Search for optimal methods for calculating atypical spatial structures on the example of a climbing wall

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Abstract. The article presents an analysis of approaches to solving non-standard spatial structural schemes with the use of modern modeling and calculation tools, by the example of the construction of the climbing wall of a complex spatial shape.

One of the difficulties of calculating spatial structures is the interpretation and transition from the real design to the computational scheme, which allows some simplifications [1]. The simplification here refers to the transition from a spatial pattern to the calculation of plane frames or trusses, assessment of enclosed structures by the load, without regard to their participation in the spatial work, etc. In the case of traditional structural systems such as frames of buildings frame or braced systems, there are well-established and proven methods of layout of design schemes.

However, modern requirements for buildings and structures determine the emergence of more difficult and non-standard structural systems. At the same time, the development of software products for modeling and calculation of structures allows to meet the increasing requirements [1].

In accordance with [2], the design schemes and the basic assumptions of calculation should reflect the actual conditions of steel structures.

In [1] the following computational models of load-bearing structures are considered:
- individual structural rod elements (stretched, compressed, eccentrically compressed, compressed-bent and bendable);
- flat or spatial unfettered systems. The calculation of such structures is carried out by calculating the individual elements taking into account their interaction with each other and with the base according to [2];
- flat or spatial systems, not fixed. When calculating such structures, along with checking individual elements, it is necessary to consider the possibility of reaching the limit state of the system as a whole;
- sheet structures (shell rotation).

In some cases, the answer to the question if the complexity of computational models is required by striving for maximum details is not evident. Technically, in most cases, this possibility exists with the use of such calculation systems as ANSYS, SolidWorks, etc., but this leads to a significant increase in the complexity of solving the problem, and therefore to an increase in the timing and cost of design.

In this article, the authors consider the advantages and disadvantages of calculation methods on the example of non-standard design of the climbing wall (Figure 1) – dimensional irregular rod system exposed to dynamic alternating loads and forced displacement from external factors.
The construction of the climbing wall represents a spatial rod system of bent-welded closed profiles, based on existing reinforced concrete beams and metal structures of the building.

The main bearing elements are inclined struts, crossbars and ties. Spatial rigidity and geometric immutability are provided by a system of horizontal and inclined links. The connection of the elements with each other is made by means of bolts and welding. The design of nodes connection is provided by the hinge elements.

The structure operates in a complex stress-strain state in the presence of many external factors. Under the influence of temporary loads, the roof of the building during operation acquires a deflection of various sizes depending on the load. Part of the nodes interface elements of the climbing wall with the truss cover and columns of the building is designed using oval holes in the plates of the node to eliminate the influence of deformation of the building frame from the temporary loads on the construction of the climbing wall. Such pliable attachment points of the climbing wall elements involve the transfer of limited vertical and horizontal forces to the truss in values not exceeding the permissible ones and at the same time, not being included in the work of the building frame as load-bearing elements not perceiving additional load.

The hinged frame of the climbing wall (adjustable panel mounting elements (Figure 2) includes a spatial rod system located between the supporting frame and the work surface (panels) of the climbing wall.

The frame is made of rods of variable cross-section-steel pipe and threaded studs. Fastening of the hinged frame to the supporting frame is carried out through steel shapes by means of bolts. All joints are hinged.

The geometric immutability of the suspended frame is provided by a rigid disk formed by the working surface (panels) of the climbing wall.

Permanent effects are applied to the mounting points of the climbing wall panels. The constant load is distributed evenly over the surface of the climbing wall, so the average calculated value of constant loads on one mounting point is used.

As a result of approximately steady location of panel mounting points on the surface of the climbing wall and their high density, we assume the possible location of the climbing athletes on the climbing wall discrete and tied to these points.

**Figure 1.** General view of the climbing wall.
Destination - panel attachment points, united in one group, describing the most likely direction of the athlete's movement along the surface of the climbing wall. Within one route in calculated combination of efforts, only one load is allowed, created by a falling athlete. The load from the falling athlete is applied only to individual points of insurance (all points of attachment of panels belonging to the routes located at a height of 3000 mm and above the floor, as well as the upper points of the routes located directly on the supporting structure).

According to the calculation method described above, 1118 loads were made, including:
- № 1 - own weight of load-bearing structures;
- № 2 - constant loads from the climbing wall structures (panels, fasteners, etc.);
- № 3 ... 557 - loads in each node from the athlete of 98 kg applied on 33 routes. Within each route, loads are mutually exclusive;
- № 558...1118 – loads of the falling athletes (1010 kg). All loads in this group are mutually exclusive.

