

PERFORMANCE OF A HIGH-RISE REINFORCED CONCRETE BUILDING WITH A SLIDING BELT, TAKING INTO ACCOUNT THE NONLINEAR CHARACTER OF DEFORMATION

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Abstract

Introduction: The relevance of seismic isolation is driven by the need to improve the safety of buildings and structures in conditions of high seismic activity. Earthquakes pose a serious threat to human life and can result in significant economic and material losses. With the development of urbanization and increasing building density in earthquake-prone regions, there is growing demand for methods that effectively mitigate the destructive impact of seismic waves on structures. **Purpose of the study:** The study aims to analyze the performance of a high-rise reinforced concrete building with a sliding belt, taking into account the nonlinear nature of deformation. **Methods:** Calculations were performed using the LS-DYNA software through the direct dynamic method with explicit schemes for direct integration of the equations of motion, employing a nonlinear model of concrete and reinforcement. Foundation–structure interaction was modeled using the substructure method, while the nonlinear behavior of the soil foundation was described by the Mohr–Coulomb model. **Results and discussion:** The analysis shows a decrease in the effectiveness of seismic isolation in the form of a sliding belt at the foundation level of high-rise buildings. Considering all structural characteristics, it is possible to select optimal parameters for the seismic isolation sliding belt to effectively protect the building from seismic loads.

Keywords: seismic isolation, sliding belt, high-rise buildings, nonlinear behavior, soil foundation.

Introduction

Earthquakes are powerful natural phenomena that can cause extensive damage to buildings and infrastructure, as well as pose a serious threat to human life and safety. Ensuring the seismic resistance of buildings is therefore one of the key priorities of modern construction, particularly in regions with high seismic activity (Dzhinchvelashvili and Bulushev, 2014). To date, a variety of methods and technologies have been developed and implemented to improve the resistance of structures to seismic loads (Gorshkov and Kuznetsov, 2020). Among them, seismic isolation has become one of the most effective approaches (Pan et al., 2012; Uzdin et al., 2022). There are several types of seismic

isolation (Eisenberg, 2004). Rubber-metal bearings (RMBs) (Mkrtychev and Bunov, 2014) and pendulum sliding bearings (PSBs) (Figs. 1, 2) (Mkrtychev and Arutyunyan, 2016) have been extensively used

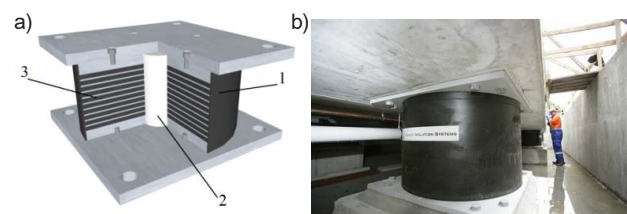


Fig. 1. RMB device (a): 1 — rubber; 2 — lead core; 3 — internal steel plates with rubber layers; Installation of an RMB at a construction site (b)



Fig. 2. PSB device (a): 1 — housing plate; 2 — articulated slider; 3 — sliding coating; 4 — concave plate; 5 — stainless steel concave surface; Installation of a PSB at a construction site (b)

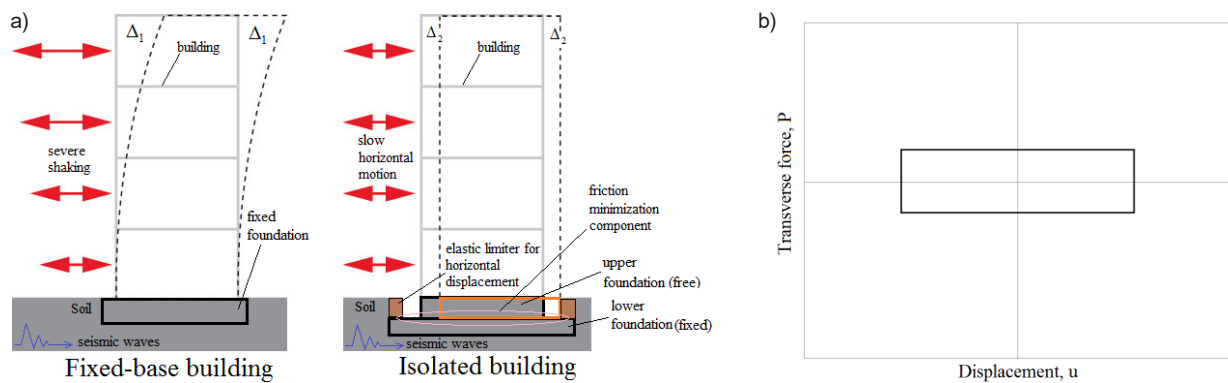


Fig. 3. Operating principle of the seismic isolation sliding belt at the foundation level (a); Functional scheme of the seismic isolation sliding belt (b)

in construction practice, which makes them the most widespread and sought-after solutions. In comparison, the sliding belt system, installed at the foundation level, represents a simpler seismic isolation solution than RMBs and PSBs (Kuznetsov and Chen, 2011). Its structural simplicity reduces both the installation time and the associated costs, which makes it an attractive alternative to more complex isolation devices.

