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Investigation of seismic base isolation systems and their properties

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Abstract

The use of various seismic isolators instead of changing the dimensions of the structural elements is an increasingly common practice in the design of buildings against earthquakes. The differences in soil properties, inadequacy in inspections and workmanship errors negatively affect the earthquake performance of the structures. Similarly, the complexity of earthquake forces that cannot be formulated adequately makes structural engineering solutions difficult. All these factors can be counted as the reasons that make the insulators, which enable the structure to make different displacements from the ground, stand out as a solution tool. In this study, the types and properties of seismic base isolation systems were investigated.

1. Introduction

Earthquakes are a natural disaster that does not show any symptoms before and can cause great loss of life and property due to the lack of an early warning system [1]. Alpid Belt, one of the two important earthquake belts in the world; It extends from Spain, Italy and Greece to Northern India and Afghanistan, and Turkey is located in the so-called Mediterranean Earthquake Belt on this belt. There are two major fault zones in Turkey, 92% of which is on this seismic belt. These are East Anatolian and North Anatolian faults. Turkey can be divided into the following four seismotechnical regions [2];

1. North Anatolian Fault Zone
2. East Anatolian Fault Zone
3. Bitlis Thrust Zone and East Anatolian Compression Zone
4. Aegean (Western Anatolia) Grabens Zone.

The fact that most of the existing building stock in Turkey is not built-in accordance with the current earthquake regulations, workmanship-material defects, the inhomogeneity of the soil properties and the lack of public awareness about earthquakes increase the loss of life and property in earthquakes. Reasons such as increasing urban population, unplanned construction considering today's facilities and technology, it is not acceptable to experience loss of life in a possible earthquake. This situation causes the concept of earthquake resistant building design to gain importance. Contemporary regulations prepared to meet current needs allow for quality building design and production, and our latest earthquake regulation [3] which came into force in 2018, is a good example of this. However, the fact that the earthquake has a complex structure limits its deterministic features to be used in engineering solutions. For this reason, it is necessary to use approximate data in engineering calculations and to stay on the safe side at the highest degree in proportion to these. This undoubtedly increases the cost. Earthquake resistant building design can be roughly summarized for two purposes and these are; The structure is of sufficient quality and the cross-sectional forces that will occur during the earthquake are calculated in such a way that they can be met at a sufficient rate [4]. In the traditional design approach; It is expected that the seismic energy coming into the structure will be damped by the inelastic deformations that the structure will exhibit before it collapses. It is expected that the structure designed for this purpose will be damaged at a level that can be repaired in a moderate earthquake, and that collapses that will cause loss of life in a severe earthquake will not occur [5]. In summary, the traditional approach aims to meet the seismic loads that will affect the structure with damage that will occur at a level that will not collapse. Increasing the rigidity of the structure for less damage; It will also increase the earthquake forces that will affect it. This situation creates the need for a different way to design earthquake resistant structures. Today, this need has been met by means of special elements that absorb the energy that affects the structure in the event of an earthquake. The techniques for protecting the structure from seismic loads acting on it can be divided into active and passive protection systems. Active control methods, in general terms, are systems in which an energy source is used to keep the displacement of the structure at the desired level. Passive control methods mentioned above; It provides the energy acting on the structure with special elements that absorb and absorb it [6]. In this study, seismic isolation systems, which are one of the passive protection methods, are emphasized and an example image of them is presented in Figure 1 [7].

