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Savings in Consumption of Concrete and Steel and in the Related Cost of Various Reinforced Concrete Frame Buildings with Shear Walls Due to Implementation of Base Isolation Strategy

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Abstract

In 2017 the author has published a paper "*Demonstration of the Cost-Effectiveness of Base Isolation Strategy on the Example of the 16-Story Reinforced Concrete Frame Buildings with Shear Walls*" [1]. This work described details on materials' and costs' savings for two base isolated buildings and has drawn the interest of many researchers and designers. They approached the author through the well-known scientific networks with the request to provide more information on this topic. To satisfy these multiple queries the below paper was prepared which presents data on savings in consumption of concrete and steel and in relevant cost of other three residential complexes due to implementation of base isolation strategy. Savings were revealed by comparison of base isolated buildings with the fixed base buildings. The key point is that all the three residential complexes with fixed base buildings were designed before they were given to the author with the request to redesign them applying seismic isolation systems. This gave the possibility to directly compare data on consumption of concrete and steel in new innovative and previous conventional designs.

Keywords: Base isolation; Reinforced concrete buildings; Structural concepts; Construction materials; Consumption; Savings.

1. Introduction

Since 2003 seismic isolation technologies in Armenia were designed and then extensively applied in construction of multi-story buildings. These were 10-18-story base isolated residential complexes "Our Yard", "Cascade" [2, 3], "Arami", "Dzorap" [4, 5], "Northern Ray" [6] and "Baghramian" [7], as well as a 20-story business center "Elite Plaza" [8]. These projects were designed in 2004-2008. The designs included floors for parking, offices, shopping centers, fitness clubs, etc. Also, a 15-story residential base isolated building "Avan" [9] was designed in 2010 within the framework of the governmental program for providing apartments for young families. Finally, a 17-story multifunctional complex "Sevak" was designed in 2011 [10]. Construction of all the mentioned complexes has already been completed. Their earthquake response analyses were carried out in two versions, i.e. when the buildings are base isolated and when they are fixed base. Several time histories were used in the analyses and for both cases the buildings were analyzed also according to the requirements of the Armenian Seismic Code. Comparison of the obtained results indicates the high effectiveness of the proposed structural concepts of isolation systems.

In the above-mentioned paper [1] the large residential complex currently under construction in Zeytun district of the city of Yerevan which consists of three buildings was considered. The sketches of the basement/parking floors, the ground floors and the typical floors, as well as vertical elevations were presented based on the conventional design and on the design with application of seismic (base) isolation system. From these sketches it follows that in conventionally designed buildings columns have cross-section mainly 600×1200 mm or 600×900 mm and all the beams in the buildings have width equal to 600 mm. 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 thickness of the shear walls, however, does not change along the height of the buildings and equals to 300 mm. Vertical elevations also show that foundation of the fixed base buildings consists of the strip beams with the cross-section of 900×1200(h) mm and a slab with the thickness of 300 mm above them.

The structural concept of these fixed base buildings was then converted into the concept of the base isolated buildings. From newly developed 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 and typical floors, the columns have cross-section mainly 400×400 mm and all the beams in the superstructure have width equal to 400 mm. The height of all floors' beams is the same (500 mm), but the thickness of floors' slabs equals to 150 mm. The base isolation system is designed within the basement/parking floor. Location of the shear walls at the basement/parking floor of the base isolated building differs from the location of these structural elements at the ground and typical floors of fixed base buildings and the thickness of the shear walls at the basement/parking floor now equals to 200 mm. However, 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 [8-10].

The brief information given above make it obvious that base isolation brings to significant decreasing of the cross sections of structural elements. The volumes of construction materials for different structural elements of the fixed base and base isolated buildings were calculated directly from the structural drawings developed for the both cases [1]. This allowed to make direct comparison of the obtained results, which have clearly shown that application of base isolation reduces the cost of the bearing structures of the above-mentioned buildings by 40% on average. 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 1.6 on average. Thus, given example proves 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 buildings could be achieved.

