Magnetorheological Damper for Performance Enhancement Against Seismic Forces

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Abstract. In recent years, there were a huge loss of human life and infrastructures after earthquakes in the world. This has led to the need for building safer structure for livelihood. Many research were done on vibration control devices by taking into account factors like the viscous, friction and tuned mass dampers. Magnetorheological (MR) dampers have the ability to tune and adopt its mechanical properties by varying its magnetic field. For civil engineering application dampers with high damping force and low energy input are required. The results of experimental investigation carried out on a frame with 500 kN have been discussed in this paper. The damper used to be single piston shear mode, which was scaled down single bare RC frame. The damper was placed diagonally on the frame. When comparing the displacement in the RC frame with and without damper it is observed that 40 to 50% reduction in displacement is noticed. There is an increase in energy dissipation capacity from 45 to 60%, finally ultimate load carrying capacity and lateral stiffness was observed for the RC frame with MR damper.

Keywords: MR damper · MR fluid · Energy dissipation · Semi-active · Cyclic load test

1 Introduction

With the continued deterioration of an infrastructure under seismic forces, there is a keen need for smart structures which are able to maintain its strength and serviceability criteria throughout the design life. Due to large structural responses under dynamic loading (earthquake), cracks are developed more which degrades the overall and also the local strength of the structural elements. Control systems is increasingly researched and implemented in civil engineering structures in order to limit the response in structures. The potential failure in the structure caused by the vibration can be controlled by one of the promising new seismic load designs and it can be achieved by vibration control device (Magnetorheological Damper) attached to the structure in order to reduce the vibration which in addition has high dynamic range, less power, robustness, large force capacity and mechanical simplicity. The desired friction and

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stiffness force are to be emulated in MR Damper. For vibration reduction in structures, more analytically have been done under the seismic vibration but very less experimental works have been carried out.

Many studies have been carried out considering different number of coil, different piston shape, [1] optimized MR damper using finite element analysis for different configurations of MR damper piston, MR fluid gap, and Dampers housing. The performance of MR damper with various piston configuration is found in the single coil with fillet end which gives better result. [3] After investigating the design, manufacturing, and testing of a large capacity MR damper it is found that some discrepancy between measured and tested result. [4] Developed a new concept for MR damper which combined shear and squeeze working modes. [5] Studied about the optimal design of double coil MR damper for various pistons and compared with experimental results and found it to validate the result.

Moment resisting frame with MR Damper are derived from seismic fragility relationships. Direct performance based control design to resist the random seismic motion. The fragility estimation for 9 storey building with various controlled design aspects on giving seismic hazard levels been studied numerically [6], therefore Semi-active vibration control with MR Dampers for harmonic structural excitation, the vibration is reduced between 12 to 60% due to damping controlled by relative motion. The performance of hybrid 1, hybrid 2 and semi-active damper are compared with the performance of coupled building with MR Damper and elastomeric base isolation. The bearing displacement and base shear for the time periods are within their acceptable limits are controlled by semi active dampers [8]. Numerical simulation of 3 the storey shear building is investigated with variable energy dissipation algorithm. The semi-active device supplies various voltages with maximum variable energy dissipation algorithm. The peak Interstorey drifts and peak floor acceleration for various controllers are evaluated. Logic control algorithm seismic response of a semi active of having podium structure using multiple MR Damper real time control system. The comparison of displacement, acceleration of peak and RMS responses of 12 storey building is analyzed [10], the experiments on multi-dimensional earthquake isolation and mitigation device with visco elastic damper tested in shake table model frame with and without devices shear mode MR Damper. The displacement reduced by 35.57%. The MR Damper investigated theoretically under different magnetic field, For design calculations, viscosity of fluid, volume, width of annular in the damper is derived. The double ended shear mode combined with valve mode MR Damper with maximum force of 20 kN equipped with 5 storey frame with two MRF-04 K Dampers and the theoretical study of semi-active prediction control system reducing the structural responses under different earthquake. Therefore, no experimental investigation is done in RC frames under cyclic load test to know the behavior of single end shear mode MR Damper.

