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Methods for Improving the Seismic Performance of Structures - A Review

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Abstract. There has been an enormous research in the field of seismic performance of structures. The improvement in the performance is still a challenging task for researchers and engineers. Many strategies have been considered in this regard to achieve desirable result. Base isolation is considered to be the most popular method of protecting structures against seismic actions. However, use of different dampers has also been a major revolution in improving the seismic action of buildings. This review article is intended to illustrate different techniques for improving the seismic performance of buildings and bridges. The study mainly emphasizes on the effect of different isolators and dampers in mitigating the damage of buildings and other civil infrastructures. Pertinent study in the review explores the possible application of the devices towards effective utilization in buildings, bridge piers and other structures.

Keywords: Base Isolators, Dampers, Seismic Performance

1. Introduction

Over the centuries the decoupling of buildings from the ground to prevent damage has been an area of major concern for the researchers and engineers [1]. Residential and commercial buildings in metropolitan cities are often constructed in close proximity to faults making them prone to strong ground motion [2]. Different aseismic construction designs and technologies are developed to mitigate the effects of earthquakes on buildings, bridges and potentially vulnerable contents [3]. The use of base isolation systems (BISs) is a comparatively new and growing technology of this kind [4]. It is way out in becoming an extensive technology for the seismic protection of artefacts, buildings, infrastructures, industrial facilities and equipment [5]. The principle of base isolation is to incorporate flexible bearings or pads to detach structures from the ground thus reducing vibration or damage during earthquakes. It partially uncouples a structure from the seismic ground movement using specially designed, replaceable devices inserted between the structure and its foundation [6]. A number of strategies have been developed to induce base isolation in structures which includes elongation of the shift period and the limitation of the seismic shear force [7]. Different isolators have been identified in the literatures for the base isolation of structures. The main function of isolators is to provide horizontal flexibility, dissipation of energy and rigidity against normal lateral loads [8].

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Dampers are also making their way out as promising devices for improving the performance of building against seismic forces. The principle of dampers is to increase the stiffness of the buildings which in turn lowers their risk of damage and failure of the structures. The objective of the present study is to investigate the effect of different isolators and dampers on the seismic performance of structures. The review will explore the possible applications of the devices in the prevention of damage and failure of buildings structures and bridges due to high seismic movements.

2. Mechanical devices for seismic mitigation

Mechanical devices such as base isolators and dampers are way out in improving the performance of buildings and civil structures against strong seismic actions. A number of isolators such as Elastomeric Bearings, High Damping Bearings, Lead Rubber Bearings, Flat Slider Bearings, Curved Slider Bearings or Pendulum Bearings, Ball & Roller Bearings and dampers such as Mass Dampers, Liquid Damper, Elasto-plastic Damper, Visco Damper, Magneto-rheological Damper, and Shape Memory Alloy Dampers have been prominently addressed in the literatures. Figure 1 illustrates different dampers and isolators used for improving seismic performance of structures.



Figure 1. Different types of base isolators and dampers.

2.1. Base Isolation System

Base isolation is a state of the art earthquake hazard reducer in which a structure is separated from the ground by means of a suspension system to mitigate the effect of seismic vibrations. A number of base isolation systems have been developed in the field of earthquake engineering which is introduced in the seismic structures for better vibration control.



Figure 2. Base Isolators $(A)^{[52]}$ and $(B)^{[53]}$

2.1.1. Elastomeric Bearings. One of the major devices for base isolation of buildings is Elastomeric Bearing. It has low buckling load and low shear rigidity and is more slender which results in lower deformation of structures [9]. The primary advantage of elastomeric bearings is that it has no moving parts, is corrosion resistant, reliable, cheap and require no maintenance [10]. Nezhad et al. [11] proposed a base isolation system which uses Stable Unbonded Fiber Reinforced Elastomeric Isolator (SU-FREI) bearing. The bearing consists of unfilled soft Neoprene rubber as the elastomer and bidirectional carbon fiber as reinforcement. Results reveal that the bearing act as a suitable seismic isolator. Time history analysis performed on 2-storey prototype base-isolated structure and fixed base structure reveals that the proposed isolation method can be suitably applied in mitigating earthquake hazard in low rise buildings located at high seismic zones. Niranjani and Aravinthan [12] investigated the dynamic characteristics of a 4-storied building using modal analysis. Elastomeric bearing is designed for the column. The investigators observed that there was an increase of absolute displacement but decrease in the relative displacement thus reducing the damage of structure during earthquake. There was also a decrease in the shear and bending moments due to higher time period which further reduces acceleration of structures. The damping behaviour is also found to be increased due to base isolation devices.

