Using Seismic Base Isolation Systems in High-Rise Hospital Buildings and a Hybrid Proposal

E. Bakkaloğlu, N. Torunbalcı

***Abstract*—**Earthquakes are inevitable natural disasters in Turkey. Therefore, buildings must be prepared for this natural hazard. Especially in hospital buildings, earthquake resistance is an essential point because hospitals are one of the first places where people come after earthquake. Although hospital buildings are more suitable for horizontal architecture, it is necessary to construct and expand multi-story hospital buildings due to difficulties in finding suitable places as a result of excessive urbanization, difficulties in obtaining appropriate size land and decrease in suitable places and increase in land values. In Turkey, using seismic isolators in public hospitals, which are placed in first degree earthquake zone and have more than 100 beds, is made obligatory by general instruction. As a result of this decision, it may sometimes be necessary to construct seismic isolated multi-story hospital buildings in cities where those problems are experienced. Although there is widespread use of seismic isolators in Japan, there are few multi-story buildings in which seismic isolators are used in Turkey. As it is known, base isolation systems are the most effective methods of earthquake resistance, as the number of floors increases, the center of gravity moves away from the base in multi-story buildings, increasing the overturning effect and limiting use of these systems. In this context, it is aimed to investigate structural systems of multi-story buildings which are built using seismic isolation methods in the world. In addition to this, a working principle is suggested for the disseminating seismic isolator used in multi-story hospital buildings. The results to be obtained from the study will guide architects who design multi-story hospital buildings in their architectural designs, and engineers in terms of structural system design.

***Keywords*—**Earthquake, energy absorbing systems, hospital, seismic isolation systems.

I. Introduction

As it is known, Turkey is located in a region with high seismicity. In this context, after an earthquake, loss of life and property can be experienced in Turkey, as in many parts of the world. Hospitals are one of the first places people apply after an earthquake. With epidemic diseases that have become widespread recently, both importance of hospital buildings and need for bed capacity of hospitals have increased. For this reason, hospital buildings may need to be built as multi-story buildings, especially in city centers, due to the inadequacy of land suitable for hospital construction, as well as expensiveness and high population/capacity requirement especially in big cities.

Hospital buildings not only should have been built as resistant to earthquake, but they should also offer seismically uninterrupted service.

The Republic of Turkey Ministry of Health has made it obligatory to use seismic isolators in hospitals, on the condition of "100 beds or more, which are in in areas with high earthquake risk and structural system of hospitals will be designed with seismic isolators" [1]. With this condition, seismic isolators are defined in general. Also, it is aimed that using opportunity of seismic isolation systems in multi-story buildings is specified in this paper. Base seismic isolation has been used in many buildings in Turkey recently. Also, it is seen that these buildings are generally horizontal hospital buildings. In addition, when applications in Turkey and the world are investigated, it is seen that using seismic isolation systems in multi-story high-rise buildings are not widespread. When looking at seismically isolated buildings, it is seen that these buildings are mostly horizontal. It is planned to present a seismic base isolation application proposal for high-rise hospital buildings by investigating the seismic isolation applications in high-rise buildings. The reason for focusing on hospital buildings in this study is based on;

- the need for hospital buildings to include many users,
- the need for uninterrupted use during an earthquake,
- the need for including advanced technological devices,
- an increase in the need for high-rise buildings with increases in population,
- the need to increase capacity during pandemics such as with coronavirus.

For these reasons, hospital buildings and high-rise buildings with seismic isolators from around the world were examined in detail. Moreover, conditions and limitations when applying hybrid seismic control methods in multi-story buildings are studied.

If seismic isolators are used in a building, there should have been a necessity of balance between multi-story building period and isolator period. Otherwise, buildings can be affected by overturning and uplift effect. Therefore, these concerns can prevent using of seismic isolator in multi-story buildings. Moreover, use of base isolation systems requires additional precautions in the decision of using seismic isolators. Hence, in the study, use possibilities of base isolation systems in multi-story buildings and isolators will be investigated.

II. Examination of Passive Seismic Control Systems/ Mixed (Hybrid) Systems

Not only can energy absorbing systems and base isolation systems can be used together, but also different types of base

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isolation systems can be used alone. Application of a base isolation system in multi-story buildings can be in two ways. The first of these methods is the TASS (TAISEI Shake Suppression) System in which slide and rubber isolators are used together, whereas the other can be considered as systems which dampers are preferred for support purposes. For example, it is seen that rubber-based isolators are used together with a spring-type system due to their vulnerability to the buckling effect. Generally, energy absorbing systems and seismic base isolation systems are used together in multi-story buildings to reduce the effect of horizontal loads, horizontal displacement and overturning effect. If a building has different heights, different types of seismic isolators can be used in the same building.

The improvement in dynamic performance depends on the force-displacement relationship in the basement level which includes the isolator. An innovative base isolation system called the Hybrid TASS System has been developed to reduce dynamic response independently of the natural period of the superstructure. It has been observed that multi-story buildings with a long natural period can perform better against earthquakes when rubber and sliding systems are used together [1]. The hybrid TASS system is also an economically advantageous system. The use of steel dampers, lead dampers and rubber isolators together and the use of sliding and rubber isolators together were compared in terms of economy [1].

