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NUMERICAL ANALYSIS OF ANTISEISMIC SLIDING BELT PERFORMANCE

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Abstract: One of the effective methods for ensuring seismic resistance of buildings and structures located in seismic-prone areas is the use of an active seismic protection system. The most common at present is an active seismic protection system based on seismic isolation. Seismic isolations in the form of rubber-metal (RMB) and pendulum sliding bearings (PSB) have gained great popularity in our country and abroad. Also known seismic isolation in the form of a sliding belt at the foundation level. Unlike RMB and PSB, the sliding belt is easier to manufacture, install, maintain, however, it is less studied and there are still a lack of sufficient design justifications. In this study, the effectiveness of a seismic isolating sliding belt at the foundation level with PTFE plates was investigated: a methodology for calculating a building with seismic isolating sliding belt at the foundation level using the direct dynamic method was developed; studies were conducted on the influence of the friction coefficient of the friction minimization component on the effectiveness of the anti-seismic sliding belt using the example of a 9-story monolithic reinforced concrete building under one-component seismic excitation. As a result of the calculations, graphs of relative displacements and accelerations, stress intensity, also pictures with displacement isofields, stress intensity and deformations were obtained. The analysis of the obtained results shows that the most effective component for friction minimization is the use of PTFE plates.

Keywords: active seismic protection, seismic isolation, sliding belt, PTFE, direct dynamic method

ЧИСЛЕННЫЙ АНАЛИЗ ЭФФЕКТИВНОСТИ РАБОТЫ АНТИСЕЙСМИЧЕСКОГО СКОЛЬЗЯЩЕГО ПОЯСА

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Аннотация: Одним из эффективных методов обеспечения сейсмостойкости зданий и сооружений, расположенных в сейсмоопасных районах, является использование системы активной сейсмозащиты. Наиболее распространенным в настоящее время является система активной сейсмозашиты, основанная на сейсмоизоляции. Большую популярность в нашей стране и за рубежом получили сейсмоизоляции в виде резинометаллических (РМО) и маятниковых скользящих опор (МСО). Также известна сейсмоизоляция в виде скользящего пояса в уровне фундамента. В отличие от РМО и МСО, скользящий пояс является более простым в изготовлении, в установке, в обслуживании, однако она мало изучена и для данной системы сейсмозащиты до сих пор отсутствуют в необходимом объеме расчетные обоснования. В данной работе проводилось исследование эффективности работы сейсмоизолирующего скользящего пояса в уровне фундамента с фторопластовыми пластинами: разработана методика расчета здания с сейсмоизолирующим скользящим поясом в уровне фундамента прямым динамическим методом; проведены исследования влияния коэффициента трения компонента минимизации трения на эффективность антисейсмического скользящего пояса на примере 9-тиэтажного монолитного железобетонного здания при однокомпонентном сейсмическом воздействии. В результате проведенных расчетов были получены графики относительных перемещений и ускорений, интенсивности напряжений, а также картины с изополями перемещений, интенсивности напряжений и деформаций. Анализ полученных результатов показывает, что наиболее эффективным в качестве компонента минимизации трения является применение фторопластовых пластин.

Ключевые слова: активная сейсмозащита, сейсмоизоляция, скользящий пояс, фторопласт, прямой динамический метод

INTRODUCTION

The catastrophic consequences of earthquakes are well known. Approximately 25% of the territory of the Russian Federation is located in earthquake-prone areas, where there is a probability of earthquakes with intensity up to 9 points on the MSK-64 scale. In this regard, ensuring the seismic resistance of buildings and structures erected in earthquake-prone areas is one of the urgent and practically important problems in construction.

At present, to ensure seismic resistance of buildings and structures, various systems of active seismic protection are used (with switch-off ties [1], systems of gravity type, systems with dynamic vibration dampers, with suspended supports, pendular sliding supports (PSS), rubber-metal supports (RMS) [2, 3, 4], with a sliding belt device in the foundation level). In our country and abroad, seismic protection in the form of RMS is most widely used. However, this type of active seismic protection has a number of disadvantages: high cost, complexity of installation and maintenance.