The seismic isolation sliding belt consists of several key components, each performing a specific function to ensure effective protection of the structure from seismic impacts (Fig. 3). The primary elements are sliding supports, which enable the building to move freely in the horizontal plane relative to the foundation. These supports are made of low-friction materials, such as Teflon, to minimize friction between contact surfaces. In some designs, displacement limiters are incorporated to control excessive horizontal movements. Such limiters help regulate the amplitude of displacements and ensure that the building returns to its initial position after a seismic event (Mirzaev and Turdiev, 2021).

In the 1970s and 1980s, seismic protection in the form of an earthquake-isolating sliding belt became one of the research priorities in the USSR in the field of earthquake-resistant buildings and structures, as well as in experimental design and construction. The developed system was intended to reduce seismic loads on the superstructure of buildings. To evaluate the operability and effectiveness of the seismic isolation sliding belt, a wide range of experimental studies was carried out on seismic platforms. These included investigations of different material pairs for sliding elements, tests of elastic limiters made of spring steel, experimental studies of a nine-story building model with seismic isolation, and design developments for buildings of three, five, and nine stories. In addition, three-story buildings with a specially developed sliding belt construction technology were built in Frunze (Polyakov et al., 1989).

Seismic isolation in the form of a sliding belt at the foundation level is therefore relatively well established and has found practical application. However, currently, the design justifications for this type of seismic isolation remain incomplete, particularly with regard to the interaction of the building, the isolation system, the foundation, and the soil base. This gap continues to limit its broader implementation in modern construction practice.

Methods

The study examined the performance of a 24-storey monolithic reinforced concrete building with a seismic isolation sliding belt, considering the nonlinear nature of deformation under the action of an intense earthquake and accounting for the deformability of the soil base (Fig. 4).

The building employs a cross-wall structural system. The load-bearing elements are made

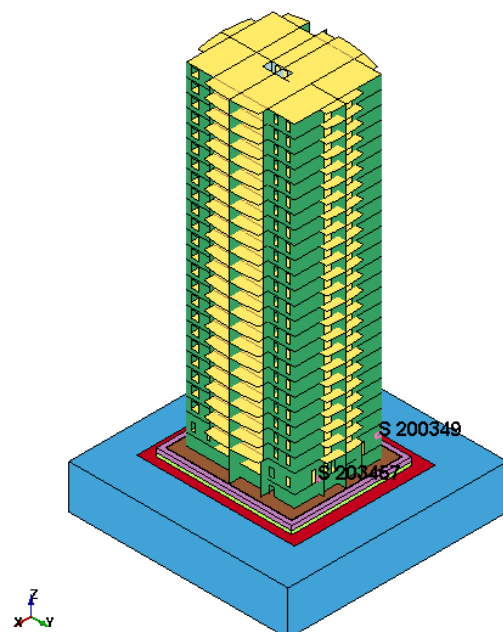


Fig. 4. Design scheme of a building with seismic isolation on a soil base

of concrete of class C20/25. The building dimensions in plan are 24.7×19.8 m, with a typical floor height of 3.0 m. Wall thicknesses are 0.20 and 0.25 m, while floor slabs are 0.22 m thick. Floor beams have a cross-section of 0.40×0.56 m.

The configuration of the seismic isolation sliding belt is shown in Fig. 5. Fluoroplastic plates (PTFE + PTFE) with friction coefficient $\mu_p = 0.05$ are used as friction-reducing elements.

The elastic limiter for large horizontal displacements is represented by sand ($\rho = 1,680 \text{ kg/m}^3$, $E = 100 \text{ MPa}$), placed along the perimeter of the upper foundation slab at a distance of 15 cm. The sand layer is assumed to have a height and width of 1.0 m. The coefficient of friction between concrete and sand is taken as $\mu_s = 0.3$.

A two-component accelerogram of the external seismic excitation, corresponding to an earthquake intensity of 9 points on the MSK-64 scale, is shown in Figs. 6 and 7.

The study was conducted using the LS-DYNA software package. The analysis employed the direct dynamic method with explicit schemes for direct integration of the equations of motion, incorporating a nonlinear model for concrete and reinforcement.

