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Finite Element Analysis of MR Elastomers in Steel Structures as Dampers with Seismic Loading

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Finite Element Analysis of MR Elastomers in Steel Structures as Dampers with Seismic Loading

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Civil Engineering

by

Saurabh Singhal

Thesis Committee:
Professor Lizhi Sun, Chair
Associate Professor Farzin Zareian
Assistant Professor Anne Lemnitzer

2017

DEDICATION

To

my parents and friends

in recognition of their worth

an idea

Ideas are like rabbits.
You get a couple and learn how to handle them,
and pretty soon you have a dozen.

John Steinbeck

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I would like to express my sincerest thanks to the committee chair, Professor Lizhi Sun, who suggested the idea and motivated me to work on it. His brilliance in this field helped me to come this far. Without his guidance and persistent help this dissertation would not have been possible.

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ABSTRACT

Finite Element Analysis of MR Elastomers in Steel Structures as Damper with Seismic Loading

By
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Master of Science in Civil Engineering
University of California, Irvine, 2017

Professor Lizhi Sun, Chair

During the Northridge earthquake of 1994, many steel structures collapsed as a result of the connection failures in the structure. After investigation, it was concluded that the connections in the steel structure, including the column base connection, have to be made stronger and to be able to dissipate energy during seismic motion. To facilitate that, a new kind of damper system having Magnetorheological Elastomers (MRE) as the damping material is proposed here. MRE was taken because of its ability to dissipate energy and provide extra stiffness when needed. The damper system along with the column base connection was then modelled, and modal, harmonic and transient analyses were performed on the model using Finite Element Analysis in ANSYS. The results showed that MRE successfully decreased the moment reaction at the connection, making it more reliable during strong earthquakes. The analyses were performed with prescribed loading by SAC, and El Centro ground motion, and in both the cases the designed damper system showed its capability of dissipating energy. It was also seen that with MRE as damper, the natural frequency of the connection can also be controlled, which can prove useful in certain cases. A parametric study was then conducted to see how the effect varies with different material and physical parameters of MRE.

1 Introduction

1.1 Northridge Earthquake

On 17th January of 1994, an earthquake hit the San Bernardino valley of Los Angeles with a magnitude of 6.7, later came to be known as the Northridge Earthquake. Losses occurred were grave in nature as it can be seen from the number of casualties occurred, which were 57, and the damages faced in excess of $30 billion. On investigation, it was realized that the most damage was faced by steel buildings in that area. Prior to this, steel structures were considered to be ductile and strong in nature, making them to be the ideal candidate in earthquake prone areas for tall buildings. After the earthquake, the myth was broken and it was realized that even steel structures have shortcomings when faced with high magnitude earthquakes [1].

To make sure that this doesn't happen again in future, FEMA started a project named SAC Steel Project to investigate the causes of failure of the structures, and suggest preventive measures. SAC Steel project was a collaboration of three major associations- Structural Engineers Association of California (SEAC), Applied Technology Council (ATC), and Consortium of Universities for Research in Earthquake Engineering (CUREE). After thorough investigation, SAC came to conclusions and recommendations, which were penned down in FEMA 350 [2]. The investigation concluded that although steel moment frames are resilient during earthquakes, during strong ground motions they are not capable of holding the ground as expected. Member joints are not able to dissipate the surge in energy and tend to fail during strong ground motions. Also, the connection lacks required stiffness which can help resist connection from failing in case of strong earthquake. The study included inelastic and elastic investigation of various cases of steel structure [3].

Following the study, it became a necessity to device steel structures and their connections such that, they are able to withstand the strong ground motions occurring during high magnitude earthquakes. To facilitate that, this study deals with a column base connection of steel structures with Magnetorheological Elastomers (MRE) damper system. MRE has that quality of variable stiffness, which can be controlled with application of external magnetic field. Along with that, being an elastomer based material, it can provide the required dissipation of energy as well. This study deals with a preliminary design of a column base connection with MRE based damper system. It does not deal with the complexity of implementing MRE along with its magnetic circuit. It just aims to show the effectiveness of MRE as a damping material in steel connections.

1.2 Damper Systems

Buildings have always been the soft target for earthquakes, which always results in heavy losses of life and property. To safeguard our infrastructure from that, structural engineers have always been trying to come up with new techniques. One of the technique involves implementing external damper systems to building frames so that all the energy is dissipated by them and the frame is back to its existing shape. This features helps in minimizing the losses as well as it reduces the cost of retrofitting.

Since 1980's, a lot of research has been done in this field and various types of dampers have been introduced. Foremost were the frictional dampers, which dissipated the seismic energy through friction. Most common type of friction dampers is rotating friction dampers which are commonly used with eccentrically braced frames. As the earthquake happens, the ground motion forces the metal in the dampers to rotate and slide against each other, eventually dissipating the seismic energy [4]. They are one of the most common types of dampers and have been used in numerous tall steel buildings over the year. After friction dampers, Pendulum Vibration Dampers (PVD) started gaining name. They are small dampers installed in braced frames and works basically on the plasticity of the lead core inside them. Lead has a high plasticity and is hysteric in nature, just like iron. So, in case of an earthquake, it is able to plastically deform in a cyclic nature and dissipate the seismic energy [5].

Later down the years, new unconventional materials like alloys, elastomers, fluids, etc., have started replacing the old conventional materials in the damper systems. One of the most famous dampers is the Shape Memory Alloy (SMA). SMA is an alloy, commonly consisting of nickel and titanium, which has a high ductility compared to any other metal or alloy. Because of its high ductility, it has been used to make damper systems which can be implemented in buildings where high ductility in connections are needed. One the use is in the column-beam connection of self-centric buildings [6]. In case of an earthquake, these alloy tendons do not yield, and it makes sure that the connection and the building itself comes to its original position after the earthquake. Although because of its high ductility, it has been effective in making sure that the connection between the members does not break, it has not been able to solve the problem of energy dissipation. SMAs do not take part in dissipation of seismic energy, they only make sure that the connection between the members do not break. This limitation has led to the development of dampers involving viscous materials like Magnetorheological Fluids (MRF) as the damping material.

MRF is a semi fluid compound with magnetic particles suspended in it. When an external magnetic field is applied, these magnetic particles align themselves with each other and create a chain like structure. This chain like structure imparts extra stiffness to the structure, and the fluid part imparts damping to the frame. MRF based dampers are usually used in braced frames, where the dampers are connected to the braces [7]. Although these dampers have been effective, they come with few limitations. As it is a fluid based damper, it is not an active damper and have to be always applied with magnetic field to make it functional. Also, the fluid inside it makes it difficult to handle and maintain it, as there is a high probability of leakage and accumulation. These shortcomings made MRE to be a better option for dampers. Although, MRE have been used in base isolation of buildings for some time now [8], they haven't been implemented as a damper in structures yet. This study aims to discuss about such a damper system in steel structures. As it was discussed earlier, after Northridge earthquake there was a need to look into the member connections in the steel structures. To make them stiffer and be able to dissipate energy, a MRE damper system at the column base connection is proposed in this study. The damper system is then analyzed for modal, harmonic and transient analyses, to evaluate its elastic and inelastic behavior. The study aims to highlight the effectiveness of MRE as a damper in steel structures.

2 Introduction to MRE

2.1 About MRE

Magnetorheological Elastomers, commonly known as MRE, are a compound mixture of ferrous particles embedded in a elastomer matrix. The effect was first discovered by Rabinow [9] in late 1940s. Although, the effect was developed early in the century, it was in 1980s when researchers taking it seriously and tried implementing it in various areas. The pioneer work was led by Rigbi and Jilken, (1985) [10] where they tried to measure the potency of MRE in medical devices as vibration dampers. This study created a platform for a comprehensive study on MRE by Jolly et al in 1996 [11]. They created a quasi-static model to explain the modulus change behavior of MRE. They did experiments on an elastomer matrix with ferrous particles embedded inside them to verify the model. The study attracted other researchers to conduct study on MRE and since then various models have been developed to implement MRE in varied fields of engineering.

MRE is essentially a compound composed of three basic materials- elastomer matrix, ferrous materials and additives. All the components are mixed together homogeneously to form MRE. The process of making MRE consists of few intricate details that can’t be looked upon if a well-functioning batch of MRE is needed. The first step in the process is to mix all the components- elastomer matrix, ferrous material (iron particles) and additives (usually silicone oil) thoroughly to prepare a homogeneous mix. The mix is then given treatment in the vacuum chamber or a heat treatment to remove air trapped inside the mix. This is done to maintain the flexibility and the high permeability of the material. The mix is then cured either in the presence or absence of magnetic field. If treated in absence of magnetic field, the MRE formed will be isotropic in nature and will exhibit the same physical properties in all the directions. But if it is cured in presence of magnetic field then the developed MRE will be anisotropic and will exhibit enhanced strength in one of the direction. To prepare anisotropic MRE, the magnetic field used should be in excess of 0.8 T. When cured in presence of magnetic field, the ferrous particles present in the matrix will align themselves in the direction of the field and will have enhanced in the direction of the field. So, in anisotropic MRE, the ferrous particles are linked together while in isotropic MRE they are uniformly dispersed. Anisotropic MRE can be used in special cases where extra stiffness is required in one of the directions. The curing is done at a temperature (usually above 120 C) to maintain the flexibility in the matrix. After curing, MRE goes under chemical process of vulcanization or polymerization to form links between the polymer chains. This is done to make the material more durable. The vulcanization duration depends on the type of elastomer matrix and the engineering application of the MRE formed eventually. The longer the duration, the more durability the material will have. Generally, soft rubber is cured for a longer duration to impart the required durability. Vulcanization makes sure that the elastomer is not sticky anymore and have enhanced mechanical properties [12].

2.2 Properties of MRE

MRE being an elastomer based material, mainly comprises of two types of engineering material properties- hyperelasticity and viscosity. Being a hyperelastic material, it has the capability to be flexible and maintain its shape even after high level of strains are applied on it. When a linearly elastic material is applied with a high level of strain, it will lose it elasticity and will start behaving as a plastic material. In case of hyperelastic materials, they behave as elastic materials even when applied with high level of strains. The stress strain relationship of hyperelastic materials are non-linear, isotropic, incompressible and independent of strain rate. As it is non-linear in nature, a hyperelastic material cannot be modelled as a linearly elastic material. This property makes elastomers highly flexible and hence, a star material for engineering applications.

The other property of MRE, viscosity, makes the MRE capable of dissipating energy and provide damping where needed. Both the properties combined together makes MRE to be a viscoelastic material. When discussed in terms of modulus, viscoelastic materials change its modulus over the period of time when applied with force. They have an initial modulus, commonly termed as the storage modulus, which decreases with time when applied with stress. This property helps them to dissipate energy and provide damping [13].

In case of linearly elastic materials, when stress is applied, they immediately respond with a strain and the ration between the two is known as the modulus. That modulus will have a constant value throughout, but in the case of viscoelastic materials, the case is entirely different. The modulus of viscoelastic materials is complex in nature and have two terms associated with it. The shear modulus *G* of viscoelastic materials can be further divided into two terms, *G'* and *G"*. *G'* is the storage modulus while *G"* is the loss modulus [14].

$$G = G' + jG'' \qquad (1)$$

The storage modulus is responsible for the energy stored in the elastomer when stress is applied, while the loss modulus is responsible for the energy dissipated. When magnetic field is applied on MRE, it makes the ferrous particles link together and form a chain like structure. These chain like structures make the elastomer stiffer in the direction of magnetic field and help impart extra stiffness. When discussed in terms of shear modulus, the initial modulus will be *G*, and the magnetic field will increase its value by *ΔG*. This increase in modulus is a characteristic feature of MRE. Now, as MRE is a hyperelastic material, its elasticity won't be affected in case of high strains and it will be in its pre yield region most of the time, making it an active damper. In the pre yield region, the modulus of the elastomer is the most important property and will define how the material will behave in case of stress. As we can increase the value of that shear modulus by applying magnetic field, it helps to modify the material according to the need.

Because of this property, MRE is implemented in varied engineering applications where the stiffness is needed to be controlled.

To be applied with magnetic field, the MRE system is to be designed such that a magnetic circuit is there all the times to supply the magnetic field. Either a permanent magnet or a solenoid is used as the magnetic circuit. Although permanent magnets have the potential to supply a strong and uniform magnetic field, solenoids magnetic field can be controlled according to our need. In case of solenoid, the direction and magnitude can be altered. The new age magnetic circuit uses both type of magnets together. The permanent magnet is used to supply a constant strong magnetic field all the time, while the solenoid is used to control the magnetic field according to the system's need. Also, the magnetic field applied has to be uniform and has to be uninterrupted all the time. To get the maximum magnetic effect the magnetic field should be applied in the perpendicular direction to the elastomer movement. It has to be made sure that there is minimum energy loss and an enclosed path is there for the magnetic flux. The most common type of circuit is the C shaped circuit, which encloses the MRE in a C shape with either poles at the either sides of the MRE [15]. The poles should have minimum distance between them so that the energy loss in the air is minimized and the magnetic field is strong and uniform. These limitations make the designing of the magnetic circuit a challenge, and is still considered to be a limitation in the application of magnetorheological materials.

2.3 Uses of MRE

The most useful property of MRE is to dissipate energy and provide damping in engineering applications. This property has made MRE to be used as a damper or a vibration in many engineering applications. Some of the applications are discussed here.

2.3.1 Vibration Absorbers

Often known as tuned vibration absorbers (TVAs), they are used to absorb the vibration caused in mechanical systems such as motors, pumps, engines, etc., because of the structure imbalance between the components. The vibration caused in the systems are arbitrary in nature and can have different types of frequencies. To adjust to those frequencies, we need an active damper rather than a passive damper. As MRE is active in nature, it has shown its effectiveness in vibration absorption. The vibration absorbers developed using MRE are also known as adaptive vibration absorbers. The frequency of these absorbers can be changed using the field dependent stiffness property of MRE, which makes them suitable for a wide range of frequencies.

The first kind of MRE based TVA was developed by Ginder et al (2001) [16]. The MRE based system was closed circuit, with MRE sandwiched between the two end poles (Figure 1). The mass was mounted on top of a steel plated which was placed between the MRE samples, which works in shear mode in this case. The closed circuit makes sure that uninterrupted, uniform and strong magnetic flux is transmitted between the two poles. With this magnetic field, the stiffness of MRE can be controlled. When the mass experiences vibration, the MRE attached to the steel plate damps it and makes it difficult to move, in turn, damping the vibration. Vibration with varied frequencies can be damped as the stiffness of MRE can be controlled. The circuit was made magnetic by wrapping wired coil around the circuit. Later, Deng et al [17] improved the design by adding another wired coil on the other side of the circuit. This helped improve the magnetic flux intensity received by MRE.

