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Structural Concept and Analysis of the 17-Story Base Isolated Apartment Building "Sevak"

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Abstract— **In recent years seismic isolation technologies in Armenia were extensively applied in construction of multi-story residential and business center complexes with parking floors and with floors envisaged for offices, shopping centers, fitness clubs, etc. They are briefly described in the paper, which is, however, mainly dedicated to a 17-story base isolated apartment building "Sevak" designed and constructed recently in the city of Yerevan. The structural concept, including the new approach on installation of seismic isolation rubber bearings in this building, is described and 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. Comparison of the obtained results indicates 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.**

Index Terms— **Seismic code analysis, seismic isolation, structural concept, time history response analysis.**

I. 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 during the last 13 years. The seismic isolation plane in all buildings is designed above two or three parking floors, although there is a case where there are four floors below the isolation plane, of which two floors are underground and two floors are above ground. All the mentioned buildings (Fig. 1) were analyzed using the provisions of the Armenian Seismic Code, as well as using different time histories. 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. Calculations 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 [1], [2]. 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. In this case 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 1.75 times in average [3].

Fig. 1. Design views of the multi-storey base isolated buildings newly constructed in Yerevan

a – 16- and 10-story buildings of the multifunctional residential complex "Our Yard" [1], b – 11-story building of the multifunctional residential complex "Cascade" [4], c – 20-story business center "Elite Plaza" [5], d – 16- and 14-story buildings of the multifunctional residential complex "Arami" [6], [7], e – 18-story buildings of the multifunctional residential complex "Northern Ray" [8], f – 16- and 13-story buildings of the multifunctional residential complex "Dzorap" [3], g – 17-story building of the multifunctional residential complex "Baghramian" [9], h – 15-story building of the multifunctional residential complex "Avan" [10]

This means that some further measures should be taken in order to more realistically reflect characteristics of seismic

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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 for seismic isolation systems. The comparative analysis carried out for the mentioned residential as well as for the business center 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.

II. STRUCTURAL CONCEPT OF THE 17-STORY BASE ISOLATED APARTMENT BUILDING "SEVAK"

One of the recent projects financed by ITARCO Construction, CJSC on analysis and design of 17-story base isolated building "Sevak" (Fig. 2) was accomplished in 2011. Construction of this building in Yerevan was completed in 2014.

Fig. 2. Design view of the 17-story base isolated apartment building "Sevak" constructed in Yerevan and its current view

Similarly to the buildings briefly described above, the considered building has three floors (envisaged for parking and offices) below the isolation plane designed using strong and rigid reinforced concrete (R/C) structural elements. The cross section of columns here is equal to 650×650 mm and of beams below the seismic isolators – 650×500(h) mm and above them – 650×700(h) mm. The thickness of shear walls in the lowest underground floor is equal to 500mm and in the next two floors is equal to 300 mm. The foundation is designed in the form of R/C slab with the thickness of 1300 mm. 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 14 residential floors) should have substantial rigidity for the same purpose. This was achieved by using R/C columns with cross section of 400×400 mm and 160 mm thick shear walls between them. The thickness of R/C slabs was set at 120 mm for all floors. The drawing provided in Fig. 3 presents the vertical elevation of the building. Plan of location of seismic isolators is shown in Fig. 4.

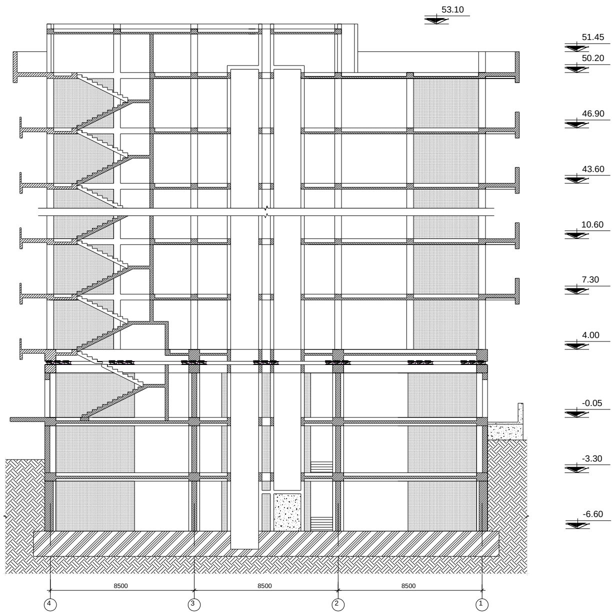

Fig. 3. Vertical elevation of the 17-story base isolated apartment building "Sevak" in the direction along the letters axes (between the axes "B" and "C")