2 MR Fluid

Magnetorheological fluid commonly known as MR fluid is the combination of magnetic, smart material and a carrier oil which effect on the applied magnetic field. The applied magnetic field have power over significant rheological factors such as yield stress and apparent viscosity. Their increased contribution in space technology, through domestic products are noteworthy. Further MR fluid posses several important applications such as controlling vibrations. Particularly their uses in dampers, power steering pumps, brakes and control valves. Moreover, owing to its high magnetic energy density they possess a high dynamic field strength which is the main advantages of MR fluid. Due to its induced dipole- dipole interaction fluid like form to semi solid state is achieved due to the presence of applied magnetic field, as the MR fluid material can be polarized magnetically leading to the formation of fibrid like structure which exhibit high yield stress and increased viscosity. Owing to its wide range of applications in various fields, many researchers in civil engineering are currently focused on the study of MR fluid behavior in dampers for structures. In the present work, it is proposed to prepare MR fluid using Nano Fe_3O_4 particle and silicone oil by 60% weight and their efficiency towards MR damper is investigated.

The micron size MR fluid is applicable to the automobile applications since the vibrations occurs number of times, thereby sedimentation is not a big problem, but for seismic applications earthquake does not occur frequently thereby occurs sedimentation on using micron size material for MR fluid. As the nano materials exhibit Brownian movement sedimentation is controlled. The sedimentation ratio is lesser in nano size material compared to the micron size particle.

Figure 1 illustrate the rheological behavior of MR Fluid in the presence and absence of magnetic field. When the absence of magnetic field in the MR Fluid the iron particle dispersed randomly in the silicone oil. These MR Fluid exhibits non-newtonian behaviors the viscosity of the MR Fluids is described as

$$\eta = \frac{\tau}{\gamma} \tag{1}$$

η is the viscosity of a MR Fluid with no magnetic field applied, τ is the shear stress and γ is the shear rate.

When the presence of a magnetic field in the MR Fluid which has various yield strengths. This viscosity of this MR Fluids is described as

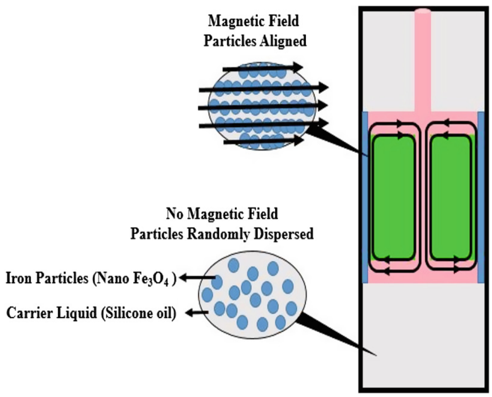


Fig. 1. Damper with and without Magnetic field

$$\eta = \frac{\tau - \tau_B}{\gamma} \tag{2}$$

τ_B is the response of yield stress applied during magnetic field. The viscosity of this fluid depends on magnetic induction field $_B$.

2.1 X-Ray Diffraction Studies

The powder XRD pattern of synthesized Nano Fe_3O_4 was shown in the Fig. 2 obtained using the Model (Schimadzu, LAB X, XRD – 600) using CuKα radiation. The whole experiment was carried at room temperature measured in 2θ scale at a range of 20º to 90º, with a scanning speed of 0.03°/s and a step time of 4 s. The prominent XRD peaks observed were indexed and analyzed using the ICDD database. The planes at (111), (220), (311), (400) and (440) were corresponds to the following angle 21.37°, 33.18°, 35.44°, 41.23° and 62.63° respectively, which matches the JCPDS file no. 79-0417 suggesting the magnetite structure. The average particle size of the material was examined using the most intense plane (311) by the most popular Scherrer equation.

$$D = \frac{0.94\lambda}{\beta \cos\theta} \tag{3}$$

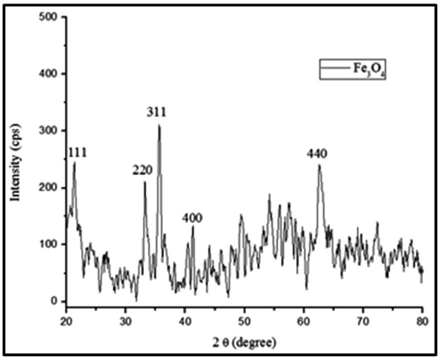


Fig. 2. XRD pattern of Fe_3O_4 iron particles

Where

D is the average particle size in nm

λ is the wavelength of the X-ray used.

