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A Review on the Magnetorheological Fluid, Damper and Its Applications for Seismic Mitigation

Daniel C [a*], Hemalatha G [a], S. Vincent Sam Jebadurai [a], Sarala L [a], Tensing D [a], S. S. Judith Emiliah Christy [b]

[a] *Department of Civil Engineering, Karunya Institute of Technology and Sciences, Karunya nager, Coimbatore, India.*

[b] *Internal Quality Assessment Cell, Karunya Institute of Technology and Sciences, Karunya nager, Coimbatore, India.*

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Abstract

Magnetorheological (MR) fluids and dampers have wide advances as smart materials because of its unique properties, notably, viscosity increases in the presence when magnetic field applied MR Fluids composed of three key components, including carrier fluid, surfactants and metal particles. The major applications of MR Fluids are in brakes, dampers, journal bearings, fluid clutches, pneumatic artificial muscles, aerospace etc. where electrical energy is converted to mechanical energy (Damping Force) in a controlled manner. Within a few milliseconds the fluid converts from liquid to semi solid state. Over the years, researchers were concerned on the ways to enhance the modelling precision. Though the proposed Dynamic models of MR Dampers represent displacement and force behaviour. In this review paper, the advances of MR Fluids, MR Damper, Damper Models, Energy harvesting and their applications for seismic resistance of structures are briefly discussed in the present study.

Keywords: MR Damper; MR Fluid; Seismic; Energy Harvesting Device.

1. Introduction

MR Fluid consists of magnetic iron particles and carrier oil. Under a magnetic field the rheological characteristics of the MR fluid can be changed rapidly in a controlled fashion [1]. MR fluid has enormous applications in aerospace, automobile industry, biotechnology, medical and seismic because which can exhibit changes in apparent viscosity (shear rates 0.1 to 1 Pa-s) for applied various magnetic flux densities of 1 T. Normally the magnetic particles size used in MR fluid possess dia in μ-meter. μ-meter varies according to different manufacturing process. Leading Manufacturer for MR fluids in the world is Lords Corporation. Typical MR fluid Key features are shown in the below table 1. Viscosity of the Magnetorheological fluid depends on magnitude and direction of the applied magnetic field and also shear rate. Apparent viscosity and other rheological characteristics of MRFs can be controlled by manipulating intensity of the applied magnetic field. In most applications of magnetorheological fluids, response time of MRFs has the greatest importance. This time varies in the range of 10-20 milliseconds depending on magnetic circuit design. Therefore, MRFs are one of the fastest electromechanical interfaces for mechanical applications. A magnetorheological fluid based on its composition and flux density is able to demonstrate dynamic yield stress up to 100 kPa [2-4].

* Corresponding author: danielckarunya@gmail.com

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Table 1. MRF Key Features [5]

Representative feature	Typical MR fluid
Maximum yield stress	50-100kPa
Power supply	2-24 V at 1-2 A
Response time	Few ms
Operational field	Up to 248 kA/m
Energy density	0.1 J/cm^3
Stability	Useful for contamination
Operational temperature	- 40C up to +148 C

2. Composition of MR Fluid

The composition of MR fluid consists of 3 parts namely carrier liquid, magnetic particles and surfactants [6]. Some of the magnetic particles used are Co, Fe3, Fe3O4, Fe Ni etc... Among these Co – Fe alloy has more magnetic permeability and saturation (µ0Ms = 2.4 T). However, in the present scenario, CI with 0.1~ 100 **µ**m diameter was used as smart materials in MR fluid due to its high magnetic saturation value (µ0Ms = 2.1 T) [7]. To have a Brownian motion of iron particles selection of carrier liquid is important for MR fluid. Silicone oil, synthetic oil, mineral oil, polyethers, water, polyesters are the typical carrier liquid. The characteristics of carrier liquid should have appropriate viscosity which means when the magnetic field is zero should have less viscosity therefore lesser viscosity gives better characteristics of carrier oil. As the viscosity reduced the sedimentation become worst. Low cooling point and high temperature point confirms the MR fluid has extensive working temperature of various operating range. Surfactants includes dispersant and anti-sedimentation agent. Sedimentation stability, zero viscosity, reduce wear, dispersion and yield strength of MR fluid is the main function of surfactants. Oligomer containing hydrogen, organoclay, ultrafine amorphous silica, organo metallic silicon copolymer, hydrophilic silicone oligomer and high polymer are the anti-sedimentation agent. Oleic acid, oleic acid salt, sulfonate, stearic, alcohols, naphthenate, phosphate, glycerol monooleate and silica are the dispersant [8].

2.1. Characteristics of MR Fluid

When a magnetic field applied in an orderly movement to micro or Nano size iron particles are magnetized. These iron particles change its orientation to have a structure like chain formation when a magnetic field is applied. This is depicted in figure 1. The magnetic particles are normally rigid sphere in structure [9].

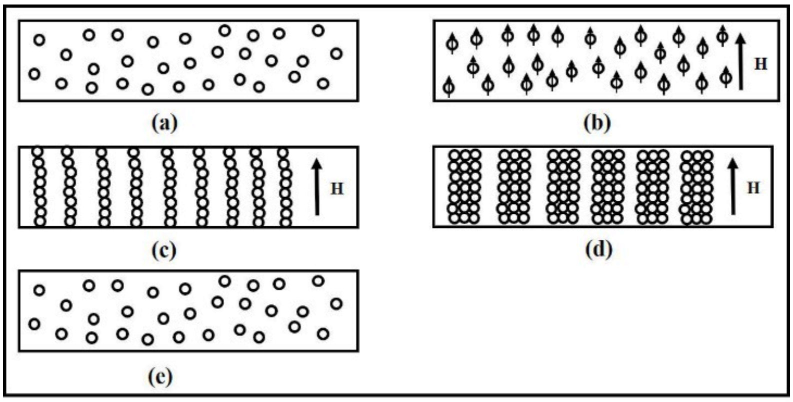

Figure 1. Characteristics of MR Fluid

Figure 1a indicates iron particles dispersed under Brownian motion in a carrier liquid at zero magnetic field. Figure 1b indicates iron particles magnetized and form dipoles under magnetic field. Figure 1c indicates iron particles connecting chain under average magnetic field and viscosity increases. Figure 1d indicates increased in number of chains, apparent viscosity, diameter of chain thickened, and yield stress continues to increase. Figure 1e indicates state of irregular dispersion and recover quickly to its original state under the absence of magnetic field.

2.2. Modes of MR fluid

Depends on the working of MR fluid, they are classified into 3 basic modes such as shear, valve and squeeze modes. Each mode is depicted in Figure 2. In the shear mode, the MR fluid is made to flow between two parallel proportionally moving plates. The shear mode possess application in structural composites, breakaway devices, dampers, locking devices, clutches and brakes. In the valve mode, the MR fluid flows due to the pressure gradient arises in between two immobile plates. Its potential applications are in actuators, shock absorbers, dampers, servo valves and hydraulic controls. [10]. In the squeeze mode, the MR fluid is made to flow between two plates that are perpendicular to each other and in mobile state. This is applied in impact dampers and low amplitude vibration but more dynamic forces [11-15].

