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(RESEARCH ARTICLE)

Base isolation design and analysis for the 7-story apartment building "Stepanakert-sections-4-5" with R/C monolithic load-bearing walls and asymmetric plan

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Abstract

In recent years seismic isolation technologies in Armenia were extensively applied in construction of multi-story residential, medical, hotel, airport, and business center complexes with parking floors and with floors envisaged for offices, shopping centers, fitness clubs, etc. To date there are 55 seismic isolated buildings in the country newly constructed or retrofitted by base or roof isolation systems. Of this number of buildings 48 were erected thanks to the works of the author of this paper and in nowadays Armenia is well known as a country where seismic (base and roof) isolation systems are widely implemented in civil construction. The number of seismically isolated buildings per capita in Armenia is one of the highest in the world – second after Japan. The paper given below emphasizes achievements also in local manufacturing/testing of seismic isolation laminated rubber-steel bearings (SILRSBs). Several remarkable projects on construction of base isolated buildings are briefly mentioned in the paper to demonstrate the experience accumulated in Armenia. Based on the gained experience further developments take place and unique base isolation structural concepts and technologies created by the author are applied more and more in construction of new buildings. In this paper base isolation design and analysis by the Armenian Seismic Code for the 7-story apartment building to be constructed in Stepanakert is described. This will be a first application of base isolation technology to a building the bearing system of which consists of reinforced concrete (R/C) monolithic load-bearing walls and building has an asymmetric plan. It is stated that suggested seismic isolation strategy will reduce the cost of construction of the given building on about 35% in comparison with the cost of conventional construction. Obtained results indicate the high effectiveness of the proposed structural concept of isolation system and the need for further improvement of Seismic Code provisions regarding the values of the reduction factors.

Keywords: Seismic (Base) Isolation; Extensive Experience; Apartment Building; Structural Concept; Load-Bearing System; Monolithic R/C Walls; Asymmetric Plan; Seismic Code Analysis; Low-Cost Technology.

1. Introduction

Base isolation of multistory buildings in Armenia is developing mainly through the projects financed by private companies. The original and innovative structural concepts were developed and implemented in construction of new buildings during the last 19 years. All the mentioned buildings (Table 1) were analyzed using the provisions of the Armenian Seismic Code, as well as using different time histories.

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Table 1 Views of some newly constructed base isolated buildings in Armenia with seismic isolation systems located at different levels

a - 4-story apartment building with reinforced masonry bearing walls in Huntsman Village of Gyumri city [1], b - 3-story clinic building in Stepanakert (Melkumyan, 2004), c - 6-story hotel/commercial center building [1], d - 11-story building of the multifunctional residential complex “Cascade” [2], e - 16- and 10-story buildings of the multifunctional residential complex “Our Yard” [3], f - 16- and 14-story buildings of the multifunctional residential complex “Arami” [4], g - 18-story buildings of the multifunctional residential complex “Northern Ray” [5], h - 16- and 13-story buildings of the multifunctional residential complex “Dzorap” [1], i - 20-story business center “Elite Plaza” [6], j - 17-story building of the multifunctional residential complex “Baghramian” [7], k - 17-story building of the multifunctional residential complex “Avan” [8], l - 15-story building of the multifunctional residential complex “Sevak” [9].

In Table 1 the buildings from “c” to “l” have the structural system with R/C bearing frames and shear walls and were constructed in Yerevan. The number of seismically isolated buildings per capita in Armenia is one of the highest in the world – second after Japan. In [10] it is stated that: “Armenia remains second, at the worldwide level, for the number of applications of such devices per number of residents, in spite of the fact that it is still a developing country”. Together with that SILRSBs different by their shape and dimensions, as well as by damping (low, medium, and high) were designed and more than 5000 SILRSBs were manufactured in the country, tested locally, and applied in construction. The seismic isolation plane in all the mentioned buildings is designed above two or three parking floors, although there is a case (see Table 1f) where there are four floors below the isolation plane, of which two floors are underground and two floors are above ground.

