

# Building practice of energy efficient earthquake-resistance buildings

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**Abstract.** The article discusses technologies for constructing energy-efficient, earthquake-resistant buildings that have increased rigidity and strength in their main components. These technologies utilize structures with enhanced damping and active seismic insulation systems. Practical implementations, design features, and technological aspects are examined. An analysis is conducted on the characteristics of current technologies, the conditions for production and installation, repairability, and their impact on the building's energy efficiency during operation. Technologies are systematized and categorized based on their principles of seismic protection during the analysis process. The analysis was conducted based on the following main criteria: steel consumption, suitability of repairable technologies used, possibility of implementing seismic protection during building reconstruction, ability to withstand seismic effects, feasibility of implementation, and energy efficiency. It has been determined that traditional technical solutions to increase rigidity and strength, such as introducing structures with increased damping used for buildings with precast, monolithic, and precast-monolithic frames, require a significant amount of additional resources. These solutions are characterized by accumulation of failures in individual hidden elements due to seismic loads, low maintainability, and often decrease the energy efficiency of the building. The use of seismic energy-absorbing mechanisms with high efficiency can significantly reduce resource costs for construction and increase maintainability, thus improving the overall sustainability of the structure. Based on the findings of the analysis, the following recommendations are made for conducting further studies on active protection systems in terms of design, development of construction technology, and potential application in the renovation of existing buildings.

## 1 Introduction

Most of the actively developing regions of the Russian Federation (the North Caucasus, the South of Russia and Siberia, Altai, the Far East and others) are located in seismically dangerous zones, where the issue of earthquake-resistant construction is extremely important. The topic of energy efficiency of structures is no less relevant for buildings erected in earthquake-prone areas, reflecting the need to reduce the cost of heating and air conditioning of premises. According to existing estimates, there are 143 million seismically active regions

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of the Russian Federation. m<sup>2</sup> of housing stock that do not meet the requirements of earthquake resistance [1].

In February 2023, a powerful earthquake with a magnitude of 7.7 occurred in Turkey, damage reached 34.2 billion US dollars, the cost of restoration will amount to 66.1 billion dollars, 1.25 million people lost their homes and 46,104 thousand people died [2]. Despite the fact that the effects of the earthquake have not been recorded on the territory of the Russian Federation, there are fears that it is caused by the movement of tectonic plates to the north and is likely to cause repeated earthquakes already in the territory of Southern Russia.

The methods traditionally used in the construction of earthquake-resistant buildings have common disadvantages: an increase in the seismicity of the construction site inevitably leads to an increase in material and labor content [3], solutions that increase seismic resistance, after the influence of seismic activity, are characterized by low maintainability, the occurrence and accumulation of failures in operation [4]. The use of seismic isolation mechanisms will reduce material costs and increase maintainability.

## **2 Increasing the stiffness and strength of the main connection of construction**

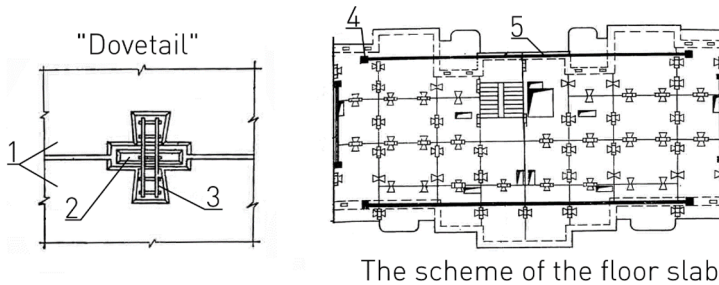
This solution has become widespread in structure cast-in-situ. The resulting seismic forces are completely absorbed by the construction. To increase the resistance to tangential stresses, the length of the anchoring joints and the degree of reinforcement of concrete structures are increased. However, since the forces of seismic influence are dynamic, this imposes certain difficulties in the construction of structures. For example, overlapping reinforcement is prohibited on construction sites with high seismicity; if the diameter of the reinforcement is more than 20 mm, in order to avoid the formation of a joint of plasticity during the operation of dynamic forces, the connection must be carried out either using welding or reinforcing steel splice. These requirements are regulated in SP 14.13330.2018 of the Russian Federation and DIN 4149 of Germany. Filling of reinforced concrete structures with reinforcement negatively affects thermal conductivity, leads to the creation of low energy efficiency structures in need of additional thermal insulation [5].

