Earthquake resistance of buildings with suspended structures

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Abstract. There are different approaches to providing earthquake resistance for buildings. One implies selection of efficient structural systems with high dynamic characteristics, the use of which can significantly reduce seismic loads on buildings. One of such solutions suggests the use of suspended buildings. Due to various structural solutions in the buildings, a significant increase in the natural period of oscillations and, therefore, decrease in seismic loads on buildings can be achieved. Structural solutions of these buildings were analysed and dynamic characteristics of solutions under review were examined. Design investigation was performed with involvement of software applications SCAD and SOFiSTiK based on a technique using finite elements. The most efficient structural solution for a suspended building was defined. It was demonstrated that a higher ductility may lead to a dangerous oscillation of a building, especially under low-frequency seismic impacts. To limit dangerous shifts, it is suggested to introduce special damper elements in the flooring level to improve reliable and safe behaviour of buildings with suspended structures during earthquakes.

1. Introduction

The latest earthquakes in Russia, Japan, China, Turkey, Italy and other countries that resulted in numerous victims and huge material loss have yet again shown the importance of earthquake protection for buildings and structures. Furthermore, the list of the most endangered areas including Eastern Siberia, Far East and Northern Caucasus has now been supplemented by the earthquake-prone territories of Crimea with densely populated cities and developed infrastructure of civil and industrial engineering. Due to this, issues of earthquake protection for buildings and structures with various functions are becoming more relevant.

The anti-seismic construction industry employs specific approaches and requirements for building and structural design, which is set out in normative documents [1]. One of the principal requirements is to select the most efficient structural systems for the facilities with uniform distribution of mass and rigidity. Such requirements can be met by various design solutions, among which the most unique position is held by buildings with suspended structures notable for their high variety of geometrical shapes, layout and structural concepts. The buildings are widely used in modern high-rise construction. Due to their structural features, including, first of all, significant ductility, they have gained widespread use not only in safe regions of the world, but also in areas with high seismic activities. The natural period of oscillations of buildings with suspended structures is several times higher than that of traditional solutions. This confirms the efficiency of using suspended structures in the seismic load area.
The main phase of construction of buildings with suspended structures was observed at the end of 20th century. Publications of Wolfgang Schuller [2] were among the first covering the buildings, as well as publications containing numerous scientific research, design, and patent offers for (without limitation) anti-seismic construction [1-15]. In the former USSR, suspended systems were studied by Korchinsky, Grigorieva, Skladnev, Chanukvadze and many more. Examples for implementation of the structural systems are presented on figure 1 [16].

![Figure 1. Scheme and example of structural solution of core-suspended building.](image)

The main load-bearing structure of a building under consideration that takes loads and impacts is represented by a core (of closed or open section) to the entire height of the building. The core is commonly placed in geometrical centre of layout and is called the "stiffening core". The core system was implemented in two forms: with transmission of all loads to the core through suspenders and cap (core and suspended), or through a strong arm at the core base (core-arm).

In the core and suspended system, floors rest on the core internally and on suspenders externally. Suspenders are fixed to a cap at the core apex. Examples of suspended structures for earthquake-prone areas are shown in figure 2.
In 1971, Korchinsky suggested and patented his model of a suspended building with high earthquake resistance (figure 2 (a)) depending on a type of cantilevered beam for several cores [3]. Later on, the model was updated due to the introduction of stiffness correctors [7]. Figure 2 (b) [4] shows the model of a suspended building, with the main difference of prestressed suspenders and connections of floors with a central core — stiff and hinged with floor-by-floor alternation. Despite the large scope of the research, the buildings were never built. The current situation was contributed to, on the one hand, by difficulties with structural implementation of the systems, and on the other hand, the lack of software tools at that time that allow substantiated theoretical and computation studies to be performed. However, an important factor should be noted that is subject to consideration during implementation of the structures. As previously stated, the structural system is very ductile due to an extended natural period of oscillations that may exceed 1 s. In the case of seismic impacts, the spectrum of which contains a prevailing amount of low-frequency constituents with significant shifts of basis, one must take into account a serious swing of the building that can be limited due to introduction of additional oscillation suppressing components or dampers into the building structure. In view of the above, and for an assessment of the efficient use of buildings with suspended structures in earthquake regions, it was necessary to conduct the additional research specified below.

2. Methods
A review of the earthquake resistance of buildings with various suspended structures was performed with various structural solutions of a stiffening core in the form of single or double reinforced concrete core. The assumed configuration of the building is cylindrical. The building height varied from 5 to 30 storeys. Calculations were performed against spectral technique and impact of the strong earthquake accelerograms with various frequencies. Maximum ground acceleration amounted to 2 m/s², equal to magnitude 8. The study was performed using various analytical models. During the first stage, a building model with a conventional core system was considered. In this option the load was transmitted from floor to foundation via the stiffening core and metallic I-shaped columns located along the perimeter. A system with suspended structures was considered at the following stage. Assumed models are shown on figure 3.
Figure 3. Analytical models of the building: (a) conventional core system; (b) with suspended structures.

In this model the transmission of load from floors to foundation was performed depending on the type of suspended building. In addition, in this model floor slabs were suspended on jack stays not only on the outer loop, but also on the internal loop.

3. Results and discussion

The design research was performed with the use of software packages SCAD and SOFiSTiK. Some preliminary results of completed theoretical computation analysis are presented in publications [17-19]. With the introduction of additional parameters for the building under study, it was found that main dynamic property, the natural period of oscillations of buildings with suspended structures, is much more than the oscillation period for buildings with a conventional core system that is illustrative of a possible decrease in seismic loads in the buildings under consideration. Therefore, efficiency of using the suspended buildings was confirmed. Nevertheless, where the conventional solution must be used, it is reasonable to increase the natural period of oscillations due to the addition of flexible supports into the foundation that function as seismic isolation, in view of recommendations [20]. Performed studies of buildings with suspended structures showed a significant increase in displacements on height. This fact is indicative of the need to introduce additional elements of the oscillation suppression. Due to this, additional damping elements were introduced into the utility model of the building with suspended storeys. SOFiSTiK software package assisted in implementation of the above.

4. Conclusions

The below was found following the results of performed studies:

1. Buildings with suspended structures could be regarded as earthquake-resistant in the case where one is able to increase the natural oscillations period by two or more times. However, this may cause serious sway of the building during the earthquake and so the systems should be equipped with additional damping elements to be installed at floor levels.

2. If in a building with a stiffening core the load is transmitted from floor to foundation via a reinforced concrete core (first model), an increase in natural period of oscillations and thereby a decrease in seismic load is possible, provided that, on the one hand, there is a significant increase in number of storeys, and on the other hand, a decrease is achievable via introduction of ductile elements in the form of seismic isolation elements into the foundation of the building.

3. Use of suspended structures may provide specific economic results due to the fact that a portion of load is taken by tension elements enabling a decrease of their sections to a minimum.
4. Buildings with suspended structures may be both low-rise and high-rise. Here, the floor height may vary.

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