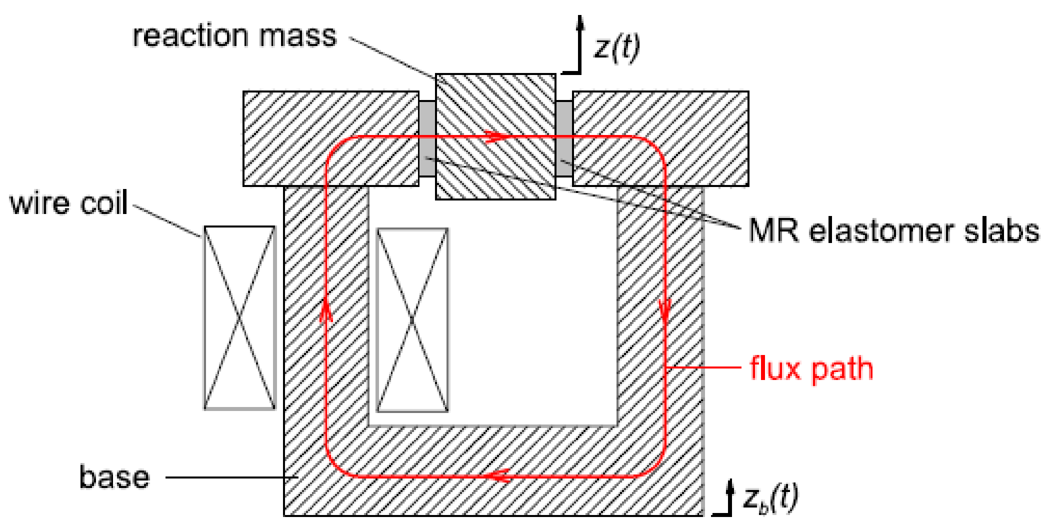

Figure 1 Magnetorheological elastomer tuned vibration absorber by Ginder et al [16]

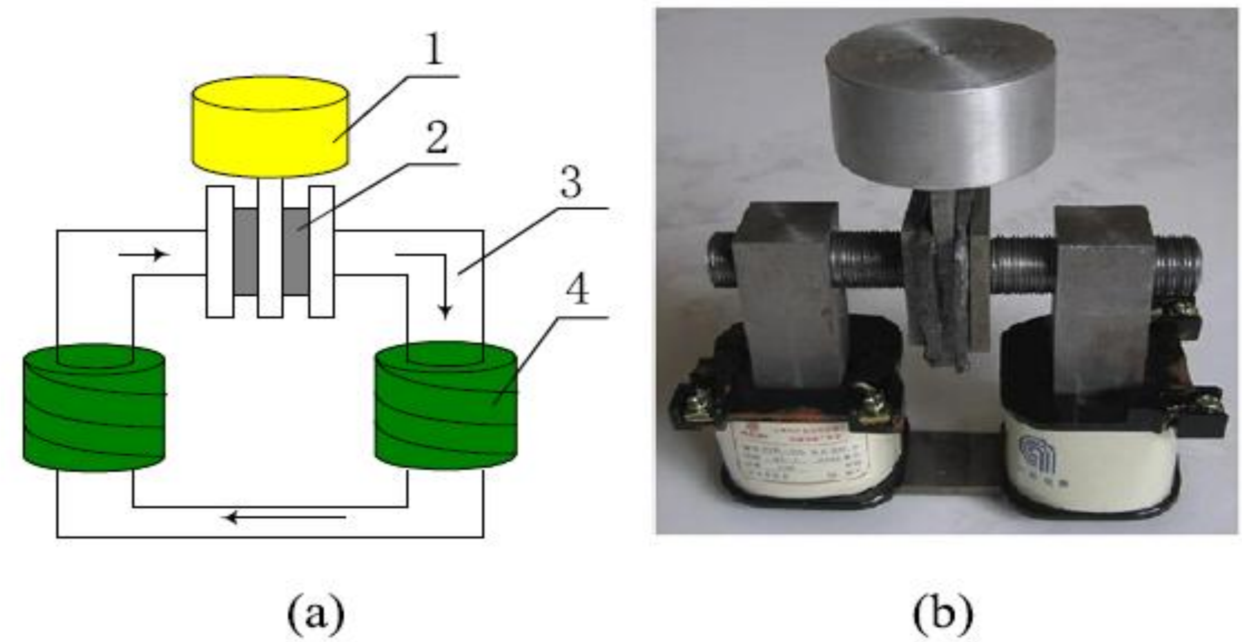

Figure 2 ATVA proposed by Deng et al (2006) (a) Sketch: 1. Oscillator; 2. MR elastomer; 3. Magnetic Conductor; 4. Coils (b) Experimental Setup [18]

The basic model was modified by many researchers to improve its effectiveness and efficiency. Zhang et al (2008) used anisotropic MRE and changed the current input to improve the frequency on which the TVA will work [18]. Deng et al (2006) improved the circuit design to reduce the magnetic flux losses (Figure 2) [17]. Hoang et al used the similar kind of shear TVAs to damp vibrations in rotational motion [19]. They modified the assembly by introducing rotating rings rather than translating steel plates. Kallio et al developed TVAs that can be used in squeeze mode [20]. The compressive forces applied on the TVA can be countered by controlling the compressive modulus of MRE. Although a variety of MRE based TVAs have been developed till now, but all of them have the basic components as the same. They all had MRE with a mounted mass which is enclosed by a C shaped magnetic circuit. The TVAs developed till now have been implemented in variety of mechanical and aerospace engineering applications.

2.3.2 Vibration Isolators

To isolate a part of the structure from vibration, vibration isolators are used. In civil engineering applications these vibration isolators are termed as base isolators. The other type of vibration isolators are force isolators which work on the same concept as the base isolators. In base isolators, MRE is attached between the part that is to be isolated and the rest of the structure. When the structure experiences any kind of vibration, the MRE present damps the vibration as much as possible and only some of it is transferred to the isolated part. This is used in applications where a specific part of the structure is needed to preserved from vibrations. MRE being an active damper proves to be a better kind of isolator compared to passive dampers. Vibrations are generally unique in nature and have different kind of frequencies associated with it. MRE isolators are able to tune according to the vibration frequency and are adaptive in nature.

Ginder et al (2000) developed vibration isolators for wheels which can be used in either translation and rotation (Figure 3) [21]. The isolator developed consisted two steel hollow cylinders, between which MRE was sandwiched. The inner cylinder had the magnetic circuit attached to it. In case of vibration, MRE works in the shear mode. The model was then modified by Du et al (2011) to develop vibration isolators for seats (Figure 4) [22]. MRE was sandwiched between an inside solid core and an outer bracket, and the seat is mounted on the inside core. The magnetic circuit is inside the outer bracket. In this model, MRE works in all 3 modes- shear, elongation and compression.

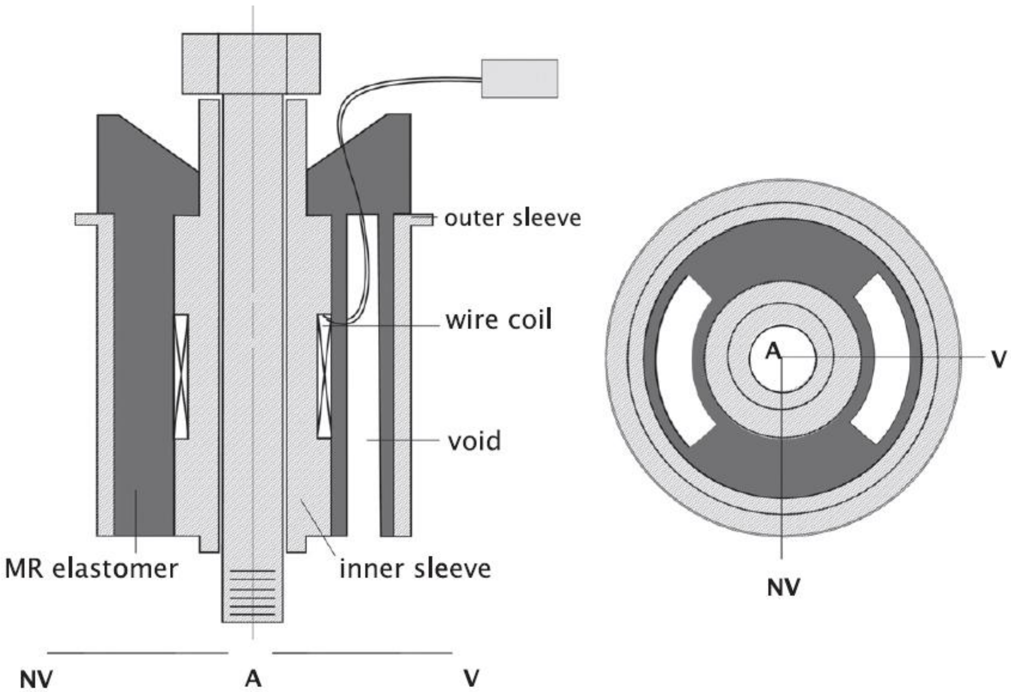

Figure 3 MRE vibration isolator by Ginder et al (2000). Sectional view is along NV-A-V, where NV is the non-voided direction, V is the voided direction, A is the axis of rotation [21]

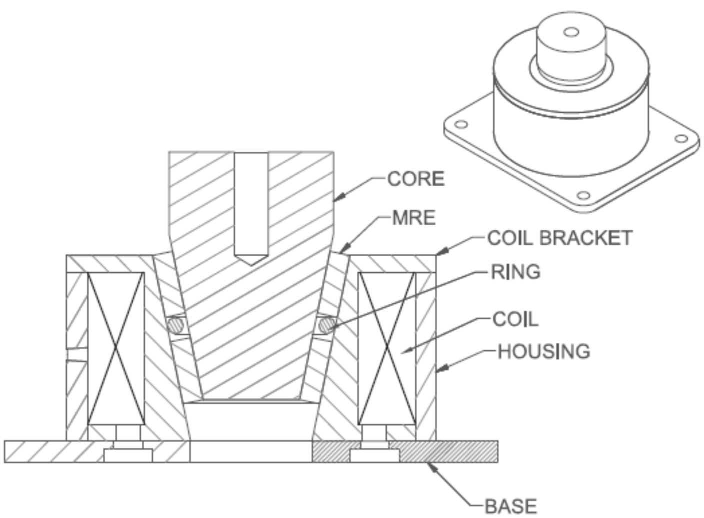

Figure 4 Seat vibration isolator by Du et al [22]

In case of civil engineering, MRE is used to develop base isolators which isolate the building from the ground motions during earthquake. In case of an earthquake, the ground experiences extreme motions which are then passed from the foundation to the structure. In most of the cases, the structure is not able to handle that kind of motion and ultimately collapses or gets critically damaged. To prevent this from happening, base isolators were developed to isolate the building from the ground. Li et al (2013) proposed a laminated base isolator using MRE and steel plates (Figure 5) [23]. The isolator was formed using alternative layers of MRE and steel plates. MRE is present there to dissipate energy and damp the motions. It will work in the shear mode.

Steel plates are present to impart vertical stiffness to the isolator. The isolator is placed between the foundation and column, so that when the foundation experiences motion, it will not get transferred to the building. The proposed model has been extremely successful and has been used to develop base isolators at commercial level.

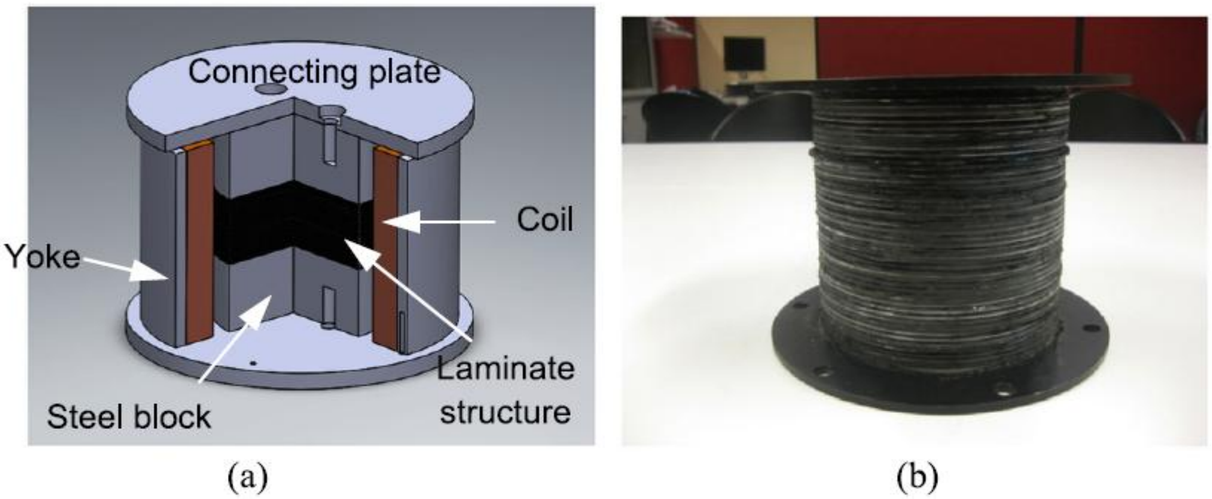

Figure 5 MR elastomer based base isolator by Li et al (a) Cross section view (b) Experimental Setup [23]

2.3.3 Sensing Devices

When magnetic field is applied to MRE, changes occur to the structure of the elastomer at the micro level. The spacing between the particles along the chain structure changes when extreme load is applied, which causes change in the electrical property of the elastomer. This develops features such as magnetoelasticity, magnetoresistance, magnetostriction, piezoresistance and thermoresistance in MRE [14]. These features make MRE suitable to be used in sensing devices like temperature, pressure and chemical sensors. Li et al (2009) developed a force sensor using the piezoresistnace of MRE (Figure 6) [24]. They developed a sensor to identify normal loading using the relationship between the loading and the voltage output. The experiments conducted by them showed a linear relationship and repeatability between the two. The filed is comparatively new for researchers and still require a lot of research to be done.

