Load carrying ability and optimal characteristics of the roof slab made of profiled sheeting

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Abstract. The subject of the study is the roof slabs, made of profiled sheetings, supported by bottom truss systems. The profiled sheet, being the upper belt of these structures, experiences longitudinal-transverse bending under the distributed transverse load and a longitudinal eccentric compressive force. Analytical and numerical studies determined the stress-strain state of the profiled sheeting. The dependences of the limiting value of the distributed load on the compressive longitudinal force and the eccentricity of its application are revealed. A technique for optimizing the design parameters of roof slabs has been developed. The studied roof slabs made of profiled sheeting, supported by a truss system, have a rather complicated design with many parameters, on which the performance criteria depend. Studies of the ties between these parameters are quite laborious. Therefore, it is not possible to solve the problems of optimizing these structures by known analytical and numerical methods. To find the rational parameters of the studied slabs, we used the method of phased numerical experiments using simplex optimization. Using this technique, the optimal structural parameters of the slabs with spans of 6-12 m were determined for a given efficiency criterion.

Keywords: profiled flooring, truss roof slab, performance criteria, optimal characteristics, supercritical operation, local stability, eccentric compression.

1 Introduction

One-story prefabricated buildings made of light metal structures are always in great demand. The main objectives of improving such buildings are to reduce the weight of building structures, reduce the complexity of their manufacture, installation and, as a consequence, the cost of construction. One of the ways to achieve this is the use of steel cold-formed thin-walled profiles as supporting and enclosing structures.

Light steel cold-formed thin-walled structures (LSTS), which were introduced into construction practice at the end of the last century, are today widely used as enclosing and supporting building structures. They also have a perspective in terms of their variety. The consequence of this is the emergence of a large number of scientific publications devoted to the development [1-5], calculation and optimization [6-10] of LSTS. Great attention is also paid to experimental studies of structures made of thin-walled cold-formed sections [11-14].

Among LSTS stand out structures made of profiled steel sheeting, which is widely used as supporting or enclosing elements of floors and roofs. The main feature of the behavior of the profiled sheet under the load is that some compressed sections of the walls and shelves may lose local stability, which begins even in the elastic stage. Such feature is typical for almost all cold-formed thin-walled profiles. The loss of local stability significantly affects the performance of the sheeting and, as a rule, leads to a large irregularity in distribution of stresses over the cross section in the supercritical loading stage. Therefore, the design and improvement of methods for calculating roofs from profiled sheeting is an urgent problem. There are publications on this issue [15-20]. In [21-24], the stress-strain state of layered roofs made using profiled sheets was studied.

In the truss roof sheeting considered in this paper [25-28], in contrast to the classic use, profiled sheeting combines enclosing and load-bearing functions, thereby more fully using its strength and stiffness characteristics. As a consequence, it becomes necessary to assess the load carrying ability and determine the optimal parameters of these structures.
2 Materials and methods

The main element of the roof slab, that defines load carrying ability of a structure, is an upper belt made of profiled sheeting. The main feature of the behavior of the profiled sheet under the load is that some compressed sections of the walls and shelves may lose local stability, which begins even in the elastic stage. Such feature is typical for almost all cold-formed thin-walled profiles. The loss of local stability significantly affects the performance of the sheeting and, as a rule, leads to a large irregularity in distribution of stresses over the cross section in the supercritical loading stage.

It is known that steel profiled sheeting is designed as bendable element, and existing documents, to assess its load carrying ability, show the calculated geometric characteristics of the cross-sections, defined only out of the performance of the profiled sheet in a supercritical state under the action of bending only. However, in the roof slab, the profiled sheeting undergoes bending with compression, so the loss of local stability and supercritical behavior of the profile may differ from performance under the action of bending. Therefore, the parameters of the reduction of geometric characteristics, which took into account the presence of compressive force, were used in the calculations [20].

The research was based on the works of native and foreign scientists in the theory of calculating steel thin-walled structures, the hypotheses of structural mechanics, the theory of elasticity and the theory of thin plates. This work was made based on analytical and numerical studies, as well as experimental studies by the method of full-scale testing of structures.

