# CHANGE OF AXIAL FORCES IN LAYERED RUBBER–STEEL BASE ISOLATORS OF HIGH-RISE BUILDINGS AT EARTHQUAKE IMPACT

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***Abstract:*** *Seismic isolation technology makes buildings more capable of withstanding earthquakes, protecting them from major damages or collapse. The same methods of analyses are not suitable for all types of buildings. The isolation system used Armenia, unlike foreign countries ones, cannot take any tension forces since the system doesn't have structural connections to superstructure and substructure of a building. The consequence of this fact can be the occurrence of additional stresses after the redistribution of axial forces in rubber base isolations in high-rise buildings during a seismic action. The stress-strain state analyses of rubber base seismic isolation systems in reinforced concrete dual frame-wall buildings with application of a finite element method carried out in the manuscript. An increase of the stresses during seismic action is discussed and investigated using both Fast-nonlinear time history analysis (FNTHA) and Direct-integration nonlinear time-history analysis (DINTHA). Analysis of the results of the study shows that the axial forces after their redistribution during horizontal earthquake loads in most seismic isolators of high-rise building do not exceed 8%, but for some isolators this difference varies within the range of 12-18%. Taking into account the vertical component, the difference does not exceed 20%, with the exception of three isolators, where it can reach up to 23%. An average increase of the compressive axial forces in the seismic isolation bearing systems of the tall building as a result of redistribution can be taken about 10%. In this case, the displacements and the axial forces of the seismic isolators during analysis of their bearing capacity must be considered simultaneously, but not separately from each other.*

***Keywords:*** *base isolation, high-rise building, earthquake, nonlinear analyses.*

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## Introduction

Safety issues are always primary in terms of priority in building science. Therefore, various technologies for reducing the risk of emergency situations are in the focus of researchers. Armenia is located in one of the highest seismic risk zones in the region and has experienced many strong earthquakes over the centuries. The latest huge one was Spitak earthquake in 1988 (M7.0), many buildings were destroyed. The territory of Armenia is divided into three seismic zones, in which ground acceleration can be achieved up to 0.3g, 0.4g and 0.5g respectively [1]. The use of various type of seismic isolation systems is one of the main directions for reduction of seismic risk. Therefore, after the Spitak earthquake, seismic isolation systems began to be used in Armenia.

Development of seismic isolation all over the world began in 1909 with the patent of Johannes Avetician Calantarients, a medical doctor from the northern English city of Scarborough. It was an early example of earthquake resistant design strategy known as base isolation or seismic isolation [2]. This marked the beginning for the implementation of seismic isolation systems throughout the world. A lot of mechanisms have been invented since 1909. Nowadays, different types of active and passive seismic isolation devices are used all over the world, such as: Laminated Natural Rubber Bearings (NRB), Laminated Lead Rubber Bearings (LRB), Laminated High Damping Rubber Bearings (HDRB), Rotating Ball Bearings (RRB), Slide Bearings (SB) with

High and Low Friction. Together with the seismic isolation systems, dampers are also used, such as: Hysteresis (Steel, Lead or other types) Dampers (HD) and Fluid (Viscous or Oil) Dampers (FD). Seismically isolated layered rubber-steel bearing devices are the main type of isolation system used in Armenia. (Fig.1), while synthetic (hot-vulcanized) rubber is used instead of natural rubber. Elastomeric isolators are made up of alternating layers of steel laminates and hot-vulcanized rubber, due to the type of rubber compound.

**Fig. 1.** *Layered rubber bearing seismic isolators used in Armenia [4]*

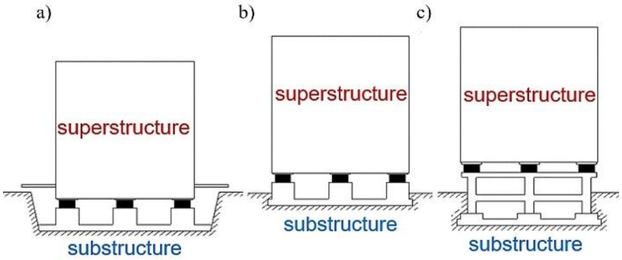

**Fig. 2.** *The main types of seismic base isolation system location*

In the Republic of Armenia, there are more than fifty (new and reconstructed) buildings with seismic base isolation. In terms of the number of buildings with seismic isolation, Armenia is ranked sixth globally, it lags behind Japan, China, Russia, Italy, the USA, and is ahead of France, Taiwan and New Zealand [3].

Due to the fact that only one type of seismic isolation support has been adopted as a standard in Armenia, seismic isolators in the buildings are located close to each other, in contrast to analogues in foreign countries, where the isolators are mainly located singly. The preliminary number of seismic supports is selected depending on the maximum allowable vertical load acting on a support. Seismic Isolation Laminated Rubber Steel Bearings (SILRSBs) are placed between the substructure (foundation or the several lower stories of the building) and the superstructure (part of the structure above the seismic isolation system) (Fig.2).

## Materials and Methods

In accordance with the Armenian earthquake resistant construction design codes the oscillation period of buildings with seismic isolation is determined depending on the total stiffness of the seismic isolation supports as a Single Degree of Freedom System (SDFS). The fundamental period of a natural oscillation of the building by the 2D or 3D Finite Element Method (FEM) shows that the value is greater than the same one obtained from the SDFS calculation.

