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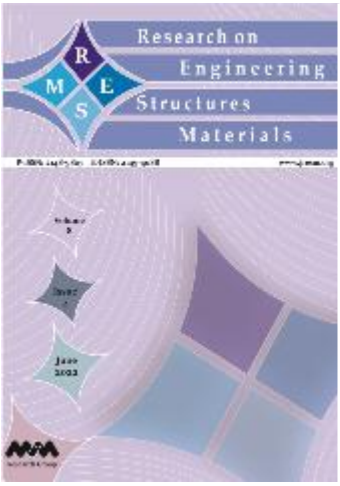

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Research Article

Seismic performance analysis of RCC benchmark problem with magnetorheological damper

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Abstract

Incorporation of the seismic response control system plays a vital role in structural engineering. Conventional method of structural design involves the higher flexibility and lower damping characteristics during the application of seismic loads which leads to inelastic deformation to an acceptable limit. Modern technique of seismic energy dissipation aims towards achieving stringent performance requirement. This paper aims towards analysis of structural response of the benchmark building with semi active damper namely magnetorheological damper. The magnetorheological damper work depends on the Structural Control Algorithm and Current input. G+5 Reinforced Concrete Building response is studied with a connection of large scale 200KN MR Damper (MRD) for three proposed numerical models, namely Kelvin Voight Model, Hyperbolic Tangent model and Maxwell Non-linear Slider model. The predictive ability of numerical models is analyzed for varying current. For simulating seismic application three earthquake data were considered, El Centro, Imperial Valley and Northridge. Numerical models of MR Damper are studied under varying current and exponential value. The comparison of displacement and base Shear of the structure response gives satisfactory response in the analysis.

1. Introduction

During Structural Control can be achieved through both internal damping and external damping. Vibration of the Structure occurs due to structural resonance, specific frequency at which the dynamic motion will get amplified. Amplification of dynamic motion can be reduced by adding effective energy dissipation device. Internal damping involves the joint damping, where external damping involves the active damping, passive damping. The phase between both passive damping and active damping is semi active damping. Semi active device plays a successful role during dynamic loading condition because of its dynamically varying property with a minimal amount of power [1]. Effective performance is expected to be offered by a semi active device over a variety of amplitude and frequency range. This paper presents the study of performance of the magnetorheological damper for various proposed numerical models under varying current and exponential value. Low voltage power will be required for the working of MR damper [2-3]. Optimum current shows better structural response reduction. By the application of MR damper to the structure, during the application of dynamic load, structural response such as displacement, acceleration and base shear can be reduced. The Hysteretic behaviour of MR

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damper is a function of amplitude excitation and also depends on the current. Magnetorheological fluid is a non-Newtonian fluid with shear yield strength and the reaction of the fluid can be controlled by varying the Magnetic field condition and current [4]. Magnetorheological fluid shows significant changes in rheological property such as transition to semi solid state from free-flowing state. In case of pre-yield stage MR fluid shows viscoelastic behaviour and in case of post yield stage, it shows viscous Newtonian fluid [5]. To predict the performance of MR damper when connect to the structure under different magnetic field for the varying excitation appropriate method should be used. This involves the appropriate selection of numerical models for the modelling of MR damper [6]. The focus of the research to study the performance analysis of 200KN magnetorheological MR damper for seismic application under different numerical model condition. Even though passive devices, including base isolation, metallic friction damper, viscoelastic dampers are commercially successful in energy dissipation, control force in MR damper can be varied by appropriate adjustment in stiffness and damping characteristics [7]. Stiffness and other damping properties of MR damper will vary based on the numerical models proposed for MR damper. Three proposed numerical models used for modelling of large-scale MR dampers used in this study are Kelvin Voight model, Hyperbolic Tangent model, Maxwell Non-Linear slider model [8]. RD-8041-1 MR Damper has the stroke length of 55 mm and has the extended length till 208 mm. The body of the MR Damper is 42.1 mm and the shaft diameter is 10 mm. The maximum damping force is 2.45 kN at 1 Ampere current. The structure is analysed for a variable stiffness of MR damper. Variable stiffness and damping properties depend upon the numerical model in which one of the parameters current (I) plays a major role [9]. In the present research work, the analysis of the G+5 benchmark building with 200 kN capacity MR Damper for three proposed numerical model is investigated.

2. Structural Model

The structural model considered for study is a 6 storey RCC building. Damping ratio of the structure is considered as 5% for all modes and mode shape of the structure is shown in Fig. 4 and Fig. 5 [10]. Detail of the structure is shown in Table1. RCC Benchmark building is designed in accordance with Argentina code IC103. The total mass per floor is 1x106 kg. Youngs modulus of the concrete E=24,800Mpa, fundamental period T1 =0.374s. The seismic acceleration for Northridge has 1.82 g, El Centro has 0.15 g and Imperial Valley has 0.21 g. RCC Benchmark Building with MR Damper is shown in Fig. 1.

