Self-Centering Passive Base Isolation System Incorporating Shape Memory Alloy Wires for Reduction in Base Drift

MS STRUCUTRES Thesis DISSERTATION

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Dedication

I dedicate this Research to my mentor Dr. Muhammad Usman, Parents, family members

And

close friends

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Abstract

An earthquake is one of the most terrifying natural disasters that humans cannot control but use of proper technology can minimize its effect. Base isolation is one of the most widely implemented and well-known technique to reduce structural vibration and damages during an earthquake. This study proposes the use of SMA wires for the reduction in base drift while controlling the overall structure vibrations. The structure presented is a multi-degree of freedom (MDOF) structure along with base isolators and SMA wires in diagonal. Shape Memory Alloys (SMAs) are a new generation of smart materials with the capability of recovering their pre-defined shape after experiencing a large strain. The isolation bearing considered in this study consists of laminates of steel and silicon rubber. The performance of the proposed structure is evaluated and studied under different excitations including harmonic loading and seismic excitation. To assess the seismic performance of the proposed structure, shake table tests are conducted on base isolated MDOF frame structure incorporating SMA wires, which is subjected to incremental harmonic and historic seismic loadings. Root mean square acceleration, displacement and drift are analyzed and discussed in detail for each story. To better understand the structure response, percentage reduction of displacement is also determined for each story. The result shows that the reduction in the response of proposed structure is much better than conventional base isolated structure

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Chapter 1: Introduction

1.1 Base Isolation in Structures

An earthquake is one of the most terrifying natural disasters that humans cannot control as it causes maximum damage to life and buildings, especially multi-story buildings which are prone to destruction by earthquakes. Different traditional techniques i.e., increasing the dimensions of structural members (beams and columns) to strengthen the structure have been in use for a long period. A structure designed by this technique may survive an earthquake but may lead to a higher cost of building which is not efficient. To overcome the drawbacks of the traditional techniques many vibrations control measures have been studied over recent years. Base isolation is one of the most widely implemented and well-known technique to reduce structural vibration and damages during an earthquake. Presently base isolation is adopted all over the world as a reliable technique in earthquake designs of buildings. The concept of base isolation is to decouple a structure from earthquake ground movement by providing an isolation device that separates the base of the structure(super-structures) from the foundation(sub-structures). Using this technique in high-rise buildings, the deformation of superstructures can be dramatically reduced as the base isolation technique mitigate/lower the vibrations of earthquake transferring to the superstructure. Main isolation control systems are passive control systems, active control systems and semi-active control systems. In addition, dampers can be used with an isolation system to attain vibration reduction within the system. Several types of isolation devices are in use today including Natural rubber bearing, lead-Plug bearing, high damping rubber bearing, laminated rubber bearing and frictional/sliding bearings. Natural rubber bearing has two steel end plates (top & bottom) and multilayer thin rubber sheets bonded onto multi-layer thin steel shims. Lead rubber bearing is like silicon rubber bearing except for the lead core that supplies extra stiffness to the isolators. Similarly, laminated rubber bearings are made from high purity elastomer.

Despite significant success in improving the seismic performance of structures, practical implementation of base isolation technique is still constrained by factors like large relative displacements in isolation layers, possibility of uplift of isolators under severe earthquakes. Studies have been carried out to eliminate excessive base drift by providing dampers along with base isolation systems. Researchers have introduced the use of smart materials as isolator elements to reduce vibrations and noise. Although SMAs have some benefits, there are some practical limitations which potentially affect its application on real structures.

1.2 Shape Memory Alloy System (SMAs)

Shape memory alloy (SMA) is the class of smart materials that offer unique characteristics of undergoing large reversible inelastic deformation and enhance the performance of various structures subjected to earthquakes. SMAs can recover their pre-defined shape after experiencing a large strain. SMAs undergo a phase transition that will occur between the high-temperature phase, austenite and a low-temperature phase, martensite. Due to these material features, SMAs has found its applications in devices like vibration absorbers, vibration isolators (adaptive seismic isolators). The application of SMA wires in civil engineering structures, especially for a base isolation system has drawn a lot of interest of the researchers as these wires are used as an additional element to improve the performance of base isolation and attain vibration reduction within a system.

1.3 Problem Statement

Although base isolation system is very effective in suppressing vibrations, but it has a limitation of excessive base drift which may cause failure of isolator itself or failure of utilities. There is a need to develop large scale smart base isolator which can support larger vertical loads and respond to a wider range of earthquake excitations so that the performance range of conventional base isolation systems can be increased. Comprehensive testing on SMA based seismic isolated structures (SMA wires in diagonal to base isolators) needs to be conducted using standardized parameters for a convincing demonstration of the effectiveness and versatility of the seismic protection strategy under various seismic activities.

1.4 Research Objectives

This research is conducted with the view to achieve following objectives:

- To design and fabricate passive base isolation system incorporating shape memory alloy wires.
- To conduct shake table testing for experimental validation.
- To investigate the effect of passive base isolator (along with SMA wires) on vibration response of 3DOF system.
- Comparison of the response between conventional (without SMA wires) and proposed (with SMA wires) base isolation systems.

1.5 Scope of Research

This study proposes the development of shape memory alloy system (SMAs) having an isolated structure with simple straight SMA wires provided in a diagonal arrangement at the base level. The study aimed to investigate shape memory alloy system (SMAs) under harmonic as well as seismic excitations.

1.6 Thesis Organization

The first chapter provides a brief introduction of the base isolation and shape memory alloy system. The second chapter provides an insight into the available literature. The third chapter discusses the methodology of simulation. The fourth chapter presents the results and discussions. The fifth chapter deals with conclusions and recommendations.

Chapter 2: Literature Review

One of the most popular and well-known methods for minimizing earthquake-related structural vibration and damage is base isolation. Different base isolation systems have been developed and adopted all over the world as a reliable technique in earthquake designs of buildings. By installing an isolation mechanism that separates the superstructure from the substructures, the idea behind base isolation is to divorce a structure from earthquake ground movement. Using this technique in high-rise buildings, the deformation or distortion of superstructures can be dramatically reduced as the base isolation technique mitigate/lower the vibrations of earthquake transferring to the superstructure. In addition, this is a cost-effective technique to reduce inter-story drifts and floor accelerations.

2.1 Base Isolation Systems

Base isolation system is made up principally of multi-layer thin rubber sheets bonded onto multi-layer thin steel shims, with metallic plates at both ends to connect with the structure to be isolated as shown in Figure 1.

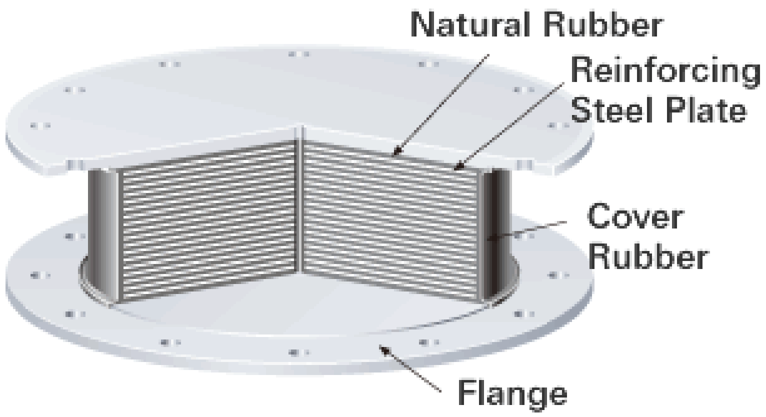


Figure 1: Laminated Rubber Bearing

Components of Base Isolation Systems

Elastomeric systems and sliding systems are the two main categories of base isolation systems.

2.2 Elastomeric System

The most popular base isolator is made of elastomeric material. These isolation devices are made up of alternating horizontal layers of vulcanized elastomer and reinforcement. The reinforcement improves the isolator's compression properties, enabling the composite device to acquire the strength and stability required to support the underlying structure. Their resilience is their main benefit. Durability and service load deformation, however, could be a problem. Natural rubber bearings, low damping rubber bearings, lead rubber bearings, and high damping rubber bearings are some examples of typical elastomeric devices. In this part, the details of the aforementioned devices will be discussed.

2.2.1 Natural Rubber Bearings

Natural rubber or neoprene is used to make natural rubber bearings, also referred to as laminated rubber bearings. Figure 2 depicts a natural rubber bearing setup.

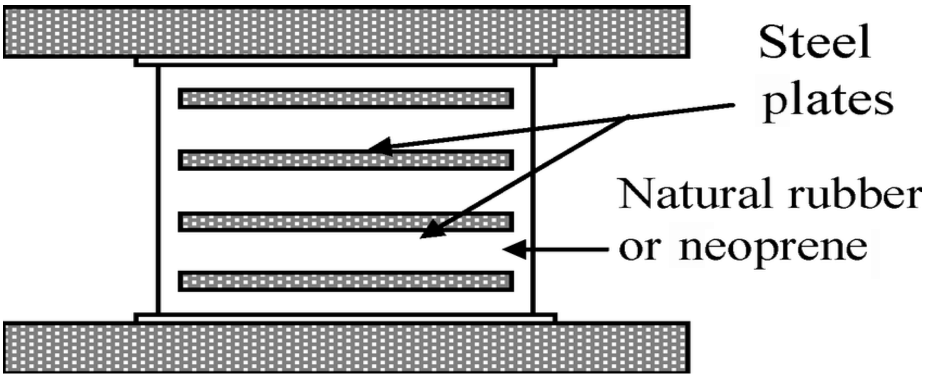


Figure 2: Natural Rubber Bearing

The typical design of a natural rubber bearing includes two steel end plates (top and bottom) as well as multiple layers of thin rubber sheets adhered to multiple layers of thin steel shims. Steel shims give the bearings vertical rigidity and keep the rubber from bulging out when there is a lot of axial compression load. Shims have little impact on a bearing's lateral stiffness. The two steel end plates are utilized to make it easier to connect the isolation system to the foundation.

Natural rubber bearings' main flaws are their poor damping and inability to withstand service and wind stresses. By altering the elastomeric material's qualities, damping properties can be improved. Natural rubber bearings, however, are simple to install and produce. Their actions are simple to model, evaluate, and designed.

2.2.2 Lead Rubber Bearings

A lead plug is inserted into a hole that has already been cut out of an elastomeric bearing to create a lead rubber bearing (LRB). Natural rubber is used in the production of LRB. Figure 3 depicts an example of a lead rubber bearing setup.