This is associated with the influence of the fundamental period of natural oscillation of the superstructure, i.e. the first fundamental period of natural oscillation will be equal to the sum of ($T$) the fundamental period of natural oscillation of SILRSBs calculating as for SDFS and ($T_{sup1}$). The first fundamental period of natural oscillation of the superstructure is defined as for a free-standing and at the bottom fixed building:

$$T_{build1} = T + T_{\sup 1}\,, \tag{1}$$

The value of the free oscillation period $T$ for buildings and structures with seismic isolation systems with horizontal stiffness corresponding to the effective stiffness of the seismic isolators is determined by (2):

$$T = 2\pi \sqrt{\frac{Q}{K_{eff}\, g}}\,, \tag{2}$$

where $Q$ is the sum of the nominal gravity static loads (weight of the superstructure) taking into account short-term live load’s reduction factor, $K_{\mathrm{eff}}$ is the stiffness of the seismic isolation system, which is equal to the sum of effective stiffnesses of the seismic isolators that comprise the system, $g$ is the gravitational acceleration.

The design horizontal displacement of SILRSBs is determined by (3):

$$D = Agk_o \frac{\beta[T]}{\beta[\theta]}\left(\frac{T}{2\pi}\right)^2, \tag{3}$$

where the values of $k_0$ and $A$ are determined from [1], the coefficient $\beta$ [$T$] depends on the soil category of the foundation base, and the values of the coefficient $\beta$ [$\theta$] depending on the critical damping coefficient $\theta$ are given in Table 1, where intermediate values of $\theta$ and the value of $\beta$ [$\theta$] are determined by linear interpolation. The value of $\beta$ [$\theta$] in various building codes and standards are varies, while the highest values are taken in Japanese building codes[1].

According to the Earthquake resistance building codes of Armenia [1], seismic isolation is used for buildings and structures with a natural period of oscillation no more than 3.0 sec. At the same time, the natural period of the same system without seismic isolation (with regular foundation) has to be within 0.1 - 1.0 sec. Elastomeric isolators are very stiff in the vertical direction and can support the dead load with negligible creep effects during the whole life of the structure. Seismic isolators are flexible in the horizontal direction and have high vertical stiffness, and at the same time the damping is about 10 - 15%. The shear modulus G ranges from 0.4 to 1.4 MPa.

By the structural concepts, according to [1], two types of seismic isolation systems are used. The first type is the system located below the level of the pavement around the building, and second type is the system located above the level of the pavement but not higher that second-story level of building. The choice of the seismic isolation type is determined by subsoil conditions and the functional purpose of the building.

The analyses of buildings and structures with seismic isolation systems are carried out by two methods: according to design response spectra [1] or by earthquake response spectra compiled on the basis of recorded or synthetic accelerograms generated for the specific construction site. The design forces should be taken as the least favorable of the two analyses mentioned. The preliminary number of SILRSBs was calculated based on response spectral analysis, providing all the conditions specified in the building codes of Armenia. At the second stage, a time history nonlinear analysis is considered, and the change in axial forces in SILRSBs is estimated, taking into account the vertical component of the earthquake load as well as the lack of seismic isolators' work under axial tension forces.

According to the main geometrical and physical-mechanical parameters of SILRSB are presented below:

- number of rubber layers ($n$ = 14),
- number of internal steel plates (13),
- external diameter (D = 2R = 380 ± 2.0 mm),
- internal diameter – central hole (19 ± 1.0 mm),
- height (202.5 ± 2.5 mm),
- thickness of the rubber layers ($t_r$ = 9.0 ± 0.1 mm),
- diameter of the steel shim plates (360 ± 0.5 mm),
- thickness of the steel shim plates (2.5 ± 1.0 mm),
- external diameter of flanges (376 ± 0.5 mm),
- thickness of flanges (20.0 ± 0.2 mm),
- thickness of flanges' cover layer (2.0 ± 0.1 mm),
- mass of the SILRSB (W=77.5 ± 2.5 kg),
- shear modulus ($G$ = 0.97 ± 0.15 N/mm$^2$),
- vertical stiffness ($K_{eff,v}$ = 300 kN/mm),

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[1] The Building Standard Law of Japan, 2016. https://www.bcj.or.jp/en/services/publication/

- effective stiffness ($K_{eff} = 0.95$ kN/mm),
- horizontal stiffness ($K_d = 0.81 \pm 0.1$ kN/mm),
- elastic stiffness ($K_e = 2.95$ kN/mm),
- maximal displacement ($D_{max} = 280$ mm),
- maximal allowable vertical force ($P_{max} = 1500$ kN),
- yield force ($F_y = 56$ kN),
- equivalent viscous dumping ($\beta_{eff} = 10$ %).

There are two main parameters that characterize seismic isolators. The first one is $S_1$ - Primary Shape Factor (PSF), which mainly characterizes the vertical stiffness of the seismic isolator and the bending stiffness, and the second one is $S_2$ - Secondary Shape Factor (SSF), which characterizes the horizontal stiffness of the seismic isolator and the bending stiffness[2]. Most of the seismic isolators (SILRSB) have a cylindrical shape. In Armenia just only cylindrical seismic isolators are used in the buildings.