The complexity of design and calculation of such a structure consists of several factors:
1. Multivariance of load combinations, each of which is critical.
2. The combination of several structural systems - bearing frame of the climbing wall, hinged adjustable frame, working surface in the form of panels (Figure 2).
3. A high degree of dependence (both from the point of view of structural solutions and external influences) on existing structures of the building in which the installation of the climbing wall is carried out.

The calculation of the structure is performed in the software complex SCAD [4]. Creation of the spatial calculation scheme of the considered design is difficult without application of other means of spatial modeling. SolidWorks, Autodesk AutoCAD, Tekla Structures software packages were used as auxiliary tools to create the calculation scheme.

The complex geometry and the uniqueness of the design lead to the need to use an iterative approach to find the optimal design solution. Thus, a direct relationship is established between the number of performed calculations of various options and quality indicators of the structure. In turn, the

![Figure 2. Schematic scheme of the device climbing wall.](image)
number of calculations per unit of time, using the same resources, is determined by their complexity [5].

One of the ways to improve the performance of the iterative approach can be parameterization or automation of the process of creating a structure [6], [7], [8], [10] according to some initial data. In the case of atypical and unique structures, such a solution is impractical.

Thus, in order to improve the quality of the final product in the design of a real structure within the framework of the technical specifications with clearly defined deadlines, there is a need to simplify the calculation scheme. However, in the case of unique structures, this is a non-trivial task, because the assumptions that are used in traditional designs, in this case have not been tested and their impact on the result may be decisive [5], [9], [11].

The calculation was performed in several versions in order to assess the degree of influence of certain assumptions in the calculation scheme on the final result.

In total, 3 options of design schemes were considered:
1. Flat scheme
2. Spatial scheme without panels
3. Spatial scheme with panels

1. Flat scheme
A flat scheme is the simplest option from the point of view of geometry. However, considering the complex outline of the structure, both in plan and in any section, such a task turned out to be more complicated than modeling a spatial system. The difficulty lies in the correct interpretation of the boundary conditions and the mutual influence of the elements of the spatial system.

![Figure 3. Values of total displacements [mm] (a) and efforts [kN] (b) in the elements of one of the fragments of the climbing wall in the calculation of the flat scheme.](image)
In addition, there are software issues. For example, the replacement by boundary conditions of elements of the coupling lattice, whose local axes are not collinear to the common coordinate system, in most calculation complexes is not a direct task and requires an individual approach in each case.

Based on the analysis of the preliminary spatial graphical model of the climbing wall, isolated parts of the structures were identified. According to preliminary estimates, it would be advisable to perform their calculation according to a flat scheme. One of these parts was the truss shown in Figure 3. The analysis of numerical results was performed only for the main supporting structure (Figure 2).

The maximum value of the deflection of the inclined section (segment 2) of the supporting structure was 15.6 mm, and the maximum longitudinal force in the same element was 70.5 kN. However, at this stage the reliability of the obtained results of calculations of the flat scheme, instead of the spatial one, remained unclear.

Further calculations were aimed at assessing the correctness of the assumptions and finding the right solutions for modeling boundary conditions in order to obtain a correct planar calculation scheme. A spatial finite element model was created for this purpose.

2. Spatial scheme without panels
   The main task of this stage is to assess the reliability of the results obtained at the previous stage in the calculation of the flat scheme, making the necessary adjustments and continuing the calculation of the elements according to the flat scheme. The spatial calculation scheme is shown in Figure 4.

   Reliability here means the achievement of calculation results that are negligibly little different from each other or, at least, have satisfactory convergence.

   ![Figure 4](image)

   **Figure 4.** A general view of the spatial calculation scheme of the climbing wall (a) and the considered fragment of the scheme (b).

   To accomplish this task and compare the results obtained, a fragment is selected that corresponds to the flat calculation scheme considered earlier (Figure 4, c).

   As a result of the calculation, results are obtained that differ significantly from the calculation according to a flat scheme. The maximum deflection of the inclined section (segment 2) of the supporting structure was 20.9 mm, and the maximum longitudinal force arises in the inclined rack (segment 3) – 24.3 kN.

   Thus, the difference between the obtained maximum forces in the rods (70.5 kN in the first case and 24.3 kN in the second case) was 190%, which is a categorically unacceptable result for further use of the calculation method according to the planar scheme of such a spatial structure. This once again confirms the need to use spatial calculation schemes for the calculation.

