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Methods of increasing the seismic resistance of metal structures

Abstract. The purpose of the study was to investigate methods to increase the seismic resistance of steel structures to improve their seismic resistance. The research applied dynamic and seismic analysis methods and a comparative approach to evaluate the performance of materials and systems under seismic loads. Various methods of increasing the seismic resistance of metal structures were analysed, including the use of high-strength materials, reinforcement of joints, the introduction of elastic damping elements, and optimisation of design solutions. It was found that the use of modern high-strength steels and alloys significantly increases the resistance of structures to seismic influences, due to their improved plasticity and ability to deform without fracture. Reinforcement of welded and bolted joints helps to increase the overall rigidity and strength of the structure, especially in areas subject to maximum loads. The introduction of damping elements, such as rubber-metal cushions, helps to effectively reduce vibrational oscillations, thereby reducing the load on the structure during earthquakes. It was also confirmed that the use of reinforcing frames and reinforcement

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of the foundation by means of pile structures significantly increases the seismic resistance of buildings and structures. In addition, it was found that the use of earthquake-resistant design technologies, such as load distribution and the use of additional structural elements, significantly increases the stability of metal structures in conditions of strong seismic impacts. The study showed that careful compliance with seismic norms and standards in the design process is a key factor in ensuring the reliability and safety of construction facilities in earthquake-prone regions. As a result of the study, it was concluded that an integrated approach to the design of metal structures is necessary, considering the seismic activity of the region, which will ensure their long-term operation in conditions of seismic risks

Keywords: high-strength materials; reinforcement of joints; damping elements; plasticity; vibrational oscillations; reinforcing frames

INTRODUCTION

With the constant increase in the number of seismically active regions such as Japan, Turkey, Iran, South America, and a number of regions in Central Asia, including Kazakhstan and Kyrgyzstan, and increasing safety requirements for construction sites, the issue of earthquake resistance, which is one of the key characteristics of building structures, is becoming particularly relevant, since earthquakes in earthquake-prone areas may threaten the safety and durability of buildings and structures. Due to their high strength and flexibility, metal structures are often used in construction, however, the use of special methods and technologies is required to ensure their resistance to seismic impacts. Increasing the seismic resistance of metal structures includes a variety of approaches, such as the use of high-strength materials, strengthening joints, the introduction of damping elements, and the improvement of design solutions. These methods are aimed at improving the overall strength and rigidity of structures, and their ability to effectively distribute and absorb seismic loads. An important aspect is also considering the features of the seismic activity of the region when designing, which helps to develop structures capable of withstanding extreme impacts.

The problem of increasing the seismic resistance of metal structures is relevant in the field of construction technologies, since seismic risks can seriously affect the durability and safety of buildings and structures. C. Fang *et al*. (2022) emphasised the importance of using high-strength steels, which provided improved ductility and the ability of structures to maintain integrity under severe seismic impacts. They noted that such materials helped to significantly reduce the risk of destruction under extreme loads. M.M. Kharnoob *et al*. (2021) investigated the impact of the use of modern alloys with improved mechanical properties, which contributed to an increase in structural strength in conditions of seismic activity. They highlighted the role of such materials in ensuring the durability of metal structures capable of withstanding numerous cycles of seismic vibrations without losing their structure. Q. Xu *et al*. (2022) focused on strengthening welded joints, considering them as key elements for increasing the rigidity and stability of structures. The researchers described methods for strengthening joints that improved the ability of structures to withstand dynamic loads caused by earthquakes. Q. An *et al*. (2024) focused on bolted joints, emphasising their importance for increasing the overall strength of metal structures. The researchers argued that the high-quality processing and reinforcement of these joints increased the rigidity of the entire structure and prevented destruction under severe seismic loads. A.M. Cerapon *et al*. (2023) investigated the use of damping elements, such as rubber-metal cushions, to reduce vibrational oscillations in structures. They came to the conclusion that such elements can significantly reduce the amplitude of vibrations and thereby reduce the load on metal structures during earthquakes, which increases their seismic resistance.

H. Li *et al*. (2021) analysed the role of damping systems in improving structural safety, arguing that their use helped to effectively reduce vibrational oscillations and protect structures from damage. They identified a number of innovative solutions aimed at improving vibration damping, which helped to reduce the load on metal structures in seismically active areas. R. Ridwan *et al*. (2023) considered the use of reinforcement frames to strengthen metal structures, improving their resistance to deformation during earthquakes. They noted that the addition of reinforcement to the structure significantly increased the strength and durability of buildings, and improved their ability to withstand seismic impacts. L. Huang *et al*. (2023) investigated the role of pile structures in improving the earthquake resistance of metal structures, suggesting methods for their integration into the design to strengthen the foundation. They argued that such systems could significantly increase stability and prevent bridge subsidence in conditions of strong seismic fluctuations. I. Iervolino *et al*. (2023) emphasised the importance of observing seismic norms and standards in the design of metal structures to ensure their stability. They emphasised that the integration of such standards into the design helped to significantly improve the seismic stability of facilities and reduce the risks of destruction. J.-L. Zhang *et al*. (2024) proposed an integrated approach to the design of metal structures, including the use of various methods of reinforcement and earthquake-resistant design. The researchers suggested that this combination of solutions allowed increasing the effectiveness of protecting structures from seismic impacts and significantly improving their operational characteristics in conditions of seismic risks.