SILRSB, used in Armenia, has the following characteristics: $R = 190$ mm, $n\,t_r = 14 \times 9 = 126$ mm, $t_r = 9.0$ mm. As a result, we have the following main parameters:

$$S_1 = \frac{0.5R}{t_r} = 10.6, \; S_2 = \frac{2R}{nt_r} = 3.0. \qquad (4)$$

PSF increases as the rubber layer is thin, SSF indicates the degree of flatness of the laminated rubber bearing. For the design of buildings and structures with seismic isolation, it is necessary to know the force-displacement relationship (Fig.3) and various physical-mechanical parameters of seismic isolators (SILRSB).

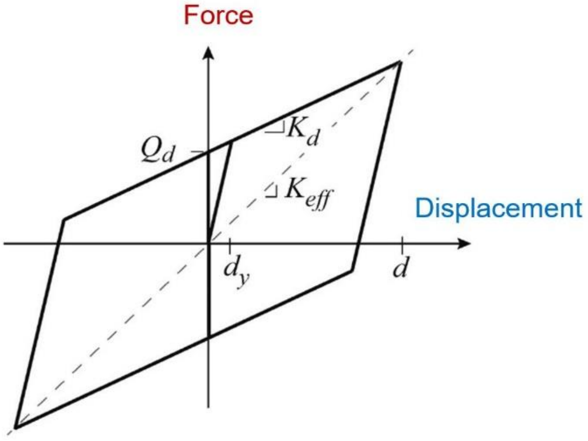

**Fig. 3.** *Force-displacement relationship of the SILRSB*

The buckling analysis of a seismic isolator is based on a linear theory [5] that is similar to the longitudinal bending analysis of a column and, as in conventional theory, provides a longitudinal bending load or stress when it is buckling in an undeformed position. This is of crucial importance in the structure of the seismic isolator, since the maximum compressive load on it will occur simultaneously with the maximum horizontal displacement, and in combination, this will be one of the limit states for which it will need to be calculated.

Complex nonlinear analysis is needed to study the behavior of a seismic isolator under the combination of a vertical axial load and maximum horizontal displacement. There are two hypotheses [6] for approaching the limit state of an isolator when it is simultaneously subjected to a vertical load and a horizontal force.

The first hypothesis is that the critical displacement, defined as the displacement at which the isolator exhibits zero increasing horizontal stiffness, is the lateral displacement at which the compressive stresses of the reduced zone are determined from the ratio of the vertical force to the area $A_r$ (Fig.4). $A_r$ is the overlapping sectional area of the top and the bottom of the seismic isolator, and $\theta$ is a half of the angle located between the extreme points of the area $A_r$.

The second hypothesis is that the area $A_r$ is replaced by $0.5A \times A_r$. This option is more reliable because the concentration of vertical stress caused by displacement will not affect the bending stiffness, but may reduce the shear stiffness [6].

In all cases, the maximum compressive stresses in this section can increase up to $P_{cr}$ (Fig.5). Both hypotheses for the supports are considered in the work. Calculations were carried out on the basis of both hypotheses [6] for seismic isolators used in Armenia[3].

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[2] How to Plan and Implement Seismic Isolation for Buildings, The Japan Society of Seismic Isolation, 2005.

[3] AST 261-2007, Seismic Isolation Laminated Rubber Steel Bearing. Specification, Yerevan, 2007. https://www.armstandard.am/en/standart/1673.

The ratio of the values $P$ and $P_{cr}$ for an isolator having a circular cross section, according to the first hypothesis [6], is equal to

$$\frac{P}{P_{cr}}=\frac{2}{\pi}\left(\frac{\pi}{180}\arccos\frac{D}{2R}-\frac{D}{2R}\sin\left(\arccos\frac{D}{2R}\right)\right). \tag{5}$$

The ratio of $P$ and $P_{cr}$ for the same isolator, according to the second hypothesis [6], is equal to

$$\frac{P}{P_{cr}}=\sqrt{\frac{2}{\pi}}\cdot\sqrt{\frac{\pi}{180}\arccos\frac{D}{2R}-\frac{D}{2R}\sin\left(\arccos\frac{D}{2R}\right)}. \tag{6}$$

Assuming a linear relationship, the ratio of $P$ and $P_{cr}$ will be equal to

$$\frac{P}{P_{cr}}=1-\frac{D}{D_{cr}}, \tag{7}$$

where:

$$P_{cr}=\frac{\pi^2R^3}{2nt_r}\sqrt{\frac{GE_c}{3}}=\frac{3.14^2\times0.19^3}{2\times9\times0.014}\sqrt{\frac{970\times4\times10^5}{3}}=3055\text{ kN}, \tag{8}$$

in this case, the following condition is satisfied:

$$S=\sqrt{\frac{E_c}{6G}}=\sqrt{\frac{4\cdot10^5}{6\times970}}=8.3>5. \tag{9}$$

The results of the calculations, depending on the angle $\theta$ in the range from 0 to 900 and the displacement $D$, are shown in Figure 5.