To minimize the number of joints and joints cold, to create a single monolithic floor-slab disk rigid, they resort to the construction of a method of lifting finished slabs on jacks (lift-slabs). In addition to increasing rigidity in comparison with other construction methods, this solution is characterized by a high level of mechanization, reduced consumption of building materials and labor extra.

Separately, it is worth considering large-panel construction. The main place of stress concentration are the joints of the panels, they account for the greatest load and torques [6], therefore, to increase the rigidity of building structures and a more uniform distribution of forces between the panels of the building, rigid joints are arranged: a large number of rods connecting, fixing pins in concrete and cement joggle are distributed along the entire joint. The main disadvantage of such a solution is over-reinforcement of joints: it is difficult to achieve the required degree of compaction of the mix concrete and filling voids, the thermal conductivity of the joint increases and energy efficiency decreases.

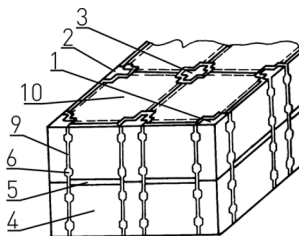
Exist the different, experimental approach to the construction of earthquake-resistant large-panel buildings, which is based on the assumption that the tangential stresses arising between the floor-slab panels are perceived by concrete. Based on this, the number of fixing pins in concrete and rods connectings on the sides of the panels is reduced and shifted to the ends, and to ensure the unity of the floor-slab disk rigid, large cement joggle are used located across the joints line of the floor slabs, for example, of the «dovetail» type, which are able to perceive tangential forces in the joints between precast members of the floor slabs [7]. This solution is more energy efficient, reducing the amount of metal in the joints of the panels. To

increase the rigidity of the floor slabs and increase the crack-resistance of the concrete filling of joints, stretched reinforcement is placed along the perimeter of the overlap, which, after tension, combines the panels into a single hard disk (Fig. 1). To reduce the amplitude of vibrations of the building under the influence of seismic activity, rope reinforcement is placed in the channels of vertical joints between the outer wall panels, fixed in the foundation, and after the construction of a certain number of floors (9, 16), vertical tension is performed and sealing of the channels is performed. This approach has made it possible to reduce the metal consumption of joints, simplify the filling of joints with concrete, reduce labor content and improve the quality of joints. Experimental buildings built using this technology are based on the I-464AS apartment building series, the overall structural strength of which has been increased by 12.5% compared to the original series.



**Fig. 1.** The scheme of the overlap of earthquake-resistant large-panel houses: 1 — floor-slabs; 2 — cement joggle; 3 — reinforcement; 4 — dead-end anchorage, 5 — anchorage of reinforcement

The idea of using cement joggle in panels that perceive tangential force was developed in a prefabricated reinforced concrete frame (Fig. 2) formed from of columns of X-shaped, T-shaped and angular cross sections and floor panels. The load-bearing exterior walls are made of large panels with octagonal cement joggle that can withstand tangential forces [8]. The large space of the joints is exposed to the environment, and additional thermal insulation is required in these places.



**Fig. 2.** Earthquake-resistant building structure by Sapozhnikov: 1, 2, 3 — columns with angular, T-shaped and X-shaped cross section, respectively; 4 — wall panels; 5 — belt with expansion in the zone of floor-slab; 6- octagonal cement joggle; 9 — joints between wall panels; 10 — floor-slab panels

### 3 Construction of buildings with increased damping

Resistance to external influences is based on the performance of any work by seismic forces in building structures or on the redistribution of forces arising in structures, which significantly reduces the impact of an earthquake.

This principle is most applicable for large-panel buildings. Friction forces arise in the seams of wall panels and floor slabs, which absorb seismic energy [9]. Therefore, a common requirement for large-panel buildings is to increase the joints between precast members

length due to the shape of cement joggle and joints. However, buildings with similar seams can withstand seismicity up to 7 points.

