Magneto-Rheological Dampers for Seismic Mitigation of Building Structures

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Abstract

Building structures generally contain inherent low damping capability and hence are vulnerable to seismic excitations. Control devices are therefore playing a useful role to provide safety to building structures subject to seismic events. In recent years semi-active dampers have gained considerable attention as a structural control device in the building construction industry. Magneto-rheological (MR) dampers, a type of semi-active damper, have proven to be quite effective in seismic mitigation of building structures. MR dampers contain a controllable MR fluid whose rheological properties vary rapidly with the applied magnetic field. Although some research has been carried out on the use of MR dampers in building structures, proper design guidelines have not been established for consideration by practicing engineers. This paper intends to generate new code requirements for incorporating MR dampers in building structures in order to obtain seismic performance that will satisfy current design codes and standards. The MR damper model was developed integrating control algorithms commonly used in MR damper modelling. Variation characteristics of the developed MR damper are computed according to a seismically excited structure as a time domain function. Building structure models, with different heights, will be evaluated in real time scenarios to identify the influence of MR damper properties and locations on their seismic performance. Those parameters which contribute towards acceptable structure performance will be evaluated to formulate new design rules. Finally, the performance of building structures retrofitted with MR Dampers having the desirable properties identified above, will be compared with the performance of the same structures designed based on current design guidance.

Keywords: Earthquake engineering, Energy dissipation, MR damper, design guidelines

1 Introduction

Earthquakes generate seismic waves that can lead to the destruction of manmade structures with catastrophic outcomes. Since 1900, an average of 18 major earthquakes (magnitude 7.0-7.9) and one larger earthquake (magnitude 8.0 or more) have occurred annually [1]. While this average has been relatively stable, long-term prediction of earthquakes is difficult making it critical to construct buildings to withstand credible seismic excitations.

The dynamics of a high rise building greatly depends on its stiffness, mass, shape and damping. While current engineering knowledge can predict the first three scenarios to a greater extent, damping of a building is yet to be adequately quantified and researched [2].

Cited as the two main damping sources, inherent and supplemental damping, dissipate the potentially destructive energy of a building during a seismic activity. Damping due to the structure itself such as from its building materials, cladding and the foundation is known as inherent damping, which is unsure and difficult to predict in most of situations. But supplemental damping is more reliable and its influence could be predicted to a higher level of accuracy. New design codes and guidelines [3] [4] [5] [6] encourage the use of energy dissipation devices to mitigate earthquake effects. Desired structure performance, regardless of changes in structural dynamic properties and the ability to mitigate a structure's response through multi-modes, instead of just the fundamental mode, are some of advantages that could be achieved through supplemental damping.

Base isolation, passive energy dissipation, active energy dissipation and semi-active control strategies are popular supplemental energy dissipation methods used in current practice. Base isolation is expensive and needs to be considered at the design stage. Passive devices have limited capacity while active devices require a power supply which might not be available at all times, especially during a seismic event. The Magneto-Rheological (MR) damper, a specific semi-active device has gained significance due to its high damping capacity, reduced power requirements, mechanical simplicity and greater performance index [7].

2 Designs with MR dampers

2.1 Design procedure

This paper will adopt the evaluation criteria used for Fluid Viscous Dampers (FVDs) in the current codes (mentioned above) to assess buildings fitted with magneto rheological dampers (MRDs) with some modifications as the MRD contains controllable MR fluid.

The codes and guidelines recommend performing a design review for buildings incorporating energy dissipation devices. According to ASCE 41-06 [6], the following procedure is to be adopted:

i. Carry out a preliminary design of the building and sizing of the damping devices

ii. Conduct prototype testing of the damping devices according to code recommendations
iii. Carry out the final design of the building and perform seismic analysis with the damping devices in place. Check for satisfactory performance. If not return to step i.
iv. Develop a quality control program for the energy dissipation device to evaluate its performance over time and its required maintenance.

To achieve a better design, thorough coordination between the MR damper developer and the engineering panel is vital. The engineer reviewing the adoption of the MR damper for the seismic mitigation of a building should be experienced in seismic analysis, and the theory and application of energy dissipation methods. This paper aims to make this coordination easier for structural engineers and hence provide an effective outcome of the design of the MR damper system.