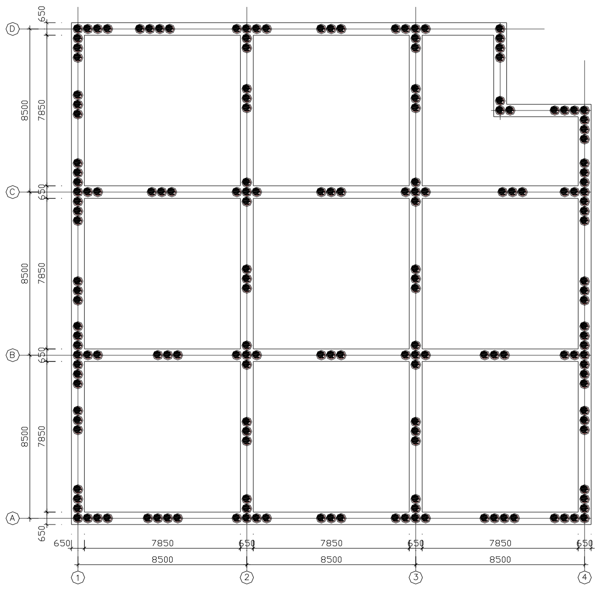

Fig. 4. Plan of location of seismic isolation rubber bearings at the mark of -3.10 in the 17-story apartment building "Sevak"

In the considered building the approach suggested earlier [3], [6], [11] on installation of the cluster of small rubber bearings instead of a single large bearing under the columns or shear walls was used. Corresponding examples of installed isolators are shown in Figure 5, where a gap in stairway is also shown. From Figures 3, 4 and 5 it can be seen 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 [12], [13].

Fig. 5. Examples on installation of rubber bearings' clusters in the 17-story base isolated apartment building "Sevak" in the course of construction

The approach 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 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. Then, 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. [5], [14]. 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 [10]. Thus, thanks to the suggested approach, more rational solution can be achieved, which is increasing the effectiveness of isolation system in general.

III. Results of Analysis of the 17-Story Base Isolated Apartment Building "Sevak"

Earthquake response analysis of the considered building was carried out using SAP 2000 non-linear program and 8 selected acceleration 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 building was analyzed based on the provisions of the Armenian Seismic Code. The design model (Fig. 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.

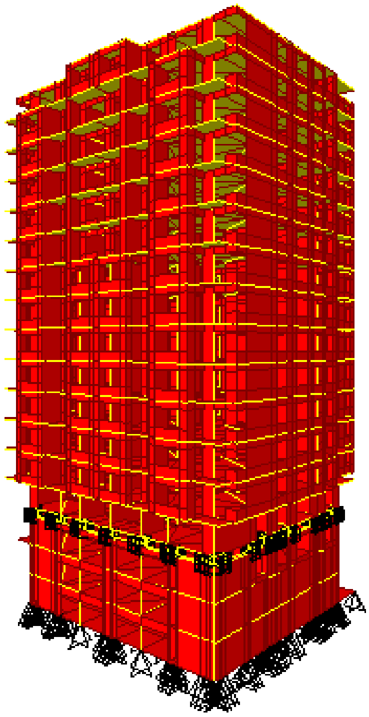

Fig. 6. Design model of the 17-story base isolated apartment building "Sevak"

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 buildings the soil conditions of the site where the considered building was going to be constructed correspond to category II, for which the soil conditions coefficient k_0=1. The site is located in zone 3, where the expected maximum acceleration is equal to a=400 cm/sec^2. There are different allowable damage coefficients envisaged in the Code. For this particular case of R/C frame building with shear walls it is required 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 Code requires 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.

Some results of the analyses by the Armenian Seismic Code and time histories are given in Table I. 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 [5], [10], [15]–[18]. 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 I. Some results of the analyses of 17-story base isolated apartment building "Sevak" by the Armenian Seismic Code and acceleration time histories

Parameters obtained by the analysis based on the Armenian Seismic Code		
Period of vibrations (sec)	T_x=1.98	T_y=2.03
Inter-story drift (mm)	1.6 (k_1=0.4) 3.5 (k_1=0.8)	2.3 (k_1=0.4) 4.7 (k_1=0.8)
Horizontal shear force on the level of foundation (kN)	16175 (k_1=0.4) 32092 (k_1=0.8)	16590 (k_1=0.4) 33030 (k_1=0.8)
Displacement of the isolation system (mm)	108.0 (k_1=0.4) 215.0 (k_1=0.8)	111.0 (k_1=0.4) 222.0 (k_1=0.8)
Average parameters obtained by the 8 acceleration time histories analyses		
Inter-story drift (mm)	1.4	2.1
Horizontal shear force on the level of foundation (kN)	14838	15131
Displacement of the isolation system (mm)	99.6	100.0

It also can be noticed that the displacements of isolation system, inter-story drifts and horizontal shear forces obtained by calculations of the base isolated building by the Armenian Seismic Code are close to the same values obtained by the time history analysis when the applied allowable damage coefficient (reduction factor) k_1=0.4. Differences in these values are of about 10% in average. But in case if k_1=0.8 the Code based results are higher by a factor of 2.2 in average. Therefore, the Code needs a more accurate designation of reduction factors for seismic isolation systems. At this stage it is suggested by the author of this paper to accept k_1=0.6 for zone 3 in the next edition of the Code, as a compromise solution.

