CHAPTER 2

REVIEW OF LITERATURE

2.0 General

Earthquakes have been known to man since ancient times. They represent one of natural hazards human society has to face, often without any kind of warning. It involves a severe, shaking of the earth below our feet affecting all systems and structures standing on it. Generally, it lasts for a fraction of a minute but will often causes great loss of life and property.

Structural engineers usually consider two aspects of earthquake engineering in every seismic design. These can be described as demand and capacity. The demand is the level of seismic loading that might be applied to the building while the capacity is the resistance of the building to resist the demand. The conventional seismic design attempts to make the buildings that do not collapse under strong earthquake shaking, but may sustain damage to non-structural elements and to some structural members in the building. This may render the building non-functional after the earthquake, which may be problematic in some structures like hospitals, which need to remain functional in the aftermath of the earthquake. The need to minimize earthquake damage is critical and important. This
has led to the use of seismic base isolation strategy on a large scale in several earthquake prone developed countries.

The base isolation works by decoupling the building or structure from the horizontal components of the earthquake ground motion by interposing a layer with low horizontal stiffness between the structure and the foundation. This layer gives the structure a fundamental frequency that is much lower than both its fixed base frequency and the predominant frequencies of the ground motion. The first dynamic mode of the isolated structure involves the deformation only in the isolation system, the structure above being, to all intents and purposes, rigid. The higher modes, which produce deformation in the structure are orthogonal to the first mode and consequently also to the ground motion. These higher modes do not participate in the motion so that if there is high energy in the ground motion at these higher frequencies this energy cannot be transmitted into the structure.

In 1909, a medical Doctor Calantarients in England applied for a British patent on an earthquake-resistant design approach. Frank (1921) was the first person to implement the idea of base isolation. He applied the base isolation idea to the foundation design for the Imperial Hotel in Tokyo in 1921, under the site was an eight feet layer of fairly good soil and below that a layer of soft mud. Accordingly, the idea of floating the building came into the picture for the resistance of earthquake shock.

The flexible first-storey concept was first proposed by Martel (1929) and further studied by Green (1935), Jacobsen (1938). In this approach the lateral stiffness of the columns of the first-storey would be designed to be much lower than that of the columns above, and
under earthquake loading the deformations would be concentrated in these first-storey columns.

In the search for a mechanism that can overcome the difficulty of a flexible first-storey, Ryuiti (1941, 1951, 1952) and Caspe (1970, 1984) proposed many types of roller bearing system and several have been patented and tested. However, as the earthquake movement can be in any direction, these types of roller bearing system did not become popular. As a result, it made necessary to use spherical bearings or two crossed layers of rollers. Lee and Medland (1979) examined the effectiveness in respect of EI Centro earthquake excitation of a multi-storey shear type structure isolated by the lead rubber bearing. Tadjbakhsh and Ma (1982) and Pan and Kelly (1983, 1984) studied the seismic response of base isolated buildings by modeling the superstructure as a rigid block supported on an isolation system.

The hysteretic force deformation behavior of the lead rubber bearing is modeled as bi-linear. Tadjbakhsh (1983, 1985, 1985a) studied the response of a shear type building supported on the laminated rubber bearing system under random ground motion. Kelly and Tsai (1985) studied the seismic response of light internal equipment in base isolated multi degree shear type structures. They had shown that the use of base isolation can not only attenuate the response of the primary structural system but also reduce the response of the secondary systems. Mostaghel and Khodaverdian (1987) proposed the resilient-friction base isolation (R-FBI) system. Paul and Novak (1989) studied the response of base isolated building to wind loading by modeling the superstructure as a rigid block supported on an isolation system. Tasi and Kelly (1989) demonstrated effect of superstructure flexibility using a discrete multiple degrees of freedom system having only horizontal degree of freedom at each floor. Ghobarah and Ali (1989) proposed a simple
design procedure for highway bridges, which aims at optimum balance between the shear forces transmitted to the supports and tolerable deck displacements for isolated highway bridges using the inelastic response spectra approach. Simplified charts are presented which provide a design aid for new bridges as well as the retrofitting and upgrading of existing ones. The method is shown to be simple and reasonably accurate. It takes into account the flexibility of the pier and is suitable for a code-type approach.

Briseghella et al. (1989) presented a design approach for applying base isolation technologies to typical medium-span continuous concrete deck bridges. A method for constructing non-linear response spectra for rigid-plastic systems is explained in which a direct strength-displacement relationship is obtained without depending on the elastic period.

Kelly (1990) illustrated through a linearised theory of base isolation the effect of superstructure flexibility using two degrees of freedom system. Fan and Ahmadi (1990) observed that use of base-isolation system eliminates the resonance peak of the floor spectra, which occurs at the natural frequency of the fixed base system for earthquake ground excitation. In their study they had modeled the superstructure as a shear type building.

Koh and Kelly (1990) presented a fraction Kelvin model to define the force-deformation relation of elastomeric bearings: An efficient numerical integration scheme is presented for the solution of the equation of motion for a base isolated system. The numerical examples reveal a good performance of the algorithm developed. In addition, a shaking
table test indicated that the fractional derivative model agrees well with the experimental model.

Su et al. (1991) proposed the design of the sliding resilient-friction (S-RF) base isolator. This isolator combines the desirable features of the EDF and the R-FBI systems. It was suggested to replace the elastomeric bearings of the EDF base isolation by the R-FBI units.

