Structural Concept Features of Suspended Structures for Seismic Areas

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Abstract. The key task of the building design is the comprehensive elimination of hazards arising from various impacts on buildings, including seismic ones. Recently, new structural systems have been developed to ensure the earthquake resistance of buildings, as well as the already known ones are being improved. One of the types of structural systems that can be used in seismically active areas are buildings with suspended structures. There are many design solutions for buildings with suspended structures that differ in the type of supporting structure, suspension system and geometric shape. The possibility of using suspended structures under dynamic influences is explained by a load decrease in the load-bearing elements of the building due to the flexibility of these structures, as well as a large natural period of oscillations of buildings with suspended structures. Some aspects of the use of buildings with suspended structures are not fully understood, which prompted a study of the behavior of these buildings using various structural solutions in earthquake conditions. For the effective use of these structures in the practice of earthquake-resistant construction, an important issue is to understand the behavior of suspended structures under seismic influences of a wide frequency spectrum. The results of the study are presented in the paper.

1. Introduction

Suspended structures are distinguished by the rational use of constructional materials, because the loads in suspension systems are perceived by stretched elements that are not subject to stability loss during bending or eccentric compression. The use of suspended structures allows you to create open spaces both inside the building and in the levels of the lower floors outside, giving the building architectural expressiveness. The systems are widely used, as they have an advantage: in these systems, it is possible to minimize the suspensions sections due to the absence of the need to reduce the safe allowable stress.

The desire to fully apply the positive aspects of the use of suspended structures in buildings has led to the creation of numerous design solutions. Currently, suspended systems are characterized by a variety of geometric shapes, depending on the installation method, space-planning requirements and many other factors.

The first and most complete attempt to systematize the solutions of high-rise buildings with suspended structures was made by W. Schuller (Figure 1) [1].
Figure 1. Classification of suspended systems of high-rise buildings.

The most commonly implemented suspended structures in construction are the structures of suspended systems with a rigid core. Figure 2 shows some examples of the implementation of this solution.

Figure 2. Suspended systems: a) with cantilever on a single core; b) with cantilever beams on several cores; c) with frames in the form of trees or trusses; d) arch; e) with suspensions along the core; f) suspension bridge system.

We will focus on the most commonly implemented suspended structures with a rigid core. The main positive property of structures with rigid cores is the rational use of building materials. Also, in many studies [2-16], it was noted that these structures are distinguished by their flexibility, which allows them to be considered earthquake-resistant.

The disadvantages of systems of this type include the necessity of creating powerful structures of the rigidity core, since they must fully perceive horizontal loads. At the same time, these structures must take into account the relative movements between the core and the structures of suspended floors, which occur, for example, during seismic impacts. Also, for the support of the rigidity core, it is necessary to create considerable foundation structures.
Due to the probability of negative effects when using suspended structures in seismic areas, the question arises about the possibility of using these structures in earthquake conditions with different frequency characteristics. This paper is devoted to the study of this issue.

2. Methods
For the calculations, five structural schemes were selected, which use the principle of suspension of floors to the rigidity core (Figure 3-7). The foundations for the simulated buildings are made in the form of a monolithic reinforced concrete slab with a thickness of 1 meter. The thickness of the floor slabs is 0.2 meters, and the thickness of the bearing walls of the rigidity core is equal to 0.5 meters. Reinforced concrete structures are made of concrete of class B25, the grade of steel elements is adopted C255 and 09g2c. The rigidity core is made of monolithic reinforced concrete structures.

The first structural scheme is a suspended type building with a cantilever head on a single reinforced concrete core (Figure 3). The building includes 15 floors with a height of 4 meters, and the total height of the building is 64 meters. The rigidity core of the building has a width of 8 m, the floor is 16 m. The cantilever head is formed by a metal space framework. The suspensions situated along the rigidity core are hingedly adjoined to the cantilever head. The ceilings are suspended on 16 suspensions along the perimeter of the slab and on 8 along the inner contour.

The second structural scheme is similar to the first, except for the absence of a cantilever head: all floors are directly suspended from the reinforced concrete core (Figure 4). The suspensions installed along the inner contour of the floor slab are located at an angle to the core of the building, which allows you to create a force that returns the shifting floors to their original position.

The load-bearing structures of the third structural scheme are represented by four rigidity cores connected in the upper floor level by six trusses with parallel chords (Figure 5). Loads from suspended floors are transmitted to the mega-frame by 30 suspensions. The total height of the simulated building, which has 15 floors with a height of 4 meters, is 63 meters. The width of the rigidity core of the simulated building is 6 meters, the dimensions of the floor are 16 and 12 meters.
A building with suspended structures with suspension bridge system is presented in the fourth calculation model (Figure 6). The simulated building has 6 floors with a height of 4 meters, the total height of the building is 32 meters. Three trusses with semidiagonal lattice are installed on two 8-meter-wide rigidity cores. The floors have dimensions of 48 and 12 meters. The loads from the floors are partially transmitted directly to the trusses through 39 suspensions. Also, three cables are involved in transferring the load to the trusses.

