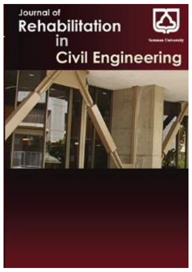
Journal of Rehabilitation in Civil Engineering 8-2 (2020) 37-61



Journal homepage: http://civiljournal.semnan.ac.ir/

Base Isolation Systems – A State of the Art Review According to Their Mechanism

A. Beirami Shahabi[1], Gh. Zamani Ahari[2*] and M. Barghian[3]

1. Ph. D. Student, Department of Civil Engineering, Faculty of Engineering, Urmia University, Urmia, Iran.
2. Assistant Professor, Department of Civil Engineering, Faculty of Engineering, Urmia University, Urmia, Iran.
3. Associate Professor, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran.

Corresponding author: g.zamani@urmia.ac.ir

ARTICLE INFO

Article history:
Received: 21 October 2018
Accepted: 02 December 2019

Keywords:
Seismic Isolation Methods,
Passive Control,
Friction Pendulum Isolators,
Lead Rubber Bearing,
High Damping Rubber Bearing.

ABSTRACT

Seismic isolation is a method to reduce the destructive effects of earthquakes on a structure in which the structure is separated from its foundation by devices called seismic isolators. As a result, the horizontal movements of the earthquake transmitted to the structure are reduced. The seismic isolation is used for both newly constructed structures as well as for retrofitting the existing buildings. Due to the appropriate functioning of the isolators in past earthquakes, many structures are now equipped with these earthquake-resistant systems. So far, some review research works have been conducted on the seismic isolation techniques but in the limited and regional application form. In this paper, a historical evolutionary review of the isolation techniques has been conducted in chronological order. The methods of seismic isolation have been categorized based on their mechanism. The advantages and disadvantages of these methods are discussed. In addition, the latest advances and new methods developed in this field have been introduced.

1. Introduction

Modern seismic isolation has been started from more than a century ago as a method to reduce the effects of earthquakes on structures. In this method, seismic isolators with low horizontal stiffness and high vertical stiffness are placed between the foundation and the structure. The isolators reduce the amount of the acceleration transmitted to the structure. The seismic isolation is used for both newly constructed structures as well as for retrofitting the existing buildings, especially for historical buildings and monuments. This method is more beneficial for low-rise and medium-rise buildings than high-rise ones. In addition to conventional buildings, seismic isolation is also applied to other structures such as bridges and nuclear power plants.

DOI: 10.22075/JRCE.2019.16186.1306

Seismic isolation systems are commonly used in earthquake-prone countries such as the United States, Japan, New Zealand, and China, (Buckle and Mayes, [1]), and hundreds of structures equipped with these systems are built annually in these countries (Patil and Reddy, [2]).

Studies show that the horizontal component of earthquakes plays a major role in the structure destruction, and if it is possible to reduce the effect of this component on the structure, a large amount of the earthquake's structural damages will be reduced (Kelly, [3]). This damage reduction can be achieved by increasing the natural period of structures which is possible by means of seismic isolation. Using the isolation, the structure's natural period is shifted from the high-risk zone to the low-risk one (Harvey and Kelly, [4]). The seismic isolation shifts the structure's natural period from less than one second to 2 up to 4 seconds (Warn and Ryan, [5], Fasil and Pillai, [6]). Fig. 1 shows the change in the natural period of the isolated structure and the effect of damping on it. As it is seen from this figure, the isolation increases the structure's natural period and decreases the acceleration response. In addition, damping plays a positive role in this regard**.** As it is known, the increase in damping controls the relative displacement and acceleration, indicating the importance of damping in a seismic isolation system.

By using the isolation system in a structure, the structure acts as a mass with a high degree of rigidity. Although a significant relative displacement occurs between the structure and its foundation, a slight relative displacement occurs between the structural floors, which significantly reduces the amount of internal forces in the structural members (Jain and Sanghai [7], Clemente and Martelli, [8], Kunde and Jangid [9]). Reducing the relative displacement between floors causes the structure to behave in or near the elastic phase; therefore, it causes an increase in the safety of the structure against earthquakes (Naveena and Nair [10]). In other words, the isolated structure acts as a single degree of freedom system, thus the structure deforms almost in its first mode, and the effect of higher modes are almost negligible (Semwal and Dyani [11], Rai and Mishra [12], Verma et al. [13], Panchal and Soni [14]). The seismic isolation does not dissipate the earthquake energy; instead, it reflects the energy and prevents the structure from transferring the earthquake energy using a certain mechanisms, (Girish and Pranesh [15], Clemente [16]).

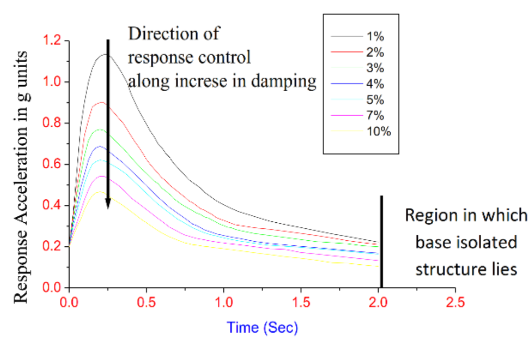


Fig. 1. Effect of the seismic isolation and damping on the structure's natural period and acceleration response,[2].

Depending on the soil type beneath a building; in some cases, the seismic isolation may cause resonance phenomena, in which the isolation is not recommended (Gupta et al. [17]). Generally, the performance of a seismic isolation system can be determined by two indices; first, the ability to move the natural frequency of the structure from the hazardous zone to the low-risk zone and second, the ability to create a proper damping to control the displacement between the foundation and structure (Bhaskar and Khanchandani [18], Jangid and Datta [19]).

Nowadays, different methods of seismic isolation techniques have been developed and numerous studies have been conducted on different types of seismic isolation systems, and their results have been published as research papers and textbooks such as Skinner et al. [20], Naeim and Kelly [21].

Among the well-known seismic isolation methods, the followings can be mentioned: lead rubber bearing (LRB), low damping rubber bearing (LDRB), high damping rubber bearing (HDRB), friction pendulum system (FPS) in the single, double and triple types, Teflon sliding support, orthogonal rod bearing, steel ball bearing, mushroom-shaped bearing and springs type bearing. So far, some research works have been conducted on the review of base isolation techniques but in the limited and regional application form. In this paper, a historical evolutionary review on the isolation techniques has been conducted in chronological order, and the latest developments in this field have been surveyed and the corresponding study results are discussed. In this paper, the methods of seismic isolation have been categorized into four groups based on their underlying mechanisms.

2. Categories of Seismic Isolation Methods

So far, various methods have been invented for seismic isolation. Each of these methods has some advantages and disadvantages. Some of them have high operating costs, others require high construction technology, some have maintenance problems, and some of them lose their initial functionality over time. This makes some of these methods more useful and practical than others. In general, seismic isolation methods can be categorized into four groups:

a. Elastomeric-based methods

b. Sliding-based methods

c. Rocking-based methods

d. Innovative methods

In the following sections, each of these groups has been studied, and the corresponding theoretical and laboratory studies are discussed.

3. Elastomeric-Based Methods

Elastomeric-based methods are one of the most popular groups of seismic isolation techniques. The general form of an isolator in these methods consists of rubber layers as well as thin layers of steel plates or fiber layers, which are compressed and interconnected through a special process to form the isolator. So far, several types of these isolators have been developed, including low damping rubber bearing (LDRB) (or natural laminated elastic rubber bearing), high damping rubber bearing (HDRB), lead-rubber bearing (LRB) and fiber-reinforced rubber bearing (FRB). These isolators are discussed in the next sections.

3.1. Low Damping Rubber Bearing (LDRB)

The low damping rubber bearing (LDRB) (or natural laminated elastic rubber bearing) is formed of steel and rubber layers, which are joined together in a layered form. The overall schematic of this isolator is shown in Fig. 2. (Constantinou et al. 2007, [22]). As it is seen from the figure, steel plates are regularly arranged between the sheets of rubber, which causes the vertical stiffness of these parts to be high and the horizontal stiffness to be low. Two types of rubber are used in this isolator; with low damping or with high damping. In Fig. 3, the force-displacement hysteresis diagrams for a low damping rubber bearing in horizontal and vertical directions are shown.

As shown in Fig. 3, the horizontal stiffness of the LDRB isolator is much less than its vertical stiffness, which is necessary for the isolation. The disadvantage of this isolator is that it dissipates little energy during the structural vibration. The damping of this type of isolator is between 2% and 3% of the critical damping in 100% of shear strain capacity. Because of the low energy dissipation of rubber in these types of isolators, additional dampers such as viscous or yielding dampers should be installed.

Sofar Various researchers have studied this type of isolator. To predict the behavior of these isolators, Koh and Kelly [23] proposed a simple linear model to predict the behavior of elastomeric bearings. In this model, the effects of both shear and flexural deformations were considered. In their study, an approximate mechanical model involving both shear and flexural deformations was employed to represent the P-Delta effect of elastomeric bearings. It was concluded that the model could properly explain the bearings height reduction, the effect of axial load on the stiffness, and the damping ratio. The schematic of the proposed model for the elastomeric bearing is shown in Fig. 4.