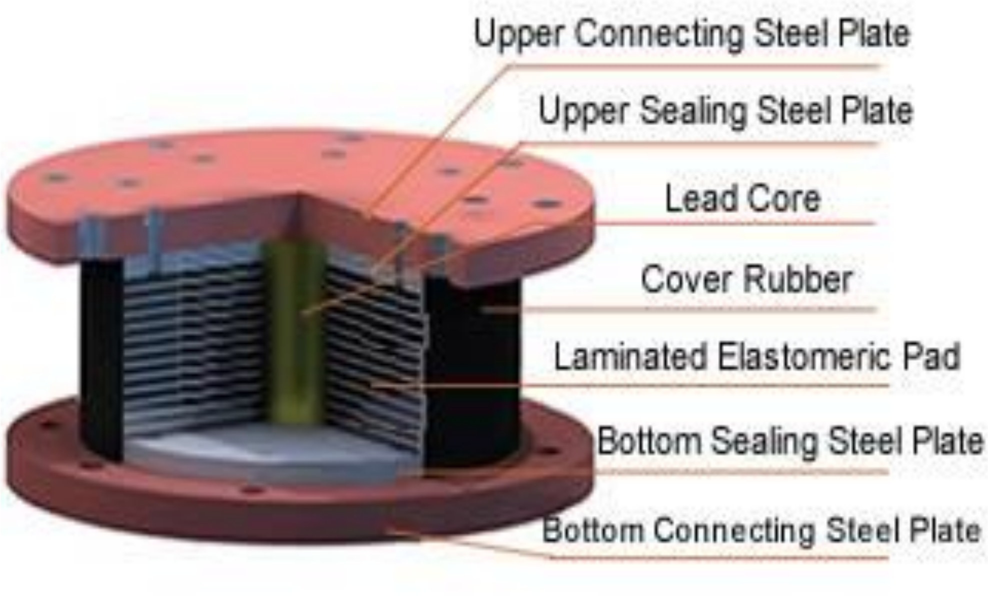


Figure 3: Lead Core Rubber Bearing

The main components of a lead rubber bearing are multiple layers of elastomeric material, with steel plates, and a central lead core. Regarding service loads and heavy lateral loads, the lead core offers stiffness and energy dissipation. Lead rubber bearings are far better able to offer sufficient rigidity for wind and traffic loads than natural rubber bearings are. Lead rubber bearings are rigid both laterally and vertically when they are subjected to low lateral loads, such as small earthquakes. Lead rubber bearings are very simple to make and install. Their behavior is simple to model, evaluate, and designed.

2.2.3 High Damping Rubber Bearings

Lead rubber bearings are high damping rubber bearings (HDR). It is made up of layers of steel between special rubber with exceptional damping properties. The bearing's vertical rigidity can be significantly improved by the steel plates. The rubber is precisely made to provide the necessary damping (often a compound based on natural rubber).

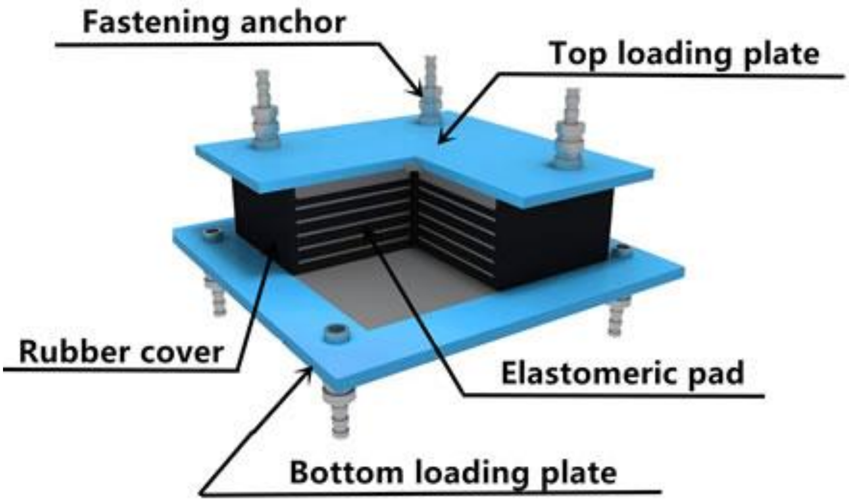


Figure 4: High Damping Rubber Bearing

The isolation interface can be provided simply, affordably, and without maintenance using High Damping Rubber Bearings (HDRBs). They are capable of being built to withstand earthquakes without suffering serious damage.

2.3 Sliding System

The second most typical kind of isolation system that employs sliding components between the foundation and base of the structure is sliding isolation. High tension springs, laminated rubber bearings, or a curved sliding surface can all be used to manage the sliding displacements. A restoring force is applied by the sliding isolation system to bring the structure back to balance. Pure friction devices, robust friction-based devices, and friction pendulums are some examples of the sliding base isolation devices. The following section will go over the specifics of the aforementioned devices.

2.3.1 Pure Friction Bearings

The simplest and most effective isolation mechanism to withstand powerful earthquakes is a device that only uses friction. To put it simply, they stand in for a sliding joint that separates the superstructure from the ground. Because the load is insufficient to overcome the static friction force, the structure behaves like a fixed base building when subjected to service wind loads. When static friction is overcome by high seismic loads, the bearing slips.

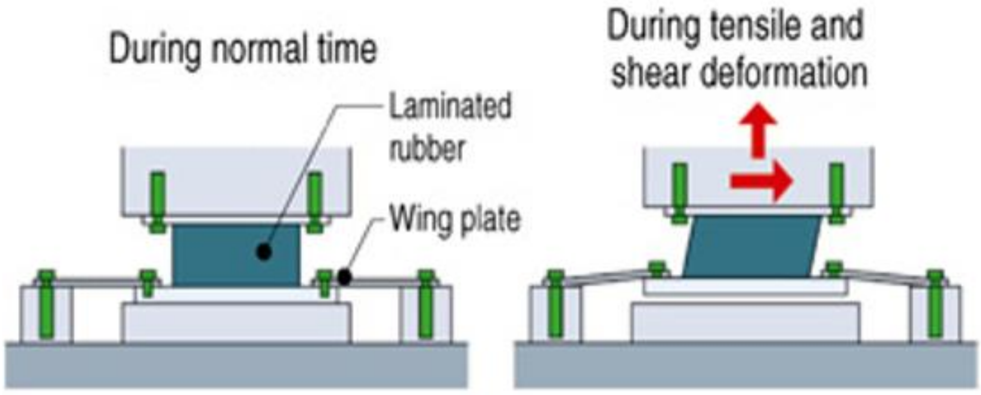


Figure 5: Pure Friction Bearing

2.3.2 Resilient Friction Bearing

The resilient friction-base isolators (R-FBI) are made up of a number of sliding flat metal plates with a rubber core in the middle. The metal rings are shielded from corrosion and dust by an extremely flexible rubber covering that surrounds them. The sliding plates have a Teflon coating to lessen friction. The lateral displacement, velocity, and height of the isolator are all distributed with the aid of the rubber cores. The coefficient of friction of the sliding parts and the overall lateral stiffness of the rubber cores serve to identify resilient friction-base isolators. In the R-FBI system, the Teflon and stainless-steel contact serves as a structural fuse to withstand low levels of horizontal load. Teflon and steel layers release energy by sliding during moderate to severe earthquake loads, while the core restricts the relative displacements.

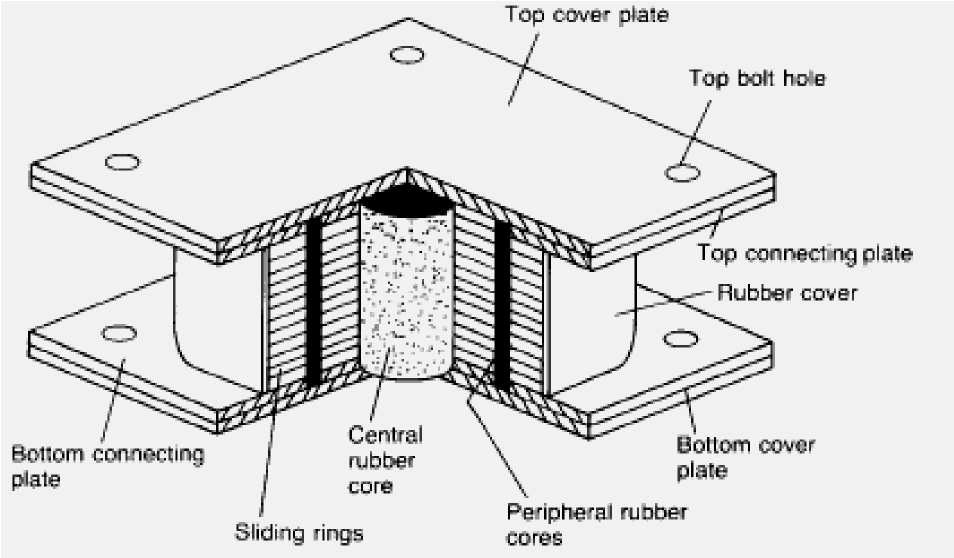


Figure 6: Resilient Friction Bearing

The amount of friction that forms between the plates is sufficient to withstand service wind loads. Rubber has a limited ability to dampen seismic loads; friction damping serves as the primary energy dissipator instead.

2.3.3 Friction Pendulum Bearing

Friction pendulum bearings are based on the pendulum's working principal. Due to friction created by the movement of the numerous moving parts, they enable a structure to be moved horizontally during an earthquake. Following the earthquake, the supporting structure is pulled back to its original position by gravity due to the base's curved sliding surface.

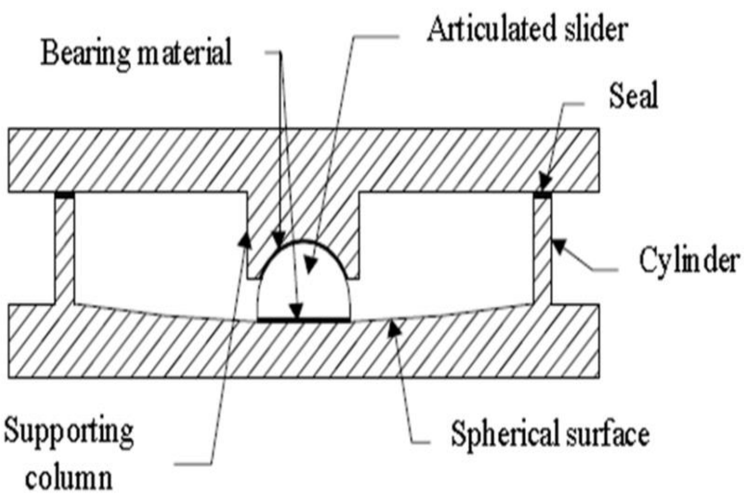


Figure 7: Friction Pendulum Bearing

Friction pendulum seismic isolators can be used to build new structures or to strengthen and better withstand seismic stresses in an already-existing structure. Under normal circumstances, they serve as bearings, transmitting vertical forces and accommodating displacements and rotations in conjunction with supplementary horizontal force bearings or dampers. A very effective and affordable seismic protection tool is the friction pendulum system, which modifies the force response of the structure at the base isolation level.