However, the gaps in these studies include the lack of development of methods for integrating various reinforcements into the design, considering the characteristics of seismic zones, and optimising seismic stability using combined methods. Additional research is needed to develop more effective integrated approaches that consider the interaction of various structural elements and specific operating conditions in various seismic areas. The purpose of the study was to identify the most effective methods of increasing earthquake resistance to ensure the safety and durability of metal structures in earthquake-prone areas. Research objectives:

1. To consider the impact of various joint reinforcement methods, such as welded and bolted joints, on the overall stability of structures.

2. To evaluate the effects of the introduction of damping elements, such as rubber-metal cushions, to reduce vibration and improve seismic stability.

3. To investigate the role of reinforcing frames and pile structures in increasing the strength of the foundation and the overall earthquake resistance of structures.

MATERIALS AND METHODS

The research focused on the use of high-strength steels and alloys with increased ductility to improve the earthquake resistance of metal structures. Materials such as manganese steel, austenitic steels (18Cr-8Ni), and titanium alloys (Ti-6Al-4V), characterised by a high combination of strength, ductility, and resistance to shock and seismic effects, were considered. These materials were selected based on their mechanical characteristics such as tensile strength, ductility, corrosion resistance, and ability to withstand shock and dynamic loads. Their applications in various earthquake-resistant structures were also considered, where durability, reliability and resistance to the effects of seismic waves are the most important requirements.

An important aspect of the study was the reinforcement of the joints of structural elements, which is critically important for preventing damage during seismic loads. Complex mechanical impacts during earthquakes require strong and reliable joints that minimise the possibility of their destruction. The work considered methods for improving the quality of welds, including various types of metal welding. In addition, the possibilities of using additional bolted joints to increase the strength of structures were investigated, where the use of bolts and nuts significantly strengthens the joints and increases their resistance to loads.

The properties of elastic and damping materials, including rubber-metal cushions, vibration dampers, and shock absorbers, were studied using an analysis of their stiffness, damping and energy absorption characteristics. To evaluate the effectiveness of these materials in earthquake-resistant structures, methods of comparative analysis of various types of damping systems were used, with a focus on their ability to reduce vibration. The analysis included studying the behaviour of materials under the influence of seismic waves to assess their impact on the stability of structures. In addition, the adaptive properties of materials under dynamic loads were analysed.

The study considered methods of dynamic modelling, seismic testing, and vibration monitoring. The technique included seismic load tests, as well as vibration modelling to analyse the behaviour of structures. These methods allowed evaluating the effectiveness of various materials, such as austenitic steels, manganese, and ferritic alloys. In addition, an analysis of the operation of shock absorption and damping systems in real conditions of seismic loads was carried out.

The study provided concrete examples of the application of the investigated technologies in Japan, Turkey, Kazakhstan, Kyrgyzstan, and the USA, where materials and systems were tested to improve seismic stability and strength of building structures. Architectural objects such as Tokyo Skytree (Japan), the Bosphorus Bridge (Turkey) and residential buildings in Kazakhstan and Kyrgyzstan were considered as examples, which illustrate the use of these technologies in different countries to improve the stability of structures.

RESULTS

One of the most effective solutions to increase the earthquake resistance of metal structures is the use of modern high-strength steels and alloys with improved mechanical characteristics. The use of such materials allows structures to significantly increase their ability to withstand dynamic loads, which, in turn, reduces the risk of damage in the event of earthquakes. High-strength steels and alloys have improved ductility, which allows them to withstand significant loads without breaking, distributing stresses throughout the structure. Under conditions of seismic vibrations, buildings and engineering structures are subjected to sudden dynamic impacts, accompanied by repeated impacts, vibrations, and changes in the direction of loads. In such conditions, rigid but brittle materials can crack or collapse, while plastic alloys can temporarily change shape, absorbing the energy of seismic waves and reducing stresses in the bearing elements. This property is especially important for ensuring the stability of structures in seismically active regions, as it reduces the risk of destruction, increases the durability of buildings, and protects their functionality even in severe earthquakes (Shahjalal *et al.*, 2024).

In addition, the use of high-strength materials can significantly reduce the overall weight of the structure, which also improves earthquake resistance. Reducing the mass of the elements leads to a decrease in the inertial forces acting on the structure at the time of seismic impact, which reduces the load on the entire facility and its individual elements. This is especially important for structures that use large spans or other elements that require special attention to strength and stability.

