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CHANGE OF STRUCTURAL CONCEPT AND NUMBER OF STORIES OF A BUILDING UNDER CONSTRUCTION WITH APPLICATION OF THE ROOF ISOLATION SYSTEM EXCLUDING STRENGTHENING OF ALREADY CONSTRUCTED BEARING STRUCTURES

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ABSTRACT: *One of the key features of anti-seismic design of buildings is the possibility to control inertial load values depending on the structural concept of the buildings. In the 1950s, when the spectral theory of seismic stability was developed, the flexible ground floor was regarded as the basic approach for reducing the seismic action level. However, the consequences of strong earthquakes such as the 1963 Skopje, the 1988 Spitak or the 2008 Sichuan Earthquakes, etc. have shown that in this case the bearing structures (mainly columns) of the ground floors were severely damaged and further use of buildings was impossible despite the upper floors were well preserved. Therefore, continuing efforts are made by researchers to determine the most efficient methods of seismic protection of buildings for their practical application. One of these methods is the application of tuned mass damper (TMD), a passive vibro-protecting device, known as a single degree-of-freedom appendage of the primary structure. Dampers have been widely investigated in connection with seismic protection problems. The author of this paper has already accumulated considerable experience in protecting of existing buildings by application of innovative seismic isolation technologies in the form of additional isolated upper floors (AIUF), as well as in the form of isolated upper slabs (IUS). These concepts represent the roof isolation technology. Developed structural solutions of AIUF or IUS are bringing to creation of diverse types of TMDs on the top of the existing buildings. Such systems give the opportunity to efficiently control the vibrations. Based on this experience the number of suggestions were made which allowed to solve the set task for the building under consideration in the given paper. Structural concept of earthquake protection system designed for application in the existing reinforced concrete building together with some other measures is described. The building is currently under construction in the city of Yerevan, the capital of Armenia. This research and design work are unique as for the first time in construction practice substantial changes to the initial design were requested in the course of construction works.*

KEYWORDS: Structural Concept, Story Building Under Construction, Load Bearing Structures, Roof Isolation System

INTRODUCTION

One of the key features of anti-seismic design of buildings is the possibility to control inertial load values depending on the structural concept of the buildings. In the 1950s, when the spectral theory of seismic stability was developed, the flexible ground floor was regarded as the basic approach for reducing the seismic action level. However, the consequences of strong earthquakes such as the 1963 Skopje, the 1988 Spitak or the 2008 Sichuan Earthquakes, etc. have shown that in this case the bearing structures (mainly columns) of the ground floors were severely damaged and further use of buildings was impossible despite the upper floors were well preserved. Therefore, continuing efforts are made by researchers to determine the most efficient methods of seismic protection of buildings for their practical application. One of these methods is the application of tuned mass damper (TMD), a passive vibro-protecting device, known as a single degree-of-freedom appendage of the primary structure [1]. Dampers have been widely investigated in connection with seismic protection problems [2, 3, 4, and 5].

The author of this paper has already accumulated considerable experience in protecting of existing buildings by application of innovative seismic isolation technologies in the form of additional isolated upper floors (AIUF) [6, 7], as well as in the form of isolated upper slabs (IUS) [8]. Design models of the buildings protected with these systems are shown in Figure 1. These concepts represent the roof isolation technology. Developed structural solutions of AIUF or IUS are bringing to creation of diverse types of TMDs on the top of the existing buildings. Such systems give the opportunity to efficiently control the vibrations. Based on this experience the number of suggestions were made which allowed to solve the set task for the building under consideration in the given paper.

a. b.

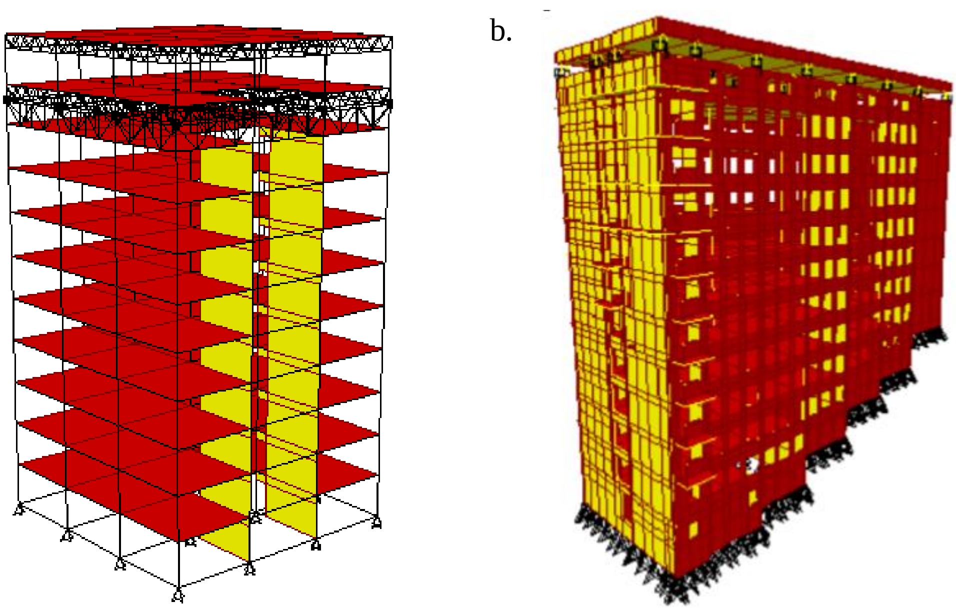


Figure 1. Design models of frame buildings with shear walls protected by roof isolation systems: 9-story apartment building protected by AIUF (a) and 12-story office building protected by IUS (b)

Below a structural concept of earthquake protection system designed for application in the existing reinforced concrete building together with some other measures is described. The building is currently under construction in the city of Yerevan, the capital of Armenia. This research and design work are unique as for the first time in construction practice substantial changes to the initial design were requested in the course of construction works.