2. Expenditures of Construction Materials in the 16- And 10-Story Base Isolated Buildings of the Multifunctional Residential Complex "Our Yard" And Their Comparison with Expenditures in the Fixed Base Buildings of the Same Architectural Solutions

Base isolated buildings for the residential complex "Our Yard" were designed by the author of this paper in 2004-2005 (Fig. 1a) and their construction was completed in 2007 (Fig. 1b) in the city of Yerevan. This multifunctional complex consists of three buildings: one 16-story and two 10-story R/C frame buildings with shear walls. Previously these buildings, having the same architectural solutions, were designed by other engineers with the fixed base structural systems.

Foundations of the fixed base buildings were designed as a solid slab with the thickness of 1500 mm. Cross section of columns in the parking floors was 700x700 mm and in superstructures – 600x600 mm. Cross section of beams in the parking floors was 700x600(h) mm and in superstructures – 600x520(h) mm. Thickness of the floors' slabs at all levels of fixed base buildings was 200 mm. Thickness of shear walls in the parking floors was 400 mm and in superstructures – 300 mm.

However, in the base isolated buildings the concept of foundations was changed to the strip beams with the cross-section of 900×1500(h) mm. Cross section of columns in the parking floors was not changed, but in superstructures it was changed to 500x500 mm. Cross section of beams in the parking floors was changed to 700x500(h) mm and in superstructures – to 500x350(h) mm. Thickness of the floors' slabs at all levels of base isolated buildings was changed to 150 mm. Thickness of shear walls in the parking floors was changed to 300 mm and in superstructures – to 160 mm.

Consequently, due to application of base isolation strategy the volume of concrete in structural elements of the considered residential complex was reduced by a factor of 1.5 on average. In the same time the amount of steel was reduced by about 2.5 times. For comparison detailed data on consumption and cost of the construction materials in the different structural elements (including seismic isolators and the beams below and above them) are presented in Table 1.

The base isolation system is designed within the parking floors (basements). All columns of this floors at the level immediately below the seismic isolators are connected by so-called lower beams with the cross section 700×400(h) mm. No slab envisaged at this level. Seismic isolators with the total number of 464 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 [8-11]. Then immediately above the seismic isolators so-called upper beams with the cross section 700×750(h) mm are designed and structurally connected to each other in horizontal direction by a 150 mm thick slab.

As it is revealed from Table 1 by direct comparison, application of base isolation reduces the cost of the bearing structures of the whole multifunctional residential complex "Our Yard" by 41%.

Table-1. Comparison of consumption and cost of the concrete and steel in the structural elements of the 16- and 10-story R/C frame buildings with shear walls of the multifunctional residential complex "Our Yard" for two cases: when buildings are fixed base and base isolated

Structural Elements		Fixed Base Buildings	Base Isolated Buildings
Consumption of concrete	Foundation	3131(25)	1648 m^3 (B25)
	Columns	3148 m^3 (B25)	1499 m^3 (B20)
	Beams	4254 m^3 (B25)	2488 m^3 (B20)
	Shear walls	2715 m^3 (B25)	1939 m^3 (B20)
	Slabs	4308 m^3 (B25)	3282 m^3 (B20)
	Beams below seismic isolators	-	334 m^3 (B25)
	Beams above seismic isolators	-	705 m^3 (B25)
Total consumption of concrete		17556 m^3	11895 m^3
Total consumption of steel		2635 t (150kg/m^3)	1071 t (90kg/m^3)
Total cost	of concrete	$ 1,773,156	$ 1,179,500
	of steel	$ 2,239,750	$ 910,350
	of seismic isolators	-	$ 270,200

Total cost of construction materials for the whole building	$ 4,012,906	$ 2,360,050
Savings comprise		41%

3. Expenditures of Construction Materials in the 15-Story Base Isolated Building of the Multifunctional Residential Complex "Avan" and Their Comparison with Expenditures in the Fixed Base Building of the Same Architectural Solution

Base isolated building for the residential complex "Avan" was designed by the author in 2010 (Fig. 2a) and its construction was completed in 2013 (Fig. 2b) in the city of Yerevan. This multifunctional complex consists of one 15-story R/C frame building with shear walls, which includes a ground floor (below the seismic isolation plane) envisaged for shops and offices. Previously this building, having the same architectural solution, was designed by other engineer with the fixed base structural system.