The soil conditions in all cases are good and the soils here are of category II with the predominant period of vibrations of not more than 0.6 sec. Dynamic analyses were carried out by SAP 2000. The results of the analyses of some of these buildings based on the Code were presented and discussed earlier [11, 12]. For the time history non-linear earthquake response analysis, a group of accelerograms was used including synthesized accelerograms. They were chosen so that the predominant periods of the Fourier spectra do not exceed 0.5-0.6 sec. Carried out analyses brought to conclusions that the total shear forces on the level of isolation system, the maximum displacements of the isolators, and the maximum story drifts of the superstructure calculated based on the Code provisions are differing from the same values calculated by the time histories in about 1.75 times in average [13].

This means that some further measures should be taken in order to more realistically reflect characteristics of seismic isolated buildings in the design models during the calculations based on the Code. In other words, further improvement of the Code provisions is needed regarding the reduction factors K_1 for seismic isolation systems, as well as for the dynamic coefficient $\beta(T)$. Anyway, comparative analyses carried out for the mentioned complexes for cases with and without application of seismic isolation clearly show the high efficiency of seismic isolation. They prove once again that if properly designed seismic isolation brings to rational structural solutions of high reliability.

2. Structural concept of the 7-story base isolated apartment building “Stepanakert-sections-4-5”

One of the recent projects financed by the government of Artsakh is the analysis and design of the residential complex in the city of Stepanakert consisting of six base isolated buildings. Construction of this complex is planned to start in 2020 and design of one of the buildings in this neighborhood (Fig. 1) named “Stepanakert-Sections-4-5” was accomplished in 2019. Structural concept of this 7-story building with R/C monolithic load-bearing walls and asymmetric plan is presented below.

Figure 1 Design view of the residential complex consisting of 9- and 7- story base isolated buildings to be constructed in the city of Stepanakert in 2021

Architectural design of this complex was carried out by the “Maxim Atayants’ Architectural Studio” LLC based in Saint-Petersburg. Bearing structure of the building under consideration is different than of the buildings briefly described above. For the first time the base isolation technology will be applied to a building the bearing system of which consists of R/C monolithic load-bearing walls. The considered building has strip foundations with the width and height of footstep equal to 1200 mm and 300 mm, respectively. The width of main strip and the total height of strip foundations are equal to 800 mm and 1000 mm, respectively. Seismic isolation interface is designed within the basement floor. Structures below the isolation plane are designed using strong and rigid R/C structural elements, namely, lower pedestals and shear walls. The cross-sections of lower pedestals envisaged under the SILRSBs are different and designed to accommodate one, two or three isolators (Fig. 2). Generally, the lower pedestals are connected to each other by the 200 mm thick shear walls, although, some of them are designed as the separate columns.

There are upper beams designed above the seismic isolators with the cross-section equal to 640×780(h) mm. These beams are unified by 120 mm thick R/C slabs. The accepted structural solution allowed obtaining a rigid system below the isolation plane, which provides a good basis for effective and reliable behavior of isolators during the seismic impacts. Of course, the superstructure (the part of building above the isolation plane, which consisted of 7 residential floors) should also have substantial rigidity for the same purpose. This was achieved by designing the walls in the form of 160 mm and 200 mm thick R/C monolithic load-bearing walls in mutual perpendicular directions (Fig. 3). The thickness of R/C slabs for all floors was set at 120 mm and these slabs are unifying the floor beams with the cross-section equal to 600×250(h) mm. The drawing provided in Figure 4 presents, as an example, the vertical elevation of the building's seismic isolation system in one of longitudinal directions.