2.1.2 High Damping Bearings. It is a system which lowers the natural frequency of the structure and shifts them away from energy containing frequencies of earthquake [13]. They possess highly nonlinear behaviour at low strain levels (< 2%) [14]. Arya et al. [15] carried out modelling and finite element analysis of high damping rubber bearing using ANSYS 12.0. In order to analyse the behaviour of isolators during seismic movements, a displacement analysis was performed. The investigators observed that the proposed isolator can undergo a maximum displacement corresponding to 350% of shear strain or 350% of rubber layer thickness without compromising its stability. However, the isolator can withstand 400% of shear strain but there are high chances of damage of isolator can withstand cyclic loading for accelerations of around 0.3g. The investigators further concluded that isolator developed using CFRP show similar behaviour and more efficient as compared to steel plates. The use of CFRP plates reduces the weight of the bearing thereby finding a wide range of applications.

2.1.3 Lead Rubber Bearing. It is a laminated elastomeric bearing comprising of combined features of vertical load support, horizontal flexibility and energy absorbing capacity for mitigation of seismic vibrations [16]. Salic et al. [17] proposed a lead-rubber bearing (LRB) system for a G+7 storey building to investigate its effect on the seismic performance. The investigators concluded that there was an increase in natural period of the structure from 0.46 sec to 2.38 sec and reduction of base shear

up to 4.6 times in X direction in 3.5 times in Y direction. There was also an increase of displacement from 0.0197 m to 0.1458 m in X direction and from 0.0127 m to 0.1538 m in Y direction and reduction of inter-story drifts. The results further conclude that there was a reduction of story accelerations of 3.07 times in X direction and 2.27 times in Y direction. The study shows that there was an increase of the fundamental period and decrease of inter-story drifts, floor accelerations and base shear of isolated buildings compared to fixed base structures.

2.1.4 Flat Slider Bearings. It consists of sliding bearing, bearing plates and horizontal springs and is mainly of two types based on their performance such as rigid type and elastic type [18]. Ozbulut and Hurlebaus [19] studied the seismic performance of a sliding-type base isolation system taking into consideration the environmental temperature changes. The proposed system consists of steel-teflon sliding bearing which carry vertical loads and dissipates energy along with a shape memory alloy (SMA) device which incorporates re-centering force and additional damping. A five-span continuous bridge was considered and neuro-fuzzy model was developed which records material response at different temperatures and loading frequencies. Nonlinear time history analysis was also considered. Results reveal that sliding-type isolation system consisting of SMA re-centering device can mitigate seismic vibrations of bridges irrespective of temperatures.

2.1.5 Curved Slider Bearings or Pendulum Bearings. This isolation system consists of sliding surfaces which are spherical in shape and provides sliding and re-centering in one unit [20]. Arathy and Manju [21] investigated building deflection, inter story drift and overturning moment of building isolated with friction pendulum bearing system. Non-linear time history analysis was performed in E-tabs 2015 software. The investigators concluded that restoring forces were 1.22 and 11.04 times on double and triple pendulum bearing against single pendulum bearing. The values of base shear, drift, displacement and overturning moment was decreased due to higher time periods implementing lower acceleration on structures. The result further shows that triple pendulum isolator was superior compared to single and double pendulum bearing system. Gulhane et al. [22] employed friction pendulum bearing for building base isolation and observed that it is a reliable method for earthquake resistant design. The researchers also observed that introduction of friction pendulum bearing enhances the time period of base isolated structures compared to fixed base structure. Further case study reveals reduction in acceleration per unit time for base isolated structures compared to fixed structures.

2.1.6 Ball & Roller Bearings. They are found in isolation applications in machinery and include cylindrical rollers and balls. The rollers and balls resist vibrations and damping corresponding to the material used. Ball Rubber Bearing (BRB) type isolators can be easily manufactured similar to the standard elastomeric bridge bearings and can provide significant energy dissipation during an earthquake through friction provided by steel balls inside the cylindrical core as investigated by Alp Caner et al. [23]. The researchers concluded that the BRB system has better damping than elastomeric bearings with the same type of elastomeric material.

2.2 Dampers

Dampers are vibration absorbers that reduce vibrations and shocks. It is a mechanical device that is intended to disperse the kinetic energy produced in a body or structure. A numbers of dampers are being identified that finds promising applications in bridge piers, buildings and civil infrastructures.