Constantinou et al. (1991) proposed an isolation system consisting of multi-directional sliding Teflon bearings and displacement control devices. The displacement control devices provide re-centering capability and displacement control during earthquakes and rigidity under service loads.

Mayes et al. (1992) presented an overview of the basic concepts and design principles of seismic isolation and discussed the objectives and philosophy of the provisions of American Association of State Highway and Transport Officials (AASHTO, 1991) and concluded with a procedure to compare the performance of isolation systems with different damping values.

Fan and Ahmadi (1992) studied the seismic response of secondary systems in base isolated shear type structures. They had shown that the use of base isolation provides considerable protection for structural contents. Gueirreiro and Azevedo (1992) studied the ductility demand of base-isolated structure with non-linear behavior. They considered superstructure as elasto-plastic and isolation system as bilinear. They constructed design diagrams for behavior coefficients to be used for a given structure and base isolation
system, as a function of the structures allowable ductility. Chen and Ahmadi (1992) examined the sensitivity of the base isolated structure to the fluctuating component of the wind, by modeling the superstructure as a rigid block supported on an isolation system. Lin and Hone (1993) have proposed a new system of free circular rolling rods located between the base and the foundation. The most attractive feature of this type of isolator is their low value of rolling friction coefficient, which allows a very low earthquake force to be transmitted to the superstructure.

Okoshi et al. (1993) studied the behavior of a nine-storey computer center building in Tokyo, base isolated with lead rubber bearings. They checked the aseismic safety of the building for different real earthquakes. It was found that the base isolation system is very efficient to reduce the earthquake response of the building and to increase the seismic safety of the building and its contents. Luca and Faella (1993) compared the response of base isolated and conventional structures. The investigations were carried out on several multi-storey frames characterized by different number of storeys and designed for high and low ductility. The frames were subjected to four earthquake input motions having different frequency contents. The comparison of the responses was performed in terms of interstorey drifts and distribution of bending moments throughout the structure. It was concluded that base isolation can be an efficient mean for improving the performance of structures even in the most severe cases which are represented by higher number of storeys and earthquake input ground motions characterized by large spectral values in the low frequency range.

Young and Lee (1993) studied the seismic response of support isolated secondary structures in a multi-storey structure. They had modeled the multi-storey structure as a
shear type building and found that the support-isolation system of the secondary structure on the fixed base structure is very useful for reducing the response of the secondary structure and can be utilized to increase the safety of the safety-related items.

Audi and Kelly (1993) investigated the optimum isolation damping for minimum acceleration response of a base isolated multi degree shear structure with lumped mass system subjected to stationary random excitation. In their study they had modeled the behavior of the bearing as linear.

Tsai and Kelly (1993) studied the influence of isolation damping on the seismic response of heavily damped base isolated buildings using a discrete multiple degrees of freedom system having only horizontal degree of freedom at each floor with lumped mass system. In their study they had modeled the behavior of the bearing as linear. They concluded that when the damping ratio of the isolation system is beyond a certain level, increasing the isolation damping will enlarge the base and super structural accelerations.

Skinner et al. (1993) investigated the effects of the degree of isolation on the modal profiles and period, and on the seismic motions and loads using a continuous uniform shear structure. Chen and Ahmadi (1994) studied the performance of a high damping rubber bearing base isolation system in protecting the structure and the structural content. In their study they idealized the superstructure as a non-uniform shear beam.

Pan and Cui (1994) carried out a series of parametric studies to obtain the dynamic characteristics of base-isolated shear buildings supported on laminated rubber bearings. In their study they idealized the superstructure as a uniform shear beam for which the girders
are rigid and the columns do not deform axially. They concluded that higher mode frequencies and participation factor of the fundamental base-isolated mode is affected significantly by variation in mass ratio. The stiffness ratio affects more on higher mode participation factors. Here, the stiffness and mass ratios are the ratios of stiffness and mass of the base isolation system to the shear beam. They also observed that compared with the fundamental mode, participation factors in the second and higher base-isolated modes are very small.

Jangid and Datta (1994) investigated the optimum isolation damping for minimum acceleration of a base isolated multi degree shear building with lumped mass system subjected to earthquake ground excitation.

Ahmadi et al. (1995) studied the influence of non-linearity on the response of rubber isolators to earthquake motions, in which they had modeled the superstructure as a shear type building. Jangid (1996),Safak and Frankel (1996) studied the effects of ground motion characteristics on the response of six-storey and seven-storey base-isolated buildings. They observed that the effectiveness of base isolators is strongly dependent on the amplitudes and frequency characteristics of ground motion. Allred et al. (1996) studied analytically the effects of impact of base-isolated building with moat walls. A moat wall may be a retaining wall, constructed round the base-isolated building's exteriors to ensure the desired seismic-gap and to prevent instability of the building in the event of earthquake having intensity more than that assumed for the design. A mathematical model of a realistic four storey base-isolated model was considered for fixed-base, isolated without impact and isolated with impact model. They found that impact affects the high frequency components of the structure while longer period components are unaltered. Contents such
as electronic equipments, cabinets and other sensitive high frequency components will suffer the most due to impact. Hwang and Chiou (1996) have established an equivalent linear model for the seismic analysis of base isolated bridges with lead-rubber bearings. Kikuchi and Aiken (1997) had proposed an analytical hysteresis model for elastomeric seismic isolation bearing for the purpose of accurately predicting the seismic response of base isolated structures. Tsai (1997) studied the dynamic response of base isolated structure bumping against stops by modeling the superstructure as a shear beam. Higashino et al. (1998) showed that high initial stiffness of laminated rubber bearings and stiffness due to viscous dampers provided in addition to bearings can result in higher actual frequency of the base-isolated structure than the designed value, which is based on the assumptions that stiffness of isolation system is constant, and fluid of damper is Newtonian fluid. Jain and Thakkar (1998) carried out parametric study to understand the behavior of multi-storied base isolated buildings. Kelly (1999) studied the role of damping in seismic isolation by modeling the structure as a two-degree of freedom system having only horizontal degree of freedom at each floor. He had shown that as the damping in the isolation system increases, the isolator displacement and structural base shear may be reduced, but the floor accelerations are increased.