2.2 MR damper behaviour

This research focuses on semi-actively controlled MR dampers which consist of actuators, sensors, control units, and signal processing units. Combining favourable features of both active and passive control systems, these control devices have properties which do not input energy into the system that is being controlled. The power supply can change the magnitude of the damper force by changing the intensity of the magnetic field which depends on the earthquake strength. Figure 1 shows a schematic diagram of a building – MR damper system. It shows the closed loop control of the MR damper system once integrated within the seismically excited building. The damper controller identifies the damping force according to the current generated due to the earthquake. Then the system controller monitors the damped structure and direct current driver to generate the required damper force. This loop will continue until the structure stills within a very short time.

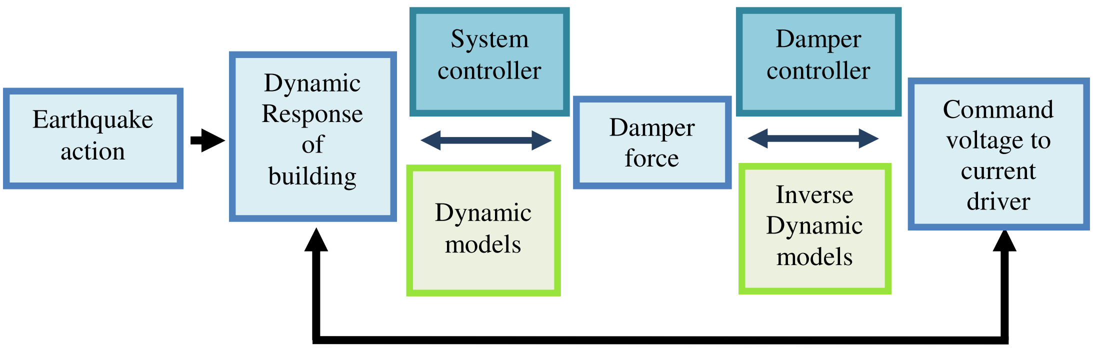

Figure 1: Schematic diagram of MR

Clipped optimal control proposed by Dyke [10] is used as the control algorithm. The following architecture [8] is used to define the MR damper control system,

i. The control voltage to the i^{th} device (V_i) is restricted to the range $V_i = [0, V_{max}]$
ii. For a fixed set of status, the magnitude of the applied force increases when V_i increases, and decreases when V_i decreases.

The aim is to design a linear optimal controller K_c which calculates a vector of desired control forces, $f_c = [f_{c1}\ f_{c2} \dots\dots\dots f_{cn}]^T$ based on the measured structural response $\boldsymbol{Y}$ and the measured control force vector $\boldsymbol{f_d}$ applied to the structure.

$$f_c = L^{-1}\left\{-K_c L \begin{Bmatrix} Y \\ f_d \end{Bmatrix}\right\} \tag{1}$$

where, $L\{.\}$ is the Laplace transform.
The algorithm for selecting the command signal for the i^{th} value of the MR damper can be written as:

$$V_i = V_{max} H((f_c - f_i) f_i) \tag{2}$$

V_{max} = maximum voltage applied to the current driver (with saturation of the magnetic field)
f_c = desired optimal force
f_i = force produced by the i^{th} MR damper
H = Heaviside step function

Simulations were conducted for a three storey lumped mass structure with integrated MR damper as shown in figure 2. The North-South (NS) component recorded at the Imperial Valley Irrigation District substation in the El-Centro earthquake [9] was used as the input.

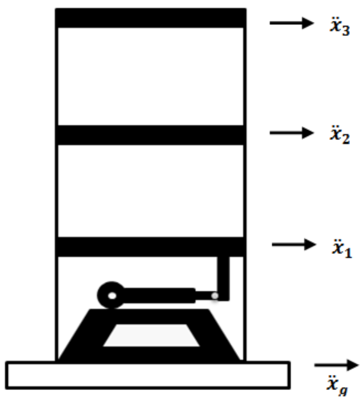

Figure 2: Building with mounted MR damper

Simulation results were compared with results obtained by Dyke [10] in Table 1 and Table 2. Table 1 corresponds to the uncontrolled structure while Table 2 shows results

for the structure controlled with the MR damper using a clipped optimal control algorithm. Results agree well with each other.
Displacement-Time records of the three floors for clipped optimal algorithm is shown in Figure 3.