Fig. 1 shows a comparison of the Hybrid TASS System with another typical example of the base isolation system. In the hybrid system, rubber isolators are placed under columns, whereas steel and lead dampers are used together for energy absorption. In the other system, use of only sliding and rubber isolators under the columns is sufficient. In this way, multi-story buildings with strong seismic performance can be achieved without a high increase in construction costs [1].

In summary, as it is known, using only rubber isolators is not preferred in high-rise buildings. As a solution, two alternatives emerge when rubber isolators are used together with other systems. The first of these is to be used with dampers such as lead and steel, and the second is to be used with sliding isolators. As a result of research, it has been concluded that use of rubber isolators with sliding isolators is more economical than use of dampers such as steel and lead [1]. Accordingly, a solution can be made more economical by converting the type of some isolators under columns from a rubber isolator to sliding isolator instead of using additional dampers.

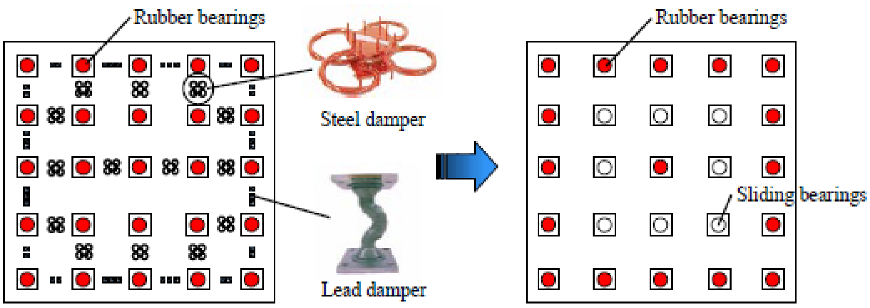

Fig. 1 Comparison of hybrid TASS system and other base isolation system [1]

When looking at general usage, it has been seen that rubber and sliding isolators are used together, and sometimes oil and lead dampers are used for support purposes in addition to these types of isolators (Table I).

TABLE I
EXAMPLES OF COMBINED USAGE OF DIFFERENT TYPES OF SEISMIC ISOLATORS [1], [6]-[13]

Building Name	Type 1	Type 2	Type 3
Thousand Tower	Rubber Bearing	Sliding Bearing	-
Sendai MT Building	Rubber Bearing	Sliding Bearing	-
Iidebashi First Building	Natural Rubber Bearing (40)	Lead Damper (40)	-
Nakanoshima Festival Tower	Lead Rubber Bearing	Oil Damper	-
Shiodome Sumitomo Building	Lead Damper (100)	Lead Rubber Bearing (LRB) (41)	Steel Damper (14)
Shimizu Building	Lead Rubber Bearing (32)	Rubber Isolator (10)	Oil Damper (10)

Number of isolators are specified in parentheses.

As seen in Table I, rubber and sliding bearings can be used together, as well as dampers and rubber bearings. The main point here is that rubber bearings are supported by either sliding bearings or dampers.

III. USING SEISMIC ISOLATOR IN MULTI-STORY BUILDINGS

The use of only seismic isolators may not be sufficient for buildings where the effectiveness of seismic isolators is less; that is, for buildings with a building period of 1.5 seconds and higher, and in slender buildings where the ratio of short side to long side is low in plan. For this reason, additional dampers or a combination of different solutions may be required in the superstructure. As it is known, a large amount of energy input caused by earthquakes is absorbed by the base isolators in basement-level isolated structures. Accordingly, base isolation systems have been recognized as one of the most effective ways to minimize damage to a superstructure, so only partial repair may be required even after a destructive earthquake [2].

Within the scope of difficulties of seismic isolation application in high-rise buildings, there is a general belief that base isolation systems are insufficient in high-rise buildings, but they have been used in some slender high-rise buildings.

However, it is generally preferred in low-rise buildings with a period of less than 1 second. In order to provide an effective seismic performance in multi-story buildings, some problems must be overcome. Until now, many problems have been encountered in the application of base isolation in multi-story buildings. These problems are defined as:

- Uncertain response reduction effect of base isolation in multi-story buildings,
- Effect of using base isolation system in high-rise buildings to reduce livable comfort of users under strong wind effect,
- Tending to overturn as a result of unstable equilibrium position (if horizontal displacements of a base isolation system are insufficient, the stability of the superstructure evolves to an unstable equilibrium position; that is, the superstructure tends to overturn)
- Need to increase rigidity of the superstructure,
- Possibility that the base isolation system will cause significant increases in the cost of building,
- Unknown response characteristics and stability of large-size rubber isolators exposed to tensile forces.

For solving these kinds of problems, the response reduction effect of base isolation in multi-story buildings can be obtained by parametric analyzes using a base isolation system. To sum up, a building's natural period becomes unimportant thanks to the application of seismic isolation systems. For instance, a response reduction effect can be found with parametric analysis. In a study conducted in this context, the seismic isolation floor and superstructure part of a building with isolators are modeled as two masses and two swing points, namely two degrees of freedom. In the study, it is assumed that the superstructure is a reinforced concrete frame system, and the basic isolation system is of hysteretic energy absorbing type [1].