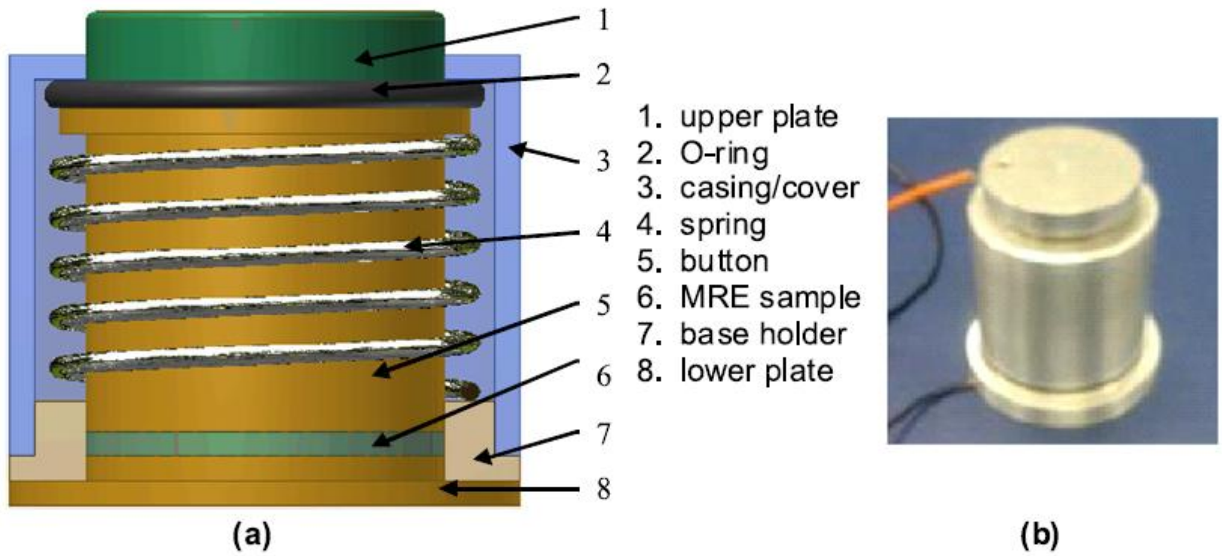

Figure 6 Force sensor by Li et al (a) Schematic diagram (b) Prototype [24]

2.3.4 Other MRE devices

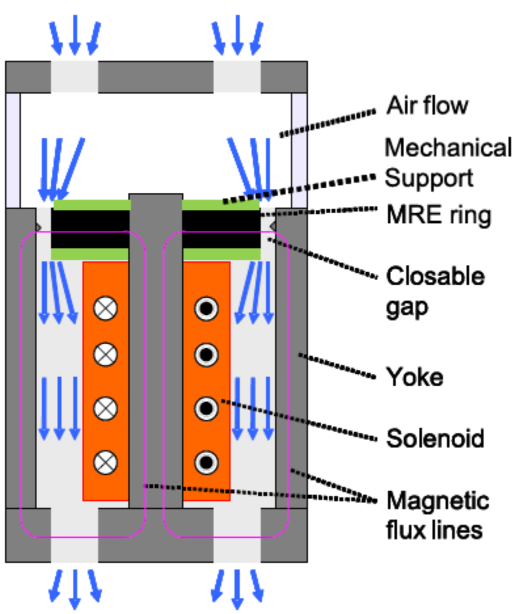

Figure 7 Controllable valve by Bose et al [25]

When a magnetic field is applied to MRE, the magnetic particles inside the elastomers move along the magnetic field, called as the field-active mode. This develops the feature in MRE for having high level of strains and faster response time. These features make MRE to be an ideal candidate in development of soft actuators, fast artificial muscles, etc. Bose et al (2012) developed a controllable valve using soft MRE [25]. As the magnetic field is applied on MRE, it expands and can control the flow of air through the valve. The developed system is shown in Figure 7, as the magnetic field is applied, the MRE expands and closes the gap between the yoke and the ring. Same way, if we change the magnetic field, we can increase the gap as well to allow more air in.

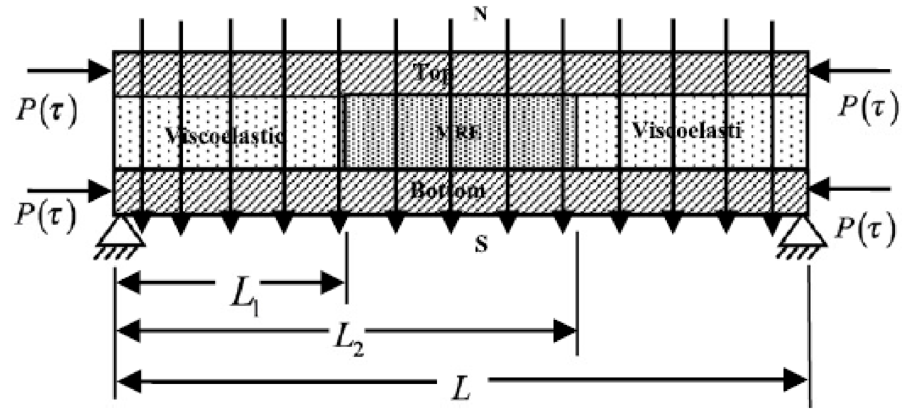

Figure 8 MR Elastomer sandwiched beam by Zhou et al [26]

Apart from this, sandwich beams have been prepared using MRE in between as the magnetic field causes shift in the physical status of MRE. Zhou et al (2009) first came up with the idea to develop sandwich beams using MRE in adaptive structures (Figure 8) [26]. They conducted numerical and finite element investigation to see the effectiveness of MRE in reducing structural vibration. Nayak et al (2012) followed and conducted numerical investigation to prove the hypothesis [27].

3 Column Base Connection

3.1 Review

As discussed earlier, connections in steel structures are the most critical part of it. When talked about column-beam connection, a lot of research has been done on it to make it strong and robust, but for the column beam connection there is still scope for improvement. At the foundation level, earlier research involved application of base isolators between the column and the foundation. Although, it has proved to be extremely effective, the process of its installation is complex and costly. This is the main reason that the method has not been that famous when it comes to the implementation part.

Kanvinde et al (2014) [28] conducted research on the performance of the connection between HSS column and foundation. The research was primarily aimed to evaluate the performance of current column base connection using base plate and anchor rods (Figure 9). HSS columns are used as the corner columns in moment resisting frames and cantilever columns systems for mezzanines and storage racks. For the designing of these connections, Steel Design Guide One has prescribed specific guidelines regarding the placing of tension bars along the base plate. The pattern although makes sure that the connection between the base plate and the foundation is not lost, it is not able to prevent the base plate from fracturing. Kanvinde et al analyzed the performance of the present guidelines for the connection and then suggested improvements that can be made to strengthen the base plate.

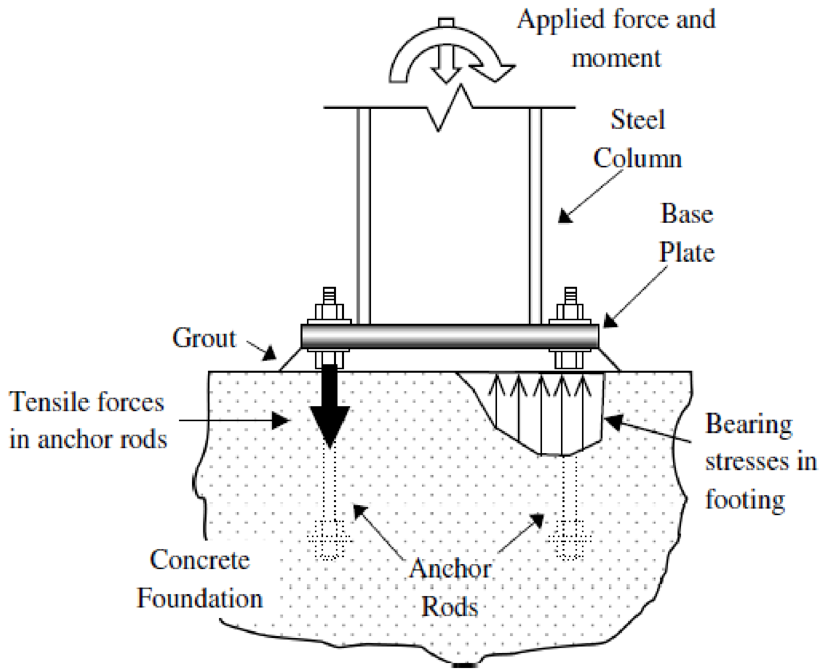

Figure 9 Schematic diagram of an exposed column base connection [28]

The HSS columns are a built up box sections which are connected to base plates with a single weld. These welds are single sided welds with no access to the inner material of the column. This makes the connection heavily reliant on the base plate. When the column experiences flexure, the weld interacts with the yield line along the base plate and make it yield. The yield line is formed along the corners of the section, making it compromise the strength and the deformation capacity. Although it does not cause any damage to the column or the anchor rods, the connection gets compromised. The present model suggested by the Steel Design Guide One employs four anchor bolts at the four corners of the base plate. The calculation of inner stresses and strains are based on the interaction of column, base plate, rods and grout on the basis of the mentioned model. There haven't been any calculations yet considering a model with a different type of setup or anchor bolts arrangements. Kanvinde et al decided to increase the number of anchor bolts from four to eight, by adding bolts along the center line as well. By doing this they measured the performance of the new setup compared to the present one.

To analyze the performance, they conducted a series of eight tests with different setup of components and loading. The setup consisted of a cantilever column, welded to the base plate. The total length of the column was taken as 3200 mm with cycling loading at the top. Welds were complete joint penetration (CJP) welds from the outside of the column. The base plate was connected to the concrete foundation with anchor rods. The anchor rods ran all the way through the foundation and were secured at the bottom using bolts. Between the base plate and the foundation, a grout made up of mortar was also present. The grout was there to prevent any damage happening to the foundation. The foundation was placed on top of two spacer beams, so that they can have access to the bottom part of the foundation for installation of load cells. Load cells were in connection to the anchor rods, and were capable of recording the tension developed in the rods.

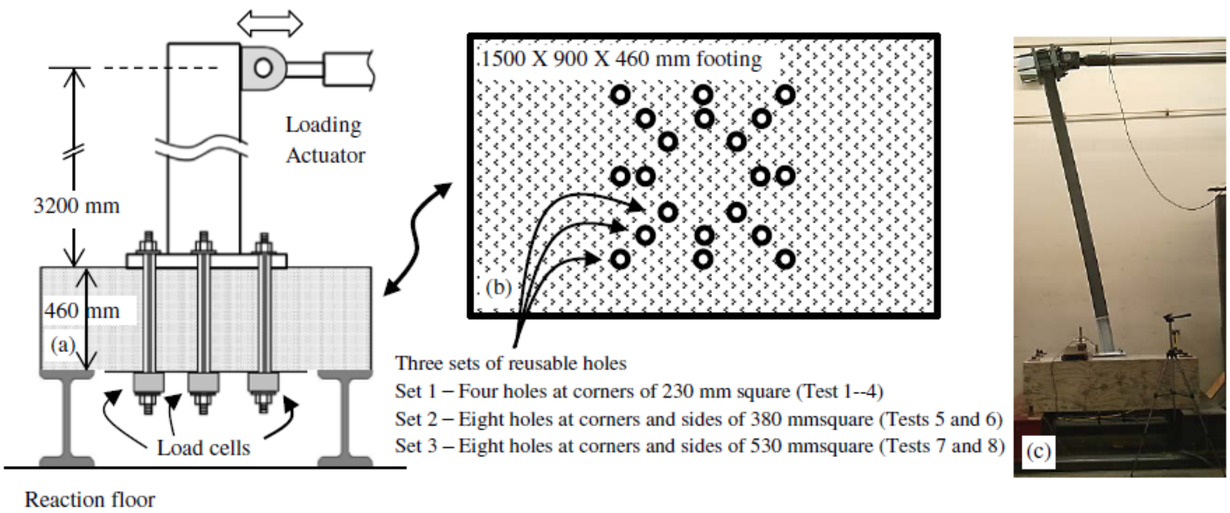

Figure 10 Test setup: (a) Schematic elevation; (b) Plan view; (c) Test in progress [28]

The test setup can be seen in the Figure 10, where the dimensions of the foundation and column is given along with the pattern for the anchor rods. A total of eight tests were conducted with different anchor rods pattern, base plate sizes and peak rotations. The edge distance was kept constant at 38 mm. The properties of all the components, with their dimensions for each setup has been mentioned in the Table 1.

Table 1 Test Matrix [28]

Test number	Column size (mm)	Column material properties F_y (MPa)	Column material properties F_u (MPa)	$M_p^{column} = Z \cdot F_y$ (kN · m)	Plate size B, N (mm)	t_p (mm)	Base plate material properties F_y (MPa)	Base plate material properties F_u (MPa)	Rod layout	Peak base rotation θ_{base}^{max} (rad)	Peak drift Δ^{max} (rad)	M_{max}^{test} (kN · m)	M_{max}^{test}/M^{DG-1}	M_{max}^{test}/M^{new}
1	HSS 127 × 127 × 9.5	457	538	78.8	305 × 305	19	337	487	4 rods	0.130	0.166	59	1.58	NA
2										0.071	0.111	57	1.52	
3	HSS 152 × 152 × 9.5	444	524	114.0	305 × 305	19			4 rods	0.086	0.112	77	2.03	
4										0.082	0.110	83	2.19	
5	HSS 203 × 203 × 9.5	414	514	197.9	457 × 457	19			8 rods	0.092[a]	0.111[a]	115	1.60[b]	1.50
6										0.110	0.129	145	2.02[b]	1.89
7	HSS 254 × 254 × 12.7	414	518	408.6	609 × 609	31.75	354	518	8 rods	0.057[a]	0.070[a]	239	1.26[b]	1.05
8										0.058[a]	0.070[a]	234	1.24[b]	1.03

[a]Fracture observed at weld.
[b]*Steel Design Guide One* method applied disregarding inner row of rods.

Concrete was assumed to have its 28-day compressive strength, i.e., f'c = 28.1 MPa. All rods were of 19 mm diameter and assumed to be of ASTM F1554 Grade 105 (Fu = 723 MPa). Columns were A500 Grade B, whereas the base plates were nominally A36.

The loading is applied at the top of the column using an actuator. The loading is a displacement loading prescribed by SAC [29] (Table 2) for seismic performance testing of SMRF components and assemblies. The cyclic displacement loading is based on the drift angle which is the peak deformation for the cycle and has to be multiplied by the total height of the column (3.2m) to get the actual displacement at the top. The deformation is kept constant for a certain number of cycles after which it is increased with reduced number of cycles. The loading is represented in the table and the graph below. The base plate is assumed to be flat on the foundation. For that to happen a certain pretension was applied in the anchor rods.

Table 2 SAC prescribed loading in terms of peak drift

Load Step Number	Peak Drift Angle θ	Number of Cycles
1	0.00375	6
2	0.005	6
3	0.0075	6
4	0.01	4
5	0.015	2
6	0.02	2
7	0.03	2
Continue with increments of 0.01 in θ, and perform two cycles at each step		

As the loading was applied and the experiments were performed, the results were obtained in terms of the moment generated at the connection and the corresponding rotation produced in the column. All the test specimens showed good deformation capacity with maximum column drift ratios in the range of 7-16%. The anchor rods remained elastic in tension throughout. The design approach mentioned in Steel Design Guide One was able to predict the forces with fine accuracy for the four rods layout, but when the same approach was applied in the eight rod layout it turned out to be conservative in nature and couldn't predict the forces as expected. For the mentioned case, Kanvinde et al developed a new design approach considering the forces in the inner row of rods as well.