   After analyzing the deformed schemes and the nature of the distribution of forces, a series of adjustments of the flat design scheme was performed, after which it was possible to achieve convergence of the results within 10%. However, the adopted corrections were not universal and were not suitable for other sections of the spatial system. In addition, the initial data for these adjustments
were based on the results of the calculation of the spatial scheme, which was originally intended to be abandoned. And if it is necessary to change the geometry of the structure, the established dependencies do not remain relevant.

Figure 5. Values of total displacements [mm] (a) and efforts [kN] (b) in the elements of one of the fragments of the climbing wall in the calculation of the spatial scheme without panels.

Simplification of the design scheme while maintaining the reliability of the results proved to be a more time-consuming task than creating a spatial model. Therefore, the final solution for the calculation of the structure was the creation of spatial design schemes for various variations of structural solutions, which are also not without some assumptions.

3. Spatial scheme with panels

One of the most significant assumptions was if it is necessary to take into account elements of the outer shell-climbing wall panels in the spatial work of the building. On the one hand, they significantly increase the rigidity of the structure and contribute to a more uniform distribution of forces on the elements of the grid, on the other – the panels cannot be made absolutely rigid connections with each other both structurally and on the basis of design assumptions. The second is due to the creation of hinged and pliable nodes interface elements of the supporting frame of the climbing wall in order to free from the perception of loads acting on the frame of the building.

Therefore, a spatial scheme with panels was calculated based on the assumption of the joint work of all the elements of which it consists.
Figure 6. Values of total displacements [mm] (a) and efforts [kN] (b) in the elements of one of the fragments of the climbing wall in the calculation of the spatial scheme taking the panels into account.

An analysis of the obtained longitudinal forces using the example of the fragment mentioned earlier (Figure 4) showed that the convergence in the calculation schemes №2 and №3 is much higher, but still significant and amounts to 28%. At the same time, the nature of the distribution of efforts among the elements has become comparable in both cases. The calculation results are shown in Figure 6.7.

Further increase of calculation accuracy is possible only due to transition to modeling by volume finite elements with given boundary and contact conditions in nodal connections (Figure 8). According to the authors, such an approach in the scale of building structures and constructions today is impractical, because in addition to excessive labor intensity, it requires special computing resources. And the calculation result is too sensitive to the initial data used, which in real conditions have a high degree of error. Nevertheless, this issue is a relevant and important subject of future research.

Therefore, based on the analysis of design schemes No. 2 and No. 3, the worst design combinations of forces were selected to select the type and size of the cross section of the elements, as well as the largest support reactions, to calculate the support attachment points to the existing building frame.

Based on the example of the considered design it is established that the difference of the received maximum efforts in elements according to the results of calculation of flat and spatial settlement schemes reaches 190% (Table 1). In addition, it can be seen that the maximum values of forces and displacements within the considered fragment are distributed differently, and within one segment the forces differ by more than 5 times when calculated according to different calculation schemes.
Figure 7. Isopoles [mm] of the total displacement of the elements of the panels of the climbing wall.

Figure 8. The constructive solution of the joint of panels with each other using steel plates, as well as the connection of the system of cords with panels through the corners (hardware is not shown conditionally).

Table 1. Forces and displacements in a fragment of the scheme by results of calculation of various settlement schemes.

|                     | Efforts in the segment of the fragment under consideration, kN | Total displacements in the segment of the fragment under consideration, mm |
|---------------------|---------------------------------------------------------------|---------------------------------------------------------------------------|
|                     | 1    | 2    | 3    | 1    | 2    | 3    |
| Flat scheme         | 21,2 | 70,5 | 49,5 | 15,5 | 7,6  | 0,7  |
| Spatial scheme      |      |      |      |      |      |      |
| without panels      | 4,9  | 15,8 | 24,3 | 15,5 | 20,9 | 9,7  |
| Spatial scheme      |      |      |      |      |      |      |
| with panels         | 15,5 | 11,2 | 31,0 | 15,5 | 11,2 | 0,4  |

It is established that the calculation of the flat scheme in this case does not reflect the actual stress-strain state of the structure and cannot be used to make design decisions.

In conclusion, it should be noted that the transition from spatial schemes to the flat ones requires a special approach when it comes to unique structures. In many cases, the creation and calculation of spatial systems is less time-consuming than the correct formulation of the problem in its simplified
form. Modern software products allow to perform modeling of structures with maximum details and reflection of real working conditions. However, this circumstance allows the other extreme, when the degree of detail is beyond the reasonable use of resources and does not lead to a tangible result. This issue is subject to further investigation.

In terms of the abundance of software, in each case of applied problems not only the optimal design solutions should be sought, but also the best approaches to their calculation.

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