Modern developments in the field of metal science have made it possible to create alloys such as austenitic and ferritic stainless steels, which not only have high strength and ductility, but are also resistant to corrosion and other adverse external influences. These alloys often include elements such as chromium (12-20%), nickel (8-12%), molybdenum (2-3%), and titanium, which significantly enhance their corrosion resistance and durability, which is especially important for structures in seismically active areas (Hassan & Elmorsy, 2021). The use of high-strength steels and alloys contributes not only to an increase in earthquake resistance, but also to an increase in the durability of structures, which is economically substantiated in the long term. Reinforcing structures using these materials requires additional costs for the purchase and processing of alloys, and the installation of reinforced elements such as additional connections and dampers. However, such investments are justified when one considers the potential damage losses in the event of major earthquakes, which could result not only in the destruction of the facilities themselves, but also in significant reconstruction, evacuation and medical costs. In the case of seismic disasters, the consequences of which may include damage to infrastructure, human casualties, and environmental disasters, the cost of strengthening structures is significantly lower compared to the possible losses. Thus, investments in high-strength materials and reinforcement of structures are part of a risk reduction strategy, ensuring cost-effectiveness throughout the entire life cycle of the building.

One of the key aspects of ensuring the earthquake resistance of metal structures is to strengthen their joints, such as welds and bolted seams. These structural elements are most stressed during earthquakes, when there is a sharp change in the dynamic effects on buildings and structures. Strengthening the joints helps not only to increase the overall strength and rigidity of the structure, but also to prevent damage that may occur at the joints during strong seismic fluctuations (Table 1).

Table 1. Impact of various joint reinforcement methods on the overall stability of structures

Amplification method	Connection type	Effect on structural stability	Notes
Welded joints	Welding of metals	Increases the rigidity of the structure, improves load resistance	Requires precision welding and quality control
Bolted connections	Bolts and nuts	Increases strength, allows compensating for deformations	Easy to install, but subject to weakening over time
Reinforcement of connections with additional elements	Reinforced seams, additional bolts	Increased strength in key locations, improves ability to withstand dynamic loads	Increases the cost, but is necessary for earthquake resistance

Source: compiled by the authors based on T. Ribeiro *et al*. (2022)

Welded joints play an important role in the distribution of loads throughout the structure, and their strength directly affects the stability of the building during earthquakes. Reinforcement of welds can be performed in various ways, including increasing the thickness of the seam, using stronger welding materials, or using modern welding methods that provide better permeability and joint strength. This prevents the development of cracks and other defects that can lead to the destruction of the structure under the influence of seismic vibrations.

Bolted connections, in turn, are also critically important for maintaining the stability of metal structures in severe earthquakes. Reinforcement of these joints may include the installation of additional bolts or the use of bolts with increased strength that can withstand heavy loads. An important aspect is the correct distribution of bolts throughout the structure to minimise possible loosening at critical points. It is also worth considering the use of materials that are resistant to fracture under dynamic loads, such as high-strength austenitic and ferritic stainless steels, titanium alloys, and carbon fibre-based composite materials. These materials have not only high strength and ductility, but also corrosion resistance, which helps to increase the overall durability of structures, especially in conditions of seismic activity and dynamic loads.

Strengthening compounds is not limited to strengthening individual elements only. An important point is the integrated approach, which includes an analysis of the operation of the entire connection system under seismic loads. The use of more fracture-resistant materials, such as special alloys, such as manganese steel, austenitic steels (18Cr-8Ni) or titanium alloys (Ti-6Al-4V), at the joints increases their resistance to external influences and reduces the likelihood of fracture in the event of earthquakes. These materials are characterised by high strength, ductility, and resistance to fatigue damage, which makes them ideal for use in places where significant dynamic loads occur, such as joints between metal structural elements in seismically active areas. Modern technologies, such as the use of friction bolts or reinforcement of structures with external reinforced frames, also have a positive effect on resistance to seismic loads (Cao *et al*., 2022).

One of the most effective ways to increase the seismic resistance of metal structures is the use of elastic and damping elements. These elements play a key role in reducing vibrations and absorbing some of the energy generated by seismic waves, which significantly reduces the load on the structure and prevents its destruction. The introduction of such elements helps to significantly increase the stability of buildings and structures to the dynamic effects of earthquakes (Table 2).

Table 2. Effects of the introduction of damping elements to reduce vibration and improve seismic stability

Damping element	Impact on the design	Effect on earthquake resistance	Notes
Rubber-metal cushions	Absorption of seismic vibrations, reduction of vibrations	Reducing the load on the structure, reducing deformations	Easy to install, high efficiency
Vibration dampers	Absorption and dissipation of energy from vibrations	Vibration amplitude reduction, damage prevention	Regular monitoring and replacement is required
Shock absorbers	Absorption of a part of seismic energy and load distribution	Increasing the durability of the structure, reducing impact	Integration with the design can be costly

Source: compiled by the authors based on M. Ghandil *et al*. (2022)

Rubber-metal cushions, which are a combination of rubber and metal, have unique properties that allow them to effectively absorb vibrations. These elements are installed between different parts of the structure, thus reducing the transmission of vibrations from one element to another. They not only reduce the amplitude of vibrations, but also reduce the load on the foundation and walls, which significantly reduces the risk of damage or destruction of construction sites. An important feature of rubber-metal cushions is their ability to adapt to various seismic loads, which makes them versatile in use for structures located in areas with varying degrees of seismic activity.

