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Structural concept and analysis of the 16- and 14-story base isolated apartment buildings constructed on one stylobate in the multifunctional complex "Arami"

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Abstract

Seismic isolation strategies were developed in Armenia due to the efforts of the author of this paper. Many medium and high-rise base isolated buildings were constructed in different regions of the country. Among them there are multi-story residential and business center complexes with parking floors and with floors envisaged for offices, shopping centers, fitness clubs, etc. Some complexes are briefly mentioned in the paper. However, the main information in this paper is given to describe the 16- and 14-story base isolated apartment buildings constructed on one stylobate in the multifunctional complex "Arami" in the city of Yerevan. The complex has unique structural concept, including the suggested by the author approach on installation by clusters of seismic isolation laminated rubber-steel bearings (SILRSBs) in seismic isolation interfaces of these buildings. Some details of the suggested concepts and construction peculiarities are described. Also, some results of the earthquake response analyses are given. The building was analyzed using several time histories and also according to the requirements of the Armenian Seismic Code.

Keywords: Seismic isolation; Unique structural concepts; Clusters of seismic isolation rubber bearings; Construction peculiarities; Response analysis; Time history; Seismic code

1. Introduction

Base isolation of multistory buildings in Armenia was generally implemented in construction carried out by private companies. The author developed unique and innovative seismic isolation structural concepts for multistory buildings and they were widely applied during the last 23 years in construction of new and retrofitting of existing buildings. According to the requirements of the Chapter X of Armenian Seismic Code RABC 20.4 currently in force, seismic isolation plane in buildings can be located below the level of the pavement around the building (Figure 1a) or above the level of the pavement (Figure 1b, c), but not higher than the second story level. In case of the considered in this paper multifunctional complex "Arami", there are four floors below the isolation plane, of which two floors are underground and two floors are above ground. Design model of this complex is described below.

Some of the mentioned multistory buildings are shown in Table 1. They were analyzed based on the provisions of the Code, as well as using different time histories. These buildings were constructed on the soils classified in the Code as of category II. Predominant period of vibrations of these soils is not more than T_0=0.6 sec. SAP 2000 program was used to carry out analyses. The results of the analyses of some of these buildings based on the Code were presented and discussed earlier (Melkumyan, 2005, 2013).

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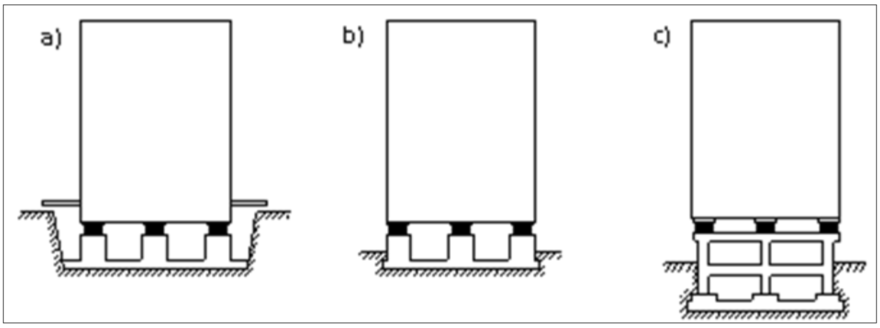

Figure 1 Main types of location of seismic isolation systems

Table 1 Views of the multistory base isolated buildings newly constructed in Yerevan

			
a.	b.	c.	d.
			
e.	f.	g	h

a – 16- and 10-story buildings of the multifunctional residential complex "Our Yard" (Melkumyan, 2005), b – 11-story building of the multifunctional residential complex "Cascade" (Melkumyan et al., 2005), c – 20-story business center "Elite Plaza" (Melkumyan, 2011), d – 15-story building of the multifunctional residential complex "Avan" (Melkumyan, 2014a), e – 18-story buildings-twins of the multifunctional residential complex "Northern Ray" (Melkumyan & Gevorgyan, 2010), f – 16- and 13-story buildings of the multifunctional residential complex "Dzorap" (Melkumyan, 2009), g – 17-story building of the multifunctional residential complex "Baghramian" (Melkumyan & Gevorgyan, 2008), h – 17-story building of the multifunctional residential complex "Sevak" (Melkumyan, 2014b)

