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New approach in design of seismic isolated buildings applying clusters of rubber bearings in isolation systems

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Abstract. The given paper presents a new approach in design of seismic isolation systems of base isolated buildings. The idea is to install not one big size rubber bearing under the columns and/or shear walls, or one by one with certain spacing under the load-bearing walls, but to install a group/cluster of small size bearings, in order to increase the overall effectiveness of the isolation system. The advantages of this approach are listed and illustrated by the examples. Also the results of analyses of some buildings where the approach on installation of clusters of rubber bearings was used in their isolation systems are given for two cases: i) when the analyses are carried out based on the provisions of the Armenian Seismic Code, and ii) when the time history analyses are carried out. Obtained results are compared and discussed. Paper also presents, as an example, detailed analysis and design of the 18-story unique building in one of the residential complexes in Yerevan. Earthquake response analyses of this building were carried out in two versions, i.e. when the building is base isolated and when it is fixed base. Several time histories were used in the analyses. Comparison of the obtained results indicates the high effectiveness of the proposed structural concepts of isolation systems and the need for further improvement of the Seismic Code provisions regarding the values of the reduction factors. A separate section in the paper dedicated to the design of high damping laminated rubber-steel bearings and to results of their tests.

Keywords: seismic isolation; new approach; cluster of small size bearings; base isolated buildings; analysis and design; seismic code; time history; fixed base building; comparison of results; design and tests of bearings

1. Introduction

During a period of the last 19 years about 46 buildings and structures have been designed in Armenia using seismic isolation technologies. Of these designed buildings the total number of already constructed and retrofitted buildings or those currently under construction has reached 38. It should be mentioned that seismic isolation in the country initially (1994-2001) developed mainly through the projects financed by international institutions (World Bank, UNIDO, Huntsman Corporation, Caritas Switzerland). However, the advantages of seismic isolation were so obvious that in the subsequent years great interest in application of this technology has been shown by private companies and even by the Government of Armenia.

Therefore, further development of seismic isolation continued (2002-2012) through the projects

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financed by the Hayastan All-Armenian Fund, private companies such as PCG International, LLC (USA), Elite Group, CJSC (Armenia), Tufenkian Hospitality, LLC (Armenia), ITARCO Construction CJSC (Armenia) as well as individuals who constructed their own houses and also by the governmental program for providing apartments for young families. The new approach in design of seismic isolation systems with installation of small size rubber bearings by clusters was elaborated and widely implemented in these projects. Given the local manufacturing of different types of rubber bearings, the developed seismic isolation techniques lead to significant savings in construction costs. Construction of ordinary (apartment) buildings and critical facilities (schools, hospitals, etc.) using seismic isolation costs 30-35% cheaper in comparison with the conventionally designed buildings. Much higher savings were attained in retrofitting of an apartment building and a school building. In these cases due to seismic isolation the cost of retrofitting was about two times less in comparison with the cost of conventional retrofitting. These facts attract the attention of the international professional community, of different institutions and private investors (The World Bank Implementation Completion Report 1997).

There are several reasons for the mentioned savings. One of them is that rubber bearings manufactured in Armenia cost significantly cheaper than bearings manufactured elsewhere in the world. This is conditioned by the lower labor cost, availability of rubber components in the country, as well as existence of several competing factories capable of manufacturing high quality rubber bearings with low (LDRB), medium (MDRB) and high (HDRB) damping. Also, the provisions of the Armenian Seismic Code for seismically isolated structures are much more progressive in comparison with, for example, the USA Code in terms of analysis and design of superstructures of base isolated buildings. As a result a huge amount of reinforcement could be reduced in superstructures of *R/C* base isolated buildings designed in accordance with the Armenian Code. In addition, cross-sections of the bearing structures (columns, beams, shear walls) are smaller, and there is no need to apply high strength concrete for them. Therefore, large amounts of concrete and cement may also be saved in superstructures.

Thus, successful implementation of seismic isolation technologies in the last 19 years, the presence of industry capable of local manufacture of seismic isolators, the presence of capable scientific and engineering brainpower for local development and design of seismic isolation systems, the possibility of retrofitting by seismic isolation without interruption of the use of the facilities (Melkumyan 2011), the low cost of retrofitting and new construction with seismic isolation, and the possibility of speeding up the retrofitting process fully justify further practical application of the advanced seismic isolation technologies in Armenia. Furthermore, worldwide experience proves that seismic isolation is the most reliable technology. Excellent examples demonstrating the effectiveness and high reliability of seismically isolated buildings during the destructive Hanshin-Awaji (Japan) earthquake in 1995 (Fujita 1999) and the Great Sichuan (China) earthquake in 2008 (Zhou *et al.* 2009) are well known.

2. The idea of applying clusters of small size rubber bearings

At the beginning stages of base isolation design and implementation for buildings in Armenia before 2001, the usual way was to install a single rubber bearing under each of the columns of a frame building or to place rubber bearings one by one with certain spacing under the load-bearing walls of the building (Whittaker and Robinson 2009, Garevski 2010, Martelli and Forni 2011). However, having analyzed and designed an increasing number of base isolated buildings and with

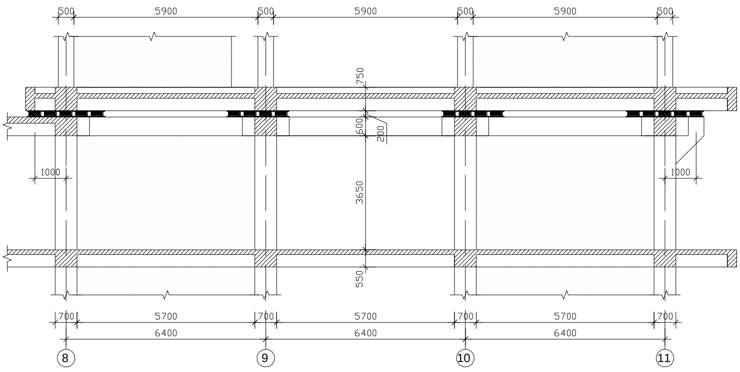


Fig. 1 Vertical elevation of the isolation system of 14-story building in "Arami" complex with the increased distance between the edge bearings

transition from low-story small buildings to large multistory buildings, as well as via thorough observations after the process of creating seismic isolation systems on the construction sites, the author of this paper gradually came to a conclusion that the better way is to use a cluster of small bearings instead of a single large bearing. This seemed beneficial also from the viewpoint of local manufacturing of rubber bearings.

