Design of low-rise buildings from thin-walled steel frame structures

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Abstract. Addressing sustainable development challenges, Russia is seeking new opportunities for the use of thin-walled cold-cast structures to meet the requirements of cost-effectiveness, eco-friendliness, and rapid construction. The study aims to explore the possibilities of design and calculation of low-rise buildings erected from lightweight thin-walled steel structures using frame construction technology. The design solutions for the roof, walls, floors, and foundation are exemplified using concrete examples. The load capacity off framing studs, roof beams, and floor slabs was calculated. Three methods were used for calculation - Eurocode 3, direct strength test, and ultimate load test in compliance with AISI standards.

1 Introduction

The use of cold-formed structures in the frame construction is not a novel technology, neither in the world nor in Russia. The technology was developed several decades ago.

For the first time, cold-cast structures were used in construction in the 1950s [1]. The first buildings of thin-walled steel structures were erected in North America and Great Britain. They possessed a number of distinctive features, including cost-effectiveness, energy efficiency, and environmental friendliness.

In 1933, at the World Exhibition in Chicago, the “house of the future” was presented; it was made from steel frame structures. The Architect Howard T. Fisher, the project manager, borrowed the engineering ideas from research into steel for the manufacture of rail cars.

In 1939, the American Iron and Steel Institute funded the research project Cornell University. The results of the study were published in 1946, and the first edition of AISI “Specification for the Design of Light Gage Steel Structural Members” was published. With the release of the first specifications, systematic development and use of steel thin-walled structures began in America.

In Russia, the beginning of construction from lightweight thin-walled steel structures is associated with the study of roll-formed structures (roll-forming) in the engineering sector. In the 1970s, the directives of the 23rd CPSU Congress set an ambitious goal of reducing metal consumption by 20-25%; it was planned to achieve this goal through the use of thin-walled structures in construction. According to the Central Research Institute of Building Structures and the “Ukrproektstalkonstruktsiya” Institute, metal savings in the production of

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trusses from cold-formed elements were estimated at 10-30%, while the labor costs decreased by 50%, and the cost was reduced by 25% .

The popularity of the thin-walled steel structures in the USSR is confirmed by the fact that in 1980 the efficiency of replacement of high-quality rolled metal products with thin-walled cold-formed structures in the construction of facilities resulted in the savings of 200 million rubles and 1.7 million tons of metal.

With all the obvious advantages, this technology was not been widely developed in Russia due to the lack of a regulatory framework.

Currently, this technology is in the focus of attention of engineers, and the possibility of using thin-walled cold-formed elements in the building structures is explored [2 - 5]. In addition to the properties of cold-formed structures mentioned above, resistance to corrosion and thermal insulation were described in a number of publications [6 - 10]. From 2012 to 2018, the volume of construction using thin-walled steel structures in Russia grew by about 4 times. Also, the interest in the calculation of cold-formed structural elements has led to the development and wider dissemination of methods for determining their bearing capacity.

In this article, we will describe a comprehensive method for designing a low-rise building from thin-walled steel structures. In the process, we will perform the modeling of the stress-strain state of the entire building in the SCAD Office program and the modeling of the behavior of individual elements in the CUFSM program, and estimate the bearing capacity of different structural elements using methods of Eurocode 3 and AISI specifications.

2 Materials and methods

We consider the basics of designing residential low-rise buildings made from thin-walled steel structural elements, using frame technology. The following basic structural elements are used in low-rise building design:

- studs (external and internal);
- floor beams;
- roof structures (beams or trusses);
- linking elements (upper and lower edges of wall panels, struts and braces).

For structures of the outer contour of buildings, the so-called thermal profile, or perforated profile is used, in which a heat flow elongation occurs due to cuttings, which leads to better thermal insulation properties. In bending structures, it is preferable to use structural elements with stiffeners due to their significant spans.

Since the "skeleton frame" building from thin-walled steel structures is a multi-element, interconnected system, the static calculation should be performed in special software systems to account for the interaction of the maximum possible number of factors.