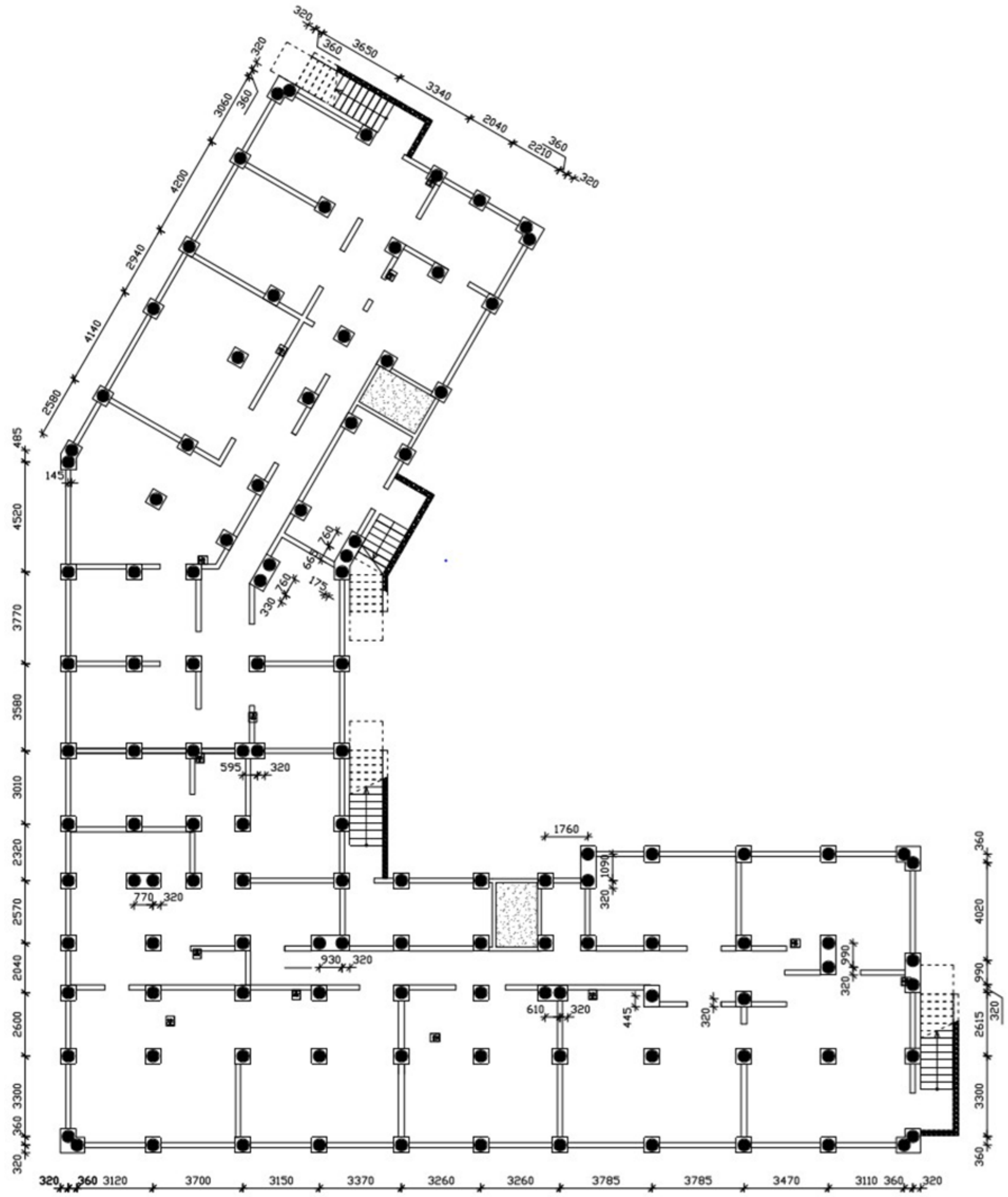


Figure 2 Plan of location of SILRSBs on the lower pedestals in the basement of the 7-story apartment building "Stepanakert-Sections-4-5" with R/C monolithic load-bearing walls