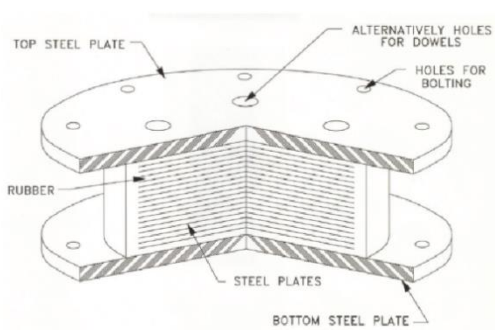


Fig. 2. Schematic of a laminated elastic rubber bearing isolator, [22].

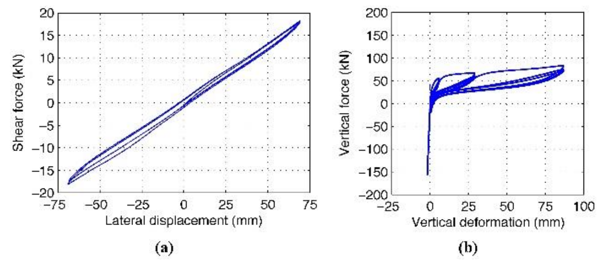


Fig. 3. Hysteresis diagrams of a low damping rubber bearing isolator (LDRB) for (a) horizontal and (b) vertical deformations, [5].

Abe et al. [24], experimentally studied three types of bearing and found out that in the case of high damping rubber bearings, an increase in amplitude causes an increase in the equivalent stiffness and decrease in the amount of damping ratio. Also, in the lead rubber bearing, the amount of restoring force depends greatly on the amount of vertical force. In addition, the experimental results showed that three-dimensional loading influences the behavior of the isolators.

In the other work, Abe et al. [25], based on the experimental data, proposed a mathematical model for the laminated rubber bearing. The elastoplastic model was obtained by considering a displacement-dependent isotropic hardening rule and a parallel nonlinear elastic spring.

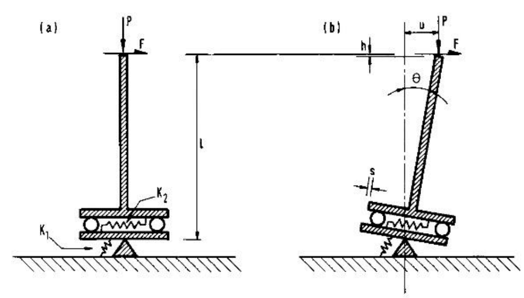


Fig. 4. (a) An approximate model proposed for the elastomeric bearing. (b) Deformation caused by applied loads, [23].

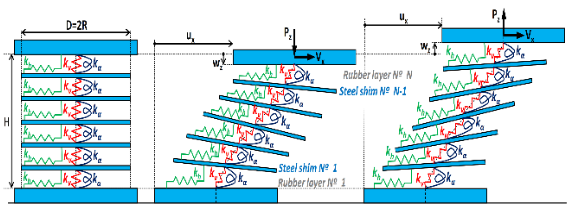
To determine the proper thickness of the rubber layers and the total height of the laminated rubber bearing (LRB), Koo et al. [26], investigated the effect of the bearing shape on its buckling load. In this study, numerical modeling and shaking table tests were carried out. The results of the study show that the horizontal stiffness variation is significant and should be considered in the design of the bearings.

In order to study the tensile behavior of the elastomeric bearings, Kumar et al. [27], conducted a series of laboratory tests. In these experiments, low-damping rubber bearings with different shear modulus and various loading conditions were tested. The main objective of this study was to investigate the factors influencing the cavitation effect of the elastomeric bearings under tensile and shear forces. Fig. 5 depicts a slip through failure surface in a post-cavitation shear test in a sample of the elastomeric bearing.

Ishii et al. [28], presented a mechanical model based on parallel tensile springs to investigate the behavior of elastomeric bearings under the influence of the shear force and the end rotation of bearings. The results of the experiments showed that the bearing rotational stiffness increased by increasing the vertical load but decreased with increasing the shear deformation.

Fig. 5. Slip through failure mode in a post-cavitation lateral displacement test (axial pressure = 0.5 MPa), [27].

Maureira et al. [29], proposed a nonlinear model to predict the mechanical behavior of the elastomeric bearings. This model can simultaneously predict the horizontal and vertical displacement behavior of the bearings. The results of the studies showed that these bearings could withstand the shear displacement up to 25% of their radius, without causing the cavitation phenomena in the rubber. The schematic of the multi-spring isolator model proposed for the elastomeric bearing is shown in Fig. 6.



a b c

Fig. 6. Schematic of the multi-spring isolator model, (a) undeformed shape, (b) deformed shape in compression and shear and (c) deformed shape in tension and shear, [29].

In order to reduce the cost of seismic isolation systems, particularly in the retrofitting of existing buildings, Crowder and Becker [30], proposed the use of elastomeric bearings at the end of the ground floor columns. For which they proposed a mathematical model and conducted laboratory experiments. The result showed that this method caused a significant reduction in the lateral stiffness of the isolated structure.

3.2. High Damping Rubber Bearing (HDRB)

The structure of the high damping rubber bearing is similar to the low damping rubber bearing type. It is made of rubber and steel sheets and in this type of isolator, some materials such as carbon black (HDRB) are added to rubber which can produce higher damping namely between 10% up to 20% of the critical damping at 100% of shear strain capacity. In Fig. 7, a sample of the hysteresis diagram of a HDRB with its characteristics is shown. By comparing the shape of the diagram of this isolator with the one of low damping rubber bearing in Fig. 3, it can be seen that the (HDRB) can dissipate more energy during the oscillating cycles, resulting in a greater ability on reducing the earthquake's damages. The shear modulus of this type of rubber in the low strains is about 4300 KPa and is decreased by increasing the strain. Its amount in the 100% of strain is about 430 KPa (Warn and Ryan [5]).

So far, many researchers have studied this type of isolator. The force-displacement behavior of this type of rubber is complex due to the viscosity. One of the main research topics in this regard is proposing a model to predict the behavior of this type of isolator.

Hwang and Ku [31], proposed a model to simulate the seismic behavior of HDRB bearings based on the test results of the shaking table. This model is based on the fractional derivative Kelvin model and a sinusoidal loading test for a shear strain of nearly 100%. American Association of State Highway and Transportation Officials (AASHTO) and the Japanese Public Work Research Institute (JPWRI) have utilized two equivalent linear models for predicting the behavior of HDRB bearing in their bridge design codes. Comparison of the results of the experiments with the results obtained from these models and the proposed model indicated better performance for the proposed model in predicting the seismic behavior of the HDRB bearings than that of the mentioned codes models. (Hwang and Ku, [31])

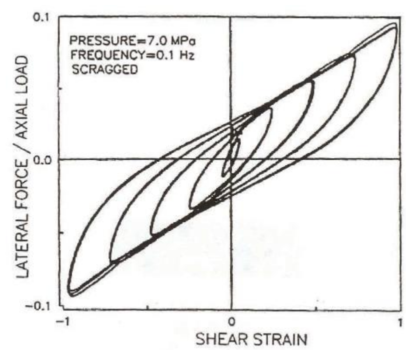


Fig. 7. Hysteresis diagram of high damping rubber bearing isolator (HDRB), [22].

In the other study, Hwang et al. [32], proposed a model to determine the shear force-displacement behavior of HDRBs based on the experimental results. In this model, ten parameters including the rubber compound, Mullins effect, scragging effect, frequency, temperature, and axial load are considered to predict the bearing behavior. A comparison of the experimental results and the proposed model indicates the good accuracy of the model.

Dall Asta and Ragni [33], proposed a viscoelastic model to predict the behavior of HDRB based on the results of experiments. The focus of the study was on the behavior of the isolator with a different range of shear strain rates and amplitudes.

Bhuiyan et al. [34], proposed a new model consists of a dashpot element. Their model is based on the Maxwell model, which is achieved by adding a nonlinear and an elastoplastic spring. To obtain the model parameters, a series of experimental tests were conducted.

Yuan et al. [35], proposed a constitutive model inspired by Zener's classic model. In this model, two hyperelastic springs with a non-linear dashpot element have been used. The diagram of the model is shown in Fig. 8. In this model, the Fletcher– Gent effect, which indicates high horizontal stiffness at small strains, is included by imposing a coefficient. This property is created by adding carbon powder to the rubber. In the model, a nonlinear viscosity coefficient is also utilized to consider the effect of the strain rate.

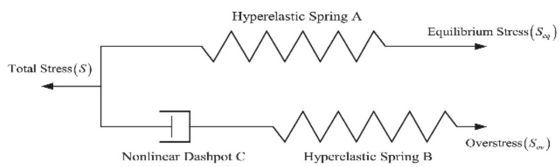
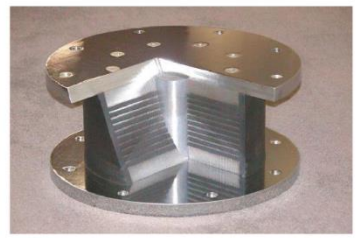


Fig. 8. Schematic diagram of the modified hyperplastic Zener model, [35].

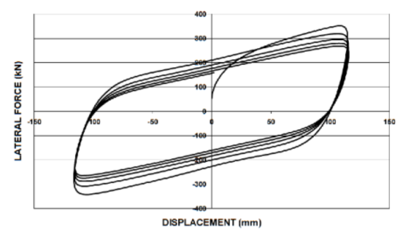
The seismic isolation is widely used in bridge construction, and many studies have been conducted in this field. Tubaldi *et al*. [36,37], studied the steel-reinforced high damping natural rubber (HDNR) bearings. In the study, the seismic response of a three-span bridge equipped with HDNR was investigated by using an advanced HDNR bearing model. This model is capable of taking into account both horizontal and vertical seismic behavior of the bridge. The results of the research showed that vertical stiffness was important in the seismic performance of the isolated bridges.