Seismic protection in the form of a seismic-isolating sliding belt at the foundation level is also known. However, this type of seismic protection is less popular, compared to RMS, since it is poorly investigated and currently it lacks the necessary calculation justifications in its entirety.

Development and research of active seismic protection were engaged by many domestic and foreign scientists. The problem of seismic resistance of buildings and constructions was addressed in the studies of Eisenberg [1, 5], Plevkov and Malganov [6], Djinchvelashvili and Mkrtichev [7], Uzdin [8], Kelly [9], Kani [10] and other researchers. The studies of Chudnetzov and Soldatov [11], Kuznetsov and Chen Xiatin [12] are dedicated to seismic protection through a seismic-isolating sliding belt. The effectiveness of this type of seismic protection has been demonstrated.

Despite the fact that seismic isolation as a sliding belt at the foundation level is quite well known and has practical applications, the issues regarding the development of adequate mathematical models and corresponding calculation methods remain unstudied so far.

The objective of the study is to assess the efficiency of application of the seismic isolating sliding belt at the foundation level with fluoroplastic plates to increase the seismic resistance of the building under the action of heavy earthquakes using the time-history dynamic method.

In order to achieve the preset objective, the following tasks were accomplished:

1. The existing mathematical models describing the actual performance of the seismic isolating sliding belt at the foundation level were analyzed;
2. The existing methods of calculation of building structures for the action of seismic loads have been analyzed;
3. The method of calculation of simple and complex systems with seismic-isolating sliding belt using time-history dynamical method has been developed;
4. Calculation scheme of the system "building-seismic isolation-foundation" describing its actual operation under seismic load is simulated;
5. The analysis of the obtained results is performed.

METHODS

To ensure the seismic resistance of buildings and structures erected in earthquake-prone areas, various methods of seismic protection are used: passive (traditional) and active. Currently, passive methods of seismic protection are the main in the construction practice. The use of the traditional approach to ensuring seismic resistance implies an increase in sections and an increase in the load-bearing elements. This leads to an increase in the mass of the structure and, as a consequence, an increase in inertial seismic forces. It is advisable in many cases to use active methods of seismic protection, e.g. seismic isolation and seismic shaking. Let's consider in more detail the principle of seismic isolation.

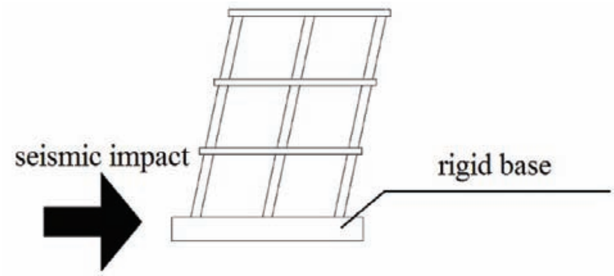


Figure 1. Deformed scheme of an uninsulated building under seismic action

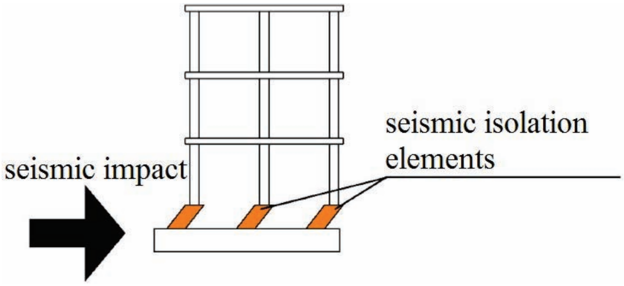


Figure 2. Deformed scheme of an isolated building under seismic action

The reduction of seismic impacts on buildings and structures is achieved through the introduction of special structural elements - seismic isolators (Fig. 1, 2), because of which the structure becomes more pliable. And this leads to increase of displacements in the upper part of the structure. Consequently, acceleration of concentrated masses, as well as seismic inertial forces are decreased [13].

Let's consider an example of seismic protection system with a sliding belt device (Fig.3).

The basis for the operation of seismic isolation in the form of a sliding belt at the foundation level is the sliding device, which includes friction minimization components and components for limiting large horizontal displacements.