What observations brought to this new idea? In designing base isolated structures very often the engineers have to deal with buildings that are irregular in their plan and along their height. Such asymmetry causes rotation to buildings as their center of mass does not coincide with the isolation system's center of rigidity. In this case if the isolation system consists of rubber bearings installed one by one under the columns or load-bearing walls, then it is difficult to avoid rotation, although, generally speaking, it is possible to do by using bearings with different horizontal stiffness (or different geometrical dimensions). But this is inconvenient in practical terms both for manufacturers and constructors. Also, the bearings installed one by one will not be uniformly loaded by the vertical forces (Moroni *et al.* 1998). The range of the vertical loads on bearings could be quite wide (Fuller *et al.* 2000) and again this will require application of bearings different by their rubber compounds and physical/mechanical characteristics. Another important factor which speaks in favor of installations of small size rubber bearings in clusters is that such bearings can be installed or replaced manually without using any mechanisms or expensive equipment. This is especially important during the execution of retrofitting works. Obviously, the space under the existing buildings to be retrofitted is usually narrow and machineries cannot operate inside such buildings to carry and install large and heavy isolators. Actually the same is true for newly constructed buildings if for some reason a need arises to replace the bearings.

It should be specially emphasized that installation of rubber bearings by clusters increases the seismic stability of base isolated buildings. Fig. 1 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). Moreover, it is both apparent and confirmed by comparative response analyses that in case of clusters of small rubber bearings the stresses and deformations from seismic impact would be distributed more evenly in the structural elements below and above the bearings without any significant concentration in one joint, as it is the case for one large bearing. Also, the use of small size bearings simplifies such construction processes as precise

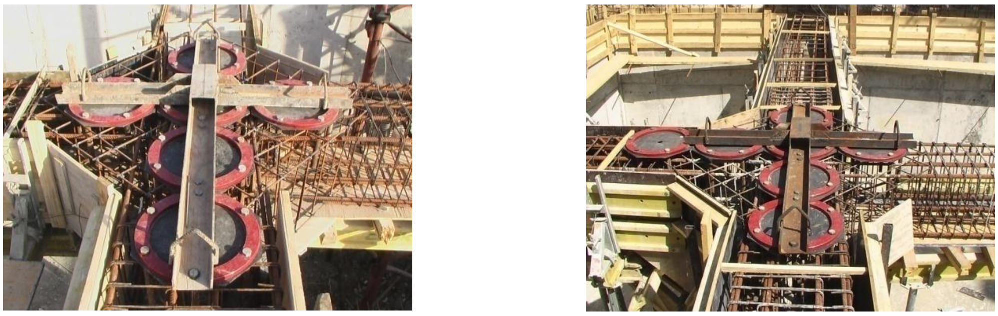


Fig. 2 Precise fixing of the isolator’s sockets in the design position using special conductors

Fig. 3 The concrete under the sockets of small size isolators is casted without difficulties and with high quality

Fig. 4 Construction process on installation of small size rubber bearings clusters

installation of isolator’s sockets, casting concrete under them and fixing them in the design position (Figs. 2-4). All these processes are much easier to implement at the construction site with a socket of small diameter than with a large one.

Thus, after 2001 a new approach in creation of seismic isolation systems by installing clusters of small rubber bearings instead of one large bearing was proposed (Melkumyan 2004, Melkumyan *et al.* 2005) and implemented in the design and construction of base isolated structures. Advantages of the proposed new approach are listed and discussed below. Original and innovative structural concepts for residential complexes, commercial/business centers, hotels, hospitals and schools were developed. Different quantities of seismic isolation rubber bearings have to be used under different columns of *R/C* frames and different shear walls of these buildings. Some examples are given in Fig. 5.

Fig. 5 Examples on installation of clusters with different numbers of rubber bearings

3. Examples illustrating advantages of the new approach on installation of clusters of small size rubber bearings instead of a single large size bearing

Based on the above observations, as well as on the analysis and design of a number of base isolated buildings, the following advantages of the new approach on installation of clusters of small size rubber bearings instead of a single large size bearing can be summarized (Foti and Mongelli 2011, Melkumyan 2011):

-increased seismic stability of the buildings;

-more uniform distribution of the vertical dead and live loads, as well as additional vertical seismic loads on the rubber bearings;

-small bearings can be installed manually, 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 of bearings in the seismic isolation plane.

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.

In order to illustrate the advantages of the suggested approach two base isolated buildings, namely “Sayat-Nova” and “Arami”, designed for construction in the city of Yerevan, were examined. These buildings were analyzed by several versions of installation of rubber bearings clusters. There is no need to bring here the results of all analyses, so only those of the last two versions for each of the considered buildings are presented and discussed below. Fig. 6 shows the plan of the isolators’ location in “Sayat-Nova” building according to a version conditionally referred to as “preceding version.” There are 250 isolators planned in this version. Some results of analysis for the preceding version are given in Table 1. The final version of the isolators’ location in “Sayat-Nova” building is shown in Fig. 7 and the results of analysis by this version are also presented in Table 1. The obtained results indicate that in the preceding version the difference in horizontal displacements along the axes “K” and “A” is 7.5 mm, which means rotation will occur in the isolation system for this version of isolators’ location. With the final version, the rotation is neutralized by changing the number and location of the isolators. The difference in horizontal displacements in this case is equal to 0.7 mm. Also, in the final version periods of the first mode of vibrations increase, whereas total shear forces and story drifts, as well as the number of isolators somewhat decrease. This means the proposed approach enables improving the overall effectiveness of the isolation system and achieving a more rational solution by manipulating the number and location of isolators.

The example of the “Arami” building is similar to the above described one. Fig. 8 displays the plan of isolators’ location for this building in the preceding version of design and analysis. The final version is illustrated in Fig. 9. Some results of the analyses for both versions are given in Table 2. For the preceding version of “Arami” building the difference in horizontal displacement

Table 1 Some results of the analyses by different versions for “Sayat-Nova” building

Parameters	Preceding version	Final version
Periods of the first mode of vibrations in transverse direction, sec	1.87	1.91
Periods of the first mode of vibrations in longitudinal direction, sec	1.90	1.95
Horizontal displacement along the axis “K”, mm	136	135.2
Horizontal displacement along the axis “A”, mm	128.5	134.5
Horizontal displacement along the axis “2”, mm	134.8	138.8
Horizontal displacement along the axis “7”, mm	133.8	137.8
Total shear force in transverse direction, kN	26760	26350
Total shear force in longitudinal direction, kN	26190	25830
Maximal story drift in transverse direction, mm	4.60	3.97
Maximal story drift in longitudinal direction, mm	6.40	6.07
Total number of seismic isolators	250	240
Number of isolators with vertical load of up to 1000 kN	109	97
Number of isolators with vertical load of 1000 - 1250 kN	126	105
Number of isolators with vertical load of over 1250 kN	15	38
Average vertical load per isolator, kN	548	571