IV. 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 17-story base isolated apartment building "Sevak" 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 building's isolation system and, consequently, in its superstructure. 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 building in longitudinal and transverse directions are almost equal to each other. 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 2.2 in average) than the same values calculated by the time histories. Therefore, the Armenian Seismic Code needs a more accurate designation of reduction factors for seismic isolation systems.

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Mikayel Melkumyan started his scientific and practical activity in 1973, immediately after graduation from the Civil Engineering Department of Yerevan Polytechnic Institute, carrying out both design works and experimental-theoretical research to study the behavior of various reinforced concrete structures under seismic actions. In 1983 he defended his thesis for the degree of Candidate of Engineering Sciences and began to lead the Department of Earthquake Resistant Construction at the Armenian Scientific-Research Institute of Construction and Architecture.

From April 1990 through March 1991 he conducted research at the Institute of Industrial Science (IIS), University of Tokyo, where he was invited by Prof. Tsuneo Okada, Director of the Institute. On the basis of his experimental research works he created a new hysteresis model to describe the shear behavior of reinforced concrete structures (walls, diaphragms). As it is indicated in the Certificate granted to him by the IIS, this model and the formula proposed by him for calculation of horizontal stiffness of diaphragms were accepted in Okada and Nakano laboratory, and the model was incorporated in the computational software for earthquake response analysis of multistory frame buildings with predominance of shear deformation. It is also mentioned in the Certificate that this research work will have a considerable contribution to earthquake resistant construction and earthquake damage mitigation in the world.

After his return from Japan, from 1992 through 1996 he was a teaching Professor at the College of Engineering of the American University of Armenia, giving lectures on non-linear behavior of reinforced concrete structures and design principles thereof in earthquake resistant construction. At the same time he led the Earthquake Engineering Center of the National Survey for Seismic Protection under the Government of Armenia. From 1993 he started his work on development and application of seismic isolation systems for buildings and structures in Armenia, in the meanwhile defending his thesis for the degree of Doctor of Engineering Sciences in 1997 on the subject "Formation of the Dynamic Design Models for Seismic Response Analysis of Reinforced Concrete Buildings and their New Structural Solutions".

During a short period of time in 1995-1996, devoting him to the challenge of increasing earthquake resistance of existing buildings, he developed two unique methods of protecting existing buildings from earthquakes through base isolation and isolated upper floor without interrupting of the use of the buildings. His new technologies were successfully implemented in Armenia, where for the first time in the world a 5-story stone apartment building and over 60 years old 3-story stone school building, which had a historical and architectural value, were retrofitted by base isolation without evacuation of inhabitants and interruption of school functioning. Besides, for the first time seismic resistance of two existing 9-story apartment buildings was enhanced by application of the isolated upper floor. These works are unprecedented in the world practice of earthquake resistant construction of the time. Later on, his technology for seismic isolation of existing stone buildings (Patent of the Republic of Armenia № 579) was successfully applied in Russia during retrofitting by base isolation of a 100 years old bank building in Irkutsk city. Afterwards, the Government of Romania ordered a design for retrofitting about 180 years old municipality building in Iasi city, which he accomplished using the same technology.

His works in the fields of both non-linear behavior of reinforced-concrete structures and seismic isolation are well known to the international professional community by the weighty contribution to the science and practice of earthquake resistant construction. He has authored and co-authored 200 scientific works, including 15 books, 10 normative documents, and 12 inventions. As a principal structural engineer he has designed 90 earthquake resistant residential, civil, and industrial buildings. 125 of his scientific works have been published in international journals and proceedings of the World, European, and National Conferences in 31 countries of the world.

He is the President of the Armenian Association for Earthquake Engineering, the Vice-President of the International Association of CIS countries on Seismic Isolation, a Founding Member of the of *A*nti-*S*eismic *S*ystems *I*nternational *Soc*iety (*ASSISi*), a Member of the Saint-Petersburg Arctic Academy of Sciences, a Corresponding Member of Engineering Academy of Armenia, International Expert in Seismic Protection of Buildings and Structures of the Professional League of Experts of the CIS countries' Commission on Earthquake Resistant Construction and Disaster Reduction, an overseas Member of the Research Center of Earthquake Resistant Structures of the IIS, University of Tokyo, Founder of the "Save the Yerevan Schools from Earthquake" Foundation.