2.4 Shape Memory Alloy Material

SMA is the class of smart materials that offer unique characteristics of undergoing large reversible inelastic deformation and enhancing the performance of various structures subjected to earthquakes[10]. SMAs are capable of recovering their pre-defined shape after experiencing and undergoing large strain[10].SMAs undergo a phase transition that will occur between the high-temperature phase, austenite, and a low-temperature phase, martensite[11]. Due to these material features, SMAs are very effective in civil engineering applications[12].

Regarding the use of SMAs in isolation systems a significant amount of research has been done previously and reported in the literature. J.Wang [9] investigated the damping effect and seismic behavior of SMA using the unit-cell finite element method. H.N. Li[11] presented a re-centering damping device to minimize the deviation of civil structures subjected to earthquake ground motions. K.Varughese and R.El-Hacha [13] investigated the natural behavior of the frames strengthened with NiTi shape memory alloy wires. F.Shi [14] studied the seismic performance of shape memory alloy (SMA) braced steel frame while considering the consequences of numerous design parameters and the ultimate state of smart material that is shape memory alloy. Shi Yan and W.Wang [15] studied the mechanical properties of shape memory alloys (SMAs) wires along with SMA wire cable to actively lessen or mitigate dynamic responses of frame structure under earthquake excitations.Y.L.Han[16] investigated the effect of SMAs wires by installing SMAs dampers in a frame structure. An innovative copper aluminum beryllium wire-based sliding rubber bearing base isolator is presented and studied by W. Zheng and K. Bi,[17] for earthquake protection of civil structures in cold areas. C.Qiu and S.Zhu [18] studied self-centering steel frames with innovative shape memory alloy braces (SMAB), which uses super elastic Ni-Ti wires. Design and experimental study using SMA-based devices for the control of civil infrastructure proposed by G.Song and H.N.Li [19]. The pseudoplastic response of shape memory alloy (SMA) helical springs under axial force is studied both numerically and experimentally by R. Mirzaeifarand[20]. H. E. Karaca presented NiTiHf-based systems to point out their remarkable shape memory properties, effects of alloying, aging, and microstructure of transforming phases and precipitates[21]. Y.Araki [22] investigated the application of Cu-Al-Mn super-elastic alloy (SEA) bar as a damping element in a frame structure by conducting shaking table tests. Developments in the application of passive energy dissipation system for earthquake protection of structure studied by M.D.Symans and A.M.ASCE [23]. Farzad Shafiei Dizaji [24] proposed and evaluated a superplastic memory alloy re-centering damper system for enhancing and improving the performance of steel frame structures that have been exposed to several levels of seismic excitations and earthquake movements. The effect of temperature on the dynamic properties of SMAs was studied under different prestressed levels by Haoyu Huang[25]. R.Desroches and B. Smith studied the basic properties of shape memory alloys, focusing on the factors affecting their response and highlighting the potential, as well as the limitations of the material for the seismic/ ground motion applications[26].

Y.Liu and J.van Hurnbeeck studied a critical heat treatment process for deformed NiTi SMAs to obtain a high martensite damping capacity[27]. R.DesRoches studied the characteristics of super elastic Ni-Ti shape memory alloys under periodic loading to evaluate the capacity for the applications in earthquake design[28]. Qianhua Kan reported the effect of strain rate on the cyclic deformation of a super-elastic NiTi shape memory alloy (SMA)[29].

2.5 SMA in combination with Base Isolation Technology

SMA is used in numerous control systems due to its distinct features. The ability of SMA to dampen reaction and plastic deformation of structures subjected to high loads is its most crucial quality. Through ground isolation methods, SMAs can be employed successfully for this purpose. The seismic energy transmitted from the ground motion to the superstructure is filtered by SMA-made isolators, which are put between the superstructure and the ground, reducing the damage to the superstructure. Another benefit of this alloy as an isolator is that it offers variable stiffness to the structure in accordance with the excitation levels, in addition to energy dissipation and restoration after unloading. To use SMAs in seismic devices, some experimental and numerical research have been done recently. SMA wires are taken into consideration because of their distinctive qualities, including recentering ability and super elastic effect. These wires are an additional component that will improve the functionality of the suggested structure.

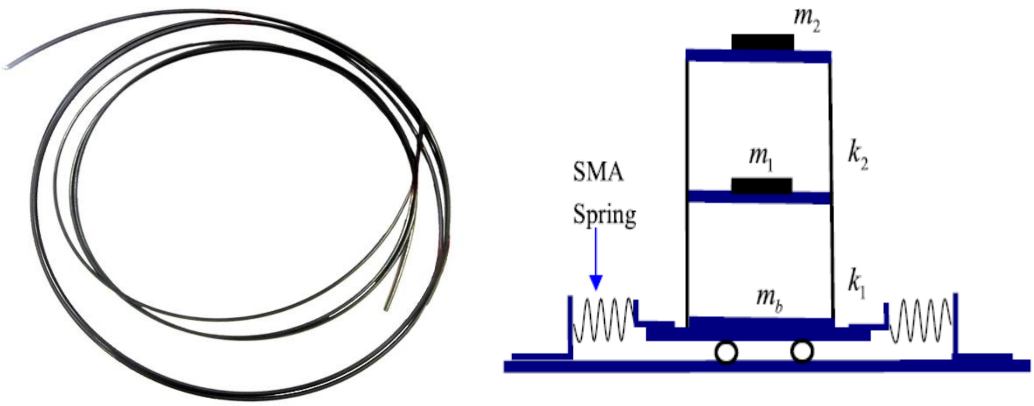


Figure 8: (a) SMA wire; (b) Model of Base Isolated Structure along with SMA wires

SMA materials come in a variety of forms, such as copper-zinc alloy, iron manganese alloy, and nickel-titanium alloy (Cu-Zn, Fe-Mn, NiTi). However, Nitinol Shape Memory Alloys have the distinctive ability to undergo significant, reversible inelastic deformation, which improves the performance of a variety of earthquake-prone buildings. When heated above their transition temperature, these wires restore their original shape. NiTi wires have become very popular in commercial applications due to their high performance and strong ductility.

2.6 Engineering Applications

Due to their high-power density, solid state actuation, high damping capacity, durability, and fatigue resistance, SMAs have found use in a variety of fields. SMA can be a passive, semi-active, or active component when combined with civil structures to lessen damage from environmental effects or earthquakes. Even though most SMAs applications research activities are still in the laboratory, a handful have been adopted for field applications and have proven successful.

Chapter 3: Methodology

This chapter discusses the methodology employed for carrying out the simulation. A process flow chart showing the complete process of simulation adopted during this study is shown in Figure 1. The chapter gives details about different materials, processes and equipment used to fabricate, assemble, and experimentally test the base isolator. Figure 2 shows a schematic diagram of the isolator.

3.1 Design of Base Isolators

The isolation system studied is a combination of two passive base isolators along with NiTi SMA wires in diagonal. The primary parameter considered for the design of an adaptive base isolator is the vertical load-carrying capacity of the base isolation system. The loading capacity of the adaptive isolator depends on rubber material property(stiffness), shape factor effective area and maximum strain of natural rubber therefore, an optimal design of base isolator is required for proposed structure[33].

The weight capacity of the adaptive base isolator is calculated by the following equations:

$$W=A.G.S.\gamma_w \quad (1)$$

In this equation **'A'** is the area of isolator which is basically the overlap of the top and bottom of the base isolator, the shear modulus of rubber is **G** and **S** is the shape factor of the rubber layer while γ_w is the allowable shear strain due to weight.

S is the shape factor for a circular base isolator:

$$S=\varphi/4t \quad (2)$$

where φ is the diameter and **t** is the thickness of the circular plate.

The horizontal stiffness of the passive base isolator is simplified as:

$$K_b=GA/h \quad (3)$$

From the above expressions, if the cross-sectional area of a laminated structure is reduced or the thickness of the rubber layer is increased, low horizontal stiffness can be attained in the construction of base isolators. When exposed to seismic excitations, an isolator may become unstable if its cross-sectional area is insufficient or the rubber layer is too thick. Therefore, an optimization of the parameters must be considered to retain the stability and enhance the effectiveness of the adaptive passive base isolator. The final assumed design parameters while considering the stability and performance of the base isolator have been shown in Table 1.

Table 1: **Structural Design Parameters of Passive Base Isolator**

Parameters	NRBs
Diameter of round rubber sheet	100mm
Rubber Layer thickness	2mm
Number of Rubber sheets	14
Total Thickness of rubber sheets	28mm

3.2 Fabrication of Base Isolators

Passive base isolators generally have two steel end plates (top and bottom) and multi-layer thin rubber sheets bonded onto multi-layer thin steel shims. The material used to fabricate rubber sheets was silicon rubber (RTV1505-A and RTV1505-B)[34]. The fabrication procedure of the sample consisted of mixing, molding & curing. The mold used for casting silicon rubber elastomers was made from polylactic acid (PLA) filament. PLA is probably the most widely available and popular filament used in 3D printing as it can be printed at a low temperature. To fabricate elastomers first, 50% of part A (RTV1505-A) and part B (RTV1505-B) of silicon rubber was added to a beaker and mixed manually. Then the sample was poured into a mold (100mm diameter, 2mm thickness) for curing. The curing time for the sample was 4-5 hours.

Figure 9: (a) Molding of silicone rubber layers in 3D printed molds (b) Steel and rubber layers along with the epoxy used (c) Prepared laminated Rubber Bearing

The material used for steel shims fabrication was galvanized iron sheet. Holes were drilled on the top and bottom plate of base isolators to fix the isolators to the frame structure and on the shake table as well.

3.3 Test Structure

Based on the discussion in section 2.1 above, an experimental model of the frame has been designed and fabricated. The design parameters of the frame are based on the stiffness and weight of the base isolator. The experimental model have been adopted from Bin Huang that was fabricated in the Smart Materials and Structures Laboratory at the university of Houston[6].