Table 2 Some results of the analyses by different versions for “Arami” building

Parameters	Preceding version	Final version
Periods of the first mode of vibrations in transverse direction, sec	1.98	2.00
Periods of the first mode of vibrations in longitudinal direction, sec	1.95	1.96
Horizontal displacement along the axis “I”, mm	169.4	153.2
Horizontal displacement along the axis “A”, mm	150.4	155.5

Table 3 Some results of calculations for different base isolated buildings by the Armenian Seismic Code and by the time histories in transverse (X) direction

Name of building	By the Armenian seismic code			By the time histories		
	Q, kN	D, mm	Δ, mm	Q, kN	D, mm	Δ, mm
10-story “Our Yard” building, T=2.04 sec	20950	220	3.1	13037	133	2.1
11-story “Cascade” building, T=1.91 sec	21386	188	3.6	12583	112	2.3
14-story “Arami” building, T=2.00 sec	17860	218	4.3	11303	132	2.9
13-story “Dzorap” building, T=2.00 sec	12831	217	4.0	6970	130	2.0
17-story “Baghramian” building, T=2.46 sec	51810	259	5.7	25943	138	3.0
15-story “Avan” building, T=2.03 sec	44341	222	2.3	24068	106	0.9
17-story “Sevak” building, T=1.98 sec	32092	215	3.0	19838	100	1.4

along the axes “I” and “A” is 19 mm, while for the final version this difference is only 2.3 mm. This was also achieved by manipulating with the number of isolators and changing their location in plan of the isolation system.

4. Analyses of some base isolated buildings by Code requirements and by the time histories

4.1 Results of analyses of some buildings where the approach on installation of clusters of rubber bearings was used in their isolation systems

The earthquake response analyses carried out for different buildings have shown that in comparison with the fixed base buildings, seismic isolation significantly reduces the maximum spectral acceleration, also proving to be cost effective for the isolated structures and ensuring high reliability of their behavior under seismic impacts. All the sites where base isolated buildings are constructed in Armenia are located far enough from epicenters so that the effect of the vertical accelerations on the buildings is negligible. 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 story drifts in the

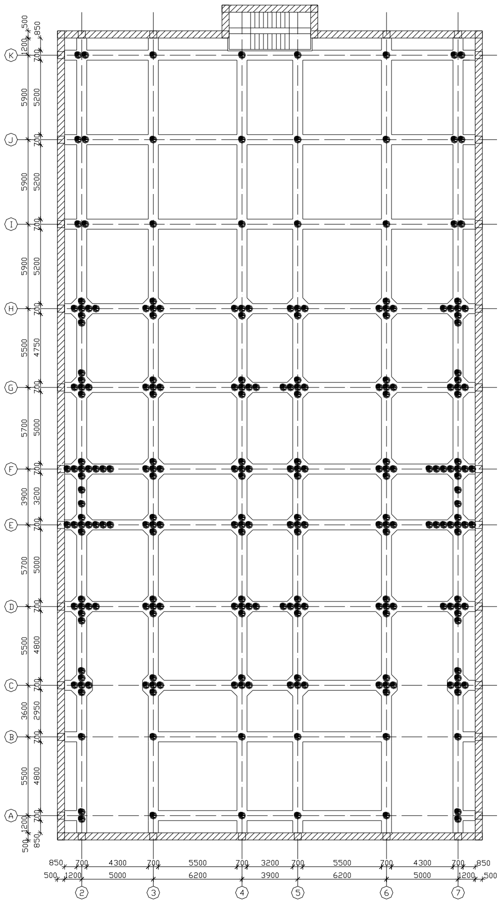


Fig. 6 Preceding version of the isolators' location plan in "Sayat-Nova" building

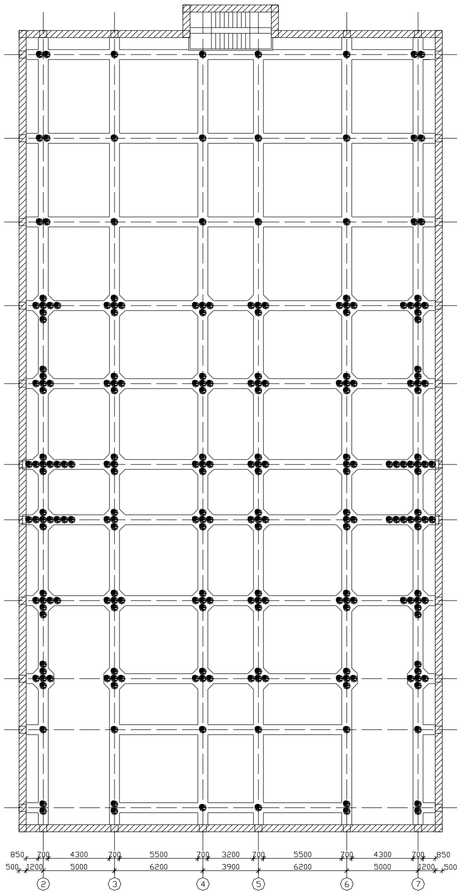


Fig. 7 Final version of the isolators' location plan in "Sayat-Nova" building

superstructures calculated based on the Armenian Seismic Code provisions are considerably higher than the same values calculated by the time histories. To demonstrate this, some results of calculations for different buildings are given in Table 3.

Q - horizontal shear force at the level of isolation system; *D* - maximum horizontal displacement of isolation system; Δ - maximum story drift in superstructure

Using the data of Table 3 the average values of *Q*, *D* and Δ were calculated for both cases and compared to each other. The results of comparison are as follows: horizontal shear forces calculated in accordance with the Code provisions are greater than those calculated by the time histories (Table 4) by 1.85 times, maximum horizontal displacements of isolation systems are larger by 1.89 times and maximum story drifts in superstructures – by 2.03 times in average. Obviously, the differences should have not been so large. This means some further steps should be taken to more realistically reflect the characteristics of seismically isolated buildings (including the reduction factors for isolation systems) in the design models for the calculations based on the Code (Melkumyan 2005, Saito 2006). For zone 3, where the expected maximum acceleration is equal to a=400 cm/sec^2 there are different permissible damage coefficients stipulated in the Code for base isolated structures. It is required to apply the permissible damage coefficient (reduction factor) of k_1=0.4 for superstructure and k_1=0.8 for seismic isolators and structures below the isolation plane.

