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Development and implementation of vibroseismic protection of buildings and structures from external dynamic loads

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Abstract. The article considers the results of vibration dynamic tests of the vibration acceleration levels of a vibration insulated reinforced concrete slab and floors of a residential building, which have confirmed the effectiveness of the seismic vibration isolation system using rubber elements. The registered levels of vibration accelerations in residential premises on different floors do not exceed permissible levels according to sanitary standards, which ensures comfortable living conditions in the presence of dynamic influences. To determine the actual vibration levels of the soil and piles vibration and dynamic studies were carried out. Based on the results of these studies, numerical calculations were carried out to determine the compliance of the predicted vibration levels in residential premises with the existing sanitary standards when they are exposed to real anthropogenic loads.

1. Introduction

Recently, the protection of mechanisms, buildings and structures from dynamic loads of natural and anthropogenic nature with the help of rubber and rubber-metal Seismic Vibration Blocks (SVB) has been widely applied in Japan, China, the USA, the Russian Federation, Canada, Ukraine, Kazakhstan, New Zealand, Italy and other countries with the calculated seismicity at construction sites from 6 to 9 points.

It is enough to consider scientific publications in this field to assess the importance of the problem under consideration [1-25]. Most of these publications are devoted to methods of seismic vibration protection of buildings and structures using special devices: systems with kinematic supports; systems with dynamic vibration dampers; with a sliding belt; with rubber shock absorbers, etc. In recent years, competition between the similar devices in terms of price-quality indices, at least for residential buildings (9-27 floors), tends to favor of rubber elements [19-23]. Therefore, in the known literature, most scientific works are devoted to the calculation of the dynamics of structures of buildings with the elements under various influences of natural and anthropogenic nature. However, calculations of rubber elements are paid absolutely insufficient attention, and the available publications in most cases are of a recommendatory nature.

At the same time, this problem is very urgent, since the efficiency and durability of the vibration isolation system depends on the correct choice of parameters and the calculation of the stress-strain state of shock absorbers. This article is devoted to solving exactly this problem. Besides the problem of vibration protection, also an important problem is vibration measurement, control and monitoring.

Ukraine is included in the seismic risk zone. There is a high probability of earthquakes occurrence with intensity of 6 to 9 points according to Medvedev–Sponheuer–Karnik scale (MSK-64 scale). In addition to natural earthquakes in Ukraine, there are quite strong earthquakes (up to 5, 6 points) of anthropogenic origin. For example, in Kryvyi Rih basin in the areas of intensive mining, explosions are practiced, which lead to local earthquakes and activate the dangerous natural and anthropogenic processes as rock falls, rock bumps, landslides, etc.

The urgency of the problem is increasing at the moment due to the Russian invasion of Ukraine. Throughout Ukraine, Russian troops are destroying residential buildings, enterprises, bridges and critical infrastructure. Entire cities are destroyed. In this regard, the acute question arises of restoring destroyed buildings and constructing new buildings, taking into account new standards and the latest developments in this area.

The vibration isolation system is designed to reduce the dynamic response of building objects and protect them from earthquakes; it can be used for buildings and structures protection from industrial vibrations, dynamic effects of an underground, road and rail transport, as well as shock waves from explosions in quarries. The system is installed between the foundation and the upper part of the building structure (the so-called superstructure according to the terminology of Eurocode 8 [25]); the superstructure is considered to be completely vibration isolated, if, in the event of a seismic situation, it remains within the elastic range.

The authors of this work were directly involved in the development of national regulatory documents, including: DBN V.1.1-12:2014 “Building in Seismic Regions of Ukraine” [1], which are harmonized with Eurocode 8 “Design of Earthquake-resistant Structures” (EN 1998-1: 2004, Eurocode 8) [25]. These documents include section “Design of Seismic Isolation Systems” [1, 25] and are provided with a given level of safety for the design of vibration-resistant structures.

The considered vibration isolation system consists of rubber elements with high dissipative properties; it includes devices for limiting the displacement of the upper part of the building structure and makes it resistant to wind loads.

Seismic vibration protection of buildings and structures allows: to reduce seismic loads by 2-3 times; reduce relative horizontal floor displacements (floor skews); reduce the estimated construction cost by 3-6%; reduce materials consumption (mainly due to savings for reinforcement and concrete) of buildings; reduce labor-intensity of construction by 4-6%; expand the scope of application of standard series by building up areas with increased seismicity and anthropogenic impacts; when using seismic insulation in multi-storey residential buildings (9-27 floors), savings of $35-50 thousand or more per residential building are achieved by reducing the consumption of concrete and reinforcement.