Jangid (2004) studied the influence of isolator characteristics on the response of base isolated structures. They have modeled the structure as a multi degree shear building mounted on isolation systems.

However, substantial reduction in shear modules is observed for moderate seismic excitation and this effect should be taken into account while computing foundation impedance. Recent revisions in the Uniform Building Code (ICBO, 2001) impose stringent performance requirements on the design of base isolated buildings. The more stringent code requirements and the potential impact of near fault earthquakes has led to the way for the need for control devices.

2.1 Control devices

Control devices for civil structures can be divided into four classes passive, active, semi active and hybrid. Passive devices, generally, are those that have fixed properties and require no energy to function. In contrast, the controllable forces generated by active devices are induced directly by energy (electrical or otherwise) put into the device. Between passive and active are semi active devices that are passive devices with properties that are controllable by application of a small amount of energy. Hybrid devices are combinations of the other three classes. The literature on each of these is reviewed briefly in the following paragraphs, with greater emphasis on semi active devices.

Passive devices, such as visco-elastic dampers, viscous fluid dampers, friction dampers, metallic dampers, tuned mass dampers, and tuned liquid dampers can partially absorb structural vibration energy and reduce response of the structure. These passive devices are relatively simple and easily replaced. However, the effectiveness of passive devices is
always limited due to the narrow frequency ranges in which they tend to be effective, the dependence of their force only on local information, and their inability to be modified if goals change.

Active control devices, including active mass dampers and active tendon systems, can reduce structural response more effectively than passive devices because feedback and/or feed-forward control systems are used. However, large power requirements during strong earthquakes and other hazards hamper their implementation in practice. Further, active devices have the ability to inject dynamic energy into the structural system; if done improperly, this energy has the potential to cause further damage to the structure. In particular, this can occur when the assumptions used to design the control algorithm are incorrect or do not have a proper characterization of the structural dynamics.

Inaudi and Kelly (1990) investigated active base isolation of a four story building model employing electro hydraulic actuator. Nagarajaiah et al. (1993) applied the active base isolation idea to a bridge with steel and Teflon bearings and a hydraulic actuator.

Reinhorn et al. (1993) presented three control algorithms for the hybrid system applied to bridges. Two of these algorithms are verified experimentally, and the third is verified with an analytical model. The results show that the hybrid system is capable of significantly improving the seismic response of the bridges. Yang et al. (1993) presented a method for controlling seismically excited bridges by using variable dampers. A simulation study using a continuous girder bridge is conducted to examine the effectiveness of the control algorithm in reducing the absolute acceleration of the bridge girder and the relative
displacement between the girder and the supports. Simulation results indicate that the performance of the control method is excellent.

Yang et al. (1994, 1995) presented control methods for hybrid protective systems for bridges. The control methods are based on the theory of variable structure system or sliding mode control. Simulation results demonstrate that the control methods are robust with respect to system parametric uncertainties and performance is quite remarkable. Sensitivity studies are conducted to evaluate the effectiveness of hybrid protective systems and passive sliding isolators for reducing the response of seismic-excited bridge structures. Yang et al. (1996) examined sliding mode controller for a four story base isolated building model employing a hydraulic actuator.

Housner et al. (1997) studied the active control devices, including active mass dampers and active tendon systems, shown that it can reduce structural response more effectively than passive devices because feedback and/or feed-forward control systems are used. However, large power requirements during strong earthquakes and other hazards hamper their implementation in practice. Further, active devices have the ability to inject dynamic energy into the structural system; if done improperly, this energy has the potential to cause further damage to the structure. In particular, this can occur when the assumptions used to design the control algorithm are incorrect or do not have a proper characterization of the structural dynamics.

Dyke et al. (1996) shown that smart devices offer highly reliable operation at a modest cost and can be viewed as fail-safe in that they default to passive devices should the control hardware malfunction. Soong and Dargush (1997) shown that the passive devices,
such as visco-elastic dampers, viscous fluid dampers, friction dampers, metallic dampers, tuned mass dampers, and tuned liquid dampers can partially absorb structural vibration energy and reduce response of the structure.

Fideliu (1998) presented classical optimal control strategy with full known state for seismic response control of cable-stayed bridge. The parameters for control strategy are proposed based on energetic interpretation for the optimisation index applied to a three-dimensional cable stayed bridge, equipped with many active devices. Symons and Kelly (1998) investigated the effectiveness of a hybrid system containing semi-active dampers through an analytical and computational study of the seismic response of a bridge.

