Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2017, 4(7):317-326**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Demonstration of the Cost-Effectiveness of Base Isolation Strategy on the Example of the 16-Story Reinforced Concrete Frame Buildings with Shear Walls

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Abstract Armenia is well known to the international professional community as a country where seismic isolation technologies are well developed and widely implemented due to research and design works of the author of this paper. Advantages of seismic (base or roof) isolation systems are obvious, however, clients are always interested to know also about the cost-effectiveness of these systems. Therefore, the relevant comparative analyses for the fixed base and base isolated buildings were carried out by the author in the past. In the given case, the client (private construction company "SpitakTnak" LLC), which is going to start a project on construction of a large residential complex, has requested to demonstrate the cost-effectiveness of base isolation strategy in case of its application in this project. With this purpose a comparative analysis of the construction cost of the bearing structures of a 16-story reinforced concrete (R/C)frame buildings with application of innovative base isolation technology vs. the construction cost of the same buildings with conventional design (fixed base)was carried out and presented. The fixed base buildings were designed by some architectural company unknown to the author and the sketches of this conventional design were kindly provided by the client to the author. Paper briefly describes the structural concepts of both buildings, namely, fixed base and base isolated. Obtained results have shown that due to application of base isolation the construction cost of the bearing structures of base isolated buildings could be reduced by about 40%.

Keywords Concrete Frame Buildings, Shear Walls

Introduction

The above Abstract stipulates that Armenia is well known to the international professional community as a country where seismic isolation technologies are well developed and widely implemented. Indeed, in [1] describing the activities of the World Bank financed Armenia Earthquake Zone Reconstruction Project it is emphasized that "…the housing subcomponent has established new technologies for the strengthening of existing structures, notably new techniques for installing seismic isolation systems in new and existing occupied buildings. The project is the world-wide pioneer for several techniques, andproject structures have attracted international professional attention by establishing appropriate low-cost technology methods for the strengthening of existing structures…".In [2] Armenia is mentioned among the few of developing countries where projects that apply low-cost base isolation systems for public housing have been successfully completed.

In [3] it is stated that "A historical building of an Irkutsk Bank needed retrofitting and upgrading as observation and analysis have brought to conclusions that seismic reliability of the building doesn't meet the current Seismic Building Code requirements. As a rule, jacks are used in the existing building for seismic isolation bearings installation. But in this case the method of Prof. Melkumyan was used. This method cost has proved to be lower in comparison with the cost of the traditional strengthening technologies. The reliability of the considered building with seismic isolation is considerably higher than that of a building with the conventional strengthening".As it is mentioned in [4] "…the number of new applications of innovative anti-seismic techniques, especially seismic isolation, is particularly large in Japan, P.R. China and Armenia…". "Some other countries are beginning to follow the excellent example of Armenia (…where seismic isolators are locally manufactured also for foreign markets…)"; "…an existing bank building at Irkutsk-City in Russia, retrofitted by applying the technology invented by Prof. Melkumyan in Armenia…".

Also in [5] it is stated that "In Armenia base isolation has been used to convert weak and vulnerable buildings to earthquake resistant structures". Reference is made to "…an existing five-story apartment building in Vanadzor, Armenia located in a highly active seismic zone. It was retrofitted with seismic isolators without interruption to building occupancy". In [6] it is specified that "In the developing countries, base isolation technique has rarely been used due to non-existence of domestic production of bearings and high cost of the bearings produced in the developed countries. In some of these countries, as is Indonesia, Iran and Algeria, there have been some attempts to popularize this technique through development of low-cost bearings and their installation in demonstration structures, but no attempt for production has been made and hence there hasn't been any mass application of such bearings. A greater success in application of base isolation (with isolation of a large number of buildings) was achieved in Armenia where, in addition to placement of isolators in buildings, their production was also adopted".

There is also a statement in the above Abstract that implementation of base isolation brings to significant reduction of the construction cost of bearing structures. In [7] it is mentioned that: "…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…".Some experts may argue saying that in many countries vice versa base isolation brings to increasing of the construction cost. However, in Armenia the picture is different.