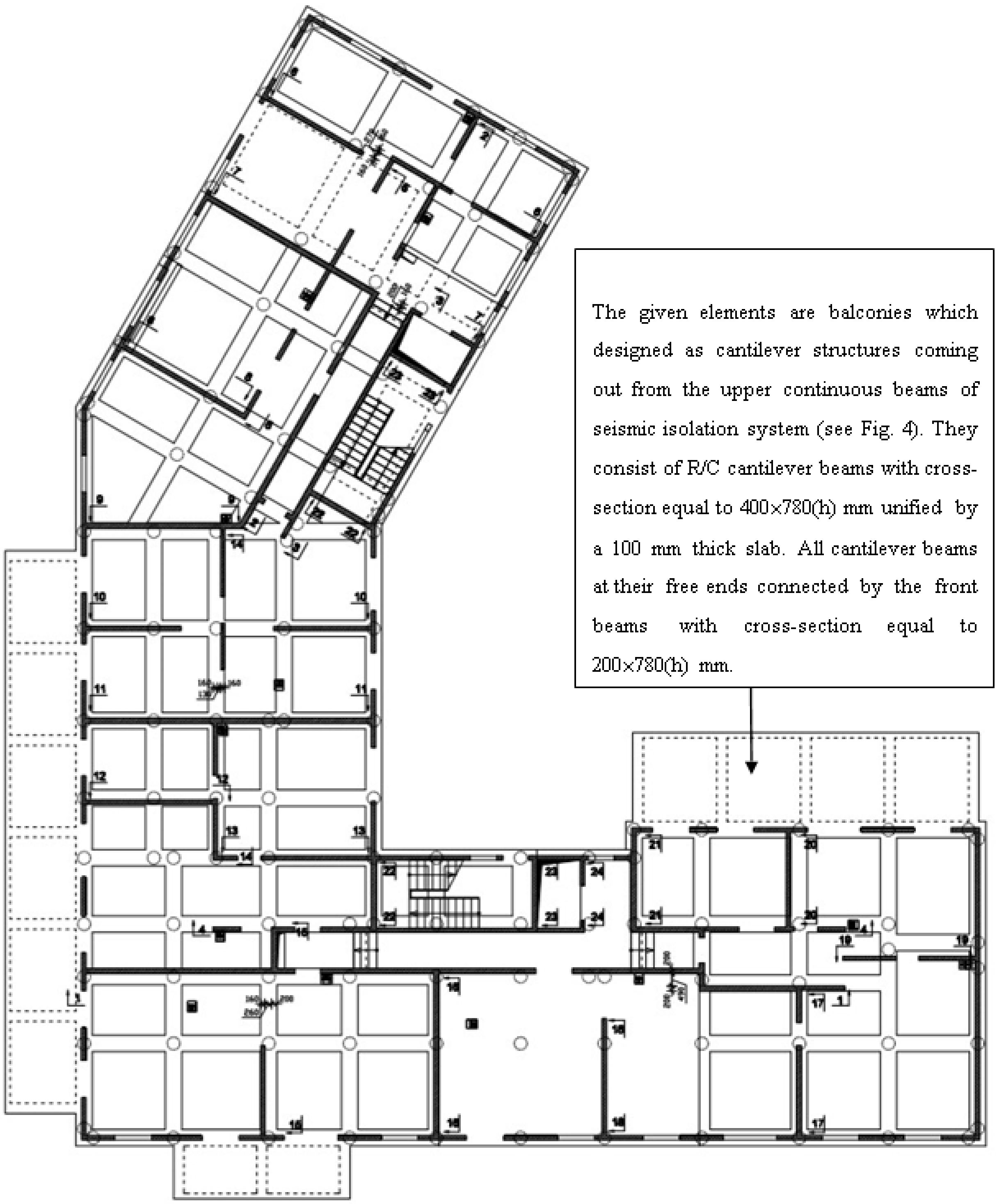


Figure 3 Plan of location of the first floor's R/C monolithic load-bearing walls on the upper beams of seismic isolation system of the 7-story apartment building "Stepanakert-Sections-4-5"

Figure 3 shows that in the middle part of the plan the upper beams are absent and the slab here was designed thicker (150 mm) on the level just above the SILRSBs. This was dictated by architectural solution requiring creating here the main entrance to the building (see also Fig. 4, mark 766.27).