β is Full Width Half Maxima

Θ is diffraction angle.

The average particle size obtained using the above mentioned equation was found to be approximately 12 nm.

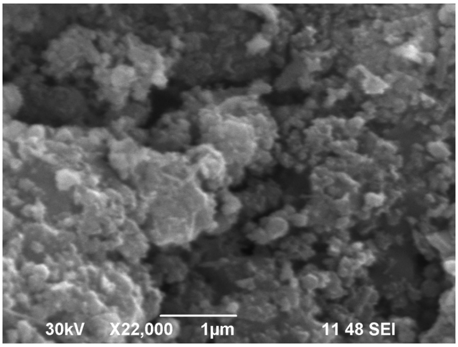


Fig. 3. SEM image of Fe_3O_4 iron particles

2.2 Surface Morphology Studies

In order to study the morphology of the synthesized Fe3O4, Scanning Electron Microscopy (SEM, JEOL 6390) was carried out; the Fig. 3 shows the SEM image of the synthesized compound. The uneven spherical like structure is observed for the synthesized Nano Fe_3O_4. The average particle size of the material was calculated and was found to be in good agreement with the XRD results.

2.3 Preparation of MR Fluid

The schematic representation of MR fluid is shown in Fig. 4. The smart material and the carrier oil were mixed and sonicated with 60% by weight. The resultant MR Fluid was used in the single end shear mode MR damper.

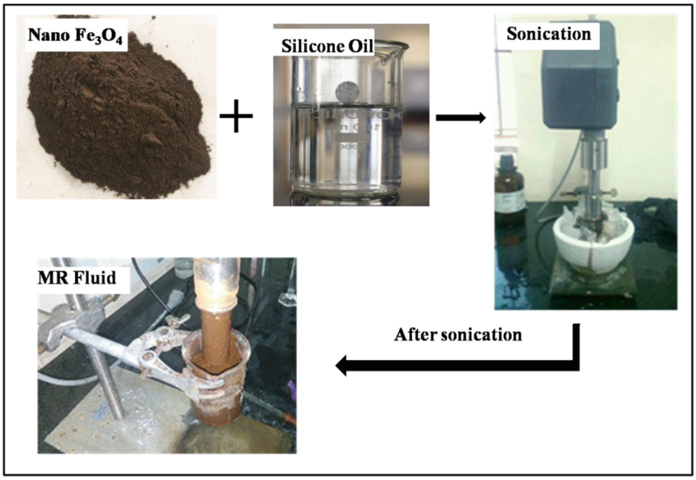


Fig. 4. Schematic representation for preparation of MR fluid.

3 Modes of MR Damper

MR Damper provides less input current requirement with a huge damping force which classified into following categories

Damper in Valve Mode

All these MR Damper consist of a cylindrical housing, piston, MR Fluid, piston pole and coil. In this MR Fluids when the magnetic field applied the flow is controlled. These flow modes are applicable for semi active system. Eg. Heavy Vehicle suspensions single and double end piston rod is in these various MR Damper.

Damper in Shear Mode

Shock absorber with MR Fluid has been developed by many researchers for the car suspension system. The vibration energy is dissipated when the piston subjected to vibration the shear occurs in the MR Fluid. In automobile applications this system installed in the vehicle chassis and tested and found a huge reduction in the response of the vehicle. For civil engineering application when the damper is placed in various locations and direction. Diagonally the damper system placed, when the piston subjected inside the damper the shear occurs due to the piston pole gap less than 2 mm. These shear mode devices are integrated with Bingham Model.

Damper in Squeeze Mode

The manufactured MR Damper product developed by lords' corporation working principle is squeeze mode. For much industrial application active control system has been used. Here the moving of a disc is axial to its initial motion or two pistons from both directions will squeezing the fluid when it is magnetized, therefore viscous to viscoelastic behavior occurred in the damper which dissipate more energy on the damping force and damper. Squeeze mode only can achieve relatively motion force, for dynamic forces and less amplitude of vibration devices.