		First floor	Second floor	Third floor
Peak Displacement (cm)	Experiment	0.538	0.820	0.962
	Simulation	0.545	0.828	0.968
Peak Acceleration (ms^{-2})	Experiment	8.56	10.3	14.0
	Simulation	9.09	10.20	12.9

Table 1: Peak response comparison – Uncontrolled

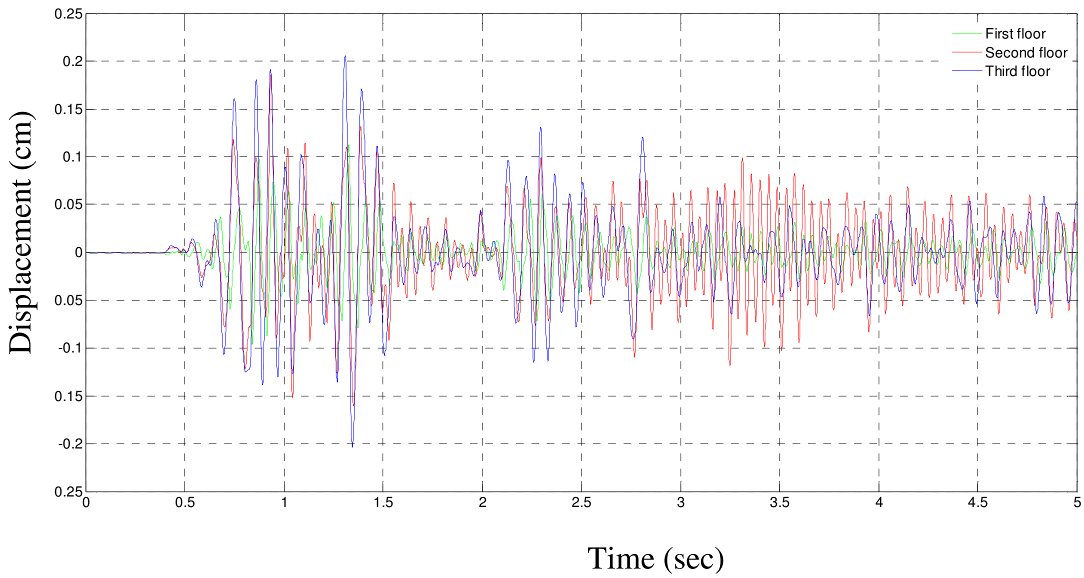

Figure 3: Floor displacement of MR damper controlled structure for Clipped optimal control

		First floor	Second floor	Third floor
Peak Displacement (cm)	Experiment	0.114	0.185	0.212
	Simulation	0.113	0.186	0.206

Table 2: Peak response comparison – Clipped optimal control

Based on the above validation it can be concluded that clipped optimal control algorithm was successfully employed in the MR damper. This verifies the capability of the developed modelling technique to capture the MR damper behaviour.

3. Methodology

The development of the procedure for the use of MR dampers in the seismic mitigation of buildings will be enacted according to the following steps:

i. Establish performance criteria of the building
ii. Establish the response spectra for the Design Based Earthquake (DBE) and Maximum Considered Earthquake (MCE)
iii. Use conventional methods to design and analyze the building
iv. Identify damping requirements
v. Proceed to find optimal parameters for buildings performance when fitted with the designed MR damper.

Performance criteria include tip deflection, tip acceleration and inter story drift ratio considering both the DBE and MCE. Since a MR damper has relatively improved characteristics, it can accommodate higher performance values. Establishing response spectra might require site specific response spectra to be determined and hence the assistance of a geotechnical engineer. A structure must be designed to remain in the elastic region when the damper is added. Number of dampers, damper size and damper location are considered in the optimal seismic design of the building

Modelling of the building structure fitted with the damper can commence after its performance criteria are established. Thus far, MR damper behaviour has not been introduced to commonly used design software packages. Therefore the numerical software package, MATLAB [11], with Simulink dynamic simulator [12] has been used to conduct the modelling. A schematic diagram of the simulation process is shown in Figure 4. This platform facilitates real time speed simulation capability with desired varying damping force and ability to design the control algorithm for the damping controller.