Hybrid systems can ensure comfort of life in high-rise buildings and they are not affected by horizontal loads, especially wind effects that can be encountered frequently. Using of seismic isolators in high-rise buildings can decrease complaint by residents about comfort of life. On the other hand, the overturning effect in buildings caused by strong winds can make users uncomfortable. However, this problem can be prevented with a hybrid system.

One of the important problems of limiting seismic isolator use in multi-story buildings is the tendency of the superstructure to overturn.

It is known that in the design of slender high-rise buildings, mostly, corner isolators are affected by vertical load and overturning force during a major earthquake. It is seen that isolators pass the test in small-sized samples, but when this test is applied to a life-size isolator, it may not pass the isolator test. In this context, it can be predicted that the limit values of the isolators will be lower than the value in the small-scale test. Prevention of the overturning tendency is solved by increasing support on columns at the corners and calculating the dead load on isolators on the narrow side of the plan according to the tensile force caused by an earthquake.

Another problem is the need to increase the rigidity of the superstructure, which can be solved with large braces (mega brace) to be formed around the superstructure; in this way, the horizontal stiffness of building can be increased. These braces can be in the form of viscous, steel or other types of dampers, or building can be stabilized with steel braces. Alternatively, building columns with reinforced concrete filled steel profiles can also be planned as an improvement suggestion. When looking at the application, it is seen that these two systems are used by adapting to each other. Looking at Tokyo Institute of Technology building, it is seen that the superstructure was stiffened by using reinforced concrete filled steel columns and a mega brace system around the building facade of the superstructure [3].

Because of the fact that base isolation system causes significant increases in building cost, this cost increase can be kept at an optimum level by making the right isolator selections. In hybrid system, using sliding isolators/pendulum systems with rubber isolators will be a more economical solution to reduce horizontal load and overturning effect than using steel and lead dampers with rubber isolators.

Considering the unknown response properties and stability of large-size rubber isolators exposed to tensile forces, the solution can be obtained by determining design criteria of tensile and shear strain limit values. It is known that vertical loads affect isolators, especially in corner columns, during overturning tendency in high-rise buildings. However, stability and response characteristics of large-sized rubber isolators are not known by tensile forces. Before the building application with seismic isolators, small models of planned isolators are made and tested. However, in the research, it is seen that small-scale samples can pass the test, but one-to-one scale samples cannot pass the test. For this reason, instead of trying to find tensile forces, design criteria are determined in limit values of tensile strain and shear strain. With these design criteria, the response stress strain can be kept lower than the failure limit [4]. In this context, the difficulties encountered in seismic isolator applications in multi-story buildings are grouped under seven main headings, and improvement methods for them are also explained. Considering relevant recommendations, connecting superstructures to ground with seismic isolators will enable to create more robust and redundant structural systems [1].

IV. Seismic Isolation Using Examples in the World

Day by day, the number of buildings with seismic isolators is increasing; its application in multi-story buildings continues to be seen in Russia, America and China, and especially in Japan, which is the world leader with more than 5000 buildings with seismic isolators and more than 3000 buildings with energy absorbers [5]. For instance, five high-rise seismically controlled buildings from Japan were examined in the context of precautions they took against the above-mentioned problems, especially overturning.

Sendai MT Building is the first tallest building in Japan with seismic isolators. The Sendai MT building performed well after the off-shore Miyagi 2003 earthquake. According to measurements made by seismographs, it became an exemplary building for other buildings [6]. As a solution to above-mentioned limitations, following applications have been implemented.

1) High-strength materials (60 N/mm^2 class high-strength concrete and SD490 reinforcements as longitudinal reinforcement) are used in columns and beams.
2) Beams of hybrid structure span 15 m, whereas middle part of beams contains steel, high-strength concrete is used more intensively in parts close to support sections of beam.
3) High-rise building supplies strong seismic performance and sustainability with seismic isolation method.

As seen in Fig. 2, isolators are located at underground level and the ratio of sliding isolators to all isolators in columns is designed so that the yield force can be greater than the wind force. Sliding isolators are mostly placed under the inner columns and these columns are mostly located where the fluctuation of axial force is relatively small due to the seismic forces. The adaptation of this wide span system also reduces the number of columns in residential area [6]. Maximum accelerations of this building, in the Miyagi 26 May 2003 earthquake, were measured and data analyzes showed that application of the system in the high-rise building was effective and the design analysis model was sufficient [1], [7].