The interaction between the structure and the soil base was modeled using the substructure method (soil–structure interaction (SSI)) (Fig. 8) (Herrera and Bielak, 1997; LSTC, 2018; Mkrtychev et al., 2013).

Using this approach, the equations of motion in the time domain for the structure–soil system can be expressed as follows:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{m}_{ef} \cdot \ddot{\mathbf{u}}_f^0 + \mathbf{k}_{ef} \cdot \mathbf{u}_f^0, \quad (1)$$

where: $\mathbf{M}$ is the mass matrix of the entire system, including the structure, foundation, and soil:

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_{ss} & \mathbf{M}_{sb} & 0 \\ \mathbf{M}_{bs} & \mathbf{M}_{bb} + \mathbf{M}_{ff} & \mathbf{M}_{fe} \\ 0 & \mathbf{M}_{ef} & \mathbf{M}_{ee} \end{bmatrix}, \quad (2)$$

$\mathbf{C}$ is the damping matrix of the construction materials and the soil:

$$\mathbf{C} = \begin{bmatrix} \mathbf{C}_{ss} & \mathbf{C}_{sb} & 0 \\ \mathbf{C}_{bs} & \mathbf{C}_{bb} + \mathbf{C}_{ff} & \mathbf{C}_{fe} \\ 0 & \mathbf{C}_{ef} & \mathbf{C}_{ee} \end{bmatrix}, \quad (3)$$

$\mathbf{K}$ is the stiffness matrix of the system:

$$\mathbf{K} = \begin{bmatrix} \mathbf{K}_{ss} & \mathbf{K}_{sb} & 0 \\ \mathbf{K}_{bs} & \mathbf{K}_{bb} + \mathbf{K}_{ff} & \mathbf{K}_{fe} \\ 0 & \mathbf{K}_{ef} & \mathbf{K}_{ee} \end{bmatrix}, \quad (4)$$

$\mathbf{m}_{ef}$ is the auxiliary mass vector of the soil base:

$$\mathbf{m}_{ef} = \begin{bmatrix} 0 \\ \mathbf{m}_{ff} \\ \mathbf{m}_{ef} \end{bmatrix}, \quad (5)$$

$\mathbf{k}_{ef}$ is the auxiliary stiffness vector of the soil foundation:

$$\mathbf{k}_{ef} = \begin{bmatrix} 0 \\ \mathbf{k}_{ff} \\ \mathbf{k}_{ef} \end{bmatrix}, \quad (6)$$

$\mathbf{u}$ is the vector of relative displacements, and $\mathbf{u}_f, \ddot{\mathbf{u}}_f^0$ represent the external seismic excitation in the form of a seismogram and accelerogram.

The nonlinear behavior of the soil under intense seismic loading is described using the Mohr–Coulomb model (Mkrtychev and Busalova, 2014; Mkrtychev, Dzinchvelashvili and Busalova, 2014; Mkrtychev and Dudareva, 2018).

The soil base consists of medium-density sand (Table 1).

For numerical modeling, rod elements (672 FE), plate elements (36,596 FE), and volumetric finite elements (200,896 FE) were used.

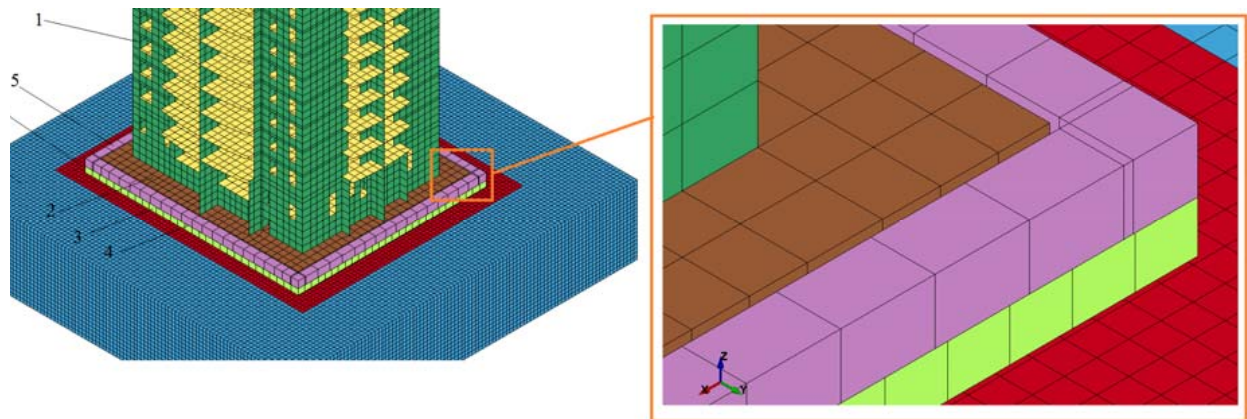


Fig. 5. Fragment of the design scheme of a building with a seismic isolation sliding belt: 1 — building; 2 — upper slab of the foundation; 3 — lower slab of the foundation; 4 — friction-reducing component; 5 — elastic limiter for horizontal displacements (sand); 6 — soil; 7 — soil with PML layer