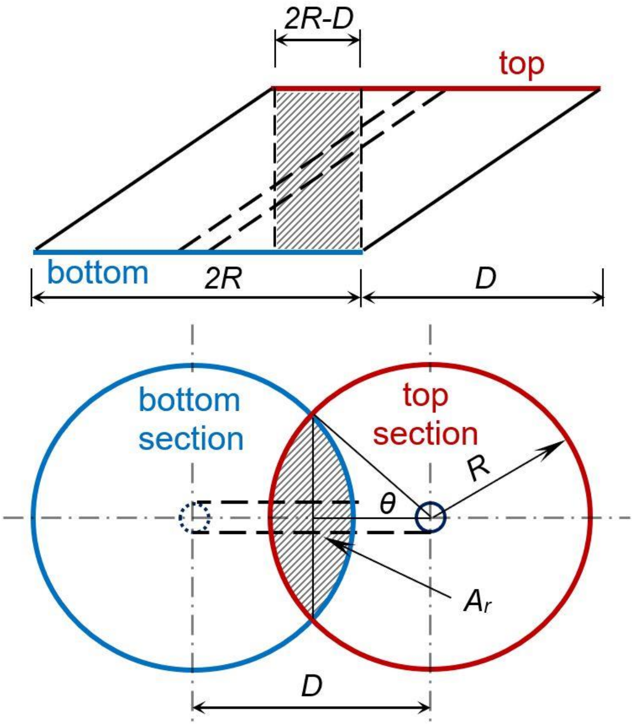

**Fig. 4.** *Overlapping sectional area of the top and bottom sections of the SILRSB at displacement D*

Analyzing the obtained data, it should be noted that seismic isolators have various permissible values of horizontal displacements at different vertical axial loads, that is, limiting horizontal displacement, the corresponding allowable value for the vertical axial load must be specified. The seismic isolator used in the Republic of Armenia based on second hypothesis, with a maximum allowable vertical load of 1500 kN[4], has a 244 mm horizontal displacement when the isolator remains stable (Fig.5). However, with a displacement of 280 mm, the vertical load should not exceed 1200 kN, thus, according to calculations, the loss of stability of the isolator according to both hypotheses occurs at different displacements. For base isolators with axial forces less than *0.2* $P_{cr}$, the use of isolators is assessed as ineffective, and for axial forces more than *0.8* $P_{cr}$, problems arise related to the reliability of the isolators. These conditional limits are ensuring both the reliability and efficiency for usage of base isolation [7].

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[4] AST 261-2007, Seismic Isolation Laminated Rubber Steel Bearing. Specification, Yerevan, 2007. https://www.armstandard.am/en/standart/1673

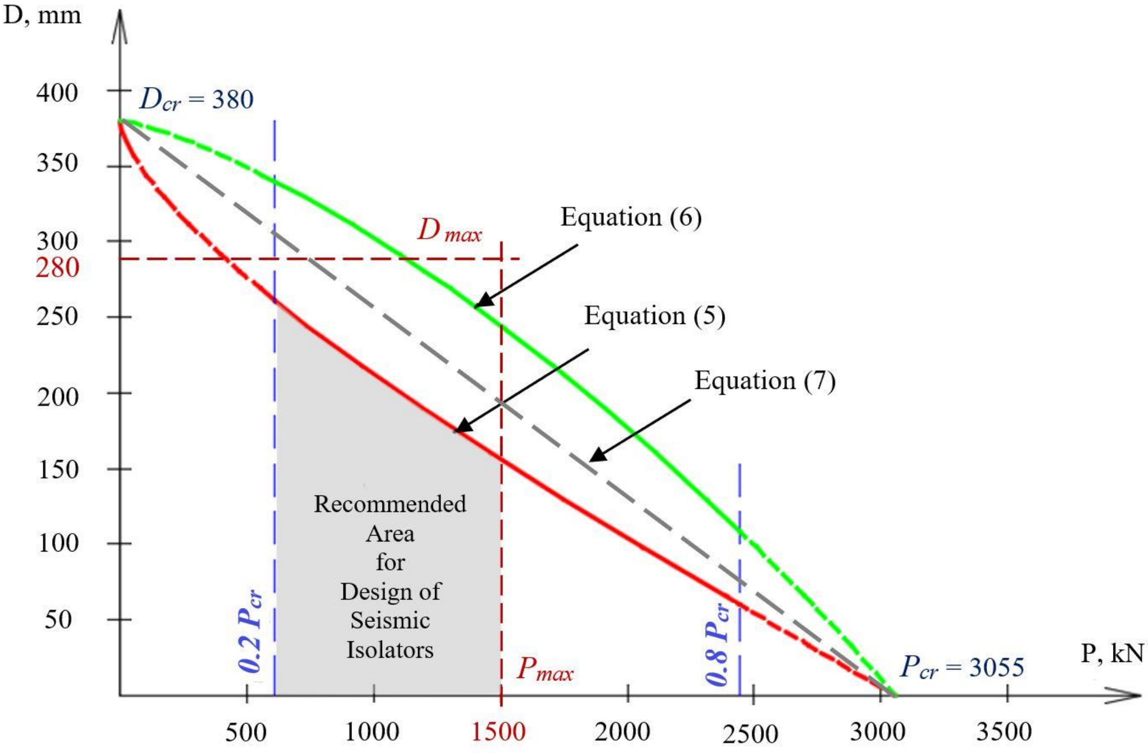

**Fig. 5.** *Dependence of the maximum displacement of the seismic isolator used in the Republic of Armenia on the vertical force*

16-storey reinforced-concrete frame-shear wall building (Figs.6,7,8) with SILRSB seismic isolation systems calculated under seismic action is considered in the work. The distribution of columns and shear walls is symmetrical according to the main axes (longitudinal X and transverse Y). A quantity of seismic isolators (206 isolators) (Fig.8) was determined from the two main conditions that the maximal horizontal displacement at the top of the isolator will be less than 280 mm and the maximal vertical design load will be less than 1500 kN. Different options of seismic isolators are considered in the manuscript: the first problem with base isolators supporting in the vertical direction (Z), both compressive and tensile forces are assumed, and the second problem, carried out by isolators in the vertical direction (Z), takes only compressive forces.