There are two different approaches to building construction based on the principle of increased damping. The first is that it is necessary to increase the mass of the building. Due to the increased mass, a large seismic force is required to set the building in motion, as a result of which the amplitude of vibrations decreases and deformations of the building decrease. This approach is clearly visible on the example of the soviet serial apartment buildings: vertical structures are made of large blocks, in the floor-slab zone, to ensure the unity of work, a reinforced concrete seismic belt is arranged, which increases the concentration of mass. The disadvantage of such buildings is the inability to ensure normal bolting bond between concrete and blocks, which is solved by a large number of anchors and clamps fastening the blocks, by the device of dowels in the blocks. However, these actions, which significantly increase labor content, do not eliminate the problem of joining materials. The seismic belt of reinforced concrete has a negative effect on the energy efficiency of the building: a cold bridge is formed, which needs additional insulation.

Another approach is to maximize weight reduction through the use of lightweight building materials, which reduces the load on building structures and the amplitude of vibrations. Soviet building codes recommended the construction of large-panel buildings made of lighter expanded-clay concrete. Modern research shows high seismic resistance of large-panel buildings made of concrete-polystyrene panels [10]. For individual house construction, it is advisable to use lightweight structures, including wooden frames [11] and wooden-polystyrene foam panels (SIP-panels) [12]. Such solutions involve the use of building materials with a large number of enclosed voids and demonstrate high energy efficiency.

Also, the design solution with increased damping is widely used in the construction of public buildings and structures made of more-connection metal frames. Due to the large number of connections, the earthquake energy is evenly distributed among a large number of rods, which reduces the load on each rod individually. Such a solution can lead to the formation of a large volume of unused air spaces that need to be heated in a cold climate or cooled in a warm one, which reduces the energy efficiency of the building.

The considered methods are traditional, their application has disadvantages associated with an increase in material costs and labor content. Building structures manufactured using these building practice have low maintainability, failures occur and accumulate after several cycles of seismic impact, destruction occurs, and energy efficiency turns out to be extremely low, with the exception of means implying a reduction in the mass of the structure.

## **4 Construction of buildings with an active seismic isolation system**

Seismic isolation systems are special mechanisms that are installed between a rigid seismically strong foundation and the supporting structures of a building, which allows you to protect building structures from the dynamic effects of earthquakes.

There are several types of seismic isolation systems that differ in the principles of operation:

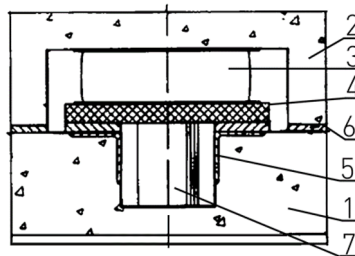
- 1) flexible supporting structures ("flexible first floor")

This solution is used in monolithic frame or large-panel buildings. The structures of the first floor are intentionally malleable. Due to the redistribution of efforts, it is possible to increase the seismic resistance of the building, but the solution also has a significant drawback — under the influence of low-frequency vibrations, building structures achieve significant movements, which leads to the destruction of flexible structures, and subsequently the entire building.

Therefore, when building a flexible structure, additional damping devices should be taken in the building structure [13].

## 2) systems with rubber and rubber-metal supports [14]

In this system, rubber supports are installed between the vertical supporting structures of the building and the foundation. At the base, where the mechanism element will be mounted, a special groove is arranged, which is bordered by corner elements (Fig. 4). Next, special supports are arranged for the building and an insulating element is mounted: a power plant is installed in the groove, and a rubber-metal element is installed on top. Thanks to the power plant, the element is pressed by its upper surface against the base of the structure and compressed until the necessary stresses occur. To maintain this condition, an additional stop is installed between the element and the corners, the power plant is removed and used at the next installation point. Upon completion of the installation of all elements, the building is detached from the foundation by the support forces and the special support element is removed. This solution has a wide range of applications. The system does not depend on design features and can be installed in buildings with both frame and wall bearing systems [15]. An additional advantage is delayed installation — the possibility of installation even in a finished building, which allows you to reconstruct an existing building and increase its seismic resistance. When studying the calculation models of the educational and administrative building of the Russian International Olympic University in Sochi, it turned out that the introduction of rubber-metal supports allows in this cases to reduce the forces in the building structures by 56.5% and reduce movements the upper part of the building to 45% [16]. But this system has a significant drawback — over time, the elastic element changes its properties, plastic deformations develop, which is essential in buildings that are designed with a service life of 50 years or more. In addition, such elements are very sensitive to temperature change, and exposure to fire can lead to fatal consequences for the supporting structures of the building. Regular monitoring of the condition of the elements and periodic repair of the antiseismic mechanism is required. However, in the process of exploitation, the high deformability of rubber in the horizontal plane makes itself felt [17, 18], which is why significant horizontal movements from wind loads to the upper floors occur in multistorey buildings.