The test setup used in this study was a 3-story steel frame made from galvanized iron sheet. Each story of the experimental model has the same height, mass, and stiffness, as shown in figure 10. For each story, the beam and column lengths were 15 and 12 inches, respectively. The beam and column measured 3 inches in width.

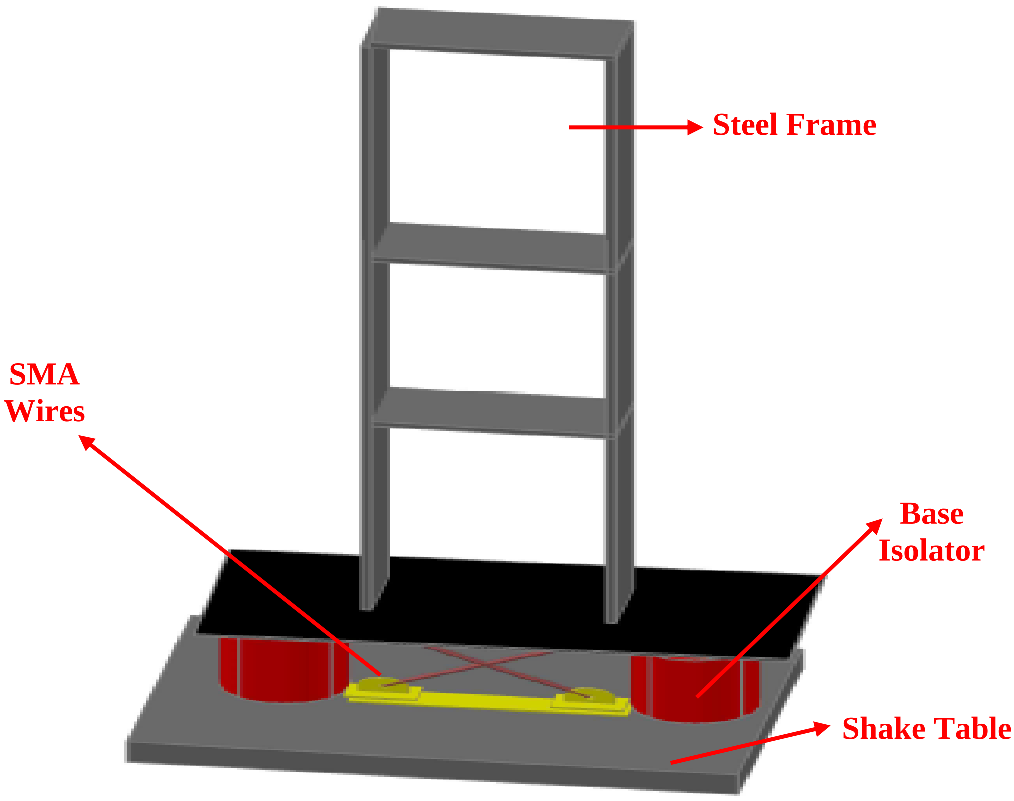


Figure 10: Experimental Setup including 3DOF base isolated structure with SMA wires at the base level, on the shake table

Table 2 lists the parameters, which include mass, stiffness, and natural frequency.

Table 2: Primary Structure Parameters

Story Level	Mass kg	Stiffness N/mm	Modes	Natural Frequency(rad/sec)
1	3.5	4444.5	First	15.85
2	3.5	4444.5	Second	44.43
3	3.5	4444.5	Third	64.2

3.4 Provision of NiTi SMA wires:

Nitinol Shape Memory Alloys have the distinctive ability to undergo significant, reversible inelastic deformation, which improves the performance of a variety of structures subjected to earthquakes. These wires experience deformation at one temperature and regain their earliest shape when heated above their transformation temperature. Due to high performance and good ductility, NiTi wires gained wide popularity in commercial applications.

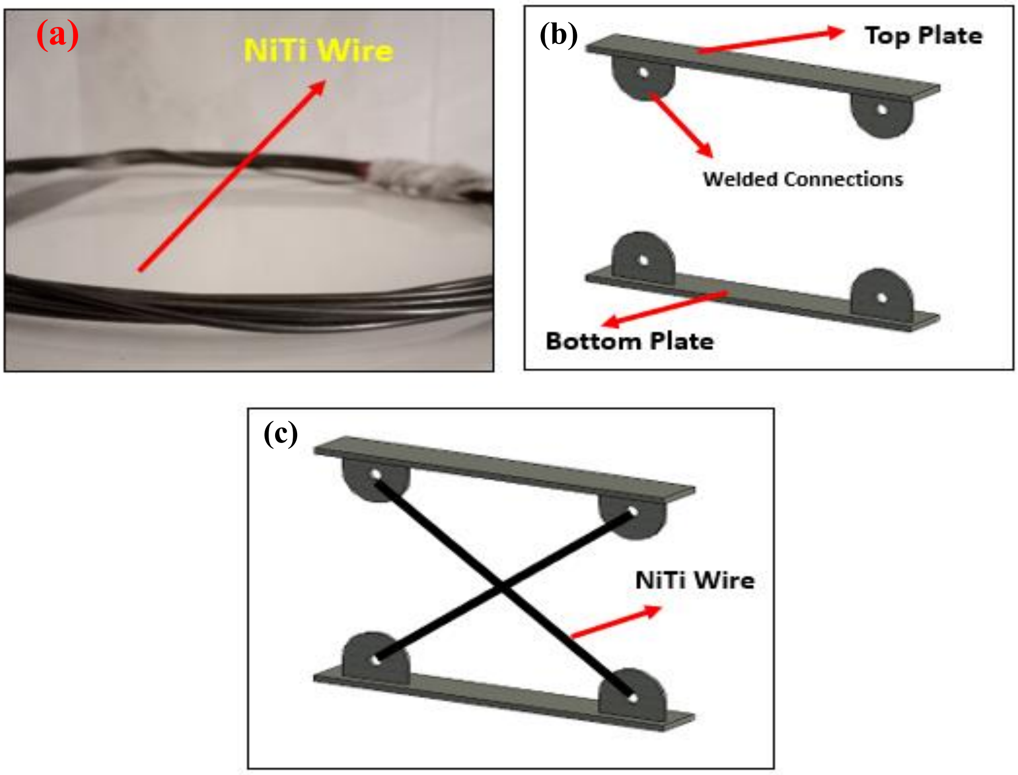


Figure 11:(a) NiTi SMA Wire sample (b) Top and Bottom plates fabricated to hold the SMA wires (c) Diagonal arrangement for SMA wires

In this study, NiTi wires (diameter=3mm) were used. The chemical composition of Nickel-titanium SMA wire is Nickel 55-56% and Titanium 44-45% while the transition temperature of the wire is 40ºC. Above this temperature, the wire will recover its original shape. Fig 11 shows the NiTi wire used in the proposed structure. Nitinol is very erosion resistant and has self-centering properties. It does not require any special handling or protection from moisture and is non-toxic.

3.4.1 Material Characterization:

The 3mm diameter Nickel Titanium SMA wire used in the test was manufactured by BAOJI ZHONGYU RARE METALS CO., LTD. (Baoji, Shaanxi, China). Table 3 shows the mechanical properties of SMA wire specimen.

Table 3: Mechanical Properties of SMA wire specimen

Alloy	Alloy	Content (%)		Diameter	Mass Density	Tensile Strength	Elongation
		Ni	Ti	(mm)	(kg/m^3)	(MPa)	(%)
Given	Nickel Titanium	55-56	45-46	3	6450	895	25-50
Experimental	-	-	-	-	6450	854.5	38.8

The tensile testing of SMA wire was carried out using universal testing machine at National University of Science and Technology Islamabad. The test setup was composed of different parts, such as the sensor, upper fixture, lower fixture and SMA wire as shown in Figure 12. The gauge length of wire in the test setup was 90mm which corresponds to the distance between upper and lower fixture. The load and displacements of the test specimens were directly recorded by test sensors. All the tests were conducted at room temperature (approximately 20-25°C).

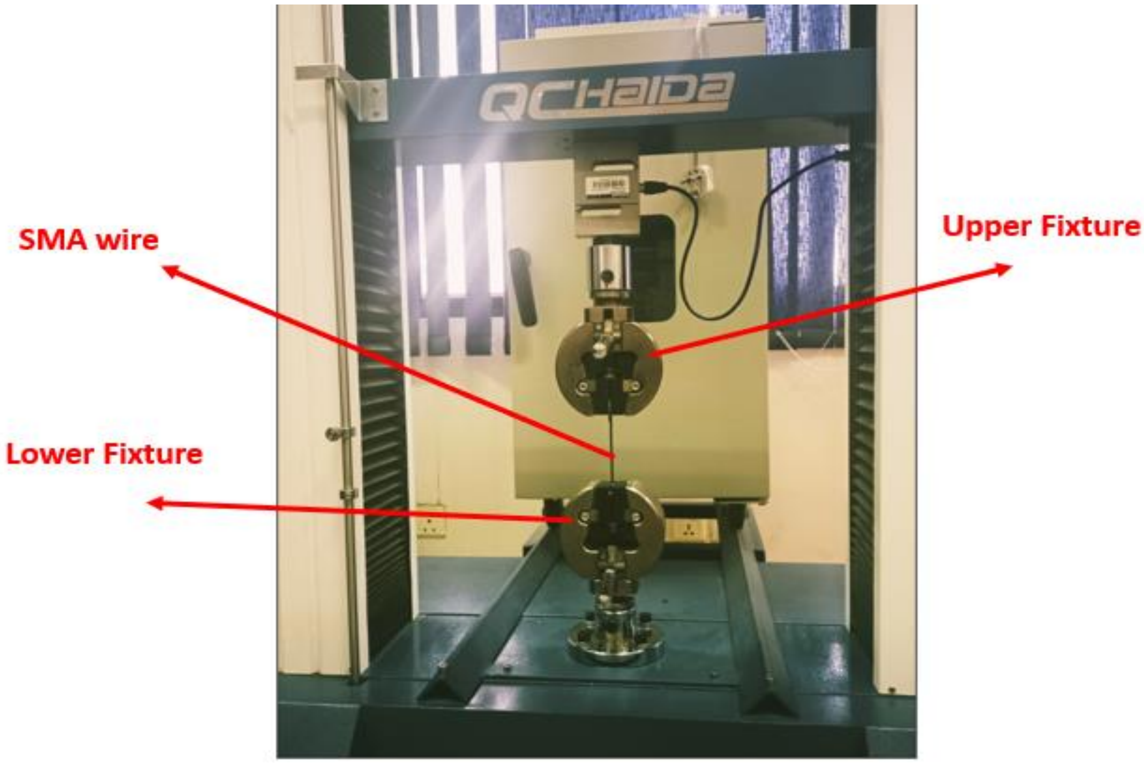


Figure 12: Experimental Setup including SMA wire Specimen

The test was performed to study the behavior of SMA wire. The specimen wire was tested at a loading rate of 3mm/min and continued till the final rupture of wire. Results from the tensile testing of NiTi wire is shown in Figure 13.