There are various materials used as a friction minimization component: elastic coating graphite, stainless steel, fluoroplastic plates (PTFE), etc. When the total inertial force exceeds a certain value in the support elements of the seismic isolation device, slippage occurs. This leads to a decrease in the acceleration peaks in the system.

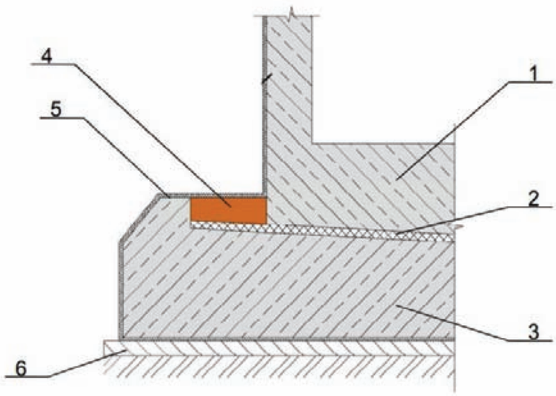


Figure 3. Scheme of seismic isolating sliding belt: 1) lower part of the building at foundation level 2) fluoroplastic plates 3) foundation 4) damper (coarse sand) 5) waterproofing 6) concrete layer

In this study, the effect of the friction coefficient on the efficiency of the antiseismic sliding belt was investigated. The following materials were considered as friction minimization component: PTFE over PTFE (PTFE+PTFE) with friction coefficient 0.052; PTFE over steel (PTFE+Steel) with friction coefficient 0.07; steel over steel (Steel+Steel) with friction coefficient 0.15.

Differential equations of motion of the system with a finite number of degrees of freedom in matrix form [14]:

$$M\ddot{u} + C\dot{u} + Ku = f^{a} \tag{1}$$

where $\mathbf{u}$ is the unknown vector of nodal displacements;

$\dot{\mathbf{u}} = \mathbf{v}$ is the nodal velocity vector;

$\ddot{\mathbf{u}} = \mathbf{a}$ is the nodal acceleration vector;

$\mathbf{M}$ is the mass matrix;

$\mathbf{C}$ is the damping matrix;

$\mathbf{K}$ is the stiffness matrix;

$\mathbf{f}^{a}$ is the vector of applied loads.

Solution of system (1) can be obtained by using explicit and implicit schemes of direct integration of motion equations. If methods implementing implicit scheme of integration are used, expression (1) at a moment of time t_{n+1} can be represented in the form:

$$\mathbf{M}\ddot{\mathbf{u}}_{t+\Delta t} + \mathbf{C}\dot{\mathbf{u}}_{t+\Delta t} + \mathbf{K}\mathbf{u}_{t+\Delta t} = \mathbf{f}^{a}_{t+\Delta t} \tag{2}$$

The difference approximation of the nodal accelerations $\ddot{\mathbf{u}}$, velocities $\dot{\mathbf{u}}$ and displacements $\mathbf{u}$ has the form:

$$\ddot{\mathbf{u}}_{t+\Delta t} = \frac{1}{\alpha \Delta t^2}\left(\mathbf{u}_{t+\Delta t} - \mathbf{u}_t\right) - \frac{1}{\alpha \Delta t}\dot{\mathbf{u}}_t - \left(\frac{1}{2\alpha} - 1\right)\ddot{\mathbf{u}}_t \quad (3)$$

$$\dot{\mathbf{u}}_{t+\Delta t} = \mathbf{u}_t - \Delta t\left(1-\delta\right)\ddot{\mathbf{u}}_t + \delta \Delta t \ddot{\mathbf{u}}_{t+\Delta t} \quad (4)$$

$$\mathbf{u}_{t+\Delta t} = \mathbf{u}_t + \mathbf{u}_t \Delta t + \left[\left(\frac{1}{2} - \alpha\right)\ddot{\mathbf{u}}_t + \alpha \ddot{\mathbf{u}}_{t+\Delta t}\right]\Delta t^2 \quad (5)$$

where α and δ are the integration parameters.