In all the test cases, column was able to withstand the forces, but in three of the test cases, with eight rods layout, fracture was observed in the base plate. When both the layouts were compared, the eight rod layout may not be able to provide significantly higher strength but was able to reduce the deformation capacity. It can be noted that the eight rods layout is helpful in the cases where the column is experiencing high out of plane moment. For designing of these cases, the new approach developed can be used to calculate the forces more accurately. The current design approach only deals with the strength and deformation capacity, which can be altered using the number of rods or the thickness of the base plate. It still is unable to deal with the energy dissipation characteristic of the connection. This is one of the area where more research is required.

3.2 Finite Element Modelling

The main aim of this report is to analyze the column base connection with MRE as the damper. To do that it was needed to model the whole system in an existing finite element based analysis software and then do the analysis. To get the best results, it was necessary to model the system as accurately as possible. This was done by using one of the test cases used by Kanvinde et al for modelling. First test case was considered and was modelled in ANSYS 16.2. After modelling, it was analyzed for cyclic displacement loading as it was done in the paper. The results were then compared to the actual results obtained in the paper. By doing this, it was made sure that the model which was developed is capable of producing results as it will do in the case of actual experiments.

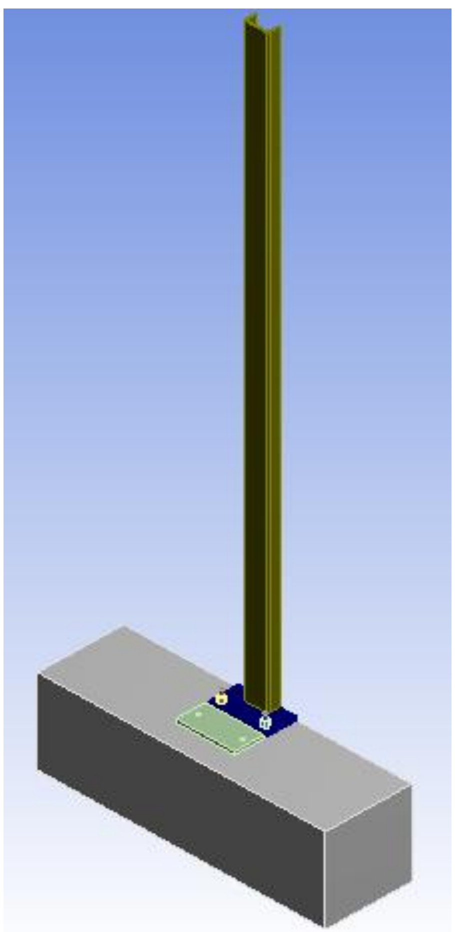

Figure 11 3-D model of column base connection in ANSYS

To do the analysis, ANSYS 16.2 Workbench was used. As ANSYS is a Multiphysics software, there were various options depending on the analysis to be done. Out of those, ANSYS Mechanical – Transient Structural was used, as our model is a transient analysis of a structure. The modelled setup is shown in the Figure 11. The loading was applied at the top as shown. As along the direction of loading, there is a plane of symmetry in the model, only half of the whole was modelled to reduce the analysis time.

Before the analysis, the model had to undergo various stages of development. First one being the designing of the model. In the Design Modeler of ANSYS, the whole model was developed part by part. Designing started with one of the component and then designing the attached components one by one. While designing the attached component, it had to be made sure that it is in contact with the other components and is not penetrating into any of them. This was done by carefully examining the dimensions and designing on its basis. All the components were designed separate to the other components and were assigned material properties correspondingly. The engineering properties of all the materials were defined early on and were later assigned to the respective component.

After the designing, the contacts between each set of components were defined separately according to their behavior in the setup. ANSYS has the capability to automatically recognize if two bodies are touching together and then they represent it as a contact. These contacts were then defined separately according to their behavior in the setup. The weld connection between the column and base plate was defined as a bonded connection as it is expected from the connection to not fail. Foundation and base plate connection was modeled as a frictional contact with a friction coefficient of 0.45. As the anchor rods can slide against the concrete, the connection was modeled as a frictionless contact. All other connections were between two different steel components and were modeled as a frictional contact with a friction coefficient of 0.8.

After completing the contact modelling, the setup was ready to be meshed into smaller elements for finite element analysis. The mesh was developed using a 20 node 3-D solid element called SOLID186 in ANSYS. The mentioned element exhibits quadratic displacement behavior with three degrees of freedom per node. The reason for using the above mentioned element was that it supports plasticity, large deflection, large strain, hyperelasticity. Total number of solid elements present were 14187. It was made sure that the nodes at the contacts were modelled in a same way, from either side and will not change its position other then it is expected from its definition. The mesh produced was a mixture of different element sizes depending on its position. The elements close to the contacts were made smaller in size compared to the elements present in between the geometry. After defining the type of mesh, it was generated and was checked for any irregularities.

The created meshed body was then applied with loads and boundary conditions, in preparation for analysis. Kanvinde et al in their paper mentioned that the first setup has pre-stressed anchor rods. This was done to make sure that the base plate is flat and is in contact with the foundation completely. The mentioned pre-stress was 4-9 kPa, hence, an average value of 7 kPa was used for all the four rods. The load applied was the same cyclic displacement load as was considered in the paper. It was applied at the top of the column. For the boundary condition, the foundation was assumed to be fixed. The components were assumed to be present with weight, hence, the standard earth gravity was assumed to be present in the downward direction.

Table 3 Model Components and their properties

Component	Model	Density (kg/m3)	Strength (MPa)	Poisson's Ratio	Young's Modulus (MPa)
Base Plate	Bilinear Isotropic Hardening	7850	F_y = 337, F_u = 487, Hardness Modulus = 756	0.26	200000
Column	Bilinear Isotropic Hardening	7850	F_y = 457, F_u = 538, Hardness Modulus = 408	0.26	200000
Concrete	Isotropic Elastic	2400	f'_c = 38	0.2	25000
Rods	Bilinear Isotropic Hardening	7850	F_y = 862, F_u = 976, Hardness Modulus = 782	0.26	200000

The engineering data for each component was defined for ach material type and was later assigned to each component accordingly. For the column, it was assumed to be an elastic material with a bilinear isotropic plasticity. Density, poisson's ratio, yield strength and the ultimate strength, were also defined for the steel separately. Base plate and anchor rods were also defined with the same material model as the column steel, but with different values of properties. Concrete was expected not to develop much stress or strain and will remain elastic the whole time. For this reason, it was modelled as an elastic metal, with density, poisson's ratio and strength mentioned separately (Table 3).

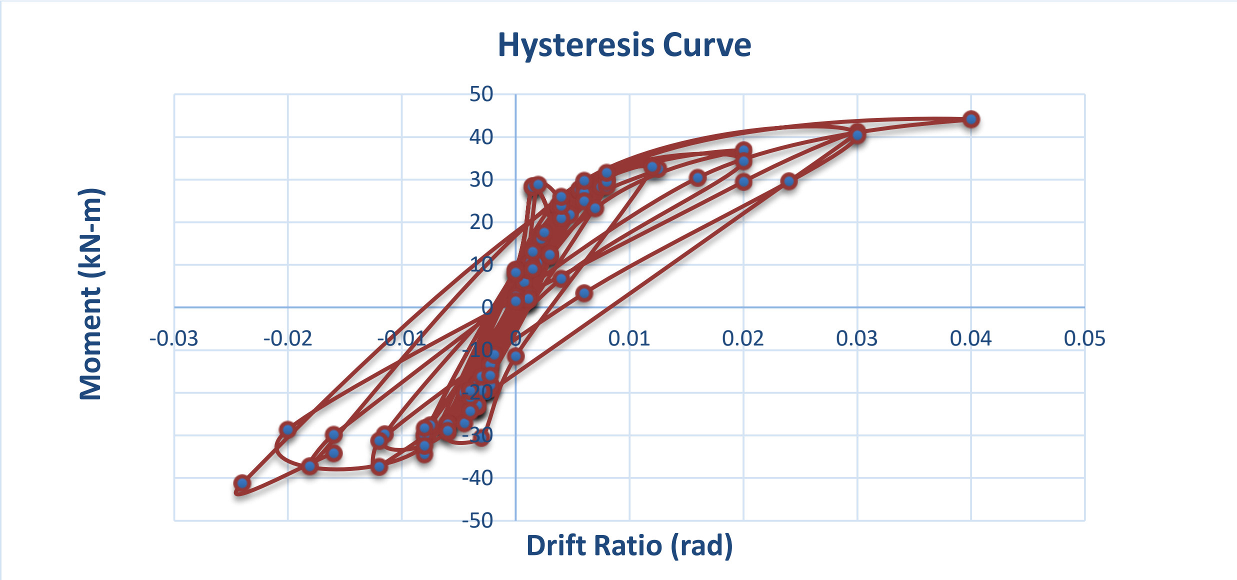

Figure 12 Hysteresis curve obtained in ANSYS

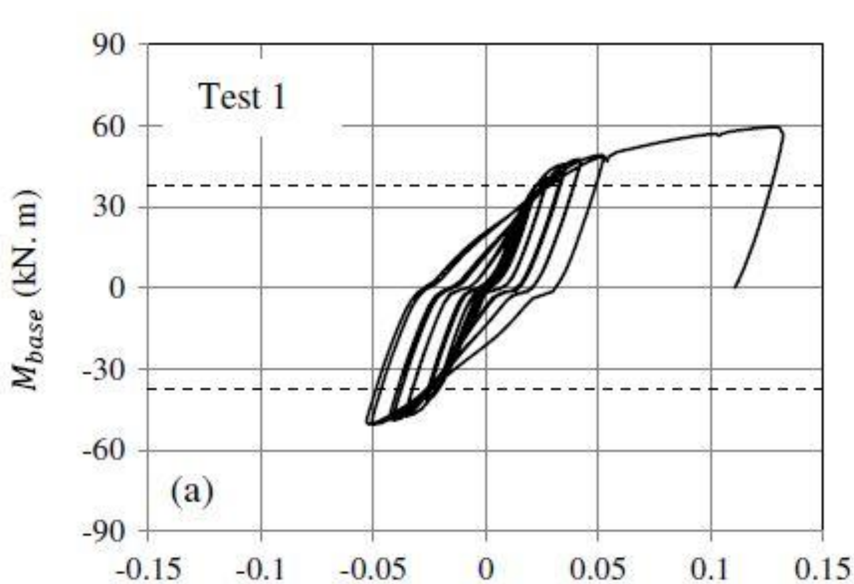

Figure 13 Hysteresis curve obtained by Kanvinde et al [28]

The analysis was conducted and the moment hysteresis curve was obtained with respect to the drift ratio (Figure 12). The obtained hysteresis curve was compared to the one obtained in the paper (Figure 13). At first sight, the curve didn't seem to show the hysteresis as it was expected after seeing the one obtained in the paper. This was due to the lack of data points in the analysis. Still, the curve was able to show us how the model behaved when applied with the prescribed loading. It can be seen that a base moment of about

40 kNm was developed with a drift ratio of 0.03, which was similar to the value obtained in the paper. Also, the curve appeared to be hysteric in nature and had the similar cyclic nature compared to the original one. Although, the analysis didn't give us the precise results, but it was enough to show that the behavior of the model is similar to the actual experimental setup and can be used for further analysis.

4 Analyses

4.1 Column Base Connection with MRE

In the previous section, we were able to successfully model a column base connection using ANSYS. Now the next step is to analyze the performance of the connection with MRE as the damper. To do that, we need to design the connection with MRE in it. MRE being a magnetic elastomer, requires the setting up of a fully functioning magnetic circuit along with it. As this report deals with the preliminary details regarding the working of MRE as a damper in steel structures, we neglect the circuit and other geometrical limitations associated with it. In the new model, MRE connected to the column in the simplest way possible. This will help to analyze the effect of presence of just MRE as a damper at the connection.

The designing of MRE was done by simply attaching it to one of the outer faces of the column. The other end of MRE was constrained by a side plate. This side plate was attached to the foundation in the same way as the column is attached. The properties of the side plate were same as the column. MRE was sandwiched between the side plate and the column, but moves freely over the foundation. The designed model can be seen in the Figure 14. As MRE was attached in the direction perpendicular to the direction of the movement, it would work in shear.

MRE was considered as an elastomer matrix, and was modelled using two models- Neo-Hookean and Shear Prony Series. Both the models are discussed in details in later sections. The mesh was developed using the same SOLID186 element in ANSYS. The total number of elements were 18895. Density of MRE was taken as 1.3 kg/m^3. It was assumed to have a Poisson’s ratio of 0.48. The

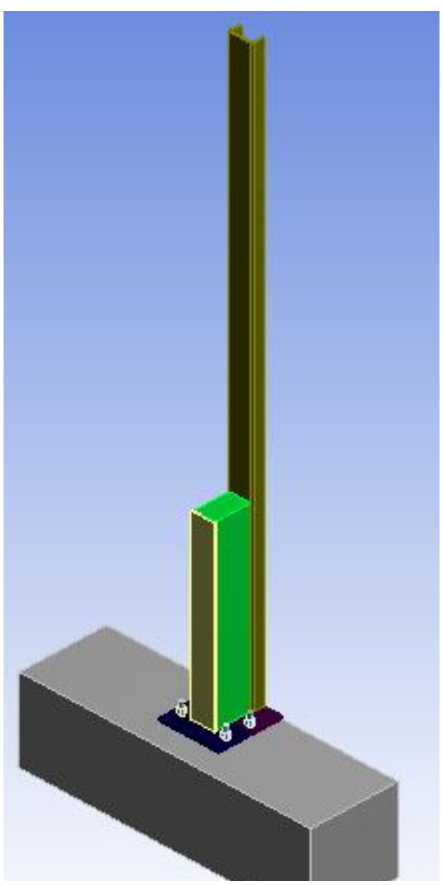

Figure 14 3-D model with MRE

Column
MRE
Side
Plate
Concrete
h
d

width of MRE was same as the clear width of the column, while the height was decided on the secondary seismic effects developed in the column. When buildings face ground motion, the load on the columns will not act along the center line anymore. Because of the lateral movement, the loads will act at a distance from the centerline of the column and will create eccentricity in it. This eccentricity causes a secondary effect in the column known as the P-Δ Effect [30]. This effect causes the column to develop a hinge near the connection and makes them eventually fail. At times during designing, this effect is ignored. But, as we are developing the connection that will be present in the buildings during high magnitude earthquakes, we need to consider the effect in our case. There is no way to determine where exactly it will occur, but generally it is assumed to occur at about 0.2H from the location of the connection (H=height of the column). In our case H =3.2 m, hence a nominal height of 1m was considered for the MRE so that it can provide extra strength at that location and prevent it from happening. This height was later varied to perform a parametric study. The depth of MRE, from side plate to the column, was assumed to be 180 mm. The depth was also later varied to perform a parametric study. After the designing was done, different types of analyses were performed on it to evaluate its performance.

4.2 Modal Analysis

After designing, the next step to evaluate the performance of the model was to perform elastic and inelastic analyses on the model. Before going to the inelastic analysis, we needed to see the elastic performance of the material. For this, we started with modal analysis to determine the natural frequency for the initial 5 modes of the model. This helped to determine whether MRE was able to provide significant change to the stiffness of the model and eventually the natural frequency of the model.