2.2 Types of semi active devices

Different types of semi active devices have been developed recently. The types of semi active dampers are variable-orifice dampers, controllable fluid dampers, and controllable friction devices. Variable-orifice dampers use an electromechanical variable orifice to alter the resistance to flow in a conventional hydraulic fluid. MR or ER fluids change their properties in the presence of a magnetic or electric field, respectively. These fluids were originally developed in the 1940s. Rabinow (1948), Winslow (1949) started working on this fluid, but few applications were foreseen at that time. While ER fluids showed early promise for civil applications. Another type of semi active device is a semi active stiffness device such as those developed by Kobori and Takahashi (1993), Yang et al. (1996) and Patten et al. (1999). They are on-off hydraulic devices capable of providing mainly variable damping and limited variable stiffness capability. Nagrajaiah and Ma (1996) introduced a variable stiffness device that consists of four sets of spring elements and telescoping tube elements. Spencer et al., (1997) shown that controllable fluid dampers are
passive hydraulic dampers containing a fluid, such as magneto rheological (MR) or electro rheological (ER) fluid, with controllable yield stress. Varying the position of the springs with a servomotor produces the continuously-variable stiffness. Controllable fluid dampers use fluids with properties that can be modified by some outside influence. Ehrgott and Masri (1992) worked on ER fluids. Spencer et al.(1997) started using MR fluids due to their insensitivity to impurities, relatively constant behaviour over a wide range of operating temperatures, and the low voltage required to activate them.

Active control devices operate by using an external power supply. Therefore, they are more efficient than passive control devices. However the problems such as insufficient control force capacity and excessive power demands encountered by current technology in the context of structural control against earthquakes are unavoidable and need to be overcome. Recently a new control approach-semi-active control device, which combines the best features of both passive and active control devices, is very attractive due to their low power demand and inherent stability. The earlier papers involving SATMDs may traced to 1983. Hrovat et al. (1983) presented SATMD, a TMD with time varying controllable damping. Under identical conditions, the behaviour of a structure equipped with SATMD instead of TMD is significantly improved. The control design of SATMD is less dependent on related parameters (e.g, mass ratios, frequency ratios and so on), so that there greater choices in selecting them. The concept of multiple tuned mass dampers (MTMDs) together with an optimization procedure was proposed by Clark (1988). Since, then, a number of studies have been conducted on the behaviour of MTMDs a doubly tuned mass damper (DTMD), consisting of two masses connected in series to the structure was proposed (Setareh 1994). In this case, two different loading conditions were considered: harmonic excitation and zeromean white-noise random excitation, and the
efficiency of DTMDs on response reduction was evaluated. Analytical results show that
DTMDs are more efficient than the conventional single mass TMDs over the whole range
of total mass ratios, but are only slightly more efficient than TMDs over the practical
range of mass ratios (0.01-0.05). Recently, numerical and experimental studies have been
carried out on the effectiveness of TMDs in reducing seismic response of structures [for
instance, Villaverde(1994)]. In Villaverde(1994), three different structures were studied,
in which the first one is a 2D two story shear building the second is a three-dimensional
(3D) one-story frame building, and the third is a 3D cable-stayed bridge, using nine
different kinds of earthquake records. Numerical and experimental results show that the
effectiveness of TMDs on reducing the response of the same structure during different
earthquakes, or of different structures during the same earthquake is significantly
different; some cases give good performance and some have little or even no effect. This
implies that there is a dependency of the attained reduction in response on the
characteristics of the ground motion that excites the structure. This response reduction is
large for resonant ground motions and diminishes as the dominant frequency of the ground
motion gets further away from the structure's natural frequency to which the TMD is
tuned. Also, TMDs are of limited effectiveness under pulse-like seismic loading.

