A Review on Seismic Analysis of Buildings using Passive Energy Dissipating Devices

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Abstract – *Structures constructed in developing world are generally RC frames with masonry infill. These structures have very little resistance for lateral masses caused by earthquake and wind. Even for adequately designed structures conjointly, because of permissible deformation on the far side elastic limits, failure of masonry causes severe loss of life and property. Within the case of structures designed to sustain excessive deformation like of defence institutions, functioning and utility of machines and instrumentality put are adversely affected. This co-lateral harm is also reduced by adopting another style philosophy of structure response control. During this methodology, a supplementary damping device is incorporated within the primary structure, which absorbs most of the seismic energy imparted to that, proscribing the structural response inside serviceable limits. These devices is also passive, active, semi-active or hybrid sorts. Aside from passive all choices are measure technology-intensive and obsessed on external energy supply, not a favourable proposition for developing nations. This paper presents a summary of literature associated with the behaviour of passive energy dissipating devices on structures. The review includes different dampers like fluid viscous dampers, visco elastic dampers and friction dampers.*

Key Words: Passive dampers, fluid viscous dampers, viscoelastic dampers, friction dampers.

1. INTRODUCTION

Over the past few decades world has experienced several devastating earthquakes, leading to increased loss of human life due to collapse of buildings and severe structural damages. Prevalence of such damages throughout earthquakes clearly demonstrates the high seismic hazards and also the structures like residential buildings, lifeline structures, historical structures and industrial structures need to be designed very cautiously to guard from earthquakes. Structural design approach using seismic response control is currently widely accepted and often applied in civil engineering. In the recent years, attention has been paid to the study and development of structural control techniques like passive control system, active control system, and semi active control system giving special importance on improvement of seismic responses of building and also the bridges. Passive control systems don't need any power source. Active control systems need external power supply and operate based on sensors that are connected within the structures. Semi-active control systems are combination of both passive and active control systems that need external power supply and they operate based on sensors connected within the structures. However once there's no power source, passive control systems control the vibrations of structures. Both control systems are often used for robust earthquakes. Serious efforts are undertaken to develop the structural control concept into a workable technology and such devices are installed in structures.

2. LITERATURE REVIEW

Structural control systems increase the energy dissipation capability of structures during an earthquake by transforming mechanical energy into heat energy. Different forms of energy dissipation systems are given below:

2.1 Fluid Viscous Dampers

Constantinou, et.al. [1] conducted an experiment on models including 3-story steel structure and the bridge structure. The 3-story model was tested with and without FVD dampers installed as braces at an angle of about 35o .Tests were conducted with four dampers installed at the first story and with six dampers installed in pairs at each story. Testing of the bridge model was conducted with fifteen different isolated system configurations. Four fluid dampers similar to those used in 3-story building were added to the isolation system. Experimental results demonstrated that fluid dampers are very effective in reducing the seismic response of structures to which they were attached.

Mcnamara and Taylor [2] designed a 39-story office tower using conventional wind engineering methods of code loadings and deflection limitations and was model tested in a wind tunnel in Canada. An extensive design program was undertaken with various damper configurations vertically located in the tower and with many variations on fluid viscous damper parameters. Fluid viscous dampers in the E–W direction were diagonally placed in two bays at the inner core on every other floor between the seventh floor and the 34th floor, while TBD systems are assigned to bays along the N–S direction at the same level. The static lateral analysis and design were conducted using ETAB 6.2. The dynamic response and fluid viscous damper design of the TBD system was analyzed using SAP2000.Tuned mass dampers and sloshing dampers required valuable office space at the top of the building and proved to be very expensive, although very effective. Fluid viscous dampers proved to be the most cost-effective and least space-intrusive on the office tower.The tested performance of structures with fluid dampers showed that tremendous gains in performance could be realized at relatively low cost.