A group of accelerograms was used for the time history non-linear earthquake response analyses of these base isolated buildings. Synthesized accelerograms were also used in calculations. They, as well as accelerograms of the real earthquakes were chosen so that the predominant periods of their Fourier spectra do not exceed 0.5-0.6 sec. In (Melkumyan, 2009) it was mentioned that analyses of these buildings based on the provisions of the previous Code RABC II-6.02-2006 bring to the results when calculated total shear forces on the level of isolation system, the maximum displacements of the isolators, and the maximum story drifts of the superstructure are differing from the same values calculated by the time histories in about 1.75 times in average.

That is why the author of this paper was always demanding to take measures in order to more realistically reflect characteristics of seismic isolated buildings in the design models during the calculations based on the Code. He was constantly emphasizing that further improvement of the Code provisions is needed regarding the reduction factors for seismic isolation systems. At last, the previous Code was fully revised and now results of analyses based on the new edition of the Chapter X "Buildings and Structures with Base Isolation Systems" of the Armenian Seismic Code RABC 20.4 (Melkumyan, 2021) are match close with the time history non-linear earthquake response analyses results.

However, in all cases, comparative analyses carried out for the mentioned residential as well as for the business center complexes 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 and to significant reduction of the construction cost.

2. Structural concept of the 16- and 14-story base isolated apartment buildings "Arami"

The project on analysis, design, and construction of the 16- and 14-story base isolated apartment buildings constructed on one stylobate in the multifunctional complex "Arami" (Figure 2) in the city of Yerevan was financed by the "Elite Group" CJSC.

Similarly to the buildings briefly described above, the considered buildings also have floors (envisaged for the offices, shops, and parking) below the isolation plane designed using strong and rigid reinforced concrete (R/C) structural elements. As it is mentioned in Introduction the multifunctional complex "Arami" has a stylobate below the isolation plane consisting of four floors, of which two floors are underground and two floors are above the ground level. Overall dimensions of stylobate are equal to 65200×51200 mm.

The cross section of columns of stylobate between the axes "1"-"4" and "8"-"11" is mainly equal to 900×700 mm. However, the cross section of columns of stylobate between the axes "4"-"8" is equal to 500×500 mm. The cross section of beams immediately below the seismic isolators is equal to 700×600(h) mm, but immediately above them – 700×750(h) mm. Other beams between the axes "1"-"4" and "8"-"11" have cross section equal to 700×550(h) mm. A rigid R/C slab of the thickness equal to 150 mm is designed at the upper level of the beams only above the seismic isolators. There is no slab at the level of beams immediately below the seismic isolators. The thickness of the rest three slabs in the parking floors is also equal to 150 mm. Considering that two floors of stylobate are designed below the ground level the thickness of the exterior shear walls here is equal to 400 mm. The cross section of the foundation strips between the axes "1"-"4" and "8"-"11" is equal to 900x1200(h) mm, but between the axes "4"-"8" is equal to 700×700 mm. The cross section of beams in this part of stylobate is equal to 500×550(h) mm.

From the above it is obvious that accepted structural solution permits obtaining a rigid system for stylobate (below the isolation plane). This provides the good conditions for effective and reliable behavior of seismic isolators during the earthquake impacts. It goes without saying that superstructures (the parts of buildings above the isolation plane, which consisted in one case of 16 residential floors and in another case of 14 residential floors) must also have substantial rigidity for the same purpose. This was achieved by using R/C columns in superstructures with cross section of 500×500 mm and 160 mm thick shear walls between them. The thickness of R/C slabs was set at 150 mm for all floors. Beams in superstructures were designed with cross section of 500×350(h) mm. Plan of location of seismic isolators is shown in Figure 3.

In the considered multifunctional residential complex the approach suggested earlier (Melkumyan, 2007, 2009) on installation of the cluster of small rubber bearings instead of a single large bearing under the columns or shear walls was used. Examples of installed clusters of seismic isolators are shown in Figure 4. From Figures 3 and 4 one can see that different numbers of rubber bearings are installed under the different structural elements. However, all of them are of the same size (diameter - 380 mm, and height - 202 mm) and characteristics. They have horizontal stiffness equal to 0.81 kN/mm, a damping factor of about 9-10%, can develop horizontal displacement of up to 280 mm (about 220% of shear strain), and can carry a vertical design load of up to 1500 kN. They are made from neoprene and were designed and tested locally (Melkumyan, 2001, Melkumyan & Hakobyan, 2005).