Multiple passive TMDs for reducing earthquake induced building motion. Allen J. Clark
(1988). The performance of both passive and active tuned mass damper (TMD)
systems can be readily assessed by parametric studies which have been the subject
of numerous research. Few experimental verifications of TMD theory have been
carried out, particularly those involving active control, but the results of those
experiments generally compared well with those obtained by parametric studies. Despite
some serious design constraints, a number of passive and active tuned mass damper
systems have been successfully installed in tall buildings and other structures to reduce
the dynamic response due to wind and earthquakes. Mitigation of response of high-rise structural systems by means of optimal tuned mass damper. A.N Blekherman (1996). In this paper a passive vibration absorber has been proposed to protect high-rise structural systems from earthquake damages. A structure is modelled by one-mass and n-mass systems (a cantilever scheme). Damping of the structure and absorber installed on top of it is represented by frequency independent one on the base of equivalent visco-elastic model that allows the structure with absorber to be described as a system with non-proportional internal friction. A ground movement is modelled by an actuator that produces vibration with changeable amplitude and frequency. T. Shimazu and H. Araki (1996). A method of estimating the parameters of tuned mass dampers for seismic applications. Fahim Sadek et al (1997). In this paper the optimum parameters of TMD that result in considerable reduction in the response of structures to seismic loading has been presented. The criterion that has been used to obtain the optimum parameters is to select for a given mass ratio, the frequency and damping ratios that would result in equal and large modal damping in the first two modes of vibration. The parameters are used to compute the response of several single and multi-degree of freedom structures with TMDs to different earthquake excitations. The results show that the use of the proposed parameters reduces the displacement and acceleration responses significantly. The method can also be used for vibration control of tall buildings using the so-called ‘mega-substructure configuration’, where substructures serve as vibration absorbers for the main structure. Structural control: past, present, and future. G. W. Housner et al (1996). Structural vibration of tuned mass installed three span steel box bridge. Byung-Wan Jo et al (2001). To reduce the structural vibration of a three span steel box bridge a three axis two-degree of freedom system is adopted to model the mass effect of the vehicle; and the kinetic equation considering the surface roughness of the bridge is derived based on Bernoulli-Euler beam ignoring the
torsional DOF. The effects of TMD on steel box bridge shows that it is not effective in reducing the maximum deflection, but it efficiently reduces the free vibration of the bridge. It proves that the TMD is effective in controlling the dynamic amplitude rather than the maximum static deflection. Optimal placement of multiple tuned mass dampers for seismic structures. Genda Chen et al (2001). In this paper effects of a tuned mass damper on the modal responses of a six-story building structure are studied. Multistage and multimode tuned mass dampers are then introduced. Several optimal location indices are defined based on intuitive reasoning, and a sequential procedure is proposed for practical design and placement of the dampers in seismically excited building structures. The proposed procedure is applied to place the dampers on the floors of the six-story building for maximum reduction of the accelerations under a stochastic seismic load and 13 earthquake records. Numerical results show that the multiple dampers can effectively reduce the acceleration of the uncontrolled structure by 10–25% more than a single damper. Time-history analyses indicate that the multiple dampers weighing 3% of total structural weight can reduce the floor acceleration up to 40%. Seismic effectiveness of tuned mass dampers for damage reduction of structures. T. Pinkaew et al (2002). The effectiveness of TMD using displacement reduction of the structure is found to be insufficient after yielding of the structure, damage reduction of the structure is proposed instead. Numerical simulations of a 20-storey reinforced concrete building modelled as an equivalent inelastic single-degree-of-freedom (SDOF) system subjected to both harmonic and the 1985 Mexico City (SCT) ground motions are considered. It is demonstrated that although TMD cannot reduce the peak displacement of the controlled structure after yielding, it can significantly reduce damage to the structure. In addition, certain degrees of damage protection and collapse prevention can also be gained from the application of TMD.
Tuned Mass Damper Design for Optimally Minimizing Fatigue Damage. Hua-Jun Li et al[47](2002). This paper considers the environmental loading to be a long-term nonstationary stochastic process characterized by a probabilistic power spectral density function. One engineering technique to design a TMD under a long-term random loading condition is for prolonging the fatigue life of the primary structure. Seismic structural control using semi-active tuned mass dampers. Yang Runlin et al(2002). This paper focuses on how to determine the instantaneous damping of the semiactive tuned mass damper with continuously variable damping.

An off-and-towardsequilibrium(OTE) algorithm is employed to examine the control performance of the structure/SATMD system by considering damping as an assumptive control action. Two numerical simulations of a five-storey and a ten-storey shear structures with a SATMD on the roof are conducted. Devendra P. Garg et al(2003). The advances made in the area of vibration suppression via recently developed innovative techniques (for example, constrained layer damping (CLD) treatments) applied to civilian and military structures are investigated. Developing theoretical equations that govern the vibration of smart structural systems treated with piezo-magnetic constrained layer damping (PMCLD) treatments; and developing innovative surface damping treatments using microcellular foams and active standoff constrained layer (ASCL) treatments. The results obtained from the above and several other vibration suppression-oriented research projects being carried out under the ARO sponsorship are also included in this study. Performance of a five-storey benchmark model using an active tuned mass damper and a fuzzy controller.
Bijan Samali, Mohammed Al-Dawod (2003). This paper describes the performance of a five-storey benchmark model using an active tuned mass damper (ATMD), where the control action is achieved by a Fuzzy logic controller (FLC) under earthquake excitations. The advantage of the Fuzzy controller is its inherent robustness and ability to handle any non-linear behaviour of the structure. The simulation analysis of the five-storey benchmark building for the uncontrolled building, the building with tuned mass damper (TMD), and the building with ATMD with Fuzzy and linear quadratic regulator (LQR) controllers has been reported, and comparison between Fuzzy and LQR controllers is made. In addition, the simulation analysis of the benchmark building with different values of frequency ratio, using a Fuzzy controller is conducted and the effect of mass ratio, on the five-storey benchmark model using the Fuzzy controller has been studied. Behaviour of soil-structure system with tuned mass dampers during near-source earthquakes. Nawawi Chouw (2004). In this paper the influence of a tuned mass damper on the behaviour of a frame structure during near-source ground excitations has been presented. In the investigation the effect of soil-structure interaction is considered, and the natural frequency of the tuned mass damper is varied. The ground excitations used are the ground motion at the station SCG and NRG of the 1994 Northridge earthquake.