Kokil and Shrikhande [3] investigated optimal locations for a given number of fluid viscous dampers (FVDs) in a 3-D 10-storey model shear building, with or without eccentricities.General approach for finding optimal placement of supplemental dampers in structural systems with arbitrary degree of complexity in configuration was been proposed. A linear combination of maximum inter-storey drift and maximum base shear of the damped structure normalised by their respective undamped counterparts was taken as the objective function. The effect of soil-structure interaction on maximum response reduction and also on the optimal placement of dampers was studied for various degrees of soil compliance. It was found that the supplemental dampers were more effective in reducing the seismic response of a symmetric building and its effectiveness reduces as either plan irregularity, or soil compliance increases.

Lin and Chopra [4] investigated steady-forced and earthquake responses of SDF systems with a non-linear fluid viscous damper (FVD). A general approach for locating best placement of supplemental dampers in structural systems with capricious degree of complexity in configuration has been suggested. To seek the optimal location of dampers, a linear combination of maximum inter-storey drift and maximum base shear of the damped structure are normalised by relevant undamped elements has been taken as the objective function. For this purpose, comparative nonlinear time history analyses of single and multiple story chevron based frames (CBFs) with and without the VFDs are conducted using ground motions with numerous frequency characteristics scaled to represent minute, moderate and large intensity earthquakes.

Sorace and Terenzi [5] presented a research study on a damped bracing system incorporating pressurized silicone fluid viscous devices for seismic protection of frame structures. An inverse-chevron brace configuration, where a pair of interfaced devices were placed, parallel with the floor-beam axis, at the tip end of each couple of supporting steel braces. Experimental section of this study consisted of a pseudo dynamic testing campaign on a 2:3-scale three-story steel frame and a full-scale three-story reinforced concrete frame seismically retrofitted by the technology was considered. The effectiveness of the protection system was further compared with the numerical response of a traditional undamped bracing solution. This revealed that, although rather comparable interstory drift reductions were obtained, no benefits were offered by undamped braces in terms of story shear, as compared to the bare frame response. Also a remarkable constraint of costs was derived from mounting the protective system in the two bottom stories only, while an adequate enhancement of seismic performance was achieved.

Ras and Boumechra [6] conducted a 3D numerical investigation by considering the seismic response of a twelve-storey steel building moment frame with diagonal FVD that have linear force versus velocity behaviour. Nonlinear time history, which is being calculated by Fast nonlinear analysis (FNA), of Boumerdes earthquake (Algeria, May 2003) was considered for the analysis and carried out using the SAP2000 software and comparisons between unbraced, braced and damped structure was done. The results of the various systems were studied to compare the structural response with and without FVD were thus obtained. The conclusions showed that the formidable potential of the FVD to improve the dissipative capacities of the structure without increasing its rigidity. The results also showed that the use of the passive control device FVD in buildings generates a very significant reduction of the structural response compared to the unbraced ones.

Guo et.al. [7] designed procedure of seismic upgrading of existing buildings using FV dampers. Discussions were made on some key issues for seismic upgrading using FV dampers, including the analytical damper-brace model under large earthquakes and strategies for damper layout. Case study was made, in which a 21-story hotel built in 1991 was seismically upgraded. One special feature of this project was that only the first six stories can be structurally modified, resulting in limitations on the damper layout. According to the proposed design procedure, 56 FV dampers were suggested for this project, which provided a supplemental damping ratio of 5.3%. As a result, the seismic responses of upper stories could be significantly reduced, which avoids damaging the decoration of the building above its sixth story and enables short and economic construction.

Diclelia and Mehta [8] have carried out parametric study of steel chevron braced frame system equipped with and without viscoelastic damper when subjected under seismic load For this purpose, comparative nonlinear time history analyses of single and multiple story chevron based frames (CBFs) with and without VFDs are conducted using ground motions with numerous frequency characteristics scaled to represent minute, moderate and large intensity earthquakes. The analysis results revealed that the seismic performance of the CBFs without VFDs is very poor and sensitive to the frequency characteristics and intensity of the ground motion due to brace buckling effects. Installing VFDs into the CBFs significantly improved their seismic performance by maintaining their elastic behaviour. Furthermore, VFDs with smaller velocity exponents and larger damping ratio are observed to be more effective in improving the seismic performance of the CBFs. However, VFDs with damping ratios larger than 50% do not produce significant additional improvement in the seismic performance of the CBFs.