Figure 2 View of the 16- and 14-story buildings of the multifunctional residential complex “Arami” constructed in Yerevan (Melkumyan, 2006)

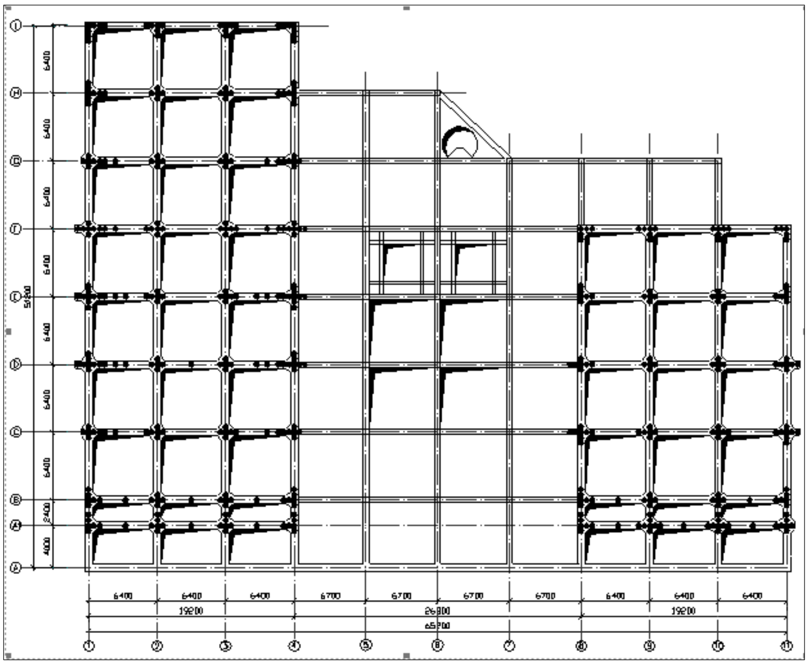

Figure 3 Plan of location of seismic isolation rubber bearings at the mark of 8.70 under the 16-story (between the axes “1”-“4”) and 14-story (between the axes “8”-“11”) apartment buildings “Arami”

The approach suggested by the author of this paper on installation of the cluster of small rubber bearings instead of a single large bearing is not a typical one for the buildings with isolation systems. The advantages of this approach are summarized below:

- Increased seismic stability of the buildings (Figure 5);
- 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. (Foti and Mongelli, 2011, Melkumyan, 2011).

Figure 4 Examples on installation of rubber bearings' clusters in the 16- and 14-story base isolated apartment buildings of multifunctional residential complex "Arami"

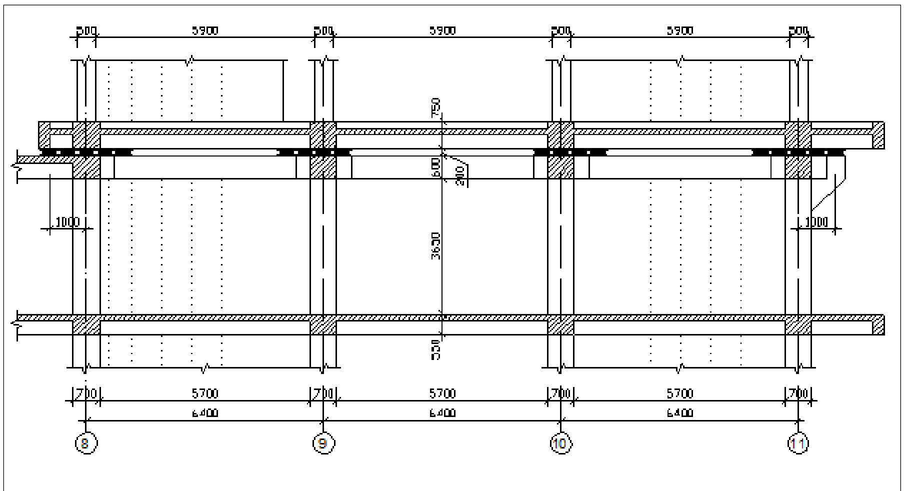

Figure 5 Vertical elevation of the isolation system of 14-story building in "Arami" complex with the increased distance between the edge bearings