The investigation shows that the soil-structure interaction and the characteristic of the ground motions may have a strong influence on the effectiveness of the tuned mass damper. But in order to obtain a general conclusion further investigations are necessary. Wind Response Control of Building with Variable Stiffness Tuned Mass Damper Using Empirical Mode Decomposition Hilbert Transform Nadathur Varadarajan et al (2004). The effectiveness of a novel semi-active variable stiffness-tuned mass damper. For the response control of a wind-excited tall benchmark building is investigated in this study. The benchmark building considered is a proposed 76-story concrete office tower in
Melbourne, Australia. Across wind load data from wind tunnel tests are used in the present study. The objective of this study is to evaluate the new SAIVS-TMD system that has the distinct advantage of continuously retuning its frequency due to real time control and is robust to changes in building stiffness and damping. The frequency tuning of the SAIVSTMD is achieved based on empirical mode decomposition and Hilbert transform instantaneous frequency algorithm developed by the writers. It is shown that the SAIVSTMD can reduce the structural response substantially, when compared to the uncontrolled case, and it can reduce the response further when compared to the case with TMD. Additionally, it is shown the SAIVS-TMD reduces response even when the building stiffness changes by 15%. Effect of soil interaction on the performance of tuned mass dampers for seismic applications. A. Ghosha, B. Basu (2004). The properties of the structure used in the design of the TMD are those evaluated considering the structure to be of a fixed-base type. These properties of the structure may be significantly altered when the structure has a flexible base, i.e. when the foundation of the structure is supported on compliant soil and undergoes motion relative to the surrounding soil. In such cases, it is necessary to study the effects of soil-structure interaction (SSI) while designing the TMD for the desired vibration control of the structure. In this paper, the behaviour of flexible-base structures with attached TMD, subjected to earthquake excitations has been investigated. Modified structural properties due to SSI has been covered in this paper. Optimal design theories and applications of tuned mass dampers. Chien-Liang Lee et al (2006). An optimal design theory for structures implemented with tuned mass dampers (TMDs) is proposed in this paper. Full states of the dynamic system of multiple-degree-of-freedom (MDOF) structures, multiple TMDs (MTMDs) installed at different stories of the building, and the power spectral density (PSD) function of environmental disturbances are taken into account. The optimal design parameters of TMDs in terms of the
damping coefficients and spring constants corresponding to each TMD are determined through minimizing a performance index of structural responses defined in the frequency domain. Moreover, a numerical method is also proposed for searching for the optimal design parameters of MTMDs in a systematic fashion such that the numerical solutions converge monotonically and effectively toward the exact solutions as the number of iterations increases. The feasibility of the proposed optimal design theory is verified by using a SDOF structure with a single TMD (STMD), a five-DOF structure with two TMDs, and a ten-DOF structure with a STMD. Optimum design for passive tuned mass dampers using viscoelastic materials. I Saidi, A D Mohammed et al (2007). This paper forms part of a research project which aims to develop an innovative cost effective Tune Mass Damper (TMD) using viscoelastic materials. Generally, a TMD consists of a mass, spring, and dashpot which is attached to a floor to form a two-degree of freedom system. TMDs are typically effective over a narrow frequency band and must be tuned to a particular natural frequency.

FWong (2008). The energy transfer process of using a tuned mass damper TMD in improving the ability of inelastic structures to dissipate earthquake input energy is investigated. Inelastic structural behaviour is modelled by using the force analogy method, which is the backbone of analytically characterizing the plastic energy dissipation in the structure. The effectiveness of TMD in reducing energy responses is also studied by using plastic energy spectra for various structural yielding levels. Results show that the use of TMD enhances the ability of the structures to store larger amounts of energy inside the TMD that will be released at a later time in the form of damping energy when the response is not at a critical state, thereby increasing the damping energy dissipation while reducing the plastic energy dissipation. This reduction of plastic energy dissipation relates directly
to the reduction of damage in the structure. Dynamic analysis of space structures with multiple tuned mass dampers. Y.Q. Guo, W.Q. Chen (2008). Formulations of the reverberation matrix method (RMM) are presented for the dynamic analysis of space structures with multiple tuned mass dampers (MTMD). The theory of generalized inverse matrices is then employed to obtain the frequency response of structures with and without damping, enabling a uniform treatment at any frequency, including the resonant frequency. For transient responses, the Neumann series expansion technique as suggested in RMM is found to be confined to the prediction of accurate response at an early time.

The artificial damping technique is employed here to evaluate the medium and long time response of structures. Nicholas A. Alexander, Frank Schilder (2009). In this the performance of a nonlinear tuned mass damper (NTMD), which is modelled as a two degree of freedom system with a cubic nonlinearity has been covered. This nonlinearity is physically derived from a geometric configuration of two pairs of springs. The springs in one pair rotate as they extend, which results in a hardening spring stiffness. The other pair provides a linear stiffness term. In this paper an extensive numerical study of periodic responses of the NTMD using the numerical continuation software AUTO has been done. Two techniques have been employed for searching the optimal design parameters; optimization of periodic solutions and parameter sweeps. In this paper the writers have discovered a family of resonance curves for vanishing linear spring stiffness. Application of semi-active control strategies for seismic protection of buildings with MR dampers. Maryam Bitaraf et al (2010). Magneto-rheological (MR) dampers are semi-active devices that can be used to control the response of civil structures during seismic loads.
The second controller is developed using a genetic-based fuzzy control method. In particular, a fuzzy logic controller whose rule base determined by a multiobjective genetic algorithm is designed to determine the command voltage of MR dampers.

Vibration control of seismic structures using semi-active friction multiple tuned mass dampers. Chi-Chang Lin et al.(2010) There is no difference between a friction-type tuned mass damper and a dead mass added to the primary structure if static friction force inactivates the mass damper. To overcome this disadvantage, this paper proposes a novel semi-active friction-type multiple tuned mass damper (SAF-MTMD) for vibration control of seismic structures. Using variable friction mechanisms, the proposed SAF-MTMD system is able to keep all of its mass units activated in an earthquake with arbitrary intensity. A comparison with a system using passive friction-type multiple tuned mass dampers (PF-MTMDs) demonstrates that the SAF-MTMD effectively suppresses the seismic motion of a structural system, while substantially reducing the strokes of each mass unit, especially for a larger intensity earthquake.