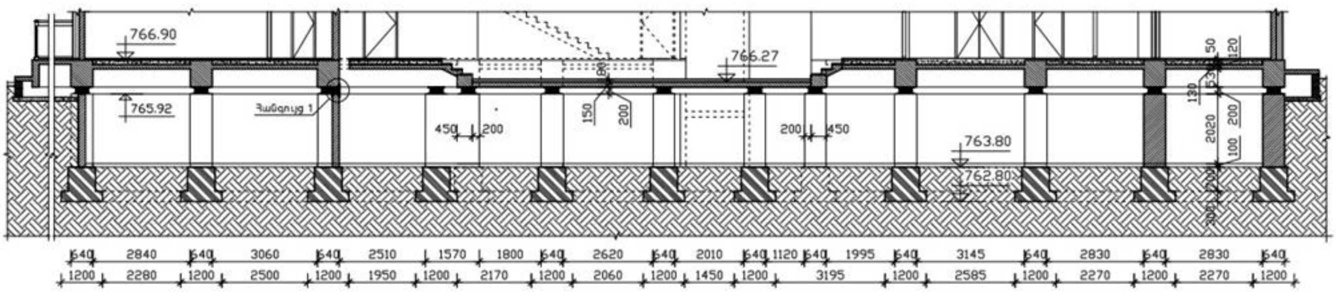


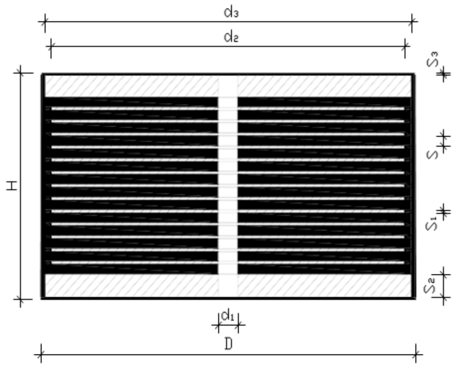
Figure 4 Vertical elevation of the building's seismic isolation system in one of longitudinal directions of the 7-story apartment building "Stepanakert-Sections-4-5" with R/C monolithic load-bearing walls

From the latter it is easy to notice that the level of the seismic isolation system in the basement of this building is lower comparing to the outside ground level. That is why a gap is envisaged around the perimeter of the building. To create the possibility for free horizontal displacement of seismic isolation system, the works are performed in a specific sequence. First, earthworks are implemented and according to the design, trenches are dug along the outer perimeter of the building. Afterwards, around the basement retaining walls are built, which are covered by cantilever slabs coming out from the upper continuous beams to protect the formed gap from precipitations and avoid possible accumulation of trash. However, the main purpose of this gap is to ensure unhindered movement of the superstructure, as well as effective action of the seismic isolation system and accommodation of its horizontal displacement during any seismic impact.

In the considered building the approach suggested earlier [13, 14, 15] on installation of the cluster of small rubber bearings instead of a single large bearing was used. Figure 2 shows that different numbers of SILRSBs are installed at different locations of the seismic isolation system. However, all of them are of the same size and characteristics given in Section 3. They are made from neoprene and were designed and tested locally [16, 17]. The advantages of the approach on installation of the clusters of small rubber bearings instead of a single large bearings are the following: increased seismic stability of the building; more uniform distribution of the vertical dead and life loads as well as additional vertical seismic loads on the rubber bearings; small bearings can be installed by hand without using any mechanisms; easy replacement of small bearings, if necessary, without using any expensive equipment; easy casting of concrete under the steel plates with anchors and recess rings of small diameter for installation of bearings; neutralization of rotation of buildings by manipulation of the number and location of bearings in the seismic isolation plane, etc. [1, 18]. One more advantage was pointed out by Prof. Kelly during the 11th World Conference on Seismic Isolation in Guangzhou, China. Positively evaluating the suggested approach, he mentioned that in the course of decades the stiffness of neoprene bearings may increase, and in order to keep the initial dynamic properties of the isolated buildings the needed number of rubber bearings can be dismantled from the relevant clusters. Thus, thanks to the suggested approach, more rational solution can be achieved, which is increasing the effectiveness of isolation system in general.

3. Parameters of the used SILRSBs and analysis of the base isolated 7-story apartment building with monolithic load-bearing walls and asymmetric plan

From the above given information, it follows that seismic isolation system of the considered building consists of lower pedestals connected by shear walls, of SILRSBs and the upper beams unified by the floor slab. Total 119 SILRSBs were used with aggregate horizontal stiffness equal to 0.81×119=96.39 kN/mm. These are manufactured in Armenia according to the Republic of Armenia Standard HST 261-2007 with the dimensions and physical/mechanical parameters given in Figure 5.