There are several reasons declared in [7] related to the savings revealed in the base isolated structures. 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. Thus, 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, floor slabs) 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.

Although the benefits and advantages due to application of seismic isolation systems are clearly defined [8-9] and buildings furnished with such systems have demonstrated excellent behaviour [10-12], still an issue of the cost remains important to the developers and construction companies. The author of this paper has devoted some of his research works to this issue [13] and obtained perfect results which speak in favour of base isolation not only in Armenia. In addition to this research, a new analysis presented below has been carried out to reveal the cost-effectiveness of base isolation strategy on the example of the 16-story R/C frame building with shear walls.

Structural concepts of the 16-story fixed base and base isolated R/C frame buildings with shear walls

The large residential complex which is supposed to be constructed in Zeytun district of the city of Yerevan consists of three buildings. The sketches of the basement/parking floors, the ground floors and the typical floors are presented in Figures 1, 2, and 3. As it was mentioned abovethe sketches of this conventional design were provided to the authorby the client, namely, "SpitakTnak" LLC. According to the Armenian Earthquake Resistant Construction Design Code RABC II-6.02-2006 this residential complex was analyzed taking into account that it locates in the Zone 3 with PGA equal to 0.4g.

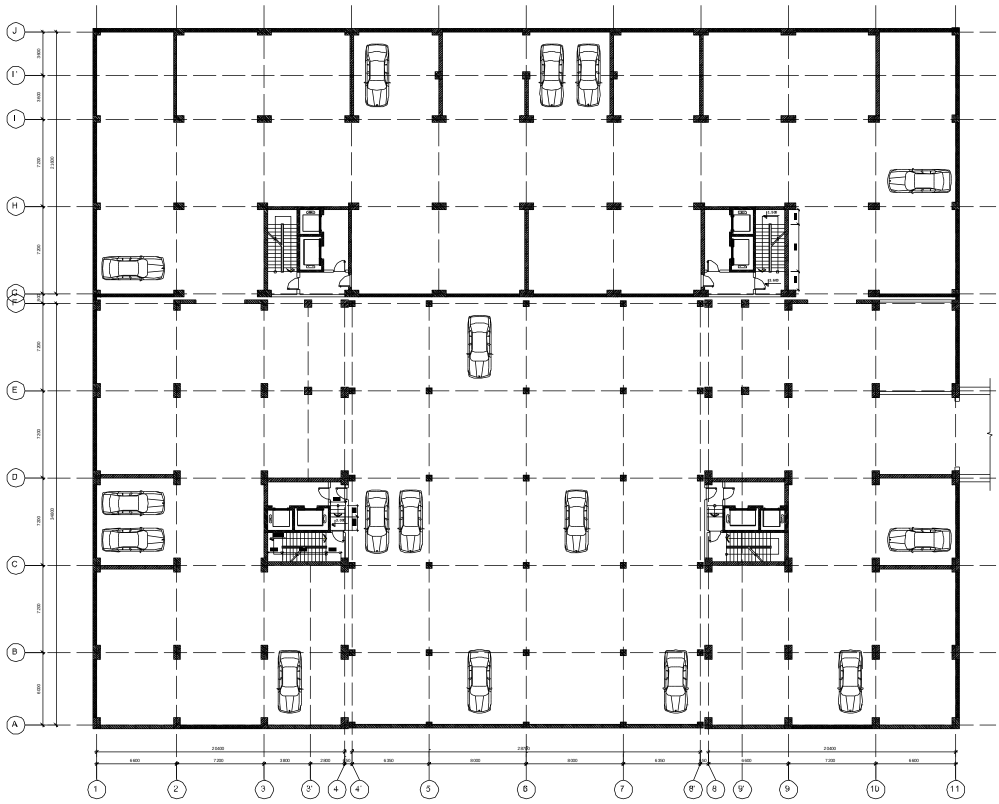

Figure 1: Plans of the basement/parking floorsof the 16-story fixed base R/C frame buildings with shear walls

From the given sketches one can see that in the fixed base building between the axes “1” - “4” and “A” - “F” the distance between the columns in transverse and longitudinal directions equals mainly to 7.2 m. However, the span between the axes “A” - “B” equals to 6.0 m and between the axes “1” - “2” and “3” - “4” – to 6.6 m. Columns have cross-section mainly 600×1200 mm, but along the axes “A” and “F” the cross-sections are equal to 600×900 mm. Consequently, all the beams in the building have width equal to 600 mm. The vertical elevation of this building is shown in Figure 4 from which it can be noted that the height of all floors’ beams is the same. It equals to 500 mm and the thickness of floors’ slabs – to 200 mm.