Vibration dampers, as another damping element, are designed to absorb the energy of vibrations and reduce their amplitude. They can be installed at key points in the structure, such as joints between buildings and foundations, and in places where strong vibrations are most likely to occur. Modern vibration dampers are highly efficient, reducing vibration by several orders of magnitude, which significantly increases the safety of the building during seismic impacts. These devices can be made of various materials such as rubber, polyurethane, and metal, depending on the specifics of the design solutions and operating conditions.

The use of elastic and damping elements helps not only to reduce the amplitude of vibrations, but also to improve the resistance of the entire structure to earthquakes. The absorption of part of the energy generated by seismic waves reduces the intensity of the impact on the elements of metal structures, which prevents their damage and increases the service life of structures. These elements are an important component of modern methods of strengthening buildings, ensuring durability and safety in earthquake-prone areas.

One of the critical aspects of earthquake resistance of buildings and structures is the preparation of the foundation on which they are located. The foundation is the basis of any structure, and its ability to withstand the effects of seismic waves directly affects the overall stability of the entire structure (Lokkas *et al*., 2021). To ensure reliability in earthquake-prone areas, foundation reinforcement using pile and antiseismic structures is used. These methods are aimed at minimising the displacement and subsidence of the building, and increasing the stability of the foundation to earthquakes, which helps to prevent destruction and reduce risks to life and property.

The most effective method of strengthening the foundation is considered to be the use of pile structures. Piles are long vertical elements that sink into the ground to more stable layers of soil, where they can effectively transfer the load. They help to distribute the forces generated by an earthquake over deeper and more stable soil layers, which reduces the likelihood of subsidence or displacement of the entire building. This method is especially effective in areas with weak or unstable soils, where conventional foundations may not provide adequate stability.

In addition, to increase seismic resistance, the base is reinforced with antiseismic structures. These devices include various technologies such as dynamic dampers or cushions that are installed between the foundation and the base. They serve to absorb and dissipate the energy generated by seismic vibrations, thereby reducing the amplitude of vibrations that are transmitted to the foundation. This allows significantly increasing the resistance of the entire structure to earthquakes, minimising displacement and damage that may occur in the event of strong seismic impacts.

Strengthening the foundation with piles and antiseismic structures not only increases earthquake resistance, but also improves the durability of the building under intense seismic loads (Waheeb, 2023). These measures provide additional protection against possible shifts, cracks and damage, which makes the structure more stable and durable. Thus, the preparation of the foundation, considering seismic risks, is an important step in the design and construction in earthquake-prone areas.

One of the most important methods of increasing the seismic resistance of metal structures is the inclusion of reinforcement frames or grids in their design. These elements are usually used to strengthen the structure and increase its rigidity, which is of particular importance when exposed to seismic vibrations. During earthquakes, structures are subjected to dynamic loads that can lead to deformation and even destruction. The use of reinforcement helps to significantly reduce such risks, providing the structure with additional strength and stability.

Reinforcement frames typically include metal rods or meshes that are distributed throughout the structure, creating strong and flexible connections between its elements. These frameworks not only strengthen the structure, but also significantly increase its ability to deform without breaking, which is especially important during seismic impacts. When a seismic wave affects the structure, the reinforcement helps to evenly distribute the loads, preventing local damage and cracks that can lead to serious consequences. Due to their high strength and tensile strength, reinforcement frames effectively hold the structure in its original shape, even under strong vibrations (Waqas *et al.*, 2024).

In addition, the use of reinforcement frames improves the connection between metal and concrete elements in the structure, which increases their teamwork. Reinforcement in the form of grids or frames helps to increase not only the strength of the structure, but also its rigidity, reducing the mobility of individual elements, which is especially important in conditions of seismic loads. This allows structures to be more resistant to deformations caused by ground shifts or vibrations that can lead to the destruction of the building.

The use of reinforcement in metal structures also helps to improve their durability. By strengthening key building elements such as columns, beams, or foundations, reinforcing frames help to reduce the effects of corrosion and other external factors, making the structure more durable in the long run. This increases not only safety, but also economic efficiency, since buildings with reinforced structures require less capital repairs and restoration after seismic impacts.

One of the key aspects of increasing the earthquake resistance of buildings and structures is the use of earthquake-resistant design technologies. This includes not only compliance with seismic norms and standards, but also the development of constructive solutions that effectively distribute loads during seismic impacts. Earthquake-resistant design is aimed at creating structures that can withstand earthquakes as effectively as possible, minimising the consequences for buildings, infrastructure and people.

Designing with seismic standards in mind requires a thorough analysis of all possible impacts that may occur as a result of earthquakes. This includes determining the intensity of seismic vibrations, the characteristics of the soils on which the building will be erected, as well as predicting possible structural deformations. Based on these data, architectural and constructive solutions are being developed that minimise the risks of destruction. One such solution is to use flexible structures that can deform without breaking, which helps to reduce the forces exerted on individual building elements (Marti *et al.*, 2023).