External diameter of the bearing (D): (380 ± 2.0) mm;
Internal diameter of the bearing's central hole (d1): (19 ± 1.0) mm;
Height of the bearing (H): (202.5 ± 2.5) mm;
Thickness of the rubber layers (S): (9 ± 0.1) mm;
Diameter of the steel shim plates (d2): (360 ± 0.5) mm;
Thickness of the steel shim plates (S1): (2.5 ± 0.1) mm;
External diameter of the upper and lower flanges (d3): (376 ± 0.5) mm;
Thickness of the upper and lower flanges (S2): (20 ± 0.2) mm;
Thickness of the upper and lower flanges' protective layer (S3): (2 ± 0.1) mm;
Mass of the bearing: (77.5 ± 2.5) kg;
The bearing must withstand a maximum (design) permissible vertical loading of 1500 kN;
Shear modulus of the bearing's rubber must be (0.97 ± 0.15) MPa;
Vertical stiffness of the bearing: no less than 300 kN/mm;
Horizontal stiffness of the bearing: (0.81± 0.1) mm;
The bearing must withstand a maximum (design) permissible horizontal displacement of 280 mm, without causing cracks greater than 3 mm deep and 6 cm long;
Shore A hardness of the bearing: 70 ± 5 points;
Damping coefficient of the bearing: 13-15%.

Figure 5 Dimensions and physical/mechanical parameters of the seismic isolation laminated rubber-steel bearing

Analysis of the seismic isolation system and the whole structure was performed in accordance with the Armenian Seismic Code RABC II-6.02-2006 assuming the following parameters:

- Seismic zone 3 and soil category II;
- Soil conditions coefficient is K_0=1.0 and the site prevailing period of vibrations 0.3≤T0≤0.6 sec;
- Permissible damage coefficient for determining displacements – K_1=0.8;
- Permissible damage coefficient for analysis of seismic isolation system and reinforced concrete structures below it – K_{1z}=0.8;
- Permissible damage coefficient for analysis of the superstructure – K_1=0.4;
- Coefficient of seismicity – A=0.4.

Armenian Seismic Code requires that any base isolated building should be analyzed twice: first, by applying K1=0.8 and the obtained results will serve as a basis to design the isolation system and structures below it, and then the second analysis should be carried out by applying K_1=0.4 and the

derived results will serve as a basis to design the superstructure, to check the values of the inter-story drifts, as well as receiving the values of floors' accelerations, inertial forces, etc. It is also assumed that vibration period (T) of the base isolated building should be around 2 sec. According to the RABC II-6.02-2006 horizontal displacement of the base isolation system must be calculated by the formulas (6) and (32) of the Code:

$D= K_1×(T/2π)2×A×K_0×[β(T)/B(n)]×K_{1z}$,

where dynamic coefficient β (T) depends on soil category and determined by the formulas given in the Code. In this case β (T) =0.95. B(n) depends on the damping of isolation system and for the value of 15% Code suggests this coefficient equal to 1.56. Thus:

D=0.8×(2/6.28)2×400×(0.95/1.56)×0.8=15.36 cm.

Considering that the building has asymmetric plan Code requires increasing the obtained value of horizontal displacement by 10%. Therefore, the total displacement will be equal to:

D_{total}=1.1×15.36=16.9 cm.

This value of horizontal displacement is 1.66 times smaller than the maximum permissible displacement suggested by the Standard HST 261-2007 (28 cm), which means that high reliability of the designed seismic isolation system will be provided. According to the RABC II-6.02-2006 total seismic force on the top of isolation system (base of superstructure) must be calculated by the formula (35) of the Code:

$S=K_{eff}\times D_{total}=96.39\times 169=16290$ kN.

To calculate the vibration period of the base isolated 7-story building with monolithic load-bearing walls the masses of its floors were computed: the mass of the first floor is equal to 1215 t, the masses of 2÷7 floors are equal to each other and equal to 1008 t, and the mass of the 7th floor was calculated together with the mass of the attic floor and was equal to 2250 t. Thus, the total mass M of the building is equal to 9513 t. According to the RABC II-6.02-2006 vibration period for the base isolated 7-story building with monolithic load-bearing walls is determined by the formula (31) of the Code using the values of the total mass of this building (superstructure) and effective stiffness of isolation system:

$T=2\pi\times\sqrt{Q}/(K_{eff}\times g)=6.28\times\sqrt{9513/96390}=1.97$ sec.