Figure 3. Dampers $(A)^{[54]}$ and $(B)^{[55]}$

2.2.2 Tuned Liquid damper. It is a passive damper that uses water sloshing to dissipate energy incurred due to seismic movements [30]. The reason for increase in demand of tuned liquid damper (TLD) is accredited to high volumetric efficiency and consistent behaviour against high seismic actions [31]. TLD are low in cost, easy to handle and require lesser maintenance [32]. Banerji et al. [33] numerically simulated a single-degree-of-freedom (SDOF) structure of TLD and observed that TLD when subjected to both real and artificially generated earthquake ground motions considerably reduces the seismic movement. A larger water-depth to tank-length ratio and water-mass to structure-mass ratio can have significant impact in reducing higher seismic movements. A high depth ratio of 0.15 for TLD is effective in reducing strong earthquake movements. However, lower mass ratio of 1-4 percent can also reduce structural response. Jaksic et al. [34] investigated the effect of TLD on the dynamic performance of an offshore wind floating tension leg platform (TLP). The authors observed a decrease

^{2.2.1} Tuned Mass damper. It is a device that lowers seismic responses either by applying equal and opposite forces or by dissipating energy through damping [24]. It is one of the oldest passive vibration control devices in the field of vibration control of structural system [25]. A typical tuned mass damper (TMD) consists of a mass that is attached to the structure through a linear elastic spring [26]. Hoang et al. [27] studied the use of tuned mass damper (TMD) for minimizing the damage of bridge pier system during seismic actions. A bridge superstructure and substructure were designed in agreement with The American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications (BDS) (2012). The optimum parameters for TMD were determined which include minimization of drift and displacement of the bridge superstructure. The developed optimized TMD was compared with four different existing benchmarked TMD. The investigators observed an improvement in the performance of the proposed TMD compared to existing TMD in lowering the seismic responses. Kareem and Kline [28] investigated the effectiveness of multiple mass dampers (MMD) attached parallely under random loading and found that there is a reduction in the peaks observed in single mass damper. Different parameters of MMD are considered which include frequency range of MMDs, their individual damping ratio and the number of dampers. Random loads such as wind and seismic responses are considered in their present work. The researchers concluded that MMD system is much more effective than single TMD in controlling random loadings offering better portability and ease of installation. Lin et al. [29] investigated a novel semi-active friction-type multiple tuned mass damper (SAF-MTMD) for controlling the vibration of structures under seismic actions. The proposed SAF-MTMD has the ability to keep its mass active at random intensities of earthquake. The investigators compared the proposed system with passive friction-type multiple tuned mass damper (PF-MTMD) and observed improvement in the performance of SAF-MTMD in minimizing seismic vibrations in structures. Moreover SAF-MTMD requires lesser space for installation, performs better in low intensity earthquake compared to PF-MTMD.

in movement of structure with the introduction of liquid damper. However, the work encourages further research in the field by incorporating multiple dampers in extreme seismic actions. Hochrainer [35] carried out a numerical study on the introduction of (TLD) in civil infrastructures and observed that insertion of an actively and passively operating air spring improves the performance of TLD. The investigation further concludes that active and passive tuned liquid column damper (TLCD) is comparatively cheaper, easy to install and potential substitute to other vibration damping devices.

2.2.3 Elasto-plastic damper. It is a device that minimizes the seismic action on structures and equipments by absorbing the energy due to hysteretic deformation [36]. Pu and Kasai [37] proposed a design method for elasto-plastic dampers to minimize seismic vibration in concrete reinforced structures. The dynamic property was analysed for SDOF system and the parametric study was carried out. The researchers further developed a MDOF structure based on tuning of equivalent stiffness of the structure. Results from time history analysis on a 7-story RC building reveal that proposed design of elasto-plastic dampers is well verified and can find suitable applications. Kunisue et al. [38] retrofitted elasto-plastic dampers in an existing building with a view to enhance its structural strength and minimize its seismic actions by absorbing energy. Experiments were carried out to accomplish the effect of dampers induced in structures. The authors found that there was an increase in strength and energy absorption due to the introduction of elasto-plastic dampers. The test results show good accordance with theoretical results. The retrofitting with elasto plastic dampers is quite effective and can find promising applications to improve seismic performance in buildings.

2.2.4 Visco-elastic damper. This class of dampers consists of a cylinder containing incompressible silicone fluid and a piston and find promising applications in defence and aerospace industries [39]. Ras and Boumechra [40] carried out a 3D numerical investigation on Fluid Viscous Dampers (FVD) for a twelve-storey steel building moment. The investigators incorporated Non-linear time history for analysis of FVD which reveal that introduction of FVD reduces the dissipation capability of the structure without increasing its rigidity. There was also a reduction of the structural response of the building compared to unbraced structure. Mathew and Prabha [41] studied the effect of seismic vibration in reinforced concrete buildings with and without fluid viscous dampers. Nonlinear time history analysis was carried out using SAP2000 software. The researchers concluded that effective reduction of dynamic response is obtained with FVD incorporated structures having a damping ratio of 20% and velocity exponent as 0.5. Moreover better performance for square planes can be obtained by introducing FVD at the external corners. Kumar et al. [42] investigated the effect of viscous dampers (VD) in multi-storeyed building and observed that VD reduces two-third energy released during minor earthquake. Results from Time history analysis reveals elimination of force and displacement due to the introduction of VDs. The researchers further concluded that the damping ratio for VDs should be twice as structural intrinsic damping ratio for effective seismic performance.