Information on the building and suggested measures

Construction of a building under consideration has started in the city of Yerevan in 2014. It was supposed to be an 11-story reinforced concrete (RC) structure (including a basement floor) and its bearing system consisted of frames with shear walls (Fig. 2). During the construction process the necessity arouse to increase the number of floors as the initial purpose of the building was changed.

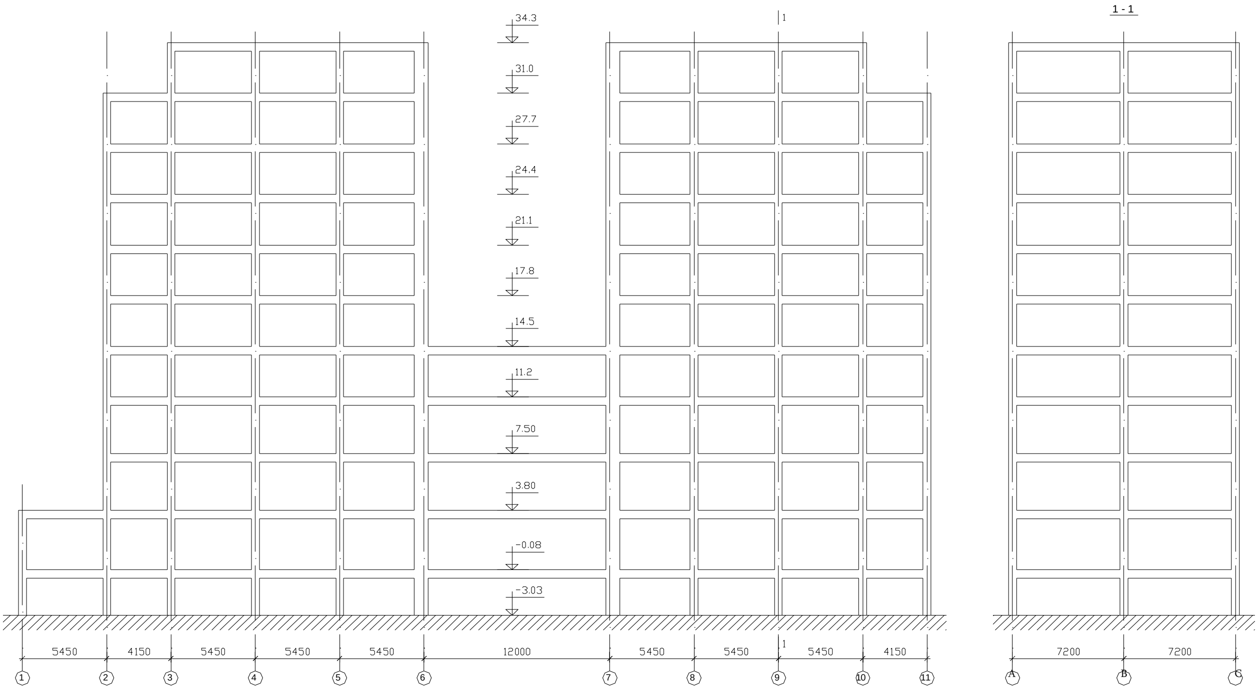


Figure 2. Schematic views of longitudinal and transverse vertical elevations of the building according to the initial design

The building was constructed up to the mark 14.50 and from this level the reinforcement frames of all the columns up to the mark 24.40 were left bared. Having the building in this condition, the owner requested changing of the building's purpose and adding two more floors. The author of this paper was approached by the owner to see if it is possible to satisfy such request without strengthening of already constructed bearing structures. After analyzing the created situation several suggestions were presented to the owner and then coming to consensus the decision was made to start implementation of the new project.

Firstly, the thorough investigations of the soil conditions by drilling several holes of 30 m deep, as it is requested by the Seismic Code in force, were carried out. Important result was revealed confirming the author's assumption that the soil in this site is of category I according to the Armenian Seismic Code but not of category II as it was wrongly accepted in the initial design. This means that coefficient of seismicity A=0.4 (dimensionless coefficient indicating the ratio of a given settlement's design ground acceleration to the gravitational acceleration) could be decreased by a factor of k_0=0.9 and will be equal to A=0.36. Factor of k_0 is defined in the Code as a dimensionless coefficient of soil conditions.

Secondly, it was suggested to add above the mark 34.30 three floors so that they will connect to each other the left and right towers of the building, thus increasing its spatial stiffness especially in longitudinal direction.

Thirdly, it was also suggested to create the roof isolation system in the form of the isolated upper slab (IUS) at the level of the third added technical floor between the marks 44.00 and 44.70 (Fig. 3). It was supposed that this system will be acting as a TMD and will significantly reduce the seismic forces and floors' displacements.