Using the explicit scheme of integration of the equation of motion of the system, obtain:

$$\mathbf{M}\ddot{\mathbf{u}}_t + \mathbf{C}\dot{\mathbf{u}}_t + \mathbf{K}\mathbf{u}_t = \mathbf{f}_t^{a} \quad (6)$$

Acceleration vector:

$$\mathbf{a}_t = \mathbf{M}^{-1}\left(\mathbf{f}_t^{ext} - \mathbf{f}_t^{\mathrm{int}}\right) \quad (7)$$

where $\mathbf{f}_t^{ext}$ is the external force vector; $\mathbf{f}_t^{\mathrm{int}}$ is the internal force vector.

Velocity and displacement vectors at the corresponding step:

$$\mathbf{v}_{t+\Delta t/2} = \mathbf{v}_{t-\Delta t/2} + \mathbf{a}_t \Delta t \quad (8)$$

$$\mathbf{u}_{t+\Delta t} = \mathbf{u}_t + \mathbf{v}_{t+\Delta t/2}\frac{\Delta t_t + \Delta t_{t+\Delta t}}{2} \quad (9)$$

The calculation was performed using an explicit integration scheme.

The calculation model of a 9-story monolithic reinforced concrete building (Figures 4, 5) with seismic insulation on a rigid soil base was adopted as the object of study.

The structural scheme of the building is cross-wall. The spatial stiffness of the structure is ensured due to the combined work of the walls and stiffening cores with the discs of the monolithic slabs. Bearing elements of the structure are made of concrete of B25 class, and steel reinforcement of A500 class. The height of the typical floor of 3.0 m. The length of the building - 24.7 m, width - 19.8 m, height - 30.9 m. The thickness of the walls and cores is 0.2m and 0.25m; floor slabs is 0.22m. Beams of rectangular cross-section are 0.4x0.56m.

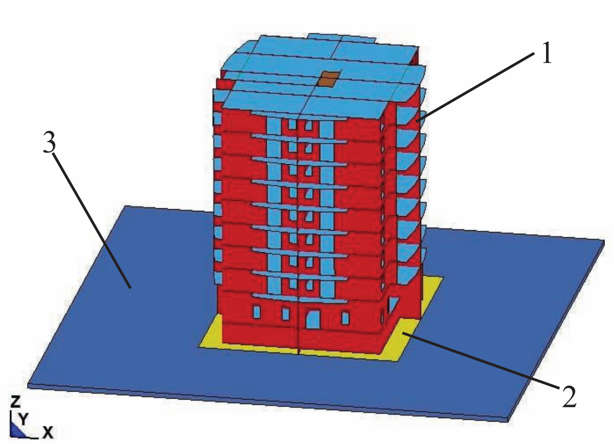


Figure 4. Finite-element model of a building with seismic isolation: 1-Building; 2 -contact surface (PTFE+PTFE/ PTFE+Steel/ Steel+Steel); 3- rigid soil base

The calculation was performed using time-history nonlinear dynamic method in a multi-purpose finite-element software package LS-DYNA. In the computational scheme, bar and spatial finite-element shells were used.

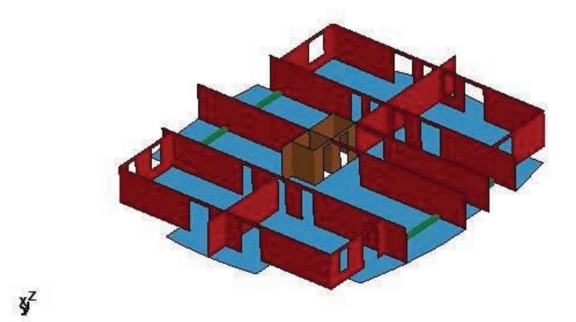


Figure 5. Finite element model of the typical floor of the building

The intensity of the earthquake is 9 on the MSK-34 scale. Figure 6 shows a one-component accelerogram of the external seismic effect.