2.3 Applications of semi active control to structures

The idea of incorporating variable stiffness/damping devices in structures is not new. These devices have been extensively researched for base isolation of structures and other structural control applications, particularly in the last decade. Dyke et al. (1996), Spencer et al. (1997, 1998) and Yang et al. (2002) have investigated MR dampers to control seismic response. Ehrgott and Masri (1992), Gavin et al. (1996a, b), Makris et al. (1996), Dyke et al. (1996) were studied the effectiveness of the ER dampers for seismic response control by proposing a clipped-optimal force control algorithm with acceleration feedback.
They obtained excellent results when this algorithm was applied to control a seismically excited three story scaled building model.

Several researchers have investigated the use of semi-active or controllable passive dampers for seismic response mitigation of base isolated structure with FPS (Feng and Shinozuka (1990); Nagarajaiah 1994; Makris 1997; Johnson et al. 1999; Kurata et al. 1999; Niwa et al. 1999; Symans and Constantinou 1999; Symans and Kelly 1999; Yoshida et al. 1999). Studies of smart base isolation have used several control design methodologies such as fuzzy control (Nagarajaiah 1994; Symans and Kelly 1999), sliding mode control (Yang et al. 1996), clipped-optimal control (Johnson et al. 1999; Spencer et al. 2000). The first full-scale implementation of smart base isolation was recently constructed at Keio Univ. (Yoshida et al. 1999). The main virtue of these semi-active controllable systems arises from the combination of the adaptable nature of a fully active control system with the stability characteristic of passive control systems, while maintaining low-power requirements.

Active and semi-active strategies may be able to provide the reduced base drifts without the increase in superstructure motion seen for passive devices (Spencer and Sain (1997)). A number of analytical studies have focused on the use of active control devices in parallel with a base-isolation system for limiting base drift (Kelly et al. (1987); Reinhorn et al. (1987; Nagarajaiah et al. (1993); Schmitendorf et al. (1994); Yoshida et al. (1994); Yang et al. (1996)). Additionally, Reinhorn and Riley (1994)) performed several small-scale experiments to verify the effectiveness of active strategies used in simulation studies. However, active control devices for base isolated structure with FPS have yet to be fully embraced by practicing engineers, in large part due to the challenges of large power
requirements that may be interrupted during an earthquake, concerns about stability and robustness, and so forth.

Dyke et al. (1996) proposed a clipped optimal controller for MR damper based on acceleration feedback, eliminating the need for a full state (velocity and displacement) feedback or velocity feedback, which are measurements difficult to obtain directly.

Ribakov and Gluck (1999) investigated the effectiveness of ER dampers in mitigating seismic response of frame structures. They used an optimal linear passive control strategy to determine the viscous constant of the ER damper and then use active control strategy to determine control forces. Through numerical simulation they found that ER dampers could reduce the peak displacement response of a seven-story frame structure up to sixty five per cent without increase in base shear forces and accelerations.

Xu et al. (2000) studied the force-displacement relationship of an MR damper or an ER damper based on a parallel-plate model and he extended his concept to include the stiffness of chevron brace supporting the smart damper. An extensive parameter study is performed in terms of the maximum yield shear stress and the Newtonian viscosity of the fluid, the brace stiffness, and the earthquake intensity. VSDDs are also studied for damping of stay cables in suspended bridges.

Varadarajan and Nagraraiah (2000) introduced the use of semiactive variable stiffness tuned mass damper to control the response of tall buildings excited by wind. The results indicate that semi active variable stiffness tuned mass damper is able to reduce the response similar to an active tuned mass damper. Yi et al. (2001) shown that the clipped
control algorithm was successfully applied and extended to multiple MR dampers. Yoshida et al. (2002) implemented the algorithm to reduce the coupled lateral and torsional response of asymmetric buildings when subjected to horizontal seismic excitations. Other works where the clipped optimal like algorithm technique used are those by Ramallo et al. (2002), Christenson and Emmons (2005), Johnson et al. (2007).

Utkin (1992) has shown that sliding mode controller (SMC) is a robust nonlinear control technique which restricts the state of a system to a sliding surface by switching the control structure on both sides of a stable hyperplane in the state space. Luo et al. (1999, 2000, 2003), Villamizar et al.(2003), Moon et al. (2003) shown the applications of SMC in structural control.


MR automotive driveline center bearing have been designed by Agarawal et al.(2002) to overcome the noise, vibration and harshness problem present in common bearings. Johnson et al. (2003) investigated the potential of improving the damping to the cables through the use of semi active damping devices. The response of the cables with a semi active damper is found to be reduced dramatically compared to the optimal passive linear viscous damper for typical damper configurations, thus demonstrating the efficacy of a semi active damper for absorbing cable-vibratory damage.

Neelakantant and Washington(2005) shown that MR fluid clutches have become an
alternative to conventional torque converters and hydraulic starting clutches which suffer from low efficiency, low robustness and uncertainties in the piston stroke. Yoo and Wereley (2002), Saito et al. (2006) prototyped and tested the MR fluid suspension seals and MR fluid valves. Perhaps the most important application of MR fluids is found in vibration suppression. Jolly et al. (1999), Ahn et al. (2005), Milecki and Sedziak (2005), Wang et al. (2006) have designed, prototyped and tested the different kinds of MR fluid dampers at different scale for different systems such as vehicles, industrial machinery, buildings, bridges, etc.