Fourthly, all floors' slabs to be constructed starting from the mark 17.80 will be of three layers with application of foam plastic in the middle layer. This was suggested to achieve significant reduction of the weight of the entire structure and to increase the stiffness of the slabs. It is necessary to mention that by the initial design there were solid RC floors' slabs with the thickness of about 220 mm. In the given design the total thickness of slabs is equal to 250 mm, where the thickness of slabs' lower layers is 80 mm and the upper layers – 70 mm.

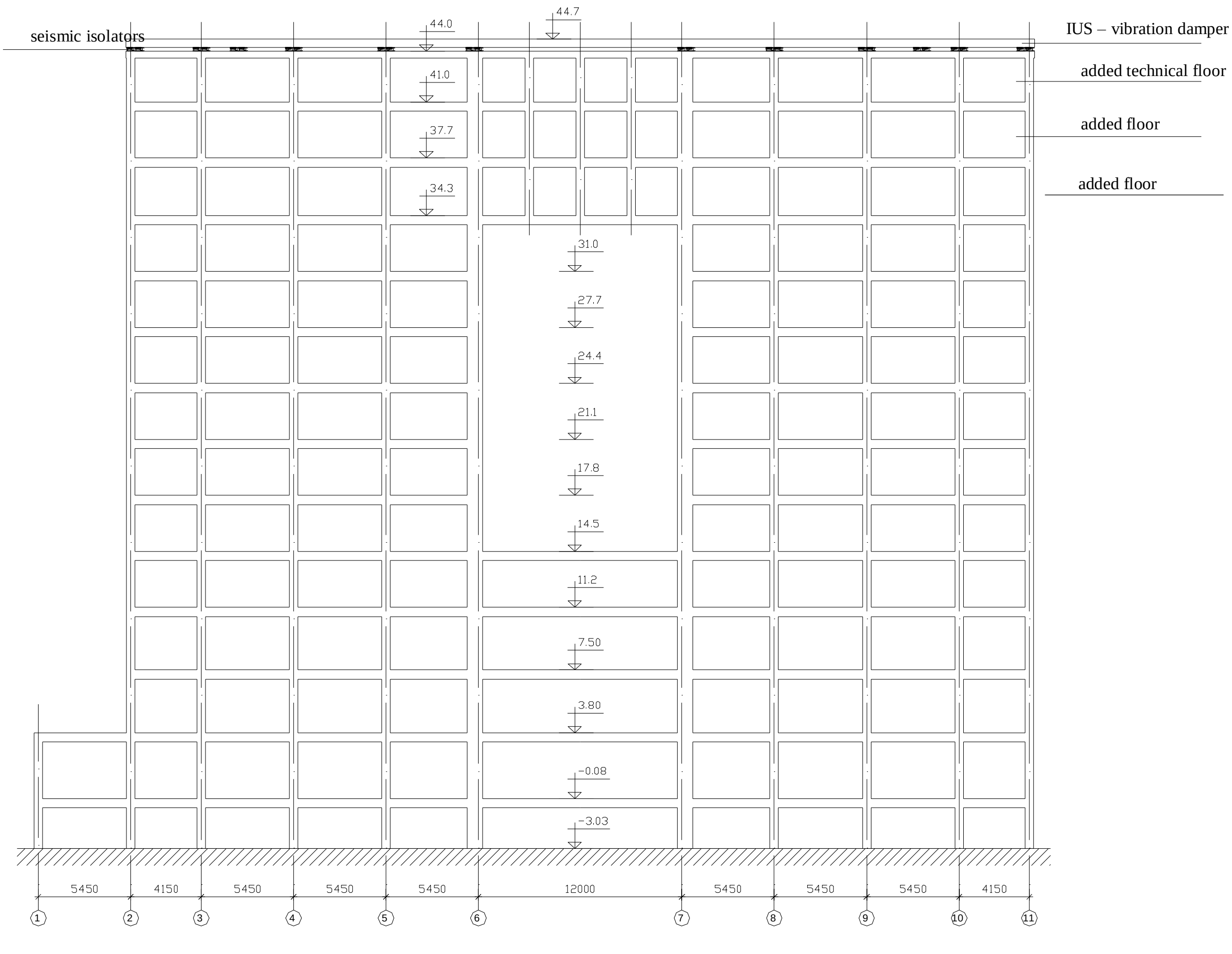


Figure 3. Schematic view of longitudinal vertical elevation of the building according to the made suggestions and newly developed innovative design

The added technical floor is an open air and in accordance with the modern design it is envisaged to have a small garden in the middle part of this floor. To the left and right sides from the garden an equipment for providing heating and ventilation systems to the building will be installed. All columns of the technical floor are connected to each other by the beams and there is no slab here at the mark 44.00. Exactly on these columns and beams the seismic isolation laminated rubber-steel bearings (SILRSBs) are installed. Above the SILRSBs the RC slab of 200 mm thick will be constructed with the parapet of 300 mm high along the whole perimeter of the slab. Location of SILRSBs is shown in Figure 4 and their geometrical dimensions, as well as physical and mechanical characteristics are given in Figure 5.