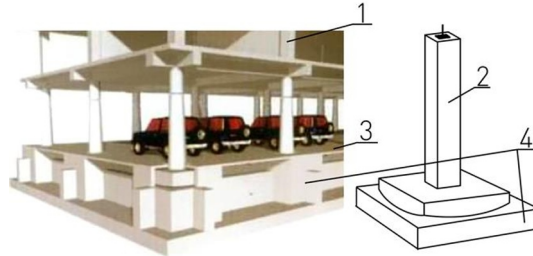


**Fig. 4.** Schematic diagram of the systems with rubber and rubber-metal supports: 1 - foundation, 2 — building, 3 — rubber support, 4 — supports, 5 — corner elements; 6 — special supports; 7 — corner elements; 8 — groove

## 3) «Kinematic foundation» by Cherepinsky [19]

The principle of operation of this system is based on shifting the center of gravity of the building and returning it to a stable position. The structural parts work together, so that the building is able to withstand high seismic loads [20]. Initially, a rigid earthquake-resistant foundation is erected, after which reinforced concrete columns with a spheroidal base are installed on it (Fig. 5). To ensure immobility, the columns at the base are supported by wedges, after which the rest of the building structures are mounted on the columns. Unfortunately, unlike systems with rubber-metal insulators, this system is applicable only in buildings of a frame scheme. After the construction of the reinforced concrete frame, the

wedges at the base of the supports are removed. Reinforced concrete slabs can be installed between the columns of the underground part for the operated floors of the underground parking. Due to the factory production of columns of certain standard sizes, the construction process is characterized by a high level of mechanization and the high-quality of finished products.

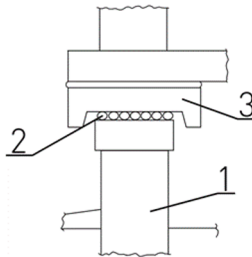


**Fig. 5.** Schematic diagram of the «Kinematic foundation» by Cherepinsky: 1 — buildings; 2 — movable column; 3 — floor slabs; 4 — foundation

However, Cherepinsky's decision is not without drawbacks. The lesser of these are concrete chips at the point of contact of the movable column and the impact of wind loads [21], more importantly, the possibility of a building tipping over and falling from kinematic supports when exposed to a load close to 8 points [22]. This solution requires further refinement and the use of additional damping structures.

4) systems based on «spherical spheroids» (sharovie spheroids) by Nazin [23]

Exist the only one building erected using a similar seismic isolation system developed by engineer Valentin Nazin, who researched issues of earthquake-resistant construction.



**Fig. 6.** Schematic diagram of the building unit of the mechanism by Nazin: 1 - the column resting on the foundation slab; 2 — the column resting on a basement floor slab; 3 — spheroids

A rigid earthquake-resistant foundation with 58 load-bearing semi-columns was built for this facility. Specially made prefabricated blocks of 119 spheroids in each are installed on each half-column (Fig. 6), on top of which the upper half-columns are mounted and the floor-slab of the first floor is arranged. The weight of the building was evenly distributed among all the spheroids, and due to their large number, a friction force arose, dampening seismic vibrations. After completion of the construction, tests were carried out by tearing off the calibrated insert with bulldozers, dropping a load weighing 80 kN from the building and hitting a projectile of the same weight at floor-slab level. All tests showed very good seismic resistance of the building: the forces of fluctuations of the level of 9 points were extinguished and perceived by the building as 6 points. Unfortunately, despite the fact that this mechanism is highly efficient, it is extremely time-consuming and difficult to install, and the technology needs to be improved. Currently, the spheroids in the mechanism have been destroyed, and the building has lost its seismic resistance.