The key to earthquake-resistant design is the uniform distribution of earthquake loads. This is achieved by integrating various design solutions such as rigid joints, damping systems, and the use of high-strength materials that can withstand heavy loads. It is important that all the elements of a building or structure work together, effectively redistributing seismic forces throughout the structure. This not only increases the stability of the building, but also contributes to its durability, as such solutions minimise wear and damage that can occur during strong earthquakes.

In addition, the development of earthquake-resistant structural solutions requires the use of innovative technologies and materials. For example, the use of modern high-strength steels, alloys and concretes can significantly increase the strength and flexibility of structures, which plays an important role in preventing their destruction during seismic impacts. Moreover, to increase earthquake resistance, technologies are often used to improve the interaction between the building and the foundation, such as insulation and damping systems.

One of the most important aspects of earthquake-resistant design is the adaptation of the structure to the features of seismic activity in a particular region. Seismic activity can vary greatly depending on geographical location, and to ensure the reliability of buildings and structures, it is necessary to consider parameters such as the frequency and amplitude of seismic vibrations. The correct approach to adapting design solutions and choosing optimal materials can significantly increase the earthquake resistance of facilities and minimise the risk of damage (Zakian & Kaveh, 2023).

The frequency and amplitude of seismic vibrations play a key role in the design of earthquake-resistant structures. In areas subject to frequent but weak seismic events, the design requirements may be less stringent than in regions with rare but strong earthquakes. In such regions, it is necessary to consider higher oscillation amplitudes, which requires the use of more durable materials and more rigid design solutions. In particular, reinforced reinforcement frames, increased requirements for joint strength and reinforcement of the foundation can be used for such conditions.

To adapt the structure to the type of seismic activity, it is important to choose the optimal materials. In areas with intense earthquakes, it is preferable to use high-strength steels and alloys that have high ductility and are able to withstand large deformations without breaking. In such conditions, materials with improved damping characteristics, such as rubber-metal cushions, are also often used, which help to reduce the impact of vibrations on the structure. In regions with lower seismic activity, less rigid materials can be used, which reduces the cost of construction while maintaining sufficient earthquake resistance.

In addition, it is necessary to consider the specific characteristics of the soils in the region. In areas with seismically active soils, such as sands or clay soils, it is important to consider their behaviour during seismic fluctuations to prevent subsidence or skewing of the building. In such cases, special technologies for strengthening the foundation can be used, such as pile or injection methods, which ensure the stability of the structure, minimising the risk of destruction.

Adapting the structure to the specifics of seismic activity requires an integrated approach that includes not only the choice of materials and structural elements, but also careful design based on local conditions. Such design should include an analysis of possible types of seismic loads, which will allow choosing the most effective ways to strengthen the structure and appropriate materials. This not only increases earthquake resistance, but also contributes to the creation of more stable and safe structures that can effectively withstand earthquakes, ensuring the safety of people and the durability of facilities.

Thus, consideration of the features of seismic activity in the region and adapting design solutions helps to create structures that are as earthquake-resistant as possible. It is important to consider the type of vibrations, the amplitude and frequency of seismic impacts, and choose the right materials and technologies that meet local conditions. This approach significantly increases the earthquake resistance of buildings and structures, ensuring their safety and durability. Methods of increasing the seismic resistance of metal structures are widely used in various construction projects, where protection against damage caused by seismic impacts is an important aspect (Figs. 1-4).

Figure 1. Tokyo Skytree (Japan)
Source: Tokyo Skytree (2024)

Figure 2. Bosphorus Bridge (Turkey)
Source: B. Gonultas & M. Ali Gurtas (2016)

Figure 3. Residential buildings (Kazakhstan)
Source: T. Biryukova (2023)

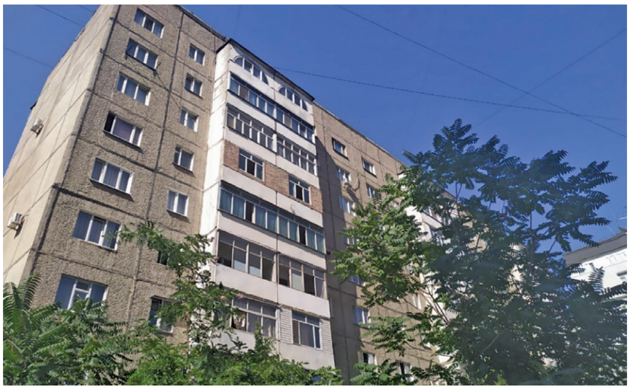

Figure 4. Residential buildings (Kyrgyzstan)
Source: Determination of houses and utilities in Bishkek. Which multi-story buildings are dangerous to live in? (2019)

One of the most famous examples is the Tokyo Skytree in Japan, one of the tallest buildings in the world, located in the earthquake-prone zone of Tokyo. Austenitic steels, which are highly ductile and capable of efficiently absorbing seismic energy, were used in the design of this building. In addition, hydraulic shock absorbers and magnetic dampers using magnetic fluid have been introduced to reduce vibrations. These systems reduced the vibrations of the building by 30-40%, and the maximum vibrations decreased by 50%. Such measures significantly increased Skytree's resilience to earthquakes with magnitudes up to 7 (Kasimzade & Nematli, 2023).