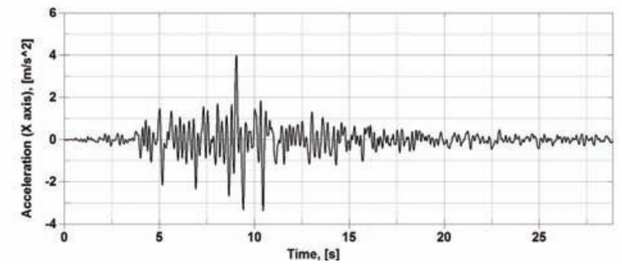


Figure 6. Accelerogram (component X)

The main results of the study are presented below (Fig.7-13, Table 1). Based on the calculation results obtained, the analysis of building operation under seismic impact with seismic-isolating sliding belt was performed using different types of friction minimization components (fluoroplastic on fluoroplastic; fluoroplastic on steel; steel on steel).

RESULTS

The graphs of relative displacements (Fig.7, 9), stress intensity (Fig.8), as well as pictures with displacement iso-fields (Fig.10), stress intensity (Fig.11, 13) and strain intensity (Fig.12) are presented below.

The main results of the study are given in Table 1. Analysis of the results shows that using PTFE+PTFE as a friction minimization component leads to 2 times lower relative movements of the whole building and 1.6 times lower relative accelerations, and to a considerable stress reduction in a certain wall element of the most loaded layer of the building.

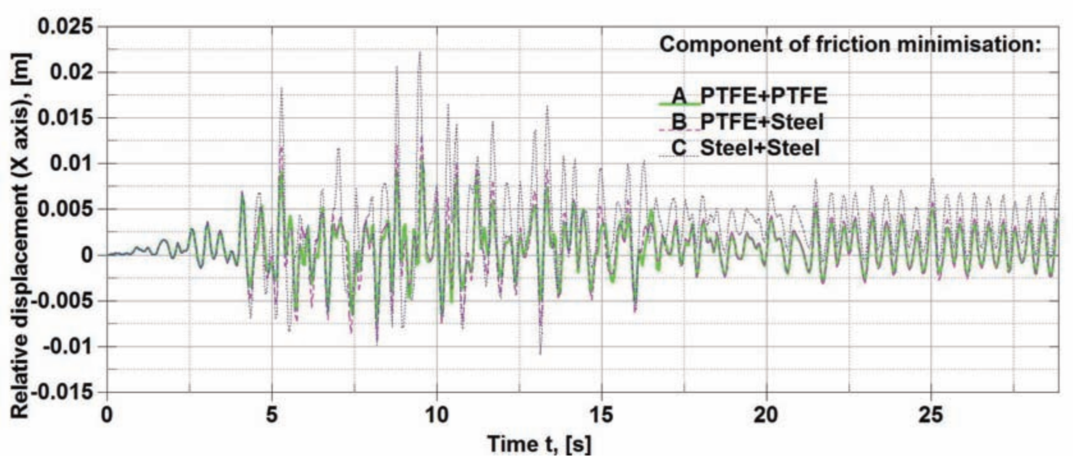


Figure 7. Displacement of the upper point of the building with respect to the soil base along the X-axis, [m]

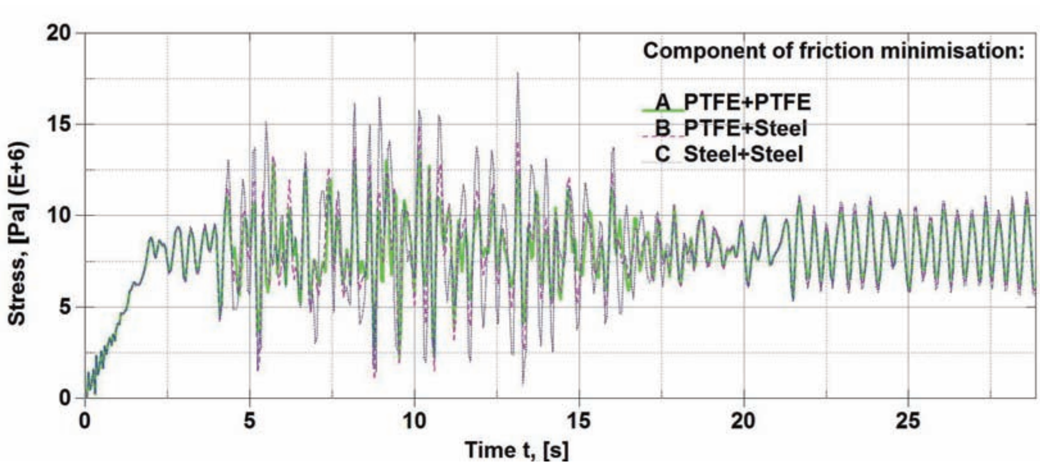


Figure 8. Stress intensity in the wall element (#160) of the 1st tier of the building, [Pa]

