Hohol et al., 2023) (algorithm of finding an effective structural solution of trusses) of a rational structural solution of long-span trusses includes the following conditions:

- determining the ratio between the prices of the profiles and choosing the profile with the lowest cost for the bars of the truss;
- the rational angle of inclination of the compressed lattice elements;
- reducing the number of truss elements, including bracings;
- the minimum number of panels of the upper chord;
- a rational ratio of the mass of the upper chord to the mass of the entire truss;
- choosing a calculation scheme that most closely reflects the actual operation of the truss.

Steel trusses made of bent-welded profiles of rectangular or square cross-section were most widely used in the construction of building coverings. Their dominant use is dictated by a number of positive constructive qualities: rational cross-sectional shapes when working under compression, the possibility of seamless connection of lattice rods using welding, a smaller surface perimeter, therefore, less consumption of paint and varnish materials and greater corrosion resistance.

At the same time, these structures, having a lower consumption of steel, which has a positive effect on the environment (European Environment Agency, 2010), in some cases are inferior in cost to light trusses made of rolled profiles due to the higher cost of a closed bent-welded profile.

The economic efficiency of open profiles is due to the high cost of closed profiles. The ratio between the cost of rectangular bent-welded profiles, profiles made of two rolled channels, rolled I-beam, respectively equals: (121): (162); (118) % (100 % is taken as the value of profiles with double rolling L-section). Therefore, according to the cost criterion, it is more rational to use rolled profiles from rectangular or square bent-welded profiles and rolled I-beams, compared to pair rolled L-sections.

As a result of the conducted research, it was established that for the considered conditions of steel roofings of buildings of small spans in the conditions of Ukraine, the use of trusses from electrically welded round pipes or from bent-welded rolled profiles, which have approximately the same weight and cost, is generally the most rational. Also worthy of attention is the upper chord of the combined truss in the form of a welded I-beam profile of small thickness (4 mm) made of high-strength steel, the cost of which is on average 20 % higher than the previous options. The least effective of all the options considered was the upper chord made of rolled I-beam profile. Its weight and cost are more than 2 times higher than the main recommended options, and therefore its use in such conditions should be declined.

It is obvious that the design of nodal connections has a significant effect on the complexity of assembling trusses and determines the complexity of manufacturing and installation. At the same time, the choice of structural solution of nodal connections of truss structures significantly affects their weight.

Thus, while preserving and observing all the necessary operating parameters, the design under consideration requires less metal compared to typical ones (Hohol, Gasii, Pents and Sydorak, 2022), and therefore the cost is reduced, which allows for installation from the most available forms of rolled steel, and the possibility of using a welded joint allows the use of different grades of steel.

Stresses in the truss, therefore, the cross-section and many structural elements largely depend on the adopted design parameters. The search for the most effective design solution option for combined trusses is one of the tasks solved at the initial stages of design (Hohol, 2018) and directly affects the subsequent labor intensity of manufacturing, installation and, ultimately, the cost of the structure.

The choice of the design of the minimum mass is based on the selection of rational geometric parameters, as well as the method of calculating SSS regulation. Regulation of the SSS of the load-bearing structure of the ring is considered as one of the tasks of managing the behavior of load-bearing building structures – a separate direction in construction mechanics. The following parameters are adopted as regulators: the rational angle of inclination of the compressed lattice elements; rational ratio of the weight of the upper chord to the weight of the entire truss; the number and location of compressed elements; choosing a settlement scheme; steel grade and truss height. Depending on these parameters, the stresses in the truss elements change and the cross-sectional area and weight of the structure change accordingly. On the basis of the accepted criterion of the effectiveness of the design solution – metal consumption, the most effective design solution of steel roof trusses is adopted. Minimization of the mass of the designed structure is the most common design criterion (Flager, Adya, Haymaker and Fischer, 2014; Li et al., 2023).