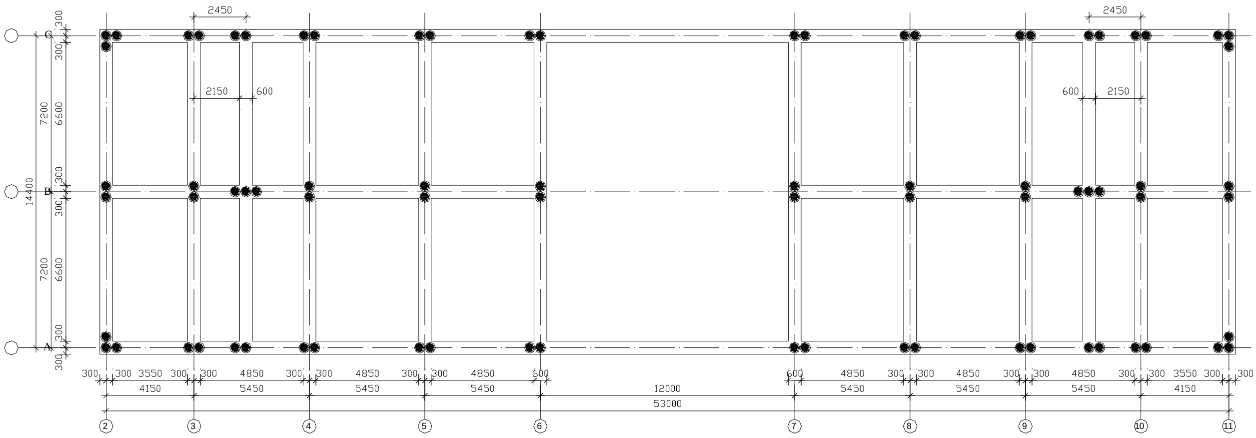
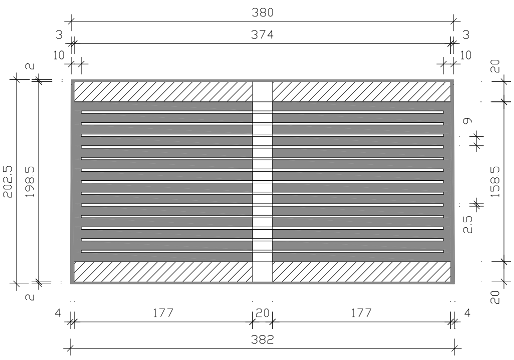


Figure 4. Plan of location of SILRSBs at the mark 44.00 in the system of vibration damper



Horizontal stiffness 0.81±0.1 kN/mm

Vertical stiffness not less than 300 kN/mm

Max. (design) permissible vertical load 1500 kN

Max. (design) permissible horizontal displacement 280 mm

Rubber shear modulus 0.97±0.15 MPa

Shore A hardness 70±5

Damping coefficient 15±1%

Mass of the bearing 77.5±2.5 kg

Figure 5. Geometrical dimensions and physical-mechanical characteristics of the applied SILRSBs

From Figure 4 it can be noticed that SILRSBs are located by clusters consisted of two or three isolators in each group. This approach was suggested earlier by the author [9] and applied in seismic isolation systems of many buildings in Armenia. All together 78 SILRSBs are used to create the roof isolation interface and their total horizontal effective stiffness equals 63.18 kN/mm.

Earthquake response analyses of the building with and without IUS (vibration damper) based on the Armenian Seismic Code and the time histories

With consideration of the above described suggestions the 3D design model of the building was developed (Fig. 6) and analysis was carried out first without application of the roof isolation system. This analysis has shown that only improving the data on the soil conditions (from category II to category I), increasing of the structure's spatial stiffness and reducing of the floor slabs' weight were not sufficient measures to exclude the strengthening of the already constructed bearing structures. It became obvious that application of the roof isolation system is needed and will permit to get the final satisfactory result.

The formation of the design model was done in accordance with LIRA-SAPR 2013 R2 software by application of several types of finite elements for shear walls, floor slabs, columns and beams, as well as for seismic isolators. Namely, bar frame finite elements and membrane finite elements, with due consideration of the structural solution of the building were used. To conduct the time history earthquake response analysis the accelerogram recorded during the 1988 Spitak Earthquake was applied (Fig. 7). This record was digitized with the step of 0.005 sec at the Okada and Nakano laboratory of the Institute of Industrial Science, University of Tokyo [10].

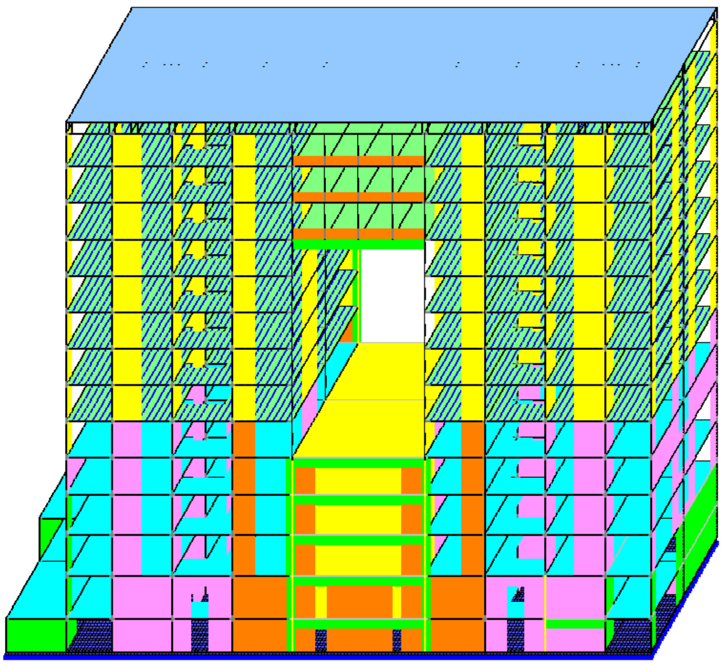


Figure 6. Design model for earthquake response analyses of the building with and without IUS (vibration damper)