3.3. Lead Rubber Bearings (LRB)

The third category of the elastomeric-based bearings is lead-rubber bearings (LRB) (also known as NZ bearings). Lead-rubber bearings were first invented and tested in New Zealand in the 1970s by Robinson and Tucker [38], and Robinson [39], and since then many other researchers investigated them. Fig. 9 shows the photo of lead rubber bearing and a sample of force-displacement graph for a lead rubber bearing. The schematic of the lead rubber bearing is similar to that of a laminated rubber bearing but for achieving more energy dissipation, a lead core is added. The lead core could provide lateral stiffness under service loads and dissipate energy under high lateral loads. The damping ratio produced by this system is a function of displacement and could be from 15% to 35%. (Semwal and Dyani, [11]). One of the main research topics in the LRB isolation system is proposing a proper model to predict the behavior of this type of isolator.



a



b

Fig. 9. (a) A photo of LRB, (b) The force-displacement curve of LRB, [22].

Ryan et al. [40], conducted a study about the behavior of LRBs. Previous models for predicting the behavior of lead rubber bearing ignored some aspects of their dynamic behavior. For example, it has been observed that lateral stiffness of the rubber bearings decreases with increasing the axial load, particularly at large deformations. The yield strength of LRB bearing varies with the axial load. In the conducted study, they included these effects and proposed a new model.

Warn *et al*. [41], conducted a research in which two types of isolation bearings, i.e.

lead rubber bearing (LRB) and low damping rubber bearing (LDRB) with the combination of axial and lateral loads were tested. They found out that the vertical stiffness of both types of bearings was decreased with increasing the lateral displacement.

Kumar *et al*. [42], proposed a new mathematical model for simulating the behavior of the LRB bearing. In the study, the effects of both lateral displacements and cyclic shear and axial loadings were investigated. This model simultaneously uses axial, shear, flexural and torsional springs. In order to include the variation of the critical buckling load capacity of the bearing with the lateral displacements, the bilinear area reduction method is used.

Han *et al*. [43], developed a model for elastomeric bearings. In the model, they used a series of vertical springs in the bottom and a shear one at the top of the bearing. The schematic picture of the proposed mechanistic model for the elastomeric bearing is shown in Fig. 10.

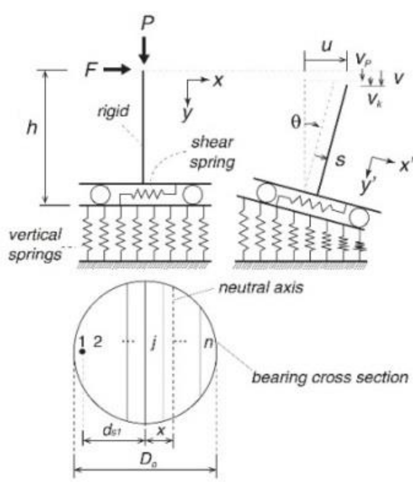


Fig. 10. Mechanistic model for the elastomeric bearing, [43].

Zhou et al. [44], proposed a model in which some influencing parameters including the reduction of the vertical stiffness at large lateral displacement, cavitation, permanent damage effects, and the variation of the horizontal stiffness due to the vertical load was considered. To validate the result of the numerical model, dynamic loading tests were conducted and the results were compared with numerical ones, which showed a good agreement.

Elastomeric bearings may also be under tensile stress in some critical conditions. This situation may occur in tall and narrow buildings. Hu et al. [45], developed a device, which was installed in conjunction with LRBs and prevented the tensile force to be created in the bearing. This device creates a low resistance to the horizontal movement of the isolator. The results of an experimental study indicated the proper functioning of this device in controlling the tensile force of the bearing.

Islam et al. [46], surveyed the performance of the lead rubber bearing and high damping rubber bearing in areas with moderate earthquake risk. In the study, a nonlinear model is presented to simulate the behavior of these types of isolators. Two groups of isolated and non-isolated structures were subjected to a variety of linear and nonlinear analyses. The results showed that seismic isolation in medium-rise buildings had significantly reduced the structural response in soft and moderate hard soils.

Attanasi et al. [47], studied the use of shape memory alloys (SMA) in a seismic isolation system. This alloy has high strength and ductility and is resistant to corrosion and fatigue. This material exhibits no permanent deformation despite it shows elastoplastic behavior. In the study, the SMA equipped isolators were analyzed by time history analysis. The results of the study showed that using this method creates a re-centering force in the system and helped to dissipate more energy in the isolator.

Attanasi and Auricchio [48], conducted a study in which they used a combination of SMA alloy by spiral springs with sliding isolators. The sliding isolator is flat and lacks re-centering force. By adding these springs, both horizontal stiffness and returning force were created in the system. The proposed system controls the horizontal forces applied to the structure while simultaneously provides the returning force for the structure.

Ozbulut and Hurlebaus [49], investigated the impact of using SMA with laminated rubber bearing and sliding isolators on the seismic behavior of bridges for near-fault ground motion. In the study, ambient temperature and lateral stiffness of the isolator were considered as the variables of the study. The results showed that the added SMA wires to the isolator increased the energy dissipation and returning forces. The results also showed that the use of SMA with smart sliding isolators was more effective than the laminated rubber bearing.

Dezfuli and Alam [50-53], conducted a survey in which they improved the performance of lead rubber bearing using shape memory alloys. As shown in Fig. 11, they provided a lead rubber bearing equipped with a shape memory alloy (SMA-LRB). They found out that shape memory alloys (SMA) could improve the re-centering and the damping capability of lead-rubber bearings. They studied this system in the multi-span continuous steel girder bridge. The results of the studies show that the shear strain of the SMA-LRB bearing is reduced by 46% and the energy dissipation is increased by 31%.

3.4. Fiber Reinforced Elastomeric Bearings (FREB)

The ordinary lead rubber bearing is usually large, expensive, and heavy. An alternative solution to mitigating these problems was to use fibers instead of steel sheets, which created a new type of isolator called fiber-reinforced elastomeric bearings (FREB). Fiber-reinforced elastomeric isolators have several advantages over traditional isolation devices, including lower manufacturing cost and lightweight. So far, some researchers have studied this type of bearing. In the following, some of them are referred.

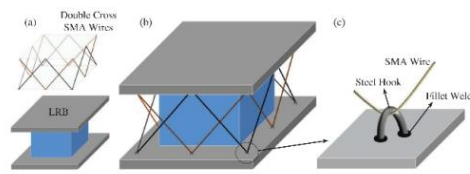


Fig. 11. SMA wire-equipped the LRB bearing: (a) separated configuration; (b) integrated configuration; and (c) details of steel hook, [50].

Kelly [54], and Tsai and Kelly [55], evaluated the mechanical characteristics of the multilayer elastomeric bearings. They investigated the influence of fiber flexibility on the vertical and horizontal stiffness of the fiber-reinforced bearings. The results of the studies showed that fiber-reinforced bearings with a behavior similar to steel-reinforced bearings could be produced.

Toopchi-Nezhad et al. [56], experimentally studied the behavior of a fiber-reinforced bearing without the top and bottom plates. In the conducted experiments, they observed the stable rollover deformation of bearings. This deformation reduces the horizontal stiffness of the bearing and causes an increase in the isolation efficiency of the bearing. They found out that this application could be suitable for seismic isolation of low-rise buildings. Fig. 12 shows a picture of the testing of fiber-reinforced elastomeric bearing and its force-displacement behavior.

Kang and Kang [57], analyzed a seismically isolated structure using fiber-reinforced elastomeric bearing subjected to earthquake excitations. The result of the study showed that isolating structures using a fiber-reinforced elastomeric bearing sufficiently reduced the story drift of the building, controlling the building's motions within allowed limits.

Angeli et al. [58], investigated the behavior of a multilayer elastomeric bearing. They employed carbon fibers as reinforcement material instead of steel sheets. This change causes the bearing to be lighter and cheaper since the carbon fibers (or Kevlar) are much more resistant than steel. In the study, to model the compression and bending behavior of the bearing, an analytical model was proposed. For the first time, the extensibility and the compressibility of the elastomer were considered in the model.

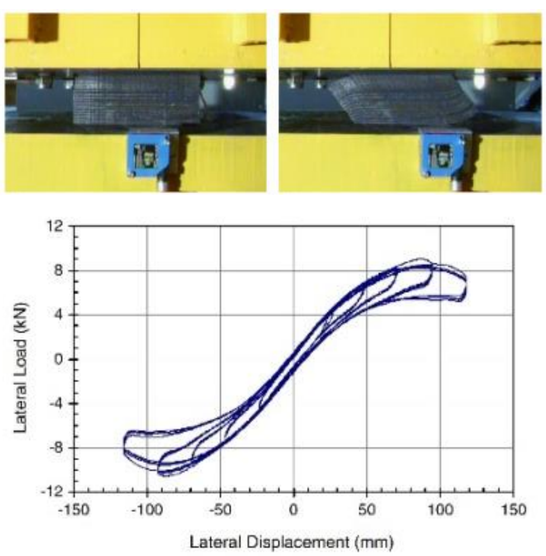


Fig. 12. Photo of testing of a fiber-reinforced elastomeric bearing and its force-displacement graph, [56].