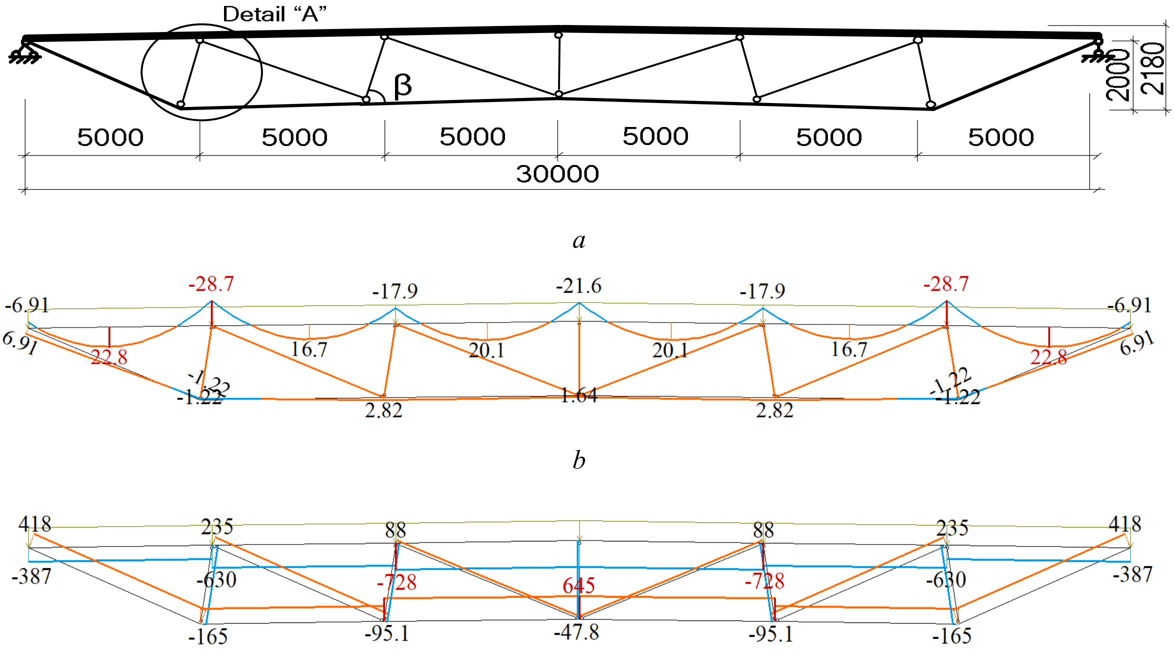
From an energy point of view, the height of typical roof trusses is assumed to be 2 meters, which makes it necessary to adopt the same height for rational combined trusses. But there are structural requirements for the height of the trusses. Usually, taking into account the requirements of transportation, installation, optimal rigidity and other factors, the height of the trusses is accepted within 1/5 – 1/9 – 10 of the span for the trusses. In this way, the length of individual compressed rods of the truss is indirectly determined, therefore, their flexibility.

In the recent past, due to the limited capabilities of computers, roof truss calculations were performed manually. For simplification, and sometimes simply for the possibility of manual determination of the internal stresses in the truss rods, assumptions were made that the rods in the truss nodes are hinged. The actual structural design of the combined truss nodes using a welded connection is essentially not hinged, and the above assumption is valid only in the case of significant flexibility of the truss rods themselves. This fact suggests that in fairly rigid rods, for a 30 m truss with a height of 2 m, which corresponds to 1/15 of the span, the development of significant nodal bending moments is possible. In this regard, there is a need to study the influence of a real rigid node on the operation of the truss in the absence of eccentricity in the nodes.

Let’s conduct a numerical experiment. Let’s consider the dependence of the influence of bending moments in the rods of the truss on its height. For research, a geometric scheme of a reference typical farm (Fig. 1) with a span of 30 m, a height of 3 and 2 m with a hinged connection at the nodes was chosen. For comparison with these trusses, we will also consider two combined trusses of the same span, also 3 and 2 m high (Figs. 2 and 3).

These four trusses were calculated on a PC with the program “LIRA-CAD 2016 R5” from a uniformly distributed load $q = 12.75$ kN / m, at the angle of inclination of the compressed rods $\beta = 80°$ with the same geometric parameters and cross sections of the elements, that is, the same mass trusses, but with different calculation schemes. Combined trusses with rigid nodes, and reference trusses with hinged ones (Fig. 2, 3).