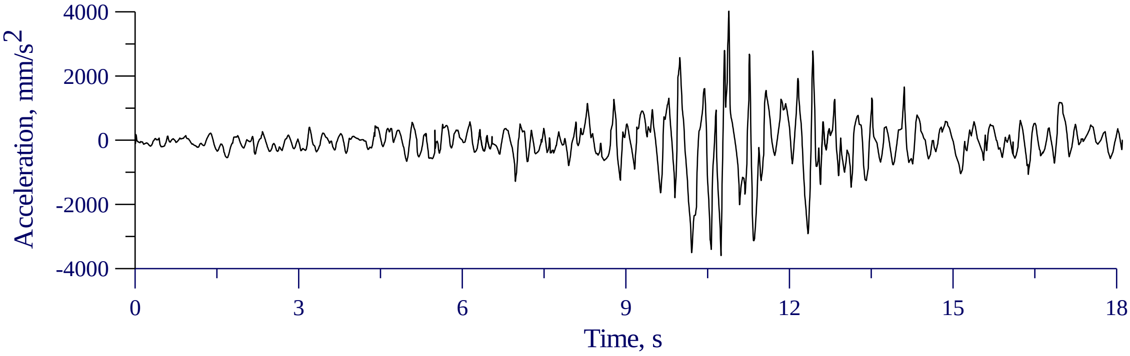


Figure 7. Accelerogram of the 1988 Spitak Earthquake recorded at Ashotsk (X direction) and scaled to 0.4g

According to the Armenian Seismic Code (RABC II-6.02-2006) the following parameters were assumed for the analyses:

- seismic zone – 3;
- soil category – I;
- coefficient of soil conditions – $k_0 = 0.9$;
- permissible damage coefficient for determining floors' displacements – $k_1 = 0.8$;
- permissible damage coefficient for analysis of seismic (roof) isolation system of the vibration damper – $k_{1z} = 0.8$;
- permissible damage coefficient for analysis of the building's bearing structure – $k_1 = 0.4$;
- coefficient of seismicity – A = 0.4;
- mass of IUS comprises 6.5% of the building total mass.

It is well known that building which is equipped with the vibration damper – IUS will have two main modes of vibrations: the first one when IUS oscillates in the same phase with the building (let us call it mode I/1) and the second one (mode I/2) when IUS oscillates in anti-phase to the building. It is this second mode that becomes prevailing and due to this phenomenon horizontal displacements and forces are reduced [11, 12].

Using the above data and considering all the suggestions made for improving the structural system of the given building the analyses were carried out showing high effectiveness of the proposed approaches. Some results of the analyses of building with and without IUS (vibration damper) based on the Armenian Seismic Code and the time history are summarized in Table 1 and Table 2, respectively.

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Table 1. Results of the analyses of building with and without IUS based on the RABC II-6.02-2006

Number of floors	Building without IUS (vibration damper) T_I = 0.886 sec			Building with IUS (vibration damper) $T_{I/1}$ = 1.134 sec, $T_{I/2}$ = 0.700 sec					
	Displacements, mm	Accelerations, m/sec^2	Seismic forces, kN	Displacements by I/1 vibration mode, mm	Displacements by I/2 vibration mode, mm	Accelerations by I/1 vibration mode, m/sec^2	Accelerations by I/2 vibration mode, m/sec^2	Seismic forces by I/1 vibration mode, kN	Seismic forces by I/2 vibration mode, kN
Base-ment	1.2	0.06	49	0.7	0.6	0.02	0.04	19	35
1	4.7	0.24	175	2.9	2.1	0.09	0.17	65	125
2	11.0	0.55	368	6.7	4.9	0.21	0.40	138	264
3	18.9	0.95	630	11.7	8.3	0.36	0.67	238	446
4	26.4	1.33	858	16.5	11.5	0.51	0.93	328	600
5	34.6	1.74	882	21.8	14.8	0.67	1.19	340	607
6	43.2	2.17	1083	27.6	18.1	0.85	1.46	423	729
7	51.8	2.60	1301	33.6	21.3	1.03	1.72	515	857
8	60.2	3.03	1509	39.6	24.1	1.22	1.94	618	970
9	68.0	3.42	1702	45.4	26.5	1.39	2.14	683	1066
10	75.0	3.77	2255	51.0	28.4	1.57	2.29	936	1370
11	81.1	4.08	2472	56.3	29.7	1.73	2.40	1045	1453
12	86.4	4.34	2614	61.2	30.4	1.88	2.45	1127	1482
13	90.6	4.55	608	65.5	30.6	2.01	2.47	285	351
14-IUS	-	-	-	162.5	-53.6	4.99	-4.32	3069	-2652
Total seismic lateral force at the foundation			16506					9829	7703