The purpose of the work is to substantiate and calculate the elements of the vibration isolation system of buildings and structures under dynamic impacts of natural and anthropogenic nature.

2. Metods

2.1. Justification of seismic vibration protection use in construction of objects under dynamic impact of natural and anthropogenic nature

Let's consider the situation in the city of Kyiv (Ukraine). A large European city – the cultural, historical, political and industrial center of Ukraine – has been developing dynamically in recent years. New buildings, enterprises and transport interchanges are being built. The traffic flow is increasing and the metro network is expanding. This fact has a negative impact on the level of man-made noise and vibration levels, which has a detrimental effect on people’s health, their productivity and the comfort of their rest. The situation is similar in other large centers of Ukraine.

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Besides it, in these conditions, the question arises of protecting previously constructed historical, religious and cultural buildings from noise and vibration. But this requires separate individual consideration.

As an example, let's consider seismic vibration isolation of a residential complex consisting of three 27-storey buildings, constructed in Kyiv on Obolonskyi Avenue and located in the zone of dynamic impact of underground trains, vehicles and micro seismic vibrations. The construction site is located 25-30 m from the shallow underground (6-10 m); the movement of trains is carried out along the ordinary (not vibration-isolated) track. Dynamic influences during the movement of one train within the construction site occur for 15-20 s, two oncoming trains – for 40-50 s. During the movement of underground trains and vehicles, soil vibrations are transmitted to the structures of buildings and cause increased, close to resonant oscillations of floors, in most cases exceeding Sanitary Standards.

To protect buildings from dynamic natural and anthropogenic impacts, the following design was chosen. On a pile foundation (piles with a diameter of 620 mm), the foundation is made in the form of monolithic reinforced concrete grillages with a grillage slab height of 1200 mm. Full-scale dynamic tests were carried out at the construction site, which showed the following results: in the absence of a vibroseismic protection system, the calculated vibration levels of the floors exceed permissible values by 1.5-4.0 times (from 2.9 to 13.0 dB). To ensure comfortable living, the vibration acceleration levels are normalized in accordance with [2, 3].

During the construction process, after laying the piles, vibration monitoring was carried out on the piles closest to the metro line in order to assess their vibration load (figure 1). The most noticeable vibrations of the soil were from the subway train. When you are at a construction site, you can feel ground vibration even without instrumental measurements.

Figure 1. Equipment for vibration monitoring and an example of vibration signals recorded as a subway train passed by.

A comparison of the experimental values of vibration levels with the permissible ones showed that under the influence of subway trains, the vibration levels of piles and soil exceed the permissible values according to sanitary standards for residential buildings by 2-11 dB (up to four times). Therefore, in the absence of vibration protection of buildings, the levels of vertical vibrations of the floors will exceed the permissible values.

Similar results of vibration impact measurements were obtained when monitoring the construction site of another residential complex (10 ten-story sections) located on Mykhaila Boichuka St. Two deep metro lines pass directly under the buildings (depth about 40 m). When subway trains move, ground vibrations are transmitted to building structures. The frequencies of dynamic influences from the subway are in the range of 30-80 Hz. The frequencies of the vertical oscillations of the floors in the living rooms of buildings range from 30 to 50 Hz. Therefore, the dynamic actions of the subway are the cause of increased (close to resonant) vibrations of floors in residential buildings located near or above the subway lines.

To reduce the level of man-made vibrations on Obolonskyi Avenue, a vibroseismic protection system was installed in the buildings. A rubber vibration insulator with a diameter of 500 mm and a thickness of 50 mm was installed on the head of each pile, after which the grillage slab was concreted (figure 2). From horizontal ground vibrations affecting the grillage slabs and underground floors, a vibration isolation system was used in the form of polystyrene slabs 100 mm thick (figure 3).

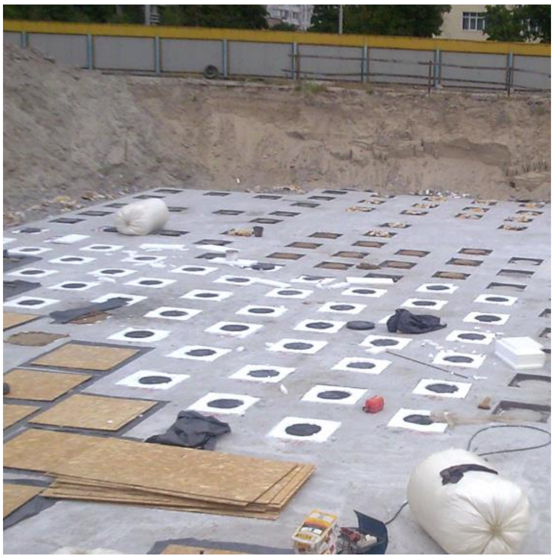


Figure 2. Installation of vibration protection system.