Damper in Valve and Shear Combined Mode

In these combinations, the piston pole gap in the cylinder housing and piston pole. When the motion of piston undergoes due to flow all the fluids are magnetized and the shear stress exists towards the annular space. These damper may be single ended or double end piston by the stability of the piston to be good. Various MR Damper mode of operations are shown in Fig. 5 a, b, c.

In this study, single end piston with shear mode MR damper is used for analytical and experimental in frames.

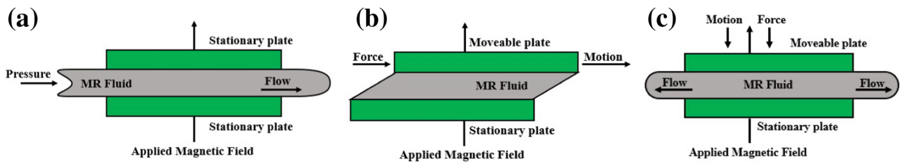


Fig. 5. (a) Valve mode, (b) Shear mode, (c) Squeeze mode

4 Analytical Design of MR Damper

The dimension of the MR damper taken for study about the magnetic field density is shown in Fig. 6. Finite Element Method Magnetics (FEMM) is the software used to analyze the Damper. The effect of MR damper due to various parameters were studied. The parameters such as Number of turns of the coil, Current intensity, Piston pole material, Piston pole gap, Use of shear mode, American Wire gauge, Percentage filled in coil were studied. From the results, it is noted that 99% filled in coil was observed for 260 turns of coil using the American wire gauge of 21 and mild steel as piston pole material which produce the maximum current intensity of 3 A. Maximum flux density, magnetic field intensity and the current density were observed for the optimized dimension as shown in Fig. 7 (a), (b), (c) for the fabrication of single end piston shear mode MR Damper.

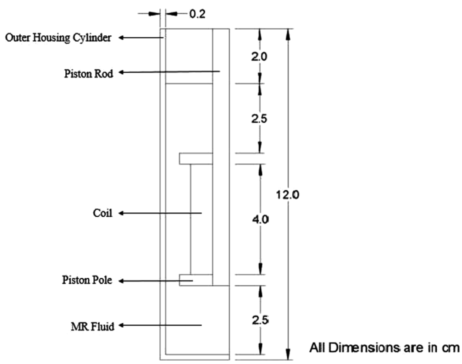


Fig. 6. Sketch of the design of MR damper

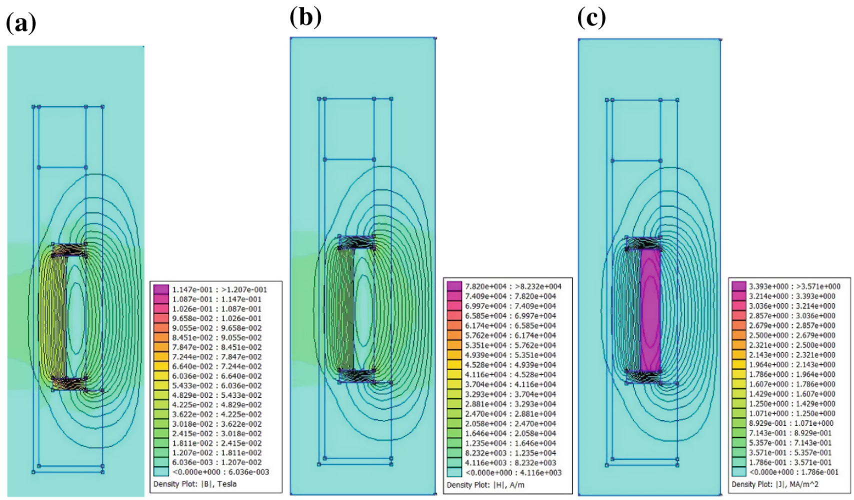


Fig. 7. (a) Flux density, Tesla, (b) Magnetic field Intensity, Am (c) Current density, MAm^2

4.1 MR Damper Fabricated

As per the FEMM which gives the best result the sizes were optimized and fabricated. The fabricated MR damper and its coil with piston cap is shown in Fig. 8 (a) and (b).