Actually, the Code requires that any base isolated building 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. However, the data regarding the analyses of multistory buildings indicate that the displacements of isolation systems, inter-story drifts and horizontal shear forces obtained by calculations of the base isolated buildings by the Armenian Seismic Code are close to the same values obtained by the time history analyses when the permissible damage coefficient of k_1=0.4 is applied. In case if k_1=0.8, the Code based results are higher by a factor of about 2 in average. Therefore, the Code needs a more accurate designation of reduction factors for seismic isolation systems. At this stage it is suggested to accept k_1=0.6 for zone 3 in the next edition of the Code, as a compromise solution.

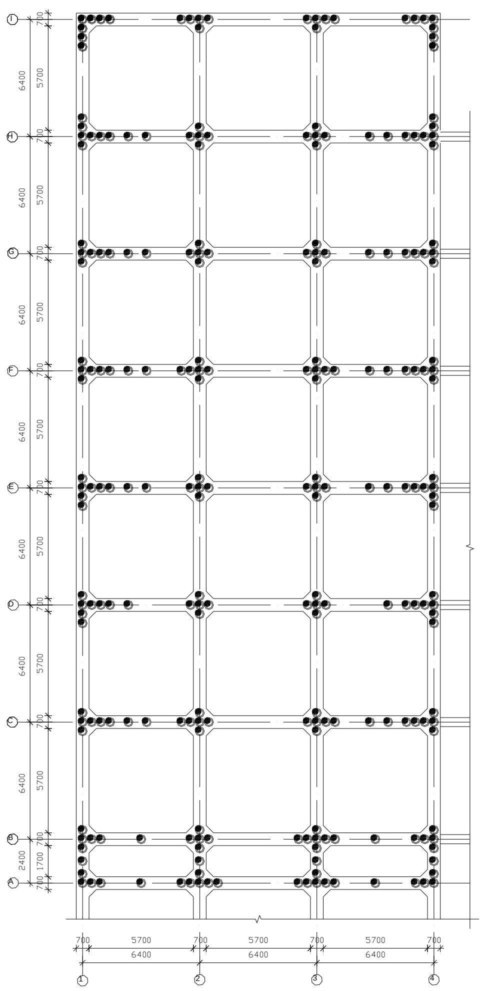


Fig. 8 The preceding version of the isolators' location plan in "Arami" building

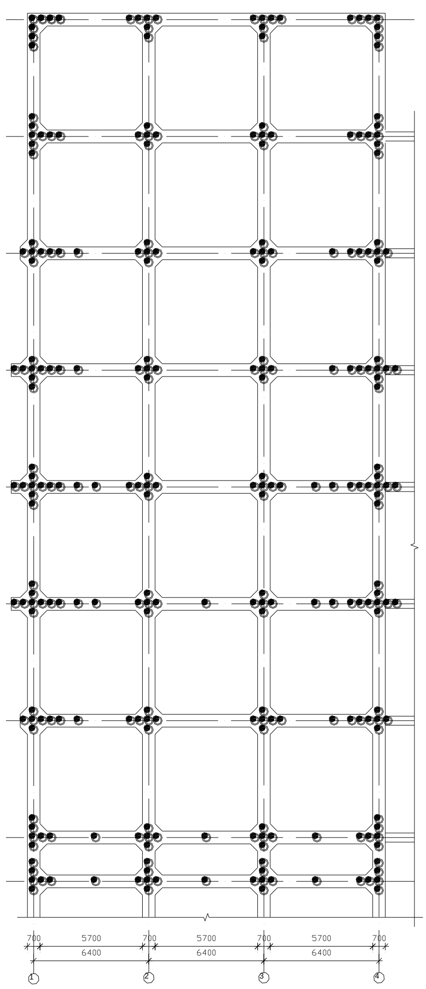


Fig. 9 The final version of the isolators' location plan in "Arami" building

4.2 Example on analysis and design of the 18-story residential complex “Northern Ray” with and without base isolation system

The project on analysis and design of the 18-story base isolated building of the multifunctional residential complex “Northern Ray” was accomplished in 2007. Construction of this complex is almost completed (Fig. 10). The considered building has one parking floor below the isolation plane designed using *R/C* strong and rigid structural elements. The cross sections of columns vary from 700×700 mm, 700×1000 mm to 700×1900 mm, and those of beams – from 700×600(h) mm to 700×650(h) mm. The thickness of shear walls is equal to 300-400 mm. The cross section of the foundation strips is 1000×1200(h) mm. The buildings are located on a very complicated terrain. The ground surface on the Northern side is about 9 m higher than on the Southern side. Therefore, a deep retaining wall was designed in order to provide free horizontal movement of the structure (Fig. 11). Both the elevators’ shafts and staircases in the building were also designed as the rigid cores with the thickness of their walls equal to 300 mm.

The accepted structural solution allowed obtaining a rigid system below the isolation plane and also the substantial rigidity was provided to the superstructure. This was achieved by using *R/C* columns with cross section of 500×500 mm and 600×600 mm and shear walls between them with the thickness of 160 mm. Along all exterior axes strong beams were designed with a cross section of 500×650(h) mm and along the interior axes the beams have cross section of 500×350(h) mm.

The thickness of *R/C* slabs was set at 150 mm for all floors. The elevators’ shafts and staircases in superstructure were designed in the same way as for the part of the building below the seismic isolation plane.

The building is designed in an unusual shape. This was dictated by architectural solution as the complex crowns the Northern Ray Street (Fig. 12) and serves as a great gate, opening a magnificent and majestic view of Mount Ararat from the North. Starting from the level of 17.45 m the building has a cantilever part the span of which increases towards the top of the building (Fig. 13).