Figure 3. Protection against horizontal vibrations.

The systems for vibration isolation of buildings are very effective: the calculated frequency of natural vertical vibrations of vibration isolated buildings is in the range of 6.3-7.2 Hz, which is much less (3-12 times) the frequency of forced ground vibrations when exposed to underground trains (20-80 Hz); in this case, the vibration levels of the floors do not exceed permissible Sanitary Standards. The calculated safety factor against overturning of buildings under wind loads around the transverse axis K_x = 107.0, around the longitudinal axis K_y = 149.0.

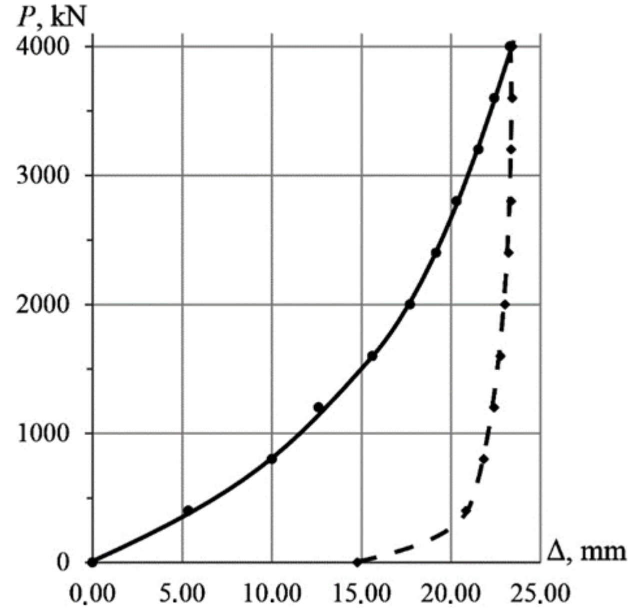
2.2. Experimental research and calculation of seismic vibration protection elements of buildings and structures

Solid cylindrical parts made of rubber containing natural rubber were applied as seismic vibration protection elements. For practical utilization, they were calculated, the design and installation method were patented, design documentation was developed, samples of four types were manufactured and tested – with a diameter of 340, 400, 420 and 500 mm, a height of 50 mm. The following tests were carried out: static tests to determine the compressive and shear stiffness at various loads; dynamic ones – to determine stiffness and dissipative characteristics. The test procedure is considered in detail in [2].

Figure 4 shows the dependence “load P – deformation Δ” for a rubber element with a diameter of 500 mm and a height of 50 mm, used as SVB in 27 - storey buildings; the compressive stiffness was 100 kN/mm (100 t/cm), the energy dissipation coefficient ψ = 0.58 (logarithmic damping decrement δ = 0.29). The dependence is experimentally determined by a laboratory testing.

For other types of rubber elements, similar load-deformation relationships were obtained.

When calculating vibroseismic isolators, analytical and numerical methods can be used. Rubber used for seismic vibration insulators has a specific set of mechanical properties, like weak compressibility, viscoelasticity, the ability to experience large deformations without destruction. Taking into account at least one of the listed properties in the mathematical model of the stress-strain state of the seismic vibration insulator leads to the impossibility of using precise analytical methods. That’s why it is appropriate to use numerical methods. The finite element method stands out among the numerical methods due to its versatility and acceptable accuracy.



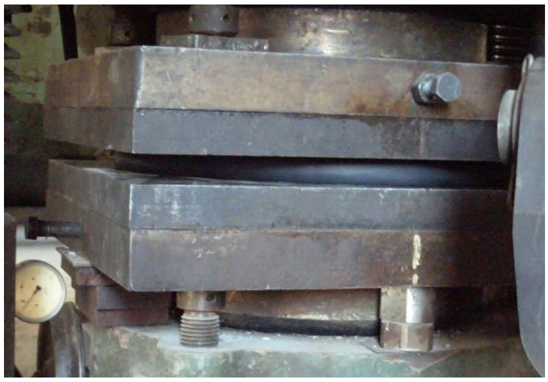


Figure 4. Dependence load-deformation for a solid rubber seismic vibration insulator with a diameter of 500 mm and a height of 50 mm.