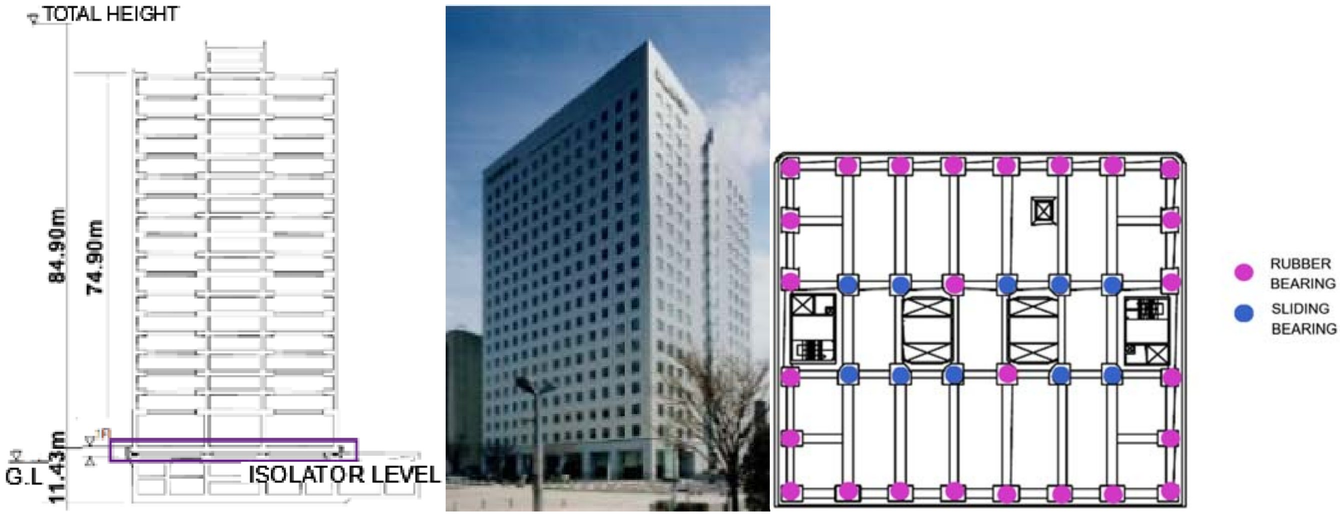

Fig. 2 Sendai MT building plan, section and photo [1]

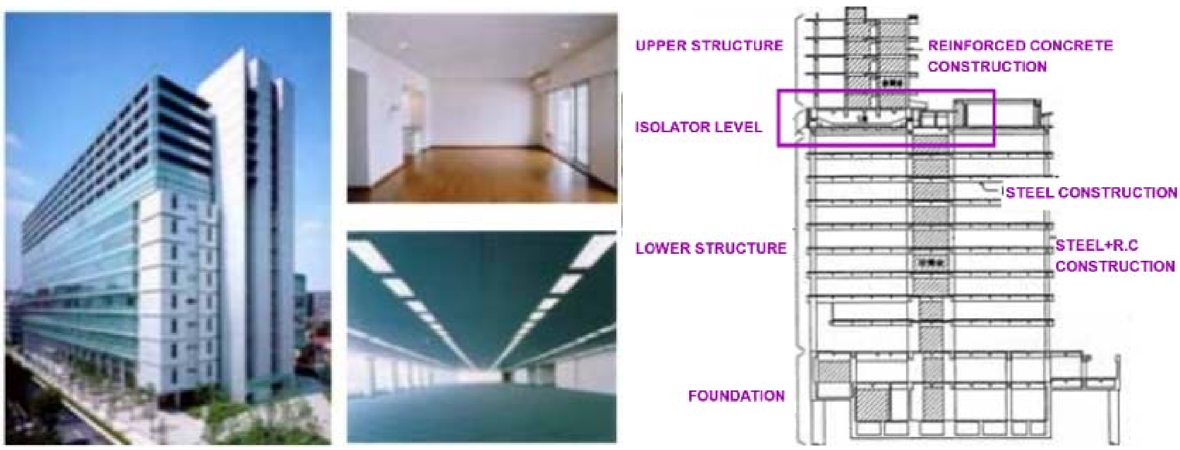

Fig. 3 The Iidebashi First Building plan, section and photo [8], [9]

The Iidebashi First building is used as an office and residential building and isolators are located on an intermediate floor (Fig. 3). The height of the building is 63.20 m, floors under the isolators are made of reinforced concrete and steel, floors above the isolator are made of only reinforced concrete. Use of isolators in the mezzanine has enabled the superstructure to create a mass damper effect. In the office area, columns were created using a steel framed system, whereas in upper residential area, privacy was provided with a reinforced concrete wall-type system to provide spaces that provide a high degree of freedom without beams and columns. The isolator layer consists of 800 φ natural rubber laminated rubber isolators and a lead damper. In all floors, stresses in the structural framework were kept within elastic limits, thus maintaining a high seismic performance [8], [9].

Thousand Tower is a residential building in the city of Kawasaki and it is a 41-floor reinforced concrete structure (Fig. 4). The basement isolators are placed at the top of the ground floor and the building height is 135 m. Prefabricated and prestressed reinforced concrete beams are used to cross a 12 m span. By using high-strength materials, cross-sections of structural elements are reduced and wider spaces are provided for architectural planning.