4. Sliding-Based Methods

Nowadays, one of the popular methods used for seismic isolation is sliding-based techniques. These methods work based on the simple principle of friction. In a sliding isolator, during an earthquake excitation, two flat or spherical surfaces slide over each other. If the intensity of the exciting force is more than the frictional force, sliding initiates. The main advantage of these systems is that they are effective for a wide range of frequencies and the maximum acceleration transmitted to the structure can be controlled by the coefficient of friction between the sliding surfaces. Sliding-based methods are divided into several categories that are referred to below.

4.1. Pure Friction System (P-F System)

The pure friction (P-F) system is the first category of the sliding isolation systems. During the ground excitation, two flat stainless steel plates slide over each other and the isolation and energy dissipation is achieved. If the excitation force exceeds the frictional force ($\mu \times m \times g$), sliding will occur. (Girish and Pranesh [15]). Hence, the response of the isolated structure is independent of the frequency and amplitude of the excitation. There are many research works on the performance of the P-F system and some of them are discussed below.

Mostaghel et al. [59], studied the effectiveness of sliding bearing for isolation of a single degree of freedom structure supported by a sliding isolator. They found out that the acceleration response level strongly depends on the coefficient of friction of the bearing so that the smaller coefficient caused lower responses. Also, they found out that in the lower coefficients of friction, the acceleration response did not vary with the frequency content of the ground excitation.

Jangid [60], investigated the seismic behavior of a SDOF structure with sliding support subjected to bidirectional ground excitations. In the study, the Coulomb friction characteristics were considered at the sliding support. It was observed that the structural response was significantly affected by the bi-directional excitations and in the case of the single-component excitation; the sliding displacement might be underestimated.

Nanda et al. [61], studied research work in which they used natural stones as sliding support. Through experimental and analytical investigations, they employed four different types of sliding interfaces, namely, green marble, high-density polyethylene (HDPE), geosynthetics, and rubber layers. The experimental result showed that the coefficient of friction valued between these interfaces lied in 0.05 to 0.15, which was appropriate for seismic protection and caused a reduction in accelerations up to 50%. Green marble and geosynthetic were found to have better performance in reducing acceleration in the friction isolation system.

4.2. Teflon Bearings

Teflon bearings have been used in seismic isolation, especially in bridges. Some researchers studied this system. Constantinou et al. [62], conducted an experimental study to assess the frictional characteristics of Teflon-steel interfaces under harmonic dynamic excitations. The results showed that the decrease in the ground acceleration and the increase in the bearing pressure both caused a decrease in the friction coefficient of the bearing.

Another type of isolator was also invented by Mostaghel and Khodaverdian [63] and was called resilient-friction base isolation (R-FBI). In this system, several Teflon ring plates are put together in the form of friction contact, and a rubber core is created in the middle of them. During an earthquake, the sliding of the sheets together provides seismic isolation and energy dissipation, and the deformation of the rubber core provides a restoring force in the bearing. By adjusting the friction coefficient of Teflon sheets, the desired bearing with suitable specifications for seismic design can be achieved.

4.3. Friction Pendulum System (FPS)

Remaining of permanent displacement in the P-F system is a problem for the isolated structures. In order to overcome this problem, the friction pendulum system was invented, in which, instead of a flat sliding surface, the curved sliding surface was used which caused the structure to move back to its original position. In fact, this system operates based on the principle of the pendulum motion. There is a variety of friction pendulum systems developed by various researchers. All of these systems are made by making some changes in the geometry of the initial model; some of them are referred to as below.

4.3.1. Single Friction Pendulum System (SFPS)

Single friction pendulum system invented by Zayas et al. [64]. Fig. 13 shows the schematic of the single friction pendulum isolator, (Petti et al. [65]). As seen from the figure, this isolator is made of a concave surface in the below and a convex steel piece at the middle and a pin joint above the bearing. During an earthquake, the upper part of the isolator moves left and right and creates isolation and energy dissipation. The natural period of the structure can be controlled by changing the radius of the concave surface (r). The natural period (*T)* of the structure supported on SFPS bearing, can be calculated by $T = 2\pi\sqrt{r/g}$. The study showed that increasing the period and decreasing the friction coefficient of the sliding surface could reduce the base shear and increased the displacement of the bearing. Because of the invariant radius of curvature, this bearing has a constant natural period, which is the main drawback of the system. If the isolation period and the excitation period coincides then the structure may experience the resonance phenomena.

4.3.2. Double Concave Friction Pendulum (DCFP)

Fenz and Constantinou [66], developed the modified model of the SFPS system and called double concave friction pendulum bearing (DCFP). Schematic of a double concave friction pendulum and a sample of its force-displacement graph are shown in Fig. 14. As shown in the figure, instead of one piece, two pieces are located between the top and bottom surfaces of this system and in total; four pieces are used. This modification increases the relative displacement capacity of the isolator and makes it possible to use the various radiuses of curvature and different friction coefficients in the sliding surfaces.

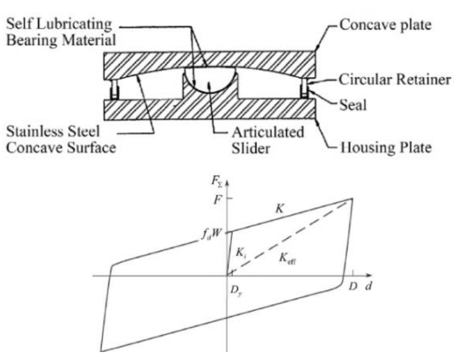


Fig. 13. Schematic of the single friction pendulum system (SFPS) and a sample of its force-displacement graph, [65].

4.3.3. Triple Friction Pendulum System (TFPS)

Fenz and Constantinou [67-69], developed the triple concave friction pendulum (TCFP) by modifying the DCFP system. The schematic of this system and a sample of its force-displacement graph is shown in Fig. 15. As shown in the figure, three pieces located between the upper and lower parts of the isolator, and in total five pieces are used. This modification increases the relative displacement and energy dissipation capacity of the TCFP isolator compared to DCFP. The surfaces of each mating part are convex and concave so that they can easily slide on each other, providing seismic isolation and energy dissipation. There are four sliding surfaces in the system in which the desired seismic capabilities can be achieved for the isolator by adjusting the radius of curvature and friction coefficient of each surface. The result of the studies shows that this isolator could be quite useful in protecting the structure from the destructive hazards of an earthquake.

4.4. Variable Frequency Pendulum Isolator (VFPI)

Pranesh and Sinha [70,71], proposed another sliding isolation system called variable frequency pendulum isolator (VFPI). In this system, they used a concave sliding surface with a variable curvature radius so that the geometry of the sliding surface was not an exact flat nor an exact spherical. This geometry causes the variable frequency of the isolator at different displacements. For small displacements, the VFPI acts similar to FPS and, in larger displacement, the behavior of VFPI can be compared to the PF system. Lu et al. [72], conducted a study to prevent the resonance phenomena and proposed a similar method so-called polynomial friction pendulum isolator (PFPI) system. In this model, the curvature of the sliding surface is determined as a polynomial function, and by proper adjustment of polynomial's coefficient, the appropriate seismic behavior of the isolator with variable frequency can be obtained. Panchal and Jangid [73], proposed a model to prevent resonance phenomena and named it the variable friction pendulum system (VFPS). The geometry of this model is similar to that of the friction pendulum system (FPS), except that in this system, the friction coefficient of the sliding surface is not constant and changes exponentially.

4.5 Convex Friction System (CFS)

Xiong et al. [74], introduced a new isolation system so-called convex friction system (CFS). The geometry of this system is similar to that of the FPS system, except that it does not have a spherical sliding surface, but

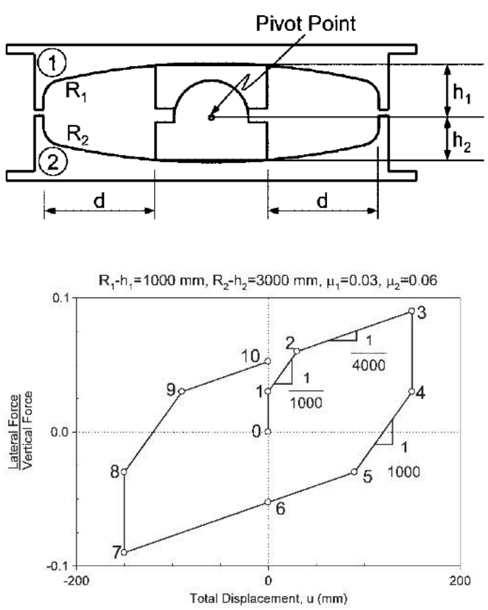


Fig. 14. Schematic of a double concave friction pendulum (DCFP) and a sample of its force-displacement graph, [66].

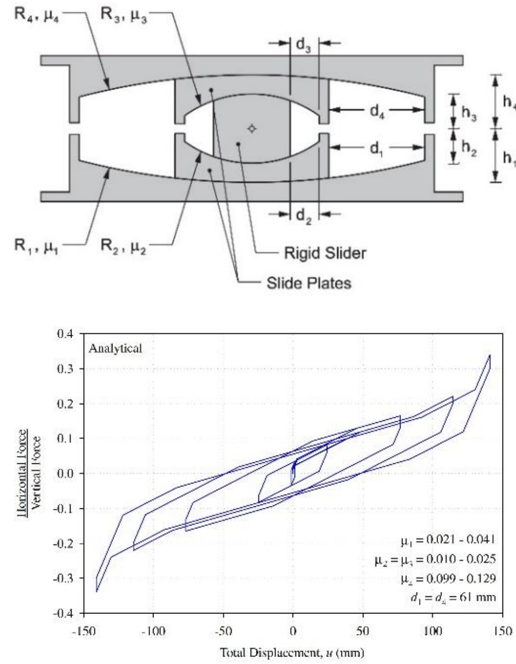


Fig. 15. Schematic of a triple concave friction pendulum (TCFP) and a sample of its force-displacement graph, [69].