Miyamoto and Singh [9] evaluated the earthquake performance of passive energy dissipaters on one, five and eleven story, three bay steel moment frames. Dampers were added at each floor and the total damping of the structure was calibrated to be equal to 20% of critical damping for the first mode. Two types of analyses were implemented. Linear dynamic analyses were performed by using nonlinear viscous fluid dampers, and nonlinear dynamic analyses were performed by using 5% plastic hardening with linear dampers. As a result of linear response history analyses, the damped frames remained elastic and provided immediate occupancy performance for most of the earthquakes. Nonlinear response history analysis proved that the damped frame gives better performance than the bare frame and plastic hinging in a bare frame can be much higher than in the damped frame, especially when frames are subjected to severe ground motions. It was concluded that the damped frame can provide immediate occupancy performance and prevent collapses. As a drawback of supplemental dampers, higher base shear was found in the damped frame than the bare frame.

Wang and Mahin [10] examined the feasibility and cost-effectiveness of various retrofit techniques to improve the seismic performance of an existing 35-story steel building. Three types of supplemental energy dissipation devices were used in conjunction with basic retrofit measures to achieve the collapse prevention performance objective of current standards. Devices considered were fluid viscous dampers (FVDs), viscous wall dampers, and buckling restrained braces. The placement of the devices was kept the same in all three cases, considering the overall architectural, programmatic, and constructability issues. The mechanical characteristics of the devices were selected using a simplified approach to achieve the same overall effective damping ratios and story drifts consistent with the targeted collapse prevention performance objective. The results of nonlinear dynamic analyses indicated that the FVD scheme was the most efficient for this structure in achieving the targeted performance goal and provided the most cost-effective means of improving the structural behaviour and reducing economic losses for Level 2 basic safety earthquake hazard events. Future research needs related to the use of supplemental energy dissipation devices in existing buildings are also discussed.

Constantinou and Symans [11] presented the results of an experimental study of the seismic response of buildings with supplemental fluid damping devices. The experimental results demonstrate that the addition of fluid dampers to the tested steel model structure resulted in reductions of interstory drifts, floor accelerations and story shear forces by factors of two to three in comparison with the response of the same structure without the dampers. The mechanical characteristics of the dampers have been determined using a testing arrangement in which a hydraulic actuator applied a dynamic force along the axis of the damper. A series of tests was performed on a model structure. The structure was a three-story 1:4 scale steel frame which modelled a shear building by the method of artificial mass simulation. For the one-story structure, the dampers were placed at the first story and consisted of either two or four damping units. For the three-story structure, the dampers were placed at the first story for the two and four damper cases and at all three stories for the six damper cases. A total of 66 earthquake simulation tests were performed on the model structure. The experimental results demonstrate that the addition of fluid dampers to the tested steel model structure resulted in reductions of interstory drifts, floor accelerations and story shear forces by factors of two to three in comparison with the response of the same structure without the dampers.

2.2 Friction Dampers

Baratia, et.al. [12] studied the seismic behavior of the existing buildings equipped by friction dampers. Seismic performance of 6- story, 9-story and 12-story steel buildings with damper and without damper were studied. The finite element modelling technique (SAP2000 Software) was used for analysis. Time History analysing was done to achieve this purpose. For nonlinear dynamic analysis, the responses of the structures to three earthquake records (Tabas, Naghan, and artificial waveform) were obtained. A series of analyses were made to determine the optimum slip load of the friction dampers to achieve minimum response. Also, in order to evaluate the performance of the friction dampers in asymmetric structures, an asymmetric structure was utilized. The obtained results show significant improvement of seismic behavior and efficiency of the friction damper for seismic retrofitting to these buildings.