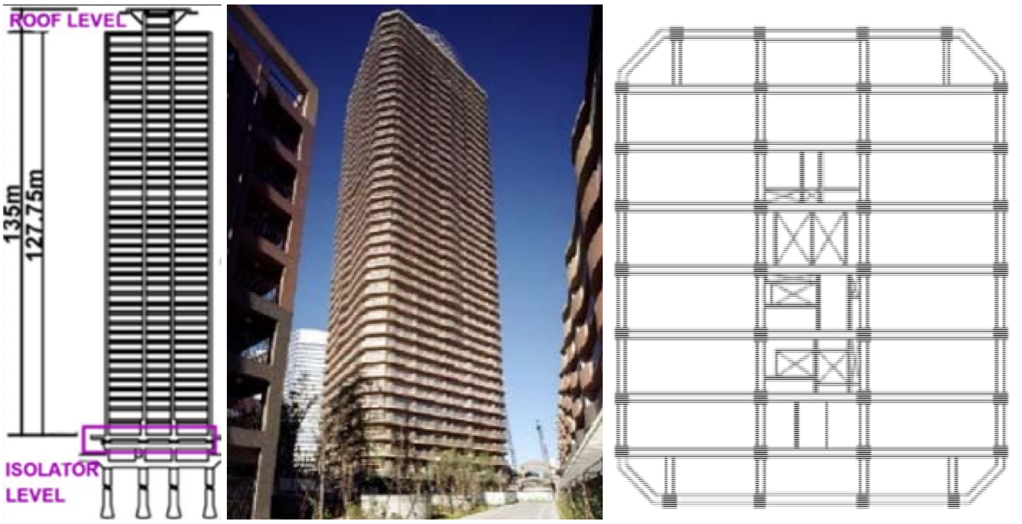

Fig. 4 Thousand Tower Building plan, section and photo [1]

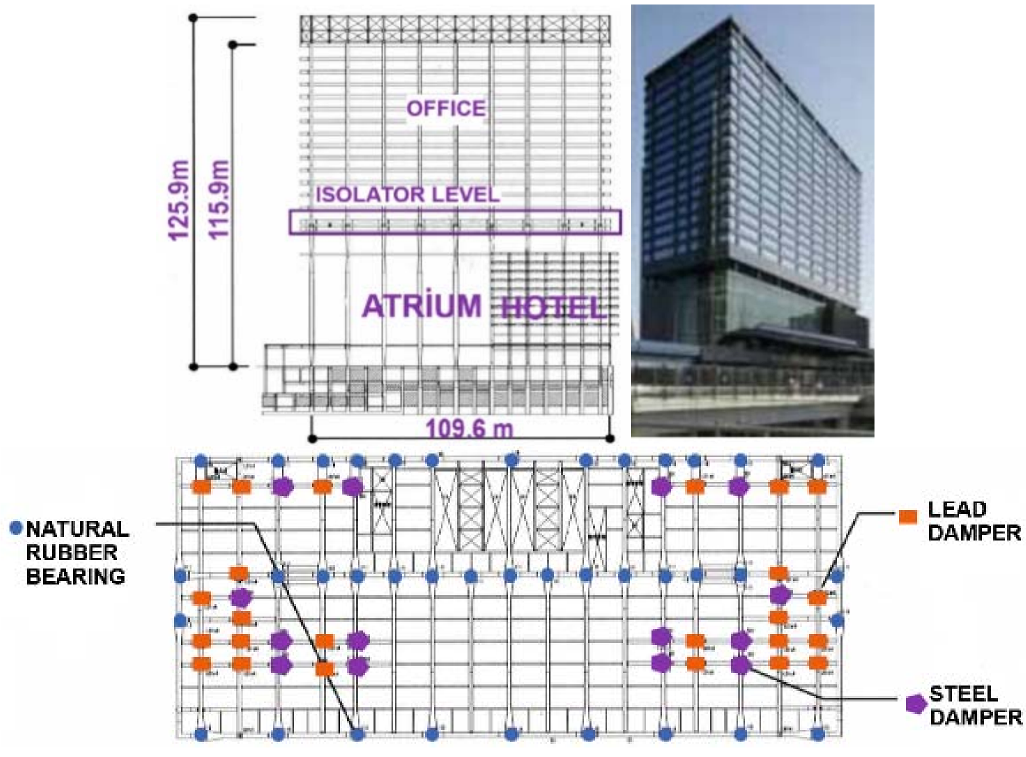

Fig. 5 Shiodome Sumitomo Building plan, section and photo [8]-[10]

Shiodome Sumitomo Building is 120 m high and has three basements and 25 normal floors (Fig. 5). There are 11 floors of hotel and the three basement floors below the isolator level, and 14 floors of offices above it. There is a large atrium with an entrance at the bottom of the isolator level. Composite columns were formed by filling steel pipe columns with reinforced concrete to ensure static efficiency. A total of 100 lead dampers, 14 steel dampers, and 41 lead rubber isolators were used in the building. Damper numbers are decided as elastic considering wind effect (expected 500 years) [8]-[10].

Nakanoshima Festival Tower was built in 1958 and again opened as a festival hall in 2008. However, the building was demolished and constructed as a new festival building with an approximate height of 200 meters and a construction area of 146.000 m^2. The building has 39 normal floors and three basement floors (Fig. 6). There is a large atrium at the entrance of building and isolators are located above it. Whereas there are viscous dampers at the top of giant steel truss system, there are rubber lead core isolators at the bottom. There is a seismic isolation system at middle floor level between living room and office floors, and this system was created by using 16 square and 34 circular lead-rubber sliding isolators and 24 oil dampers. The uplifting is minimized by mechanical properties of LRBs in the frame. It provides extra strength against horizontal loads. As building weight is concentrated in large square LRBs located along perimeter of upper floors, lift caused by tipping moment is technically minimized [7], [11], [12].