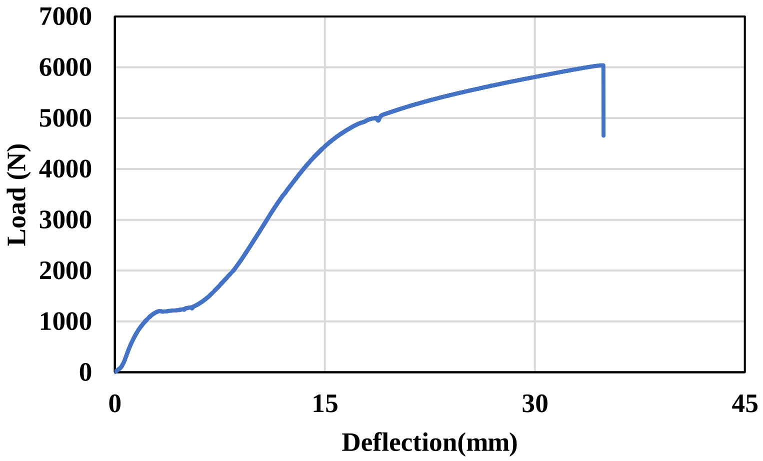


Figure 13: Load-Deflection Curve of SMA wire Specimen

Figure 13 shows the load deflection curve for a wire specimen. From curve it can be observed that at start SMA wire shows a linear elastic behavior than a point reached where wire begins to yield (marks the beginning of plastic deformation). The deflection of 38.46mm in the curve is the point where a complete rupture occurred in SMA wire. The maximum stress and strain obtained against this deflection are 854.5MPa and 38.8% respectively. Figure 14 shows the rupture of SMA wire specimen.

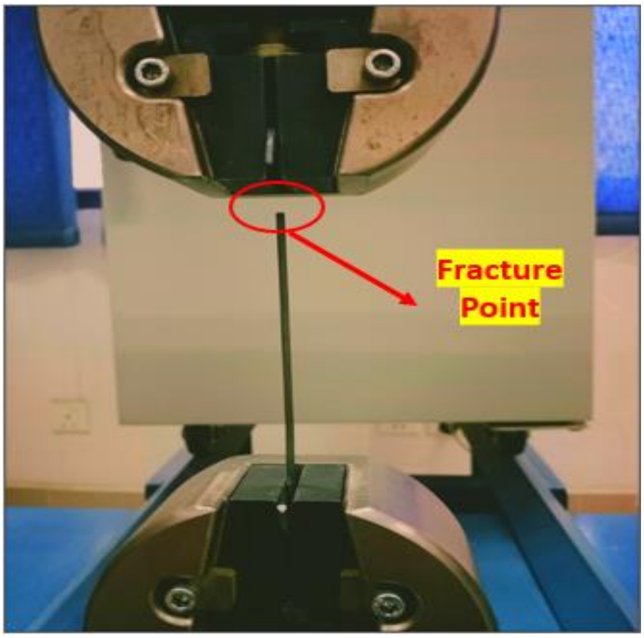


Figure 14: Rupture of SMA wire Specimen

Since the proposed structure was designed against 25% strain. From curve it can be observed that the wire is not failed against design drift of structure and is falling well in the plastic range.

3.5 Experimental Procedure

The entire setup for this study included a steel frame, passive base isolators, SMA wires, accelerometers and a Basmark shake table[35] .

The proposed system's schematic view is seen in Figure 15. Accelerometers were installed on the top of the shaking table and on each story of the steel frame building to record acceleration data during seismic excitations. The accelerometer employed in this investigation has a maximum sampling rate of 256 Hz, which allows it to record accelerations. This accelerometer has recorded data in the form of a CSV file. The experiments have been performed by using a shake table in a structural dynamic laboratory of Military College of Engineering (MCE-NUST) Risalpur. The shake table used in testing is unidirectional having a maximum payload of 15 tons. The accelerations capacity of the table is

±2g. The loading applied was harmonic and earthquake excitation.

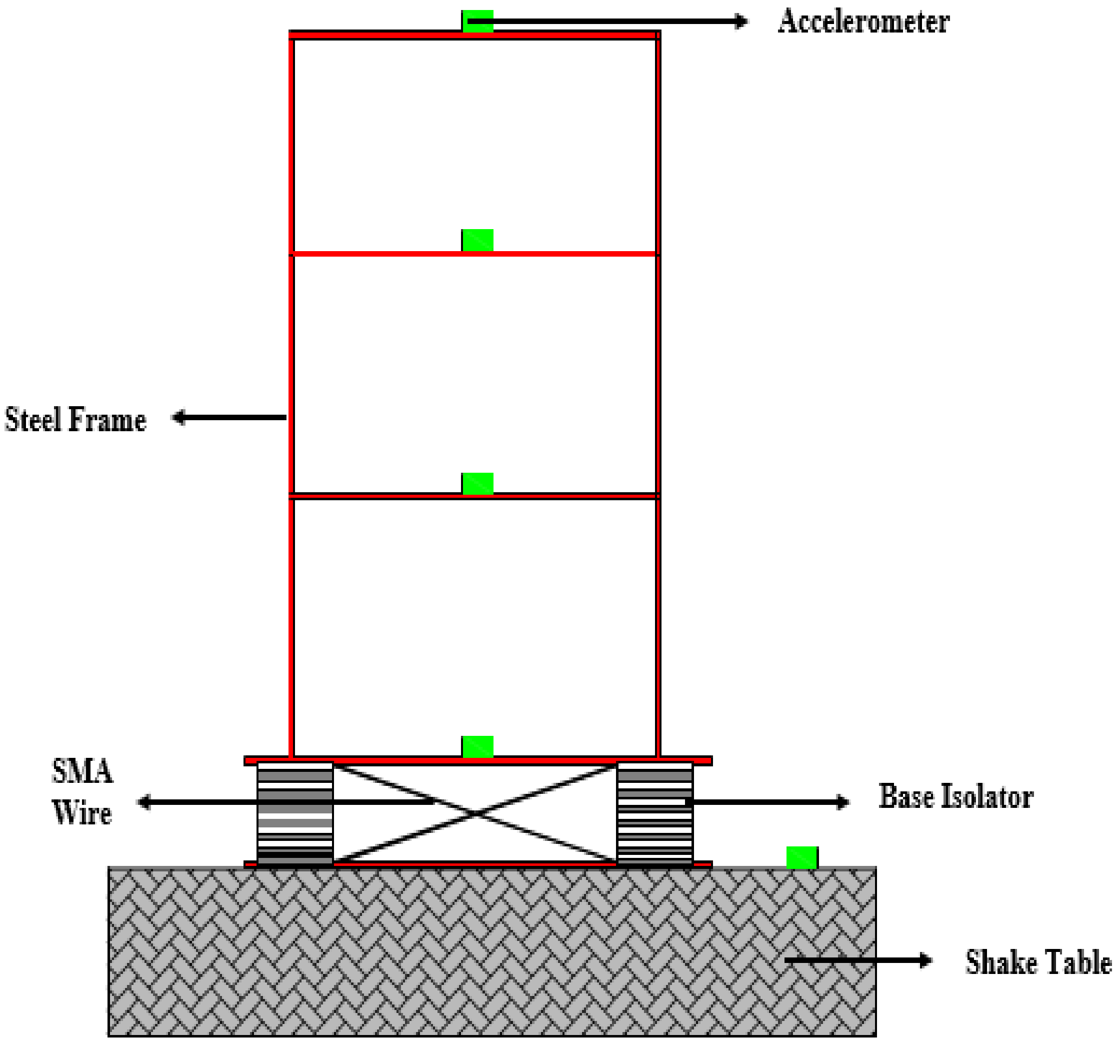


Figure 15: Schematic view of the test setup

Harmonic loadings including frequencies of 0.5Hz,1Hz, 1.5Hz, and 2Hz were applied. These loadings were applied at different amplitudes including 5mm, 10mm and 15mm. These excitations were feasible to assess the effectiveness of the proposed structure (base isolators along with wires) and the conventional structure (base isolators without wires). In earthquake excitation, the loading applied was El Centro. At first, two identical super elastic SMA wires were attached to base isolators, and then harmonic loading was applied on the structure, including 0.5Hz, 1Hz, 1.5Hz, and 2Hz at an amplitude of 5mm. The tests were repeated for 10mm and 15mm amplitudes respectively to study the effects of SMA wires on the damping properties of the proposed structure.

Table 4: Different test cases considered for the shake table testing

With wires		Without wires	
Frequency (Hz)	Amplitude (mm)	Frequency (Hz)	Amplitude (mm)
0.5	5	0.5	5
1	10	1	10
1.5	15	1.5	15
2	20	2	20
Total test cases =36			

The acceleration data was recorded from accelerometers and stored in the form of CSV files. Finally, the EI Centro earthquake excitation was applied by the shake table. The seismic excitation loading was applied for both proposed and conventional system. The accelerometers on each story record acceleration data for both cases against all loading conditions. From accelerations data, the maximum relative displacements and story drifts were obtained for the proposed system. To compare the results, same calculations were implemented and analyzed for the conventional system.

Chapter 4: Results and Discussions

4.1 Displacement Response to Harmonic Loading

The acceleration response for both cases (with wires & without wires) has been recorded for all stories. The response values indicate the vibration of the structure for all loading conditions. For analysis, the displacement response for both structures have been calculated and compared. In all loadings, the results show that the story drift of the proposed structure reduced as compared to that of the conventional structure. In the proposed structure the SMA wires used is NiTi which is very effective for base isolation as it has a strong ability of energy dissipation and recentering. To compare and analyze the results, the story drift response has been calculated for both proposed and conventional systems.

4.1.1 Base Displacement Response

Figure 16 shows the base displacement response for both structures. The response has been observed for loading on the structures including 0.5Hz,1Hz, 1.5Hz, and 2Hz with a varying amplitude of 5mm, 10mm, and 15mm respectively. Part (a) in the figure shows the response at an amplitude of 5mm. Similarly, Part (b) and Part (c) show the response of the base for 10mm and 15mm amplitude. The SMA wires used in the proposed system can reduce the base drift.