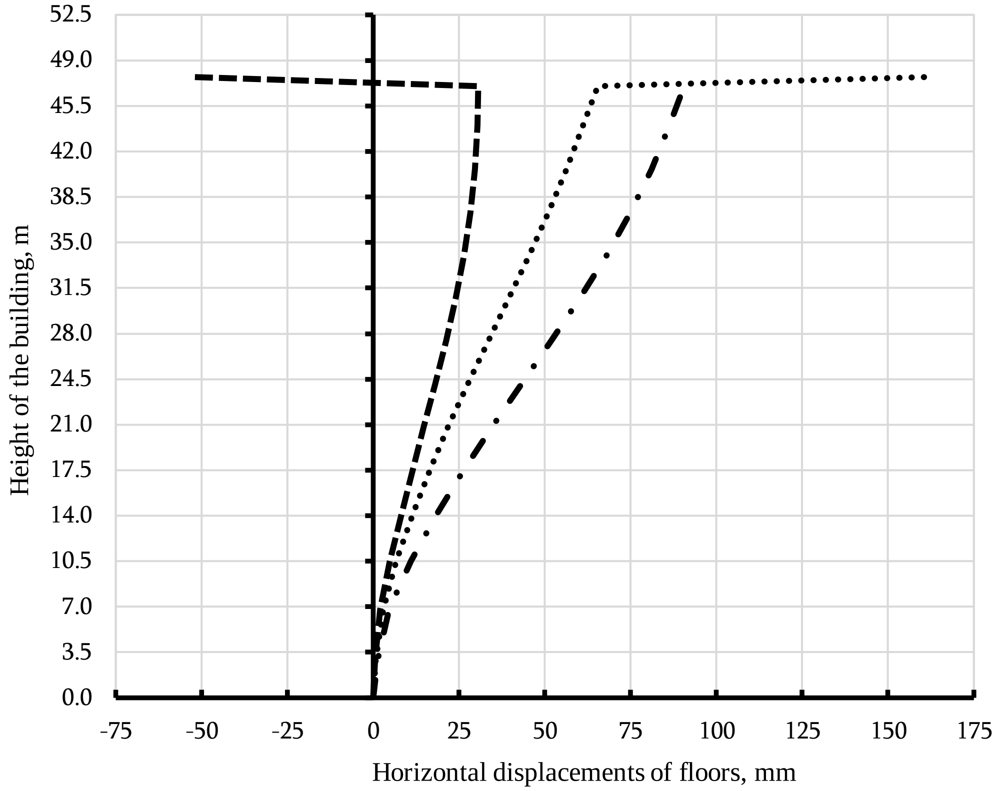
Table 2. Results of the analyses of building with and without IUS based on the accelerogram of the 1988 Spitak Earthquake recorded at Ashotsk (former Ghukassian) and scaled to 0.4g

Number of floors	Building without IUS (vibration damper) $T_I = 0.886$ sec			Building with IUS (vibration damper) $T_{I/1} = 1.134$ sec, $T_{I/2} = 0.700$ sec					
	Displacements, mm	Accelerations, m/sec^2	Seismic forces, kN	Displacements by I/1 vibration mode, mm	Displacements by I/2 vibration mode, mm	Accelerations by I/1 vibration mode, m/sec^2	Accelerations by I/2 vibration mode, m/sec^2	Seismic forces by I/1 vibration mode, kN	Seismic forces by I/2 vibration mode, kN
Base-ment	1.7	0.09	55	1.0	0.5	0.03	0.04	20	28
1	6.6	0.33	196	4.0	1.9	0.12	0.15	72	91
2	15.4	0.77	413	9.4	4.5	0.29	0.36	154	194
3	26.5	1.33	707	16.3	7.6	0.50	0.62	276	328
4	37.0	1.86	964	23.0	10.6	0.71	0.85	365	441
5	48.5	2.44	990	30.5	13.6	0.94	1.10	380	446
6	60.6	3.05	1215	38.5	16.7	1.18	1.35	471	536
7	72.8	3.66	1460	46.8	19.6	1.44	1.58	574	631
8	84.4	4.24	1694	55.2	22.2	1.69	1.79	675	714
9	95.4	4.80	1911	63.3	24.4	1.94	1.97	774	784
10	105.5	5.30	2530	71.1	26.1	2.18	2.10	1042	1008
11	114.0	5.73	2774	78.4	27.3	2.41	2.20	1164	1069
12	121.5	6.11	2934	85.3	28.0	2.62	2.26	1255	1090
13	127.0	6.38	682	91.3	28.2	2.80	2.27	318	258
14-IUS	-	-	-	227.0	-49.3	6.97	-3.98	3422	-1951
Total seismic lateral force at the foundation			18525					10962	5667

For better illustration the building's modes of vibrations with and without IUS using data given in Tables 1 and 2 on actual maximum values of floors' displacements are shown in Figures 8 a, b. From the obtained results it can be clearly seen how application of the IUS brings to division of the main mode of vibration into two modes I/1 and I/2 mentioned above. It is necessary to state that the roof isolation system was tuned in a way that its own period of vibrations would be equal or very close to the first mode of vibrations of the building without IUS. The latter is equal to $T_I = 0.886$ sec but the own period of vibrations of IUS was equal to

T_{IUS} = 0.900 sec. This become possible due to precise selection of the IUS mass (6.5% of the building total mass) and stiffness (78 SILRSBs with total horizontal effective stiffness of 63.18 kN/mm). In addition, it is necessary to emphasize that mean value of $T_{I/1}$ and $T_{I/2}$ equals to (1.134 + 0.700):2 = 0.917 sec and this value is very close to the value of T_I; their difference does not exceed 3.5%. This also proves that IUS is designed and tuned with high preciseness and together with the other suggested measures this gave the possibility to avoid the strengthening of already constructed bearing structures below the mark 14.50.

a.



b.