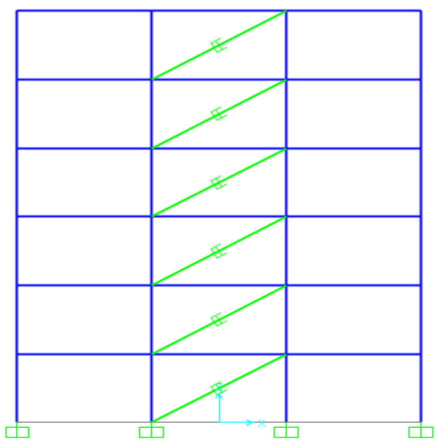

Fig. 1 RCC benchmark building with MR damper

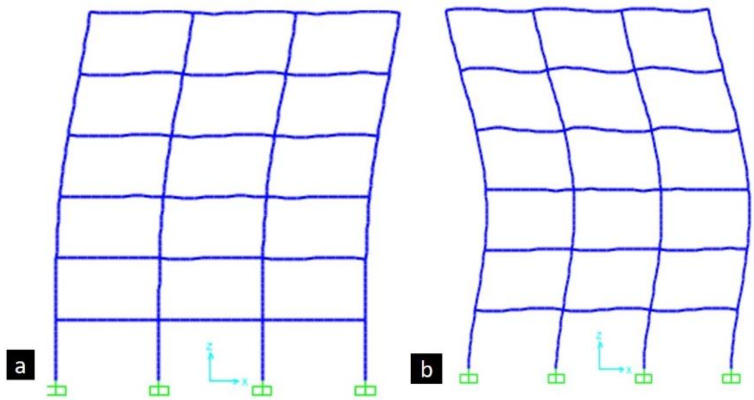

Fig. 2 Mode shapes of RC benchmark building (a) First mode shape (2.67Hz), (b) Second mode shape (7.69Hz)

Table 1 Structure details

SI.No	Design Data of 6 Storey Building	
1.	Structure type	RC
2.	Number of storey	G+5
3.	Storey height	3m
4.	Grade of concrete	M30
5.	Beam size (all stories)	0.25m x 0.45m
6.	Column 1 size (Exterior)	0.60m x 0.60m
7.	Column 2 size (Exterior)	0.55m x 0.55m
8.	Column 3 Size (Exterior)	0.50m x 0.50m
9.	Column 4 Size (Interior)	0.65m x 0.65m

3. Numerical Model of MR Damper

In order to define the significant properties of the MR damper in structural control problems, some numerical models have been proposed to describe the damping properties. High appropriate models selected for modelling of damper show higher accuracy in capturing Hysteretic response. Among all models, parametric models are found to be efficient in modelling of MR Damper [11]. Structure has been studied for three parametric models, namely Kelvin Voight model, Hyperbolic Tangent model, Maxwell Non-Linear Slider model.

3.1. Kelvin Voight Model

Kelvin – Voight model consist of spring and dash pot in parallel. It assumes strain in the spring and strain in dashpot to be same. Kelvin – Voight model is assumed to have no bending due to the parallel arrangement. The schematic diagram of the model is shown in Fig. 3

$$\sigma = E\varepsilon + \eta\acute{\varepsilon} \tag{1}$$

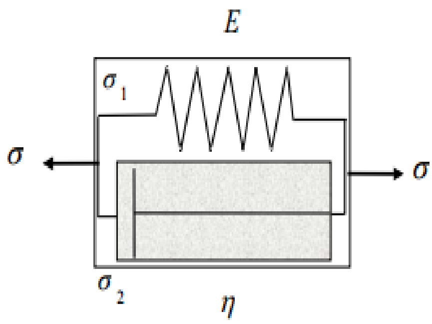

Fig. 3 Kelvin Voight Model

The stress and strain in mentioned in the equation as σ and ε. H is the viscosity of the material. In Magnetorheological damper modelled with Kelvin Voight model, there is a change in damping coefficient for different value of current input. Damping exponent changes show the higher potential of response reduction. When there is no change in damping exponent α, the response of the bare structure and the structure with MRD Kelvin Voight model are same. [12] On decreasing the exponent value to 0.1 MRD shows the seismic response reduction. Building shows 35% seismic response reduction when the magnetorheological damper is modelled with kelvin Voight model with lower exponential value is shown in Fig. 4.