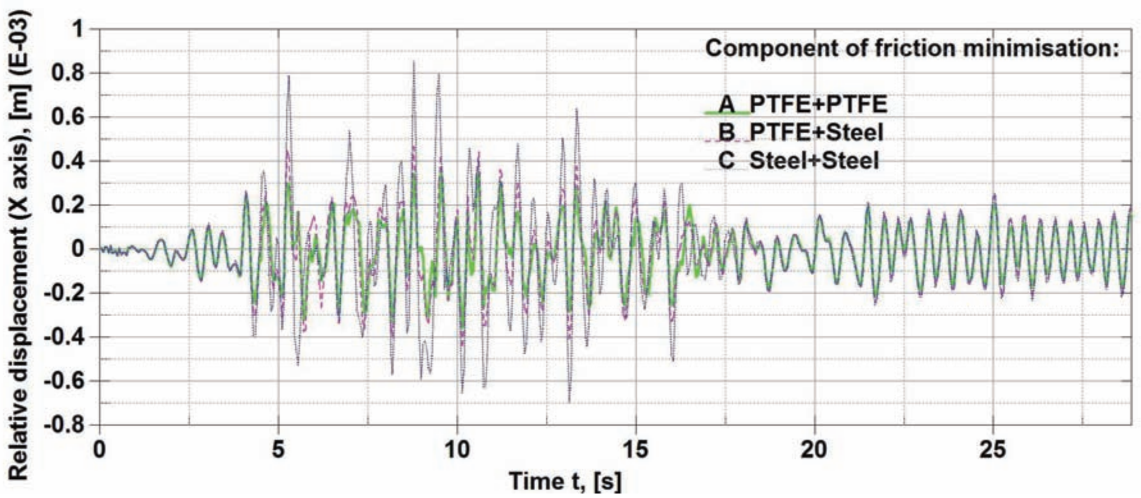
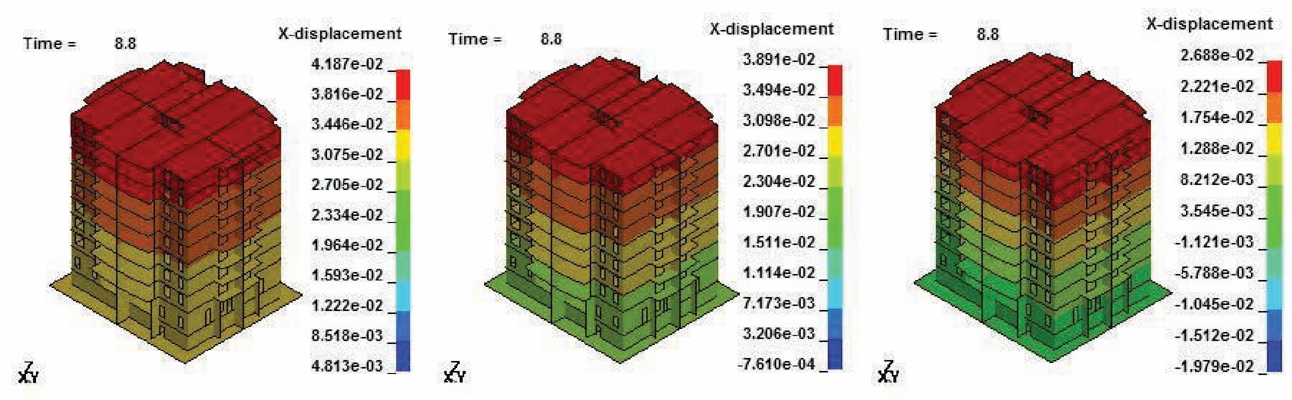
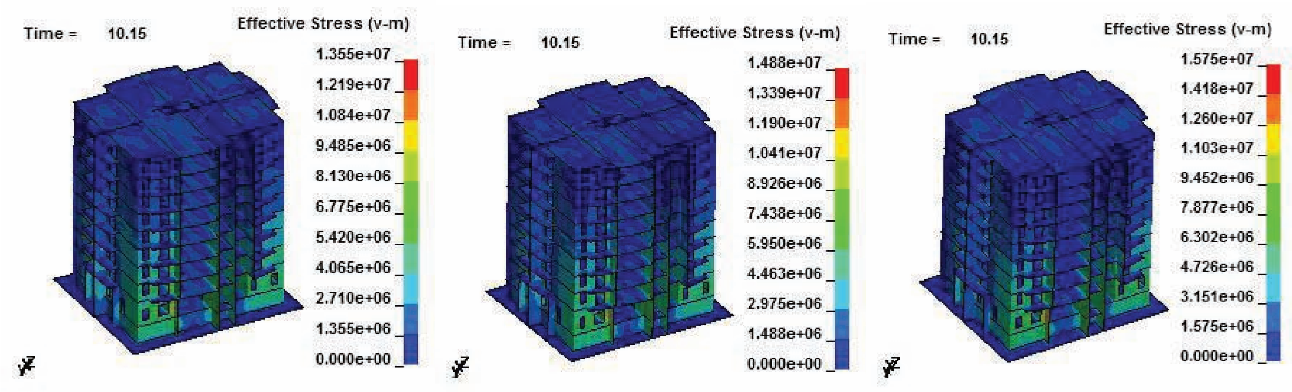