2.2.5 Magneto-rheological damper. This class of dampers are finding promising applications because of its perfectly dynamic damping behaviour [43]. They are semi-active control devices which use MR fluids to offer considerable damping forces and require small power, are reliable and quite inexpensive to manufacture [44]. Yang et al. [45] investigated the dynamic model of MR damper consisting of two parts - power supply and MR dampers. The model illustrates MR fluid stiction phenomenon along with its inertia and shear thinning. The investigators observed that the proposed model is much more effective compared to Bouc-Wen model. However the model doesn't take into account structure device interaction for which more accurate model including the coupling terms should be designed. The developed models provides new tool for design and synthesis of large scale MR dampers. Gordaninejad et al. [46] developed a large-scale magneto-rheological fluid (MRF) bypass valve damper consisting of a modular bypass MRF valve. The performance of MRF valve and combined damper was investigated through quasi-static and dynamic tests. The researchers observed that the developed combined damper can provide a maximum damping force over 200 KN that is sufficient to

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mitigate large seismic vibration. Li et al. [47] proposed a new real-time semi-active control algorithm based on the damage of bridge (RTSD) members using MR damper. The purpose of the study is to defend both the bearing and pier during earthquakes by uniform distribution of damage pattern. Results reveal that damages to the bearing and pier are balanced with the designed model and an improvement in the performance was observed compared to passive controls. Moreover the damping value can be set in a wide range of RTSD which in turn protect both the bearing and pier under high seismic actions.

2.2.6 Shape memory alloy damper. This class of dampers is made up of shape memory alloys which are basically smart materials. The materials show excellent performance in minimizing seismic vibrations and thus can be a promising candidate for the development of dampers [48]. Qian et al. [49] proposed a re-centering shape memory alloy damper (RSMAD) consisting of superelastic nitinol wires. Graesser and Cozzarelli models were used for super elastic nitinol wires. Cyclic tensilecompressive tests at different loading frequencies and displacement amplitudes were carried out on the proposed damper which reveals that the performance of damper is not sensitive to frequencies above 0.5Hz. Nonlinear time history analysis was performed on a ten-story steel frame subjected to earthquake motions with and without dampers. Results show that super elastic SMA dampers effectively reduces strong seismic vibrations. Pan and Cho [50] developed a shape memory allow micro damper made up of NiTi which exhibit pseudo-elasticity of NiTi wires for dissipation of energy. The wires were subjected to temperature and strain rates. The investigators observed better performance and energy dissipation of NiTi based micro-damper compared to conventional dampers. The developed damper finds promising application as actuator, the joint component of robotic and energy absorber for suspension system of automobile. Ren et al. [51] developed re-centering damping device made up of superelastic Nitinol wires. The device consists of pre-tensioned strands and the unpre-tensioned strands which results in suitable energy dissipation and has different advantages such as fatigue resistance, reliability, high durability and can withstand strong earthquakes without failure. The investigators further carried out shake table tests of a two-story steel frame with/without the devices which reveal that the device can not only minimize seismic vibrations effectively but also can recuperate undeformed structures at the end of action.

3. Conclusion

The improvement in seismic performance of the structures has always been a challenging task for researchers and scientists. The mitigation of damage of civil infrastructures due to high seismic vibrations is a matter of major concern to be taken care of. The present review emphasizes on different methods for improving the seismic performance of infrastructures. The work mainly focuses on base isolation and the use of dampers to enhance seismic performance. Tuned mass dampers and liquid dampers have attracted a lot of interest owing to its simple construction, lesser space requirement, easy portability and installation. Magneto-rheological damper however show a maximum damping force of 200KN which is quite sufficient to mitigate strong seismic actions. Certain shape memory alloy dampers have the property to recover from deformed structural shapes after seismic vibrations. Moreover, the seismic performance of structures can also be enhanced significantly by base isolation system. Elastomeric bearing comprising of fiber reinforced plastics serves as prime base isolator in building. High damping bearing and lead rubber bearing uses rubber plates for the purpose of base isolation. However, high damping bearing in recent times consists of CFRP plates for better seismic performance. Flat slider bearing may be rigid type or elastic type depending on their applications and mitigate seismic vibrations of bridges irrespective of temperatures. Pendulum bearing are made up of spherical shape sliding surfaces and enhances time period thus reducing seismic vibrations in structures. The review will explore the potential of base isolators and dampers in improving the seismic performance of buildings, bridge piers, equipments, in civil infrastructures and designs.

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