Location of the shear walls at the basement/parking floors differs from the location of these structural elements at the ground and typical floors. The matter is that at the level of the ground floors there was a need to provide the passages for the cars between the axes “A” - “B” and “E” - “F”. The thickness of the shear walls, however, does not change along the height of the building and equals to 300 mm. Vertical elevation also shows that foundation of the fixed base building consists of the strip beams with the cross-section of 900×1200(h) mm and a slab with the thickness of 300 mm.

The basement/parking floors (the foundation) consist of four separate parts. Three of them are under the buildings and the forth part between the axes “4′” - “8′” and “A” - “F” creates the area of the inside yard. Thus, being separated by specially envisaged gaps, this fourth part has its own one-story structural system. This was done because for Zone 3 the RABC II-6.02-2006 requires to design the buildings with the length in plan of not more than 60 m but in the given case the total length is a bit more than 70 m.

Extensive experience in design and construction of base isolated buildings in Armenia shows [7, 14, 15, 16] that under the impact of 0.4g acceleration at the level of foundation the superstructures of such buildings are experiencing only 0.14g-0.18g acceleration along their height. That is why the RABC II-6.02-2006 instructs to use the structural provisions for the base isolated buildings as if they located in Zone 1 with PGA equal to 0.2g. However, it must be underlined, that this is true in case if under the buildings there are hard soils which correspond to the category I or II of the Code. This means that, for example, the length in plan of the considered base isolated complex can be more than 60 m but not more than 80 m.