The story height for the building was unchangeable and equal to 3.0 m, the thickness of the slabs and the cross section of square columns were equal to 16 cm and 50×50 cm, respectively. The thickness of shear walls of superstructure is equal to 16 cm. Sections of the girders are different: 550x550 and 500x560 mm. All loads are assumed by the building codes. Concrete type B25[5] was used for analysis: the cube strength of concrete is 25 MPa, and the modulus of elasticity is equal to 30000 MPa. All calculations have been carried out with the implementation of both fast nonlinear time history analyses and nonlinear time history analyses with direct integration. At the same time, the Spitak earthquake accelerograms recorded in Gukasyan were used.

Maximum values of acceleration were increased to 0.4g in the horizontal direction (for the accelerogram in direction Y, Fig.9) and to 0.28g in the vertical direction (for the accelerogram in direction Z) (Fig.10). Structural FEM analysis of a three-dimensional model of the building with frame and shell elements are used in the manuscript (Figs.6,7).

The first fundamental natural period of vibration of the building in Y direction is equal 2.09 sec. The height and number of stores of the building were taken from the condition that the first fundamental natural oscillation period of the superstructure without seismic isolation would not exceed 1.0 sec. For assessing the change of forces in the base isolators during seismic action, SILRSBs located along axes 3 (Fig.11) and 4 (Fig.12) are considered.

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[5] RABC 52-01-2021 Concrete and Reinforced Concrete. Building Codes of Armenia, 2021.