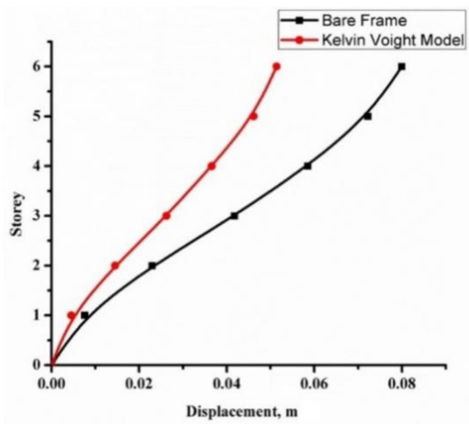

Fig. 4 Displacement distribution of Kelvin Voight and Bare frame model for El Centro 1940 earthquake

Damping Exponent is the parameter of the damper that decides the Force- Displacement graph of the damper. MRD KV model is analyzed for varying current and exponent. Potential of reponse reduction in displacement are found to be occurring in I=2A and α=0.1. Percentage of response reduction is found to be 35% in this condition is shown in Table 2.

Table 2. Comparison of maximum displacement of bare frame and Kelvin Voight model

Bare Frame (Displacement, mm)	Kelvin Voight Model MR Damper (Displacement, mm)
79.6mm	51.1mm

3.2. Hyperbolic Tangent Model

Hyperbolic Tangent model was a numerical model developed for ER Damper [13]. Damping behaviour includes both pre-yield and post yield behaviour shows in Fig. 5.

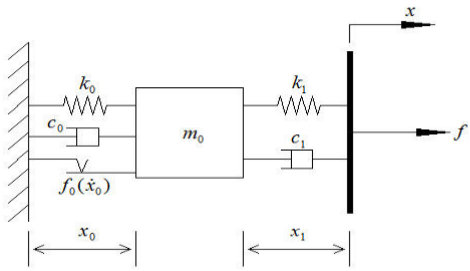

Fig. 5 Hyperbolic Tangent Model

The damping force of HPT (MRD) is given in equation (2) and (3)

$$f = C1(x - x0) + k1(x - x0) \quad (2)$$

$$m_0x_0 + (c_0 + c_1)\, x_0 + f_0 \tan h\, (x_0\, V_{ref}) = c_1x + k_1x \quad (3)$$

Where f = damping force; C0 and K0 are damping coefficient and stiffness at low velocity, C1 and K1 for higher velocity. f0 is the coefficient associated with the nonlinear friction element. Parameters of Hyperbolic Tangent Model is shown in Table 3.

Stiffness provided by the damper should be equal to the force required to resist the external excitation. When the damper possesses higher stiffness in the structure, during energy dissipation some energy will be stored in damper and it returns to the structure and cause structural oscillation. In case of higher stiffness, energy absorbed by the damper in return results in higher flexibility [14]. In Hyperbolic Tangent model when there is an increase in current, stiffness of the structure will decrease because in hyperbolic tangential model MR damper stiffness achieved in the low Ampere will be equal to the stiffness required for the damping force. MR Damper behaviour is studied under varying current from 0A to 2A. The response reduction of the structure is found to be occur in 0.5A. Analytical study shows that when the exponent value is gradually decreased to 0.1, results in a maximum displacement reduction at 0.5A. Story height divided by interstory displacement gives the interstory drift index.

Hyperbolic Tangent models shows 64% reduction in displacement at 0.5A for the exponential value of 0.5 and 76% reduction in displacement for the exponential value of 0.1 at 0.5A shows in Fig. 8 and Fig. 7. The comparison of displacement is shown in table 4, table 5 for α=0.5 and α=0.1.

Analytical results show that the drift reduction is found to be occurring at 1A and 0.5A in hyperbolic Tangent model shown in Fig. 8 and Fig. 11. [15] Drift is higher in the structure when the MRD is supplied with electrical source of higher ampere. Hence 0.5A current is taken as the optimum value for HPT MRD and is numerically compared with other models.

Table 3. Parameters of Hyperbolic Tangent Model

Parameters	Units
K0=(0.00001i4-0.00010i3+0.00013i2+0.00023i+0.00062)	kN/mm
K1= (-2.43069i4-23.75859i3-80.7025i2 +110.6199i+55.08)	kN/mm
C0= (-0.00979i4+0.09325i3-0.29955i2-0.3580i+0.1264)	kN.s/mm
C1= (0.00618 i4 -0.06726i3+0.2669i2-0.46060i+0.35673)	kN.s/mm
M0 = (0.00016i4- 0.00162i3+ 0.00548i2-0.00705i+ 0.00485)	kg
f 0 =1.51702 I4 -10.26630 i3 +2.79030i2 +94.55682i +6.19194	kN
Vref= 0.11574i4 +1.36241i3 -6.18813i2 +13.11819i +0.75927	mm/s