One of possible methods of design of a thin-walled steel frame low-rise building is shown below. A three-storey residential building was used as an example; Figures 1,3 show the plan extract and the cross-sectional view. In the structural design of the building, the following structural elements were used according to the specifications of "LASAR" company [11], Fig. 2:

Fig. 1. Plan extract. A three-room apartment is in yellow; a two-room apartment is in blue; a one-room apartment is in red.

Structural element	Profile	Dimensions, mm
external walls	TLC	175x55x15-1.5
internal walls	LC	175x55x15-1.5
floor slabs and roof beams	LCR	200x55x15-2
external strutting	TLP	175x45-1.5
internal strutting	LP	175x45-1.5
staircase	LC	300x150x50-2

Fig. 2. Shapes of profiles used, *T- ThermalProfile,OOO "LASAR" (L), C- shapedsection (S), high rigidity (R), P- shaped section (P).

Spacing between studs and roof beams was taken as 600 mm for ease of installation of thermal insulation and sound insulation. The stud height was 3000 mm; the room height was 2710 mm. The method of element conjugation was a pin joint. The structural solution of the building is shown in Figures 4 - 6.

The static analysis of the building was made in SCAD Office. Cross-sections were formed in Tonu satellite program. The design scheme of the building was created in the program AutoCad, with the subsequent import into SCAD and is shown in Figure 7.

Fig. 3. Cross-sectional view of the building.

Fig. 4. Designsolution of the roof and attic floor   Fig. 5. Design solution of the wall and floor.

3 Results

The main results of the static analysis are shown in Figures 8 – 10. The maximum compressive forces were 41.72 kN, the maximum bending moments were 7.44 kN • m, the maximum horizontal movements were 9.69 mm, the maximum deflection was observed in the roof beams and was 22 mm.

Calculation of the load-bearing capacity of thin-walled rods can be performed in different ways. In this paper, the calculation of studs was made using the Eurocode 3 method [3-5] and the Direct Strength Method (DSM) [6]. The calculation of studs was performed by the DSM. The calculation of roof beams was carried out jointly by DSM and Eurocode 3. The use of DSM was carried out in accordance with the Load and Resistance

Fig. 6. Design solution of the foundation.

Fig. 7. Design building scheme. Left: view on the digital axis. Right: graphical representation of the scheme taking into account the structural elements.

Factor Design (LRFD) [8]. The determination of the critical forces for DSM was performed using the CUFSM program [8].

For the analysis the following properties of steel we used:

- zinc plated rolled steel grade [23] – 350;
- yieldstress – $f_y = 333 \text{ MPa}$;
- Young’s modulus – $E = 210000 \text{ MPa}$;
- Poisson’s ratio – $\nu = 0,3$;

- shear modulus – $G = 80770\text{ MPa}$.
- The length of elements:
- studs – 3000 mm;
  - floor beams – 6000 mm;
  - roof beams – 7500 mm.
- The results of the calculation are presented in Tables 1-7.

Fig. 8. Longitudinal forces N inground floor studs, kN.

Fig. 9. Bending moments in ground floor beams.

Fig. 10. Deformation scheme.

Table 1. Load bearing capacity of external studs in the Eurocode 3.

Buckling mode	χ	A_{eff}, mm^2	$N_{b,Rd}, kN$
1	2	3	4
Flexural buckling about axis of max stiffness	0.940	229.9	69.94
Flexural buckling about axis of min stiffness	0.769		57.20
Torsional buckling	0.728		54.17
Flexural-torsional buckling	0.707		52.61

Table 2. Load bearing capacity of external studs in theDSM and LRFD.

Buckling form	P_y, kN	P_{cr}/P_y	P_n, kN	$P_{n,min}, kN$	$\varphi P_{n,min}, kN$
General buckling	149.77	1.15	104.04	60.6	51.51
Secondary buckling		0.23	60.6		
Distortional buckling		0.43	76.66		

Table 3. Load bearing capacity of internal studs in the Eurocode 3.