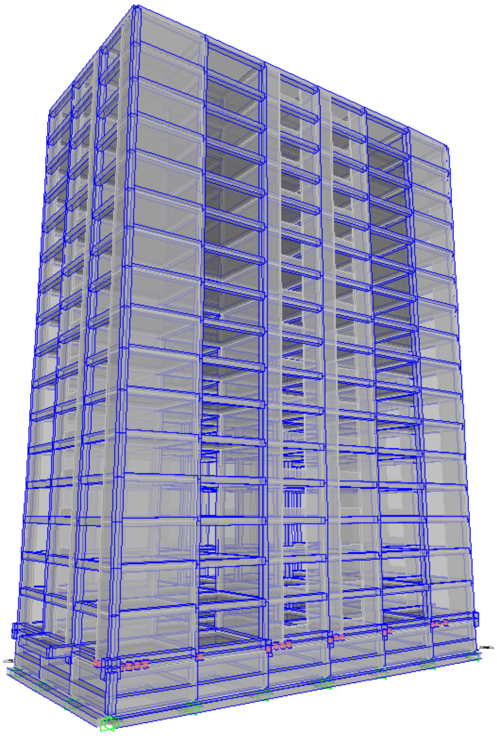

**Fig. 6.** *3D view of a building (three-dimensional model)*

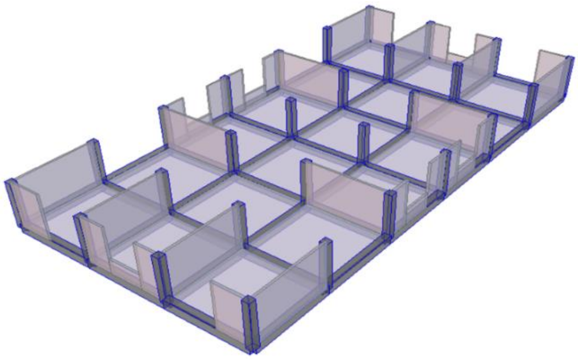

**Fig. 7.** *3D view of a bearing system: columns and shear walls*

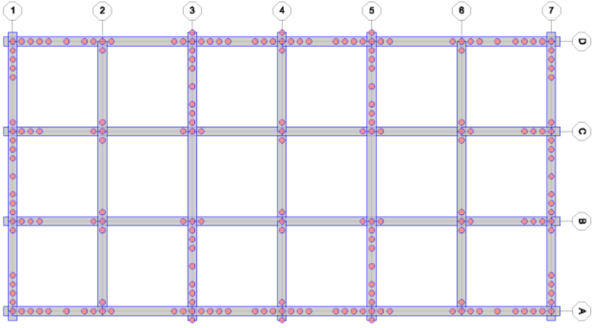

**Fig. 8.** *location of SILRSBs (206 base isolators)*

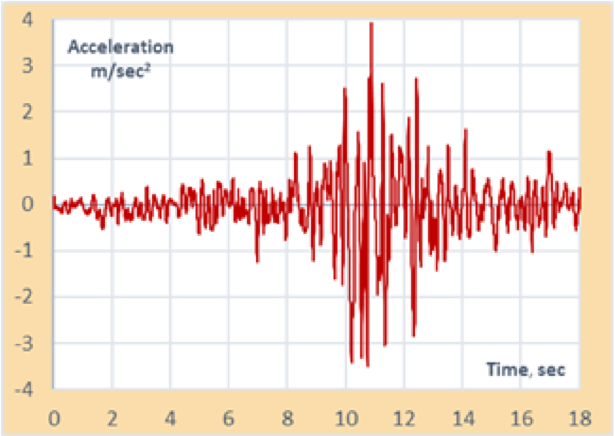

**Fig. 9.** *Horizontal record (Gukas Y)*

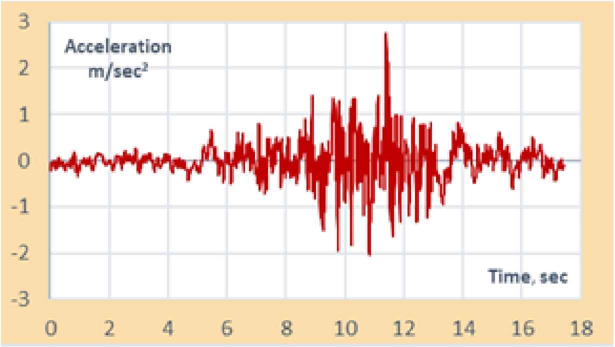

**Fig. 10.** *Vertical record (Gukas Z)*

The main peculiarity of the work is an investigation of "tensile forces" in the base isolators of high-rise buildings at seismic impact. A comparative analysis of two different models was carried out since seismic isolators used in Armenia do not work on tension. The seismic isolators in the first model are considered ordinary finite elements of seismic isolation (Link) that are accepted in SAP2000.

The seismic isolation system in the second model was described by nonlinear elements operating only on compression. A comparison analysis of seismic isolators from 1 to 21 is considered in the work (Figs.11,12).

Calculations were performed by SAP2000 software, where the effect of increasing stresses during seismic action was investigated with the best known time history nonlinear analysis methods: FNTHA (Fast nonlinear time history analysis) and DINTHA (Direct-integration nonlinear time history analysis) [8,9]. At the same time, two possible combinations were considered in the manuscript. One of them is static (dead load, short - term and long-term live loads) and earthquake load in the horizontal direction (Y axis), and second combination is the same as the first one in addition with earthquake load in the vertical direction (Z axis).

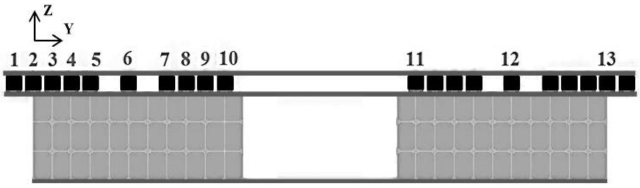

**Fig. 11.** *Location of SILRSBs along axis 3*

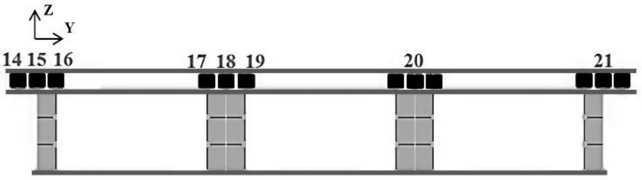

**Fig. 12.** *Location of SILRSBs along axis 4*

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## Results and Discussion

The results of the calculation using the FNTHA and DINTHA methods are presented in Tables 2 and 3. Time history analysis for some SILRSBs is presented (Figs.13,14,15).

The change in forces and displacements in seismic isolators during seismic action shows that the horizontal displacements of seismic isolators, taking into account the vertical component of the seismic load, are insignificant. At the same time, the vertical seismic load has a significant effect on the change in the vertical force in the seismic isolator (Table 2). Comparative analysis of the axial forces in seismic isolators shows that the vertical component of the seismic load (Component Z) increases the axial force from 5 to 35%, while this value depends on the location of the isolator in the plan of the building and on the other seismic isolators located close to it. The vertical component of the seismic force significantly affects the seismic isolators located in the central part of the building (see SILRSB number 10 or 20) (Figs.13,14,15), while for isolators located at the edge and corner of the buildings, the effect is not huge enough (see SILRSB number 2) (Figs.13,14,15).

The analysis of the results of a high-rise building showed that the value of axial forces in SILRSBs according to FNA, in comparison with the direct-integration method, turned out to be greater. For example, the maximal vertical force in the seismic isolator, which can take only compression, with the DINTHA method was 1476 kN, while with the FNTHA method it was 1861 kN. Some results of fast-nonlinear analysis do not provide the bearing capacity of the seismic isolator (according to the Armenian standard on SILRSB[6], the values of axial force must not exceed the ultimate value, which is equal to 1500 kN, it is the standard value from the manufacturer). In the case of DINTHA, the maximal compressive axial forces in all isolators do not exceed 1500 kN. It should be mentioned that even if some results of FNTHA don't satisfy the ultimate value of axial force, the seismic isolator can be acceptable (Fig.5), provided that the displacements of the seismic isolators are not very large and located below the line (7) – the maximum permissible values.

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[6] AST 261-2007, Seismic Isolation Laminated Rubber Steel Bearing. Specification, Yerevan, 2007. https://www.armstandard.am/en/standart/1673

**Table 1.** The values of the coefficient $\beta$ [$\theta$] depending on the critical damping coefficient

| Reference | Critical damping, % | | | | |
|---|---|---|---|---|---|
| RABC 20-04-2020 [1] | 5 | 7 | 10 | 15 | 20 |
| ASCE 7-22[7] | 1.00 | 1.10 | 1.30 | 1.60 | 1.70 |
| Eurocode 8[8] | 1.00 | 1.08 | 1.20 | 1.35 | 1.50 |
| The Building Standard Law of Japan 2016[9] | 1.00 | 1.09 | 1.22 | 1.41 | 1.58 |
| Earthquake Spectra and Design[10] [10] | 1.00 | 1.13 | 1.33 | 1.66 | 2.00 |