During the 11th World Conference on Seismic Isolation in Guangzhou, China Prof. Kelly has pointed one more advantage of the suggested approach. Positively evaluating this 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. Figure 5 shows how using clusters of bearings can enable increasing the distance between the edge bearings by 2 m (1 m from axis "8" to the left and 1 m from axis "11" to the right), which will significantly improve the overall performance of the superstructure (Melkumyan, 2011). Also, some results of the comparative analyses of 16-story building show that difference in horizontal displacement along the axes “I” and “A1” is 19 mm in the case of typical installation of the rubber bearings, while for the case of installation by clusters this difference is only 2.3 mm. Thus, significant decrease of rotation (more than 8 times) was achieved by manipulating with the number of isolators and changing their location in plan of the isolation system. From Figure 3 one can see that there are no seismic isolators envisaged along the axis “A” because the parts of the buildings between the axes “A” and “A1” were designed as cantilever structures.

3. Results of analyses of the 16- AND 14-story Base isolated apartment buildings “Arami”

Earthquake response analyses of the considered buildings (including stylobate) was carried out using SAP 2000 non-linear program and 8 selected time histories recorded in Armenia (7.12.88 Spitak, EW and NS directions), Iran (20.06.90 Manjil, NE direction), Japan (17.12.87 Chiba, NS direction), USA (09.03.49 Hollister, 20.12.54 Eureka, NE direction and 17.10.89 Loma Prieta), and former Yugoslavia (15.04.79 Bar, EW direction) and scaled to 0.4g acceleration. Also the buildings were analyzed based on the provisions of Chapter X of the Armenian Seismic Code. The design model (Figure 6) was developed by application of different types of finite elements for shear walls, floor slabs, columns and beams, as well as for seismic isolators.

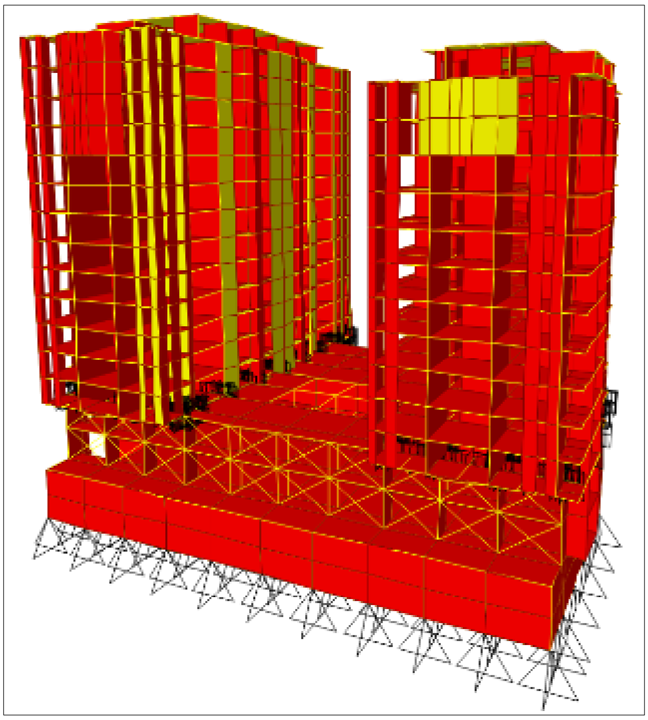

Figure 6 Design model of the 16- and 14-story base isolated apartment buildings “Arami”

Calculations were carried out taking into account the non-linear behavior of seismic isolation rubber bearings with the following input parameters: yield strength – 56 kN; yield displacement – 19 mm; effective horizontal stiffness – 0.81 kN/mm. As for the above mentioned in “Introduction” buildings the soil conditions of the site where the considered “Arami” buildings were going to be constructed correspond to category II, for which the soil conditions coefficient k_0=1. The site is located in zone 2, where the expected maximum acceleration is equal to a=400 cm/sec^2.