Chandra et.al. [13] adopted a novel structural system of friction-damped frames for construction of eighteen-storey apartment building. La Gardenia housing complex in New Delhi consisting of 7 towers of eighteen storeys with two levels of basements was considered. Pall friction-dampers were provided in steel bracing in concrete frames. Friction-damped bracing were located in partitions, around staircases or elevator shaft. A total of sixty six friction-dampers of 700 kN slip load capacity were used. Three-dimensional nonlinear time-history dynamic analyses were performed using software program ETABS. Three time-history records of the first 20 seconds, which covers the peak ground accelerations suitable for the region, were used. Viscous damping of 5% of critical was assumed within the initial elastic stage to account for the presence of non-structural components. P-Δ effect was taken into account.

Pall and Marsh [14] proposed a new concept of aseismic design for steel framed buildings by providing sliding friction devices in the bracing system of the framed buildings. To demonstrate the influence of the friction device on the seismic response, and to compare the results with alternate structural systems, three 10 story frames, were chosen for analysis. Frames considered for the analysis were Moment resisting (MR) frame, braced moment resisting (BMR) frame and friction damped braced (FDB) frame. Inelastic time-history dynamic analysis was performed using computer program "Drain-2D," established at the University of California. The earthquake record of El Centro 1940 (N.S.

component) was used for the analysis. The results shown the superior performance of the friction damped braced steel frames when compared to compute responses of other structural framing systems and the use of inexpensive friction damper in the bracings of the steel framed buildings can significantly enhance their earthquake resistance. Results of inelastic time history dynamic analysis show the proposed friction devices act, in effect, both as safety valves and structural dampers.

Shao et.al. [15] describes the use of cross-brace friction dampers for the seismic upgrade in the 36-foot tall soft-story which is a 1970's concrete shear wall building located in the greater Seattle. The first two stories consist of a relatively rigid concrete podium. The two stories above the podium contain concrete columns that support concrete shear walls in the stories above. Thus, the two stories above the podium are soft stories and were deemed seismically vulnerable for the design seismic event (10% /50 year). Retrofit of these stories involved long bracing and thus tension-only cross-braces were used wherein friction dampers were located at the brace intersection. Two 890-kN capacity cross-brace friction dampers were installed within 12 perimeter bays of the soft stories for a total of 24 friction dampers. Two prototype dampers were designed, built, and tested by Pall Dynamics Inc. to ensure their performance. The damper installation was completed in 2005. It was seen that dampers added structural integrity and improved building life safety and helped minimize post-earthquake structural and non-structural damage which reduced potential down time and repair costs after a seismic event.

Borislav and Mualla [16] have investigated the performance of a novel friction damper device (FDD) installed in a single storey steel frame subjected to seismic loading. FDD makes use of material that provides very stable performance over many cycles, resists adhesive wear well and does not damage the steel plate surfaces, thus allowing multiple use. Tests were planned to establish the FDD performance beneath sensible condition before introducing it to be used in buildings. Testing was applied for assessing the friction pad material, damper unit performance and scaled model frame response to lateral harmonic excitation. Experimental and numerical results show that the friction damper will improve the dynamic response of innovative structures as well as the existing building compared to the conventional design.

Tabeshpour and Ebrahimian [17] presented a conceptual view on retrofit design on existing buildings using an innovative friction damper (proposed by Mualla IH). A simple design procedure is used in seismic design of friction dampers based on the structural desired performance. As an example a 3-story steel structure that its strength and stiffness is not sufficient for desired performance is considered. The simple performance based method presented in FEMA is used to determine the slip load and bracing stiffness. The structure is modeled using the finite element program Sap2000 and is analysed using both non-linear static pushover analysis and non-linear time history analysis. It was seen that supplemental damping in conjunction with appropriate stiffness offered an innovative and attractive solution for the seismic rehabilitation of such structures.

Aiken et.al. [18] presented an overview of seven different passive energy dissipation systems that were studied in experimental research programs at the Earthquake Engineering Research Center of the University of California at Berkeley, describing the different types of devices, the results of the shake table experiments, and associated analytical work. Four of the systems studied were friction systems, and of these, three (Sumitomo, Pall, and Friction-Slip) were based on Coulomb friction. The fourth is the Fluor-Daniel Energy Dissipating Restraint, a device capable of providing self centering friction resistance thats proportional to displacement. The three completely different systems have different energy dissipation mechanisms: ADAS parts, that use the yielding of mild steel X-plates; viscoelastic shear dampers using 3M acrylic polymer as the dissipative element; and Nickel-Titanium alloy from memory devices. The effectiveness of the various systems is evaluated by comparing the response of the test structures without and with the energy dissipators. All of the systems exhibited characteristics valuable to improve structural response to earthquake loading.