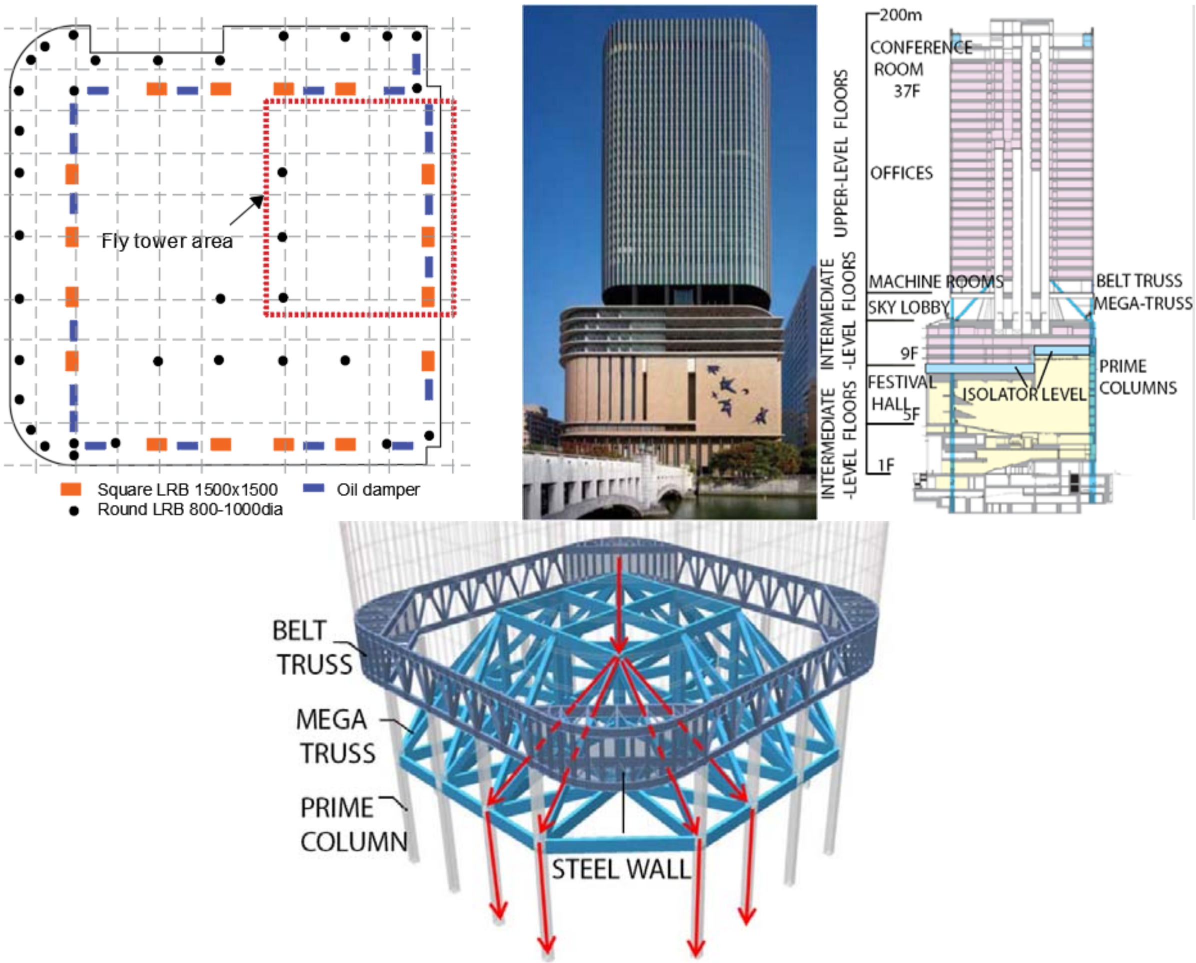

Fig. 6 Nakanoshima Festival Tower Building plan, section, photo and detailed model [7], [9]

Shimizu Corporation Tokyo Headquarters was built with a building area of 51,356 m^2 as an office structure with a height of 106 m (Fig. 7). In the building, which has three basements, 22 normal floors and one attic, structural system is designed as reinforced concrete, steel+reinforced concrete and steel frame system. Internal composite core is made of reinforced concrete, columns are made of precast concrete, and floor opening is made of steel [13]. In addition, 32 lead rubber isolators, 10 rubber isolators, 10 oil dampers were used in the building. Isolators are located below ground floor. The main reasons for choosing this structural system are; employer's desire for a superior seismic performing structure that provides support, which will play a critical role in life of building in disaster, and demands for spaces with fewer columns where office layout has maximum flexibility. 42 isolators are placed between the 1st and 2nd basement floors of the building. Precast system shear walls and tube system, used in the exterior frame seen in Fig. 7, reduced horizontal load effect and risk of the building falling over [7], [13].

V. Investigation about Seismic Isolation Application in Multi-Story Hospital Buildings in Turkey

In Turkey, buildings with seismic isolators are increasing rapidly with a notice published by the Ministry of Health [1]. In the notice published in 2013, it is written "structural systems of hospitals will be designed with seismic isolators" [1]. The use of seismic isolators has become mandatory in hospitals with 100 beds or more. In this context, when looking at hospitals with seismic isolators in Turkey, the Friction Pendulum System FPS was used in project in the newly built Çam & Sakura, Prof. Dr. Cemil Taşcıoğlu, Prof. Dr. Süleyman Yalçın and Dr. Lütfi Kırdar City Hospitals. A base seismic isolation system was applied to Marmara University Başıbüyük Hospital, which was built with a traditional method, and LRB and Natural Rubber Bearing NRB isolators were preferred in this application.