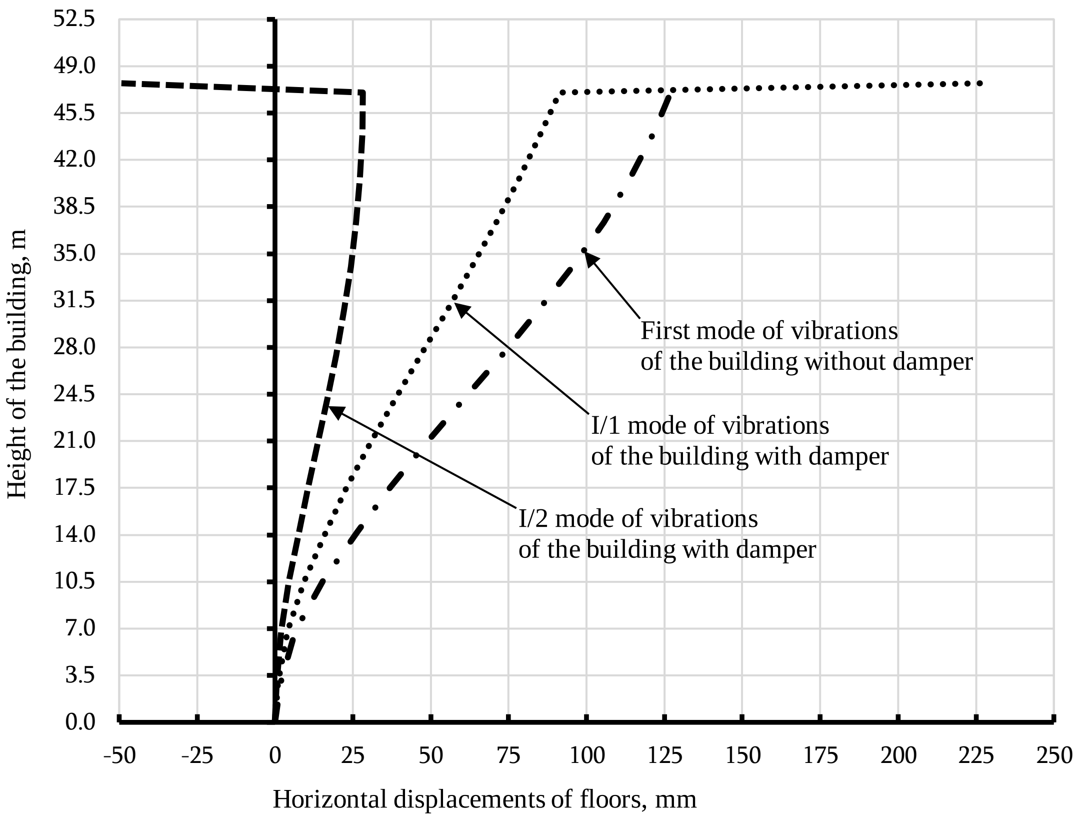


Figure 8. Building's modes of vibrations with and without IUS obtained base on the analyses by RABC II-6.02-2006 (a) and the accelerogram of the 1988 Spitak Earthquake recorded in X direction at Ashotsk (former Ghukassian) and scaled to 0.4g (b)

Obtained results also show that maximum horizontal displacements of the IUS in accordance with the Seismic Code analyses are equal to D_{IUS} = 162.5 - 65.5 = 97.0 mm by the mode I/1 and equal to 53.6 + 30.6 = 84.2 mm by the mode I/2. These values are in the limits of the permissible horizontal displacement for SILRSBs. The same is true for the displacements obtained by the time history analyses. Namely, for the mode I/1 the DIUS = 227.0 - 91.3 = 135.7 mm and for the mode I/2 – 49.3 + 28.2 = 77.5 mm. These results prove the high reliability of the designed roof isolation system.

The total seismic lateral forces at the level of foundation for the building with IUS in accordance with the Seismic Code analyses are equal to Q_{IUS} = 9829 kN by the mode I/1 and equal to 7703 kN by the mode I/2. Consequently, with consideration of both modes of vibrations the following value of the total shear force can be calculated as $\sqrt{9829^2 + 7703^2}$ = 12487.8 kN. In the same time for the building without IUS this value equals to 16506 kN. This means that IUS brings to reduction of the total shear force for about 1.32 times or about 24%. Also, at the level of the 13^{th} floor maximum horizontal displacements are decreasing due to influence of IUS 1.38 times and accelerations – 2.26 times.

In accordance with the time history analyses the total seismic lateral forces at the level of foundation for the building with IUS are equal to Q_{IUS} = 10962 kN by the mode I/1 and equal to 5667 kN by the mode I/2. Again, with consideration of both modes of vibrations the following value of the total shear force can be calculated as $\sqrt{10962^2 + 5667^2} = 12340.2$ kN. In the same time for the building without IUS this value equals to 18525 kN. This means that in case of the time history analyses IUS brings to bigger reduction of the total shear force for about 1.5 times or about 33%. And at the level of the 13th floor maximum horizontal displacements are decreasing due to influence of IUS 1.39 times and accelerations – 2.28 times.