2.3 Visco Elastic Dampers

Tezcan et.al. [19] presented analytical studies of the model structures exhibiting the structural response reduction due to these viscoelastic devices this paper is focused on the viscoelastic dampers to be used as energy-absorbing devices in buildings. The viscoelastic dampers have been modelled by the NLPROP and NLLINK data blocks of the SAP2000 program. Their advantages and disadvantages as well as their application on three model structures have been described. In order to exhibit the benefits of viscoelastic dampers, a nonlinear time history analysis was carried out for all case studies: (a) a 7-storey steel frame, (b) a 10-storey reinforced concrete frame, and (c) a 20-storey reinforced concrete frame. The top storey relative displacements, absolute accelerations and additionally the bottom shear values that were obtained indicated that these viscoelastic dampers once incorporated into the super-structure behave like a brake pedal and reduce the earthquake response considerably in proportion to the extent of damping supplied in these devices.

Min et.al. [20] performed a design process for viscoelastic dampers and experimental test results of a 5-storey single bay steel structure with added viscoelastic dampers. The mechanical properties of viscoelastic dampers and the dynamic characteristics of the model structure were obtained from experiments using harmonic excitation, and the results were used in the design process. The additional damping ratios needed to decrease the maximum response of the structure to a desired level were achieved first. Then the size of dampers to realize the required damping ratio was determined using the modal strain energy method by observing the change in modal damping ratio due to the change in damper stiffness. The designed viscoelastic dampers were put in within the first and the second stories of the model structure. The results from experiments using harmonic and band limited random noise indicated that after the dampers were installed the dynamic response of the full scale model structure reduced as desired in the design process.

Li and Reinhorn, [21] carried out an experimental investigation of different damping devices individually to allow for physical and mathematical modelling of their behaviour. Several different damping devices were used in this study: viscoelastic, fluid viscous, friction (of two types) and fluid viscous walls. Shaking table tests of a 1:3 scale RC frame structure with friction damping braces installed in the mid-bay of the frame with different configurations were conducted. The inelastic behaviour of the structure retrofitted using friction dampers incorporated in braces was investigated. The analytical modelling of friction damping devices was presented and models were implemented in IDARC2D, ver. 4.0. The experimental and analytical study showed that the dampers can reduce inelastic deformation demands.

Marko et.al. [22] investigated the mitigation of the seismic response of 18-storey and 12- storey frame-shear wall structures with embedded dampers. Three damping mechanisms were used, viz, displacement-dependant friction dampers, velocity-dependant VE dampers and hybrid system which was a combination of friction and VE dampers. Six different damping systems, arising from these three damping mechanisms in different configurations were studied. These were, friction and VE diagonal dampers, friction and VE chevron brace dampers, hybrid friction-VE dampers and VE lower toggle dampers. The damping systems were embedded in six different locations (one at a time) within cut-outs of the shear wall in the structure. Damper properties such as stiffness, damping coefficient, location, configuration and size were varied to obtain tip deflections and accelerations from time history analyses under five different earthquake records. It was seen that the dampers embedded into the cut-outs of shear walls significantly reduced the tip deflection and acceleration throughout the duration of the earthquakes. The performance of the friction dampers increased with higher inter storey drift, while the best performance of VE dampers was achieved when placed in the lowest storeys. The performance of the diagonal VE dampers was noticeably less sensitive to this aspect. It was seen that friction dampers are most effective when placed close to regions of the maximum inter storey drift, whereas VE dampers are most effective when placed in the lowest storeys.