Figure 9. Displacement of the upper point of the 1st floor of the building with respect to the bottom of the building along the X axis, [m]



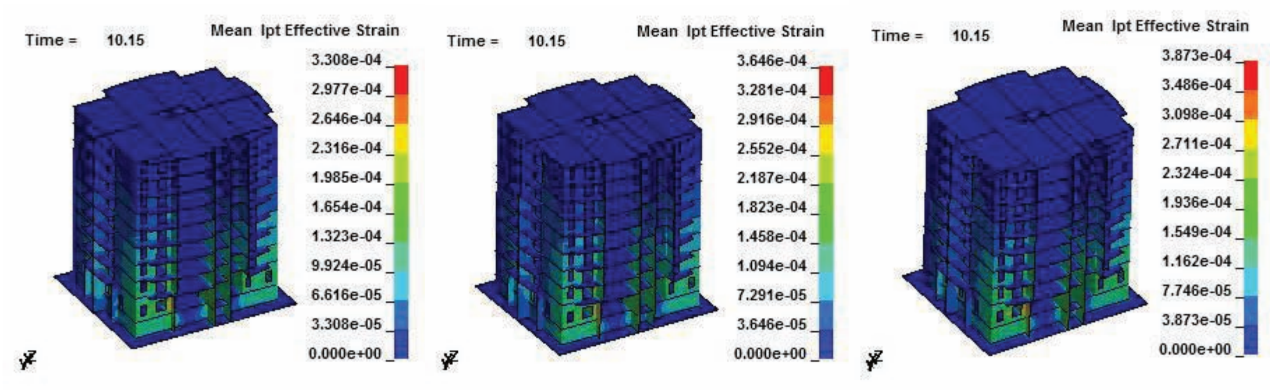
a) *b)* *c)*

Figure 10. Isopoles of displacements along the X-axis at the time t =8.8s: a) PTFE+PTFE; b) PTFE+Steel; c) Steel+Steel, [m]