From Figure 16 it has been observed that the RMS base displacement response of the proposed structure was reduced as compared to the conventional structure. For all loading proposed structure show maximum reduction as compared to the conventional system.

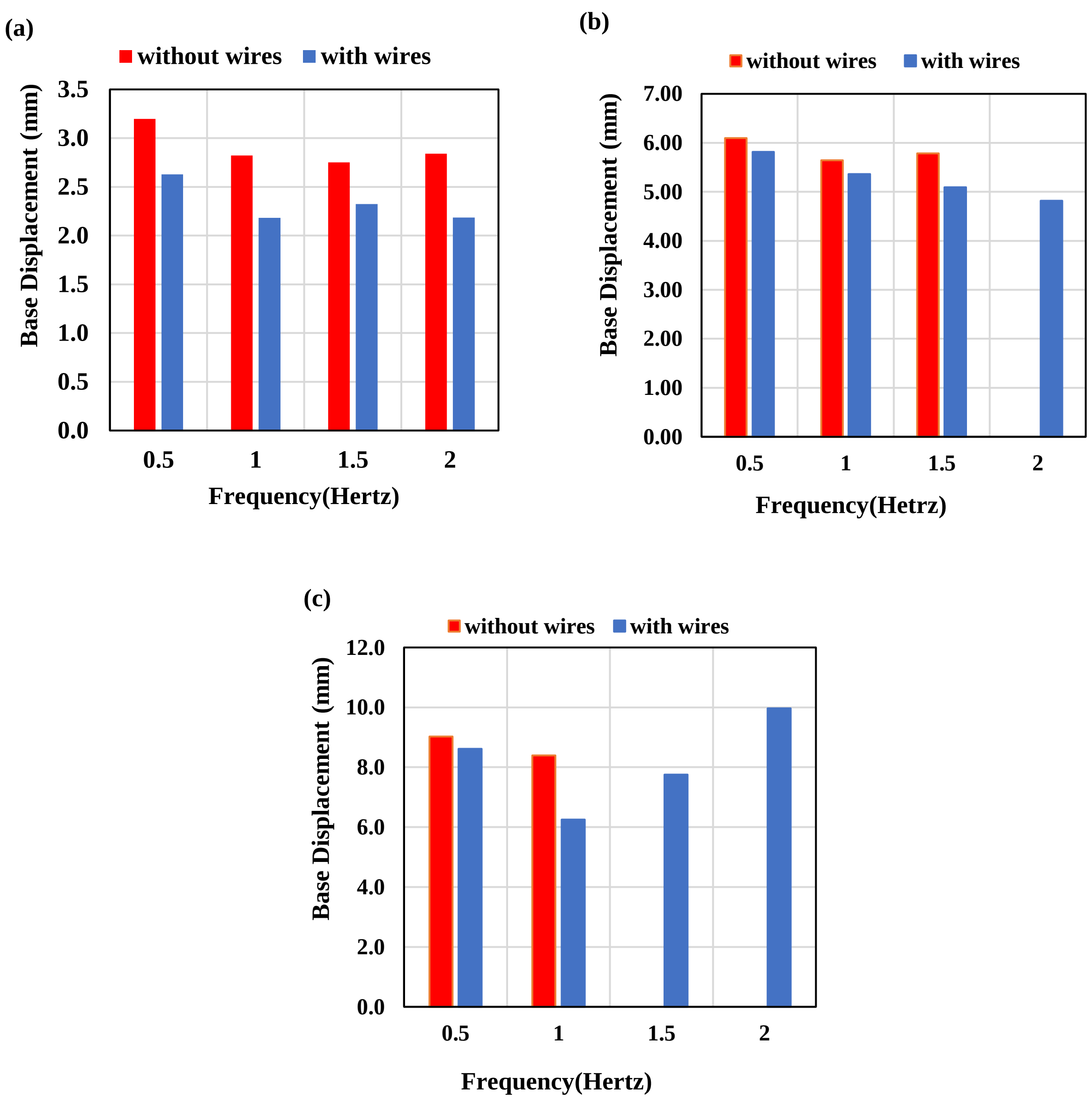
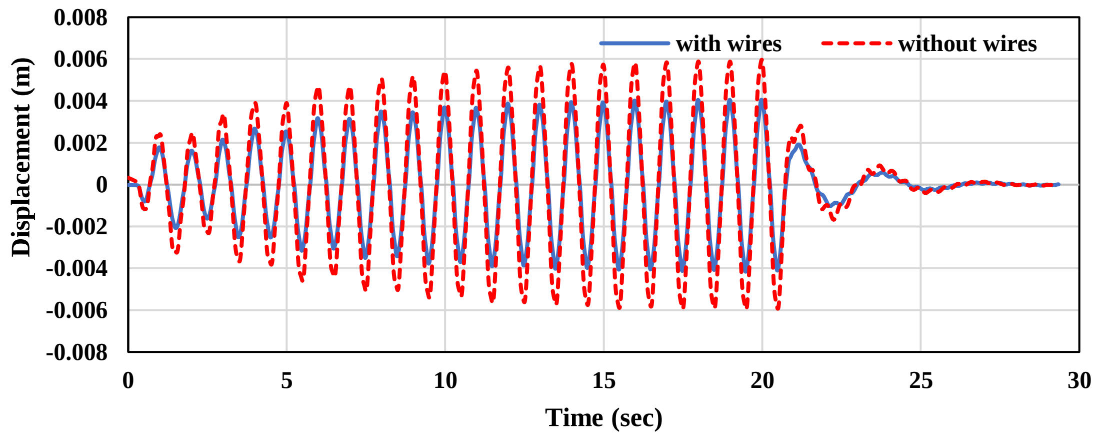


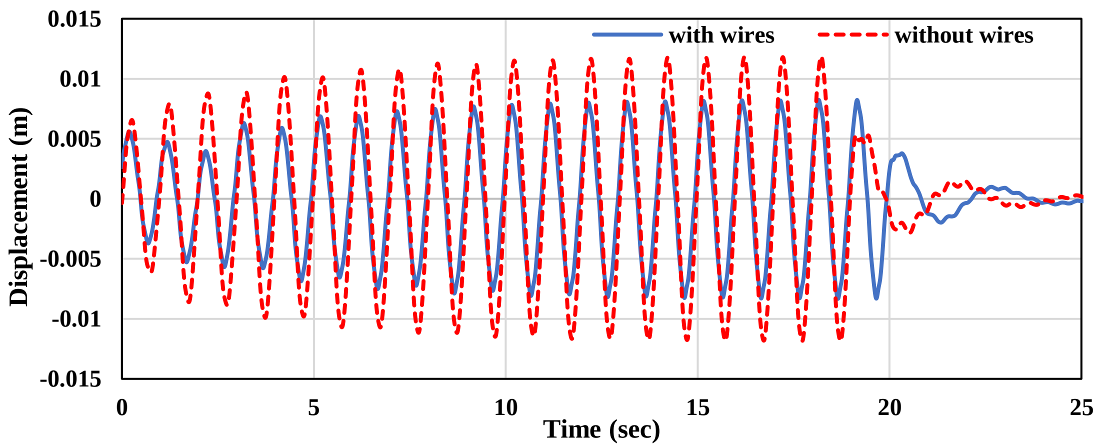
Figure 16: Base Displacements against frequencies for different amplitudes:

(a) Amplitude 5mm; (b) Amplitude 10mm;(c) Amplitude 15mm.

Part (a) in the figure shows a reduction against 0.5 Hz. For 1Hz and 2Hz, the reduction is almost the same while base displacement reduction against 1.5Hz is maximum. In part (b) maximum displacement reduction has been observed against 1.5Hz, while for 2Hz only proposed structure displacement has been shown because the conventional system (without wires) failed at this loading condition. Similarly in part(c) base displacement reduction has been observed but for loading conditions of 1.5Hz and 2Hz just proposed structure response has shown as the conventional system already failed against this loading.

Figure 17 shows the displacement response of the base for both structures. The response has been observed for loading of 1 Hz with a varying amplitude of 5mm, 10mm, and 15mm respectively. Part (a) in the figure shows the response at an amplitude of 5mm. Similarly, Part (b) and Part (c) show the response of the base for 10mm and 15mm amplitude. The proposed structure displacement response has been compared with the conventional structure response.





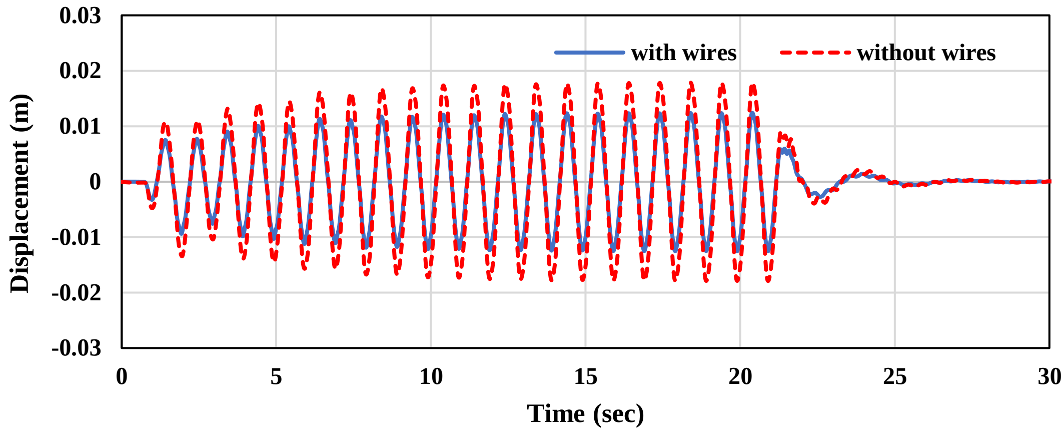


Figure 17: Base Displacement-Time graphs of proposed & conventional structure including loadings of 1 Hz (a) Amplitude 5mm; (b) Amplitude 10mm; (c) Amplitude 15mm.

From Figure 17 it has been observed that displacement of the proposed structure is reduced as compared to the conventional structure. For all varying amplitudes proposed structure shows a maximum reduction in displacement as compared to a conventional system.

4.1.2 Story Drift Response:

The story drift response for both cases (with wires & without wires) has been calculated and compared in this section. Figure 18 shows the RMS story drift response of both structures. The response has been observed for loading on the structures including 0.5Hz,1Hz,1.5Hz, and 2Hz with a varying amplitude of 5mm, 10mm, and 15mm respectively. In all stories proposed structure shows a reduction in a drift against each loading. In Figure 18 part (a) a small reduction in the drift of each story has been observed for a loading condition of 0.5 Hz and 1 Hz, while for 1.5Hz and 2Hz a large reduction of drift in each story has been observed. Similarly, in part (b) and part (c) of figure 18 drift reduction has been observed in each story for all loading conditions.