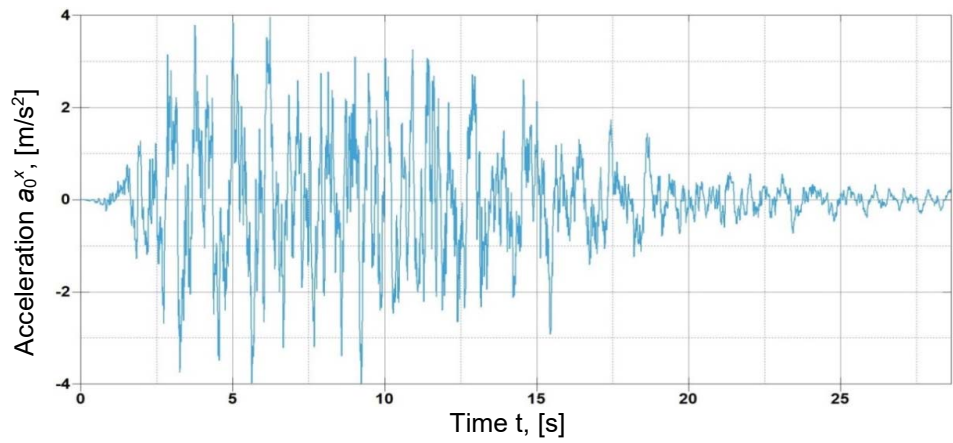


Fig. 6. Component of an earthquake's accelerogram along the X-axis for a 16-storey building

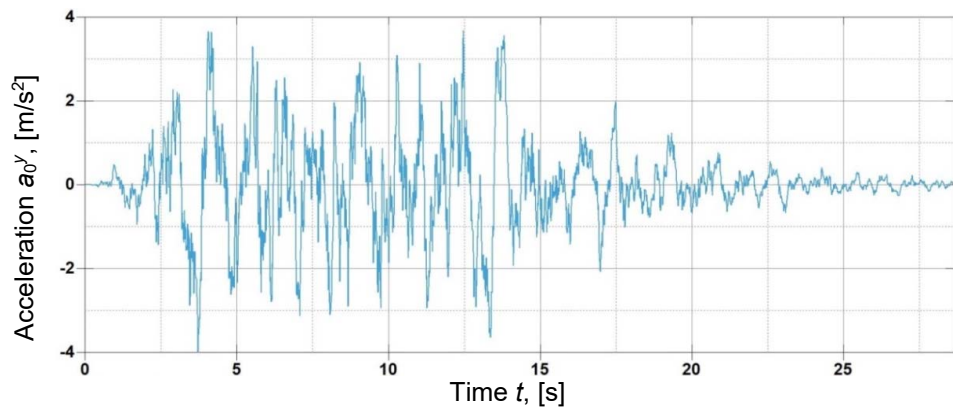


Fig. 7. Component of an earthquake's accelerogram along the Y-axis for a 16-storey building