Three semicircular arches with a span of 48 meters are used as supporting structures of the fifth structural scheme (Figure 7). The building consists of 6 floors with a height of 4 meters, the total height of the building is 26 meters.

For computational studies, accelerograms of earthquakes with different response spectrum were selected in the web database on ground motion of the Pacific Earthquake Engineering Research Center (Figure 8). The selected earthquakes have a wide frequency spectrum. Based on the prevailing oscillatory period $T_n$ in the response spectrum, a conditional division of earthquake records into high-frequency ($T_n < 0.3$ s), medium-frequency ($0.3 \leq T_n < 1$ s) and low-frequency ($T_n \geq 1$ s) was adopted. Thus, the earthquakes that occurred in the city of Almiros and Friuli region are high-frequency, an earthquake in Griva is medium-frequency, and earthquakes in Chi-Chi and the St Elias mountains are low-frequency.

![Figure 8. Earthquake response spectrum.](image)

The calculation was performed in the SCAD integrated system for finite element structural analysis. The load-bearing walls of buildings were modeled by flat finite elements, suspensions-by flat bar finite elements, elements of spatial load-bearing structures – by truss finite elements. The structures were calculated for seismic impact using the linear-spectral method. Earthquake seismograms were constructed on the basis of accelerogram packages in order to apply the displacement changes to the calculation schemes in forth integration. To take into account the joint effort of the building and the foundation, the coefficients of subgrade reaction were calculated. The supporting ground was modeled by two-node elastic coupling elements with stiffness determined on the coefficients of subgrade reaction. This made it possible to take into account the effects of the elastic supporting ground under dynamic influence.

It has been proved that buildings with suspended structures have a longer period of oscillations compared to buildings with a rigid frame, which is why there are less inner forces in the elements of the suspended system under seismic influence [17]. However, it is worth noting that the resulting relative movements between the suspended floor and the rigidity core, as well as the potentially possible rocking due to dynamic influences, pose a threat to the load-bearing structures of buildings.
Based on this, the maximum displacements and maximum accelerations of suspended floors were selected to analyze the behavior of suspended structures of buildings with different types of configurations under various seismic influences.

3. Results and discussion

As a result of the calculations, the natural periods of oscillations of the calculated models were determined. The natural period of oscillations of the first model is 3.42 seconds, the second - 3.4 seconds, the third - 3.21 seconds, the fourth - 1.51 seconds, the fifth - 0.76 seconds.

For each suspended floor of the calculated models, the maximum horizontal displacements and accelerations caused by various seismic impacts were determined (Figure 9-11).

Figure 9. Graph of maximum: (a) floor displacements of the second model against floor number; (b) floor accelerations of the second model against floor number.

The first three calculation models have similar graphs of displacements and accelerations of floors. As an example, the results of calculations for the second model are given in the article. The maximum displacement of the floors for the models was caused by an earthquake in St Elias. The maximum displacement of the floor in the first model is 1006 mm, in the second - 1192 mm, in the third - 1134 mm. The maximum accelerations are 0.829 m/s², 0.863 m/s² and 0.528 m/s² for the first, second and third models, respectively.

Figure 10. Graph of maximum: (a) floor displacements of the fourth model against floor number; (b) floor accelerations of the fourth model against floor number.
Maximum horizontal floor displacements of the fourth model were 651 mm. The maximum horizontal acceleration of the floors was 0.431 m/s².

![Graph of maximum: (a) floor displacements of the fifth model against floor number; (b) floor accelerations of the fifth model against floor number.](image)

**Figure 11.** Graph of maximum: (а) floor displacements of the fifth model against floor number; (б) floor accelerations of the fifth model against floor number.

Maximum horizontal floor displacements of the fifth model were 215 mm. The maximum horizontal acceleration of the floors was 0.397 m/s².

4. **Conclusions**

According to the results of the study, the following conclusions were made:

1. Among the calculation systems, the system in the arched form is the most resistant to earthquakes with different frequency spectra, because the floors of the fifth model had the lowest accelerations and displacements under seismic influences.
2. For areas where the occurrence of high-frequency earthquakes is characteristic, it is recommended to erect buildings based on the second calculation scheme.
3. The second calculation scheme is also recommended for use in areas with predominant medium-frequency earthquakes.
4. The use of suspended structures in high-rise buildings located in areas of low-frequency earthquakes can lead to negative effects in the form of rocking floors and damage to the integrity of load-bearing structures.
5. To reduce the dangerous movements of suspended floors during low-frequency seismic impacts, it is advisable to use damping devices, which can be used as energy absorbers of viscous and dry friction.

5. **References**

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