Such a solution would have brought to significant complications if this building were to be designed with conventional foundations. Actually, nobody in the country agreed to the design this building. Only the structural concept suggested by the author of this paper, along with application of base isolation technology, made it possible to design and erect this structure, which is very interesting from the engineering point of view and quite unusual. In the considered building the

Fig. 10 Architectural design view of the 18-story base isolated buildings of the multifunctional residential complex “Northern Ray” from the Northern side and its current view from the Southern side

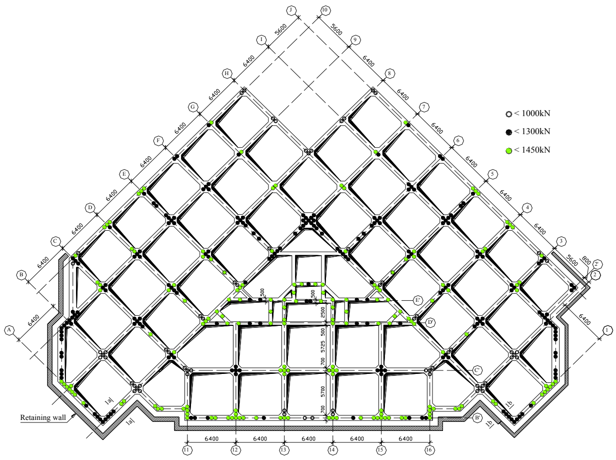


Fig. 11(a) distribution of vertical forces indicated by color-coded rubber bearings

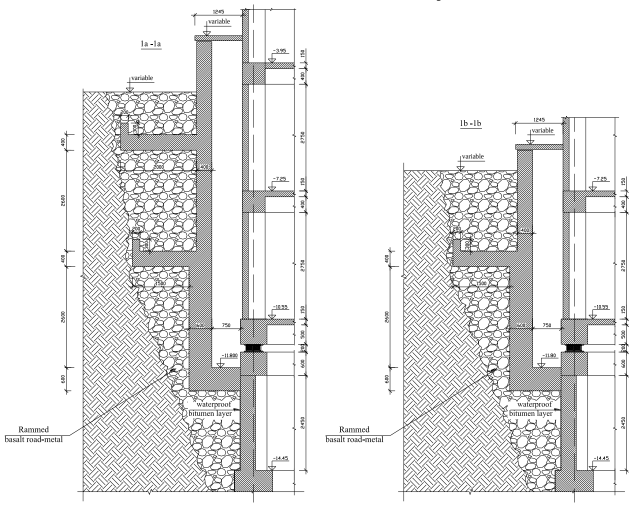


Fig. 11(b) vertical elevations of the retaining wall

Fig. 11 Plan of location of seismic isolation rubber bearings and the retaining wall

Fig. 12 Northern Ray Street in Yerevan with the view from South on the base isolated 18-story buildings at its end

approach to install clusters of small rubber bearings was used. It can be seen in Figs. 11a and 13 that different numbers of rubber bearings are installed under different columns and shear walls. All rubber bearings are of the same size and characteristics described below in Sections 5.1 and 5.2.

Earthquake response analysis of the considered building was carried using SAP 2000 non-linear program based on the developed design model shown in Fig. 14. 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. For the time history non-linear earthquake response analysis a group of accelerograms was used, including a synthesized accelerogram (Table 4). They were chosen in a manner that the predominant periods of the Fourier spectra do not exceed 0.5-0.6 sec as the soils in this construction site are classified based on the provisions of the Armenian Seismic Code as category II with the predominant period of vibrations of not more than 0.6 sec. Also the building was analyzed considering that it located in seismic zone 3 with the expected maximum acceleration of 0.4 g. Some results of calculations are given in Table 5 and Fig. 15.

It follows from the obtained results that the first mode vibrations' period of the base isolated building is longer than that for the fixed base building by a factor of 2.4 in transverse (*X*) direction and by a factor of 1.9 in longitudinal (*Y*) direction. Direct comparison of accelerations at the top level of the building shows that accelerations in the base isolated building are about 5 times smaller in average than in fixed base building. Results of calculations also show that inter-story drifts in base isolated building are in average 2.6 times smaller than those in fixed base building and horizontal shear forces are smaller by 2.3 times in average.

It also can be noticed that the displacements of isolation system, inter-story drifts and horizontal shear forces for the base isolated building obtained by calculations in accordance with the Armenian Seismic Code are close to the same values obtained by the time history analysis when the permissible damage coefficient (reduction factor) of k_1=0.4 is applied. However, in case if k_1=0.8 the Code based results are in average higher by a factor of 2.4. According to the Code requirements design horizontal displacement at the seismic isolation system level is determined by the formula

$$D = \left(\frac{T}{2\pi}\right)^2 a k_0 \frac{\beta(T)}{B(n)} k_1,$$

where: a is the expected values of the horizontal ground acceleration; k_0 is the soil conditions coefficient; $\beta(T)$ is the dynamic coefficient, which depends on soil category and the oscillation period. The values of the coefficient $B(n)$ depending on damping are given in the Code, and finally k_1 is the permissible damage coefficient equal to 0.8 for seismic zone 3 (a=400 cm/sec^2), which is typical for almost all of the territory of Armenia. Exactly this value is suggested to be decreased from 0.8 to 0.6 (see Section 4.1). This will make the results of calculations based on the Code provisions more reasonable. Code also stipulates that if eccentricity exists between the seismic isolation system centre of rigidity and the superstructure centre of mass, then the value of total design displacement with consideration of seismic isolators' torsion is equal to D_{total}=1.1D. The value of horizontal seismic transverse force generated during an earthquake at the top of the seismic isolators (base of the superstructure) is determined by the formula S=$K_{\text{eff}}\,D_{\text{total}}$, where K_{eff} is the total stiffness of the isolation system.

The strength analysis of elements connecting seismic isolators to the superstructure, as well as those to the foundation is performed under action of the above defined horizontal force. The design value of the horizontal seismic load S_K at the point k of the superstructure with weight Q_k is determined by the following formula

$$S_k = \frac{Sk_1 Q_k h_k}{\sum_{i-1}^{n} Q_i h_i},$$

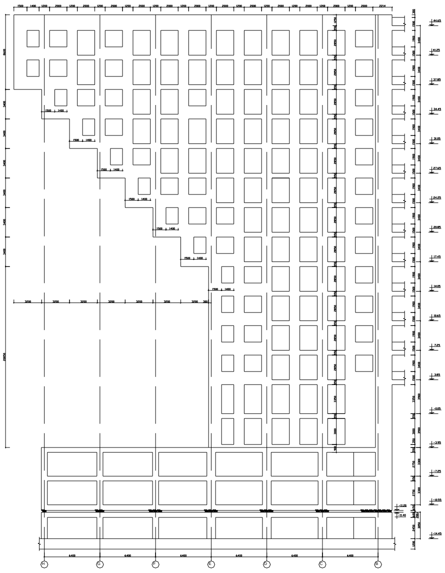


Fig. 13 Vertical elevation of the exterior frame by axis “9” of the 18-story base isolated building of the multifunctional residential complex “Northern Ray”