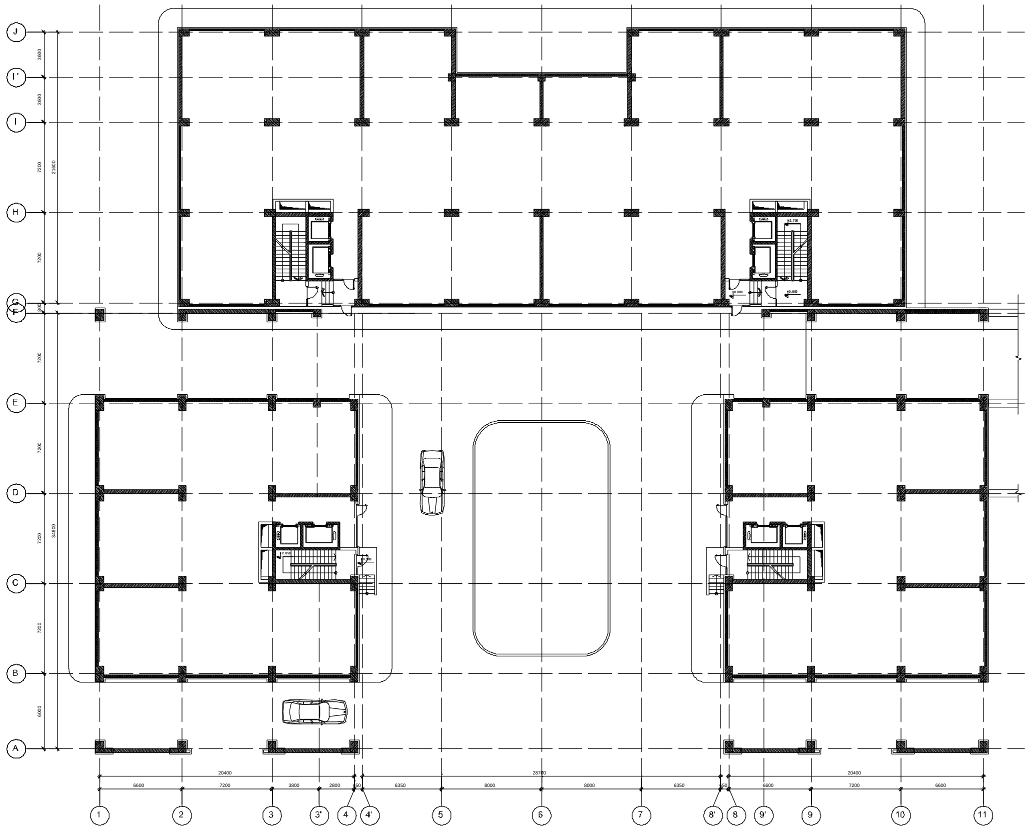

Figure 2: Plans of the ground floorsof the 16-story fixed base R/C frame buildings with shear walls

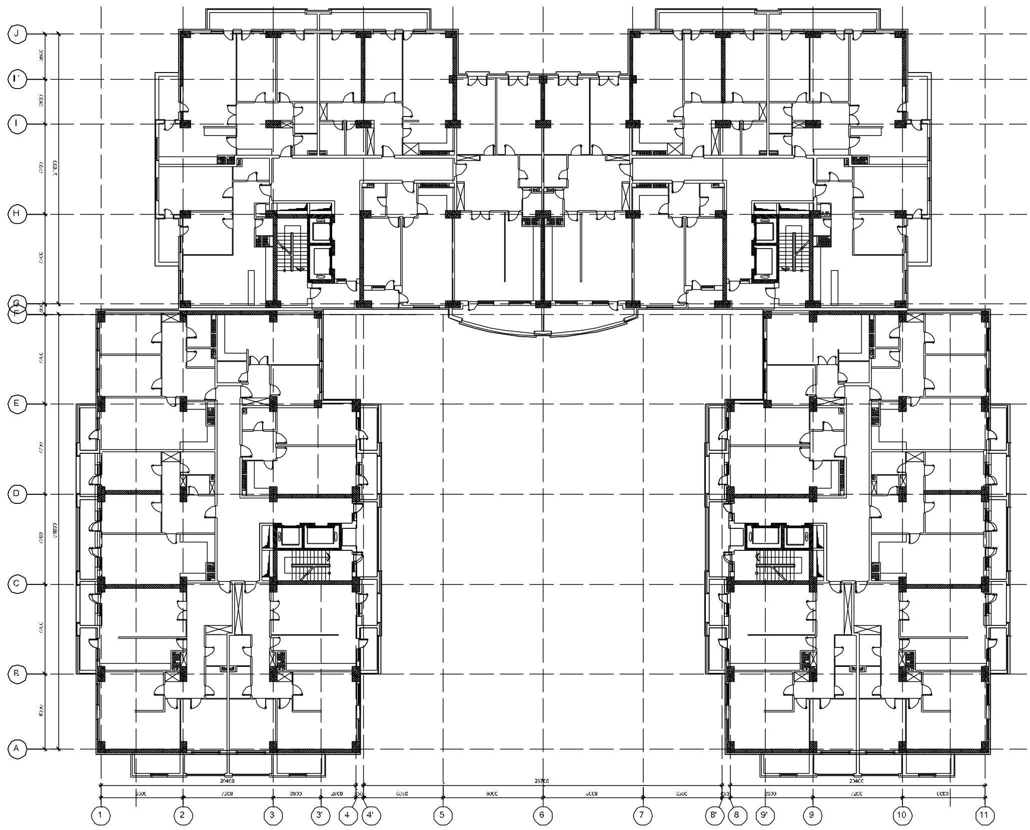

Figure 3: Plans of the typical floorsof the16-story fixed base R/C frame buildings with shear walls