Previously, based on the old Code it was required for this particular case of R/C buildings with shear walls to apply for superstructure the allowable damage coefficient (reduction factor) k_1=0.4 and for seismic isolators and the structures below the isolation plane - k_1=0.8. Actually, the old Code required that any base isolated building of the mentioned type should be analyzed twice: first, by applying k_1=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. Currently, as it is mentioned in “Introduction”, the new Seismic Code RABC 20.4 requires carrying out analysis for the whole complex using only one value of the reduction factor, namely, k_1=0.4.

Some results of the analyses by the Armenian Seismic Code in force and time histories are given in Tables 2 and 3. The carried out earthquake response analyses have shown that 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 (Naeim & Kelly, 1999, Fujita, 1999, Saito, 2006, Martelli et al., 2008, Melkumyan, 2011). From the obtained results it follows that the first mode vibrations' periods of base isolated building in longitudinal (X) and transverse (Y) directions are almost equal to each other. Thanks to the proposed approach of location of rubber bearings by clusters in seismic isolation system, in none of the isolators the vertical force exceeds 1500 kN. More or less uniform distribution of the vertical loads upon the rubber bearings was achieved and also no rotation in the building's isolation system and, consequently, in superstructure was observed.

Table 2 Some results of the analyses of 16-story base isolated apartment building in the complex "Arami" by the Armenian Seismic Code and time histories

Parameters obtained by the analysis based on the Armenian Seismic Code		
Period of vibrations (sec)	T_x=2.15	T_y=2.08
Inter-story drift (mm)	3.8	2.8
Horizontal shear force on the level of foundation (kN)	18718	19530
Displacement of the isolation system (mm)	134	114
Average parameters obtained by the 8 time histories analyses		
Inter-story drift (mm)	3.2	2.4
Horizontal shear force on the level of foundation (kN)	15768	17283
Displacement of the isolation system (mm)	122	112

Table 3 Some results of the analyses of 14-story base isolated apartment building in the complex "Arami" by the Armenian Seismic Code and time histories

Parameters obtained by the analysis based on the Armenian Seismic Code		
Period of vibrations (sec)	T_x=2.00	T_y=1.98
Inter-story drift (mm)	3.4	1.6
Horizontal shear force on the level of foundation (kN)	12392	13091
Displacement of the isolation system (mm)	139	
Average parameters obtained by the 8 time histories analyses		
Inter-story drift (mm)	2.9	1.4
Horizontal shear force on the level of foundation (kN)	11303	12010
Displacement of the isolation system (mm)	132	111

It also can be noticed that the displacements of isolation system, inter-story drifts and horizontal shear forces obtained by calculations of the seismic isolated buildings based on the provisions of the new edition of the Chapter X "Buildings and Structures with Base Isolation Systems" of the Armenian Seismic Code RABC 20.4 are close to the same values obtained by the time history analyses when the applied allowable damage coefficient (reduction factor) k_1=0.4. Differences in these values are in the range of 2-19%.

4. Conclusion

The conducted study confirms 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 and to significant reduction of shear forces in comparison with the fixed base buildings. The suggested structural concept of the 16- and 14-story base isolated apartment buildings in the multifunctional complex "Arami" and the new approach on installation of clusters of seismic isolation rubber bearings brings to rational solution of the whole bearing structure. It increases overall stability of the building and effectiveness of the isolation system, neutralizing the rotation in the buildings' isolation system and, consequently, in their superstructures. In this case almost uniform distribution of the vertical loads upon the rubber bearings was achieved. The obtained results also indicate that first mode vibrations' periods of base isolated buildings in longitudinal and transverse directions are actually equal to each other. Previously, comparison of the analyses results for many of seismic isolated buildings obtained based on the old Code RABC II-6.02-2006 with those obtained by the time history analyses indicated significant differences (by a factor of 2.1 in average). However, based on the efforts of the author of this paper, new edition of the Code RABC 20.4 has totally changed this unacceptable situation. Results of this paper prove 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 are differ from the same values calculated by the time histories only on 2-19%.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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