As can be seen from the plot in Fig. 2.b, the largest bending moment is 28.7 kN·m, which occurs at the first intermediate support. The largest bending moment in the span occurs in the first section and is 22.8 kN·m. It should be noted that a bending moment also occurs at the extreme supports due to the joint work of the lower and upper chords as inseparable and is equal to 6.91 kN·m. In the lower chord, the value of the moment ranges from 6.91 kN·m to 1.22 kN·m and changes linearly. Only compressive and tensile forces act in the lattice elements, bending moments do not occur due to the hinge connection.

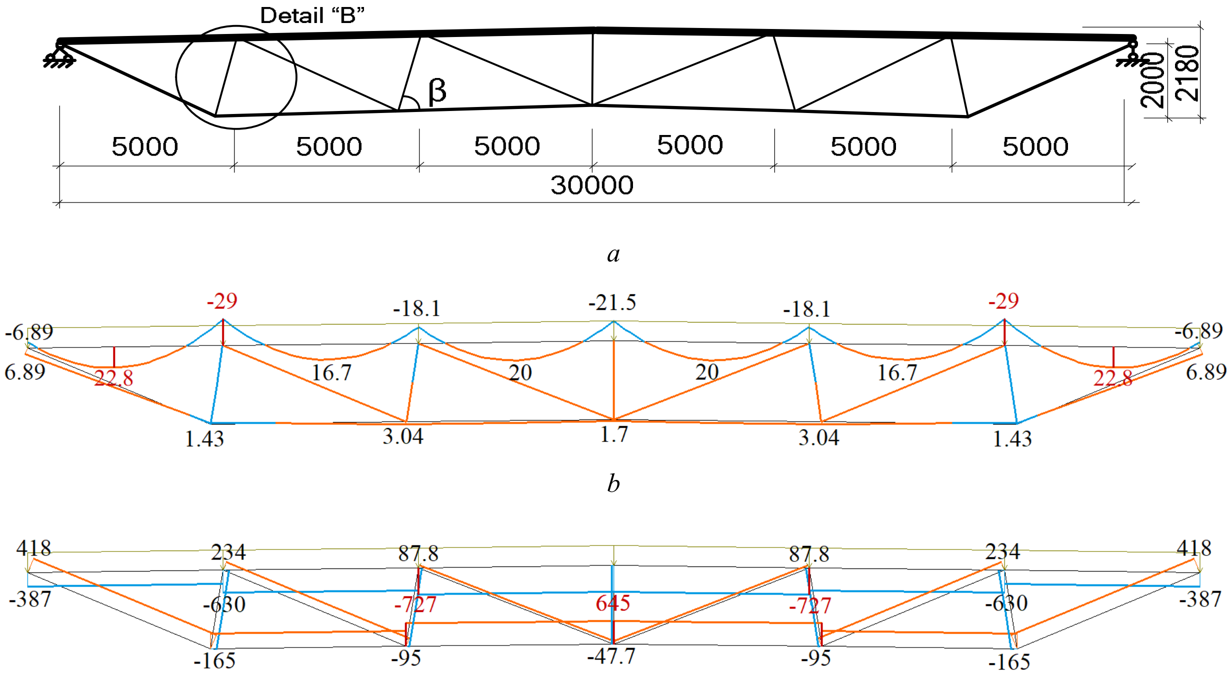


a

b

c

Fig. 2. Combined truss with a span of 30 m and a height of 2 m with non-separable chords and hinged connection of rods: a – calculation scheme; b – plot of bending moments, c – plot of normal forces



a

b

c

Fig. 3. Combined truss with a span of 30 m and a height of 2 m with non-separable chords and rigid connection of rods: a – calculation scheme; b – plot of bending moments, c – plot of normal forces

Regarding the normal forces, the highest compressive force is 728 kN in the middle section of the upper chord. Similarly, the largest tensile force of 645 kN occurs in the middle section of the lower chord. In the lattice, inclined struts absorb compressive forces, and diagonal braces absorb tensile forces. The compression in the struts increases from the central strut to the outer struts from 47.8 kN to 165 kN. The tensile forces also increase from the middle of the structure to the extreme sections and are 88 and 235 kN, respectively. For a truss with rigid nodes, the following force values were obtained, which are given on the graphs (Fig. 3).