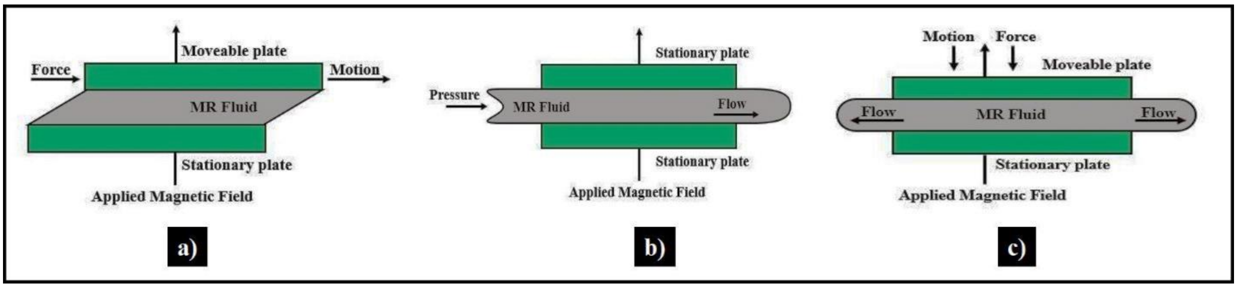

Figure 2. Three MR Fluid modes: a) Shear mode, b) Valve mode, and c) squeeze mode [15]

3. Components of MR Damper

The basic components of MR Damper involve a control valve and cylinder. Additionally, with the help of electromagnets, magnetic field can be achieved which is used to produce damping in the control valve. The cylinder contains the MR fluid with the piston attached to it were used to the movement.

3.1. Monotube Dampers

Monotube damper has simple mechanical structure for fabrication. It is also called as single end piston damper, which has divided into two reservoirs are tension and compression chamber by the piston motion. During this motion in the piston, MR Fluid flow through the control valve which change its viscosity, pressure difference and produce damping force to the controlled magnetic field [16]. Accumulator is used to change in the volume of MR Fluid using piston motion. The presence of gas chamber has a spring like effect which gives the force that generated by the damper. The O ring, ball bearings and other seals were used for preventing leakage of MR fluid [17-18]. The principle and typical mono tube damper is shown in Figure 3a and 3b.

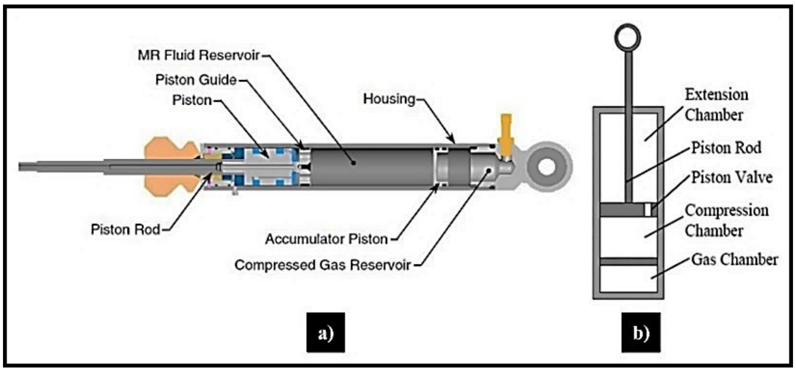

Figure 3. a) Typical mono tube damper, b) Principle of monotube passive damper [16-17]

3.2. Twin Tube Dampers

The principle and section view of twin tube damper is depicted in Figure 4a and 4b. The twin tube MR damper has an outer and an inner cylindrical housing. Inside the housing, a piston was attached, which connected to a manotube filled with MR Fluid. The internal parts of the dampers are protected by outer housing due to heat transform to the MR fluid surroundings. This valve assembly is called as foot valve. Inside the bottom valve of the inner cylindrical housing has two reservoirs for both compression and tension that helps to control the flow. The major drawback of twin tube damper was in dissipating heat from MR fluid [19-20].

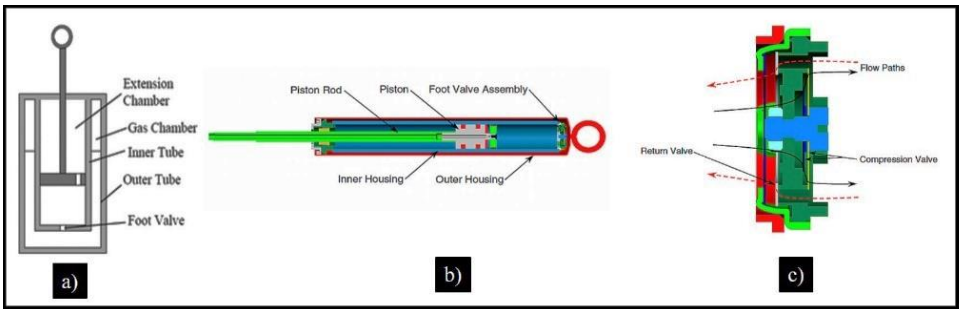

Figure 4. a) Principle of Twin Tube damper, b) Section view of twin tube damper, c) Details of foot valve [16]

In the double ended damper, the piston extends from its two ends as shown in Figure 5. Therefore, this damper does not require any gas chamber, spring, and accumulator to provide thermal expansion of MR Fluids. Mostly for earthquake resistant buildings, shock loading, impact loading and gun recoil applications this double ended damper is being used [21].

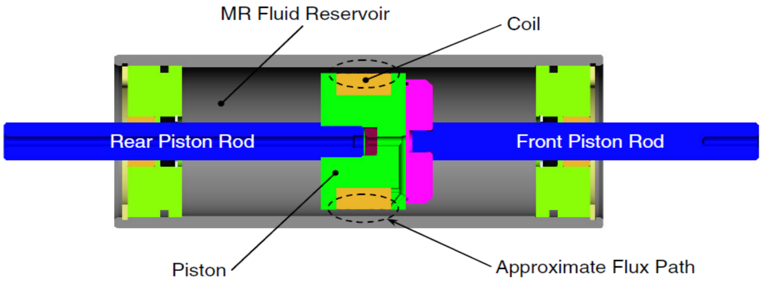

Figure 5. Double-ended MR fluid damper [16]

4. Self-Powered MR Dampers

In the present situation, practically, to trigger electromagnetic coils in MR damper require current amplifier or power supply. During the motion in the vibration system a mechanical energy can be working in power supply. Self-powered MR damper has various methods to translate mechanical energy into electrical energy. The self-power mechanism is most important in large scale structures. For seismic applications, if the high magnitude earthquake occurs, more amount of mechanical energy is converted to electrical energy and vice versa in self-power mechanism. However, this electrical energy generated is sufficient to produce damping force required to resist the buildings from seismic vibrations. Therefore, for civil engineering applications, mainly for seismic resistant buildings self-power mechanism plays a vital part in the structures. Initially the next second of seismic, while the self-power in attached with the MR Damper, therefore power supply be converting the vibrations mechanical energy to electrical energy.

