Steel and composite structural shells in the construction of high-rise building

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Abstract. In modern construction thin-shell structures are very popular because they can be easily used to make different constructive and architectural shapes. The main value of such constructions is the ability to use them as load-bearing structures and as the element of architectural image of building at the same time. Thin-shell structures allow us to solve the problems of construction rigidity and stability, therefore it is rational to use shells in high-rise building structures. At the same time construction of high-rise buildings is connected with a number of special requirements. Disregard of those requirements can cause destruction of the building. In this research there were considered some challenges of high-rise building design on the business complex example. The comparative analysis of two various bearing shells was made. The first case was a metal grid shell, and the second was the combination of metal elements and reinforced concrete ribs. The reinforced concrete ribs (stiffeners) were used to improve the rigidity of the whole structure and to increase the bearing capacity.

1 Introduction

High-rise buildings are different from ordinary buildings and have a number of features in design process and also during construction. The distinctive features are:

- A significant influence of horizontal dynamic loads (wind loads);
- Heavy load on bearing structures and foundations, in comparison with ordinary buildings;
- Increased requirements to account the anthropogenic and environmental factor influence. The most important factors are: earthquakes, floods, fires, terrorist acts and solar radiation;
- Difficult connections between steel and concrete bearing elements;

All these features must be considered in the process of high-rise building structural scheme selection.

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2 Literature review

For the first time bearing shells were used in the construction by Russian engineer C.G. Shukhov in 1896. He developed and patented three types of load-bearing grid shells: hanging, convex and tower-shell (patents of the Russian Empire No. 1894, No. 1895, No. 1896; March 12, 1899).

Nowadays the theoretical basics of bearing shell mechanics are well studied. The research results are stated in monographs: V.Z. Vlasov - "Stroitel'naya mehanika obolochek", A.P. Filin - "Elementyi teorii obolochek", K.Z. Galimova - "Matematicheskaya teoriya obolochek", H.M. Mushtari - "Nelineynaya teoriya obolochek", V.V. Novozhilov - "Teoriya tonkih obolochek", A.L. Goldenveizer - "Teoriya tonkih uprugih obolochek" and others.

Researches of many scientists are devoted for the creation and development of methods: E.L. Axelrad - "Gibkie obolochki", Yu.P. Artyuhin and P.G. Velikanov - "Raschyot anizotropnykh obolochek metodom granichnykh elementov", D.V. Vaynberg - "Matrichnyie algoritmy v teorii obolochek vrascheniya" and others.

The plasticity and creep theories are very important in bearing shell calculations. Researches in this area were made by scientists: R.A. Arutyunyan, G.I. Byikovtsev, R.A. Vasin, A.A. Vakulenko, M.A. Grekov, A.A. Gvozdev, G. Grinberg, O.Yu. Dinariev, A.S. Dehtyar and others.

In the twentieth century bearing shells were widely adopted in construction, and the number of projects with this scheme was increasing each decade. Therefore, new problems and difficulties in the construction appear in process of bearing shell technology development [1-29], but many of them are already well studied [29-37].

3 Issue definition

The aim of the research was to determine the rules of high-rise building structural scheme and materials selection. And also optimal structural scheme determination from two different variants.

4 Materials and Methods

The research object was 41-storey business complex with two various types of bearing shell. General view of the research object is shown on the Fig. 1.

Figure 1. General view of the research object.

The building has a "shamrock" shape on the plan, also, the horizontal cross-section changes along the height of the building. Due to the architectural features and the height of the building it was decided to apply the "load-bearing outer shell in combination with a central core" [38]. Central load-bearing core (stiff trunk) are usually made of reinforced concrete, steel and its combinations. Stiff trunk perform the role of rigid vertical consoles fixed in the soils and perceives predominantly horizontal loads. The rigidity of the trunk depends on the shape and cross-sectional area of the stair-elevator site, which sizes are determined according to the number of elevators and stairs requirements.

The core is rigidly connected with the metal bearing shell by monolithic reinforced concrete slabs. Bearing structures can be prefabricated or monolithic. In the initial period of high-rise building development bearing structures were normally made from steel. Currently, bearing structures are normally made from reinforced concrete, because this material has better fire resistance and lower cost, and its strength characteristics under compression is quite the same. Nowadays B80 and B100 class concretes are created, although in construction practice are mainly used lower classes of high-strength concretes (B60 and B70), because with the concrete class growth increases its cost, fragility and decreased fire resistance.

The grid shell bearing system was selected because of insulation requirements for the building facades. The elements of the grid shell were tubes of square section with 200 mm side and 14 mm thickness. The steel was selected as a material for shell rods because of tensile stresses, which concrete cannot resist.

The difference between the two cases of structural schemes was: in the first case, each wing was locked by reinforced concrete elements to improve the stiffness and to make building heavier in these parts. In the second case, instead of the stiffeners on the building edges metal shell with the same configuration as in other parts of the building was used.

The analytical models of both cases were made in the SCAD Office software complex. Loads were applied according to the code "Nagruzki i vozdeystviya" [39], including equivalent wind load that was applied statically. Analytical models are shown on Fig. 2,3.