Natural frequency defines how a mechanical system is going to behave when applied with a harmonic load. If the natural frequency coincides with the frequency of the applied load, then the system can attain resonance. During resonance the amplitude of the deformation becomes extremely high and can seriously damage the system. This can be prevented if we can alter the natural frequency of the system. Generally, it is done by increasing the natural frequency so that the risk of achieving mechanical resonance become less. Now, the natural frequency, ω of any system is given by the equation-

$$\omega = \sqrt{\frac{k}{m}} \qquad (2)$$

Where *k* = stiffness of the system and *m* = total mass of the system

When MRE was integrated into the system, the mass of the system was bound to increase, while the stiffness of the system was also expected to increase. The balance between the increase in mass and stiffness would determine how the natural frequency of the system will be affected. If the increase in stiffness was significantly higher than the increase in mass, then the natural frequency of the model would increase as well. By introducing MRE to the system, we want to increase the natural frequency of the model, so that resonance can be avoided.

To perform the modal analysis, the model was modelled in the Modal segment of ANSYS and was solved for its initial five modal frequencies. The same was done with the model without MRE, so that comparison can be made. The frequencies obtained are presented in the table. It can be seen that as MRE was introduced, the modal frequency value increased for each mode. The increase in frequency was very small, but this can be attributed to the small stiffness of MRE. As MRE is introduced, it is capable of providing significant stiffness change compared to the mass change it has produced.

The main feature of MRE is that the modulus of MRE can be increased by introducing magnetic field to it. As explained earlier, magnetic field increases the modulus value of the elastomer, which in turn will increase the stiffness of the setup. Hence, by controlling the magnetic flux, we can control the stiffness, and in turn, the natural frequency of the stiffness. To model the change in modulus of the elastomer, the shear modulus of the whole elastomer matrix was defined separately and was then increased. With the increase in the modulus, change in the natural frequency was recorded separately. The shear modulus was increased from 2 MPa to 50 MPa and the initial five modal frequencies were obtained for each case. The results can be seen in the table and graph shown below.

Table 4 Modal frequencies

	Frequency (Hz)								
		MRE							
Mode	No MRE	Y=2 MPa	Y=3 MPa	Y=5 MPa	Y=10 MPa	Y=20 MPa	Y=30 MPa	Y=40 MPa	Y=50 MPa
1	5.119	5.214	5.2514	5.324	5.4882	5.7838	6.0338	6.2487	6.436
2	11.928	11.996	12.005	12.018	12.039	12.069	12.091	12.11	12.128
3	28.77	29.674	30.043	30.675	31.834	32.63	33.331	33.992	34.617
4	31.984	32.103	32.268	32.485	31.874	33.223	34.034	34.576	34.97
5	60.875	61.27	61.38	61.57	61.93	62.395	62.694	62.912	63.085

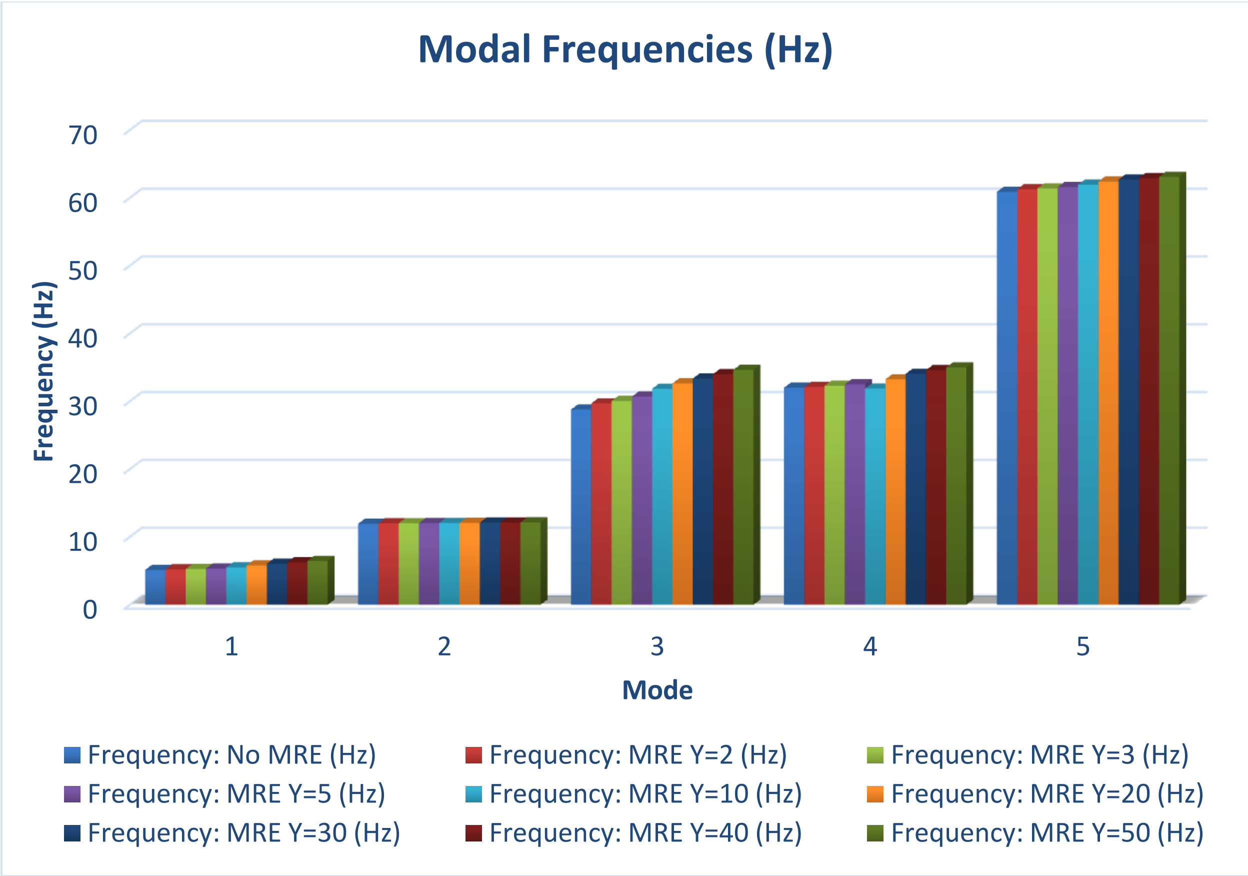

Figure 15 Modal Frequencies

For the first mode, the frequency for the connection without MRE is 5.119 Hz, but as the MRE was introduced it increases to 5.214 Hz. As the value of modulus was increased, frequency increased from 5.214 Hz to 6.436 Hz. The change is about 23% increase in value, which is a high amount of change. With this, it can be said that MRE can be used to control the natural frequency of the connection. This can be utilized when designing a building for seismic forces, which need increased natural frequency. Another thing to consider is that elastomer matrix generally has a shear modulus value less than 10 MPa. For the case of shear modulus equals 10 MPa the first modal frequency is 5.488, which is a change of about 5%. This change is not that much when compared to the case of G = 50 MPa. Although, MRE research till now is restrained to utilizing soft rubbers, in the future high strength rubbers could be used. In that case, the shear modulus value will be comparatively larger and could be utilized for bigger change in modal frequencies. The same trend in natural frequency can be seen in other modes as well.

Although MRE is a viscoelastic material, it has been considered as a pure elastic material for the analysis. This is done because modal analysis in finite element modelling is an elastic analysis. Analytically, damping produced by viscoelastic material is calculated using the energy approach. In this approach, first the maximum modal displacements are determined using the spectral analysis. These modal displacements are then converted to maximum modal physical displacements. These displacements are then used to determine the maximum strain energy generated in the damper. From the shear modulus and the dimensions of the elastomer, the dissipated energy can be determined. By calculating the ratio of dissipated energy to the maximum strain energy produced, the modal damping ratio can be determined [31]. These modal damping ratios can be used to determine the modal frequencies. As this requires an extensive amount of work, a simplified approach was used by assuming elastomer to be an elastic material. Although, this approach does not determine the frequencies precisely, it can be used to see the trend if variation of the frequency with respect to the shear modulus. Using this approach, it can be seen that MRE can successfully be used to increase the frequency of the structure, without any change in its basic model.

4.3 Harmonic Analysis

The next step in elastic analysis was to analyze the structure with harmonic load applied on it. Harmonic load is a cyclic load with a predefined frequency. Because of its cyclic nature, the analysis can predict how the model is going to behave in terms of stiffness. In harmonic analysis, the response of the system will depend on the frequency of the harmonic load applied and the natural frequency of the system. For a given load applied with a specific frequency, the response will depend on how close it is to the natural frequency of the system. If both of them are close in value, then the response will be amplified, while if they significantly differ in values then the response won't be amplified.

The general equation of motion is-

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\} \tag{3}$$

Where M = Mass of the system, C = Damping and K = stiffness of the system

While F is the force applied on the system, x is the response created by it. If the force is harmonic, the response is going to be harmonic as well.

$$\begin{aligned} \{F\} &= \{F_{max} e^{j\psi}\} e^{j\Omega t} \\ \{x\} &= \{x_{max} e^{j\phi}\} e^{j\Omega t} \end{aligned} \tag{4}$$

The excitation frequency Ω defines how the response will be. The response might have a phase shift φ, if the excitation force has phase shift ψ, or if damping is present in the system. Now, this analysis is a frequency based analysis and will determine how the response changes with the frequency of the input load. ANSYS takes input as the maximum force being applied on the system and then excites the system with the given force applied at different frequencies. The response is then obtained to determine how the system responses due to the provided force at the assumed frequency. The analysis gets completed when the response is plotted against the excitation frequency.

In our case, analysis was done by exciting the base with different accelerations and then obtaining the moment at the column-base plate connection as the response. Two different values of acceleration were considered- 9.6 m/sec^2 and 12.8 m/sec^2. For both the cases the response was generated for both the cases of system with and without MRE. For the case of MRE integrated system, value of elastic modulus of MRE was varied from 10 MPa to 50 MPa in increments of 10 MPa. Hence, for each acceleration excitation there were 6 different cases which were compared. The obtained moment at the base connection has been plotted in the Figure 16.

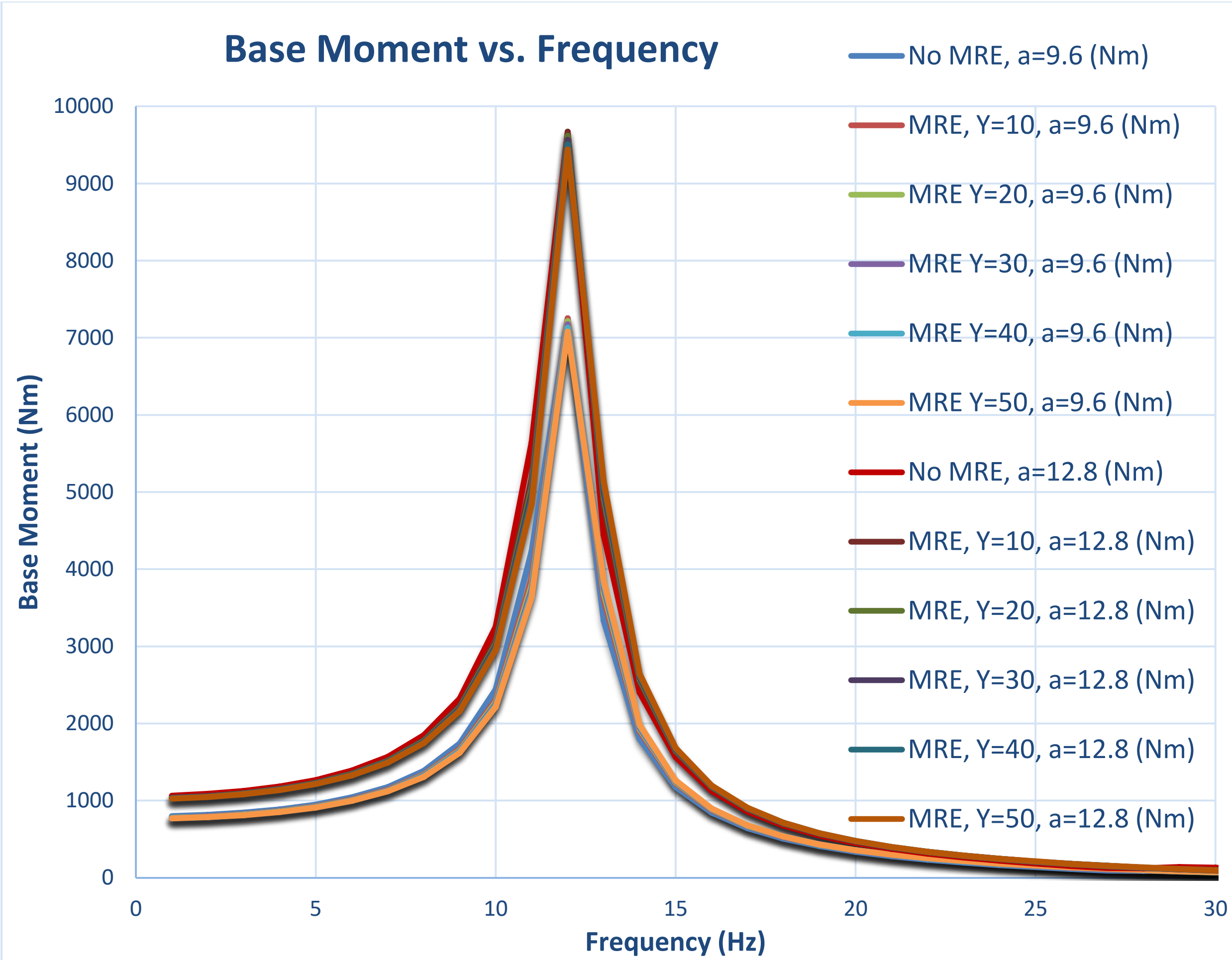

Figure 16 Harmonic Analysis: Base Moment vs. Frequency

From the results obtained, the first thing that can be seen is that the maximum response occurs at about 12 Hz frequency for all the cases. This can be attributed to the fact that second mode is the dominant mode for our structure. Now, the response for 12.8 m/sec^2 acceleration is more than the response for 9.6 m/sec^2 acceleration value. This directly goes with the maximum force being applied. As the acceleration is more, the force applied on the system is more and the response will be greater as well. The other thing which can be seen is that the response didn’t seem to be affected much with introduction of MRE. To estimate the effect in a better way, the maximum moment for each case was obtained and was plotted separately (Figure 17 and 18).