The main reason for adopting self-power mechanism is at initial second of earthquake, there will be no power supply and all the active and semi active control system will be at rest. The examined energy harvesting device with RD-1005-3 MR Damper. To study the voltage, damping force, supplied power, frequency, coil characteristics. have linear motion Electromagnetic Energy Transducer is used as shown in Figure 6a and 6b. The energy dissipation occurs when the input current applied to the coil where we can fine the voltage, damping force, supplied power, frequency and coil characteristics [22].

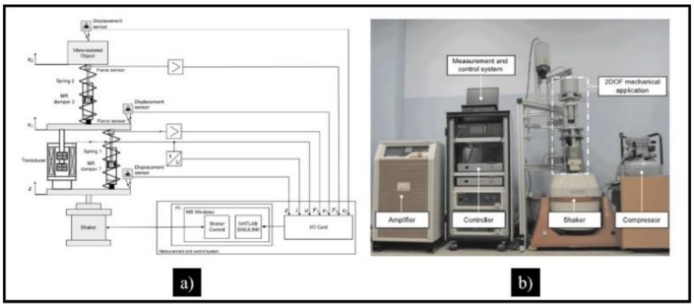

Figure 6. a) Schematic representation b) Experimental setup

They also use transducers to produce linear motion. Additionally, the energy dissipation is applied when current is supplied to the coil as shown in Figure 7. The frequency of the vibration reduction system is increased, current is produced in the coil present in the self-power device [23].

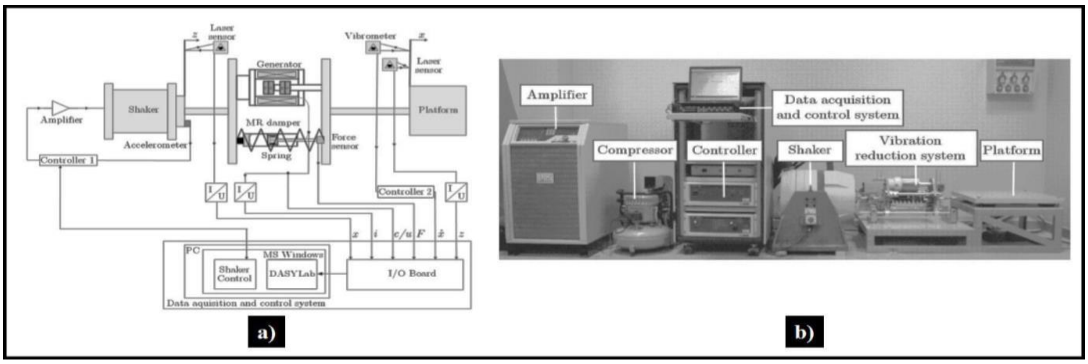

Figure 7. a) Schematic diagram control system setup, b) Test setup

Here achieved an energy harvest theoretically with quasi-Halbach array, which produces high current and voltage. The linear generator was designed with the coil and a permanent magnet and experimentally identified effectively as shown in figure 8 [24].

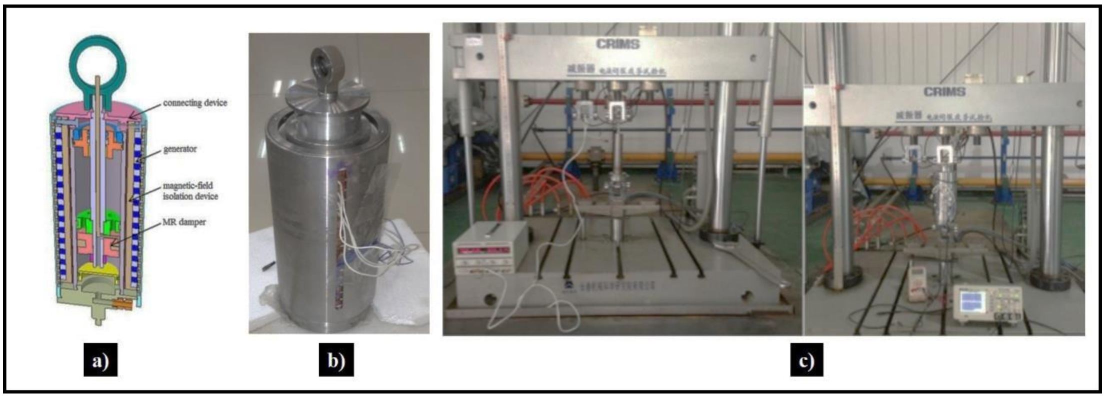

Figure 8. a) Structure of MR Damper with self-power mechanism, b) General View of self-powered MR Damper, c) Experimental Setup of self-powered MR Damper

4.1. Section Headings

To achieve self-powered mechanism in MR damper some energy harvesting devices to be added in buildings to resist seismic forces. Choi and Wereley found a new device that has a magnet, stator and spring which functions as energy harvesting dynamic vibration absorber (DVA) [25]. It not only converts mechanical energy to electrical energy when vibration is given, additionally it is also giving large decrease in control, cost, weight, volume and maintenance as shown in Figure 9. By simulation a single degree of freedom system of MR damper provide reduction in vibration performance using control techniques at rural locations where providing power supply is unfeasible.

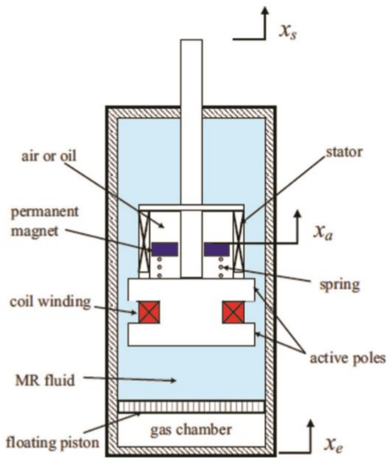

Figure 9. Schematic diagram of a self-powered MR fluid damper [25]

4.2. Addition of Electromagnetic Induction System

MR damper is incorporated with Electro Magnetic Induction (EMI) techniques for self-power mechanism. EMI device consists of solenoid coil, permanent magnet and power supply or velocity sensor. Kinetic energy is converted to electrical energy, therefore, changes in damping characteristics occurs [26-27]. Vibration in a structure occurs due to seismic forces was investigated with passive control system [28]. In vibration system MR damper was interrogated linearly and developed with EMI technique in tall buildings with smart passive system as shown in figure 10. EMI system without controllers and sensors attached in large scale construction using MR damper the input seismic force is proportional to output electric energy as depicted in Figure 11 [26]. Self-sensing MR damper which produces power with stator, mover and velocity sensor using EMI are recently designed to mount in structures as shown in Figure 12 and 13 [29-30].