Foundation of the fixed base building was designed as a solid slab with the thickness of 1500 mm. Cross section of columns in the ground floor was 700x700 mm and in superstructure – 600x600 mm. Cross section of beams in the ground floor was 700x600(h) mm and in superstructure – 600x520(h) mm. Thickness of the floors' slabs at all levels of fixed base building was 200 mm. Thickness of shear walls in the ground floor was 400 mm and in superstructure – 300 mm.

However, in the base isolated building the concept of foundation was changed to the strip beams with the cross section of 800×1500(h) mm. Cross section of columns in the ground was changed to 600x600 mm, but in superstructure it was changed to 400x400 mm. Cross section of beams in the ground floor was changed to 600x500(h) mm and in superstructure – to 400x350(h) mm. Thickness of the floors' slabs at all levels of base isolated building was changed to 120 mm. Thickness of shear walls in the ground floor was changed to 200 mm and in superstructure – to 160 mm.

Consequently, due to application of base isolation strategy the volume of concrete in structural elements of the considered residential complex was reduced by a factor of 1.5 on average. In the same time the amount of steel was reduced by about 2.4 times. For comparison detailed data on consumption and cost of the construction materials in the different structural elements (including seismic isolators and the beams below and above them) are presented in Table 2.

The base isolation system is designed within the ground floor. All columns of this floor at the level immediately below the seismic isolators are connected by so-called lower beams with the cross-section 600×400(h) mm. No slab envisaged at this level. Seismic isolators with the total number of 247 pieces are located also by clusters above the lower beams. Then immediately above the seismic isolators so-called upper beams with the cross-section 600×750(h) mm are designed and structurally connected to each other in horizontal direction by a 120 mm thick slab.

As it is revealed from Table 2, application of base isolation reduces the cost of the bearing structures of the multifunctional residential complex "Avan" by 35%.

4. Expenditures of Construction Materials in the 17-Story Base Isolated Building of the Multifunctional Residential Complex "Sevak" and Their Comparison with Expenditures in the Fixed Base Building of the Same Architectural Solution

Base isolated building for the residential complex "Sevak" was designed by the author in 2011 (Fig. 3a) and its construction was completed in 2014 (Fig. 3b) in the city of Yerevan. This multifunctional complex consists of one 17-story R/C frame building with shear walls, which includes two parking floors and a ground floor (below seismic isolation plane) envisaged for shops and offices. Previously this building, having the same architectural solution, was designed by other engineer with the fixed base structural systems.

Foundation of the fixed base building was designed as a solid slab with the thickness of 1500 mm. Unlike the buildings described above, at the time when the author started redesigning of this building applying seismic isolation system, the mentioned foundation of the fixed base building was almost constructed. That is why practically no changes were applied to the previously designed foundation. Cross section of columns in the parking and ground floors was 750x750 mm and in superstructure – 600x600 mm. Cross section of beams in the parking and ground floors was 700x600(h) mm and in superstructure – 600x520(h) mm. Thickness of the floors' slabs at all levels of fixed base building was 200 mm. Thickness of shear walls in the parking and ground floors was 400 mm and in superstructure – 300 mm.

Table-2. Comparison of consumption and cost of the concrete and steel in the structural elements of the 15-story R/C frame building with shear walls of the multifunctional residential complex “Avan” for two cases: when building is fixed base and base isolated

Structural Elements		Fixed Base Building	Base Isolated Building
Consumption of concrete	Foundation	825 m^3 (B25)	450 m^3 (B25)
	Columns	567 m^3 (B25)	363 m^3 (B20)
	Beams	1387 m^3 (B25)	853 m^3 (B20)
	Shear walls	747 m^3 (B25)	534 m^3 (B20)
	Slabs	1940 m^3 (B25)	1212 m^3 (B20)
	Beams below seismic isolators	-	76 m^3 (B25)
	Beams above seismic isolators	-	149 m^3 (B25)
Total consumption of concrete		5466 m^3	3637 m^3
Total consumption of steel		765 t (140kg/m^3)	346 t (95 kg/m^3)
Total cost	of concrete	$ 546,600	$ 345,515
	of steel	$ 688,500	$ 311,400
	of seismic isolators	-	$ 148,200
Total cost of construction materials for the whole building		$ 1,235,100	$ 805,515
Savings comprise			35%

However, in the base isolated building cross section of columns in the parking and ground floors was changed to 650x650 mm, but in superstructure it was changed to 400x400 mm. Cross section of beams in the parking and ground floors was changed to 600x500(h) mm and in superstructure – to 400x350(h) mm. Thickness of the floors' slabs at all levels of base isolated building was changed to 120 mm. Thickness of shear walls in the parking and ground floors was changed to 300 mm and in superstructure – to 160 mm.