Let's consider the peculiarities of its application for the static calculation of seismic vibration insulators. Determination of the stress-strain state of rubber structures by the traditional finite element method leads to unacceptable errors due to weak material compressibility. To eliminate these errors, a moment finite element scheme was proposed [4]. The effectiveness of its application for the calculation of vibration insulators is shown in the study of rubber [8] and rubber-metal [5] vibration insulators.

Determination of the stress-strain state of a structure according to the moment scheme of a finite element, as in the traditional method, ultimately comes down to solving the system of the form:

$$[\mathbf{K}]\{\mathbf{u}\}=\{\mathbf{P}\}, \tag{1}$$

where $[\mathbf{K}]$ is the global structure stiffness matrix, $\{\mathbf{u}\}$ is the column vector of nodal displacements, $\{\mathbf{P}\}$ is the column vector of nodal loads.

When obtaining system (1), the main and most complex procedure is the formation of a global matrix of structural rigidity, which is composed of the rigidity matrices of individual finite elements. Let's consider a spatial hexagonal finite element with linear approximation of displacements [2]. Then the dimension of such a matrix will be 24×24, and it will consist of blocks $\left[\mathbf{K}^{k'm'}\right]$, $\left(k',m'=1,\ldots,3\right)$, each of which will have a dimension of 8×8.

For an individual finite element, the stiffness matrix, according to the moment scheme for a weakly compressible material, will be represented in the global Cartesian coordinate system $O'z_{1'}z_{2'}z_{3'}$ as a sum of a shear and spherical components [6]:

$$\left[\mathbf{K}^{k'm'}\right]=\left[\mathbf{K}_D^{k'm'}\right]+\left[\mathbf{K}_S^{k'm'}\right], \quad \left(k',m'=1,\ldots,3\right). \tag{2}$$

Using the algorithm described in more detail in [2] to determine the stiffness matrix, we obtain the values of nodal displacements of finite elements.

The described technique is implemented in a software package of our own development MIRELA+ [6], which was used to study of the stress-strain state of a number of standard size vibration insulators types: height h = 0.05 m, radius R = 0.17; 0.20; 0.21; 0.25 m. Mechanical properties of rubber are described by the elastic modulus E = 5.38 MPa and Poisson's ratio ν = 0.49. The subsidence for all

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vibration insulators is taken Δ = 0.005 m. The two calculation variants were carried out, depending on the method of ends fixing: a) the ends are vulcanized to metal plates; b) free ends.

Figure 5 shows the distribution of axial displacements in a vibration insulator with a radius of 0.17 m for the first case of ends fixing.

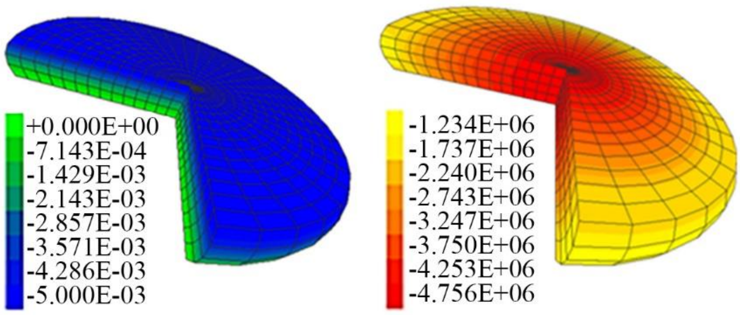
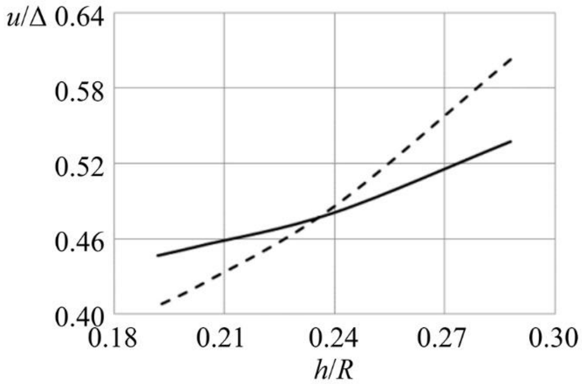


Figure 5. Stress-strain state of the vibration insulator, left – axial displacements (m); right – stress (Pa).