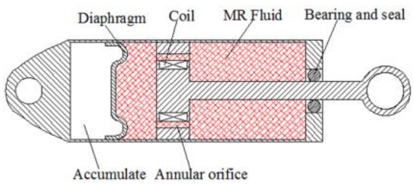

Figure 10. Schematic diagram of a smart passive system [27]

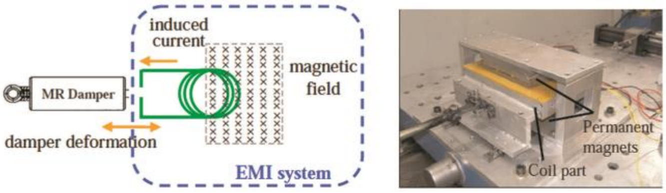

Figure 11. a) Schematic of EMI system and b) Prototype of large-scale EMI system [30]

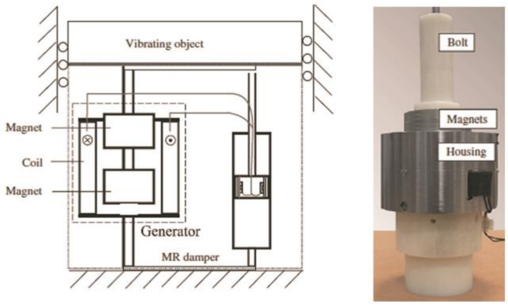

Figure 12. Schematic diagram of the self-powered MR fluid damper–based vibration control system and the generator [31]

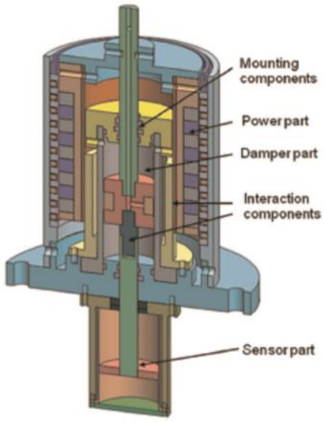

Figure 13. Sectional view of self-powered, self-sensing MR damper [29]

Using electromagnetic induction technique, an energy conserving device was suggested an electrical energy is developed, when external motion applied in between magnets and induced coils [31]. The self-power efficiency of the EMI, calculates the damping force, Figure 14 device produce approximately 750 N for 0.6 A current and 1 DC voltage [32].

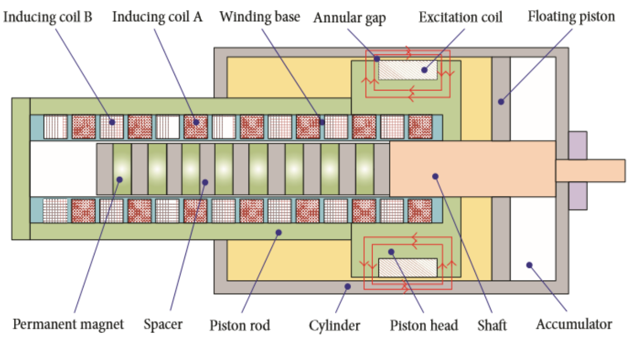

Figure 14. Schematic diagram of energy harvesting device [32]

5. Application of MR Damper for Seismic Mitigation

Lin demonstrates that a 20 KN capacity MR Damper experimentally investigated in a 12-ton supported base isolation system. The large shake table consist of many accelerometers, data controller [38]. Using Fuzzy algorithm semi active damper which mitigate the base isolation with response to mass. Semi-active and passive control system are tested for each strategy as shown in Figure 15.

Figure 15. Experimental setup of base isolation system

A base isolation system with semi active and active MR damper was conducted [39]. The Time history analysis data of various earthquake ground acceleration data was computed. The study advice power is reduced more for base isolation system. The MR dampers used in spatial structure with a control system using peak ground acceleration method, which allows large dimensions with less control forces [40]. With approximate feedback state variables, the nonlinear system is applied to solve the problem. Therefore, when using MR damper in a computational case a huge effective structural vibration is being controlled [41]. MR fluid dampers are investigated using a smart base isolated system with two degrees of freedom [42]. At University of Notre Dame Earthquake Engineering and Structural dynamics laboratory conducted an experiment on base isolation system which decrease the response of the structure when applying various loading pattern as shown in Figure 16. Using Bouc-Wen hysteresis model, the MR damper proposed with modified clipped optimal control shows better dynamic behavior of the system.

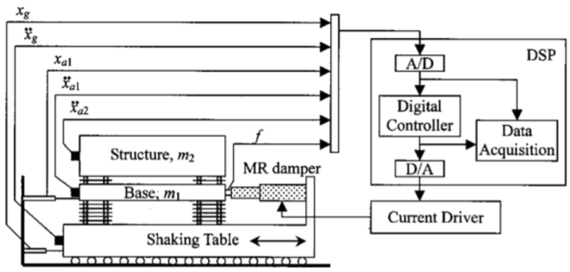

Figure 16. Schematic of Experimental setup [42]

Dyke and Spencer reports that the response reduction of seismic force with MR Damper in a three-storey structure under one dimensional ground acceleration and various amplitude are used to inspect the performance of control system over different loading condition. The implementation of Damper in structure is shown in Figure 17a, Using three Clipped Optimal controller the performance of semi active controller is better than passive control systems when comparing to the reduction of response in the structures. For a wide range of seismic forces can be reduced using MR Damper [43-44]. The constraints and requirements of control system for the three-storey structure are unique. Less power required to resist peak displacement of earthquake forces in structures. The earthquake ground acceleration of El Centro time history is used for controlled and uncontrolled structures with MR Damper than shown in Figure 17b. In the clipped optimal controller contain the control force and command signal in a time limit of 2 Seconds for El Centro Earthquake acceleration data is observed as shown in Figure 1 c.