Pong et.al. [23] developed a finite element formulation for fluid dampers for study of two different devices, a combination of tapered plate energy absorber (TPEA) and viscoelastic dampers and a combination of TPEA and fluid dampers. A comparison is made between numerical solutions and experimental results when a 2/5 scale steel structure is equipped with added viscoelastic dampers. The structural response of high-rise buildings mounted with three energy-absorbing devices, tapered-plate energy absorber (TPEA), viscoelastic dampers, fluid dampers, and two combined devices, TPEA and fluid dampers and TPEA and viscoelastic dampers, respectively, have been investigated. A parametric study of TPEA devices for high-rise buildings is conducted. The selected response parameters in this study included story shear force, floor displacement; base shear force and ductility ratio. Results show such combined devices provide a strong safe-failure mechanism as reliable energy absorbing devices. They also can sustain a wide range of loadings from minor to severe earthquake ground motion and wind loads. The combined devices can compensate for each other's shortcomings so that a satisfactory design for wind loads and seismic hazard mitigation of the structures can be achieved.

Vijay et.al. [24] carried out parametric study on the proposed Hospital building located at Delhi using VE dampers. The building is chosen such that it is a life line structure and located in a highly seismic prone zone. Finite element analysis was employed using the program ETABS version 9.7.2. A comparative study on the lateral load resisting behaviour between bare and damped structures has been studied analytically. The brace type damping mechanism has been modelled as a linear spring and dash-pot in parallel for the Visco Elastic damper. The earthquake events used in this study has been applied as response spectrum acceleration. The efficiency of the dampers was studied by varying the damper locations in plan according to the aesthetic and functional requirements. Single unit of damper is positioned at different location in plan and structural model is analysed for each case to find the maximum damping ratio. It was found that damper is effective when it is placed at the periphery of building with uniformity in both 'X' and 'Y' direction reducing the distance between the centre of mass and stiffness of floor plan by taking into account of the torsional rigidity. The investigations showed that significant increase in damping ratio of structure can be achieved by strategically placing the dampers.

Zhang et.al. [25] studied the feasibility of using viscoelastic dampers to mitigate earthquake-induced structural response. A procedure for evaluating the VE damping effect when added to a structure is proposed in which the damping effect of VE dampers is incorporated into modal damping ratios through an energy approach The developed procedure is used to estimate the damping effect of 20 VE dampers applied to a 10-storey steel frame structure. Two VE dampers are added to the main diagonals of each storey. It was observed that, by adding 20 VE dampers to the structure, its response level at each floor is reduced significantly, there being at least a 50 per cent reduction in all cases. The damped structural response also has more uniform and smaller relative storey displacement than the original and stiffened structures. It was seen that the structure's increase in stiffness, which is contributed by the VE dampers, does not help in improving the structure's seismic performance.

Aiken and Kelly [26] carried out experimentally and analytical study on the use of two different types of energy-absorbing devices viz, viscoelastic shear damper and friction device. A nine-story, moment-resisting steel frame represented the basic structure of the study. The structure was tested with both types of energy absorbers installed and also in moment-resisting and concentrically-braced configurations. Analytical methods suitable for predicting the response of the two damped structures were studied. The viscoelastic material used in the test program belonged to a class of acrylic copolymers that have been developed by the Minnesota Mining and Manufacturing (3M) Company. Sumitomo friction damper was used for test. A total of 72 channels was used for the tests of the FD and VD model as well. The damped structures were found to have base shears the same as the moment-resisting frame whereas reducing drifts to the extent of these of the concentrically-braced frame. It was found that a linear analysis incorporating damping on a modal basis produced very good results for the visco elastically damped system. Furthermore, the use of linear elastic response spectra with high values of damping gave good results for story shears and displacements.

3. CONCLUSION

Recently, use of seismic control systems has increased, however selecting best damper and inserting it in building is significant for reducing vibration in structures once subjected to the loading due to earthquake forces. The controlling devices decrease damage considerably by increasing the structural safety, serviceability and avoid the building from total collapse during the earthquake. Thus several researches are being carried out to search the simplest solution. This paper makes an attempt to provide a summary of various varities of seismic response control devices, and highlights a number of the recent developments. The experimental investigations and also analytical investigations applied by varied researchers clearly demonstrate that the seismic control techniques has the potential for enhancing the seismic performance of the structures.

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