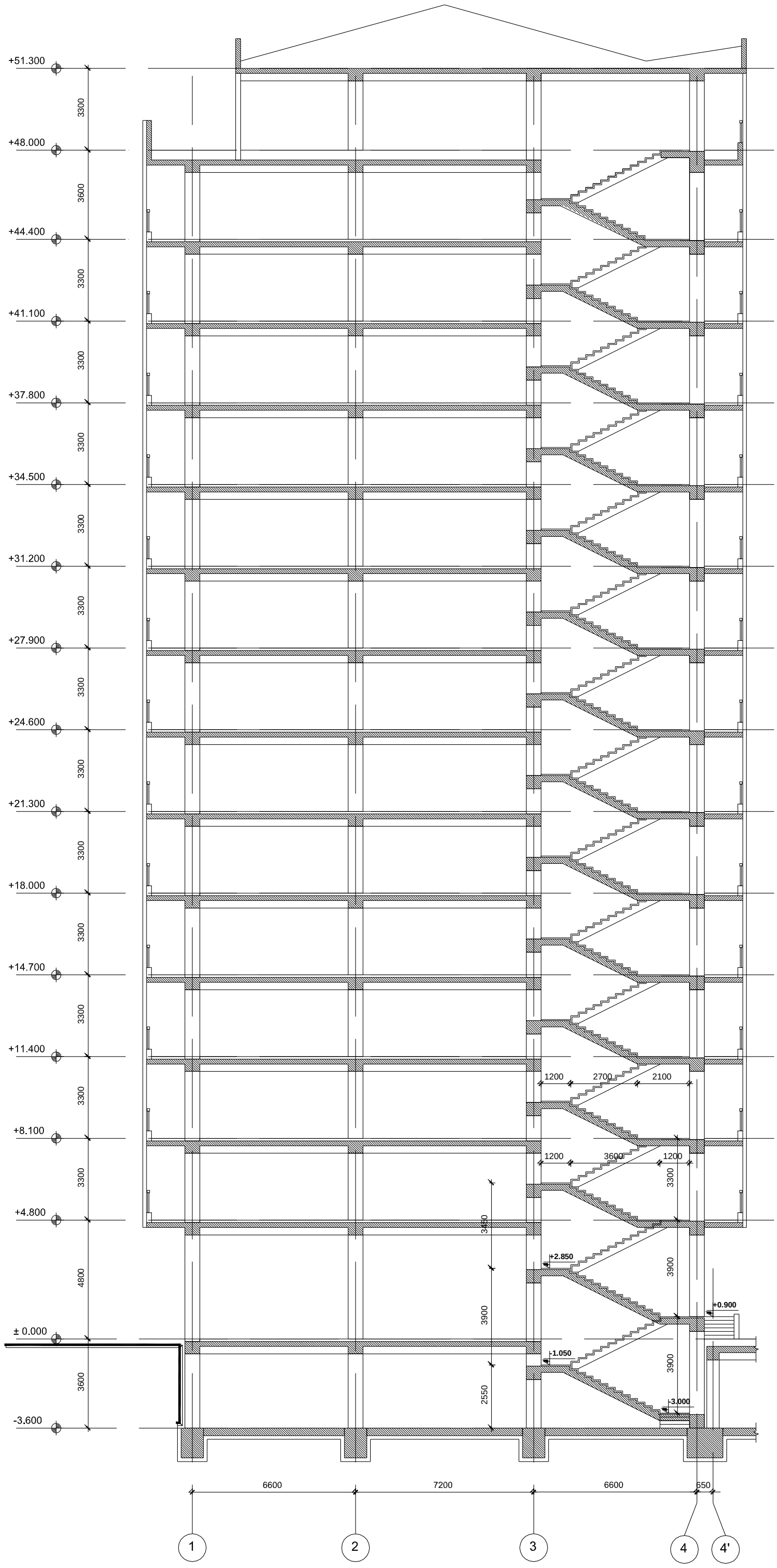

Figure 4: Vertical elevation in transverse direction of the 16-story fixed base R/Cframe building with shear walls located between the axes "1" - "4" and "A" - "F"