3 Results and discussion

3.1. Load carrying ability of profiled flooring in the composition of the roof slab

In analytical studies, a design scheme in the form of a pivotally supported beam, loaded with a uniformly distributed load \( q \) and a normal force \( P \) applied with an eccentricity \( e \) is applied for profiled sheeting (Figure 1). The beam section represents one wave of profiled sheeting.

The load carrying ability of the profiled sheeting is determined from the strength conditions of the supports and in the middle of the span:

1) Strength condition for the section above the support:

\[
\sigma_{eq}^{III} = \sqrt{\sigma_0^2 + 4\tau^2} \leq \gamma_y R_y
\]

Here \( \sigma_0 \) is the normal stresses in the lower shelf:

\[
\sigma_0 = \frac{P}{A_{eff}} + \frac{Pe}{W_{eff}^l}
\]

\( W_{eff}^l \) - the moment of resistance of the reduced cross section from the action of \( M_z \) – (for compressed lower fibers);
Figure 1. Internal forces and moments diagram.

\[ \tau = \frac{QS_x^l}{l_x \delta}, \]  \hspace{1cm} (3)

where \( I_x \) is the moment of inertia of the section of the profiled sheet, \( \delta \) is the thickness of the profiled sheet and \( S_x^l \) is static moment of the lower shelf relative to the x axis.

2) Mid-span strength condition:

\[ \sigma_{str} = \frac{N}{A_{eff}} + \frac{M}{W_{eff}} \leq \gamma_c R_y \]  \hspace{1cm} (4)

\( M = qL^2/8 - P e; \)

\( A_{eff} \) is reduced cross-sectional area;

\( W_{eff} \) is moment of resistance of the reduced section from the action of a plus bending moment \( M_x^+ \) (for stretched lower fibers).

Standard profiled sheeting has an “asymmetric” cross-section, therefore, different values of the moments of resistance relative to wide and narrow shelves: \( W_x^l \neq W_x^u \).

With the coefficient \( k = W_x^l / W_x^u = W/W \), strength conditions 2, 4 without regard to shear stresses will be as follows:

\[ \sigma_0 = P \left( 1 + \frac{e}{A} \right) \leq \gamma_c R_y \]  \hspace{1cm} (5)

\[ \sigma_{np} = \frac{M_q}{kW} - \frac{Pe}{kW} + \frac{P}{A} \leq \gamma_c R_y \]  \hspace{1cm} (6)

The optimum load carrying ability condition is \( \sigma_0 = \sigma_{np} = \gamma_c R_y \), for which, after making some transformations, we obtain the dependences of the critical load carrying ability on the height of the structure \( e \) and the value of the preload tension \( P \): \( q_{np}(P) \) and \( q_{np}(e) \), or \( M^{qp}_{\text{str}}(P) \) and \( M^{qp}_{\text{str}}(e) \), where \( M^{qp}_{\text{str}} = q_{np}L^2/8 \).

Then the dependences \( M^{qp}_{\text{str}}(P) \) and \( M^{qp}_{\text{str}}(e) \) will have the following forms:

\[ M^{qp}_{\text{str}}(P) = \frac{(1+k)R_y A}{\alpha} \left( 1 - \frac{P}{R_y A} \right) \]  \hspace{1cm} (7)

\[ M^{qp}_{\text{str}}(e) = \frac{kR_y A}{\alpha} \left( 1 + \frac{ae - k}{k(1 + ae)} \right) \]  \hspace{1cm} (8)

The plots of the obtained dependences for different values of \( k \) are shown in Figures 2, 3.
Strength conditions 5, 6 and equations 7, 8 are obtained without taking into account shear stresses from the transverse bending, which may exist in the reference section. Therefore, to evaluate them, the ratio of stresses in extreme fibers where normal stresses have a maximum value is given below:

\[ n = \frac{\tau_h}{\sigma_h} = \frac{\tau_h}{\frac{1}{\rho}R_y} = \frac{8(1 + k)Ab_h}{\rho \alpha W} \]