Back stepping approach was studied by Ikhouane et al. (1997), Villamizar et al. (2003), Villamizar (2005), Luo et al. (2006, 2007) and further developed by Zapateiro, Villamizar & Luo (2008) and Zapateiro, Karimi & Luo (2008).

Quantitative Feedback control technique was firstly introduced by Luo et al. (2004) for the vibration reduction in linear structures and was extended to structures equipped with MR dampers by Villamizar et al. (2004). A step further was done by Zapateiro, Luo and Karimi (2008) by proposing the inclusion of the hysteretic dynamics of MR dampers in the QFT control design and its feasibility was proved by numerical simulations and control. Yanget al. (2003, 2004), Narasimhan and Nagarajaiah (2006).

DAI et al. (2004) proposed semi-active control of a cable stayed bridge under multiple support excitations using LQG clipped optimal control algorithm. Lu et al. (2007) proposed stiffness controllable isolation system for near fault isolation of base isolated structure. They used a semi-active control device and showed that the base displacement and superstructure acceleration of an isolated structure can be reduced by using semi-active
control device.

Narasimhan and Nagarajaiah (2007) proposed a new semi-active independently variable damper SAIVD to control the base isolated structure. The proposed device consists of four linear visco-elastic elements and found to be adjusted smoothly in real time by varying the angle of viscoelastic element of the device. Karimi et al. (2008b) shown that mixed control have been applied to active and semi active structural control devices.

Major limitations of all the above algorithms are that they are all of bang-bang type and were implemented on simple idealized systems. Additionally, the rapid switching due to bang-bang control of semi active device increases the contribution from higher modes, increased inter-story drifts, and floor accelerations. Hence, there is a need for developing new controllers and devices with smooth switching. Also, controllers which reflect the time-frequency content of earthquake excitation need to be developed.

Neural networks have extensively been used in many fields of research due to their ability to model nonlinear systems. Neural networks can be trained to learn complicated relationships between sets of inputs and outputs. Zhang and Roschke (1998), Wang and Liao (2001), Du et al. (2006), Zapateiro and Luo (2007b) proved that neural network have the ability to learn complicated nonlinear systems and has been exploited to model MR dampers. An important advantage of neural networks is the relative ease to train them to learn the inverse dynamics of a damper, that is, a model that yields the output of a control signal that makes the damper to generate the desired damping force.
Fuzzy logic methodologies such as ANFIS (Adaptive Neuro-Fuzzy Inference System) have been used to model small- and large-scale MR dampers. The structure of an ANFIS model is similar to that of a neural network that is functionally equivalent to a fuzzy inference system. Schurter and Roschke (2000), Peschel and Roschke (2001), Atray and Roschke (2003), Oh et al. (2004) proposed a network type structure that can be used to map inputs through membership functions and associated parameters, and then through output membership functions and associated parameters to outputs.

Feasibility of fuzzy logic controllers to reduce the structure response has been studied by Casciatiet al. (1999), Choi et al. (2004), Dias (2005), Xu and Guo (2006), Gu and Oyadiji (2007). Applications of neuro fuzzy controllers can be found in Faravelli&Venini (1994), Li et al. (2002), Schurter and Roschke (2001).

2.4 Mathematical models of MR dampers

MR dampers are highly nonlinear devices. Their force-velocity relationship exhibits a hysteretic behavior modeling. Parametric models of MR dampers are built on the base of physical concepts. The Bingham, Bouc-Wen, Hyperbolic tangent and Dahl models have been adapted to recreate the MR damper dynamics as described below.

2.4.1 Bingham model

The Bingham model has long been used to characterize ER and MR dampers. Shames and Cozzarelli (1992) showed that this model is based on the Bingham plastic model which assumes that a body behaves as a solid until a minimum yield stress is exceeded and then exhibits a linear relationship between the stress and the rate of shear or deformation. Based
on this relationship, a model was proposed for ER dampers. This model, simply known as the Bingham model, consists of a Coulomb friction element placed in parallel with a viscous damper. Butz and von Stryk (2002), Zapateiro, Luo, Taylor and Dyke (2008) shown that the Bingham model does not reproduce the hysteretic behavior of ER and MR dampers. Instead it describes a one-to-one relationship that may not be suitable for control purposes.

2.4.2 The hysteresis model

Wen (1976), Sain et al.(1997) proved that the model of Bouc as modified by Wen is one of the mathematically simplest yet effective model that can represent a large class of hysteretic behavior. A phenomenological model based on the Bouc-Wen model was proposed by Spencer et al. (1997).

2.4.3 Dahl model

This essentially consists of a Coulomb friction element with a lag in the change of friction force when the direction of motion is changed. This mechanical model proposed for a shear-mode MR damper.

2.5 Concluding remark

The result of the relevant literature survey provides the state of current research in the area of active and semi active structural control and the motivation for new contributions in this area. It is seen that a comprehensive class of smart base isolated structures and new control algorithms are needed. These algorithms should incorporate better characterization of near-fault earthquakes in a stationary
sense for use with traditional optimal control designs, and time-frequency representation of the earthquakes in new non-traditional algorithms. In general, a conclusion that can be found in these works is that the speeds of execution of these algorithms are higher than that of model-based controllers. Another advantage of soft-computing techniques is that the inverse model of the damper is easier to obtain. Furthermore, these kind of controllers are robust, which is especially desirable in structural control applications characterized by uncertainties. Finally, the implementation of these controllers, particularly neural network controllers, is totally feasible because of the existence of high speed, low cost processors such as the digital signal processors.