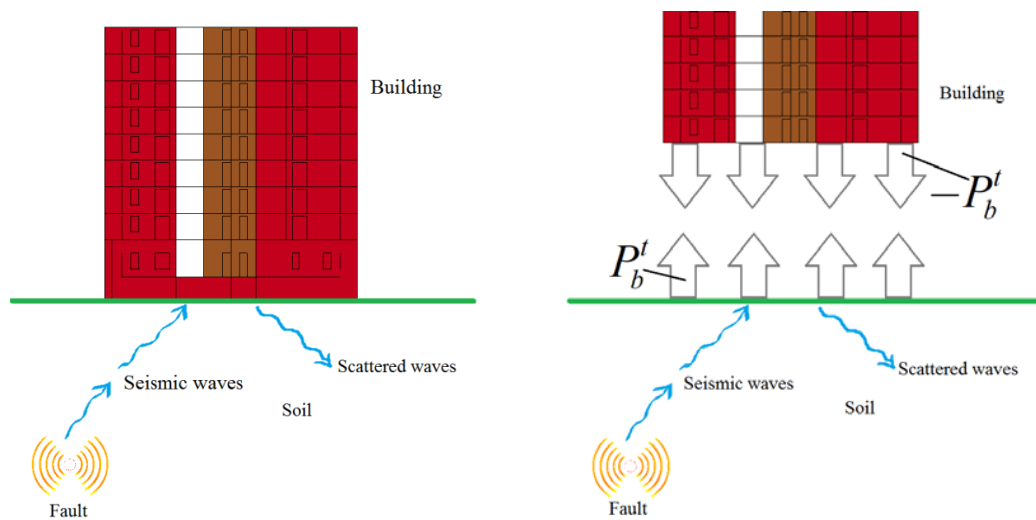


Fig. 8. Structure–soil system under seismic loading

Table 1. Physical and mechanical properties of the soil base

Medium-density sand				
Material density ρ , [kg/m ³]	Standard value of specific cohesion C_s , [kPa]	Internal friction angle γ_s , [°]	Modulus of deformation E , [MPa]	Poisson's ratio ν
1,600	2	38 (31)*	40 (320)*	0.3

* Note: Dynamic values are shown in parentheses.

Results

The calculation results are presented below.

Fig. 9 shows the intensity of plastic deformations in a wall element of the 1st floor of a building without and with seismic isolation.

Figs. 10 and 11 show isofields of the intensity of plastic deformations in a building without seismic isolation at specific moments in time.

Fig. 12 shows the intensity of plastic deformations in a wall element of the 1st floor of a building without and with seismic isolation.

Figs. 13 and 14 show isofields of the intensity of plastic deformations in a building without seismic isolation at specific moments in time.

Figs. 15 and 16 present the absolute displacement of the top point of the building along the X and Y axes, with and without seismic isolation.

The results of the study demonstrate the effectiveness of the seismic isolation sliding belt in protecting the building from external seismic

effects. From the graphs of the intensity of plastic deformations in the wall elements of the 1st floor (Figs. 9 and 12), it is evident that in the building without seismic isolation, structural damage begins after approximately six seconds of earthquake excitation, whereas in the building with seismic isolation, damage occurs after about ten seconds. When selecting a specific type of seismic protection, the parameters and structural features of the building must be considered. The analysis of the 24-storey building with seismic isolation in the form of a sliding belt at the foundation level indicates that the effectiveness of the sliding belt decreases as the number of stories increases. By accounting for all structural characteristics, it is possible to determine the optimal parameters for the seismic isolation belt to ensure adequate building protection during seismic events.

Acknowledgments

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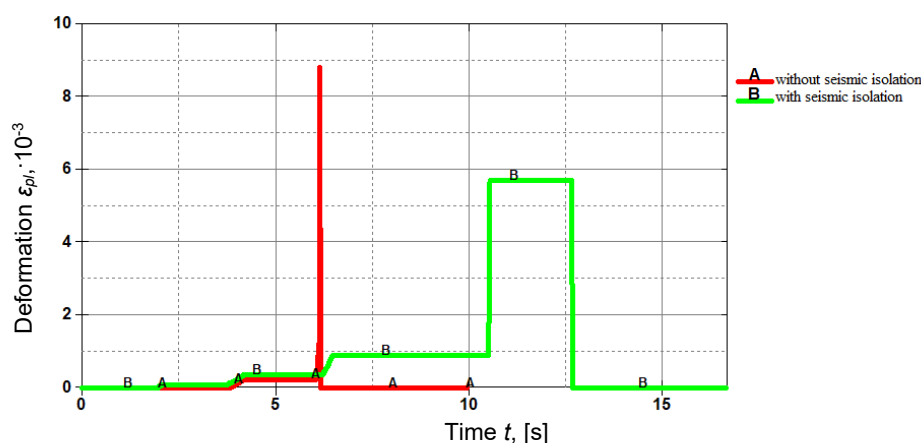


Fig. 9. Intensity of plastic deformations in wall element No. 200349 of the 1st floor of a building without and with seismic isolation