Buckling mode	χ	A_{eff}, mm^2	$N_{b,Rd}, kN$
1	2	3	4
Flexural buckling about axis of max stiffness	0.943	232.5	73.27
Flexural buckling about axis of min stiffness	0.768		60.88
Torsional buckling	0.762		59.07
Flexural-torsional buckling	0.743		57.55

Table 4. Load bearing capacity of internal studs in the DSM and LRFD.

Buckling mode	P_y, kN	P_{cr}/P_y	P_n, kN	$P_{n,min}, kN$	$\varphi P_{n,min}, kN$
1	2	3	4	5	6
General buckling	153,09	1.1533	106.496	63.04	53.6
Secondary buckling		0.243	63.04		
Distortional buckling		0.457	80.7		

Table 5. Load bearing capacity of floor beams in the DSM and LRFD.

Buckling mode	$M_y, \text{kN} \cdot \text{m}$	M_{cr}/M_y	$M_n, \text{kN} \cdot \text{m}$	$M_{n,min}, \text{kN} \cdot \text{m}$	$\varphi M_{n,min}, \text{kN} \cdot \text{m}$
1	2	3	4	5	6
General buckling	12.90	89.67	12.90	12.14	10.93
Secondary buckling		3.37	12.90		
Distortional buckling		1.77	12.14		

Table 6. Load bearing capacity of roof beams under axial compression in the DSM.

Buckling mode	P_y, kN	P_{cr}/P_y	P_n, kN	$P_{n,min}, \text{kN}$	$\varphi P_{n,min}, \text{kN}$
1	2	3	4	5	6
General buckling	224.61	0.04403	8.673	8.67	7.37
Secondary buckling		2.7068	8.7		
Distortional buckling		0.70877	145.5		

Table 7. Load bearing capacity of roof beams under bending in the DSM.

Buckling mode	$M_y, \text{kN} \cdot \text{m}$	M_{cr}/M_y	$M_n, \text{kN} \cdot \text{m}$	$M_{n,min}, \text{kN} \cdot \text{m}$	$\varphi M_{n,min}, \text{kN} \cdot \text{m}$
1	2	3	4	5	6
General buckling	12.90	89.67	12.90	12.14	10.93
Secondary buckling		3.37	12.90		
Distortional buckling		1.77	12.14		

The following notation was used in the tables:

- χ – buckling mode reduction factor;
- A_{eff} – effective cross-section area;
- $N_{b,Rd}$ – structural failure in the Eurocode 3;
- P_y, M_y – yield stress;
- P_{cr}, M_{cr} – critical buckling load;
- P_n, M_n – load bearing capacity in the DSM;
- φ – safety factor in the LRFD.

The bearing capacity of the studs was calculated for centrally compressed rods, the capacity of roof beams was calculated for bent elements, the capacity of roof beams was calculated for the section subjected to compression and bending (the critical forces of buckling were calculated separately for compression and separately for bending):

- studs

$$\frac{N_{Ed}}{\varphi P_{n,min}} = \frac{41.72}{51.51} = 0.81 < 1; \quad (1)$$

- floor beams

$$\frac{M_{Ed}}{\varphi M_{n,min}} = \frac{7.44}{10.93} = 0.68 < 1; \quad (2)$$

- roof beams

$$\left(\frac{N_{Ed}}{\varphi P_{n,min}} \right)^{0.8} + \left(\frac{M_{Ed}}{\varphi M_{n,min}} \right)^{0.8} = \left(\frac{1.66}{7.37} \right)^{0.8} + \left(\frac{4.91}{10.93} \right)^{0.8} = 0.83 < 1 \quad (3)$$

The maximum deflection of thin-walled steel structures according to Eurocode 3 was equal to

$$f_u = L/300 \quad (4)$$

As can be seen from the above data, all the building elements meet the requirements of Eurocode 3 and AISI standards.

4 Conclusions

In this paper, a method for designing and calculating a low-rise building constructed from thin-walled steel structural elements was described. Possible design solutions of an apartment building were proposed. The results of calculation of the loadbearing capacity of frame elements are in compliance with the standards: Eurocode 3, DSM and LRFD. The final calculation of the load-bearing frame was made for the minimum parameters, which ensures its higher reliability.

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