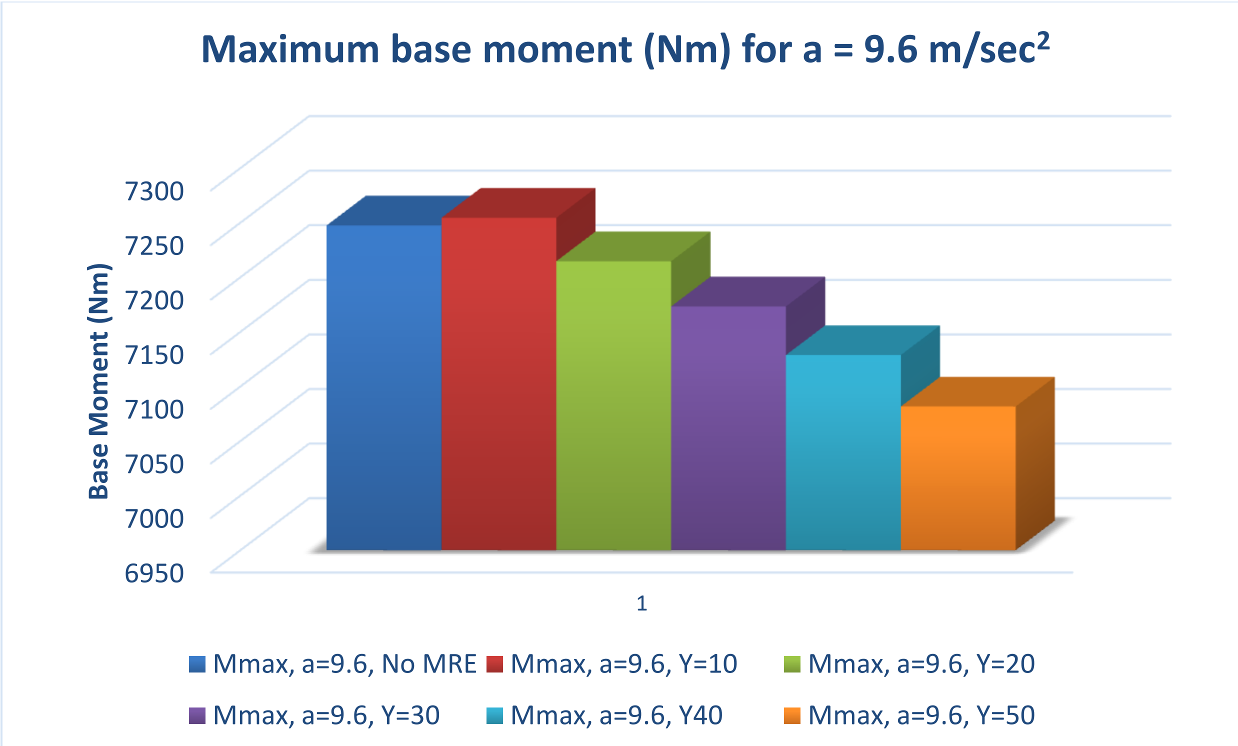

Figure 17 Maximum base moment values for a = 9.6 m/sec2

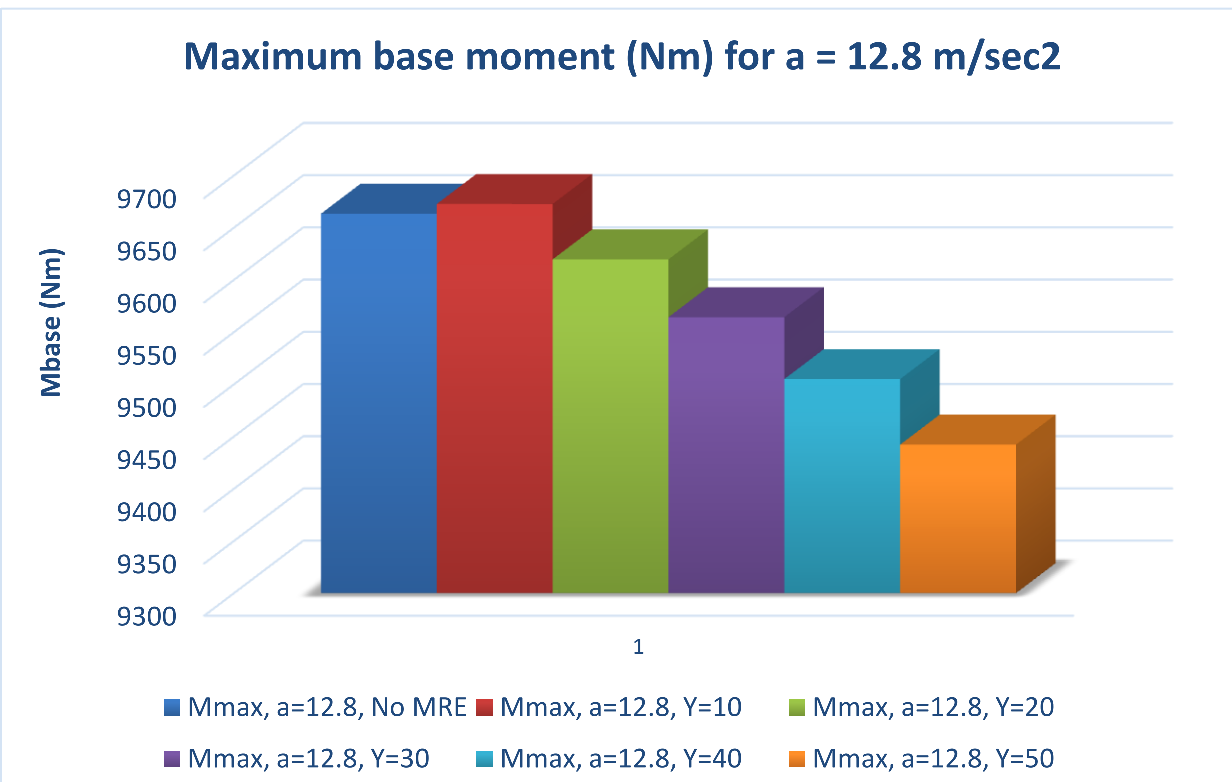

Figure 18 Maximum base moment values for a = 12.8 m/sec2

From the plots it can be seen that as the value of elastic modulus of MRE was increased, the maximum moment value decreased. This directly goes with the fact that as the modulus was increased the stiffness of elastomer matrix increased, which in turn increased the stiffness of the system as a whole. The only anomaly which was seen was that when MRE was introduced (case of Y = 10 MPa) the maximum moment value increased. Although this value decreased as the modulus was increased. This can be attributed to the natural frequency of the system. From the analysis, we have the response associated with the frequency of 12 Hz, and for the case of Y = 10 MPa, the second modal frequency was closest to the 12 Hz mark. As the excitation frequency was closer to the natural frequency, the excitation was going to be higher, which can be seen in our case. As the modulus was increased, the value decreased which could be the mix effect of increase in natural frequency from 12 Hz mark and increase in the stiffness of the system. The results obtained do not accurately define the impact of MRE on the system. MRE is a viscoelastic material and have the ability to dissipate energy over a period of time when applied with cyclic loading. In harmonic analysis, MRE is considered to be an elastic material which does not do justification to its capability as an energy dissipater. To see the viscous effect, a time variant analysis has to be performed on it. For the same reason, further section deals with transient analysis of the system.

4.4 Transient Analysis

As discussed, MRE is a viscoelastic material and to actually see the impact it makes on the performance of a structure, a time based analysis has to be performed. The option comes down to performing transient analysis with the force varying with respect to time. Viscous property makes MRE dissipate energy as the time progresses. MRE is modelled as a combination of two properties- hyper-elasticity and viscous elastomer. Hyper-elasticity helps MRE to retain its shape even after being applied with high level of strain. This property of MRE was modelled using the Neo-Hookean hyper-elastic model available in ANSYS. Neo-Hookean considers material to be linearly elastic initially, but the relationship between stress strain curve changes to plateau shape after a certain point. After this point, the elastomer is capable of going under extreme deformation without failure. This is attributed to the polymer chains in the elastomer. Initially the cross linked polymer chains will move relative to each other and as the stress is increased, the chains will stretch themselves to their ultimate limit. At certain points, stretching of the chains increases the elastic modulus of the elastomer. However, this increase is only valid for small strain and does not apply for large strains. Still, the hyperelasticity helps the elastomer to remain elastic even for large strains.

For the Neo-Hookean hyper-elastic material the strain energy density function, W [32] is given by -

$$W = C_1(\overline{I_1} - 3) + D_1(J - 1)^2 \tag{5}$$

Where C_1 is a material constant depending on the shear modulus of the material, $\overline{I_1}$ is the first invariant of the isochoric part of the right Cauchy-Green deformation tensor

And $\overline{I_1} = J^{-2/3}\, I_1$ where $J = det\,(F)$, F is the deformation gradient

In ANSYS Neo-Hookean model us defined using the incompressibility parameter which is the inverse of D_1. For our case the value of incompressibility factor considered is 0.44 MPa-1.

The viscous part of MRE was defined separately and it defined how the value of shear modulus changed over time. As the force was applied, the shear modulus value reduced as the time passes. This change in shear modulus attributed to the energy dissipation capability of the elastomer. For a visco-elastic material the shear modulus comprises of two parts. First part *G'* is the storage modulus of elastomer, which is the modulus left as the time period limits to infinity. Second part, *G"* is the shear loss modulus, which defines the loss of shear modulus over the period of time. Shear modulus of a visco-elastic material is a complex quantity and is represented as a combination of *G'* and *G"*. *G'* is the real part while *G"* is the imaginary part. The shear loss modulus, *G"* is responsible for the dissipation of energy in the elastomer. This combination of two shear modulus terms can be modelled using many existing models, in our case it was modelled using the Shear Prony Series. Shear prony series defines the value of shear modulus as value which decreases over the period of time [33]. The term is divided into two parts, the long term modulus and time variant modulus (6).

$$G(t) = G_\infty + G_i \exp - \frac{t}{\tau_i} \quad (6)$$

G_∞ is the long term modulus while the second term defines the change with time. t is the time that has passed and τ is the relaxation time. The ratio of G_∞ to G_i is called as the relative modulus and is used in Shear Prony Series to define the material. *G'* and *G"* can be represented in terms of Shear Prony Series-

$$G' = G_\infty + \frac{G_i\, \omega^2\, \tau^2}{1+\omega^2\, \tau^2} \quad (7)$$

$$G" = \frac{G_i\, \omega\, \tau}{1+\omega^2\, \tau^2} \quad (8)$$

Where ω is the excitation frequency [34].

For our case, relative modulus was considered to be 0.5 and relaxation time was taken as 20 secs. As time passes, the second term becomes smaller and in turn reduces the shear modulus value of the system. This loss of shear modulus is the cause of energy dissipation in elastomers.

To perform the transient analysis, the same two models, one without MRE and one with MRE were considered. The SAC prescribed dynamic displacement load was applied at the top of the column, and the moment generated at the connection of the column and base plate was compared. The foundation was assumed to be fixed. For all the other components, the same models were used to define them as it was done in previous sections. The results obtained were compared and are shown in Figure 19.

From the chart, it can be seen that the moment value for the MRE system is lesser throughout the whole loading. This was expected, as MRE starts dissipating energy and damps the whole connection. The value though increased as the amplitude increased, still the increase was a smaller amount compared to the system without MRE. Also, for the end cycles, the moment reduction was not much when compared to the initial cycles. This was because, the shear modulus loss has occurred and the energy being dissipated was not as much. The graph shows that MRE can be used as a damper for the column-base connection in moment frames.

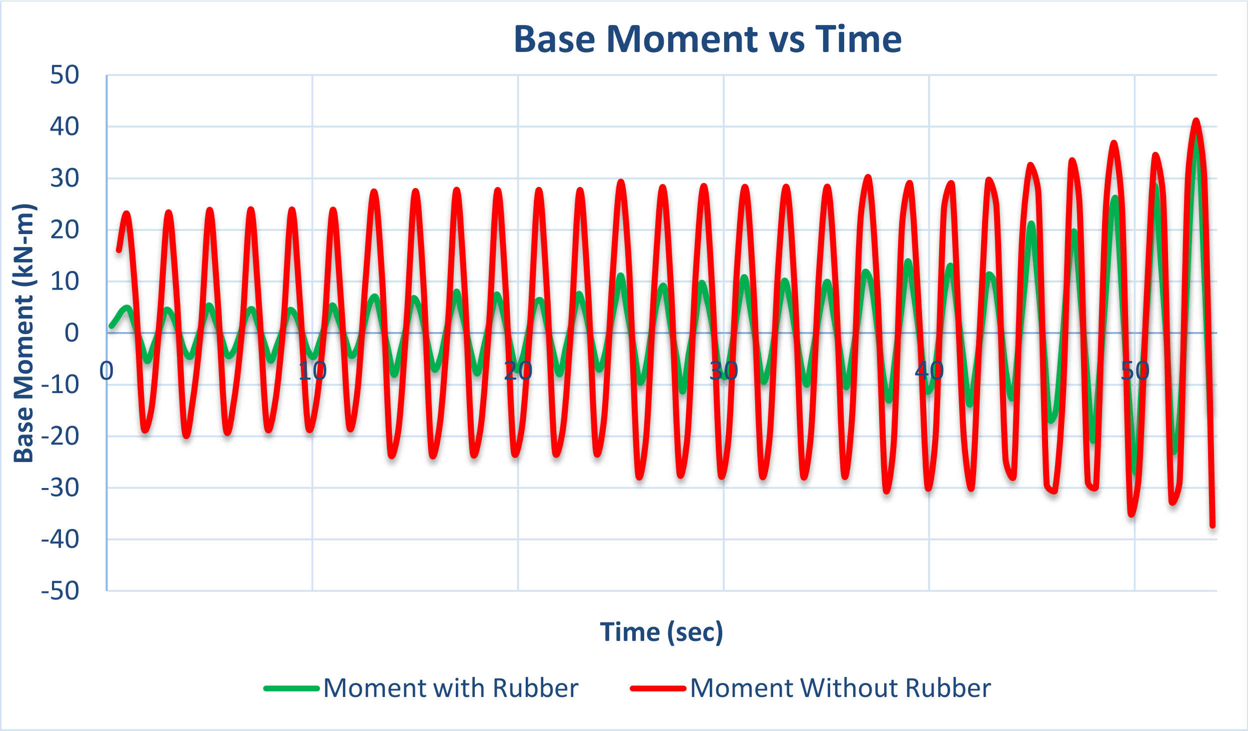

Figure 19 Base moment obtained for SAC loading

Using the same model, the analysis was repeated with loading as the ground movement during the El Centro earthquake of 1940. The strong ground motion data for El Centro is present in terms of acceleration and had to be converted into ground velocity to be used in ANSYS. For that, velocity was derived using the formula [35]–

$$v_1 = v_0 + \frac{h}{2}(a_0 + a_1) \quad (9)$$

Where v_1 is the velocity at time t_1, v_0 is the velocity at time t_0, h is the time duration passed which for our case was the time duration between two data points and was equal to 0.1 secs. a_0 is the acceleration at time t_0 and a_1 is the acceleration at time t_1.