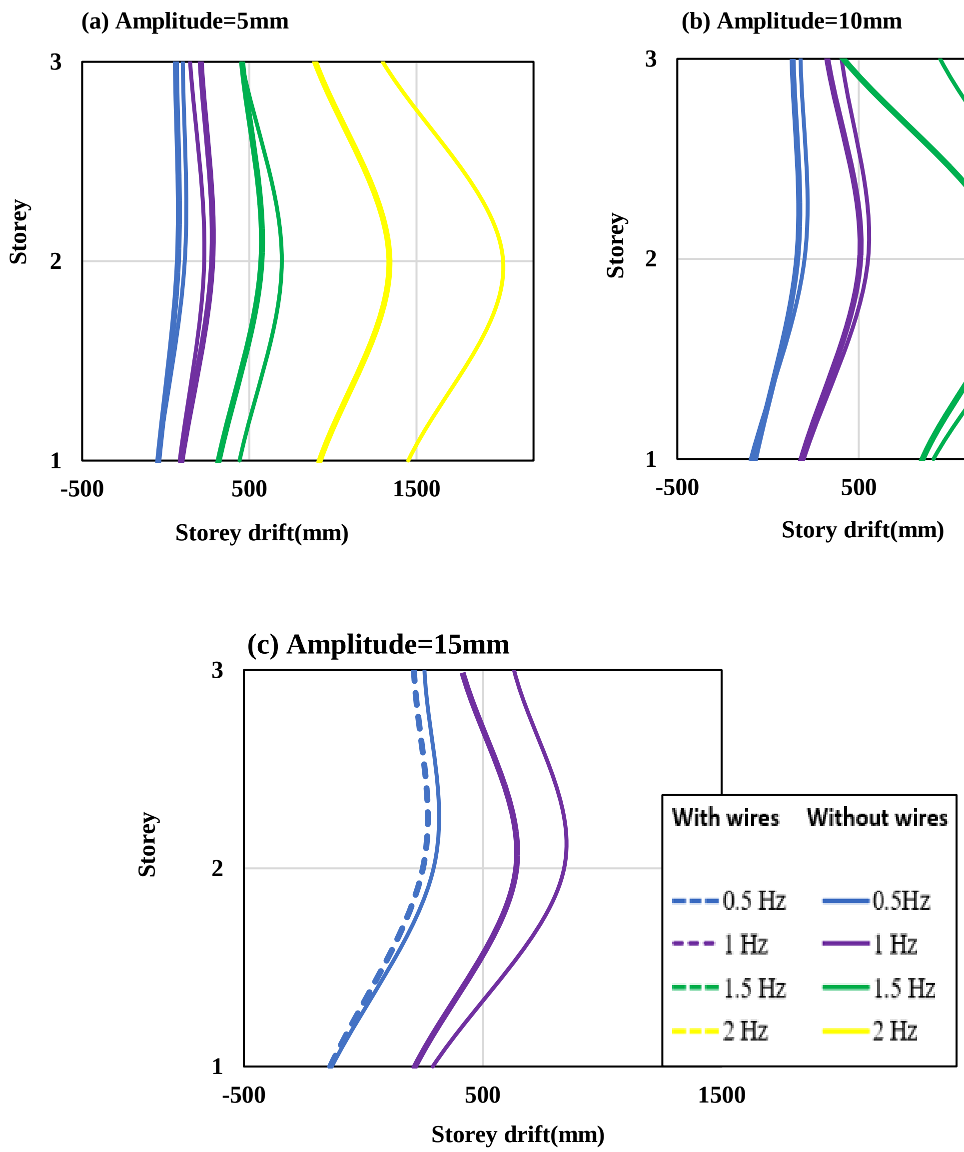


Figure 18: RMS Story Drift Response of proposed and conventional structure for different amplitudes:(a) Amplitude 5mm; (b) Amplitude 10mm; (c) Amplitude 15mm.

Figure 18 shows that with the increase in frequency the drift reduction is more visible in the proposed structure. The effect of the SMA wire used in the proposed structure is more profound at higher frequencies, due to which the story drift or structural displacements does not produce any significant effect on the structure at low frequencies.

Table 5: *Percentage reduction in the drift response of with wire over without wire*

	Amplitude=5mm			Amplitude=10mm			Amplitude=15mm	
Story Level	**0.5Hz**	**1Hz**	**1.5Hz**	**0.5Hz**	**1Hz**	**1.5Hz**	**0.5Hz**	**1Hz**
Base	**49.932**	**59.269**	**55.577**	**44.713**	**45.182**	**47.004**	**33.229**	**46.078**
1	8.089	11.278	28.266	-4.168	-0.099	0.165	-4.864	25.594
2	36.124	17.180	17.564	20.247	7.971	12.471	15.163	23.845
3	40.601	30.478	-0.794	24.445	19.504	56.257	17.219	34.594

Table 5 shows the percentage reduction in drift of with-wires structure over without wires structure with the varying amplitude of 5mm,10mm, and 15mm respectively. Among harmonic loadings, the base shows the maximum reduction response against 1 Hz loading. In 1st story, the maximum reduction response was observed against 1.5 Hz loading. Similarly for second and third stories drift reduction response has been observed against all loading conditions and varying amplitude. From this reduction response, the performance of the proposed structure has been improved using SMA wires.

4.2. Acceleration Response to Harmonic Loading:

Figure 19 shows the time histories for both proposed and conventional structures. The response has been observed for load conditions of 1 Hz with a varying amplitude of 5mm,10mm, and 15mm respectively. It has been observed that there is a slight increase in accelerations of the proposed structure as compared to that of the conventional structure. This is due to the fact, as the drift of conventional structure increases therefore to limit the base drift, the structure is shifted to the proposed isolated base structure. During this phenomenon, there is a slight increase in acceleration which is logical[36].Also the SMA wires used in this study as a base isolator element so adding dampers to the isolation system results in an increase in the acceleration response[37].

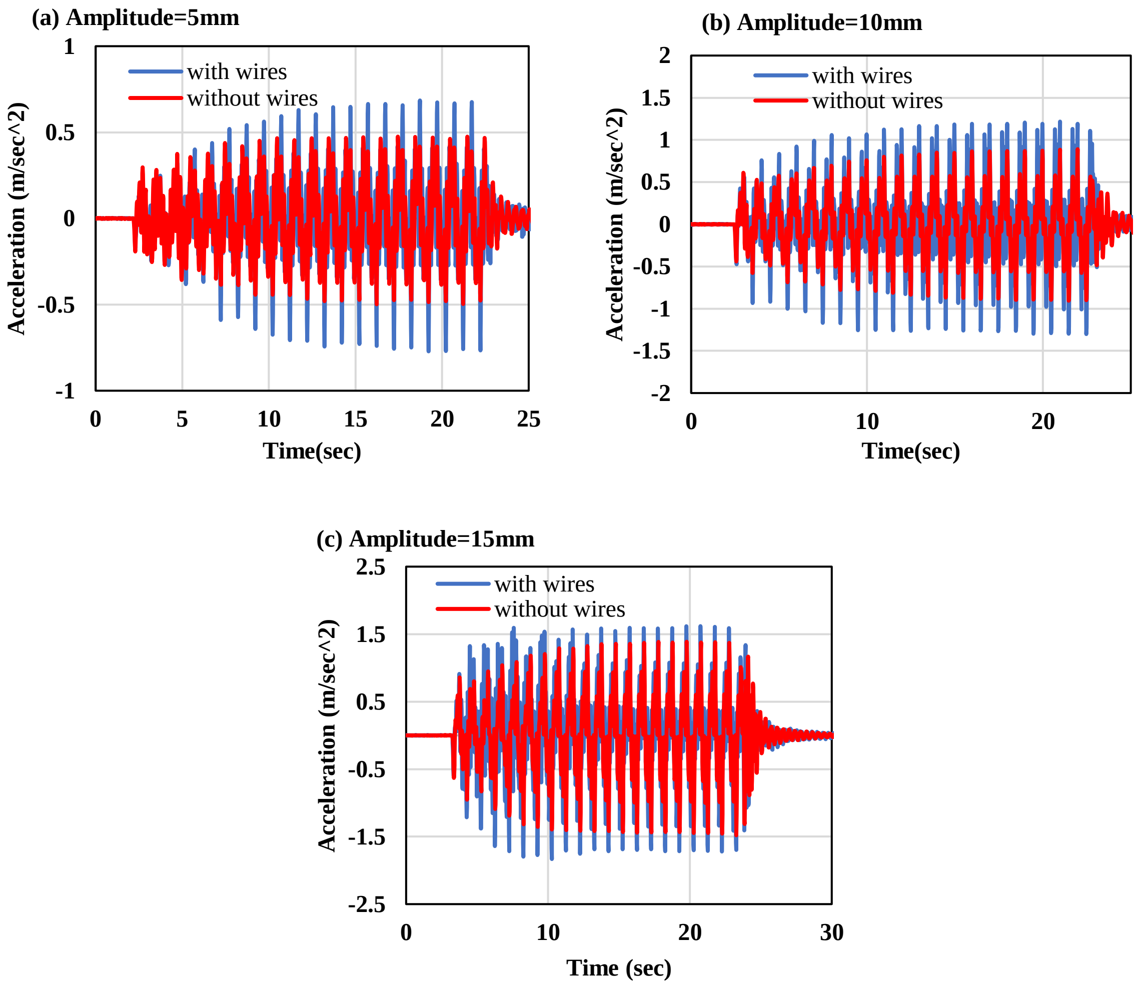


Figure 19: Base acceleration Time histories of proposed & conventional structure including loadings of 1 Hz(a) Amplitude 5mm; (b) Amplitude 10mm; (c) Amplitude 15mm.

Figure 20 shows the response of the proposed structure in the frequency domain. The power spectral density response has been investigated for all input loading conditions. Figure 20 part(a) shows the PSD response for the loading condition of 0.5Hz. Part(b) and (c) show the PSD response against 1 Hz and 1.5 Hz loadings respectively. From Figure 20 it has been observed that peaks of PSD ordinates have been suppressed and shifted in the forward direction. The shift of peak in the forward direction is due to an increase in accelerations of proposed structure[37].The suppression of these peaks is the evidence of improved performance of proposed structure.