Fig. 8. (a) MR damper, (b) Coil with piston cap

5 Cyclic Load Test

The Capacity of the loading frame is 500 kN. Given Fig. 9 shows the reinforcement details and dimensions of a frame. According to the specimen detail given in Table 1 the Casted RC frame was shown in Fig. 10.

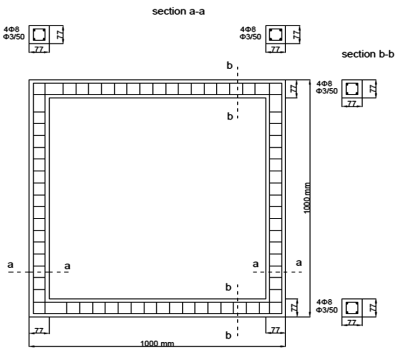


Fig. 9. RC frame specimen detailing

Test Setup

In plane lateral load was applied at the end of the top beam along its centroidal axis through one end of the servo hydraulic actuator. The other end of the actuator was supported by a strong steel reaction frame. The lateral load was applied to the beam of the moment frame by two channel sections, which is symmetrically placed on both sides of the beams and held together by high strength bolts at regular intervals. The footing was hardly placed on the strong floor by means of three bolted connections to avoid its possible vertical and horizontal movements due to the lateral loadings. The lateral support was given by the steel sections to avoid it’s out of plane movements. The test setup was shown in Fig. 11.

Table 1. Specimen details

Grade of the concrete	M25
Reinforcement details	
Beam	8 mm
Column	8 mm
Stirrups	3 mm
Grade	M25
Cement	OPC 53
Size of aggregate	10 mm
Minimum cement content	310 kg/m^3
Slump value	50–75 mm
Specific gravity of cement	3.15
Specific gravity of fine aggregate	2.605
Specific gravity of coarse aggregate	2.88
Support condition	Fixed
Mix ratio	1: 1.8: 1.7

Fig. 10. Casted RC framed specimen

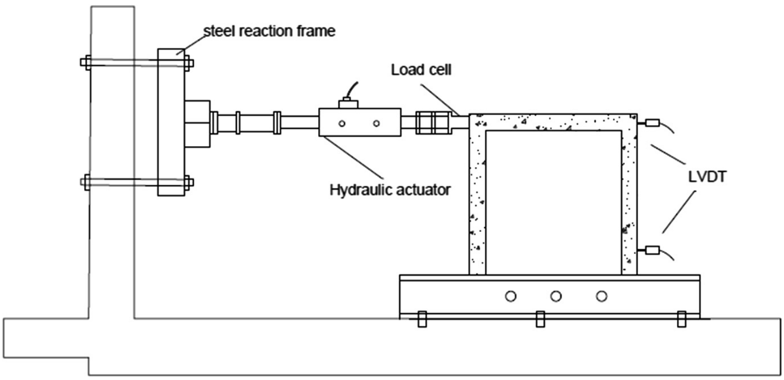


Fig. 11. Sketch of test setup

Single Bay Frame without Damper
This specimen was designated as the reference frame to compare its performance against the frame with damper. Ten displacement cycles were applied to the frame. First cracks were observed at a load of 6 kN and the corresponding displacement was at 9. 583 mm. Figure 12 Shows the loading pattern.

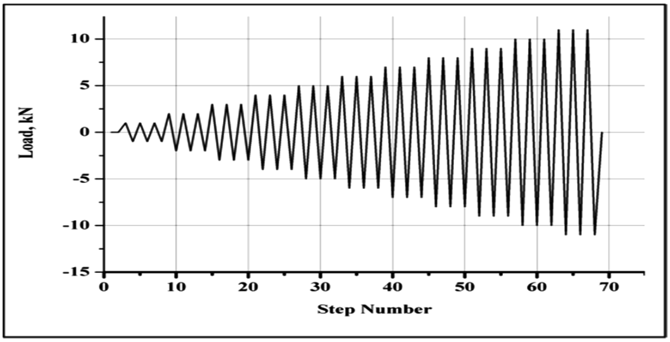


Fig. 12. Loading pattern

(a)