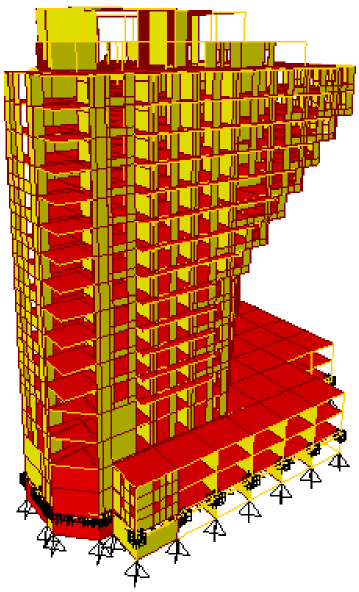


Fig. 14 Design model of the 18-story base isolated building of the multifunctional residential complex “Northern Ray”

Table 4 Acceleration time histories selected for earthquake response analysis of the 18-story base isolated building, scaled to 0.4 g

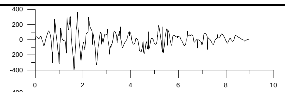
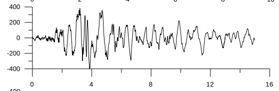
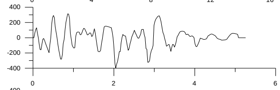
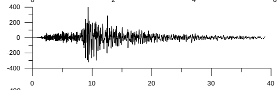
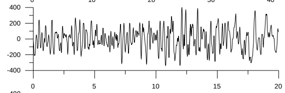
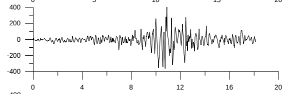
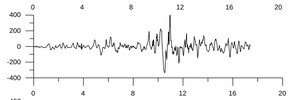
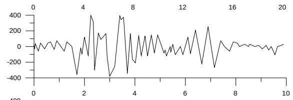
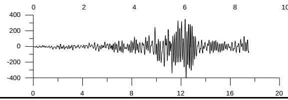
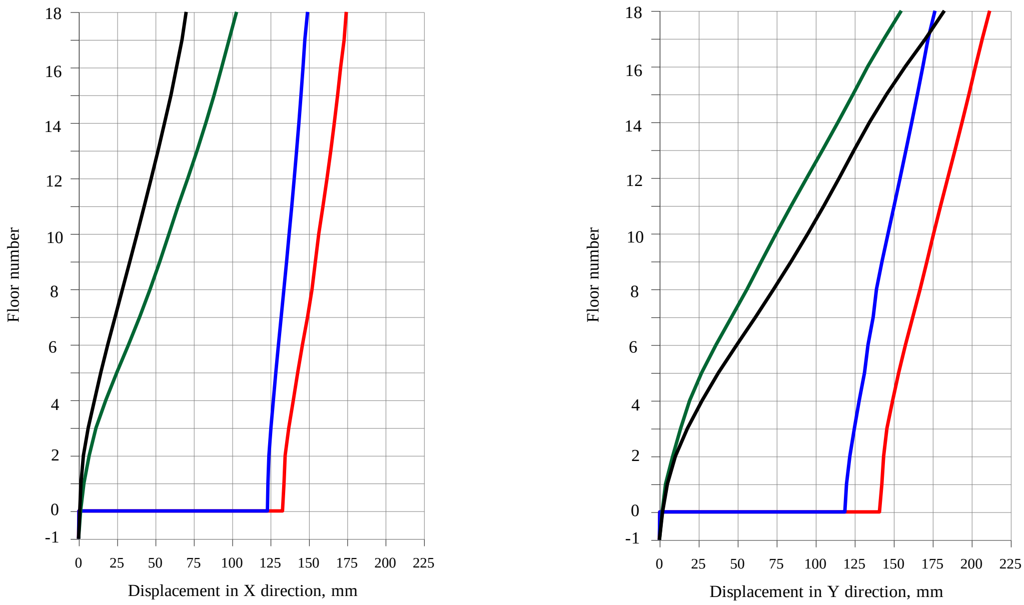
Earthquake and record component	Predominant period, sec	Duration, sec	View of accelerogram
09.03.49 Hollister (USA)	0.30	9	
15.04.79 Bar (former Yugoslavia) in horizontal EW direction	0.55	15	
21.12.54 Eureka (USA) horizontal NE direction	0.31	5	
17.12.87 Chiba (Japan) in horizontal NS direction	0.35	39	
20.06.90 Manjil (Iran)in horizontal NE direction	0.49	20	
7.12.88 Spitak (Armenia) in horizontal EW directionat Ashotsk station	0.43	18	
7.12.88 Spitak (Armenia)in horizontal NS directionat Ashotsk station	0.47	18	
17.10.89 Loma Prieta (USA)	0.34	10	
Synthesized acceleration time history (obtained by E. Gevorgyan in 2003)	0.26	18	

Table 5 Some results of analysis for the 18-story building of the multifunctional residential complex “Northern Ray” with and without seismic isolation

Design parameters	By the Armenian Seismic Code for:			
	base isolated building		fixed base building	
Period of vibrations (sec)	T_x=2.06	T_y=2.17	T_x=0.85	T_y=1.13
Inter-story drift (mm)	2.5 (k_1=0.4) 4.9 (k_1=0.8)	4.0 (k_1=0.4) 7.2 (k_1=0.8)	6.1 (k_1=0.4)	8.7 (k_1=0.4)
Horizontal shear force on the level of foundation (kN)	38786 (k_1=0.4) 96964(k_1=0.8)	41336 (k_1=0.4) 103339 (k_1=0.8)	93151 (k_1=0.4)	81452 (k_1=0.4)
Displacement of the isolation system (mm)	133 (k_1=0.4) 265 (k_1=0.8)	141 (k_1=0.4) 282 (k_1=0.8)	-	-
	Average by the time histories for:			
	base isolated building		fixed base building	
Inter-story drift (mm)	1.4	3.4	3.8	9.9
Horizontal shear force on the level of foundation (kN)	47667	49240	86042	152352
Displacement of the isolation system (mm)	123	118	-	-



fixed base building analyzed by Code
fixed base building analyzed by time histories
base isolated building analyzed by Code
base isolated building analyzed by time histories

Fig. 15 Floor displacements of the 18-story residential building with and without seismic isolation (k_1=0.4)

where: h_k is the height from the base of superstructure to the concentrated load Q_k. Thus, seismic forces in the Code are determined taking into account dynamic nature of the impact through application of the dynamic coefficients $\beta(T)$ and participation factors. However, in the final calculation of the building's bearing structures the determined seismic forces are applied statically.