The maximum values of bending moments are observed at the first intermediate support and in the span of the first span – 29 and 22.8 kN·m, respectively. At the extreme supports, the bending moment is equal to 6.89 kN·m. In the lower chord, the bending moment changes linearly in the range from 1.43 to 6.89 kN·m.

Normal compressive forces in the upper chord increase from the extreme supports to the middle, reaching a value of 728 kN. The maximum tensile force in the lower chord is 645 kN. The racks, according to the calculation, perceive forces from 47.7 kN to 165 kN. The tension in the central braces is 87.8 kN, in the extreme ones – 234 kN.

Comparing the values of the forces in the two variants of the calculation schemes, the maximum values of the bending moments on the first intermediate support differ by 0.3 kN·m or by 1 %. In the spans and on the following intermediate supports, the bending moments differ by 0.1 kN·m. Moments in the lower chord also differ within 0.1–0.2 kN·m. We can observe a similar case for longitudinal forces. Efforts in racks differ by 0.1 kN, in braces – from 0.2 to 1 kN, which is less than 1 %. The maximum forces in the upper chord differ by 1 kN, in the lower chord they do not differ, 645 kN. In summary, it can be stated that the normal forces in the truss practically do not differ with the two given calculation schemes.

After considering the value of the bending moments in the lower chord, it can be seen that the moment on the first intermediate support is 15 % greater than in the hinged connection, so it is necessary to check the bearing capacity. However, at the extreme support there is a moment 4 times greater with the same longitudinal force, so such a change (by 15 %) can be neglected. The calculation showed that the total stress change is 1 % on the first intermediate support.

As can be seen from the graphs in Fig. 2, 3, the forces practically do not differ with different calculation schemes and methods of connecting the grid. This is also confirmed by the general stress diagram (Fig. 4). The lines of the graphs for different calculation schemes are actually superimposed on each other. The difference is no more than 1.3 MPa in individual sections.

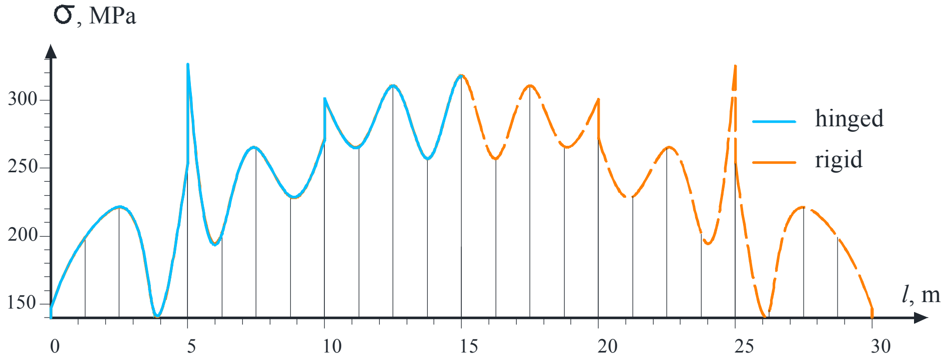


Fig. 4 Chart of normal stresses along the middle line of the stiffening girder for different calculation schemes: left half – for hinged connection; right – for rigid

When calculating for the same load of trusses with a height of 3 m, the longitudinal forces are significantly reduced due to an increase in the height of the truss from 2 to 3 m. Thus, the force in the upper chord decreased by 1.5 times to 486 kN, and in the lower chord to 432 kN. That is, the longitudinal forces are inversely proportional to the height of the truss. Struts are unchanged, except for the center strut, which has increased by 10 % to 53 kN. Instead, the tensile forces in the braces decreased to 172 and 62 kN, respectively. Thus, it is possible to reduce the cross-sections of elements for chords. However, due to the increase in the height of the truss, the calculated length of the compressed rods increases and, as a result, their flexibility λ. It is necessary to increase the stability of the rods by increasing the cross-section of the racks.