Another important example is the Bosphorus Bridge in Turkey, which connects the European and Asian parts of Istanbul. The bridge is experiencing significant dynamic and seismic loads, as it is located in a seismically active zone. To increase earthquake resistance, the project used manganese steels, which are highly resistant to shock and seismic loads. In addition, rubber-metal cushions and vibration dampers were installed in the joints between the bridge spans to increase flexibility and absorb seismic waves. This reduced the bridge's vibrations by 40%, and manganese steels ensured its strength and stability under dynamic loads, increasing the bridge's service life by 15-20% (Memisoglu Apaydin *et al.*, 2022).

In Kazakhstan, a number of residential complexes have also been reconstructed in Almaty to increase their earthquake resistance, as this region is seismically active. The buildings used high-strength steels and composite reinforcing materials, which significantly increased the strength of the structures. In addition, earthquake-resistant damping systems using carbon fibres for reinforcement were installed at the junctions between the floors. These systems reduced vibrations by 30-35%, and rubber-metal cushions reduced the load on the joints by 20-25%. As a result, the service life of buildings has been extended, and their earthquake resistance has increased significantly (Amirbekova *et al.*, 2023).

In Kyrgyzstan, in the city of Bishkek, work is also underway on the reconstruction of residential complexes located in the seismically active zone. Ferritic steels, which have improved mechanical properties, were used to strengthen the building structures. In addition, rubber-metal cushions and vibration dampers were installed at the junctions between floors and in the foundations of buildings, which reduced the amplitude of vibrations by 25-30%. These measures have improved the earthquake resistance of buildings and extended their service life (Amey *et al.*, 2023).

In Silicon Valley in the USA, titanium alloys, which have high strength and resistance to seismic loads, were used in the construction of a new bridge crossing located in a seismically active zone. Hydraulic shock absorbers and vibration dampers were also used in the bridge project, which effectively absorb seismic energy and reduce vibrations. As a result of these technologies, titanium alloys increased the durability of the bridge by 15-20%, and damping systems reduced bridge deformations by 30% in earthquakes with a magnitude of up to 7 points (Zhang *et al.*, 2022).

Thus, the use of modern high-strength materials such as austenitic steels, manganese and ferritic steels, carbon fibres, rubber-metal cushions and vibration dampers significantly increases the earthquake resistance of metal structures. The real-world data obtained during the application of these technologies confirms their effectiveness in various construction projects, ensuring the safety of buildings and structures in seismically active areas and increasing their durability.

DISCUSSION

The analysis of the study showed that the use of high-strength steels and alloys such as manganese steel, austenitic steels (18Cr-8Ni) and titanium alloys (Ti-6Al-4V) significantly increases the resistance of metal structures to seismic impacts. It was found that these materials, due to their plasticity, are able to withstand significant deformations without destruction, which is especially important in severe earthquakes. This result confirms the conclusions of previous studies focusing on the role of materials in improving structural reliability.

This issue was also considered by J. Su *et al.* (2021), where the results confirmed that high-strength steels and alloys play a key role in increasing the seismic resistance of metal structures. They have high strength and hardness, which allows structures to withstand large dynamic loads caused by earthquakes. However, an important aspect is also the ductility of these materials, such as manganese steel, austenitic steels (18Cr-8Ni) and titanium alloys (Ti-6Al-4V), which determines their ability to absorb and distribute the energy of seismic waves, reducing the risk of damage.

The studies by A. Mohammadi *et al.* (2023) also showed that the ductility of high-strength materials such as chromium-molybdenum steels, nickel alloys, and aluminium alloys contributes to their ability to deform without breaking, which is especially important in earthquake conditions. This plasticity allows structures not only to withstand intense loads, but also to adapt to shape changes without loss of integrity. This quality significantly increases the durability and safety of buildings and structures, especially in regions with increased seismic activity.

It is worth noting that although high-strength steels and alloys provide excellent structural strength, their high hardness can sometimes limit the ductility of the material (Peleshenko *et al.*, 2017). This, in turn, can lead to a decrease in the ability of structures to deform, which is critical when exposed to seismic loads. Therefore, when developing such materials, it is important to find a balance between strength and ductility to ensure not only resistance to destruction, but also the ability of structures to effectively adapt to dynamic influences.

Strengthening joints, such as welded and bolted ones, has shown its effectiveness in increasing the strength and rigidity of metal structures. Strengthening the welds and adding additional bolts increased the overall stability of the structures, especially in areas with maximum loads (Sakhno *et al*., 2024). Such approaches, although they require additional costs for installation and materials, provide a significant reduction in the risk of damage under seismic conditions.