It is also necessary to state that in none of the isolators the vertical force exceeds 1500 kN. Fig. 11(a) shows that thanks to the proposed approach of location of rubber bearings in the seismic isolation system, a more or less uniform distribution of the vertical loads was achieved. The differences in vertical loads for different isolators do not exceed the factor of 1.5 as required by the Code. Also rotation of the building in the horizontal plane is neutralized.

5. Design and testing of seismic isolation rubber bearings

5.1 Design of the bearings

Based on the carried out analyses for different buildings the high damping laminated rubber-steel bearings (HDRB) to be installed in clusters were designed. Table 6 summarizes the design details of the bearings. In all base isolated buildings constructed in Armenia the simple recess connection detail to fix the bearings was chosen. Such option necessitates a check that the bearings are safe against roll-out at the maximum horizontal displacement, with a due regard to the reduction in vertical load on some of the bearings attributable to the overturning of the building at large displacements. Geometrical dimensions of the designed HDRBs and their location in upper and lower recesses are shown in Fig. 16.

5.2 Bearing tests

The performance of the bearing design was checked by carrying out further tests. The bearings were subjected to QC tests using a single bearing testing facility soon after manufacture as well as two years later, during which time the bearings had stiffened very slightly. The degree of

Table 6 Design details of bearings

Parameters of laminated rubber-steel bearings	Values
Number of rubber layers	14
Number of internal metal plates	13
Thickness of rubber layers, mm	9
Thickness of internal metal plates, mm	2.5
Radius of internal metal plates, mm	180
Thickness of side cover layer, mm	10
Thickness of steel end-plate, mm	20
Thickness of end cover layer, mm	2
Overall height, mm	202.5
Overall diameter, mm	380
Rubber shear modulus	0.97
Static compressive stress (max), MPa	8.7
Critical load, kN	3260
Design vertical load	1500
Load for internal plate yield, kN	4800
Horizontal stiffness, kN/mm	0.81
Horizontal displacement at onset of roll-out, mm	
for design vertical load	300
for min. vertical load	260
Nominal vertical stiffness, kN/mm	400

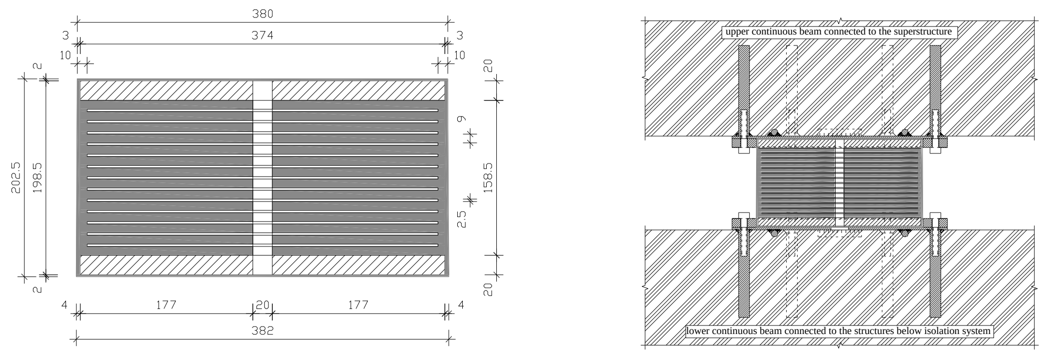


Fig. 16 Geometrical dimensions of the designed HDRBs and their location in upper and lower recesses provided by annular steel rings bolted to the outer steel plates connected to reinforcement in the upper and lower continuous beams

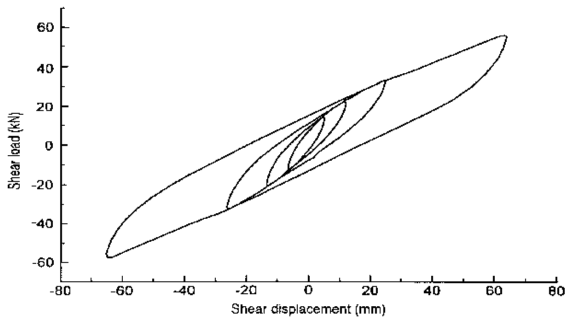


Fig. 17 Shear force-deflection loops for designed bearing. Test frequency 0.1 Hz. Nominal vertical load 500 kN

Table 7 Shear dynamic stiffness (K_s) and damping (d) of bearings

Displacement, mm	K_s, kN/mm	d%
6.5	2.20	19
13	1.60	17
26	1.30	16
65	0.87	14

stiffening (2-3%) over two years suggests a figure of 10-15% over a 50 year service life on the basis that stiffening proceeds approximately as $\sqrt{\text{time}^9}$; this would represent good long-term stability. The shear dynamic stiffness of bearings was measured over a range of rubber strains at a frequency of 0.1 Hz under a constant vertical load equal to 500 kN. These tests were carried out using a biaxial load-cell directly under the bearing. The magnitude of the vertical load applied was limited by the capacity of the biaxial load-cell, and thus the bearings could not be tested under the design vertical load; this should not have influenced the result significantly. The horizontal capacity of the dynamic test facility limited the rubber strain amplitudes to 50% (Fuller *et al.* 2000).

The sixth cycle force-displacement loops are given in Fig. 17. The corresponding stiffness and damping values are listed in Table 7 as functions of the displacement amplitude for all the tests.

The bearing stiffness is seen to decrease with increasing displacement. The stiffness at 50% of the design displacement (D) is 2.53 times smaller than at 0.05 D. The increased stiffness at small displacements reduces the movement of the building under wind loading without the need for additional wind restrain devices. In comparing the stiffness and damping with the original design values some allowance must be made for the test frequency of 0.1 Hz (cf. isolation frequency of 0.5 Hz). The small effect of frequency (2 to 4% increase between 0.1 and 0.5 Hz) can be obtained from tests on rubber specimens. The dynamic modulus of the particular batch of rubber used to fabricate the bearings was 7% above the target value (Table 6); this fact and the slight ageing over two years explain much of the discrepancy.

The observed dynamic stiffness of the bearings appears somewhat lower than expected. Using the test data for the variation of rubber shear modulus with strain to estimate a bearing stiffness at 100% rubber strain from the observed value at 50% strain, and making an allowance for the effect of test frequency and the reduced vertical load of 500 kN gives a dynamic stiffness of 0.73 kN/mm – 12% below the design value. The modulus of the rubber batch for bearings was 0.96

MPa (very close to the design requirement of 0.97 MPa). It therefore appears that calculation of the bearing horizontal stiffness from the rubber shear modulus and using the standard design equations worked less well. The reason may be that the modulus data from the rubber tests pieces correlates less well with the properties of the rubber within the bearing. The dynamic bearing tests confirmed the advisability of using a stiffer compound for bearings.