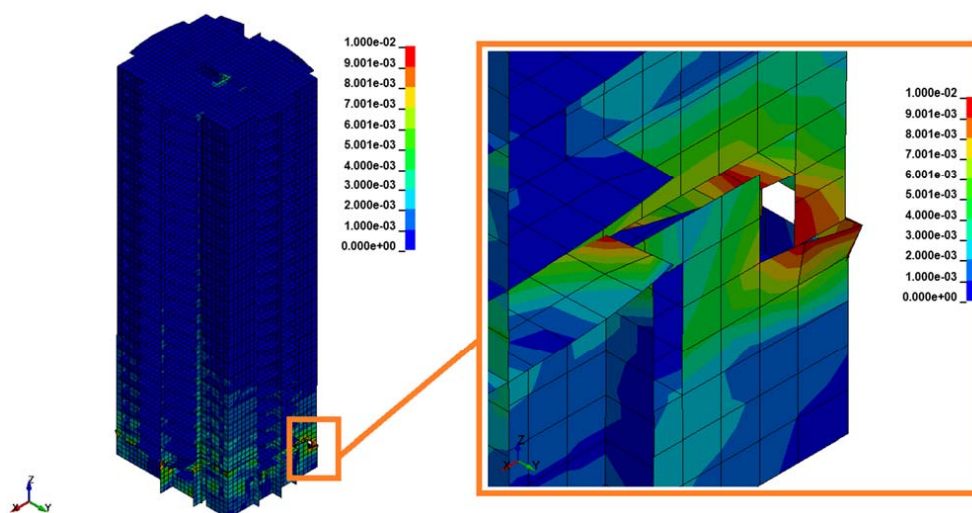


Fig. 10. Isofields of the intensity of plastic deformations in a building without seismic isolation at $t = 6.53$ s

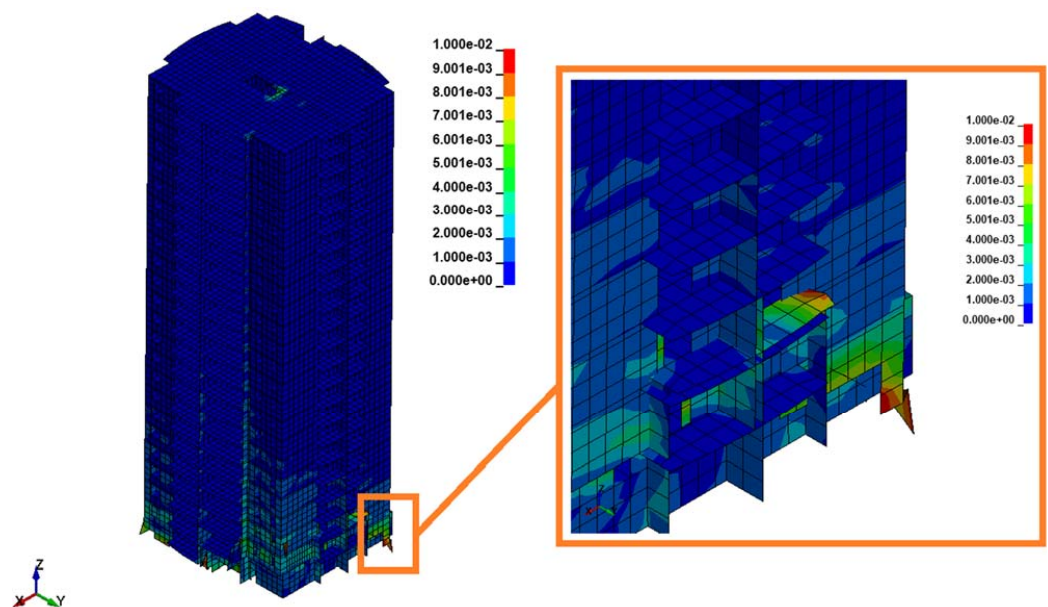


Fig. 11. Isofields of the intensity of plastic deformations in a building without seismic isolation at $t = 7.35$ s

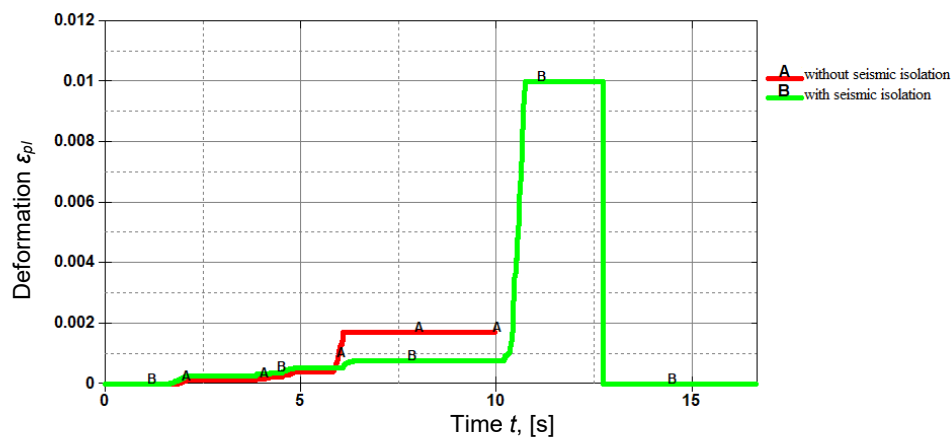


Fig. 12. Intensity of plastic deformations in wall element No. 203457 of the 1st floor of a building without and with seismic isolation