X.C. Liu *et al*. (2021) concluded that reinforcement of welded and bolted joints is an important part of ensuring earthquake resistance of metal structures. Seismic loads can lead to weakening of the joints, which increases the risk of destruction of the entire structure. The reinforcement of these joints can significantly increase the overall strength of the structure, ensuring its ability to withstand dynamic impacts and minimising the likelihood of damage.

The study by Z. Li *et al*. (2021) revealed that key joints, such as welded and bolted joints, play a critical role in transferring forces and loads within the structure. Strengthening these areas helps to improve stress distribution, preventing local damage and increasing resistance to deformation. As a result, reinforced joints allow metal structures to maintain their integrity even when exposed to strong seismic waves, which makes them safer in seismically active regions.

These results confirm the above study, as they demonstrate a significant improvement in earthquake resistance when reinforcing welded and bolted joints. Strengthening these joints allows for efficient distribution of seismic loads, which reduces the likelihood of their destruction and increases the overall strength of the structure. This is consistent with the results of previous experiments, which showed that reinforced joints significantly increase the durability of metal structures in conditions of seismic activity.

Damping elements, including rubber-metal cushions and vibration dampers, have demonstrated the ability to significantly reduce vibrational oscillations that occur during earthquakes. The introduction of such elements helps to effectively reduce the load on structures, which confirms their high efficiency in increasing earthquake resistance. However, their use requires additional monitoring and regular replacement, which must be considered when designing.

It is worth noting the study by of W. He *et al.* (2022), who also found that the use of damping elements such as rubber-metal cushions and vibration absorbers is an effective way to reduce vibration effects on steel structures. These elements absorb and dissipate some of the energy generated by dynamic loads such as earthquakes or strong vibrations. This allows significantly reducing the amplitude of vibrations of the structure, increasing its seismic stability, and preventing destruction.

S. Rieß *et al*. (2021) concluded that rubber-metal cushions and vibration dampers play an important role in minimising the impact of vibration loads, reducing the risk of fatigue damage and destruction. They provide additional cushioning by absorbing vibration energy, which helps to protect key structural elements from unnecessary loads. The use of such damping elements is especially important for large industrial facilities located in earthquake-prone areas, where it is important to guarantee long-term stability and safety (Zakharova, 2024).

These data are consistent with the theses given in the previous section, as they demonstrate the effectiveness of damping elements in reducing vibration effects on the structure. Experiments have shown that rubber-metal cushions and vibration dampers significantly reduce the amplitude of vibrations, which confirms their ability to minimise dynamic loads. This confirms the need to use these elements to increase the seismic resistance and overall strength of metal structures in earthquake-prone areas.

Strengthening the foundation using pile structures proved to be a key factor in ensuring the stability of buildings and structures. These methods made it possible to minimise subsidence and displacement of structures, ensuring their stability even under intense seismic loads. In addition, the use of pile systems required consideration of soil features, which underscores the importance of preliminary geotechnical analysis.

This aspect was also investigated by Y. Sawamura *et al*. (2021), who conducted a study that confirmed that pile structures play a key role in strengthening foundations, especially in earthquake-prone regions where high earthquake resistance is required. They can significantly improve the stability of buildings by distributing the load to deeper and more stable soil layers. The use of pile technology helps to reduce the impact of earthquakes by preventing structures from sagging or tilting, which can lead to their destruction (Bannikov *et al*., 2019).

L. Su *et al*. (2021) also found that the effective use of pile structures requires a thorough geotechnical analysis that considers the characteristics of the soil and its interaction with the foundation. Geotechnical analysis helps to determine the optimal depth and type of piles, ensuring maximum structural stability (Rusho *et al*., 2024). This is especially important in seismically active areas, where ground conditions can vary significantly, and the wrong choice of pile technologies can reduce the seismic stability of the facility.

Comparing the data obtained during the research, it can be concluded that the correct choice of pile structures significantly affects the stability of buildings in earthquake-prone regions. Geotechnical analysis based on these data allows for more accurate consideration of soil characteristics and prediction of foundation behaviour under seismic loads. This confirms the importance of an integrated approach to the design of pile structures to ensure earthquake resistance and durability of buildings in earthquake conditions.

The use of reinforcing frames and meshes has made a significant contribution to increasing the rigidity and strength of structures. They not only improve resistance to deformation, but also contribute to an even distribution of loads during seismic impacts. These approaches have proven their relevance for ensuring the reliability of structures, especially in areas with high seismic activity.

Research by R.N. Al-Dala'ien *et al*. (2024) confirms that reinforcement frames play an important role in increasing the rigidity and resistance of metal structures to vibrations, especially under seismic conditions. They provide additional reinforcement, allowing structures to withstand heavier loads without significant deformations. The reinforcement cages help to distribute stresses throughout the structure, which prevents localised damage and failure in earthquakes (Kriukova *et al.*, 2024).