To assess the reliability of the obtained analytical expressions and plots, numerical studies in Ansys software of the stress-strain state (SSS) of the sheeting were carried out based on the finite element analysis, taking into account physical and geometric nonlinearity. The studies were carried out for profiled sheets H60-845, H75-750 and H114-600, which may be used as a bearing upper belt in the considered roof slabs. A static scheme of behavior of each type of profiled sheet was modeled as a single-span beam under the transverse load and a normal force in accordance with the design scheme (Figure 1). The calculation in the finite element model was carried out in 5 stages. All transverse load was exerted during the first stage. A normal force with an eccentricity was exerted gradually over the next four stages until the equivalent stresses (according to strength theory III) were reached in the sections in the span and on the support. Moreover, the stresses on the support took into account the presence of local stresses, existing due to the uneven exert of normal force, which could not be taken into account in theoretical studies. Figures 4-6 shows the pictures of SSS obtained by finite-element modeling of profiled sheet H75-750.
As a result of the study of the SSS of sheetings of the same type with different thicknesses, it was revealed that the thickness does not affect the dependence $M_\text{str}(P)$, which confirms theoretical data. It should be noted that this dependence depends on the transmission method of the longitudinal force, that is, on the design of the support unit.

Studies have also been conducted to examine the potential for losing the overall stability of the flooring from the action of a longitudinal force together with a transverse load. For each type of sheeting, flexibility was studied in the areas between the supports 70, 80, 90, 100, 120 (Figure 7). According to the results of studies, it was found that flexibility has little effect on the bearing capacity of the flooring. The local loss of stability of the lower shelf of the sheeting in the area of outer supports in the zone of transition of effort from L-steel to sheeting is the determining form of loss of load carrying ability. This is also a factor in favor of the theory model research.

### 3.2 Optimization of the structural parameters of the truss roof slab

When designing building structures, there is a need to optimize their parameters for efficient use as directed. Studies of the ties between these parameters are quite laborious. Therefore, it is not possible to solve the problems of optimizing these structures by known analytical and numerical methods. To find the rational parameters of the studied slabs, we used the method of phased numerical experiments.
using simplex optimization. The task is further complicated by the fact that profiled sheeting, in contrast to the traditional purpose (experiencing transverse bending only), in roof slabs is affected by combined effect of bending with compression. In such cases, as established in [20], the use of the geometric characteristics of the cross sections given in GOST 24045-2016 leads to incorrect results. Therefore, in the calculations, it is necessary to use new reduced geometric characteristics, which depend on the ratio of the bending moment to the longitudinal compressive force.

In optimization of roof slabs, out of practical design considerations, for the criterion of efficiency can be taken: the ratio of load carrying ability to the weight of the structure; load carrying ability of the slab with a given type of profiled sheeting; the specific gravity of the plate with a given design load on it; cost of construction, etc. The following are the results of studies where the criterion of effectiveness is the ratio of the load carrying ability to the weight of the structure.

The parameters that affect the performance criteria of the structures under study include: type, thickness and grade of steel of the profiled sheet; quantity, location and geometrical parameters of stops; steel grade and diameter of tie; preload tightening tension value.

All parameters are divided into two groups: variable and fixed. Variable parameters have limitations that are established from regulatory design requirements, or design considerations. Below in a tabular form (Table 1-2) are lists of parameters for the considered roof slabs (Figures 8, 9).

Table 1. Lists of parameters for slabs with spans of 6 and 9 m

| Construction parameters | Span 6 m | Span 9 m |
|-------------------------|----------|----------|
| **Fixed parameters**    |          |          |
| type of sheeting        | H60; H75; H114 |          |
| profiled sheet thickness | $t = 0.6\text{--}0.8$ |          |
| profiled sheet steel grade | $C245$ |          |
| number of posts         | 2        | 2        |
| cross section and steel grade of tie | $\Phi20, C245$ | $\Phi20, C245$ |
| **Variable parameters** |          |          |
| length $a$              | $a = 0.4\text{--}2.4 \text{ m}$ | $a = 0.4\text{--}3.5 \text{ m}$ |
| slab height, $h$        | $h = 0.4\text{--}2.5 \text{ m}$ | $h = 0.4\text{--}2.5 \text{ m}$ |
| preload tightening tension | $N_3 = 0\text{--}1500 \text{ kg}$ | $N_3 = 0\text{--}1500 \text{ kg}$ |

Efficiency criteria – ratio of the load carrying ability to the weight of the slab.