**Table 2.** The values of Maximum Axial Compression Forces in the SILRSBs by Gukas Y and Gukas Z records depending on types of nonlinear analyses, finite elements of seismic isolation and directions of earthquake loads

| Seismic isolator by Figure 8 | Seismic isolators (finite elements) can take both tension and compression | | | | Seismic isolators (finite elements) can take only compression | | | |
|---|---|---|---|---|---|---|---|---|
| | Fast nonlinear time history analysis by records | | Direct-integration nonlinear time history analysis by records | | Fast nonlinear time history analysis by records | | Direct-integration nonlinear time history analysis by records | |
| | Gukas Y | Gukas Y and Gukas Z | Gukas Y | Gukas Y and Gukas Z | Gukas Y | Gukas Y and Gukas Z | Gukas Y | Gukas Y and Gukas Z |
| | kN | kN | kN | kN | kN | kN | kN | kN |
| 1 | 950.1 | 1028.0 | 920.5 | 970.9 | 1005.0 | 1114.0 | 933.4 | 987.2 |
| 2 | 1098.0 | 1197.0 | 1067.0 | 1130.0 | 1149.0 | 1297.0 | 1081.0 | 1147.0 |
| 3 | 1030.0 | 1134.0 | 1004.0 | 1068.0 | 1077.0 | 1228.0 | 1016.0 | 1083.0 |
| 4 | 937.6 | 1057.0 | 917.6 | 982.5 | 985.1 | 1131.0 | 931.8 | 993.6 |
| 5 | 880.6 | 1004.0 | 861.2 | 916.4 | 913.8 | 1056.0 | 872.5 | 924.0 |
| 6 | 775.6 | 950.9 | 756.1 | 870.1 | 776.4 | 1013.0 | 758.1 | 870.4 |
| 7 | 866.2 | 1059.0 | 851.5 | 960.6 | 871.4 | 1214.0 | 861.2 | 962.5 |
| 8 | 964.4 | 1173.0 | 953.9 | 1025.0 | 970.2 | 1343.0 | 963.2 | 1028.0 |
| 9 | 1098.0 | 1320.0 | 1086.0 | 1162.0 | 1107.0 | 1512.0 | 1097.0 | 1165.8 |
| 10 | 1237.0 | 1478.0 | 1222.0 | 1305.0 | 1252.0 | 1691.0 | 1234.7 | 1311.0 |
| 11 | 1118.0 | 1225.0 | 1094.0 | 1167.0 | 1138.0 | 1341.0 | 1109.0 | 1184.0 |
| 12 | 769.4 | 983.5 | 757.0 | 860.2 | 784.4 | 1002.0 | 758.0 | 859.4 |
| 13 | 1297.0 | 1510.0 | 1254.0 | 1345.0 | 1327.0 | 1538.0 | 1262.0 | 1353.0 |
| 14 | 896.0 | 947.7 | 854.6 | 846.0 | 958.0 | 995.4 | 871.1 | 860.2 |
| 15 | 1050.0 | 1130.0 | 1004.0 | 1038.0 | 1103.0 | 1193.0 | 1024.0 | 1051.0 |
| 16 | 998.0 | 1090.0 | 953.7 | 1019.0 | 1029.0 | 1173.0 | 972.1 | 1031.0 |
| 17 | 1103.0 | 1626.0 | 1096.0 | 1357.0 | 1120.0 | 1704.0 | 1100.0 | 1358.0 |
| 18 | 1183.0 | 1790.0 | 1179.0 | 1476.0 | 1198.0 | 1861.0 | 1180.6 | 1476.0 |
| 19 | 1080.0 | 1649.0 | 1076.0 | 1350.0 | 1089.0 | 1699.0 | 1077.0 | 1350.0 |
| 20 | 1166.0 | 1644.0 | 1161.0 | 1397.0 | 1166.0 | 1745.0 | 1164.0 | 1397.0 |
| 21 | 1189.0 | 1404.0 | 1152.0 | 1241.0 | 1214.0 | 1422.0 | 1160.0 | 1249.0 |

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[7] ASCE/SEI 7-22, Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE, 2022.

[8] EN 1998-1:2004, Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, BSI, 2004.

[9] The Building Standard Law of Japan, 2016. https://www.bcj.or.jp/en/services/publication/

[10] Damping in response-spectrum analysis. https://wiki.csiamerica.com/display/kb/Damping+in+response-spectrum+analysis.

**Table 3.** The values of Maximal Displacement of the SILRSBs by Gukas Y and Gukas Z records depending on the type of nonlinear analyses, the finite elements of seismic isolation and the directions of earthquake load

| Seismic isolators (finite elements) can take both tension and compression | | Seismic isolators (finite elements) can take only compression | |
|---|---|---|---|
| Fast nonlinear time history analysis by records | Direct-integration nonlinear time history analysis by records | Fast nonlinear time history analysis by records | Direct-integration Nonlinear time history analysis by records |
| mm | mm | mm | mm |
| 93.0 | 77.9 | 86.3 | 73.8 |

The differences between the results of the two nonlinear methods are no more than 20%, at the same time, for models with SILRSB that can take tension axial forces, the difference for the majority of elements is not more than 5%.

The top displacement of all seismic isolators is the same due to the presence of rigid diaphragms at both the top and bottom of the seismic isolators (Table 3).