Fig. 7 Shimizu Corporation Tokyo Headquarters section, photo, detail and plan [13]

Hospital buildings generally do not exhibit a slender behavior as they have horizontal architecture. City hospitals in Turkey have been built with seismic base isolation in recent years, but there are no tower-style high-rise hospital buildings yet. General preference in hospital applications with seismic isolators has been in direction of FPS system. Rubber isolators were used in the Marmara Başıbüyük Hospital Building, as it was a later application within the scope of earthquake safety. However, it is estimated that high-rise hospital buildings may become widespread in a short time with the increasing capacity need due to the pandemic and other reasons mentioned before.

	HOSPITAL NAME	OPENING YEAR	BED NUMBER	CONSTRUCTION AREA	ISOLATOR NUMBER AND TYPE
	BAŞAKŞEHİR ÇAM VE SAKURA CITY HOSPITAL	2020	2862	1.000.000m^2	2071 adet FPS
	PROF.DR CEMİL TAŞCIOĞLU CITY HOSPITAL	2020	1000	250.400m^2	506 adet FPS
	PROF.DR. SÜLEYMAN YALÇIN CITY HOSPITAL	2020	1000	257.696m^2	503 adet FPS
	DR. LÜTFİ KIRDAR CITY HOSPITAL	2020	920	323.000m2	855FPS
	MARMARA BAŞIBÜYÜK RESEARCH AND TRAINING HOSPITAL	2019	-	112.400m^2	362 LRB and 326 NTM

Fig. 8 Comparison Figure of Hospital Applications with Seismic Isolator in Istanbul [14]

It is seen that most of the new design applications in Turkey use FPS isolators, and it is also seen that various rubber isolators are applied in combination in existing buildings (Fig. 8). It is known that none of the built ones were in a style that could be accepted as a tall building and did not exhibit slender high-rise building behavior.

It is obvious that the number of hospital buildings with seismic isolators is increasing day by day in Turkey and this brings specialization in this field. Specialization in this area will lead to finding suitable solutions for seismic base isolated tower-style construction.

VI. A Hybrid System Suggestion

When seismic isolation systems are examined in multi-story building applications around the world, it is seen that seismic isolators are generally used at ground level in multi-story buildings. Also, additional measures are taken against risk of overturning with dampers or different types of isolators, especially in corner and perimeter frames. In general, seismic isolator preferences in high-rise building applications are in the direction of using rubber and sliding isolators together, there are also examples where isolators are used together with dampers. For such tower-type high buildings and especially hospital buildings, a system proposal can be made where base isolation systems and seismic energy absorbing systems can be used together. Since there are many basements in a multi-story building, when seismic isolators are used on the upper level of the foundation, a high moat requirement will arise around the building. This perimeter moat will need to be constructed in the form of a reinforced concrete shear wall and possibly with a shoring system. In proposal, special seismic dampers in the form of oil dampers are placed at appropriate points on the surrounding axes between curtain exterior wall and shoring system. In other words, special seismic dampers will be placed horizontally in the gap between the building exterior structural system and the shoring system. Then, these absorbers supply not only connection between the ground and building, but also restrict large horizontal displacement in a large magnitude earthquake. Moreover, this will provide sufficient safety against overturning effect of tower-type structures since the building is embedded in the ground.

Main aim in current applications is strengthening the connections of multi-story buildings with the ground by using different types of isolators together, However, in this proposal, building-ground connection is already provided thanks to the large extension for the building which is embedded into the ground. On the other hand, the necessity of limiting horizontal displacements of base isolators can be achieved by means of energy absorbing devices to be placed in the surrounding moat of the building. The problem of overturning, which has great importance even in tower-style buildings designed according to conventional systems, is one of the most important factors limiting design of multi-story buildings with base-isolated systems. Such a proposal is a solution that will greatly reduce possibility of such buildings overturning.

As in Fig. 9, it is thought that isolators can be a new hybrid system solution proposal, which is an example of application of foundation isolation of multi-story buildings by reducing tipping effect with help of dampers placed in space around the moat formed around the building. By placing dampers in two directions and at the level of the floor, it will ensure that dampers used in the building load-bearing system in conventional systems are used between the building and ground just like in base isolation systems, and the building will be constructed with a design that is far from requirements of conventional system. Such a system can be called a hybrid system with base and side seismic isolation. Scientific studies on the applicability of this hybrid system are still continuing, and this recommendation is still a part of an ongoing doctoral study.