It has a circular cone-type fixed-slope surface. This feature increases the isolator's re-centering ability. The results of the study showed that this system performed well in the seismic isolation of a structure compared to the FSP system and it could reduce the seismic response of the structure subjected to a near-fault earthquake up to 30%. A comparison of the geometric feature of PF, FPS, CFS, and VFPI is presented in Fig. 16.

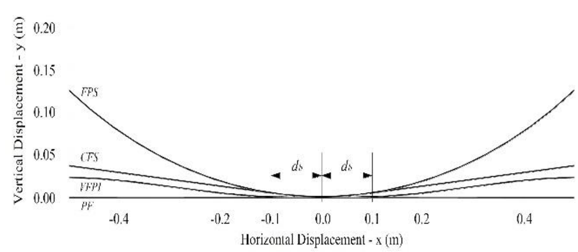


Fig. 16. Comparison of geometric shapes of PF, FPS, CFS, and VFPI, [15].

Xiong et al. [75], proposed the multi-angular pyramid concave friction system (MPCFS). This system is similar to the CFS system, except that its sliding surface is the multi-angular pyramid. The results of the studies showed that this system had some advantages compared to the FPS system producing more re-centering force and prevention of resonance during near-fault earthquakes.

Hoseini et al. [76], studied the combination of elastomeric and FPS isolators and found the optimal combination of the isolation systems under near-fault ground motions. They also studied the effect of period elongation on the behavior of the FPS isolation system and found out that the isolation system with a higher period is more effective in the studied earthquakes occurred in Iran [77].

5. Rocking-Based Method

Rocking type base isolation as a means of earthquake protection is over a century old technic but has been advanced rapidly in recent years due to an increase in research interest. The main problem of this system is that the device needed maintenance for keeping in good operation throughout its working life period. The following is a summary of the studies conducted in this regard.

Lin et al. [78], in a study, used a rolling rod as an isolator under a structure. To evaluate the seismic behavior of this system, experimental tests were conducted and the results compared to a fixed-base structure. They observed that in this system, the acceleration transmitted to the structure reduce by 56% to 60%. It was also observed that the peak relative displacement of the isolator was nearly equal to the peak ground motion. After an earthquake, some permanent displacements remain in the system.

Jangid and Londhe [79], investigated the effect of using elliptical rolling rods as isolator on a multi-story structure. The result of the study indicates that this isolator shows nonlinear lateral stiffness during an earthquake.

The defect of the rod in the isolator is that the rod can only isolate the structure in one direction. To fix this problem, Zhou et al. [80], studied a ball bearing isolator with restoring capability. They found that the stress concentration was the main problem of this method.

Jangid [81], studied the use of the rolling rod as an isolator for a multi-story structure. In this system, a cantilever beam was used to provide the re-centering force. The results indicate that the use of this system has a significant effect on reducing the impact of an earthquake on the structure.

Butterworth [82], evaluated the seismic response of the structures isolated by rollers with non-concentric spherical surfaces in the top and bottom. The results showed that the peak acceleration of the isolated structure was reduced significantly, especially in severe earthquakes, but a small reduction in peak displacement was observed.

Barghian and Shahabi [83], conducted a study in which a new pendulum base isolation system was introduced. Fig. 17 shows the schematic of the proposed system. In this method, mushroom-shaped bearings are placed under the structures as isolators. These bearings have spherical surfaces and arms that are pin connected to the columns of structure in the base story. If the length of the arm is less than the radius of the spherical surface, they act like nonlinear springs. When displacement occurs in the structure, a returning force is applied, and the stability of the structure is guaranteed. The stiffness of the spring is related to the length of the arm so that the stiffness of the spring is adjusted by changing the length of the bearing arms. The results of the study showed that the proposed method was very efficient in reducing the earthquake effects on the isolated structure.

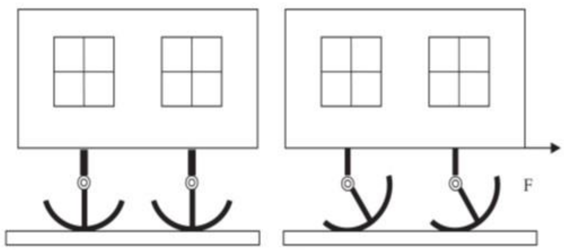


Fig. 17. Model of a base-isolated structure with a mushroom-shaped pendulum system, [83].

Chung et al. [84], studied the dynamic behavior of a nonlinear rolling isolation system. In this method, the columns of the structure eccentrically attached to the rolling. When the structure moves left or right, a resting force is created in the system and the structure is returned to its initial position. Because of the variability of the natural frequency of this system, there is no probable resonance.

Ou et al. [85], conducted a study on the seismic behavior of a roller seismic isolation bearing for highway bridges. In this system, orthogonal rolling rods are used to create bidirectional isolation. The intermediate plate of the roller is inclined, and when the roller is moved, the returning force is created in the system, and the structure returns to its original position.

Rawat et al. [86], conducted a study evaluating the dynamic behavior of a multi-story building equipped with an orthogonally elliptical rolling rod isolator. In the study, they proposed the use of elliptical rods instead of circular ones in rolling isolators. The curved surface of these elliptical rods creates the re-centering force. The seismic performance of this system was investigated and was compared to the cylindrical rolling rod and pure-friction isolators. It was concluded that the elliptical rolling rods isolation system reduced the seismic response of the structure considerably.

In a study, Shahabi et al. [87], proposed an isolation system called suspended columns for seismic isolation (SCSI). In this method, instead of being directly connected to the foundation, the structure is connected to the foundation via pendant cables. During an earthquake, the isolated structure can move to the sides resulting in a considerable decrease in the acceleration transmitted to the structures.

In a study, Becker et al. [88], compared the rules of Japanese building code and several authorities, including the US, for the design of high-rise isolated structures. The Japanese code defines comprehensive and specific criteria for the design and construction of structures with seismic isolators. However, the codes of other countries, especially the United States, have imposed a more stringent design on these structures. As a case study, it was determined that the structure designed by the Japanese code would require further modifications and reinforcement to be acceptable to the US code of practice.

6. Innovative Methods

In addition to the conventional methods of seismic isolation, some researchers proposed numerous innovative methods which some of them are mentioned as follows.

Nakamura et al. [89], proposed a system called the core-suspended isolation system.

This system is consisting of a reinforced concrete core and a seismic isolation system, which installed at the top of the concrete core. The isolation system is composed of a double layer of inclined rubber bearings. In total, different parts of the system form a seismic isolation system similar to a pendulum. A multi-story structure is then suspended from the top of the concrete core. During a ground excitation, the suspended structure rocks freely and the effect of the earthquake decreases. For the first time, a building equipped with a core-suspended isolation (CSI) system was constructed in Tokyo, Japan.

Hosseini and Farsangi [90], proposed a new seismic isolation system called telescopic columns as a new base isolation system. In this system, the main support of the structure is created on the foundation, and the structure is pin connected to the support at the structure's mass center. The connection of the structural columns to the foundation is made using a telescopic arm. The geometry of the telescopic arms is such that it can move up and down and allow the structure to go left and right, like a pendulum system and so the seismic isolation is achieved. The yielding of the steel plate of the telescopic arms dissipates the energy of the structure during ground motion.

Ismail et al. [91-93], proposed a new seismic isolation system called roll-n-cage isolation bearing (RNC) system. The system consists of a rolling body located between the upper and lower stiff bearings. Two less stiff plates are installed over the stiff bearings so that the rolling body is placed between them. To create the integrity of the system, several steel bars connect the upper and lower parts. During the ground excitation, the upper and lower supports move to the left and right and create isolation. The bars also yield during the movement and cause energy dissipation. Of course, during weak earthquakes, these rods resist and the stability of the system is provided.

Karayel et al. [94], proposed a new seismic isolation system called spring tube braces for the seismic isolation. In the proposed method, the columns of the base story are pin connected to the upper story and multiple telescopic spring braces are installed at different parts of the base story. These spring braces behave symmetrically in tension and compression for axial loading and allow the structure to move freely to the left and right, during the ground motion and thus the seismic isolation can be achieved. To evaluate the performance of this system a ¼-scaled 3D steel frame was tested on a shaking table. The results indicated that employing this method in the structure increased the natural period and reduced the seismic response of the structure considerably.

Due to the nature of the seismic isolation, a significant displacement occurs at the isolated floor as the seismic separation system. To reduce the amount of relative displacement created, one of the invented methods is using of inerter mass device, a 2-terminal flywheel device that can produce inertia proportional to the acceleration between the two endpoints of the device. In fact, this technique was developed by adding an inerter to the tuned mass damper (TMD) and was called tuned mass damper inerter (TMDI). This technic has been studied in recent years by some researchers. The results of studies conducted by Saitoh [95] in this regard showed that although this system was useful in reducing relative displacement, it could even increase displacement in vibrations with high periods. Therefore, further studies need to be conducted on their use. Hu et al. [96], studied on analysis and optimization of TMDI in SDOF structures. In the study, the effect of TMDI components arrangement in two series and the parallel mode was investigated. De Domenico and Ricciardi [97-99], conducted a series of studies in this regard. The result showed that the TMDI could generate inertia up to 200 times of its mass in the isolated structure. Also, comparing the performance of the TMD with TMDI showed better performance of the TMDI system in terms of controlling the maximum displacement of the structure and reducing base shear and floor drift. In another study, De Domenico et al. [100], investigated the performance of TMDI on different soils with different frequency contents and confirmed the usefulness of this system for different soils. De Domenico and Ricciardi [99], also studied on TMDI layout. They placed the TMDI below the isolated floor and evaluated the performance of the structure isolated by lead rubber and sliding bearings. In another study, Domenico and Ricciardi [98], examined the different modes of inerter placement and compared their proposed layout with the other five layout modes introduced by different researchers.