Consequently, due to application of base isolation strategy the volume of concrete in structural elements of the considered residential complex was reduced by a factor of 1.3 on average. In the same time the amount of steel was reduced by about 2.0 times. For comparison detailed data on consumption and cost of the construction materials in the different structural elements (including seismic isolators and the beams below and above them) are presented in Table 3.

The base isolation system is designed within the ground floor. All columns of this floors at the level immediately below the seismic isolators are connected by so-called lower beams with the cross-section 650×500(h) mm. No slab envisaged at this level. Seismic isolators with the total number of 184 pieces are located again by clusters above the lower beams. Then immediately above the seismic isolators so-called upper beams with the cross-section 650×700(h) mm are designed and structurally connected to each other in horizontal direction by a 150 mm thick slab.

As it is revealed from Table 3, application of base isolation reduces the cost of the bearing structures of the multifunctional residential complex “Sevak” by 32%.

Table-3. Comparison of consumption and cost of the concrete and steel in the structural elements of the 17-story R/C frame building with shear walls of the multifunctional residential complex “Sevak” for two cases: when building is fixed base and base isolated

Structural Elements		Fixed Base Building	Base Isolated Building
Consumption of concrete	Foundation	910 m^3 (B25)	865 m^3 (B25)
	Columns	474 m^3 (B25)	360 m^3 (B20)
	Beams	1074 m^3 (B25)	579 m^3 (B20)
	Shear walls	1108 m^3 (B25)	857 m^3 (B20)
	Slabs	2258 m^3 (B25)	1768 m^3 (B20)
	Beams below seismic isolators	-	60 m^3 (B25)
	Beams above seismic isolators	-	102 m^3 (B25)
Total consumption of concrete		5824 m^3	4591 m^3
Total consumption of steel		943 t (162kg/m^3)	468 t (102 kg/m^3)
Total cost	of concrete	$ 582,420	$ 436,145
	of steel	$ 848,700	$ 421,200
	of seismic isolators	-	$ 112,240
Total cost of construction materials for the whole building		$ 1,431,120	$ 969,585
Savings comprise			32%

5. Conclusions

Savings in consumption of concrete and steel and in the related cost on the examples of the 10-, 15-, 16- and 17-story R/C frame buildings with shear walls are calculated/demonstrated based on the carried out comparative analyses for two cases: when buildings are fixed base and base isolated.

Due to application of base isolation strategy:

- The construction cost of the bearing structures of one 16-story and two10-story buildings of the multifunctional residential complex “Our Yard” is reduced in total by 41%. This reduction is a result of decreasing of structural elements’ cross sections and of required amount of reinforcement. The volume of concrete in structural elements of the considered residential complex is reduced by a factor of 1.5 on average. In the same time the amount of steel is reduced by about 2.5 times.

- The construction cost of the bearing structures of 15-story building of the multifunctional residential complex “Avan” is reduced by 35%. The volume of concrete in structural elements of the considered residential complex is reduced by a factor of 1.5 on average. In the same time the amount of steel is reduced by about 2.4 times.

- The construction cost of the bearing structures of 17-story building of the multifunctional residential complex “Sevak” is reduced by 32%. The volume of concrete in structural elements of the considered residential complex is reduced by a factor of 1.3 on average. In the same time the amount of steel is reduced by about 2.0 times. The less degree of reduction in this case is conditioned by the fact that foundation of this building, as it was designed for the fixed base case, was almost constructed. Thus, it was impossible to make changes to foundation when the mentioned building was redesigned and then constructed with application of seismic isolation system.

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Figure-1. Design (a) and completed (b) views of the 16- and 10-story base isolated buildings in the multifunctional residential complex "Our Yard"

a.

b.

Figure-2. Design (a) and completed (b) views of the 15-story base isolated building in the multifunctional residential complex "Avan"

a.

b.

Figure-3. Design (a) and completed (b) views of the 17-story base isolated building in the multifunctional residential complex "Sevak"

a.

b.