Time history comparative analysis of seismic isolators shows that in the models with isolators, which can take both tension and compression at certain moments, have tensile stresses (see SILRSB number 1, A and B) (Fig.13). At the same time in the models where seismic isolators can take only compression forces in the same isolators mentioned before, the values of axial compressive forces decrease to zero (see SILRSB number 1, A and B) (Figs.14,15). There is a sharp increase in axial forces of isolators (see SILRSB numbers 10 and 20, B) (Fig.14), which is associated with stress redistribution at a time when some other isolators (see SILRSB numbers 10 and 20, B) (Fig.14) no longer take the vertical load. The period of time when not all seismic isolators will work under axial compressive load is not large, it can be from a fraction of a second to several seconds, while due to the sign change of the seismic load, the continuous parts will be insignificant.

This study shows that for low-rise buildings with seismic isolation, redistribution of forces in SILRSBs is not observed, since there are always only compressive forces in all elements of the seismic isolation system. The results obtained by FEM analysis show that the redistribution of forces in seismic isolation depends on different factors, the main of which is the height of the building [7]. At the same time, the forces increase depending on the ratio of the height to the length (width) of the building. In our case, a redistribution of the forces in the base isolators occurs only when an earthquake force acts in the Y direction, but all seismic isolators are compressed when the force acts in the X direction, i.e. the height to length (width) ratio has a significant influence on the redistribution of the axial forces. It is also necessary to pay attention to ensuring the bearing capacity of reinforced concrete structures located under and above the seismic isolation supports, these members should be sufficiently rigid, especially linear elements without shear walls. An increase in axial force leads to an increase in bending moments and transverse forces [11], which must be taken into account in the calculation of reinforced concrete structures.

## Conclusion

It should be noted that the increase of axial forces after their redistribution during horizontal earthquake loads in most SILRSB does not exceed 8%, but for some isolators, this difference varies within the range of 12-18%. Taking into account the vertical component, the difference does not exceed 20%, with the exception of three isolators, where it can reach up to 23%. An average increase in the compressive axial forces in the seismic isolation bearing systems of this building as a result of redistribution can be taken about 10%.

There may be cases when the displacement of the seismic isolator and its axial force are outside the recommended area for design (Fig.6), even when the conditions $D \leq D_{max}$ and $P \leq P_{max}$ are provided. For this reason, the displacement and axial force of the seismic isolator during the analysis of its bearing capacity must be considered simultaneously but not separately from each other.

For the seismic isolators used in the Republic of Armenia, the dependence of the maximum allowable horizontal displacements on the action of the vertical axial forces under seismic effects has been obtained. The necessity of taking into account the maximum horizontal displacement and the vertical force acting on the SILRSB in order to assess its bearing capacity under seismic action is shown.

The obtained numerical data for SILRSB will make it possible to more accurately estimate the possible maximum allowable horizontal displacements of the seismic isolator from vertically acting total static and seismic loads.

Often the vertical component of the seismic loads has a strong influence on the stress-strain state of building structures, and for load-bearing structures of high-rise buildings with seismic isolation can be decisive. Therefore, the application of the calculation methodology and results of the analysis specified in this manuscript will allow to study the influence of vertical seismic impact on the bearing capacity of structures in high-rise buildings with seismic isolation.

### Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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### References

[1]. RABC 20-04-2020, Building Code, Earthquake resistant construction design codes, Yerevan, 2021. https://www.arlis.am/Annexes/6/2020_N102hav.inc25.docx

[2]. F. Naeim, J. Kelly, Design of Seismic Isolated Structures: From Theory to Practice. John Wiley & Sons, Hoboken, New Jersey, 1999.

[3]. A. Martelli, P. Clemente, A.De Stefano, M. Forni, A. Salvatori, Recent Development and Application of Seismic Isolation and Energy Dissipation and Conditions for Their Correct Use, in: A. Ansal, (ed.), Perspectives on European Earthquake Engineering and Seismology, Springer, Cham, 2014, 449-488. Doi: https://doi.org/10.1007/978-3-319-07118-3

[4]. M. Melkumyan, Lusabats, New Solutions in Seismic Isolation. Lusabats, Yerevan, 2011.

[5]. J. Kelly, Base Isolation: Linear Theory and Design. Earthquake Spectra, 6 (2), 1990, 223-244. Doi: https://doi.org/10.1193/1.1585566

[6]. J. Kelly, D. Konstantinidis, Mechanics of Rubber Bearings for Seismic and Vibration Isolation. John Wiley & Sons, Hoboken, New Jersey, 2011. Doi: https://doi.org/10.1002/9781119971870

[7]. T.L. Dadayan, Redistribution of Forces in Rubber Base Isolations of Multistory Buildings During Earthquake Action. Proceedings of the 9th International Conference on Contemporary Problems of Architecture and Construction, Batumi, Georgia, September 13-18, 2017, 141-144.

[8]. E.L. Wilson, Static and Dynamic Analysis of Structures, Computers & Structures, Inc., New York, 2004.

[9]. J. Kelly, J.J. Lee, Seismic Isolation - A Primer. Computers & Structures, Inc., New York, 2019.

[10]. N. Newmark, W. Hall, Earthquake Spectra and Design. Earthquake Engineering Research Institute, Oakland, 1982.

[11]. T.L. Dadayan, Bending moments influence on shear strength of reinforced concrete elements. Proceedings of 3rd International Conference on Contemporary Problems in Architecture and Construction, Beijing, China, November 20-24, 2011, 237–239. Doi: https://doi.org/10.1049/cp.2011.1181

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