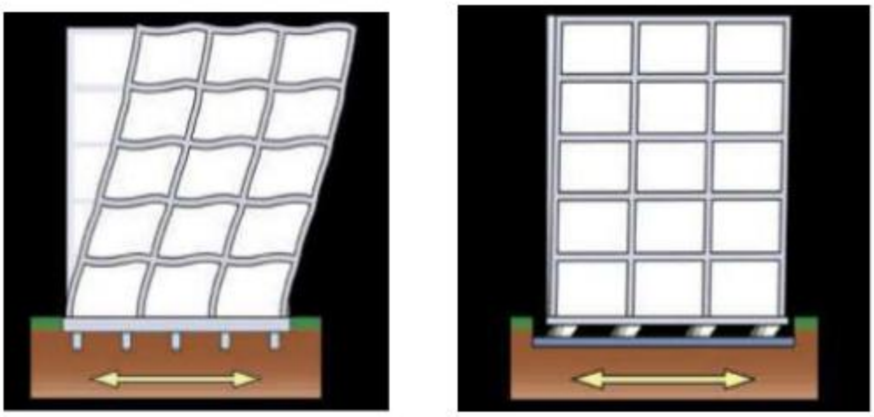

Figure 1. Behavior of normal and seismically isolated structures during an earthquake

Protecting from the devastating effects of earthquakes has been a problem that all civilizations established in earthquake regions wanted to solve, and they sought a solution to this issue. The seismic isolation provided by today's special elements has tried to be applied in different ways in historical buildings. Considering that the working principle of the seismic isolator in the building is to roughly separate the ground and the building, reducing the effect of the shaking on the building, it is possible to see an application in this logic in the Dikili Taş monument in Istanbul (Figure 2). The granite stones under the pedestal can be considered as a historical isolation system made in order to reduce the shaking that will occur on the monument during earthquake shaking [8]. Today, in parallel with the development of the properties of insulators, the number of structures using isolators against earthquakes is increasing rapidly. If the advantages of seismic isolators are examined; minimizing the damage to the structure, protecting the goods-equipment inside the building and reducing the relative floor acceleration. Also, as disadvantages; high cost, the presence of nearby buildings, and the difficulties encountered in the design of water and natural gas installations in a structure where insulators are used [9].

Figure 2. Dikili Taş monument, İstanbul

Element sizes are enlarged in order to increase the rigidity of the structure in earthquake resistant structure design. This reduces the ductility of the structure and causes it to exhibit an inelastic behavior. A structure with low ductility makes sudden and rapid displacements during an earthquake. It is not desirable for the building to behave in this way. Seismic isolators used as a solution; they are elements with low lateral rigidity used between the structure and the ground and increase the natural period of the structure. By keeping the rigidity of the structural elements small, the vibration period can be brought to the desired range. As a result, earthquake effects are reduced. For this purpose, the dominant period of the region and the natural period of the structure are kept away from each other in order to avoid the resonance phenomenon. This applies, for example, to the construction of short-term and low-rise structures in areas with hard floors and long periods. The seismic isolation tools to be used will change the dynamic behavior of the structure and reduce the force acting (Figure 3).