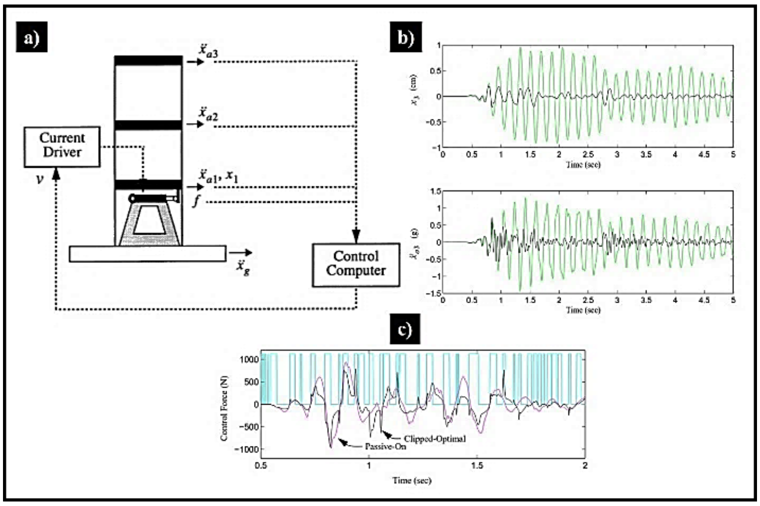

Figure 17. a) Damper Implementation, b) Controlled and uncontrolled structural responses of El Centro Earthquake, c) Command signal and control force applied in the clipped-optimal case due to the El Centro earthquake

El- Sinawi emphasizes that MR Damper placed in a 20-storey building as chevron pattern and the low order nonlinear derivation is observed from system identification with wide range of inputs. The Control of MR damper under seismic loads is based on Linear Quadratic Gaussian (LQG) Controller. To know the efficiency of this LQG four-time histories namely Hachinohe, Northridge, Kobe and El Centro ground acceleration data applied to the structure with active and passive depicted in Figure 18. The floor displacement and acceleration of controlled and uncontrolled for important locations. This simulation demonstrates the efficiency of reducing displacement and acceleration significantly at all floors of the benchmark building [45].

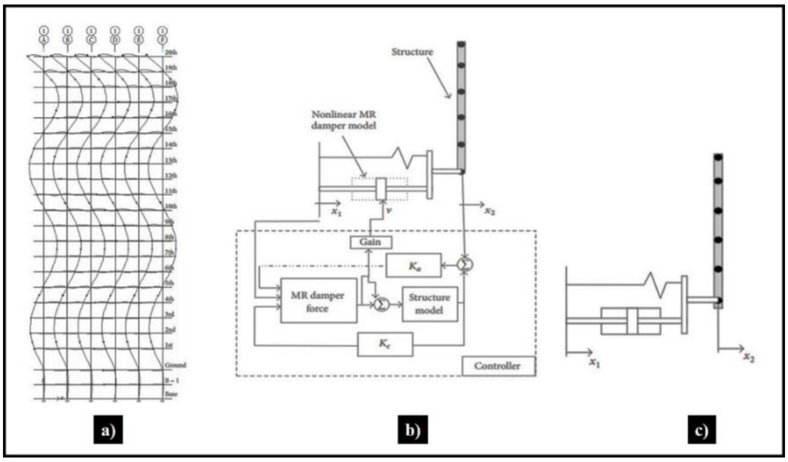

Figure 18. a) Representation of building modes of vibration, b) Active Structure, c) Passive Structure

Bharti and Dumne deplores the tendency to control coupled structure MR Damper efficiency is more effective to control wide range of seismic forces. When the semi active control strategy was being used, the shorter structure response mitigation was better [46]. In Passive strategy also, a significant control been observed so even the control algorithms fails the response in seismic mitigation will be success as shown in Figure 19 [47]. In the bottom of elastomeric bearings are fixed in the taller structure and both structures is connected with MR Damper response been observed.

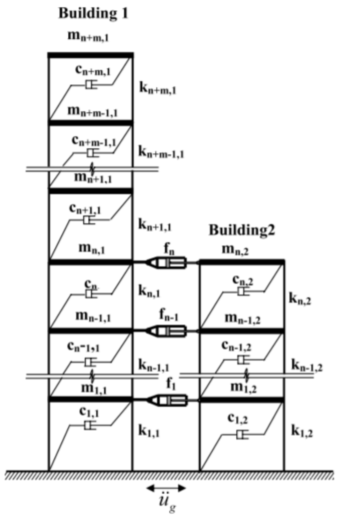

Figure 19. Building Connected with earthquake

Kanno believes that, a semi active system with MR Damper, by varying current damping force obtained. The energy dissipation is increased in shake table test for one storey steel structure prototype [48]. To control the seismic forces, stiffness ration, α and stiffness loss of damping to the frame stiffness, η has more significant on it.

$$\alpha = k \times b \times k \times f \quad (1)$$

$$\eta = \lambda \times 12 \times k \times f \times k \times f = \Lambda \times k \times f \quad (2)$$

K_b – Stiffness of the brace

K_f – Stiffness of the frame

λ – Control force

Λ - Peak displacement

In the stiffness ratio α, the control of MR Damper and peak displacement is looped in a control system, whereas the loss of stiffness is due to the stiffness of brace and the frame where we get the stiffness losses in the MR Damper as shown in Figure 20.

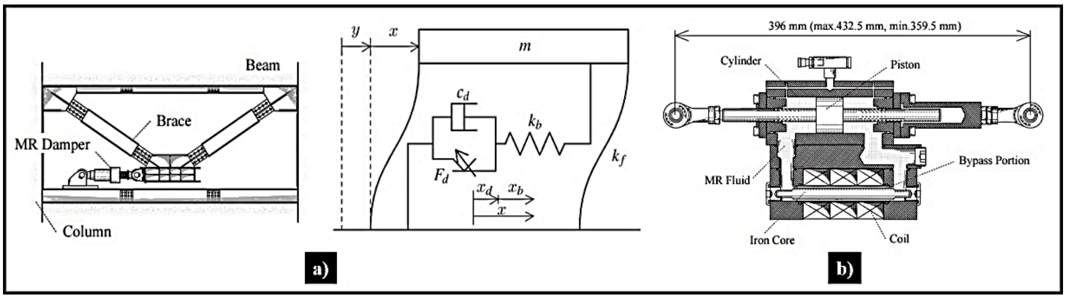

Figure 20. a) Analytical Model of MR Damper in a System, b) Schematic of 2000N MR Damper

Deshmukh urges, a 12-storey building connected with a MR Damper diagonally. The top floor response reduction under smart passive MR Damper and Semi active MR Damper is numerically compared using SCILAB 5.4.0 software [49].

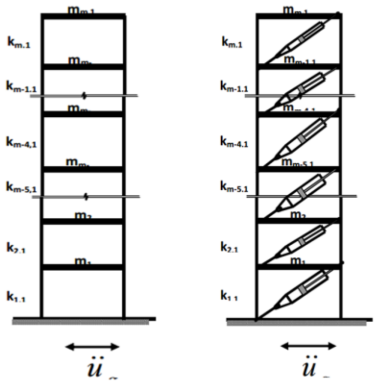

Figure 21. Controlled and Uncontrolled Building Models

Das and Gori suggests that, a 3 Storey building frame using fuzzy controller in MATLAB fuzzy tool box and control algorithm with Simulink was idealized. The storey drift, storey displacement, storey acceleration and control force have huge reduction percentage compared to clipped-optimal control [50]. Structure with time history analysis with semi active MR Damper is numerically investigated where the MR Damper peak acceleration of structure and displacement with ground acceleration as depicted in Figure 21. The optimum voltage is identified using various control algorithm [51].