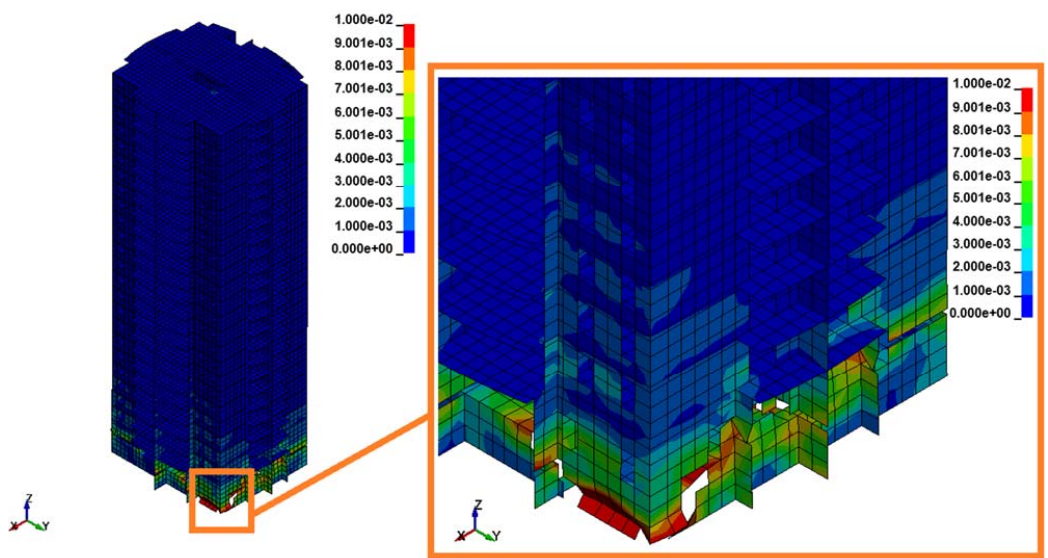


Fig. 13. Isofields of the intensity of plastic deformations in a building with seismic isolation at $t = 10.89$ s

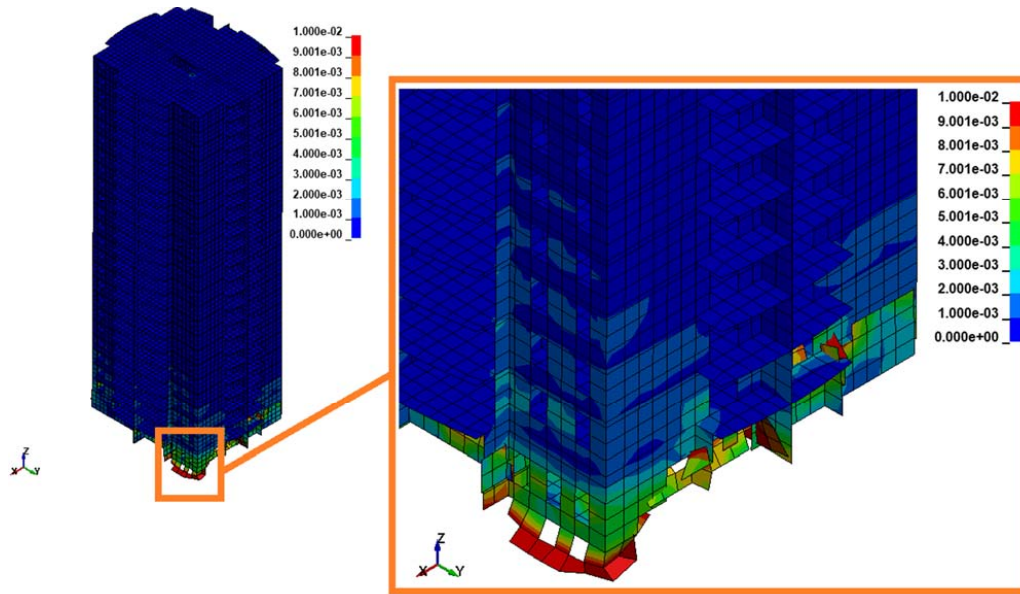


Fig. 14. Isofields of the intensity of plastic deformations in a building with seismic isolation at $t = 11.55$ s