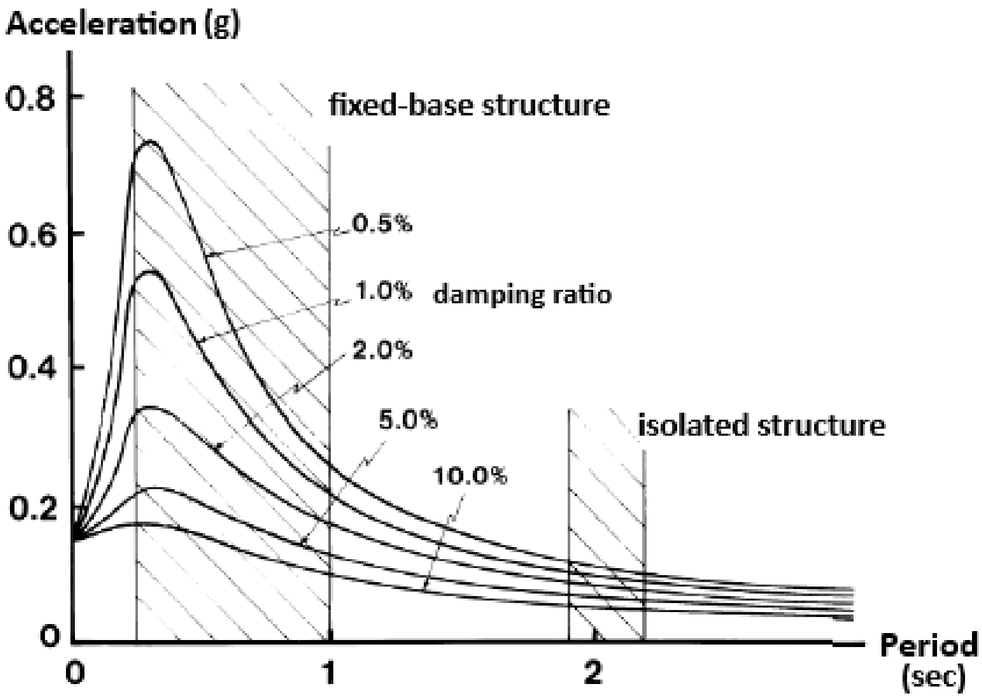

Figure 3. Changing the acceleration and damping values by increasing the period in structures

2. Types of seismic isolation

Classification can be made by considering the shapes, places of use, sizes, materials used in their production and working mechanisms of the insulators. Among these titles, French electric institution systems, EERC combined systems and TASS systems can also be analyzed as rubber-slippery systems. However, in this study, it has been grouped on the basis of slip, taking into account the working principles. Seismic isolators can generally be grouped under three headings [10]. These;

1) Elastomeric base isolation tools,
    1. Low damping natural and artificial rubber insulators
    2. Lead core rubber insulators
    3. High damping rubber insulators
2) Insulation tools designed on slip
    1. Friction pendulum systems
    2. Flexible-friction base insulation systems
    3. French Electric Institution systems (Neoprene insulators with steel plate layer)
    4. EERC unified systems
    5. TASS systems
3) Spring type systems
    1. The GERB systems

2.1. Elastomeric base isolation tools

It is the most commonly used seismic isolation type among seismic isolation systems. It is produced by bonding a steel plate with a thickness of 2-3 mm and a rubber of 8-20 mm with the effect of high temperature and pressure. It was applied for the first time in 1969, but since steel plates were not used in the application, the rubber part swelled laterally and the desired rigidity could not be achieved. During an earthquake, the structure can move upwards while making lateral displacement. The steel plates used in the production of these insulators increase the vertical rigidity of the structure. It also acts as a preventative for lateral buckling. The lateral load damping acting on the structure is related to the lateral displacement capability of the structure. This feature can be provided with an elastomeric insulator. The insulator is mounted to the structure with the steel cap parts on the top and bottom. Due to its material properties, it requires minimum maintenance. They have a long service life, but their production costs are high. Ensuring continuous production will reduce its high cost. As a material, it does not creep and is long-lasting. It does not lose its elastic properties at temperatures between -17 and 82 ℃. Production and modeling stages are easy [11, 12].

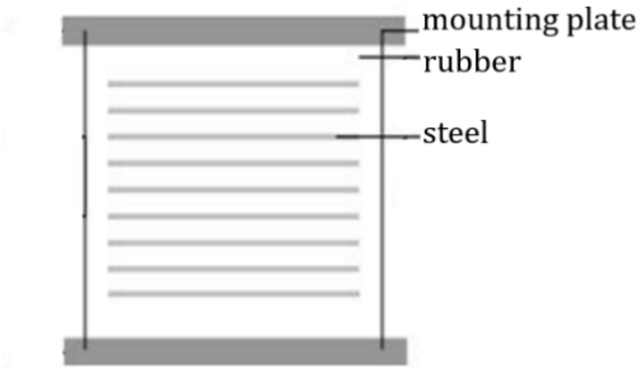

Figure 4. Elastomer insulator cross section

2.1.1. Low damping natural and artificial rubber insulators

It is a type of insulator consisting of combining a large number of sheet metal and rubber between steel heads with the effect of pressure and heat. The horizontal rigidity depends on the thickness and number of the rubber part. The desired rigidity can be achieved by changing these values. However, since the increase in the height of the insulator may cause buckling, the maximum height value is limited to half the diameter. As a material, it does not creep and is long-lasting. It does not lose its elastic properties at temperatures between -17 and 82 ℃. Production and modeling stages are easy. It shows linear elastic behavior against shear stress. The disadvantage of this isolator type is that it needs additional damper due to its low damping. The visual and force displacement behavior of this type of insulator is presented in Figure 5 [10, 11].