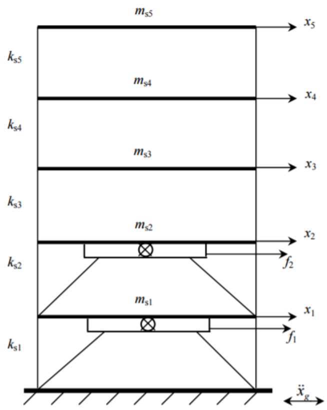

Figure 22. MR dampers with Five-story building

Mahdi reports that a three-storey building, Fuzzy control method is used to study the seismic response of the semi active MR Damper. The Figure 22 shows that MR Damper can control seismic exited building, where the displacement is reduced more compared to the uncontrolled buildings [52].

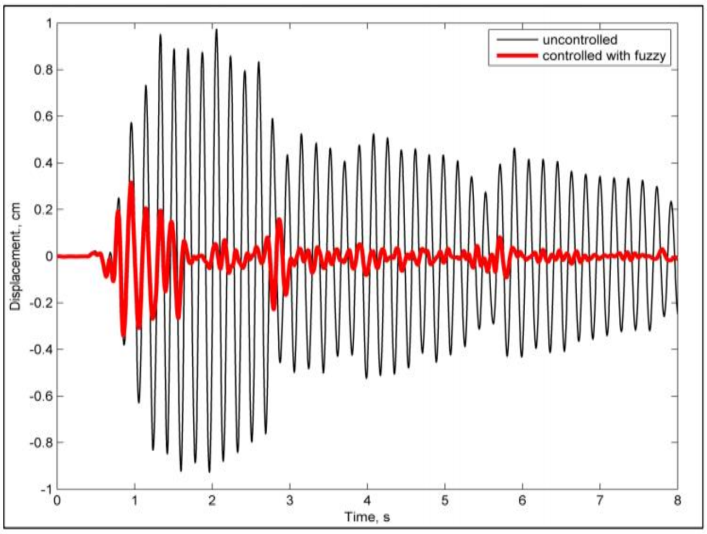

Figure 23. Third floor displacement response under El Centro earthquake

Spencer remind us that, a Prototype full-scale model response for El Centro earthquake is studied for controlled and uncontrolled structure. Figure 23 shows the schematic and this experimental setup of MR Damper. In university of notre dame, a damping force 20 ton was given to semi active control device which can be considered as a real time application [53]. Figure 24a and 24b shows the schematic representation and b is the experimental model consists of an actuator of 560 kN and a strong floor on it.

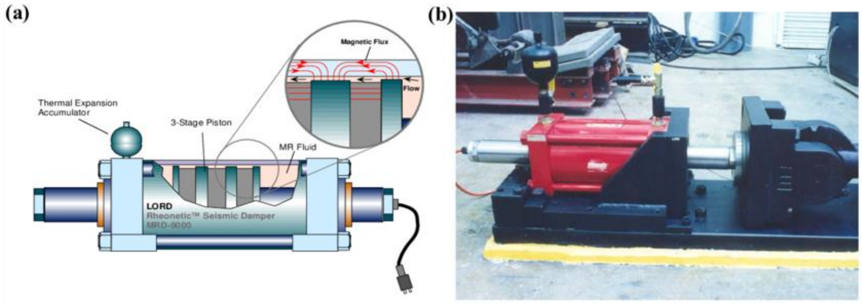

Figure 24. a) Schematic of MR Damper, b) Experimental setup of 20-ton Large scale MR Damper

Table 2. Design parameters of 20-ton MR Damper

Design Parameters	Values
Stroke	58 cm
F_{max} /F_{min}	10.1 @ 10 cm/s
Cylinder Bore (ID)	20.32 cm
Max. Input Power	< 50 watts
Max. Force (nominal)	200,000 N
Effective Axial Pole Length	8.4 cm
Coils	3 × 1050 turns
Fluid η_p	1 Pa-s
Fluid $\tau_{y(field)}$ max	70 kpa
Gap	2 mm
Active Fluid Volume	-90 cm^3
Wire	16 gauge
Inductance (L)	6.6 henries
Coil Resistance (R)	3 × 1.3 ohms

Elsinawi observes that a 20-story base isolation structure consists of a MR Damper of Nonlinear Boun-wen proposed linear Quadratic Gaussian regulator algorithm to know the behaviour. The comparison of controlled and uncontrolled displacement and acceleration of a structure for El Centro and Hachinohex earthquakes observed [54].

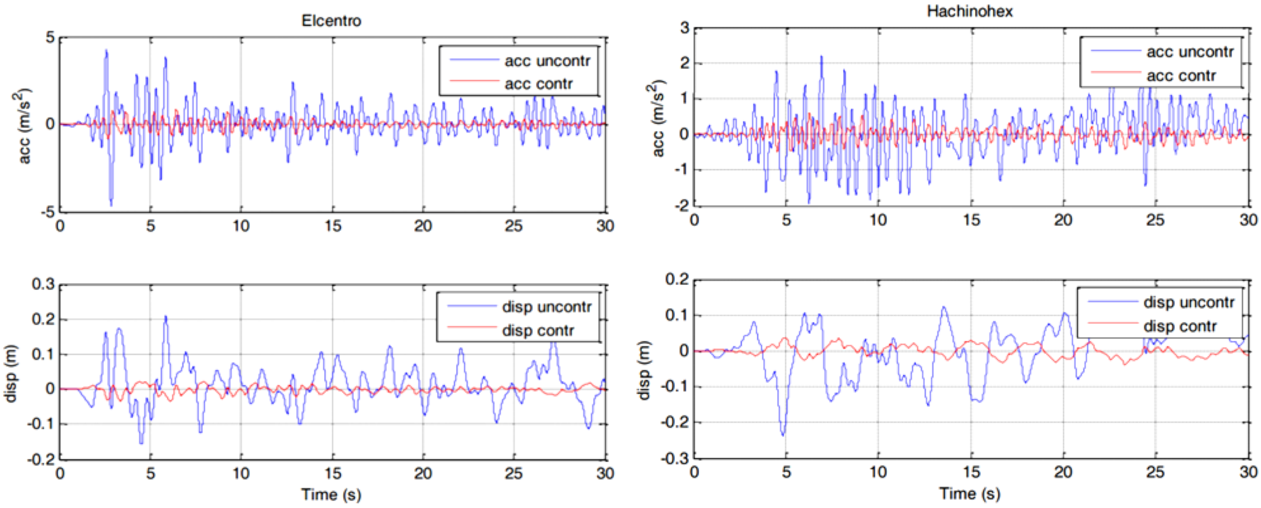

Figure 25. Displacement and acceleration of the top of the structure with and without control (El Centro and Hachinohex Earthquake) [54]

Jansen insists that, a six-story building analyzed for El Centro ground acceleration with various control algorithms Proves that MR Damper can be suitable for reducing seismic forces. The peak response of each floor in a structure for El Centro is show in figure 25 [55].