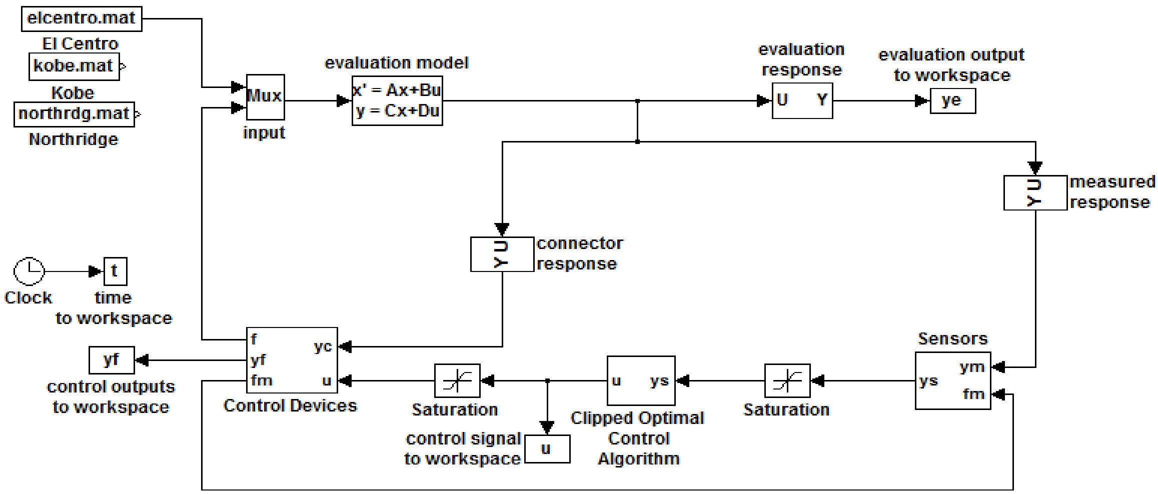

Figure 4: Simulink model for structural simulation with MR damper

4. Model Development

A FE model of a 2D frame with 6 bays in an 18 storey steel structure is used for the study. Bays are at 6m centres. Each storey is 4m high, which makes the total height of the structure 72m. Moment resisting frames provide the lateral load resistance. Columns are of 350 MPa steel having 0.4m x 0.4m cross-section. W30x99 sections of 250MPa steel wide flange beams are used in the model. The seismic mass of each floor(expressed as a weight force) is $5x10^6$ kN and for the whole structure $9x10^6$kN. This includes the mass of the steel frame, floor slabs, partitions, ceiling, mechanical and electrical services and the roof.

MR dampers are used as the control devices. The Chevron Brace configuration, where the damper is horizontally attached between two consecutive floors of the buildings is employed to place the damper on the floors.

Three earthquake excitations have been considered for the analysis:

(i) El Centro - The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May, 18, 1940.

(ii) Northridge. The N-S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994.

(iii) Kobe. The N-S component recorded at the Kobe Japanese Meteorological Agency (JMA) station during the Hyogo-ken Nanbu earthquake of January 17, 1995

Defining the location and size of the control devices is critical for obtaining the maximum output of the system. Simulations are currently being carried out to determine the response of the structure fitted with the MR damper. Results will be presented in the conference. Optimization techniques are also being critically reviewed at the time of writing this paper. The most suitable optimization procedure will be selected to be linked with the simulation procedure to yield the desired response of the structure and hence the corresponding size and locations of the MR dampers. Work is in progress and the results will be presented in the conference.

5. Conclusions

Integration of MR dampers in buildings for seismic mitigation has several advantages over other supplemental dampers. Although it has been a considerable time since MR dampers have been introduced to the building industry, many limitations exist in the context of design and analysis of buildings with MR dampers. Structural engineers lack confidence in incorporating MR dampers into buildings because of inadequate practical information currently available. To fulfil this need, the authors first developed an MR damper model for seismic mitigation of building structures and validated its performance using existing results. For a given building structure under a known credible seismic record, this model can be used to identify the required parameters in terms of damper location and size for obtaining the required seismic mitigation. This exercise using simulations will be repeated with different building structures to formulate generic design guidance. The outcome of this research will go a long way towards eliminating existing issues that practicing engineers face in the design of buildings with MR dampers.

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