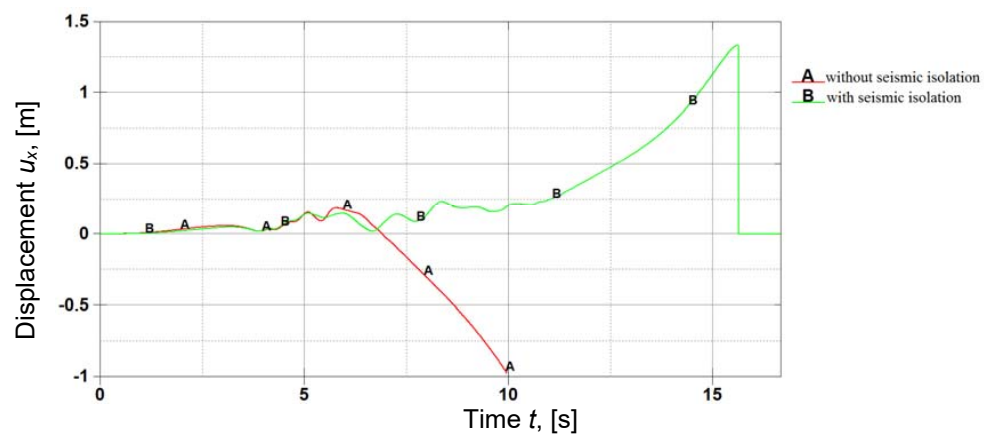


Fig. 15. Absolute displacement of the top point of the building along the X axis, [m]

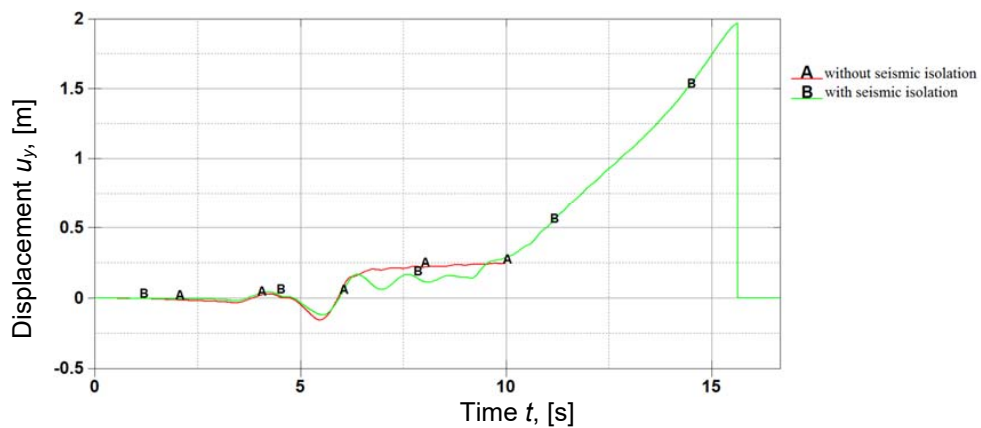


Fig. 16. Absolute displacement of the top point of the building along the Y axis, [m]

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РАБОТА ЖЕЛЕЗОБЕТОННОГО ЗДАНИЯ ПОВЫШЕННОЙ ЭТАЖНОСТИ СО СКОЛЬЗЯЩИМ ПОЯСОМ С УЧЕТОМ НЕЛИНЕЙНОГО ХАРАКТЕРА ДЕФОРМИРОВАНИЯ

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Аннотация

Введение: Актуальность применения сейсмоизоляции обусловлена необходимостью повышения безопасности зданий и сооружений в условиях высокой сейсмической активности. Землетрясения представляют серьезную угрозу для жизни людей, а также могут привести к значительным экономическим и материальным потерям. С развитием урбанизации и увеличением плотности застройки в сейсмоопасных регионах возрастает спрос на методы, которые эффективно снижают разрушительное воздействие сейсмических волн на здание. **Целью исследования** является анализ работы железобетонного здания повышенной этажности со скользящим поясом с учетом нелинейного характера деформирования. **Методы:** расчет выполнен в программном комплексе LS-DYNA прямым динамическим методом с явными схемами прямого интегрирования уравнений движения с использованием нелинейной модели бетона и арматуры; взаимодействие основания с сооружением задается методом субструктур, нелинейная работа грунтового основания описывается моделью Мора-Кулона. **Анализ результатов** показывает снижение эффективности работы сейсмоизоляции в виде скользящего пояса в уровне фундамента при повышенной этажности здания. С учетом всех характеристик здания можно подобрать наиболее подходящие параметры сейсмоизолирующего скользящего пояса, позволяющие эффективно защитить его от сейсмических нагрузок.

Ключевые слова: сейсмоизоляция, скользящий пояс, повышенная этажность, нелинейная работа, грунтовое основание.