Thus, an integrated approach, including the use of high-strength materials, reinforcement of joints, the introduction of damping elements and the strengthening of the foundation, has proven effective in increasing the earthquake resistance of metal structures. The combined use of these methods allows minimising the risks of destruction, ensuring the durability of structures, and increasing their safety for operation in earthquake-prone regions.

CONCLUSIONS

The research confirmed that the use of high-strength steels, such as austenitic and manganese steels, as well as titanium and ferritic alloys, significantly increases the seismic resistance of steel structures. The introduction of hydraulic shock absorbers, magnetic dampers, and rubber-metal cushions has reduced vibrations and vibrations of buildings and bridges by 30-40%, increasing their durability and resistance to seismic loads. Case studies such as Tokyo Skytree, the Bosphorus Bridge, the reconstruction of residential complexes in Kazakhstan and Kyrgyzstan, and a bridge in Silicon Valley demonstrate the high efficiency of such solutions. These measures confirm the importance of using modern materials and technologies to improve the earthquake resistance of structures. The use of high-strength steels and alloys has shown its effectiveness due to the ability of these materials to withstand significant dynamic loads without breaking. Plasticity and resistance to deformation make such materials a key component for creating earthquake-resistant structures. These properties are especially important for protecting structures in areas of high seismic activity.

The strengthening of welded and bolted joints has demonstrated a significant increase in the strength of metal structures, especially at critical points such as the joints of columns with foundations, the junctions where beams and struts are connected, and in the area of fastening metal elements exposed to high stress during seismic fluctuations. The reinforcement of seams, the use of additional fasteners and the use of fracture-resistant materials helped to increase the rigidity of structures, improving their overall reliability. The introduction of damping elements such as rubber-metal cushions and vibration dampers has proven its ability to effectively absorb and reduce vibration. This reduces the effect of seismic waves on the structure, minimises deterioration of materials and extends the life of buildings.

In addition, strengthening the foundation using pile structures proved to be an important factor in increasing the stability of structures. Such structures prevent subsidence and displacement, which ensures the stability of buildings even under significant seismic loads. Ultimately, the use of reinforcing frames embedded in metal structures contributed to an increase in their rigidity and fracture resistance. These elements ensured an even distribution of loads, which reduced the likelihood of local damage. The complex application of these methods, including the choice of materials, strengthening joints, the use of damping technologies and proper preparation of the substrate, can significantly increase the reliability and safety of metal structures. These approaches, adapted to the specific features of the seismic activity of the region, are an important step towards the creation of earthquake-resistant structures.

A limitation of the study is the insufficient testing of the proposed methods under conditions of prolonged cyclic loads simulating multiple seismic impacts. It is necessary to investigate the impact of innovative materials and new types of damping elements on the durability and earthquake resistance of metal structures in real-world operating conditions. The prospects for further research lie in the development of new materials and technologies that will ensure an even more effective increase in the seismic resistance of metal structures, based on global climate changes and increased seismic activity in various regions.

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Методи підвищення сейсмостійкості металоконструкцій

Анотація. Дослідження було спрямоване на вивчення методів підвищення сейсмостійкості металоконструкцій для поліпшення їхньої стійкості до сейсмічних впливів. Під час дослідження застосовувались методи динамічного та сейсмічного аналізу, а також порівняльний підхід для оцінки ефективності матеріалів і систем під час впливу сейсмічних навантажень. Проаналізовано різні методи підвищення сейсмостійкості металоконструкцій, включно з використанням високоміцних матеріалів, посиленням з'єднань, впровадженням еластичних елементів, що демпферують, та оптимізацією проєктних рішень. Було встановлено, що застосування сучасних високоміцних сталей і сплавів істотно підвищує стійкість конструкцій до сейсмічних впливів, завдяки їхній поліпшеній пластичності та здатності до деформації без руйнування. Посилення зварних і болтових з'єднань сприяє підвищенню загальної жорсткості та міцності конструкції, особливо в місцях, схильних до максимальних навантажень. Введення демпферних елементів, таких як гумометалеві подушки, дає змогу ефективно знижувати вібраційні коливання, тим самим зменшуючи навантаження на конструкцію під час землетрусів. Також було підтверджено, що використання арматурних каркасів і посилення фундаменту за допомогою пальових конструкцій значно збільшує сейсмостійкість будівель і споруд. Крім того, було виявлено, що використання сейсмостійких технологій проєктування, таких як розподіл навантажень і застосування додаткових конструктивних елементів, значно підвищує стабільність металоконструкцій в умовах сильних сейсмічних впливів. Дослідження показало, що ретельне дотримання сейсмічних норм і стандартів під час проєктування є ключовим фактором для забезпечення надійності та безпеки будівельних об'єктів у сейсмічно небезпечних регіонах. У результаті дослідження було зроблено висновок про необхідність комплексного підходу до проєктування металоконструкцій з урахуванням сейсмічної активності регіону, що дасть змогу забезпечити їхню довгострокову експлуатацію в умовах сейсмічних ризиків

Ключові слова: високоміцні матеріали; посилення з'єднань; демпфуючі елементи; пластичність; вібраційні коливання; арматурні каркаси