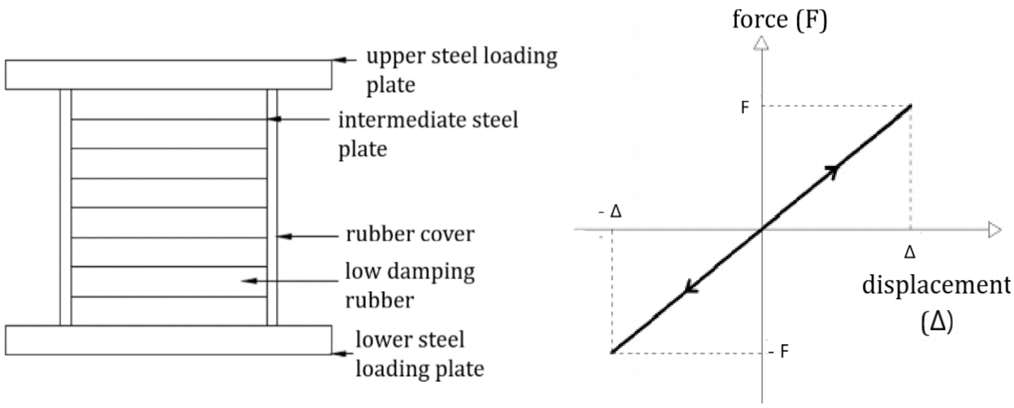

Figure 5. Cross section of low damping rubber insulator and force-displacement graph

2.1.2. Lead core rubber insulators

It is formed by placing a lead core in the center of low damping rubber insulators in order to increase the damping rate. The damping rate of this elastomer insulator type is 15-35%. After its first production in 1975, it has been widely applied in countries such as the USA and Japan. The energy absorption capacity of the lead core reduces the horizontal displacement of the insulator. The lead core used provides damping and rubber provides a stabilizing feature. Combined use of rubber and lead core; by using the stored elongation energy during the earthquake, it provides a force that returns the structure to its initial conditions after the earthquake. Lead core rubber headstock; since it is a composite combination of lead and core, there is a behavior pattern that is characteristic of both materials. The lead core increases the rigidity of the elastomer insulator. Lead-core rubber under low load shows rigid behavior both horizontally and vertically. Layers of steel plates surround the lead core externally and force it to deform under shear stress. The yield strength of the lead core is 10 MPa. When the lead reaches its yield strength, the horizontal stiffness is significantly reduced. Damping by plastic deformation of the lead is modeled by a hysterical cycle. The inability to test the central lead core after strain can be considered as the most important disadvantage of this insulator type [11-14].

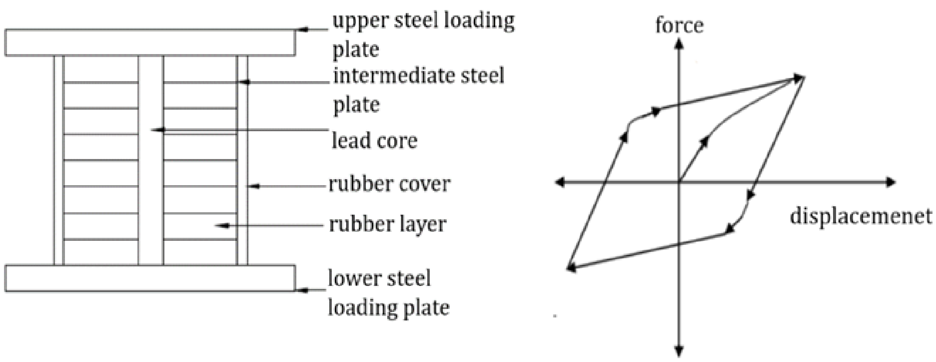

Figure 6. Cross section of lead core rubber insulator and force-displacement graph