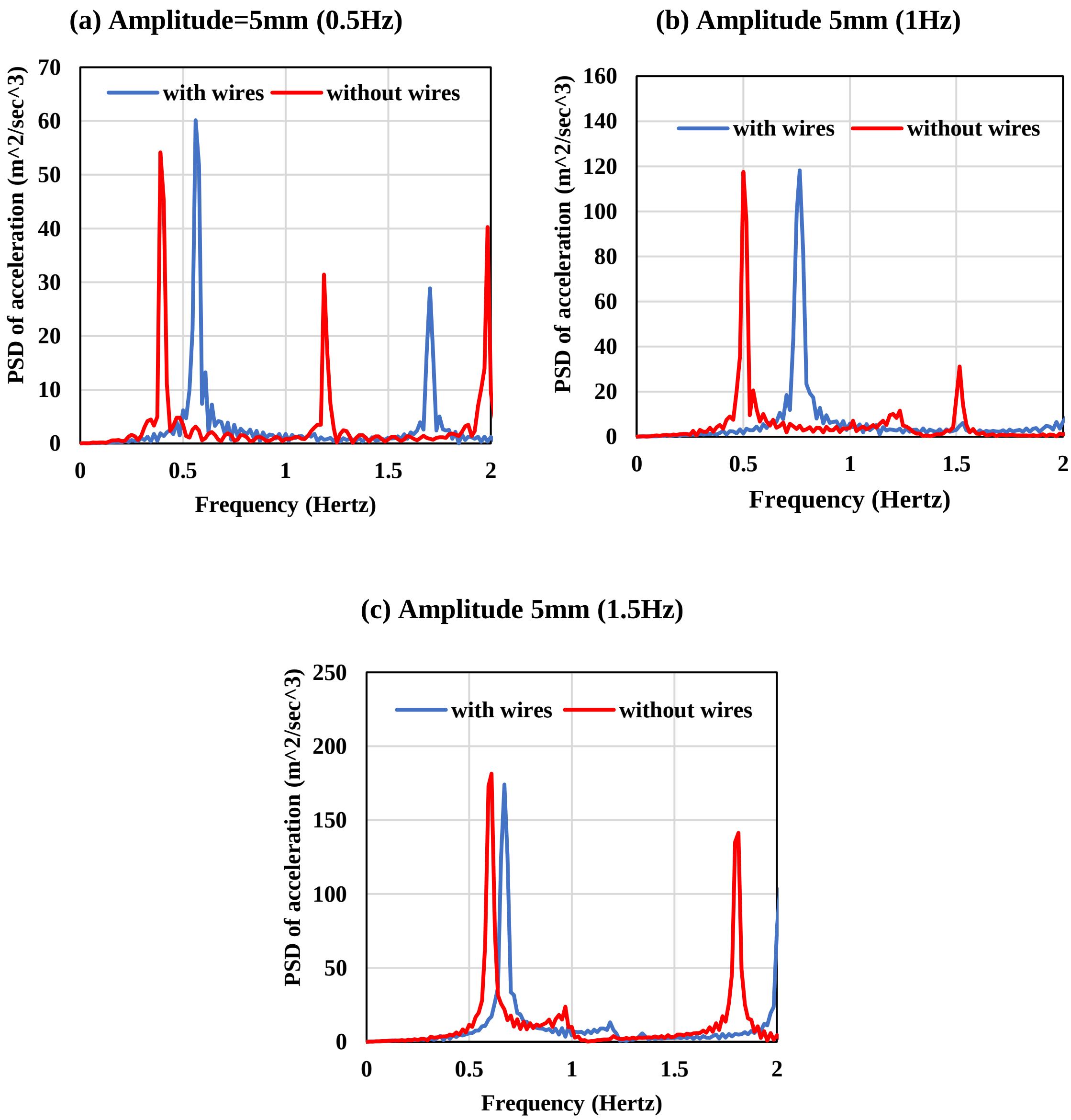


Figure 20:PSD Response for harmonic Loading:(a) 0.5 Hz; (b) 1 Hz; (c) 1.5 Hz.

4.3. Response to EI Centro Loading:

Figure 21 shows the time histories of the EI Centro earthquake for both proposed and conventional structures. At first, there is no response reduction in the proposed structure due to a sudden increase in accelerations. This is due to the fact that adding dampers to the isolation system results in an increase in the acceleration response[37].

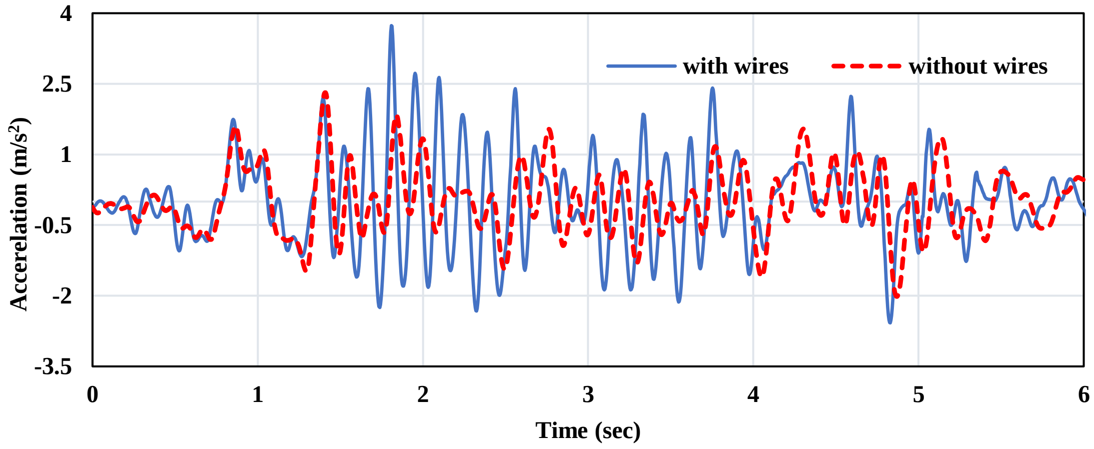


Figure 21: Acceleration Time histories of the base against earthquake loading: EI Centro

Figure 22 shows the displacement response of the EI Centro earthquake for both proposed and conventional structures. It has been observed that the displacement of the proposed structure is reduced as compared to the conventional structure.

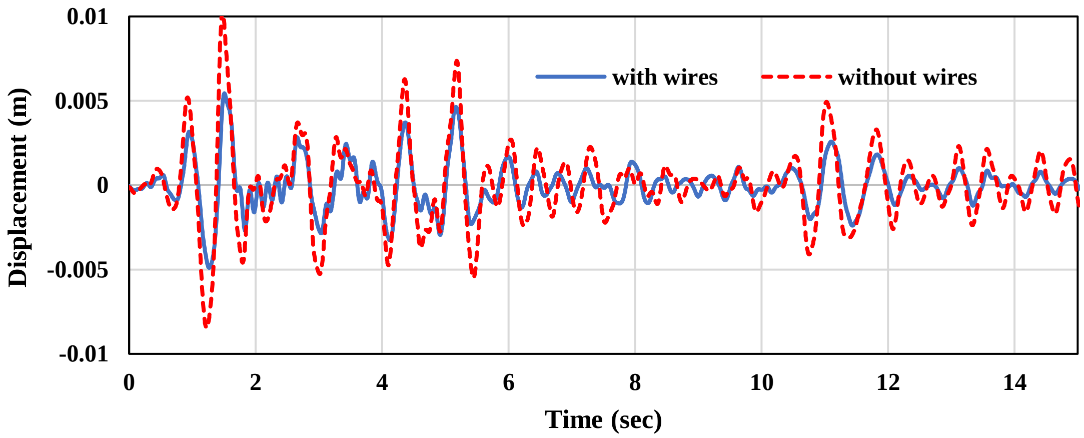


Figure 22: Displacement time graphs of base story against earthquake loading: EI Centro

Figure 23 shows the PSD curves against EI Centro earthquake loading. The peaks have been observed between 0.5 Hz and 1 Hz. The peak has been suppressed significantly in the proposed structure and shifted in the forward direction[38].

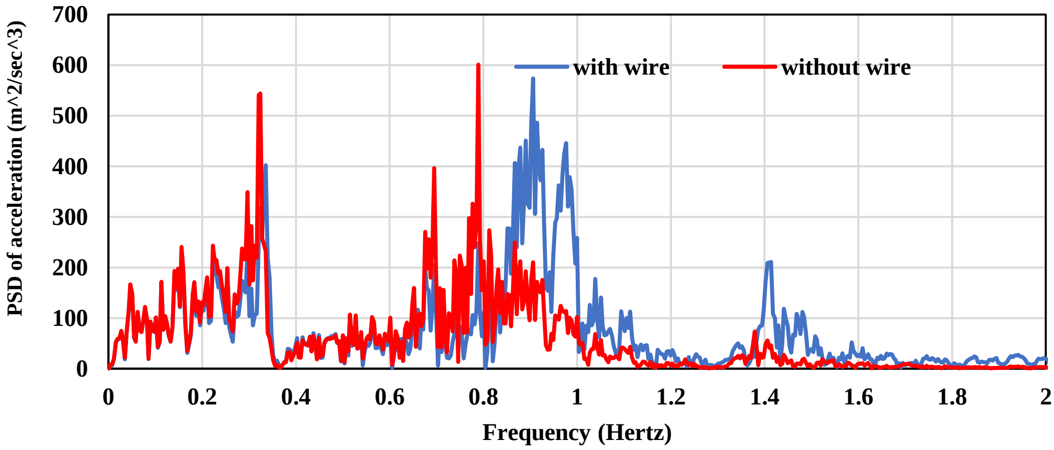


Figure 23:PSD Response for EI Centro earthquake loadings: Base 0.5

Chapter 5: Conclusions and Recommendations

Conclusions:

In this study a multi-degree of freedom structure along with base isolators and SMA wires in diagonal is proposed. For the performance optimization, an experimental model was fabricated and tested in a structural dynamic laboratory of Military College of Engineering (MCE-NUST) Risalpur. The performance of the proposed structure was studied for both harmonic loading and seismic excitations. From the experimental investigation, it was illustrated that NiTi SMA wire reduces the response of structure against all loading conditions. The SMA wires were used in diagonal to the base isolators, therefore maximum reduction against each loading was observed on the base of the structure. SMA wires improve the performance of the proposed structure by reducing the displacements of the proposed structure that is very effective in protecting the structure from large deformation. This study effectively demonstrates that the proposed SMA isolation system possesses the ability of energy dissipation as well the capability of recovering the original shape which is very suitable for a structure subjected to earthquakes.

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