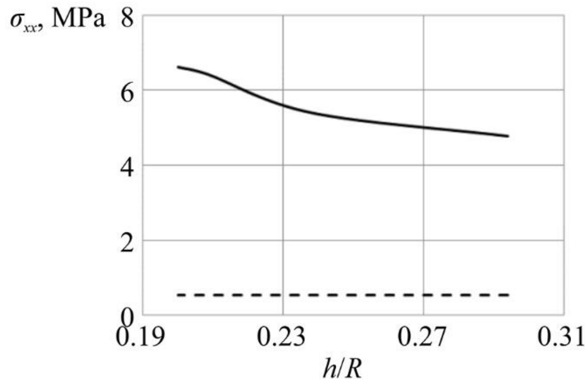
3. Results and discussion

The maximum buckling of the side surface of the vibration insulator is shown in figure 6. During the analysis this characteristic, it can be noticed the demonstration of the property of weak compressibility of rubber. With a larger *h*/*R* ratio, the value of axial deformation is compensated by radial deformation, the maximum value of which is greater for clamped ends than for free ends. The shape of the deformed surface is close to cylindrical for the case of free ends and looks like a barrel for the clamped ends. It's true for any *h*/*R* ratio; for the clamped ends with the decrease of this ratio the barrel shape increases. The decrease in the ratio *h*/*R* with free ends of a vibration insulator gives an increase in radial deformation; in the second case, the clamped ends prevent the movement of vibration insulator points in the radial direction, which leads to the increase in compressive stresses in the middle of the shock absorber array (figure 7).



——— clamped ends, ------- free ends

Figure 6. Buckling of the side surface of a shock absorber.



——— clamped ends, ------- free ends

Figure 7. Maximum compressive stresses in a shock absorber.

From the point of view of strength criteria, the scheme of free ends is more preferable due to the fact that the maximum compressive stresses are several times less than in the case of clamped ends. At the same time, the indicated stresses are practically independent of the radius of the shock absorber with free ends. In the case of clamped ends, the maximum compressive stresses increase by 30% with an increase of a shock absorber radius by 1.5 times. Therefore, when designing a structure, the decision on the number of shock absorbers and their design solution should be made with respect to maximum possible operational loads and assessment in terms of the strength of maximum stresses.

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From the point of view of deformation criteria, the buckling of the lateral surface increases with increasing radius, while in the case of free ends, the radial deformation does not depend on the radius of the shock absorber and is a constant value. In the case of clamped ends, with the increase of a shock absorber radius from 0.17 to 0.25 m, the radial deformation decreases by 5%, what also should be considered when designing vibration isolation of structures.

From the above calculation of the vibration insulator, the following conclusion can be developed. On the basis of the moment diagram of a finite element for weakly compressible materials, the stress-strain state of rubber cylindrical seismic vibration insulators for real operating conditions has been determined for the first time. The problem was solved in a three-dimensional formulation, and the proposed scheme made it possible to take into account weak compressibility of the material and, accordingly, to obtain more adequate results. The influence of structural features of seismic vibration insulators, like the radius of a structure, the scheme of ends fixing on their deformation and strength properties has been researched. This allows making sound design decisions when creating a seismic vibration protection system for real buildings and structures.

4. Conclusions

Approaches to the calculation of rubber elements applied in seismic vibration protection systems of buildings and structures from external dynamic loads, using a finite element moment diagram for weakly compressible materials, which, unlike traditional methods, allow taking into account the deformation features of this class of materials, are presented.

On the basis of the moment diagram of a finite element for weakly compressible materials, the stress-strain state of rubber cylindrical seismic vibration insulators for real operating conditions has been determined. The problem was solved in a three-dimensional formulation, and the proposed scheme made it possible to take into account weak compressibility of the material and, accordingly, to obtain more adequate results. The influence of structural features of seismic vibration insulators, such as the radius of a structure, the scheme of ends fixing on their deformation and strength properties has been studied. This allows making design decisions when creating a seismic vibration protection system for real buildings and structures.

In the experimental studies of the structures of residential buildings, the satisfactory agreement between the calculated and experimental results was obtained, which makes it possible to recommend the use of the outlined approaches when developing new types of rubber elements for seismic vibration protection buildings on Obolonsky Avenue (figure 8) and Mykhailo Boychuk Street (figure 9).

After the completion of the construction of buildings on Mykhailo Boychuk Street, vibration levels were tested on the monolithic slab of the parking lot (the non-vibration-insulated part of the building) and directly in the residential premises (figure 10).

Figure 8. Photo of three 27-storey buildings built in Kiev using vibration seismic insulation.

Figure 9. Constructed residential complex on Mykhailo Boychuk Street.

Figure 10. The process of measuring vibrations in the parking lot and in the residential part of the building.

The registered maximum levels of vibration acceleration of the floor slabs in the octave bands “31.5 Hz” and “63.0 Hz” are 14-18 dB (from 2 to 8 times) less than the permissible values according to the Sanitary Regulations, which ensures comfortable living conditions in residential premises of 10 sections built with a vibration protection system.

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