2.1.3. High damping rubber insulators

It is an elastomer insulator type in which damping rate is increased to 8%-15% by adding special materials such as carbon and resin to low damping rubber, which has a damping rate of around 2%. The support cross-section and the bonding method of the layers are the same as for the low damping rubber insulators. High damping rubber type insulators, based on the idea of eliminating the need for additional dampers; it was first developed by MRPA, a British institution, in 1982. Highly damped rubbers exhibit nonlinear behavior at shear strains of up to 20% and are modeled with a smooth elliptical hysteresis curve [11-14].

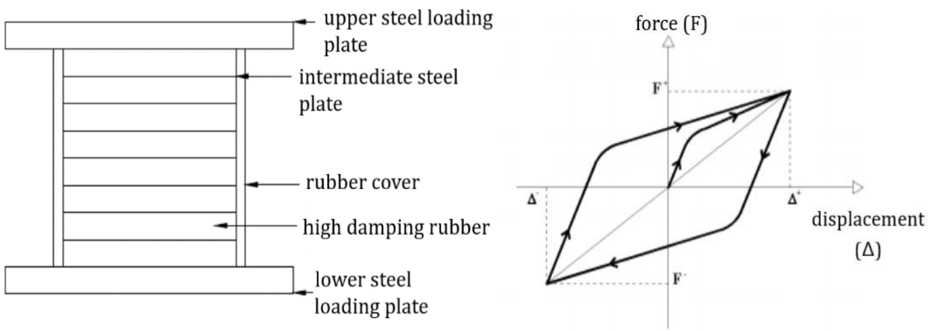

Figure 7. Cross section of high damping rubber insulator and force-displacement graph

2.2. Insulation tools designed on slip

These systems, which are based on slip as their working principle, are the oldest and simplest isolation systems. The first system based only on gliding was made by a medical doctor in 1909 in England. If the working principle is examined, there is a limitation of the shear force at the insulator interface in general. The shear force acting on the structure from the ground depends on the coefficient of the friction force, not the magnitude of the earthquake. If the materials used in the production of this type of insulator are examined, these are; It is polytetrafluoroethylene (teflon) coated on stainless steel [10].

2.2.1. Friction pendulum systems

Friction pendulum systems were first developed in 1987 for use in seismic isolation applications. If the working mechanism is examined, there is an articulated slide that moves on a spherical surface made of a stainless steel. This articulated slide absorbs the energy coming from the friction force resulting from its movement. The theory of this type of insulator is based on the Coulomb Friction Principle. Temperature, speed and cleanliness of the surface greatly affect the friction characteristics of the insulator.

Friction pendulum type insulators; they are slip-based systems that combine shear and return forces thanks to their spherical surface. The mass carried by this movement of the slider both rises and creates the return force. Here is the period of the insulator; although it is independent of mass, it depends on the radius of the spherical surface. The earthquake force acting during the earthquake is damped by the pendulum movement. The period of a simple pendulum can be calculated by the formula.

$$T = 2\pi\sqrt{\frac{R}{g}}$$

R in the formula; is the radius of curvature and g is the gravitational acceleration.

The diameter of the protective cylinder in this type of insulator; It is determined according to the largest displacement value that will occur due to the earthquake effect. Such a limitation provides safety in cases where the displacement value at the time of the earthquake used in the calculation is exceeded. In addition, this protective roller protects the inner surface from environmental pollution that affects the friction value. The force-displacement curve of friction pendulum type insulators is presented below [15, 16].