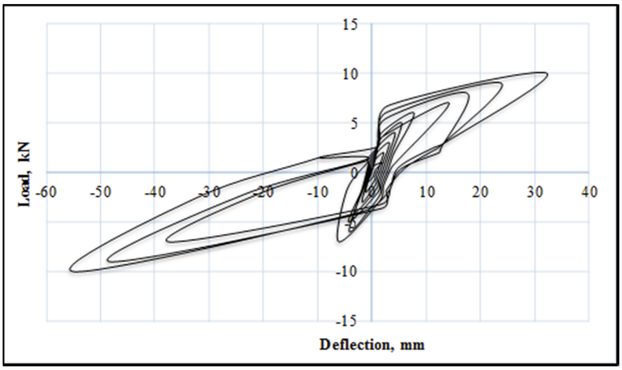

(b)


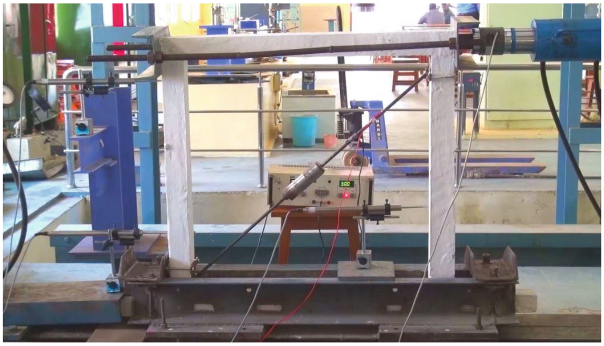
Fig. 13. (a) Bare frame without damper, (b) Load Vs deflection for bare frame

The maximum cracks opening was obtained at 1.0 mm. The ultimate load carrying capacity of bare frame is 19 kN. The load versus deflection curve is depicted in the Fig. 13b. Figure 13a illustrate the image of Bare frame without damper.

Frame with Damper

Sixteen full displacement cycles were applied to the frame with sixteen full displacement cycles. First cracks were observed at a load of 8 kN and the corresponding displacement was at 5.463 mm. 1 mm is the obtained crack opening. The ultimate load carrying capacity of bare frame is 37.7 kN. Figure 14 a and b gives the RC frame with damper and the load versus deflection curve obtained.

(a)



(b)

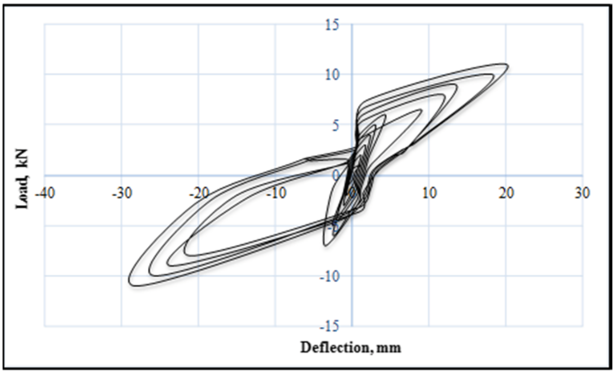


Fig. 14. (a) Single bay frame with damper, (b) Load Vs deflection for bare frame with MR damper

5.1 Analysis of Experimental Results

The expected seismic energy is a measure of the structural ability to dissipate the seismic input energy. The sum of the area enclosed by each hysteretic loop is used to determine the cumulative dissipated energy. The bare frame is the specimen which has the minimum energy dissipation capacity. The specimen with MR damper has the maximum energy dissipation capacity of 45%. The dissipated energy versus deflection relation for Frame with and without MR damper are shown in Fig. 15.

