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MODERN TECHNOLOGIES FOR ENSURING SEISMIC SAFETY OF BUILDINGS

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Abstract: This article explores modern approaches to reducing seismic risk in buildings through innovative engineering and technological solutions. The study analyzes the effectiveness of both active and passive seismic protection systems, as well as the application of smart materials and adaptive structural designs. Particular attention is given to monitoring and control systems that ensure dynamic stability during earthquakes. Based on comparative analysis, the results demonstrate that the use of modern seismic protection methods significantly increases the reliability and durability of buildings in seismically active regions. Prepared within the framework of the applied research project No. FZ-2020100661 entitled "Development of proposals to enhance the seismic resistance of buildings and structures based on theoretical and experimental studies of active seismic protection systems."
Keywords: seismic protection, risk reduction, building stability, active systems, smart materials, innovative technologies.

Introduction: In recent decades, earthquakes worldwide have caused significant damage to human life, economic infrastructure, and urban development. In particular, ensuring the seismic resilience of buildings in major cities and industrial centers located in seismically active zones has become one of the pressing scientific and technical challenges. In modern construction practices, various passive protection devices are widely used to reduce seismic risk; however, such systems only mitigate earthquake forces to a limited extent. Therefore, recent scientific research has focused on the implementation of active seismic protection systems. The main objective of this study is to analyze the effectiveness of active seismic protection devices in enhancing the earthquake resistance of buildings and structures, as well as to provide scientifically grounded conclusions regarding their structural design and operating principles [1-10]. In recent decades, earthquakes occurring worldwide have posed significant threats to human life, the economy, and social infrastructure. With increasing urbanization, the growth of large industrial centers, and the proliferation of multi-story buildings, the level of seismic risk has further escalated. Therefore, in modern construction, enhancing the earthquake resistance of buildings, i.e., reducing seismic risk, has become one of the most important scientific and practical challenges. In traditional construction approaches, seismic risk reduction is primarily achieved through passive protection methods. These include deformation joints, damping layers, flexible foundations, and the use of energy-absorbing materials. However, in recent years, new high-tech approaches such as active control systems, smart materials, and engineering solutions based on real-time monitoring have been increasingly implemented in this field. Modern seismic protection technologies, including active and semi-active systems, enable real-time analysis of vibrations and ensure the dynamic stability of structures. These systems help reduce a building's response to seismic waves, lower

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stresses in structural elements, and increase the overall level of safety. The main objective of this study is to analyze modern methods for reducing seismic risk in buildings, to identify their technical and scientific foundations, and to scientifically evaluate the differences in effectiveness between active, passive, and smart systems. This approach contributes to the development of sustainable and safe construction, as well as to the reliable protection of infrastructure in seismically active regions of our country.

Methodology: In this study, a comprehensive scientific-methodological approach was employed to evaluate, analyze, and determine the effectiveness of modern methods for reducing seismic risk in buildings. The main research directions included theoretical analysis, mathematical modeling, computer simulation, and the analysis of observational data from existing structures. First, various types of seismic protection systems passive, semi-active, and active were examined. The operating principles, structural design, and control algorithms of each system were analyzed theoretically. For this purpose, scientific literature, international studies, and practical project data were utilized. During the mathematical modeling process, the dynamic behavior of building structures was represented using differential equations [7–16]. Based on these models, the response of buildings to seismic waves was simulated in the LIRA and ANSYS software environments. To ensure the accuracy of results, the models were tested with seismic signals of varying intensities. In the experimental phase, the obtained results were compared with existing passive protection systems, and the effectiveness of active and semi-active control methods was evaluated as a percentage. The primary criteria for analysis included vibration amplitude, energy dissipation, structural deformation stability, and system response time. Based on this methodology, scientific foundations were developed for the practical implementation of modern technologies to reduce seismic risk. The results obtained during the study are presented in detail in the following sections.

Experimental Data Analysis:

The experimental analyses conducted within the scope of this study focused on investigating how various structural elements of buildings respond to seismic vibrations. The tests were performed under simulated conditions, subjected to seismic loads of varying intensities. The primary objective was to compare the effectiveness of active, passive, and semi-active seismic protection systems and to determine their impact on the structure. Initially, in a model constructed with passive systems, the average vibration amplitude was observed to reach 12–15 cm. Under the same conditions, the implementation of an active control system reduced the amplitude to 7–8 cm, representing an approximate 40% improvement in structural stability. Additionally, when semi-active systems were applied, the energy dissipation indicator increased by approximately 35%. Dynamic vibration data measured via sensor networks indicated that active protection systems allow real-time monitoring of structural conditions and facilitate appropriate response measures. The distinct advantage of these systems is their ability to automatically control vibration frequency and amplitude, thereby reducing stresses within the structure [10–16]. The experimental results also confirmed the significant role of material selection in enhancing a building's seismic resilience. Structures incorporating smart materials such as piezoelectric or viscoelastic components effectively dissipate energy and adapt rapidly to deformation. These solutions not only reduce vibration amplitudes but also ensure the long-

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term operational stability of the structure. Overall, the experiments demonstrated that the use of active and semi-active control systems significantly enhances the seismic resistance of buildings. Their application leads to a reduction in maximum stresses in structural elements, an increase in the energy dissipation coefficient, and an overall improvement in seismic safety.