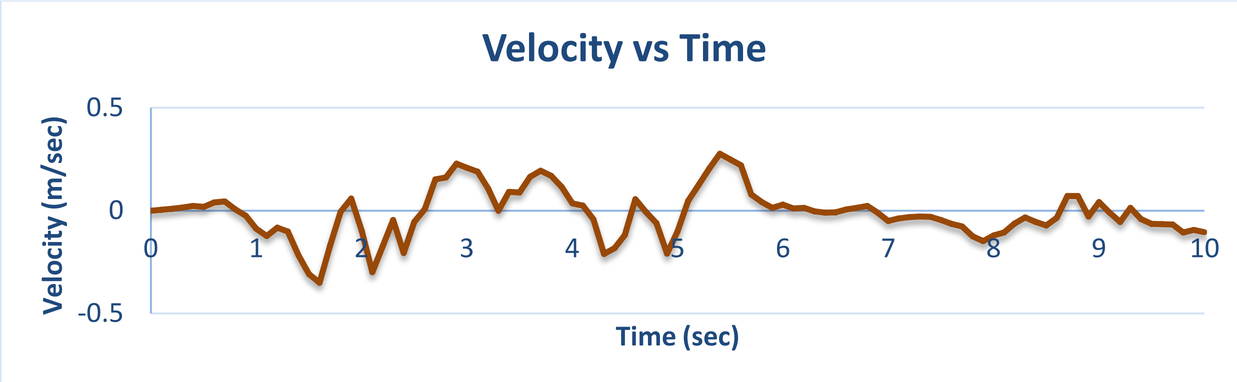

Figure 20 El Centro ground velocity

The velocity (Figure 20) was applied at the foundation, as it was the ground velocity during the earthquake. The top of the column was assumed to be fixed. The ground velocity applied can be seen in the graph.

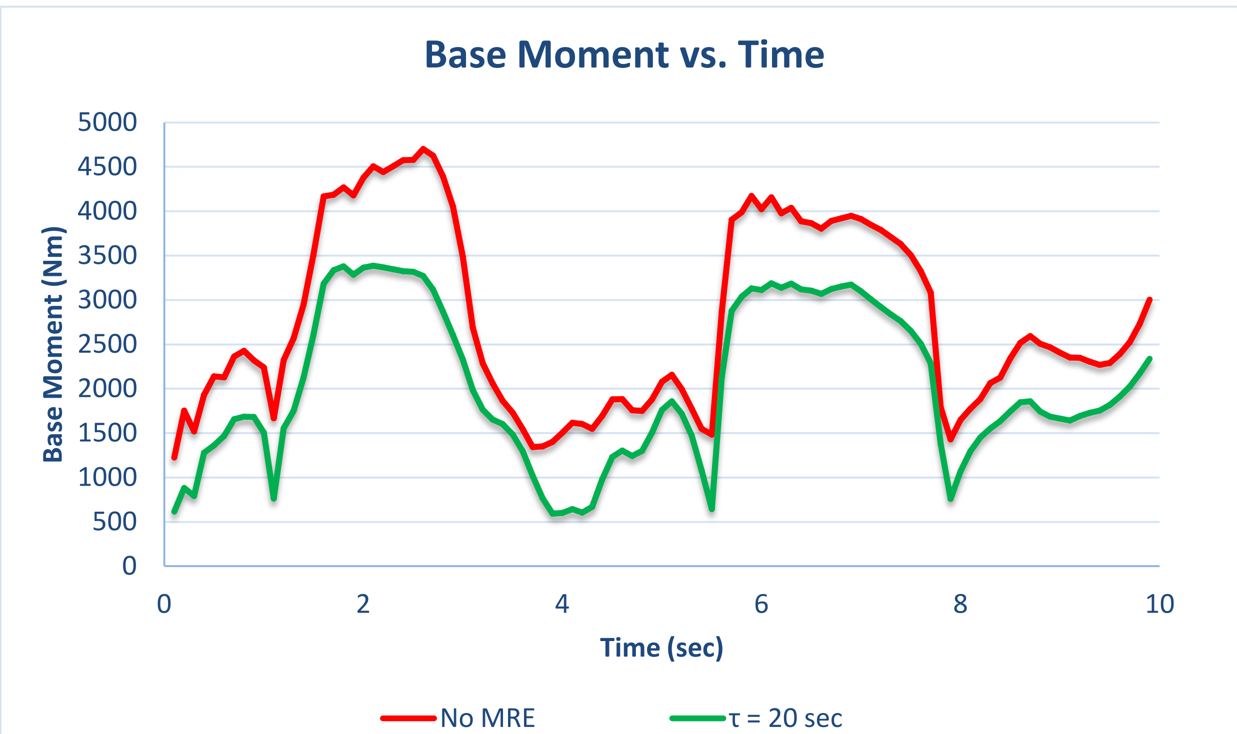

Figure 21 Transient analysis results for El Centro ground motion

The moment generated for either cases were plotted in a chart and were compared (Figure 21). Again, it can be seen that for the case with MRE the moment is reduced. This can be attributed to the damping present in MRE. It can also be seen that the difference in values is greater when the moment is greater, or in other words the energy dissipation was more when the applied strain on the system was higher. At the points where moment is lower, the values can be seen to be closer. When the moment is lower, the strain energy generated is lesser and hence the dissipation will also be less. Moreover, the entire duration of the earthquake loading was more than 1 minute, but only the first 10 seconds of the loading has been used. This was done because of the fact that around 11 secs, the connection failed and was not able to take the loading. The main aim of this study was to analyze the effect of MRE on the connection, hence the failure was not given importance in the results.

5 Parametric Study

Modelling the whole system has many parameters associated with it which can define its performance. To evaluate how the performance varied, parameters that define MRE were narrowed down. These parameters can be divided into two types of parameters- material properties and geometrical parameters. In case of material properties, the parameters which define MRE were considered. Those parameters were- shear modulus and relaxation time. In case of geometrical parameters, the height and depth of MRE were considered. For each parameter, the value was altered and transient analysis was performed. The studies are discussed in further sections in detail.

5.1 Relaxation Time

The first parameter to be considered was a material property that defines MRE. Relaxation time (τ) defines how over the period of time elastomer will lose its shear modulus. Transient analysis was done using a value of 20 secs for τ. For the parametric study, values of 10 secs and 50 secs were used along with the initial value of 20 secs. The loading considered was the El Centro ground motion data similar to transient analysis. Other than that, the model was kept the same and transient analysis was performed. The results were obtained in terms of base moment and were compared (Figure 22).

It can be seen that for the model without MRE, base moment is high. As MRE is introduced the base moment value starts decreasing as MRE starts dissipating energy. Energy dissipation depends on the amount of shear modulus loss by the equation-

$$E_d = \Pi \, G"(\omega) \, V \, {\gamma_0}^2 \qquad (10)$$

Where V is the volume of the material and γ_0 is a material property [29].

It can be seen that the more the amount of shear loss modulus, more will be the energy dissipation. From the equation (8), we can say that as the relaxation time was increased, the shear loss modulus decreased and hence, energy dissipation also decreased. This can be seen in the graph obtained. For the relaxation time of 50 secs, the shear loss modulus is smaller, hence the energy dissipation was also less. As the relaxation time was decreased, the shear loss modulus increased and hence, energy dissipation also increased. With increase in energy dissipation, the base moment value decreased.

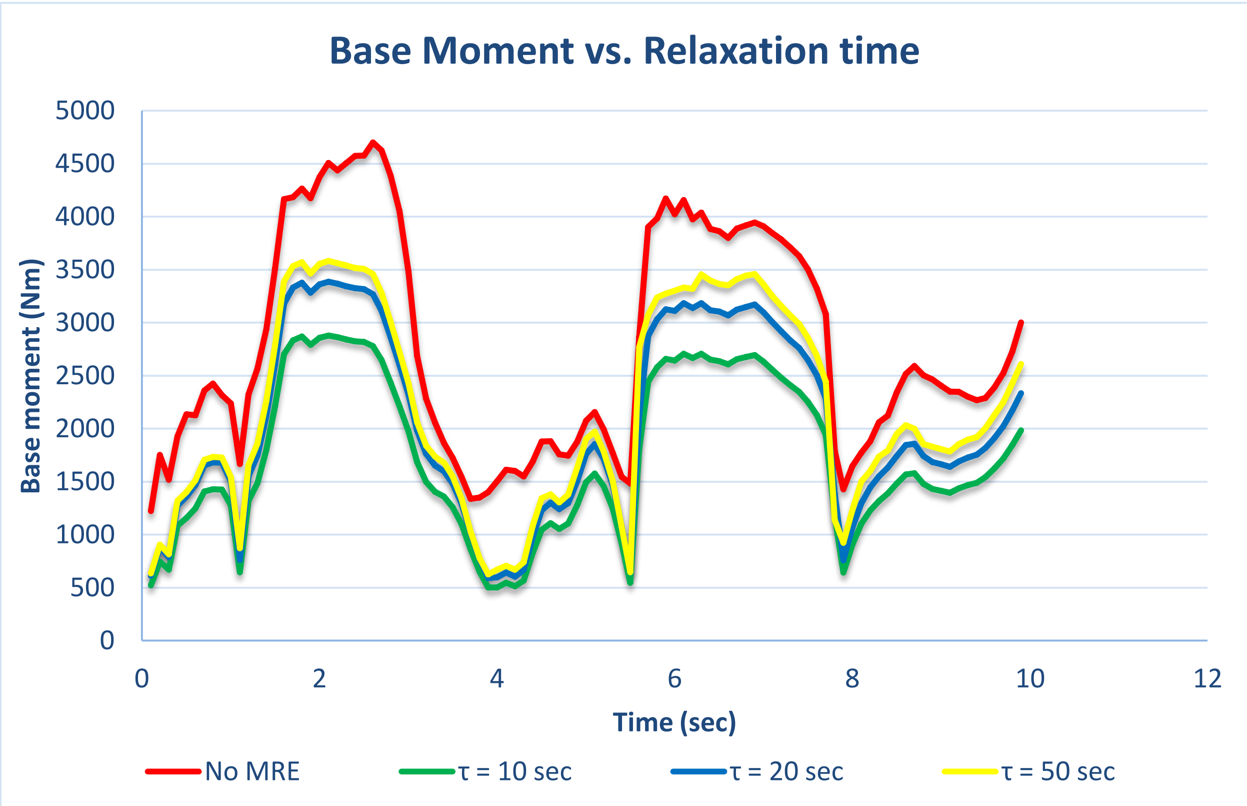

Figure 22 Base moment vs relaxation time

5.2 Shear Modulus

Shear modulus is the one property that defines the strength of MRE. Hence, it is rational to say that any positive change in shear modulus will affect the strength of the connection in a positive way. To perform the study, the shear modulus of MRE was increased from 4 MPa to 10 MPa in increments of 2 MPa. For each case transient analysis was performed separately using the El Centro ground motion data. The results obtained were in terms of moment at the column base connection and were compared to each other and to the system without MRE as well (Figure 23).

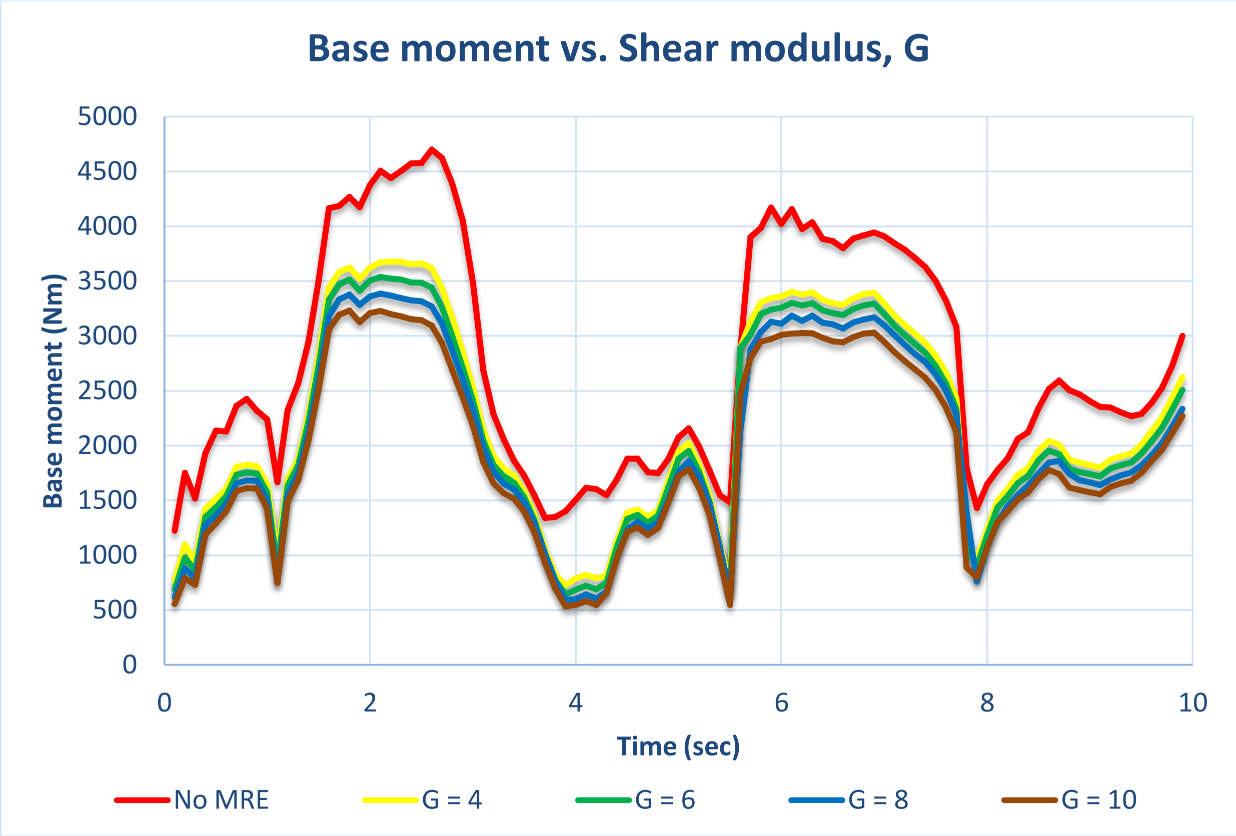

Figure 23 Base moment vs Shear modulus, G

From the graph, it can be seen that as the shear modulus increases, base moment value decreases. This result is as it was expected. As the shear modulus was increased, the strength provided by MRE to the connection increased, which decreased the moment generated at the connection. Also, the increase in shear modulus increased the shear loss modulus as well, which in turn increased the energy dissipation in MRE. This also affected the moment positively and decreased it. This behavior can be related to the behavior of MRE. When magnetic field is applied, the modulus of MRE increases. The variation of shear modulus to see the effect can be compared to the effect produced my magnetic field. Hence, it can be said that MRE can be successfully used as a damper in varying load conditions.