Let us mention that predominant period of the selected accelerogram (see Fig. 7) equals to 0.42 sec. This period is bigger than predominant period of the category I soil given in RABC II-6.02-2006 and equal to $T_0 \leq 0.3$ sec. However, this accelerogram was accepted as it will generate the more unfavorable seismic action to the building. And even with application of this time history implementation of all the suggested measures allowed successfully solving the set tasks when together with the increasing the number of floors the strengthening of already constructed structural elements was avoided. Of course, the other time histories were also considered in the analyses. Their predominant periods were within the range given in Seismic Code for soil of category I and for these versions of analyses, as it was expected, the building was in much better conditions. This proves that suggested approaches provide the high reliability to the building.

CONCLUSIONS

Change of the structural concept and the number of stories of the building under construction was proposed due to application of the various measures including: (i) thorough investigations of the soil conditions confirming assumption that the soil in this site is of category I but not of category II as it was wrongly accepted in the initial design; (ii) adding three new floors to connect the left and right towers of the building, thus increasing its spatial stiffness especially in longitudinal direction; (iii) creating the roof isolation system in the form of IUS at the level of the third added technical floor; (iv) constructing all new floors' slabs as three layers structures with application of foam plastic in the middle layer.

The structural concept of the roof isolation system in the form of IUS acting as a TMD is described and geometrical dimensions together with the physical-mechanical characteristics of the applied SILRSBs are given.

Earthquake response analyses of the building with changed structural concept were carried out in two versions: with and without the IUS based on the Armenian Seismic Code and the time histories. Obtained results have revealed the high effectiveness of the proposed approaches and the IUS being precisely designed and tuned provides significant reliability to the overall structure.

The suggested measures allowed continuing construction of the building excluding strengthening of already constructed bearing structures.

In accordance with the Seismic Code analyses it can be stated that IUS brings to reduction of the total shear force for about 1.32 times. At the level of the 13th floor maximum horizontal displacements are decreasing 1.38 times and accelerations – 2.26 times. In case of the time history analyses IUS brings to bigger reduction of the total shear force for about 1.5 times. At the level of the 13^{th} floor maximum horizontal displacements are decreasing 1.39 times and accelerations – 2.28 times.

REFERENCES

[1] Warburton, G. (1982) "Optimum Absorber Parameters for Various Combinations of Response and Excitation Parameters", Journal of Earthquake Engineering and Structural Dynamics, No.10, pp381-401.
[2] Humar, J. & Wright, E. (1977) "Earthquake Response of Steel-Framed Multistory Buildings with Setbacks", Journal of Earthquake Engineering and Structural Dynamic, Vol.5 No.1, pp15-39.
[3] Nawrotzki, P. (2003) "Strategies for the Seismic Protection of Structures", Proceedings of the 8th World Seminar on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, Yerevan, Armenia, pp48-58.
[4] Pinkaew, T. & Lukkunaprasit, P. (1999) "Semi-Active Control of Buildings Subjected to Far-Field Seismic Excitations", Proceedings of the International Post-SMiRT Conference Seminar on Seismic Ioslation, Passive Energy Dissipation and Active Control of Vibrations of Structures, Cheju, Korea, Vol.I, pp553-562.
[5] Palazzo, B., Petti, L. & De Iuliis, M. (2004) "A Passive Robust Control Strategy: Base Isolation and Tuned Mass Damping", Proceedings of the Third European Conference on Structural Control, Vienna, Austria, pp51-207 - 51-210.
[6] Melkumyan, M. (1996) "Dynamic Tests of the 9-story R/C Full-Scale Building with an Additional Isolated Upper Floor Acting as Vibration Damper", Proceedings of the 3rd European Conference on Structural Dynamics, Florence, Italy, Vol.1, pp557-560.
[7] Melkumyan, M. (2011) New Solutions in Seismic Isolation. LUSABATS, Yerevan.
[8] Melkumyan, M. (2014) "New Application of Roof Isolation System in the Form of an Isolated Upper Slab for Seismic Protection of an Existing 12-Story Office Building", International Journal on Civil Engineering & Urban Planning, Vol.1, No.1, pp1-14.
[9] Melkumyan, M. (2013) "New Approach in Design of Seismic Isolated Buildings Applying Clusters of Rubber Bearings in Isolation Systems", International Journal of Earthquakes and Structures, Vol.4, No. 6, pp587-606.
[10] Inoue T., Melkumyan, M., Kumazawa F., Nakano Y., Okada T. (1991) "Earthquake Response Analyses of Precast Reinforced Concrete Buildings Damaged due to Armenia Spitak Earthquake", Bulletin of Earthquake Resistant Structures Research Centre IIS, University of Tokyo, No. 24, pp57-64.
[11] Korenev, B. & Reznikov, L. (1981) "Design of Structures Equipped with Tuned Mass Dampers", Dynamics Design of Structures for Special Impacts: Designer's Manual, Stroyizdat Publishing House, Moscow, pp149-175.
[12] Melkumyan, M. (2013) "Experimental Investigation of Efficiency of Tuned Single and Double Mass Damper and its Application in the Form of an Additional Upper Floor for Seismic Protection of Existing Multistory Buildings", Journal of Construction Engineering, Vol.1, Issue 2, pp15-25.