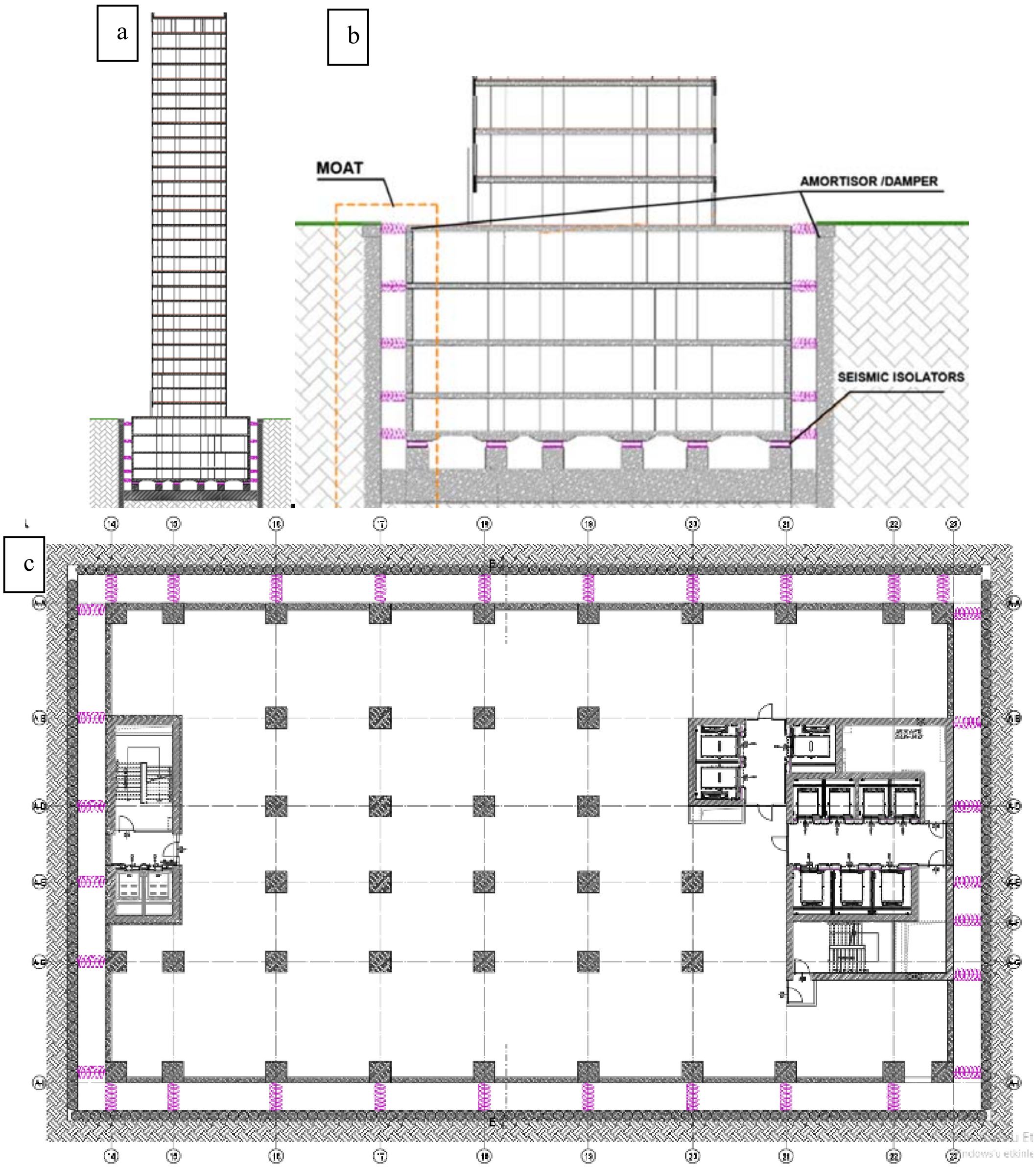

Fig. 9 (a) Representation of the proposal diagram in a typical high-rise building section example, (b) Schematic Proposal Foundation Section, (c) Plan

VII. Evaluation and Conclusion

In this study, current application examples have been researched and a system proposal has been presented in order to supply spread using seismic isolators especially in multi-story/high-rise hospital buildings. For instance, to prevent overturning, different types of base isolators are used together and also other types of seismic isolators, especially dampers, are used in superstructures in order for the load-bearing system to absorb the earthquake energy. In addition, it has been determined in examinations made that the dead load of columns in perimeter axis frames and building corners is calculated by taking into account the earthquake tensile force. Within the framework of these issues, it is seen that mostly sliding and lead isolators are used together in base isolation. There are also applications where seismic isolators are supplemented with sliding and oil dampers. Research and applications show that seismic isolation can be used effectively in mezzanine floors and wide openings can be passed. Considering the current practices, it is obvious that an efficient and reliable method is necessary for such multi-story buildings. There is no doubt that an effective and reliable solution that will eliminate above-mentioned overturning effect and the limitation of horizontal displacements in the superstructure will find widespread application in multi-story tower type structures. It is implied that the system proposed in the study will be a solution to existing problems and can be used securely. Considering these problems in the study, it is recommended to use sliding seismic isolators at the foundation level and dampers to be placed between the shoring system and building floor slabs below the ground in such multi-story buildings with a sufficient number of stories under the ground. Considering that hospital applications with seismic isolators have already become widespread as a result of the decision taken, it is thought that such an effective method will trigger the use of vertical architecture in hospital architectural design due to land costs and difficulties in finding a location, especially in big cities, and this system can be used and preferred effectively. In this context, it is aimed that such a seismic base isolation solution in hospital buildings, which should be designed according to vertical architecture, does not contain the above-mentioned problems, so that it will guide designer architects and engineers and increase the use of base isolation systems in high-rise buildings.

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