Figure 2. The analytical model in case with reinforced concrete stiffeners in SCAD

Figure 3. The analytical model in case with steel shell elements in SCAD

Reinforced concrete shell elements and the central core walls are made of B30class concrete, load-bearing columns – of B60 class concrete. The concrete ribs thickness changes along height from 400 to 200 mm. The columns diameter changes along height from 1000 mm in the lower floors to 300 mm at the top.

5 Results and Discussion

In the SCAD Office finite element environment two selected structural cases were calculated on the rigid foundation. 1-st and 41-st floors were selected for the calculation results comparison .They show the values that characterize the construction work: stresses in the elements, deformations. On the first floor compressive stresses in bearing structures from the vertical loads and bending from the wind are maximum. On the 41-st floor stresses in the elements from the force effects are very small, but there are large values of the total vertical deformations.

Deformations of the slab of the first floor on Z-axis and stresses in the shell elements are shown on Fig 4,5,6,7.

Figure 4. First floor slab deformations on axis Z (mm) in case with reinforced concrete stiffeners

Figure 5. First floor slab deformations on axis Z (mm) in case with steel shell elements

Figure 6. Stresses (N, [T]) in the shell elements in case with reinforced concrete stiffeners

Figure 7. Stresses (N, [T]) in the shell elements in case with steel shell elements

First floor slab deformations in two different cases (Fig.4,5) are almost identical. In case with reinforced concrete stiffeners tension is less, the maximum compressive stress is 414.18 t, while in case with steel shell elements - 498.59 t. The difference is 20%. This shows that there is a stresses redistribution: in case with steel shell elements more weight falls on the shell rods along the glazed facades of the building.

41-st floor on Z-axis slab deformations in two different cases are presented on Fig. 8,9.

Figure 8. 41-st floor slab deformations on axis Z (mm) in case with reinforced concrete stiffeners

Figure 9. 41-st floor slab deformations on axis Z (mm) in case with steel shell elements

Deformations of the 41-st floor slabs in different cases are considerably different. Deformations in case with reinforced concrete stiffeners is less approximately on 60-75 mm (the difference is about 73%). Furthermore, it is obvious that in case with steel shell elements, all slab in the wing parts fall on 70-80 mm comparative the central core. With increasing height of the building slabs have increasing slope from the central core to the wing edges. As a consequence, loads on the intermediate supporting columns increases.

In case with reinforced concrete stiffeners stresses are redistributed due to changes in the stiffness of the whole building. Massive reinforced concrete ribs better than the metal grid shell perceive compressive loads. Because of their greater rigidity, despite the higher stresses, that they perceive, there are also smaller deformations. In this case slab doesn't fall from the central core to the edges of the building. Slab works as a plate on two relatively rigid supports and the maximum 55 mm deflection is in the span.

In case with steel shell elements the slab at the junction to the trunk, rests on a rigid support, and on the other side (on the edge of the wing) relies on the support with a certain deformability, that leads to the whole slab tilt.

In case with steel shell elements compressive stress in the most loaded central columns is 2773.79 t, in case with reinforced concrete stiffeners – 2761.40 t. The values are almost identical (difference less than 0.5%), the difference is negligible. First floor column stresses in both cases are shown on Fig. 10,11.

Figure 10. Stresses in the first floor columns in case with reinforced concrete stiffeners (T)

Figure 11. Stresses in the first floor columns in case with steel shell elements (T)

In columns along the edges of the wings difference is much more: in case with steel shell elements compressive stress in the column is 2211.18 t, In case with reinforced concrete stiffeners – 1676.97 t.

The difference is about 32 %. The first floor columns reinforcement calculation was made in program “Arbat” and it is presented in the Tab. 1.

Table 1. Layouts and diameters of the rods of reinforcement in both cases

Construction case	Longitudinal reinforcement	Cross reinforcement	Layout of a longitudinal reinforcement
In case with steel shell elements (compressive stress in the columns is 2773.79 [T])	Longitudinal reinforcement – 20 rods, diameter 32 [mm]	Cross reinforcement along the X-axis has 10 mm diameter, rod spacing - 200 [mm] Cross reinforcement along the Y-axis has 10 mm diameter, rod spacing - 200 [mm]
In case with reinforced concrete stiffeners (compressive stress in the columns is 2211.18 [T])	Longitudinal reinforcement – 15 rods, diameter 20 [mm]	Cross reinforcement along the X-axis has 10 mm diameter, rod spacing - 200 [mm] Cross reinforcement along the Y-axis has 10 mm diameter, rod spacing - 200 [mm]

From the results it is obvious that the columns in the variation with the metal shell must be reinforced considerably stronger - required 20 rods, diameter - 32 mm, while in the construction with stiffeners – 15, diameter - 20 mm.

6 Conclusions

According to the calculation results and two variations of building structures comparison, it is possible to say that it is advisable to use the combined shell of reinforced concrete and steel elements. Grid metal bearing shell, at first, reduces the weight of building bearing structures, and secondly, allows to satisfy the insulation requirements. Stiffeners play the role of additional rigid trunks. They unload metal shell and the intermediate columns inside the building. Connection of concrete ribs with the central core in a single spatial structure increases the building rigidity, and it is a favorable factor for the wind and other specific loads perception.

In conclusion, various combinations of massive concrete elements and steel grid shell solutions is rational for high-rise construction.

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