Results:

The theoretical and experimental analyses conducted in this study demonstrated the significant importance of modern technological solutions in enhancing the seismic resilience of buildings. The results indicated that, compared to traditional passive systems, active and semi-active control mechanisms exhibit considerably higher effectiveness. According to the mathematical modeling results, active protection systems can reduce vibration amplitudes by an average of 35–45% and increase energy dissipation by more than 30%. This substantially decreases the stresses occurring in the primary structural elements of the building. While passive systems provide such results only at specific frequencies, active systems implement adaptive control in real time in response to the varying characteristics of seismic waves. Experimental tests showed that energy dissipation modules developed based on smart materials improve the deformation stability of structures and respond more quickly to dynamic vibrations. Moreover, when used in combination with flexible foundations and damping layers, the overall effectiveness of the system further increased. Monitoring results indicated that active control systems reduce the likelihood of the structure entering resonance, thereby enhancing the overall stability of the building during an earthquake. Additionally, due to the high response speed of automatic control modules based on real-time data, the system's reaction time is shortened, allowing seismic impacts to be mitigated at the initial stage [16]. These results confirm that the use of modern approaches, including active and smart systems, is one of the most effective ways to ensure engineering safety in reducing seismic risk. Their application not only increases earthquake resistance but also improves energy efficiency and long-term operational stability.

Discussion: The analysis of the results indicates that reducing seismic risk in buildings cannot be fully addressed by passive protection methods alone. While passive systems enhance structural strength, they cannot adapt to the rapidly changing nature of seismic waves. Therefore, contemporary research increasingly focuses on the widespread implementation of active and semi-active protection systems**.**

Active seismic protection systems are based on real-time monitoring, smart sensors, and microprocessor control. These technologies continuously track vibrations during an earthquake and provide an optimal response to dissipate impact energy. The study results show that such systems significantly reduce building vibration amplitudes and minimize structural deformations.

Semi-active systems are also noteworthy due to their economic efficiency and technical simplicity. They consume less energy compared to fully automated systems while maintaining high effectiveness. In particular, damping mechanisms and adaptive supports based on viscoelastic materials play a crucial role in ensuring the dynamic stability of buildings.

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The discussion further reveals that designing an effective seismic risk reduction system requires careful consideration of the placement of structural elements, the physical properties of materials, and the compatibility of control algorithms. Successful operation of active systems depends on a well-calibrated sensor network, fast information transmission modules, and reliable software [15].

At the same time, the widespread implementation of these systems faces certain economic and technical constraints. High-precision sensors, digital control units, and complex software integrations are required. However, in the long term, such technologies can substantially enhance construction safety, protect human lives, and reduce economic losses.

Conclusion and Recommendations:

The results of this study indicate that reducing seismic risk in buildings requires a comprehensive approach. In modern engineering practice, the integration of passive, semi-active, and active protection systems provides the most effective outcomes. In particular, active systems based on real-time monitoring and control mechanisms significantly enhance the earthquake resistance of structures.

Based on mathematical modeling and experimental tests, active seismic protection systems can reduce building vibration amplitudes by an average of 40% and increase energy dissipation by 35–45%. These results highlight the necessity of widespread implementation of such technologies in practical construction.

Furthermore, the use of smart materials, flexible structures, and energy dissipation devices has shown positive results in reducing seismic risk [11–28]. These solutions improve the dynamic stability of structures, enhance operational safety, and extend service life.

Based on the analysis, the following recommendations are proposed:

Ensure comprehensive seismic safety in construction projects through the combined application of active and passive protection systems.

Develop new types of energy dissipation devices based on smart materials and adaptive supports.

Implement sensor networks for real-time monitoring of buildings in seismically active areas.

Establish technical requirements for active seismic protection systems in construction standards and regulatory documents.

Develop locally adapted, energy-efficient, and economically feasible protection solutions.

In conclusion, modern methods for reducing seismic risk are not merely technical innovations but crucial factors ensuring human safety, social stability, and economic development. Therefore, expanding scientific research in this field and integrating innovative technologies into national construction practices is an urgent priority.

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