It should be noted that with the calculation scheme in Fig. 3, *b* additional bending moments arise in the racks of the lattice.

Therefore, this article considers the possible additional impact of such moments on the lattice racks, the impact of which must be evaluated and the need to take it into account.

Consider the extreme rack, which is the most loaded (Fig. 3, *a*). The compressive force in this rack is 165.27 kN. The largest bending moment of 29.0 kN·m occurs above the same rack in the upper chord.

In node "A" (Fig. 2, Fig. 5) the hinged connection of the rack to the belts on the first intermediate support is shown. For the calculation, consider this rack as the most loaded with a compressive force of 165 kN.

The calculated length of the rack will be equal to:

$$l_{ef} = \mu \times 1 = 1 \times 200 = 200 \text{ cm}, \tag{1}$$

where μ – is the anchoring factor of the rod;, l – is the actual length of the rod.

The flexibility of the rod will be equal to:

$$\lambda = l_{ef} / i_{\min} = 200 / 3.12 = 64, \tag{2}$$

where l_{ef} – calculated length of the rod; $i_{\min}$ – minimum radius of gyration.

Using the method of interpolation in the table of longitudinal bending coefficients, we find the value of φ for the given conditions:

$$R_y = 250 \text{ MPa}, \lambda = 64 \rightarrow \varphi = 0.798 \tag{3}$$

Then, for pure compression, the stress will be equal to:

$$\sigma_N = N / \varphi A = 165.27 \text{ kN} / 0.798 \times 9.2 \text{ cm}^2 = 22.504 \text{ kN/cm}^2 = 225.04 \text{ MPa}, \tag{4}$$

where N – longitudinal force; φ – is the coefficient of longitudinal bending under the specified conditions; A – is the cross-sectional area of the element.

In detail "B" (Fig. 3, Fig. 5) rigid connections in the node are given. Noticeably, in such nodes, in addition to the compressive force of 165 kN, a bending moment of 0.373 kN·m also occurs. Consider the effect of such a moment on the change in stress.

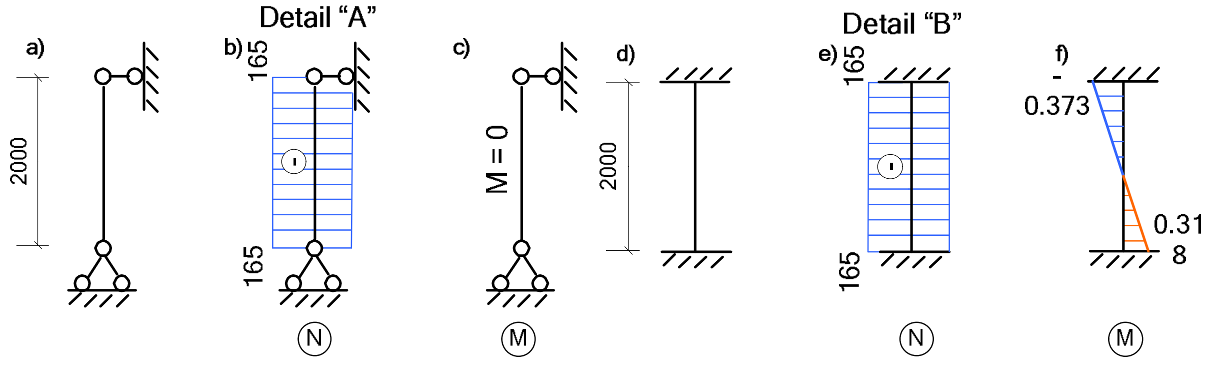


Fig. 5. Detail "A", detail "B": a – calculation scheme of a hinged rack; b – diagram of longitudinal forces; c – diagram of bending moments; d – calculation scheme of a rigidly fixed rack; d – diagram of longitudinal forces; e – diagram of bending moments

Consider the option when such a rod is eccentrically compressed, that is, the influence of both compression and bending is taken into account.

$$\sigma = \sigma_N + \sigma_M = \frac{N}{A} + \frac{M}{W} = 165.27\ \text{kN} / 9.2\ \text{cm}^2 + 0.373\times100 / 22.4\ \text{cm}^3 = 17.964\ \text{kN/cm}^2 + \\ +1.665\ \text{kN/cm}^2 = 179.64\ \text{MPa} + 16.65\ \text{MPa} = 196.29\ \text{MPa}. \tag{5}$$

In the percentage ratio, the share of stresses from bending will be equal to 16.65/179.64 ≈ ≈ 0.09 = 9 %. Thus, it is necessary to take into account the influence of the bending moment during the compression of the struts, since the change in the amount of stress is more than 5 %.