Guided by the peculiarities of earthquake-resistant building construction technologies, a comparative analysis of existing solutions was carried out. For ease of familiarization, the building practice were assigned numbers (Tab. 1).

**Table 1.** The main solutions in the construction of earthquake-resistant buildings

1	Increasing the stiffness and strength of the main connection of construction	
2	Construction of buildings with increased damping	2.1 Structures with damping forces of friction
		2.2 Increase and concentration of masses
		2.3 Lowering the mass of building structures
		2.4 More-connection frames
3	Construction of buildings with an active seismic isolation system	3.1 Flexible supporting structures
		3.2 Rubber-metal supports
		3.3 «Kinematic foundation» by Cherepinsky
		3.4 Systems based on «spherical spheroids» (sharovie spheroids) by Nazin

The analysis was carried out in several main groups: steel consumption, maintainability of the building practice used, the possibility of implementing seismic protection during the reconstruction of the building, the ability to absorb seismic impacts, accessibility and energy efficiency. Steel consumption is a key technical-economic ratio in the designing of reinforced concrete structures, and when using traditional seismic protection solutions, consumption increases and is considered excessive. The use of building structures with damping forces of friction is characterized by a lower consumption of steel, due to the redistribution or reduced of the seismic load on the building, but the most economical by this criterion is the use of seismic isolation mechanisms that allow the building to be erected without changing structures — the consumption of steel will be the same as and during the construction of a similar building outside earthquake-prone conditions. High maintainability means the possibility of replacing individual worn-out elements; low - the occurrence of failures in individual hidden structural elements under the influence of seismic loads (rupture of reinforcement, development of plastic deformations of concrete) and the inability to restore them. The possibility of applying seismic protection solutions means: high suitability of the device during rebuilding; low suitability — implementation if the building has certain features (structural system of the building, depth of foundation); unsuitable — inability to use in an existing building. The ability to absorb seismic impacts is the ability of a building to withstand an earthquake of a certain magnitude (according to the standards adopted in the territory of the Russian Federation, the assessment is determined on a 12-point scale MSK-64). Availability of implementation, it is possible to distinguish easily accessible (generally accepted regulatory and technical documentation is used in the development of project documentation) and complex (scientific and technical escort and monitoring are additionally required). The introduction of seismic protection solutions contributes to an increase in energy efficiency (which is typical for buildings with lightweight building structures) or does not affect changes, but most often has a negative impact. Table 2 shows the results of the analysis.

## 5 Conclusions

The construction of buildings using a seismic isolation mechanism does not involve the use of seismic protection solution in building structures, which, in addition to reducing construction costs, makes the building more maintainable. Since failures accumulate in the elements of seismic isolation systems with a high degree of maintainability, the building is

able to withstand a greater number of seismic cycles. The introduction of seismic protection measures in buildings with lightweight building structures contributes to increased energy efficiency in the process of exploitation.

**Table 2.** Results of analysis

Building practice	Steel consumption			Maintainability		The possibility of applying			Ability to absorb seismic impacts			Availability of implementation		Energy efficiency		
	Excessive	High	Unchangeable	High	Low	High	Low	Unsuitable	7	8	9	Easily accessible	Complex	High	Unsuitable	Low
1	+				+			+			+	+				+
2.1		+			+			+	+			+			+	
2.2		+			+	+			+			+				+
2.3		+			+			+	+			+		+		
2.4	+			+		+				+		+				+
3.1		+			+			+		+			+		+	
3.2			+	+		+				+			+		+	
3.3			+	+			+		+				+		+	
3.4			+	+			+			+			+		+	

Solutions with traditional seismic protection are actively used for various structural systems of buildings, but their application requires a large amount of additional resources. The use of seismic isolation mechanisms with high efficiency of seismic energy absorption makes it possible to significantly reduce the cost of construction resources by using structures with a high degree of factory readiness, mechanize the construction process and increase maintainability. Unfortunately, currently the use of active protection systems is not widespread, additional research is needed in the field of design, development of construction building practice and use in the reconstruction of existing buildings and structures.

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