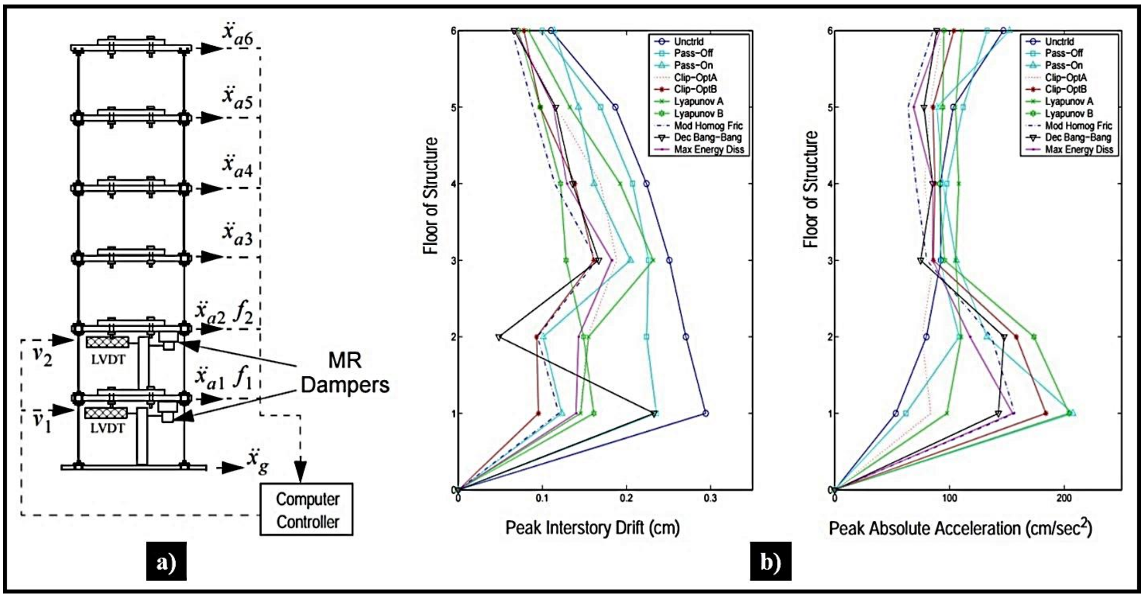

Figure 26. a) Implementation of MR Damper, b) Peak Responses of Each Floor of the Structure to the Scaled El Centro Earthquake

In case of low and high earthquake, MR Damper system can control significantly to obtain a safer system as depicted in Figure 26. The active stochastic control been optimized and designed Magnetorheological Damper in buildings where Optimization of weighting matrices with reference to probability distribution. The reference gain and quantities of interest are analyzed by sealing various design parameters. The high – viscosity MR fluid requires designed to control raises coulomb forces. Therefore, low viscosity fluid has used for workability in large scale MR dampers [56].

Mohebbi used Genetic Algorithm (GA) for Optimizing MR Damper for seismic applications. A 10-story frame connected with 10 MR Damper as shown in Figure 27 which is subjected to El Centro ground acceleration. Therefore 55% of maximum acceleration and 73% of displacement in the structure got reduced [57].

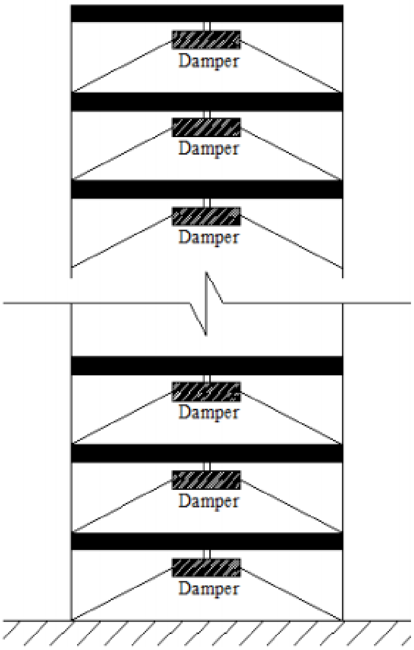

Figure 27. 10-storey shear frame with 10 MR dampers

According to soma, a sponge type MR Damper, the shear stress in the MR fluid produces damping force. The experimental and simulation in Genetic algorithm matches the results. This MR damper is effective because the frequency response in twin building control two vibration modes. GA was effective in controlling seismic response of a structure [58].

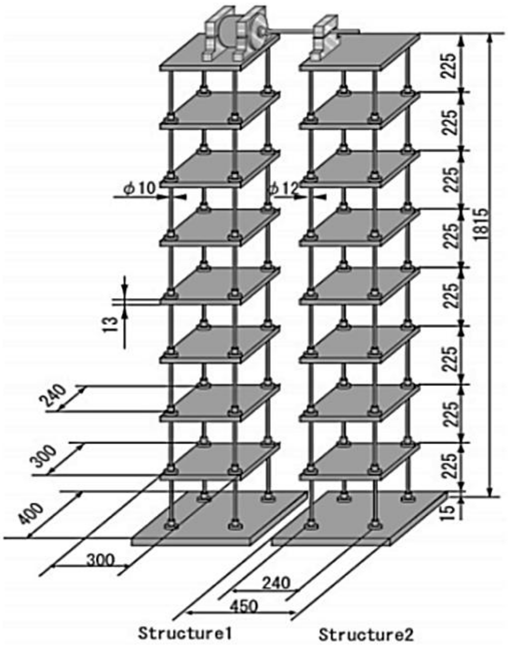

Figure 28. Control Object in the top

Raut demonstrates that, a 20-storey bench mark building with MR damper, the optimal voltage to reduce the seismic response of a building can be determined by Lyapunov, bang-bang and clipped optimal control systems as depicted in Figure 28. The semi active MR Dampers controls the pre and post-earthquake evaluation in a bench mark structure with the input voltage. The comparison of various control system with the peak ground acceleration namely El Centro, Hachinohe, Northridge, Kobe. Optimization in number of dampers and location is identified. The maximum inter storey drift floors are considered for effective location of a structure [59].