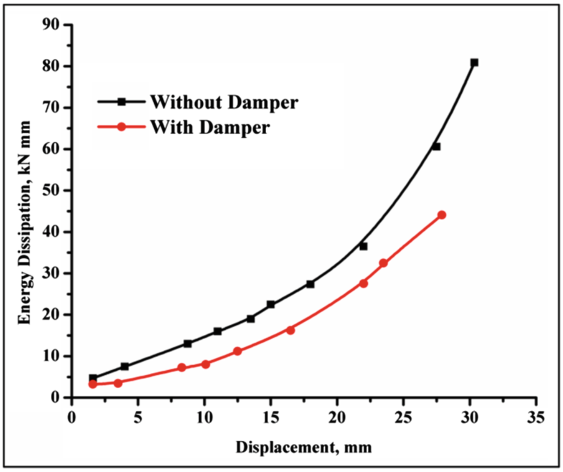


Fig. 15. Energy dissipation Vs displacement

The lateral stiffness was defined as the slope of the line connecting the positive and negative peaks of a given load–displacement cycle. Presence of MR damper reduces the lateral stiffness of the frames. As expected, the lateral stiffness increased by 49% for RC frame with damper. A variation of the lateral stiffness with respect to displacement for with and without MR damper is shown in Fig. 16.

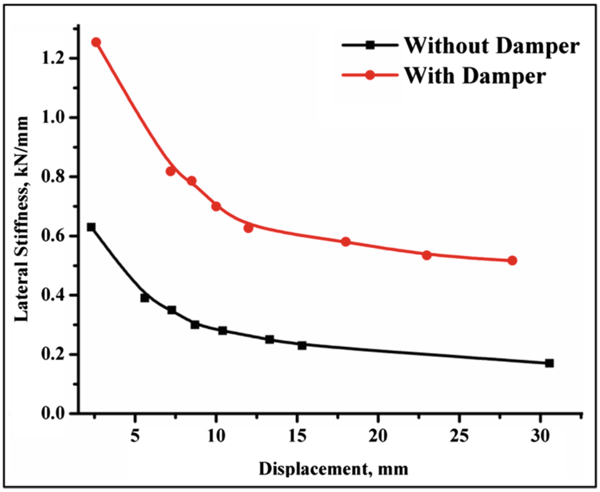


Fig. 16. Lateral stiffness Vs displacement

Figure 17 shows the load versus deflection backbone curve. The post yield hardening was noted for the RC frame with MR damper with no degradation of lateral strength upto the displacement of 11 mm. Meanwhile, the backbone curve for without damper was approximately linear upto the displacement of 7.5 mm. The strengthened specimen has the maximum displacement 11 mm when compared with bare frame. This magnification in the lateral strength of the frame was principally due to the lateral load sharing mechanism of MR damper.

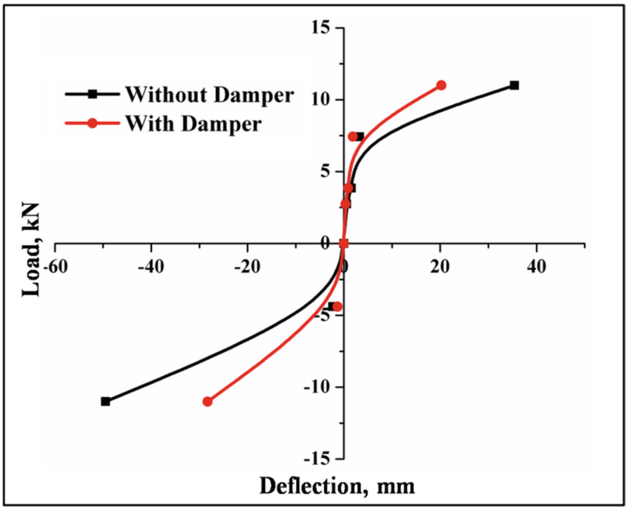


Fig. 17. Backbone curve

6 Conclusions

In conclusion, we demonstrate the MR fluid with magnetic nano Fe_3O_4 and silicone oil and the carrier oil is highly efficient towards MR damper application. Maximum vibration reduction for Shear mode MR damper is proved in Cyclic Load test where the displacement reduced by 49%. The MR Damper is designed as per the analytical result in Finite Element Method Magnetics (FEMM). The nano size of the smart material was confirmed by the XRD and SEM results and the average particle size was found to be approximately 12 nm. From the experimental results it is noted that the first crack was observed at 6 KN for Without damper whereas the damper first crack was observed at 8 KN. The saturation value of the specimen without Damper is 17 KN, but for MR damper it reaches a maximum load of 37.7 KN. The Ultimate load carrying capacity, Lateral stiffness and energy dissipation for RC frame with damper was increased by 55%, 49% and 45% respectively on compared to the bare frame.

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