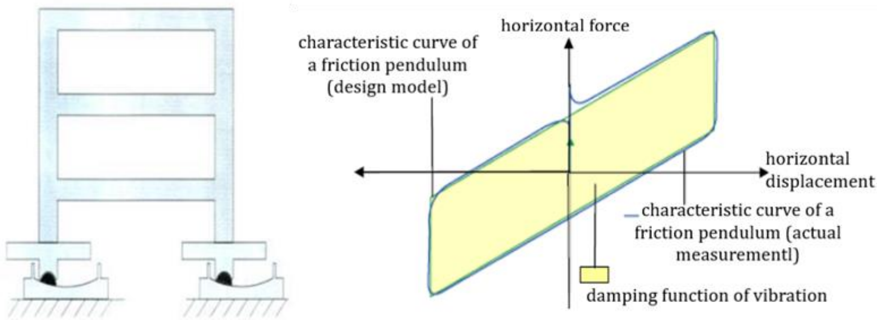

Figure 8. Cross section of friction pendulum system and force-displacement graph

2.2.2. Flexible-friction base insulation systems

It is a type of slip-based insulator with concentric and circular plates in contact with each other and a rubber core in the center. Since there is no force to return the sliding systems to the starting position, the studies have shifted to this type of insulator. Friction plates have been added to the system in order to make larger displacements to the insulator and to limit the shear stresses that will occur in the rubber core. Thanks to this layered structure, the velocity values affecting the lower and upper ends of the insulator are divided by the number of layers. Thus, the friction coefficient decreases as the speed of each layer will be lower than the total speed of the system. The rubber core in the center is used to have a reversing effect. There is a steel bar in the center of the rubber core to prevent the displacements to tag from concentrating in one spot. This type of insulators can be used in asymmetrical structures as they coincide with the centers of rigidity and mass. In addition, as long as the load acting on the system does not exceed the friction force, there will be no movement. Thus, low-impact lateral loads such as wind do not cause problems [12].

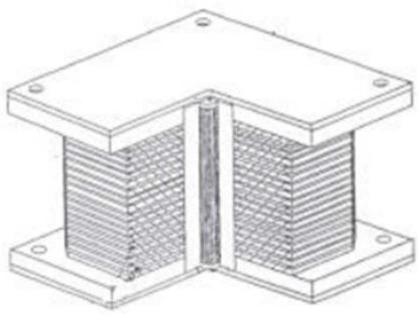

Figure 9. Flexible-friction base insulator

2.2.3. French electric institution systems (Neoprene insulators with steel plate layer)

This type of insulator, which was applied at the Koeberg Nuclear Power Plant in South Africa, was developed in the early 1970s with the support of the French Electricity Authority. Its design is achieved by placing an isolation system between two raft plates. In this system, there are steel and neoprene plates combined with a lead-bronze alloy. The sliding surface is formed between the lead-bronze alloy and the stainless-steel surface. The purpose of the friction plates is to keep the horizontal acceleration below 0,2 g. Neoprene insulator has a very low displacement capacity (+-5 cm). When the displacement exceeds this limit, the sliding element provides the necessary movement. However, since there is no reversing mechanism in the system, permanent displacements may occur [10, 11].