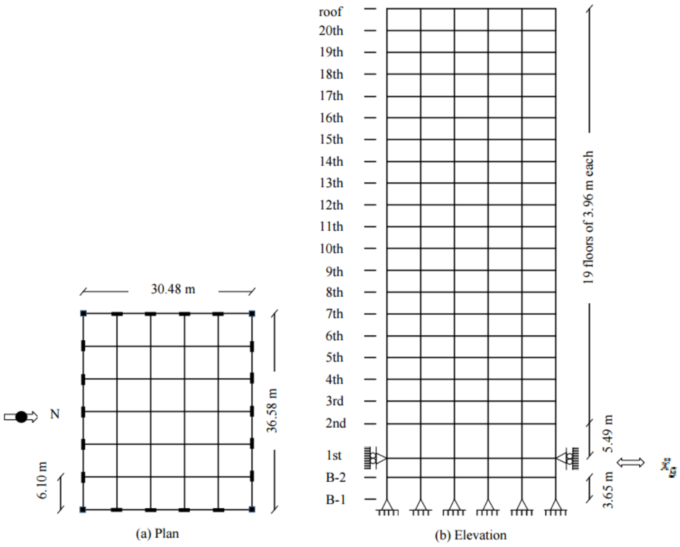

Figure 29. Benchmark building – 20 storeys

Hiemenz studied experimentally and numerically MR Damper as brace is analyzed using skyhook, LQR and CSM compared with passive MR damper for El Centro time history. The frequency response of the top floor and power density of top floor acceleration are numerically obtained in Figure 29. As compared with passive MR Damper for Energy consumption and Top floor RMS displacement are measured, where all three-control system performed well in both experimentally and numerically [60].

Figure 30. Experimental model-scale civil structure fitted with MR brace

Chae observed the pre and post yield performance of MR Damper are identified by varying the parameters. The shear thickening and thinning of MR fluid with post yield behaviors were used in the MR Damper. Therefore, the reaction time of the Damper and fluid is found by varying the input current, this was experimented using Maxwell Nonlinear Slider (MNS) model [61]. Kim suggest that, the Outrigger damping system increases the energy dissipation which is proposed to place in a perimeter column and vertical MR Damper between the columns as shown in figure 30. Where the semi active device investigated the seismic response in a building using fuzzy control algorithm. The artificial seismic load was generated for numerical simulation for outrigger MR Damping model [62].

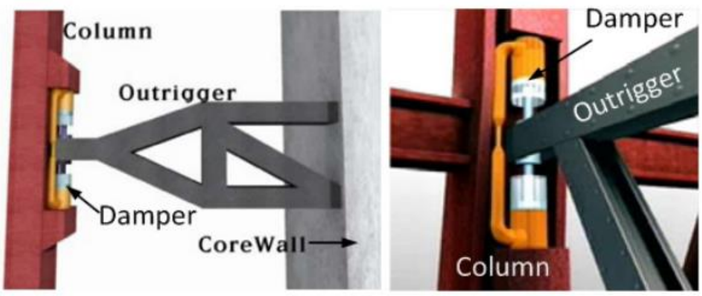

Figure 31. Outrigger Damper

Gattulli suggested that, a framed structure analysed analytically with semi active and passive strategies for mitigating the structure seismic response through MR Damper of Lord RD 1005-3 with modified Bouc Wen Rheological Model as shown in Figure 31. The mono dimensional acceleration data with mass eccentricity controlled the three-dimensional dynamics. Using clipped optimal peak response was reduced for seismic applications [63].

Braz Cesar commented on MR damper tested in a metallic frame of 3 story with 3 – DOF to control the vibration and the dynamic properties of MR Damper is tested as depicted in Figure 32 and 33. The numerical investigation using clipped optimal algorithm the system identification and dynamic behaviour of a structure system is simulated [64-65].

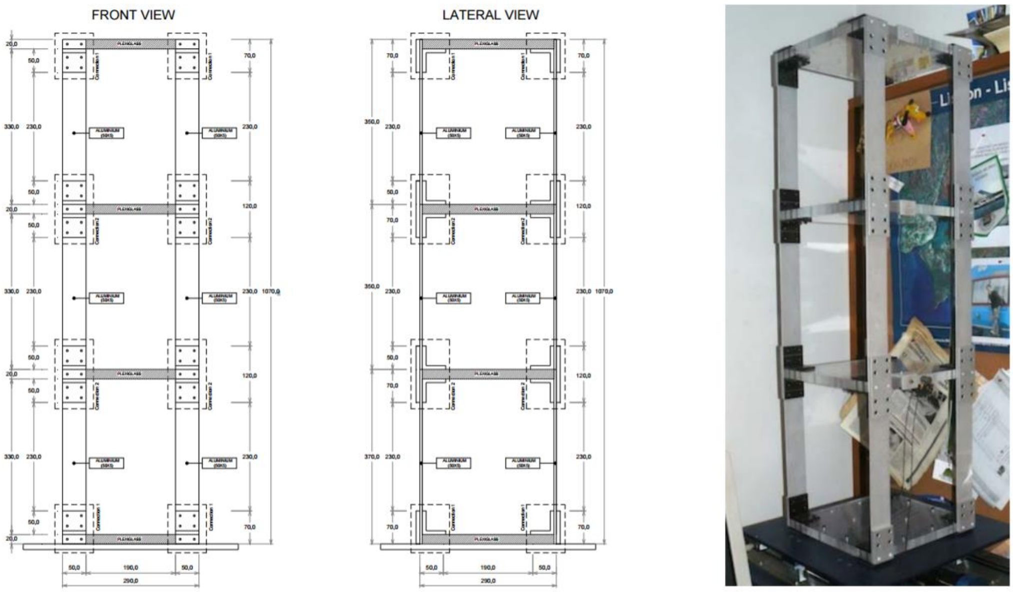

Figure 32. Metallic scaled frame: geometrical properties and perspective view

Figure 33. MR damper attached to the experimental metallic frame

6. Conclusion

In recent scenario an emerging smart material namely, magnetorheological fluid changes its transition state from visco plastic to Newtonian fluid under the action of an external applied magnetic field and vice versa in absence. It possesses wide range of application in various fields, especially its participation towards automobile technology it's noteworthy. In view of this many civil engineers suggest Smart MR Technology can be a better proposal for seismic vibrations in structures. Currently available control devices perform only under particular frequency. But Magnetorheological damper can tune to the frequency of the earthquake since the MR damper connected with self-power technique in a building. In the presence of seismic force, the displacement in the floors increased; during motion the dampers piston produce required electrical energy to yield damping force which is sufficient to control the seismic forces. The primary aim of the researchers is to increase the life span of MR devices particularly in terms of total energy dissipation. MRF technology and its applications still have many problems that need further research in following aspects: low performance of MRF; easy to leak, difficult to seal when working; poor particle sedimentation stability and instability; device cooling effect is not ideal; MRF control element, such as brake, clutch, output torque is not ideal, etc. The important significant of Magnetorheological technology are quick reaction time, bridging the electrical and mechanical data, easy, appropriate controllability and involves less moving parts. Therefore, MRF technology offer less maintenance and possess longer life.

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8. Conflict of interest

The author declares no conflicts of interest.

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