This value differs from the initially assumed period of only 1.5%. Using the obtained values, it is possible to calculate the magnitude of acceleration just above the seismic isolation interface:

$a=S/M=16290/9513=1.71$ m/sec2.

From this it follows that due to application of base isolation acceleration at the level of the first floor of superstructure decreases by about 2.3 times in comparison with the ground acceleration (4.0 m/sec2). This is very typical result showing the high effectiveness of base isolated structures. In comparison with the fixed base buildings, seismic isolation significantly reduces the maximum spectral acceleration, proving to be cost effective for the isolated structures and ensuring high reliability of their behavior under seismic impacts [1, 19, 20, 21].

Before the customer approached us with the request to develop the base isolation design for the considered 7-story apartment building using innovative technology, a prototype conventional design for construction of the same building was examined. In the conventional design the foundations were in the form of 800 mm thick solid slab, the thickness of the monolithic load-bearing walls was equal to 300 mm at the basement and 200 mm in all the residential floors. Their slabs were also designed with the thickness of 200 mm. Comparative analysis has shown that suggested seismic isolation strategy reduces the consumption of concrete by about 2 times and steel – 2.7 times. Therefore, the cost of construction of the given building decreases on about 35% in comparison with the cost of conventional construction. This magnitude of the cost reduction considers the cost of manufacturing, testing, and installation of SILRSBs.

4. Conclusion

Several remarkable projects on construction of base isolated buildings like residential complexes, hospital and hotel buildings are briefly mentioned in the paper to demonstrate the experience accumulated in Armenia in construction of new buildings.

For the first time base isolation technology is considered for application to a building the bearing system of which consists of R/C monolithic load-bearing walls and building has an asymmetric plan. Suggested structural concept of the 7-story base isolated apartment building "Stepanakert-Sections-4-5" and the approach on installation of clusters of SILRSBs bring to rational solution of the whole bearing structure. It increases overall stability of the superstructure and effectiveness of the isolation system.

The developed design and conducted analysis confirm that base isolation is one of the most effective technologies in earthquake resistant construction. It brings to simultaneous reduction of floor accelerations and inter-story drifts, as well as to significant reduction of shear forces in comparison with the fixed base buildings.

Total 119 SILRSBs are used in seismic isolation system with the aggregate horizontal stiffness equal to 96.39 kN/mm. These are manufactured in Armenia according to the Republic of Armenia Standard HST 261-2007. Their dimensions and physical/mechanical parameters are given in the paper.

Some results of analysis of the base isolated 7-story apartment building "Stepanakert-Sections-4-5" by the Armenian Seismic Code are given, showing that the structural elements below and above the seismic isolation plane will work only in the elastic phase. Total horizontal displacement comprises

16.9 cm, period of vibration – 1.97 sec and acceleration at the level above the seismic isolation interface – 1.71 m/sec2. An input acceleration of 0.4g at the foundation bed gets damped about 2.3 times in the superstructure. Almost uniform distribution of the vertical loads (not exceeding 1500 kN) upon the rubber bearings was achieved.

Comparative analysis has shown that suggested seismic isolation strategy reduces the consumption of concrete by about 2 times and steel – 2.7 times. Therefore, the cost of construction of the given building decreases on about 35% in comparison with the cost of conventional construction. This magnitude of the cost reduction considers the cost of manufacturing, testing, and installation of SILRSBs.

Comparison of the Code based analyses results with those obtained by the time history analyses indicates that the shear forces at the level of isolation systems, the maximum displacements of the isolators, and the maximum inter-story drifts in the superstructures calculated based on the Armenian Seismic Code provisions are considerably higher (by a factor of 1.75 in average) than the same values calculated by the time histories. This means that some further measures should be taken in order to more realistically reflect characteristics of seismic isolated buildings in the design models during the calculations based on the Code. In other words, further improvement of the Code provisions is needed regarding the reduction factors K_1 for seismic isolation systems, as well as for the dynamic coefficient $\beta(T)$.

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