In a study, Anajafi and Medina [101], proposed a local isolation technique in structures. In this way, some parts and tools inside the building are isolated from the structure. In the study, the optimization of the isolated components was performed to achieve the minimum structural response. The modeled structures were subjected to the earthquake acceleration with different frequency contents and the structural response was compared with the response of the conventional isolation systems and TMD dampers. The results show that the proposed method is not only suitable and comparable with conventional isolation methods and TMD damper but also it solves some limitations and problems of these methods such as weight limitation in TMD method and high displacement problem and overturning moment in conventional isolation systems.

7. Discussion

The self-centering capability of isolators after the ground motion is essential for all types of isolators. Some isolation methods such as elastomeric-based bearing (including high and low damping rubber bearing and lead rubber bearing) are more capable in this regard and some other methods including sliding based methods (such as friction pendulum system) are less capable. In the case of rolling isolators, if they laid on a special sloping surface, they will be able to return to their original position; otherwise, this type of isolator will not exhibit this ability. There always is some permanent displacement in sliding-based isolators due to friction. In these isolators, there is a high friction force while there would not be enough force to return the system to its original position. The higher the coefficient of friction of these isolators; the more permanent displacement will be created and the lower the radius of curvature of the slip surface, the lower the permanent displacement will be created. However, other factors such as maximum acceleration and displacement of isolator must also be considered. To determine the ability of the isolators for re-centering, a parameter is defined as the re-centering coefficient, which is obtained by dividing the isolator’s permanent displacement by its maximum displacement (Gandelli et al. [102]). Another parameter that affects the amount of permanent displacement is the type of damper. Friction and yielding-based dampers increase permanent displacement while viscous dampers have no effect on it.

One of the important feasibility features of the seismic isolators is the degradation of the mechanical properties of the isolators during earthquakes. The effects of severe earthquakes may disrupt the isolator functionality and as a result, the isolator cannot meet the desired expectations. Different isolation systems may each have a particular weak point. In a lead rubber isolator, the excessive lateral displacement may cause shear failure between rubber and steel sheets. In addition, the energy absorption in the lead core causes an increase in the lead core temperature and leads to a decrease in the lateral stiffness and energy dissipation. Moreover, at high relative displacements, the probability of compressive buckling is also increased (Kumar et al. [103]). In severe earthquakes, tensile forces may occur in the isolator and the cavitation mode of failure may happen. Various researchers have studied the degradation of the properties of isolators. Gent [104] has studied the phenomena of cavitation in rubber and Constantinou et al. [22], studied the post-cavitation behavior of lead rubber isolators. The cyclic movements of isolators during an earthquake, especially in high lateral displacements, cause micro-cracks to propagate in rubber and results in a lower resistance (Kumar et al. [103]).

In sliding-based isolators, the friction between the sliding surfaces increases the ambient temperature and changes the surface friction coefficient. De Domenico et al. [105], investigate the effect of temperature rise in the friction pendulum isolator. In their study, the thermo-mechanical response of the FPS isolator subjected to the bidirectional excitations was investigated analytically and numerically. The results showed that an increase in the temperature of the contact surface caused by sliding has a considerable effect on the seismic behavior of the isolator and significantly reduces the coefficient of friction.

8. Conclusion

The history of modern seismic isolation techniques dates back to more than a century ago. However, comprehensive studies and major application of these methods have been started in recent decades. Thus, researchers have carried out many studies and so various methods have been developed. So far, in some research works, the review of the seismic isolation techniques has been conducted but in a limited form. In this paper, a historical evolutionary review on the isolation techniques has been conducted and a summary of important studies on the seismic isolation methods has been presented. In addition, various methods of seismic isolation have been categorized based on their mechanisms. Moreover, their advantages and disadvantages were discussed and compared. The key results of this study are summarised as follows:

1. The more commonly used isolation techniques are the more effective ones in controlling earthquake effects, mitigating the transmitted energy and controlling the relative displacement in acceptable ranges.

2. Up to now, the best methods exhibiting appropriate properties are the elastomeric base methods especially LRB systems and the sliding-based methods.

3. The application of ball or rolling based methods is not developed due to the stress concentration and less energy dissipation capacity.

4. Due to some weak points of the existing analytical models of isolators, one of the main research topics in the seismic isolation field is to provide appropriate analytical models in order to predict the force-displacement behavior of the isolators accurately, so that the actual behavior of the isolators during an earthquake can be grasped.

5. Due to the high cost of using isolation systems as well as the high technology needed, the application of them is limited to the developed countries. To make them more popular, it is necessary to make modifications to current methods and propose new cost-effective and simple techniques.

REFERENCES

[1] Buckle, I. G., Mayes, R. L. (1990). “Seismic isolation: history, application, and performance—a world view”. Earthquake Spectra, 6(2), pp. 161-201.

[2] Patil, S., Reddy, G. (2012). “State of art review-base isolation systems for structures”. International journal of emerging technology and advanced engineering, Vol. 2(7), pp. 438-453.

[3] Kelly, J. M. (1986). “Aseismic base isolation: review and bibliography”. Soil Dynamics and Earthquake Engineering, Vol. 5(4), 202-216.

[4] Harvey Jr, P. S., Kelly, K. C. (2016). “A review of rolling-type seismic isolation: historical development and future directions”. Engineering Structures, Vol. 125, pp. 521-531.

[5] Warn, G. P., Ryan, K. L. (2012). “A review of seismic isolation for buildings: historical development and research needs”. Buildings, Vol. 2(3), pp. 300-325.

[6] Fasil, N. K., Pillai, P. R. S. (2018). “The State Of The Art On Seismic Isolation Of Shear Wall Structure Using Elastomeric Isolators”. International Research Journal Of Engineering And Technology (IRJET), Vol. 5(4), pp. 1349-1351.

[7] Jain, M., Sanghai, S. (2017). “A Review: On Base Isolation System”. IJSART, Vol. 3(3), pp. 326-330.

[8] Clemente, P., Martelli, A. (2019). “Seismically isolated buildings in Italy: state-of-the-art review and applications”. Soil Dynamics and Earthquake Engineering, Vol. 119, pp. 471-487.

[9] Kunde, M. C., Jangid, R. S, (2003). “Seismic behavior of isolated bridges: A-state-of-the-art review”. Electronic Journal of Structural Engineering, Vol. 3(2), pp. 140-169.

[10] Naveena, K., Nair, N. (2017). “Review On Base Isolated Structures”. International Research Journal Of Engineering And Technology (IRJET), Vol. 4(6), pp. 2610-2613.

[11] Semwal, S., Dyani, S. (2017). “Review Paper On Base Isolation System: Modern Techniques”. International Journal Of Research In Technology And Management (IJRTM), Vol. 3(2), pp. 32-34.

[12] Rai, A. K., Mishra, B. (2017). “A critical review on base isolation techniques for its application as earthquake resistant buildings with particular need/adherence in eastern Uttar Pradesh”. International Journal Of Engineering Sciences & Research Technology, Vol. 6(2), pp. 234-245.

[13] Verma, A., Gupta, A., Nath, B. (2017). “Base Isolation System: A Review”. International journal of engineering and science invention, Vol 6, pp. 43-46.

[14] Panchal, V., Soni, D. (2014). “Seismic behavior of isolated fluid storage tanks: A-state-of-the-art review”. KSCE Journal of Civil Engineering, Vol. 18(4), pp. 1097-1104.

[15] Girish, M., Pranesh, M. (2013). "Sliding isolation systems: state-of-the-art review". Second International Conference on Emerging Trends in Engineering (SICETE), pp. 30-35.

[16] Clemente, P. (2017). "Seismic isolation: past, present and the importance of SHM for the future". Journal of Civil Structural Health Monitoring, Vol. 7(2), pp. 217-231.

[17] Gupta, N., Sharma, D., Poonam. (2014). "State Of Art Review-Base Isolation For Structures". International Journal Of Scientific & Engineering Research, Vol. 5(5).

[18] Bhaskar, G. B., Khanchandani, M. L. (2018). "A Review On Seismic Response Of Building With Base Isolation". International Journal Of Scientific Research And Review, Vol. 7(1), pp. 92-96.

[19] Jangid, R. S., & Datta, T. K. (1995). "Seismic behavior of base-isolated buildings-a state-of-the-art review". Proceedings of the Institution of Civil Engineers - Structures and Buildings, Vol. 110(2), pp. 186-203

[20] Skinner, R. I., Robinson, W. H., McVerry, G. H. (1993). "An introduction to seismic isolation". John Wiley & Sons. USA.

[21] Naeim, F., & Kelly, J. M. (1999). "Design of seismic isolated structures: from theory to practice". John Wiley & Sons. USA.

[22] Constantinou, M. C., Whittaker, A., Kalpakidis, Y., Fenz, D., Warn, G. P. (2007). "Performance of seismic isolation hardware under service and seismic loading". Thechnical Report, MCEER-07-0012, August.