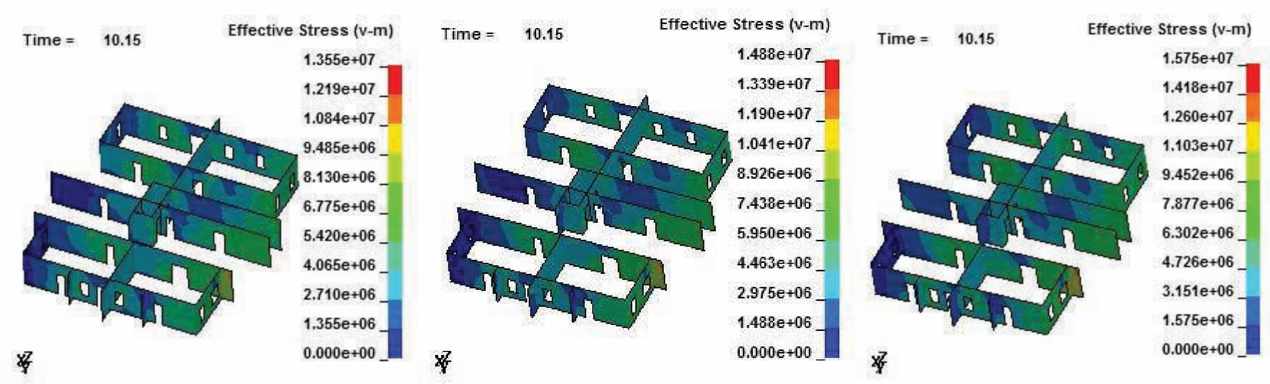
a) *b)* *c)*

Figure 11. Isopoles of stress intensity at time t =10.15s: a) PTFE+PTFE; b) PTFE+Steel; c) Steel+Steel, [Pa]



а) б) в)

Figure 12. Isopoles of strain intensity at time t =10.15s:
a) PTFE+PTFE; b) PTFE+Steel; c) Steel+Steel



а) б) в)

Figure 13. Isopoles of the stress intensity at time t = 10.15s
1st tier of the building: a) PTFE+PTFE; b) PTFE+Steel; c) Steel+Steel, [Pa]

Table 1. Main results of the study

	PTFE+PTFE	PTFE+Steel	Steel+ Steel
Relative displacement of the top of the building $\Delta u_{x.max}$, mm	10.30	13.00	22.20
Relative acceleration of the top of the building $a_{x.max}$, m/s^2	1.99	2.36	3.20
Stress in the wall element of the 1st floor of the building σ_{max}, (N/m^2)·10^7	1.35	1.49	1.78

CONCLUSIONS

The study provides evidence that the most effective component of friction minimization in a 9-story reinforced concrete monolithic building with seismic-insulating sliding belt at foundation level under earthquake conditions is PTFE+PTFE. Using PTFE+PTFE as the friction minimization component leads to the highest displacement (sliding) of the building (Fig.10), which in turn is accompanied by the lowest relative displacements. According to relative displacements diagram for the whole building (Fig.7) and the most loaded floor of the building

(Fig.9) it is evident that relative displacements under using PTFE+PTFE as friction minimization component are twice less than displacements under using Steel+Steel friction minimization component. The stress intensity diagram for the most loaded floor (Fig.8) and the isopoles of stress and strain intensity for the whole building and the most loaded floor (Figs.11-13) show that the least stresses and strains appear when sliding belt with PTFE plates is applied.

Fluoroplastic has a number of advantages. Its performance can withstand temperatures from -269 to +260°C. It does not absorb water, is chemically resistant to acids, alkalis and organic solvents, does not combust, is resistant to fungi and bacteria, does not age. The service life of the material exceeds 20 years, and is listed in the Guinness Book of Records as the most slippery material.

Research results show high efficiency of seismic protection in the form of a sliding belt at the foundation level with fluoroplastic plates when providing seismic resistance of buildings and structures. This type of seismic isolation allows to reduce considerably seismic loads on the above-ground part of the building structures, to increase the reliability of their operation during earthquakes and to reduce the material capacity and construction cost estimates. Unlike the popular RMS, seismic protection in the form of a sliding belt at the foundation level does not require factory production and can be made directly at the construction site. The simplicity of installation and maintenance of this seismic protection system also belongs to the number of advantages. The proposed approach of ensuring the seismic resistance of buildings and structures is practically acceptable and does not require substantial expenditures for anti-seismic measures.

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