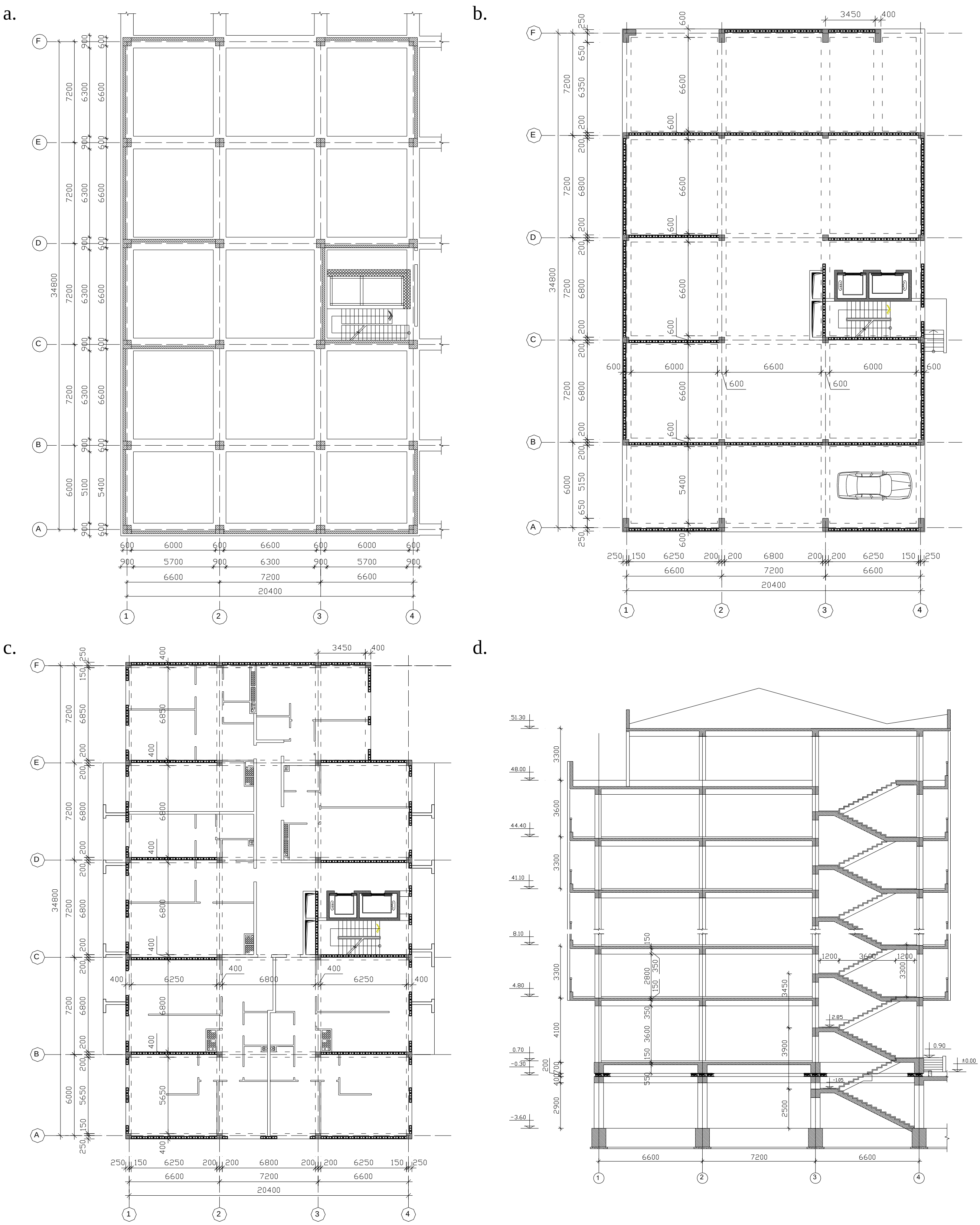

Figure 5: Plans of the basement/parking floor (a), ground floor (b), typical floors (c) and vertical elevation in transverse direction (d) of the 16-story base isolated R/C frame building with shear walls located between the axes "1" - "4" and "A" - "F"