[23] Koh, C. G., Kelly, J. M. (1988). "A simple mechanical model for elastomeric bearings used in base isolation". International journal of mechanical sciences, Vol. 30(12), pp. 933-943.

[24] Abe, M., Yoshida, J., & Fujino, Y. (2004a). "Multiaxial behaviors of laminated rubber bearings and their modeling. I: Experimental study". Journal of Structural Engineering, Vol. 130(8), pp. 1119-1132.

[25] Abe, M., Yoshida, J., Fujino, Y. (2004b). "Multiaxial behaviors of laminated rubber bearings and their modeling. II: Modeling". Journal of Structural Engineering, Vol. 130(8), pp. 1133-1144.

[26] Koo, G. H., Lee, J. H., Lee, H. Y., Yoo, B. (1999). "Stability of laminated rubber bearing and its application to seismic isolation". KSME International Journal, Vol. 13(8), pp. 595-604.

[27] Kumar, M., Whittaker, A. S., Constantinou, M. C. (2015). "Experimental investigation of cavitation in elastomeric seismic isolation bearings". Engineering Structures, Vol. 101, pp. 290-305.

[28] Ishii, K., Kikuchi, M., Nishimura, T., Black, C. J. (2017). "Coupling behavior of shear deformation and end rotation of elastomeric seismic isolation bearings". Earthquake engineering & structural dynamics, Vol. 46(4), pp. 677-694.

[29] Maureira, N., de la Llera, J., Oyarzo, C., Miranda, S. (2017). "A nonlinear model for multilayered rubber isolators based on a co-rotational formulation". Engineering Structures, Vol. 131, pp. 1-13.

[30] Crowder, A. P., Becker, T. C. (2017). "Experimental investigation of elastomeric isolation bearings with flexible supporting columns". Journal of Structural Engineering, Vol. 143(7), pp. 04017057-1-12.

[31] Hwang, J., & Ku, S. (1997). "Analytical modeling of high damping rubber bearings". Journal of Structural Engineering, Vol. 123(8), pp. 1029-1036.

[32] Hwang, J., Wu, J., Pan, T. C., Yang, G. (2002). "A mathematical hysteretic model for elastomeric isolation bearings". Earthquake engineering & structural dynamics, Vol. 31(4), pp. 771-789.

[33] Dall'Asta, A., Ragni, L. (2006). "Experimental tests and analytical model of high damping rubber dissipating devices".

Engineering Structures, Vol. 28(13), pp. 1874-1884.

[34] Bhuiyan, A., Okui, Y., Mitamura, H., Imai, T. (2009). "A rheology model of high damping rubber bearings for seismic analysis: Identification of nonlinear viscosity". International Journal of Solids and Structures, Vol. 46(7-8), pp. 1778-1792.

[35] Yuan, Y., Wei, W., Tan, P., Igarashi, A., Zhu, H., Iemura, H., Aoki, T. (2016). "A rate-dependent constitutive model of high damping rubber bearings: modeling and experimental verification". Earthquake engineering & structural dynamics, Vol. 45(11), pp. 1875-1892.

[36] Tubaldi, E., Mitoulis, S., Ahmadi, H., Muhr, A. (2016). "A parametric study on the axial behavior of elastomeric isolators in multi-span bridges subjected to horizontal seismic excitations". Bulletin of Earthquake Engineering, Vol. 14(4), pp. 1285-1310.

[37] Tubaldi, E., Mitoulis, S., Ahmadi, H. (2018). "Comparison of different models for high damping rubber bearings in seismically isolated bridges". Soil Dynamics and Earthquake Engineering, Vol. 104, pp. 329-345.

[38] Robinson, W., Tucker, A. (1976). "A lead-rubber shear damper". Bulletin of the New Zealand National Society for Earthquake Engineering, Vol 4, pp. 151-153.

[39] Robinson, W. H. (1982). "Lead-rubber hysteretic bearings suitable for protecting structures during earthquakes". Earthquake engineering & structural dynamics, Vol. 10(4), pp. 593-604.

[40] Ryan, K. L., Kelly, J. M., Chopra, A. K. (2005). "Nonlinear model for lead–rubber bearings including axial-load effects". Journal of Engineering Mechanics, Vol. 131(12), pp. 1270-1278.

[41] Warn, G. P., Whittaker, A. S., Constantinou, M. C. (2007). "Vertical stiffness of elastomeric and lead–rubber seismic isolation bearings". Journal of Structural Engineering, Vol. 133(9), pp. 1227-1236.

[42] Kumar, M., Whittaker, A. S., Constantinou, M. C. (2014). "An advanced numerical model of elastomeric seismic isolation bearings". Earthquake engineering & structural dynamics, Vol. 43(13), pp. 1955-1974.

[43] Han, X., Warn, G. P. (2014). "Mechanistic model for simulating critical behavior in elastomeric bearings". Journal of Structural Engineering, Vol. 141(5), pp. 04014140-1-12.

[44] Zhou, T., Wu, Y., Li, A. (2019). "Implementation and Validation of a Numerical Model for Lead-Rubber Seismic Isolation Bearings". Journal of Mechanics, Vol. 35(2), pp. 153-165.

[45] Hu, K., Zhou, Y., Jiang, L., Chen, P., Qu, G. (2017). "A mechanical tension-resistant device for lead rubber bearings". Engineering Structures, Vol. 152, pp. 238-250.

[46] Islam, A. S., Hussain, R. R., Jameel, M., Jumaat, M. Z. (2012). "Non-linear time domain analysis of base isolated multi-storey building under site specific bi-directional seismic loading". Automation in Construction, Vol. 22, pp. 554-566.

[47] Attanasi, G., Auricchio, F., Fenves, G. L. (2009). "Feasibility assessment of an innovative isolation bearing system with shape memory alloys". Journal of Earthquake Engineering, Vol. 13(S1), pp. 18-39.

[48] Attanasi, G., Auricchio, F. (2011). "Innovative superelastic isolation device". Journal of Earthquake Engineering, Vol. 15(S1), pp. 72-89.

[49] Ozbulut, O. E., & Hurlebaus, S. (2010). "Seismic assessment of bridge structures isolated by a shape memory alloy/rubber-based isolation system". Smart Materials and Structures, Vol. 20(1), pp. 12-015003.

[50] Dezfuli, F. H., Alam, M. S. (2013). "Shape memory alloy wire-based smart natural rubber bearing". Smart Materials and Structures, Vol. 22(4), pp.17-045013.

[51] Dezfuli, F. H., Alam, M. S. (2014). "Performance-based assessment and design of FRP-based high damping rubber bearing incorporated with shape memory alloy wires". Engineering Structures, Vol. 61, pp. 166-183.

[52] Dezfuli, F. H., Alam, M. S. (2015). "Hysteresis model of shape memory alloy wire-based laminated rubber bearing under compression and unidirectional shear loadings". Smart Materials and Structures, Vol. 24(6), pp. 19-065022.

[53] Dezfuli, F. H., & Alam, M. S. (2018). "Smart lead rubber bearings equipped with ferrous shape memory alloy wires for seismically isolating highway bridges". Journal of Earthquake Engineering, Vol. 22(6), pp. 1042-1067.

[54] Kelly, J. M. (1999). "Analysis of fiber-reinforced elastomeric isolators". Journal of Seismology and Earthquake Engineering, Vol. 2(1), pp. 19-34.

[55] Tsai, H. C., Kelly, J. M. (2002). "Stiffness analysis of fiber-reinforced rectangular seismic isolators". Journal of Engineering Mechanics, Vol. 128(4), pp.462-470.

[56] Toopchi-Nezhad, H., Tait, M. J., Drysdale, R. G. (2008). "Testing and modeling of square carbon fiber-reinforced elastomeric seismic isolators". Structural Control and Health Monitoring, Vol. 15(6), pp. 876-900.

[57] Kang, G. J., Kang, B. S. (2009). "Dynamic analysis of fiber-reinforced elastomeric isolation structures". Journal of mechanical science and technology, Vol. 23(4), pp. 1132-1141.

[58] Angeli, P., Russo, G., Paschini, A. (2013). "Carbon fiber-reinforced rectangular isolators with compressible elastomer: Analytical solution for compression and bending". International Journal of Solids and Structures, Vol. 50(22-23), pp. 3519-3527.

[59] Mostaghel, N., Hejazi, M., Tanbakuchi, J. (1983). "Response of sliding structures to harmonic support motion". Earthquake engineering & structural dynamics, Vol. 11(3), pp. 355-366.

[60] Jangid, R. S. (1996). "Seismic response of sliding structures to bidirectional earthquake excitation". Earthquake engineering & structural dynamics, Vol. 25(11), pp. 1301-1306.

[61] Nanda, R. P., Agarwal, P., Shrikhande, M. (2012). "Suitable friction sliding materials for base isolation of masonry buildings". Shock and Vibration, Vol. 19(6), pp. 1327-1339.

[62] Constantinou, M. C., Caccese, J., & Harris, H. G. (1987). "Frictional characteristics of Teflon–steel interfaces under dynamic conditions". Earthquake engineering & structural dynamics, Vol. 15(6), pp. 751-759.

[63] Mostaghel, N., Khodaverdian, M. (1987). "Dynamics of resilient-friction base isolator (R-FBI)". Earthquake engineering & structural dynamics, Vol. 15(3), pp. 379-390.

[64] Zayas, V. A., Low, S. S., Mahin, S. A. (1990). "A simple pendulum technique for achieving seismic isolation". Earthquake Spectra, Vol. 6(2), pp. 317-333.