Figure 8. Scheme of constructive design of roof slabs with spans of 6 and 9 m
Table 2. Lists of parameters for slabs with spans of 12 m

| Construction parameters | Span 12 m |
|-------------------------|----------|
| **Fixed parameters**    |          |
| type of sheeting        | H75; H114|
| profiled sheet thickness| $t = 0.8\div1.0$ |
| profiled sheet steel grade | C245    |
| number of pyramids      | 3        |
| cross section and steel grade of tie | $\Phi30$, C245 |
| **Variable parameters** |          |
| the height of the middle pyramid, $H$ | $H = 0.3\div3.0 \text{ m}$ |
| the height of the end pyramids, $h$ | $h = 0.2\div2.0 \text{ m}$ |
| length $b$              | $b = 0.3\div3.0 \text{ m}$ |
| length $c$              | $c = 0.4\div3.0 \text{ m}$ |
| preload tightening tension | $N_3 = 0\div3000 \text{ kg}$ |

Efficiency criteria is the ratio of the load carrying ability to the weight of the slab.

Figure 9. Scheme of constructive design of roof slabs with spans of 12 m

The proposed optimization technique is based on the search for rational parameters by phasing out numerical experiments with determining at each stage the values of the selected efficiency criterion (objective function) within the given limits for the varied parameters. When choosing a search direction, the principles of the simplex method are used. Thus, optimization (finding the maximum of the objective function with determining the corresponding values of the varied parameters) consists of the following steps:

1) The selection and assignment of values of variable parameters at the initial $m + 1$ points, which are the vertices of a regular polyhedron in the m-dimensional space of variable parameters. For a case with three variable parameters, it represents a tetrahedron (Figure 10, step 1).
2) Compilation of \( m + 1 \) finite element (FE) calculation models of the roof slabs with the assigned parameters and running numerical experiments with the determination of the load carrying ability for each model for both groups of the limiting state.

3) Analysis of the obtained results with determination of the gradient of the objective function, according to the results of the experiments, and assignment of the parameter values of the new point \( i = n \) to it in the space of variable parameters, thereby forming a new polyhedron for studying the gradient of the objective function (Figure 10, step 2).

4) Drawing up the FE of the calculation model for the \( n \)th model of the roof slab and determining for it the load carrying ability for both groups of the limiting state.

5) Comparison of the obtained values of the load carrying ability, determination of a new gradient of the objective function and the repetition of experiments until the extremum is reached (Figure 10, step 3-15);

The search for the optimal parameters was carried out in 2 stages.

In the first stage, the optimal parameters were determined using Lira-CAD software on a geometrically and physically linear model with beam (upper belt - profiled sheet) and truss (truss system) elements. In this case, numerical experiments were repeated with a rather large step of parameter change. The strength condition for profiled sheet in the calculations was taken taking into account the parameter of reduction of geometric characteristics, which also took into account the presence of longitudinal compressive force [20].

In the second stage, after “crude” optimization, the area around the obtained base point was investigated with a finer breakdown in experiments with a model more accurately reflecting structural properties. So, the profiled sheeting was divided into shell elements, the attachment points of the stops to the profiled sheet were more accurately modeled, and the problem was solved in a geometrically and physically nonlinear setting using Ansys.

![Figure 10](image)

**Figure 10.** Visualization of the stages of searching for optimal parameters for a slab with a span of 6 m

According to the described methodology, the problems of optimizing the structural parameters of truss plates with spans of 6-12 m were solved. Graphic visualization of the search for optimal parameters by the simplex method for a slab with a span of 6 m is shown in Figure 10. The results of the optimization of structures selected in table 1, 2 are shown in Figure 11.
4 Conclusion
1. Numerical studies confirm analytically obtained dependencies and graphs.
2. The defining areas for the study of slabs with the use of profiled sheeting are the zones of longitudinal force transmission from the truss system to the profiled sheet.
3. The proposed optimization technique allows us to determine the rational parameters of the structures under study with a relatively small number of numerical experiments.
4. Same as with most optimization methods, the disadvantage of the developed method is that it does not allow to bypass possible local extremes during optimization. The solution to this problem requires to make additional numerical experiments.

5 Acknowledgments
A full-scale test [14] was carried out over a full size 12 meter span slab, made according to the invention [27]. The results of the test are reasonably well consistent with numerical experiments on the adopted model.

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