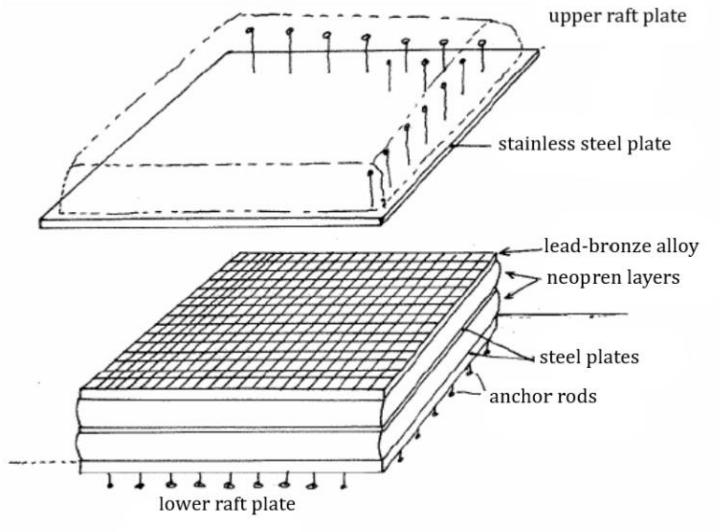

Figure 10. Cross section of neoprene insulators with steel plate layer

2.2.4. EERC unified systems

Carrying the inner columns of the building system with Teflon on the sliding elements and the outer columns with a low damping rubber support; it is an insulator type, which is a combination of sliding and elastomer bearings. The rubber part of the system ensures the re-centering of the structure after the movement, and the sliding part provides the absorption of the energy. The rubber support also controls the torsional behavior of the system. The EERC system has been used in the US at the University of Nevada Mackay School and retrofitting a hospital building [10, 11].

2.2.5. TASS systems

They are insulation systems developed by a Japanese company, in which the vertical load is carried by elements consisting of Teflon-stainless steel. The system consists of neoprene layers in addition to teflon and stainless steel. These layers do not carry vertical loads, but they provide a restoring effect to the system. The design of the system is made by taking a friction coefficient of 0.05 under 10 MPa pressure. Since the elastomer support has no vertical load carrying capacity, the system is exposed to tensile stresses. In addition, this type of system is difficult to model because the sliding surface is sensitive to low frictional velocities [17].

2.3. Spring type systems

2.3.1. The GERB systems

These systems, which are based on elastomeric and slip, are generally used to provide insulation in the horizontal direction. If there is a need for three-dimensional insulation, it is possible, but not common, to use elastomeric insulators. In such cases, it is more appropriate to use spring type systems. Developed by GERB Company in Germany for nuclear power plant turbines, this system consists of large coil springs with the ability to stretch horizontally and vertically. The vertical frequency is about 5 times the horizontal frequency. Since these springs have no damping effect, additional viscous dampers are used. With these additional dampers, approximately 30% critical damping occurs in the spring system. This type of system is suitable for structures such as nuclear reactors in nuclear power plants where the center of gravity and the center of rigidity are at the same level.

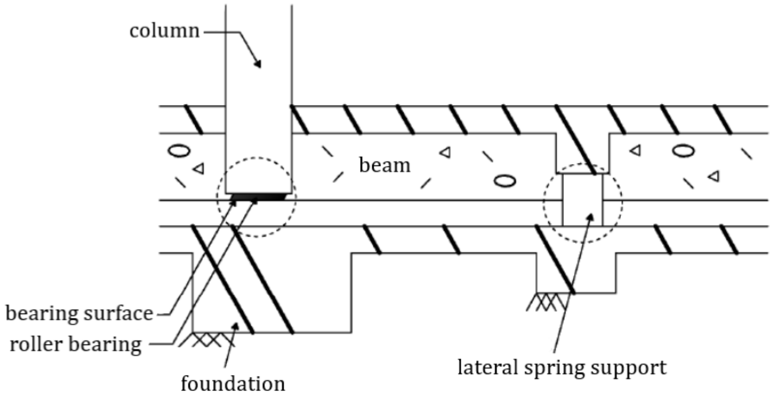

Figure 11. TASS system cross section

3. Conclusion

Minimizing the damage to the structure against earthquake effects is an important issue in the field of structural engineering. With the help of today's advanced technology, the use of insulators related to this subject has been developed and started to be applied. The use of seismic isolators, especially in special structures such as bridges and hospitals, which reduce the damage to the structure during an earthquake and which should be used during and immediately after the earthquake, is an effective solution that is becoming increasingly common.

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Author contributions:

Erden Ozan Karaca: Conceptualization, Methodology, Software **Muhammed Tanyıldızı:** Data curation, Writing-Original draft preparation, Software, Validation. **Nusret Bozkurt:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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