The damping of the bearings (after allowing for the effect of frequency and the reduction between 50 and 100% strain amplitude indicated by the measurements on rubber samples) is slightly greater than that obtained directly from tests at 100% strain on rubber samples. The bearings were finally tested quasistatically in shear under the vertical load of 820 kN up to the maximum horizontal displacement of 195 mm (Fig. 18(a)). The corresponding force-deflection plot (Fig. 18(b)) shows a slight stiffening at large deflection; there is no sign of an approach to the displacement capacity of the isolator.

Thus, a rubber compound suited to sites with severe winter temperatures has been developed. Dynamic tests on the bearings showed the performance of the design to be satisfactory. The bearing test result confirmed that their stiffness and damping is predicted reasonably well from the design equations and rubber properties, as measured on small tests pieces. The diagrams given

a. b.

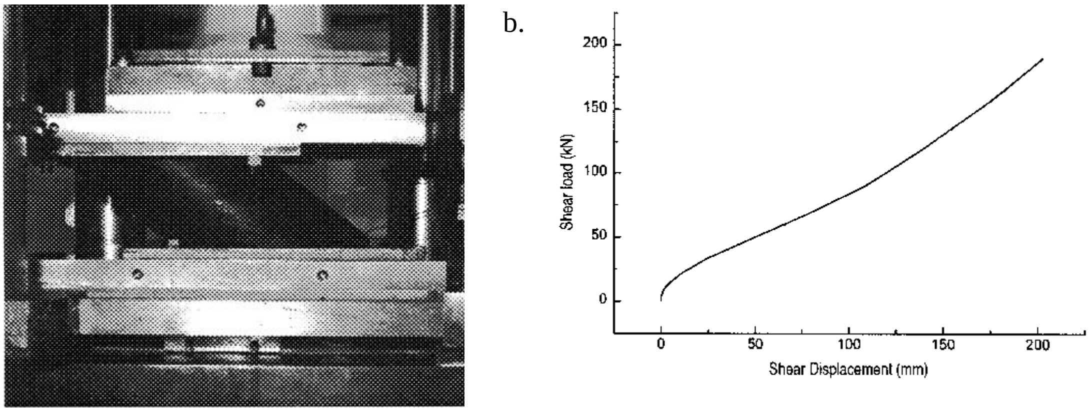


Fig. 18 Bearing tested under combined shear and compression (a) and quasistatic shear force-shear displacement curve for the bearing under constant vertical load of 820 kN (b)

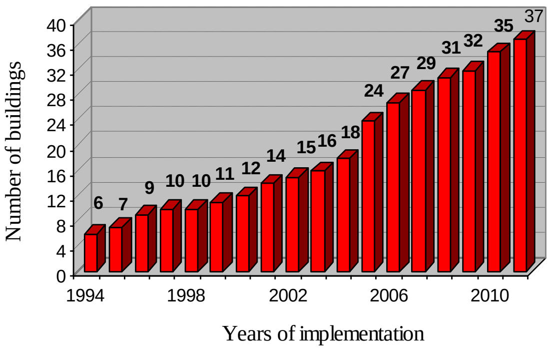


Fig. 19 Number of seismic (base and roof) isolated buildings, newly constructed or retrofitted in Armenia by years

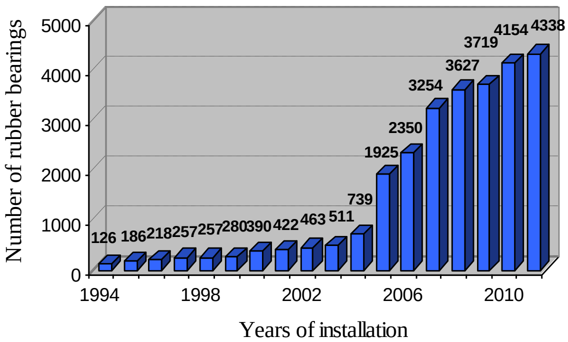


Fig. 20 Number of rubber bearings installed in the newly constructed or retrofitted buildings in Armenia by years

below (Melkumyan 2011) illustrate increase of the number of seismic isolated buildings (Fig. 19) and corresponding number of rubber bearings manufactured, tested and installed in Armenia by years (Fig. 20).

6. Conclusions

The new approach in design of seismic isolation systems of base isolated buildings by installation of clusters of small size rubber bearings under the columns and/or shear walls, or under the load-bearing walls is presented and the advantages of this approach are listed and illustrated by the examples. The obtained results indicate that due to the proposed approach the rotation in the buildings is neutralized, periods of the first mode of vibrations increase, whereas total shear forces and story drifts, as well as the number of isolators somewhat decrease. This means the proposed approach enables improving the overall effectiveness of the isolation system and achieving a more rational solution by manipulating the number and location of isolators.

The results of analyses of some buildings where the approach on installation of clusters of rubber bearings was used in their isolation systems are given for two cases: i) when the analyses are carried out based on the provisions of the Armenian Seismic Code, and ii) when the time history analyses are carried out. It was obtained that the shear forces at the level of isolation systems, the maximum displacements of the isolators, and the maximum story drifts in the superstructures calculated based on the Armenian Seismic Code provisions are considerably higher (by a factor of about 2 in average) than the same values calculated by the time histories. This means some further steps should be taken to more realistically reflect the characteristics of seismically isolated buildings (including the reduction factors for isolation systems) in the design models for the calculations based on the Code.

Detailed analysis and design of the 18-story unique residential building is described. Using 9 time histories earthquake response analyses of this building were carried out in two versions, i.e., when the building is base isolated and when it is fixed base. Comparison of the obtained average results indicates the high effectiveness of the proposed structural concept for the isolation system, the substructure and superstructure. Some information is given on the design of high damping laminated rubber-steel bearings and the results of their tests. The bearings were tested in shear under the constant vertical load up to the maximum horizontal displacement. The corresponding force-deflection plot shows a slight stiffening at large deflection; there was no sign of an approach to the displacement capacity of the isolator. Tests on the bearings showed the performance of the design to be satisfactory and confirmed that their stiffness and damping is predicted reasonably well.

The diagrams are given to illustrate increase of the number of seismic isolated buildings and corresponding number of rubber bearings manufactured, tested and installed in Armenia by years.

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