The structural concept of the above described fixed base buildings was then converted into the concept of the base isolated buildings. As an example, the newly developed sketches of the basement/parking floor, the ground floor and the typical floors for the building located between the axes “1” - “4” and “A” - “F” are presented in Figure 5 a, b, and c. From these new sketches one can see that in the basement/parking floor of the base isolated building the columns have cross-section 600×600 mm. In the ground floor the columns have cross-section mainly 400×400 mm, but along the axes “A” and “F” the cross-sections are equal to 400×900 mm. Consequently, all the beams in the superstructure have width equal to 400 mm. The vertical elevation of this building is shown in Figure 5 d, from which it can be noted the height of all floors’ beams is the same. It equals to 500 mm and the thickness of floors’ slabs – to 150 mm. The base isolation system is designed within the basement/parking floor between the marks -0.70 and +0.60. All columns of this floor are connected at the mark -0.30 by the lower beams with the cross-section equal to 600×400(h) mm. Seismic isolators with the total number of 180 pieces are located by clusters above the lower beams. Location of the seismic isolators by clusters was proposed by the author and widely used in Armenia for construction of base isolated buildings [7, 17]. Then above the seismic isolators the upper beams with the cross-section equal to 600×700(h) mm are designed and structurally connected to each other in horizontal direction by a 150 mm thick slab.

Location of the shear walls at the basement/parking floor of the base isolated building again differs from the location of these structural elements at the ground and typical floors by the reason mentioned above. The thickness of the monolithic shear walls at the basement/parking floor now equals to 200 mm but at the ground and typical floors the shear walls of the base isolated building are totally different and represented by reinforced masonry walls. Such structural solutions for the shear walls were developed and applied by the author in different base isolated buildings [7, 15].

Vertical elevation in Figure 5 d also shows that foundation of the base isolated building consists of only the strip beams with the cross-section of 900×1200(h) mm. The carried-out analysis of the base isolated building has proved that there is no need to construct a thick slab at the level of foundation as it was done in case of the fixed base building. The basement/parking floor (the foundation) of the base isolated building in contrast to the fixed base building consists only of one part as the overall dimensions of the foundation (about 50×70 m) are within the allowable limits given in RABC II-6.02-2006. Thus, for the base isolated building there is no need to create the gaps, which were envisaged for the fixed base building, and to construct double columns along these gaps.

Comparative analysis of the expenditures of construction materials in the fixed base and base isolated buildings

Above was mentioned that the sketches of the fixed base building were given to the author of this paper by the client. Therefore, the volumes of the concrete for different structural elements of the fixed based building were calculated directly from the provided sketches (Tab. 1).To determine the volumes of the concrete for different structural elements of the base isolated building the latter was analyzed following the requirements of the RABC II-6.02-2006 and considering the same input parameters as for the fixed base building. Results of this analysis have led to the development of the structural concept, which has already beendescribed abovefor the base isolated building. Using obtained results and all dimensions of the different structural elements the volumes of the concrete for them in the base isolated building were calculated. They are also given in Table 1. Here the consumption of the steel in both types of buildings is given as well and it is necessary to explain how the consumption of the steel was calculated.

To date 58 seismic isolated buildings were designed in Armenia by the author of this paper. Of these designed buildings, the total number of already constructed and retrofitted buildings has reached 50. The number of seismically isolated buildings per capita in Armenia is one of the highest in the world [18]. Together with that seismic isolation laminated rubber-steel bearings (SILRSBs) different by their shape and dimensions, as well as by damping (low, medium and high) were designed and about 5000 SILRSBs were manufactured in the country, tested locally and applied in construction.Since 2003 seismic isolation technologies were designed and then extensively applied in construction of multi-story buildings. This means that large experience in Armenia is accumulated and gives a clear understanding on the magnitude of consumption of different construction materials in seismic isolated buildings. It is obvious that the same data is available for the fixed base buildings.

Particularly, expenditure of steel per 1 $m^3$of concrete in fixed base and in base isolated buildings equals to 160 kg and 105 kg in average, respectively. Thus, based on these average values the consumption of steel for both types of buildings was calculated and also given in the Table 1.

In Armenia the cost of the 1 m^3ofB25 and B20 grades concrete equals to $ 100 and $ 95, respectively and the cost of the 1 t of steel equals to $ 1000. The cost of 1 seismic isolator of diameter 380 mm and height 200 mm equals to $ 700 in average. Based on these data the total costs of concrete, steel and seismic isolators were also calculated and included in Table 1.From the obtained results, it is clear that application of base isolation reduces the cost of the bearing structure of the building by 39%. The greatest reduction of the concrete (3.8 times) takes place in the columns and base isolation brings to significant reduction of the consumption of steel by about 2.3 times. The volume of concrete in other structural elements reduces by a factor of 1.5 in average. Thus, given example proves once again that due to implementation of base isolation a huge quantity of the construction materials could be saved but in the same time the high reliability of the building could be achieved.