Results and Discussion

The results of numerical studies showed that calculations to determine the bearing capacity of elements of combined trusses must be carried out taking into account bending moments in cases where the structural requirements regarding the ratio of the height of the trusses and the span are not met at the seamless welded connection in the nodes of rods from bent-welded profiles.

Conclusions

Significant bending moments appear in the considered truss when the height of the truss is 2.0 m or less (less than 1/10 of the span).

The most significant additional load is the bending moment on the truss chords.

The value of the longitudinal force in the rods of the trusses does not change significantly in calculations with and without the introduction of hinges into the nodes.

The maximum moment loading of the lower chord on the truss with a height of 2.0 m in the area of the supporting brace reached 15 %, which requires additional verification of its bearing capacity.

On the basis of the proposed constructive solutions of new combined rafter trusses, it is advisable in the future:

– develop a structural solution for the roofing block (which includes stiffening diaphragms and connections);

– to develop a methodology for calculating the technical and economic substantiation of the effectiveness of combined roofing structures.

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М. В. Гоголь[1], Д. П. Сидорак[1], М. М. Гоголь[2]

Національний університет “Львівська політехніка”,
[1] кафедра будівельного виробництва,
[2] кафедра автомобільних доріг і мостів

СИНТЕЗ РАЦІОНАЛЬНОГО КОНСТРУКТИВНОГО РІШЕННЯ СТАЛЕВИХ ФЕРМ ПОКРИТТЯ

Розглянуто питання виникнення та впливу згинальних моментів на несучу здатність комбінованої сталевої ферми з прямокутних гнуто-зварних профілів. Здійснено порівняльний аналіз техніко-економічних показників за матеріаломісткістю, трудомісткістю та вартістю традиційних – типових та полегшених комбінованих сталевих ферм. В роботі розглянуто сталеві ферми великопрогонових будівель із прольотом 30 м. Виконано порівняльну оцінку конструктивної ефективності різних способів приєднання решітки у раціональних комбінованих сталевих фермах і порівняння із типовими фермами за ДСТУ. Наведено переваги комбінованих конструкцій над типовими (традиційними) та переваги статично невизначених конструкцій над статично визначеними. Наведено алгоритм пошуку ефективного конструктивного рішення великопрогонових ферм. Проаналізовано ефективність використання різних типів поперечного перерізу для елементів ферм покриття. Виконано розрахунок комбінованих сталевих ферм покриття висотою 2 та 3 м. Наведено епюри зусиль (згинальні моменти та поздовжні зусилля) для різних розрахункових схем комбінованої сталевої ферми. Проаналізовано значення зусиль у комбінованій фермі для різних способів приєднання решітки до поясів. Подано епюру нормальних напружень по середній лінії балки жорсткості комбінованої ферми для різних розрахункових схем. Визначено, що за різних способів закріплення решітки зусилля у балці жорсткості практично не змінюються (до 1,0 %). Числовий експеримент показав, що за жорсткого способу закріплення у стійці виникає згинальний момент від 0,373 до 0,318 кН·м. Зокрема, за жорсткого способу закріплення решітки на першій проміжній опорі у нижньому поясі значення моменту зростає на 15 %. Виконано розрахунок несучої здатності стиснутих стержнів за різних способів з’єднання. За результатами досліджень запропоновано інженерний спосіб урахування впливу згинальних моментів. Наведено рекомендації щодо проєктування комбінованих сталевих ферм.

Ключові слова: комбінована сталева ферма; раціональне проєктування; раціональна конструкція; металомісткість та трудомісткість виготовлення; числові дослідження; порівняльний аналіз.