5.3 MRE Height and Depth

After considering MRE properties as parameters, we need to look at its geometric properties as potential parameters. As discussed earlier, dissipated energy depends on the volume of the elastomer. To change the volume of MRE, height can be used as one of the parameter. In this section, height of MRE was varied from 400 mm to 1200 mm in increments of 200 mm. The model was then applied with El Centro ground motion and response was recorded in terms of base connection moment for each case. Apart from the height of MRE, everything else was kept the same as it was there in the transient analysis. The results obtained in terms of base moment were plotted and compared for each case (Figure 24).

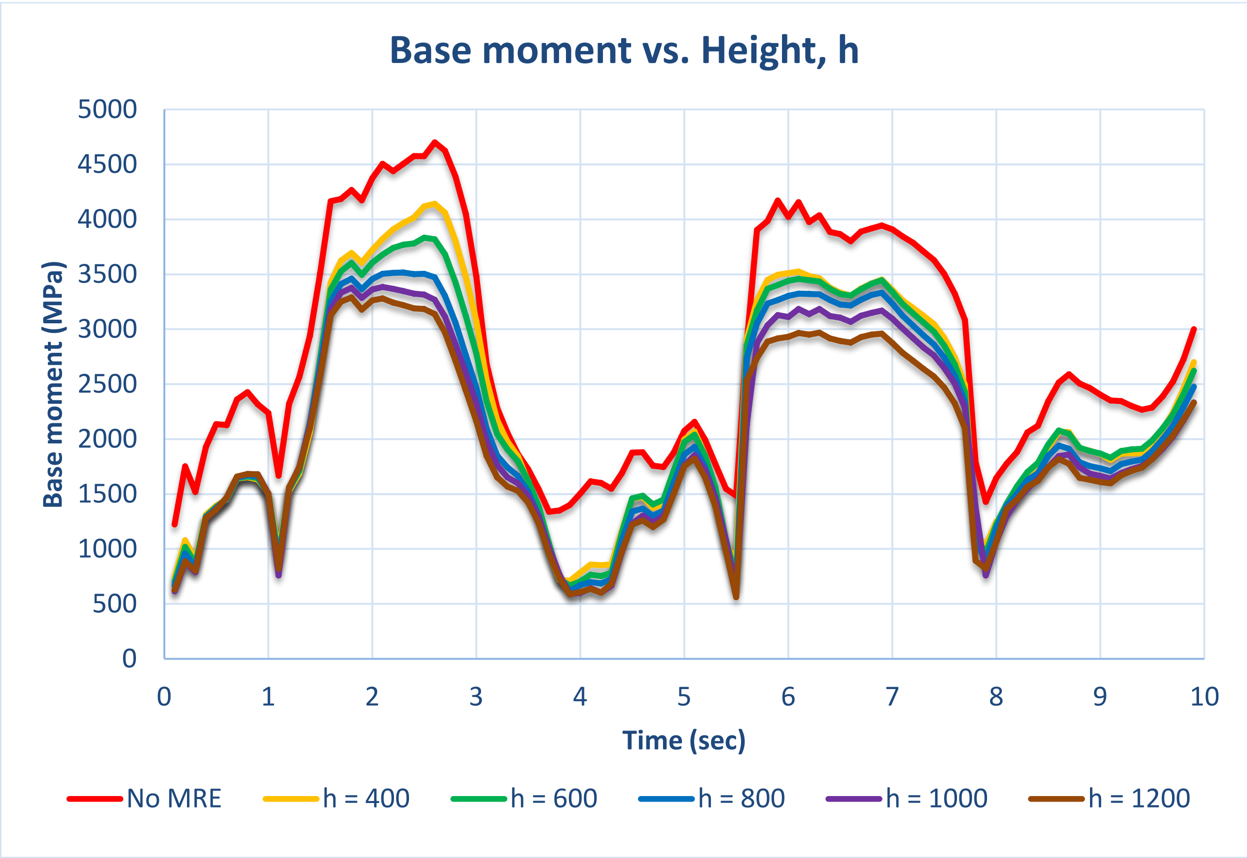

Figure 24 Base moment vs Height, h

From the graph it can be seen that as the height increased, the base moment value decreased. As height was increased more MRE was introduced in the system, which increased the stiffness as well as the energy dissipation. As the stiffness of MRE compared to steel is very low, the main impact is because of the increase in the volume of MRE. From equation (10), it can be seen that the energy dissipation directly depends on the volume of viscoelastic material present in the system. As the volume of MRE increases, the energy dissipated by MRE also increases. This damps the system more and reduces the moment generated at the column base connection. This effect can be seen in this parametric study.

Just like height, depth of MRE was also varied to determine the impact. The depth is the distance between the column and the side plate. It can be seen in the figure below. Depth was varied from 130 mm to 180 mm in increments of 10 mm. The same transient analysis was performed using El Centro ground motion data. The moment generated was compared for each case along with the case of connection without MRE. The results obtained were plotted (Figure 25) and compared.

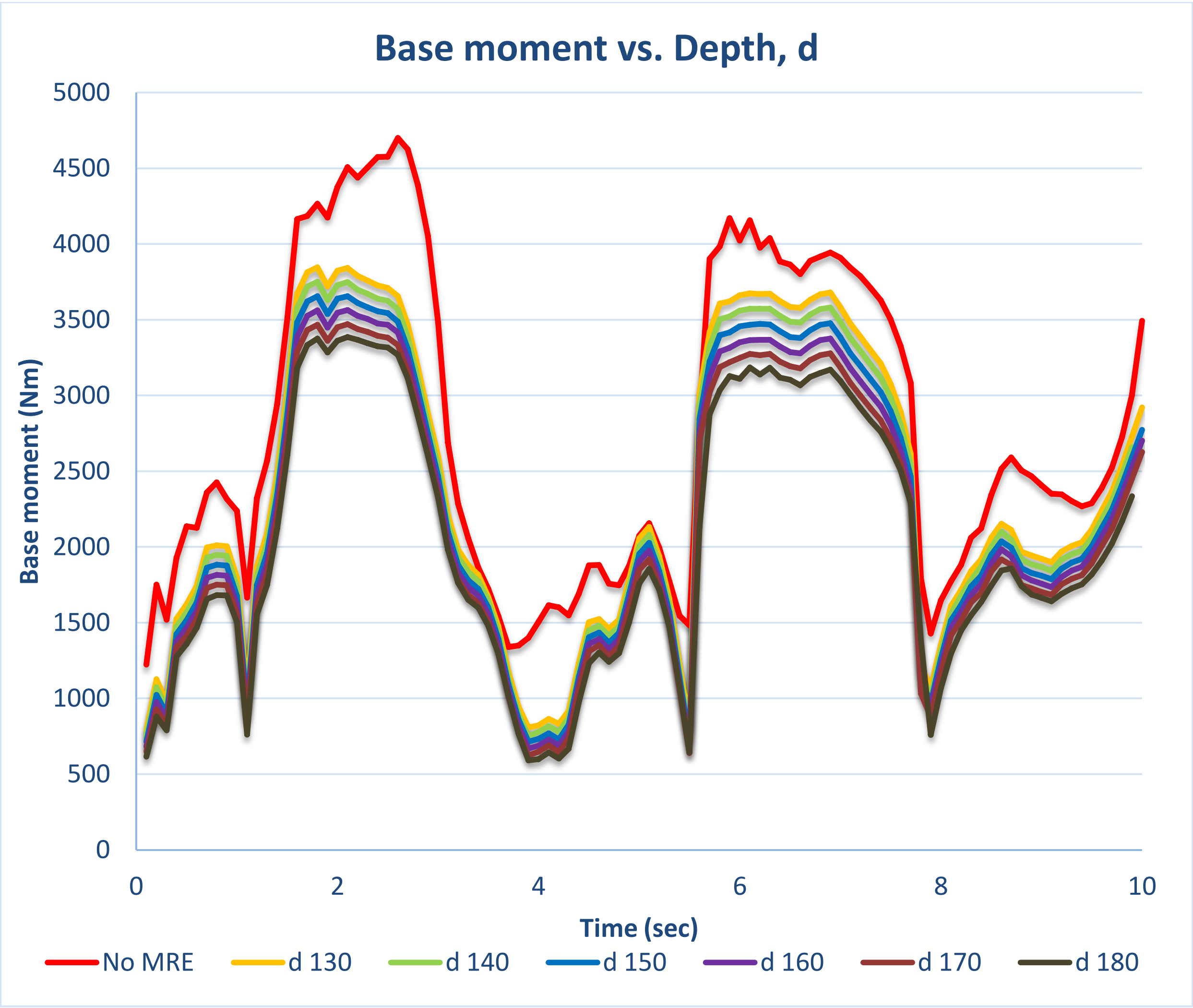

Figure 25 Base moment vs Depth, d

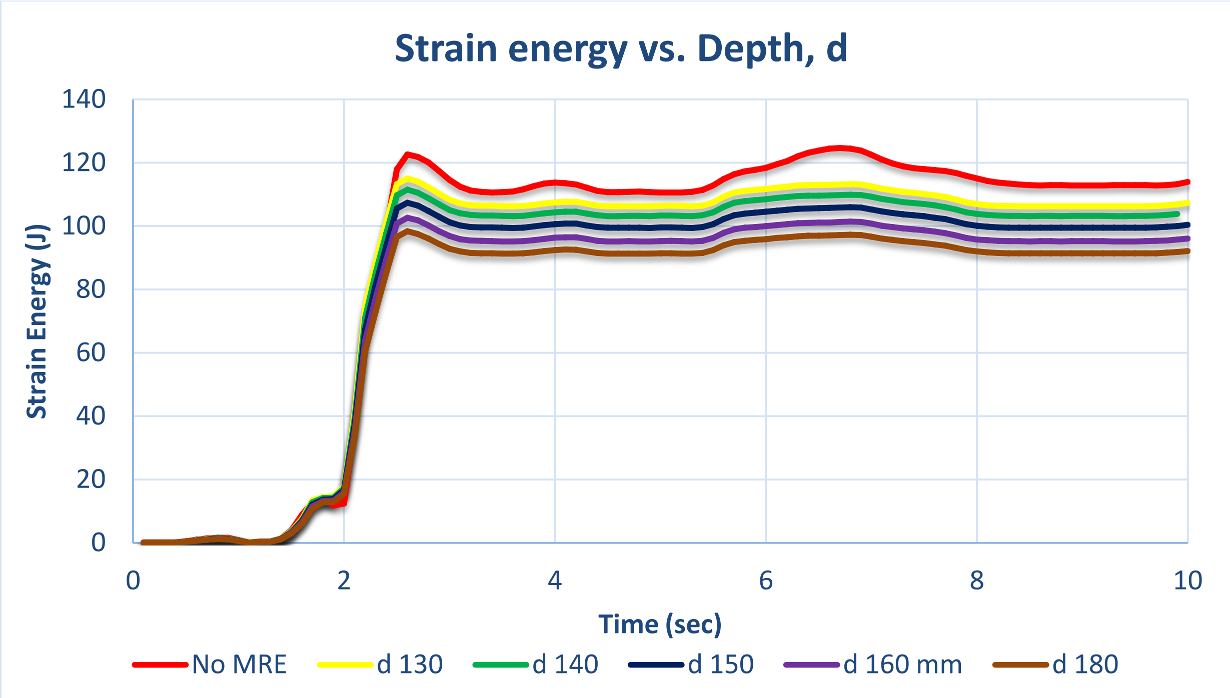

Figure 26 Strain energy vs Depth, d

It can be seen that as depth was increased, the moment generated decreased. As the depth was increased, the volume of elastomer present gets increased, which increased the energy dissipation. More the energy dissipation, more will be the damping and less will be the moment generated. This can be seen with strain energy developed in the column as well. As the depth increases, the energy dissipation also increases, reducing the strain energy developed in the column. The strain energy developed in the column for each case was obtained and plotted (Figure 26). As the depth increases, the strain energy developed decreases. This is because the increase in volume of the elastomer increases the energy dissipation as well. Another point to note here is that the strain energy surges in value at about 1.5 secs, which can be related to the change in ground velocity at that time duration. Looking at the El Centro ground velocity data (Figure 20), it can be seen that velocity changes abruptly at about the same duration. This causes the increase in the strain energy.

6 Discussion and Conclusion

Steel moment resistance frames (SMRF) have been in use in tall steel buildings frames for a long time. These frames were assumed to have the most resistance to lateral forces. After the Northridge earthquake this myth was broken. Many steel buildings were critically damaged causing loss of several lives and several millions of dollars. Since then SAC have suggested new guidelines to prevent this from happening again. One of the major issue that needs to be resolved is the energy dissipation in case of an earthquake. Over the years, various types of dampers have been developed, but none of them have shown the true potential to dissipate energy in case of strong earthquakes. To address the issue, this report deals with a new type of damper using magnetorheological elastomers.

Magnetorheological elastomer is an elastomer based compound embedded with ferrous particles inside it. When applied with magnetic field, these ferrous material can link with each other and can increase the stiffness of the material. Also, as it is an elastomer based material it has the potential to dissipate energy. To test its potential, a pretested column-base connection was modelled in a finite element based 3-D analysis software called ANSYS. At first, elastic analyses were performed by considering MRE as an elastic material. Modal analysis proved that with introduction of MRE, the natural frequency of the system can be altered. This can be useful in the cases where the natural frequency of the system needs to be increased without altering the basic structure of the building. Harmonic analysis showed that even as an elastic material, MRE is a positive influence on the connection and will only help in strengthening it.

After elastic analysis, inelastic transient analysis was performed to evaluate the potential of MRE as an energy dissipating material. Transient analysis was performed using two different dynamic loads, one being the prescribed loading by SAC for seismic evaluation of SMRF connections and the other one being the El Centro ground motion data. For both the case, the moment generated at the column base connection was much lower with MRE. This proved that because of MRE being a viscoelastic material, it can dissipate energy in case of strong earthquakes and hence, provide damping to the connection.

Parametric study was performed to determine how the material properties and geometrical properties define the effectiveness of MRE as a damper. It was expected that with increase in the shear modulus, the damping potential of MRE will also increase, and it was proved in this study. Apart from the shear modulus, the shear loss modulus value was also altered using the relaxation time of the elastomer. As the shear loss modulus decreased, the dissipation in energy also decreased, as it directly depends on it. However, the energy dissipation can be increased by increasing the volume of the elastomer. This can be done by increasing either of the dimensions of the elastomer. Here, the height and the depth of elastomer were used as the parameters to prove the hypothesis. With this, the main goal of the study was completed, which was to prove the efficiency of MRE as a damper. However, there are many areas which need to be looked upon before developing MRE damper systems on industrial scale. The designing of the magnetic circuit being the major one. Being a preliminary study, it didn’t delve deep into the designing of the actual MRE system. After that, experiments need to be performed to evaluate its performance in various conditions. I would like to conclude on the hope that someday, after all examinations, MRE will be used as a damper in tall steel buildings and will prevent them from getting critically damaged.

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