Table 1: Comparison of consumption and cost of the concrete and steel in the structural elements of the 16-story fixed base and base isolated R/Cframe buildings with shear walls located between the axes“1” - “4” and “A” - “F”

Structural elements		Fixed basebuilding (FBB)	Base isolatedbuilding (BIB)	FBB vs BIB volumes and costs’ ratio
Consumption of concrete	Foundation	431 m^3(B25)	270 m^3(B25)	1.6
	Columns	870 m^3(B25)	230 m^3(B20)	3.8
	Beams	1224 m^3(B25)	765 m^3(B20)	1.6
	Shear walls	659 m^3(B25)	487 m^3(B20)	1.4
	Slabs	1879 m^3(B25)	1470 m^3(B20)	1.3
	Beams below seismic isolators	-	62 m^3(B20)	-
	Beams above seismic isolators	-	109 m^3(B20)	-
Total consumption of concrete		**5063 m^3 (B25)**	**3393 m^3 (B20)**	**1.5**
Total consumption of steel		**810 t**	**356 t**	**2.3**
Total cost	of the concrete	$ 506,300	$ 322,000	1.6
	of the steel	$ 810,000	$ 356,000	2.3
	of the seismic isolators	-	$ 126,000	-
Total cost of construction materials for the whole building		**$ 1,316,300**	**$ 804,000**	**1.6**

Similar structural and comparative analyses were carried out also for the building located between the axes “1” - “11” and “G” - “J”. Its structural solution is the same as for above described building. That is why there is no need to repeat all the details and to bring similar sketches and vertical elevations of this building. Therefore, below the Table 2 is just given, where new volumes and costs calculated for the second building are presented. However, it is necessary to note that based on the structural analysis carried out for this building the total number of seismic isolators hereequals to 310 pieces.

Table 2: Comparison of consumption and cost of the concrete and steel in the structural elements of the 16-story fixed base and base isolated R/Cframe buildings with shear walls located between the axes “1” - “11” and “G” - “J”

Structural elements		Fixed basebuilding (FBB)	Base isolatedbuilding (BIB)	FBB vs BIB volumes and costs’ ratio
Consumption of	Foundation	884 m^3(B25)	534 m^3(B25)	1.7
	Columns	1337 m^3(B25)	349 m^3(B20)	3.8
	Beams	1920 m^3(B25)	1200 m^3(B20)	1.6

	Shear walls	1358 m^3(B25)	790 m^3(B20)	1.7
	Slabs	3369 m^3(B25)	2594 m^3(B20)	1.3
	Beams below seismic isolators	-	119 m^3(B20)	-
	Beams above seismic isolators	-	217 m^3(B20)	-
Total consumption of concrete		**8868 m^3 (B25)**	**5803 m^3 (B20)**	**1.5**
Total consumption of steel		**1419 t**	**609 t**	**2.3**
Total cost	of the concrete	$ 886,800	$ 551,300	1.6
	of the steel	$ 1,419,000	$ 609,000	2.3
	of the seismic isolators	-	$ 217,000	-
Total cost of construction materials for the whole building		**$ 2,305,800**	**$ 1,377,300**	**1.7**

Thus, is case of the second building application of base isolation reducing the cost of its bearing structure by 40%. The greatest reduction of the concrete (3.8 times) again takes place in the columns and base isolation brings to significant reduction of the consumption of steel also by 2.3 times. The volume of concrete in other structural elements reduces by a factor of 1.6 in average.

Conclusions

The cost-effectiveness of base isolation strategy on the example of the 16-story R/C frame buildings with shear walls is demonstrated based on the carried out structural and comparative analyses. Due to application of base isolation the construction cost of the bearing structures of base isolated buildings could be reduced by about 40%.

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