[65] Petti, L., Polichetti, F., Lodato, A., Palazzo, B. (2013). "Modeling and analysis of base-isolated structures with friction pendulum system considering near-fault events". Open Journal of Civil Engineering, Vol. 3(02), pp. 86-93.

[66] Fenz, D. M., Constantinou, M. C. (2006). "Behavior of the double concave friction pendulum bearing". Earthquake engineering & structural dynamics, Vol. 35(11), pp. 1403-1424.

[67] Fenz, D. M., Constantinou, M. C. (2008a). "Modeling triple friction pendulum bearings for response-history analysis". Earthquake Spectra, Vol. 24(4), pp. 1011-1028.

[68] Fenz, D. M., Constantinou, M. C. (2008b). "Spherical sliding isolation bearings with adaptive behavior: Experimental verification". Earthquake engineering &

structural dynamics, Vol. 37(2), pp. 185-205.

[69] Fenz, D. M., Constantinou, M. C. (2008c). "Spherical sliding isolation bearings with adaptive behavior: Theory". Earthquake engineering & structural dynamics, Vol. 37(2), pp. 163-182.

[70] Pranesh, M., Sinha, R. (2000). "VFPI: an isolation device for aseismic design". Earthquake engineering & structural dynamics, Vol. 29(5), pp. 603-627.

[71] Pranesh, M., Sinha, R. (2002). "Earthquake resistant design of structures using the variable frequency pendulum isolator". Journal of Structural Engineering, Vol. 128(7), pp. 870-880.

[72] Lu, L. Y., Wang, J., Hsu, C. C. (2006). "Sliding isolation using variable frequency bearings for near-fault ground motions". 4th International Conference on Earthquake Engineering, Taipei, Taiwan, pp. No.164.

[73] Panchal, V., Jangid, R. S. (2008). "Variable friction pendulum system for seismic isolation of liquid storage tanks". Nuclear Engineering and Design, Vol. 238(6), pp. 1304-1315.

[74] Xiong, W., Zhang, S. J., Jiang, L. Z., Li, Y. Z. (2017). "Introduction of the convex friction system (CFS) for seismic isolation". Structural Control and Health Monitoring, Vol. 24(1), e1861.

[75] Xiong, W., Zhang, S. J., Jiang, L. Z., Li, Y. Z. (2018). "The Multangular-Pyramid Concave Friction System (MPCFS) for seismic isolation: A preliminary numerical study". Engineering Structures, Vol. 160, pp. 383-394.

[76] Hoseini Vaez, S. R., Naderpour, H., Kalantari, S. M., & Fakharian, P. (2012). "Proposing the Optimized Combination of Different Isolation Bearings Subjected to Near-Fault Ground Motions". In 15th World Conference on Earthquake Engineering (15WCEE), September (pp. 24-28).

[77] Hoseini Vaez, S. R., Naderpour, H., Fakharian, P. (2012). "Influence of Period Elongation on Dynamic Response of Base-Isolated Buildings having FPS Isolators". Proceeding of the Second National Conference on Disaster Management, Iran, June, pp. No. 19.

[78] Lin, T. W., Chern, C. C., Hone, C. C. (1995). "Experimental study of base isolation by free rolling rods". Earthquake engineering & structural dynamics, Vol. 24(12), pp. 1645-1650.

[79] Jangid, R. S., Londhe, Y. (1998). "Effectiveness of elliptical rolling rods for base isolation". Journal of Structural Engineering, Vol. 124(4), pp. 469-472.

[80] Zhou, Q., Lu, X., Wang, Q., Feng, D., Yao, Q. (1998). "Dynamic analysis on structures base-isolated by a ball system with restoring property". Earthquake engineering & structural dynamics, Vol. 27(8), pp. 773-791.

[81] Jangid, R. S. (2000). "Stochastic seismic response of structures isolated by rolling rods". Engineering Structures, Vol. 22(8), pp. 937-946.

[82] Butterworth, J. (2006). "Seismic response of a non-concentric rolling isolator system". Advances in Structural Engineering, Vol. 9(1), pp. 39-54.

[83] Barghian, M., Shahabi, A. B. (2007). "A new approach to pendulum base isolation". Structural Control and Health Monitoring, Vol. 14(2), pp. 177-185.

[84] Chung, L., Yang, C., Chen, H., Lu, L.-Y. (2009). "Dynamic behavior of nonlinear rolling isolation system". Structural Control and Health Monitoring, Vol. 16(1), pp. 32-54.

[85] Ou, Y. C., Song, J., Lee, G. C. (2010). "A parametric study of seismic behavior of roller seismic isolation bearings for highway bridges". Earthquake engineering & structural dynamics, Vol. 39(5), pp. 541-559.

[86] Rawat, A., Ummer, N., Matsagar, V. (2018). "Performance of bi-directional elliptical rolling rods for base isolation of buildings

under near-fault earthquakes". Advances in Structural Engineering, Vol. 21(5), pp. 675-693.

[87] Shahabi, A. B., Ahari, G. Z., Barghian, M. (2019). "Suspended Columns for Seismic Isolation in Structures (SCSI): A preliminary analytical study". Earthquakes and Structures, Vol. 16(6), pp. 743-755.

[88] Becker, T. C., Yamamoto, S., Hamaguchi, H., Higashino, M., Nakashima, M. (2015). "Application of isolation to high-rise buildings: a Japanese design case study through a US design code lens". Earthquake Spectra, Vol. 31(3), pp. 1451-1470.

[89] Nakamura, Y., Saruta, M., Wada, A., Takeuchi, T., Hikone, S., Takahashi, T. (2011). "Development of the core-suspended isolation system". Earthquake engineering & structural dynamics, Vol. 40(4), pp. 429-447.

[90] Hosseini, M., Farsangi, E. N. (2012). "Telescopic columns as a new base isolation system for vibration control of high-rise buildings". Earthquakes and Structures, Vol. 3(6), pp. 853-867.

[91] Ismail, M., Rodellar, J., & Ikhouane, F. (2009). "Performance of structure–equipment systems with a novel roll-n-cage isolation bearing". Computers & Structures, Vol. 87(23-24), pp. 1631-1646.

[92] Ismail, M., Rodellar, J., & Ikhouane, F. (2012). "Seismic protection of low-to moderate-mass buildings using RNC isolator". Structural Control and Health Monitoring, Vol. 19(1), pp. 22-42.

[93] Ismail, M. (2016). "Novel hexapod-based unidirectional testing and FEM analysis of the RNC isolator". Structural Control and Health Monitoring, Vol. 23(6), pp. 894-922.

[94] Karayel, V., Yuksel, E., Gokce, T., Sahin, F. (2017). "Spring tube braces for seismic isolation of buildings". Earthquake Engineering and Engineering Vibration, Vol. 16(1), pp. 219-231.

[95] Saitoh, M. (2012). "On the performance of gyro-mass devices for displacement mitigation in base isolation systems". Structural Control and Health Monitoring, Vol. 19(2), pp. 246-259.

[96] Hu, Y., Chen, M. Z., Shu, Z., Huang, L. (2015). "Analysis and optimization for inerter-based isolators via fixed-point theory and algebraic solution". Journal of Sound and Vibration, Vol. 346, pp. 17-36.

[97] De Domenico, D., Ricciardi, G. (2018a). "An enhanced base isolation system equipped with optimal tuned mass damper inerter (TMDI)". Earthquake engineering & structural dynamics, Vol. 47(5), pp. 1169-1192.

[98] De Domenico, D., & Ricciardi, G. (2018b). "Improving the dynamic performance of base-isolated structures via tuned mass damper and inerter devices: A comparative study". Structural Control and Health Monitoring, Vol. 25(10), e2234.

[99] De Domenico, D., Ricciardi, G. (2018c). "Optimal design and seismic performance of tuned mass damper inerter (TMDI) for structures with nonlinear base isolation systems". Earthquake engineering & structural dynamics, Vol. 47(12), pp. 2539-2560.

[100] De Domenico, D., Impollonia, N., Ricciardi, G. (2018). "Soil-dependent optimum design of a new passive vibration control system combining seismic base isolation with tuned inerter damper". Soil Dynamics and Earthquake Engineering, Vol. 105, pp. 37-53.

[101] Anajafi, H., Medina, R. A. (2018). "Comparison of the seismic performance of a partial mass isolation technique with conventional TMD and base-isolation systems under broad-band and narrow-band excitations". Engineering Structures, Vol. 158, pp. 110-123.

[102] Gandelli, E., Limongelli, M. P., Quaglini, V., Dubini, P., Vazzana, G., Farina, G. (2014). "Re-centring capability of friction pendulum system: parametric investigation". 2nd European Conference on

Earthquake Engineering and Seismology, Istanbul.

[103] Kumar, M., Whittaker, A. S., Constantinou, M. C. (2013). “Mechanical properties of elastomeric seismic isolation bearings for analysis under extreme loadings”. 22nd International Conference on Structural Mechanics in Reactor Technology (SMiRT-22), San Francisco, USA.

[104] Gent, A. (1990). “Cavitation in rubber: a cautionary tale”. Rubber Chemistry and Technology, Vol. 63(3), pp. 49-53.

[105] De Domenico, D., Ricciardi, G., Benzoni, G. (2018). “Analytical and finite element investigation on the thermo-mechanical coupled response of friction isolators under bidirectional excitation”. Soil Dynamics and Earthquake Engineering, Vol. 106, pp. 131-147.