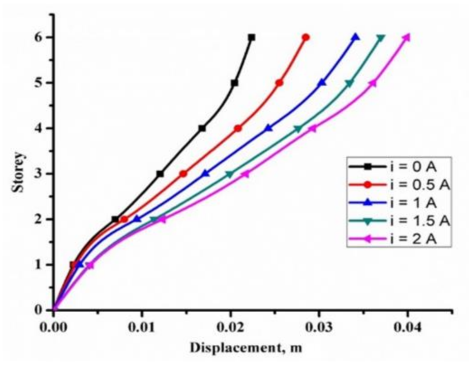

Fig. 6 Displacement distribution of Hyperbolic Tangent Model under varying current from 0A to 2A for the damping exponent (α=0.5)

Table 4. Comparison of maximum displacement of bare frame and Hyperbolic Tangent Model under varying current from 0A to 2A for the damping exponent (α=0.5)

Current	Bare Frame	0A	0.5A	1A	1.5A	2A
Displacement(mm)	79.6	22.3	28.6	34	37	39.5

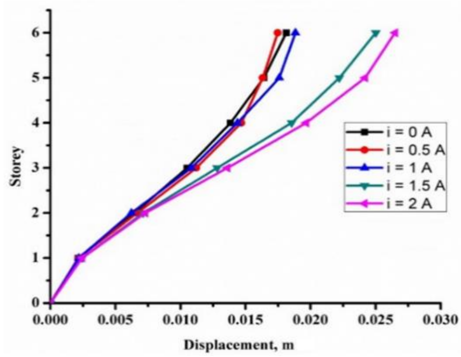

Fig. 7 Displacement distribution of Hyperbolic Tangent Model (HPT MRD) under varying current from 0A to 2A for the damping exponent (α=0.1)

Table 5. Comparison of maximum displacement of bare frame and Hyperbolic Tangent Model under varying current from 0A to 2A for the damping exponent (α=0.1)

Current	Bare Frame	0A	0.5A	1A	1.5A	2A
Displacement(mm)	79.6	18	16.5	18.9	25	26.6

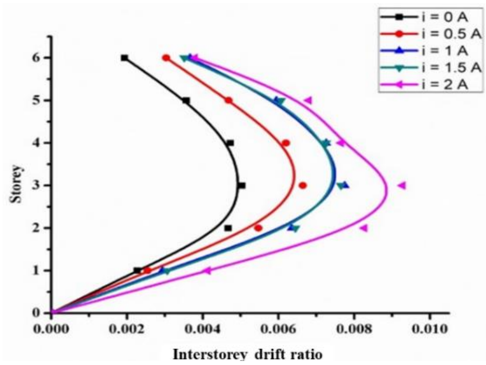

Fig. 8 Interstorey Drift distribution of Hyperbolic Tangent Model under varying current from 0A to 2A for the damping exponent (α=0.5)

3.3. Maxwell Nonlinear Slider Model

Models used for modelling of large scale MR Damper in practice are Bouc Wenn model, Hyperbolic Tangent model. Bouc Wenn model and Hyperbolic Tangent model parameters give a detail account about post yield behaviour of MRD [16]. When a MR Fluid undergoes shear deformation during seismic application, Shear thinning, and shear thickening will occurs [17]. Due to this inaccurate prediction of Damper force at higher velocities may occur. In MNS model parameters are identified for both pre yield and post yield behaviour of MR Damper, So that the response of MNS MRD can be evaluated separately for post yield and pre yield behaviour.

In Pre-Yield mode, Maxwell element with Dashpot and Spring Constant are used to determine the damper force.

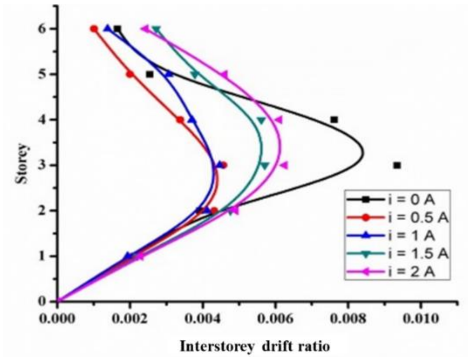

Fig. 9 Interstorey Drift distribution of Hyperbolic Tangent Model (HPT MRD) under varying current from 0A to 2A for the damping exponent (α=0.1)

$$f = k\,(y - z) = cz \tag{4}$$

Parameters of MNS MRD are calculated using the following equation;

$$c = \frac{1}{u_0 m}\frac{f_0^2+f_m^2}{f_m} \tag{5}$$

$$k = \frac{1}{u_0}\frac{f_0^2+f_m^2}{f_0} \tag{6}$$

K refers to spring constant and c indicate the dashpot constant. In Post Yield behaviour, shear thinning and shear thickening behaviour of non-Newtonian fluid are described based on Hershel – Bulkley visco plasticity theory [18]. Hershel bulkey model to describe quasi static behaviour and is found to be efficient comparing to other models used to describe the Non-Newtonian behaviour of MR Fluid under different modes shown in Fig. 10.

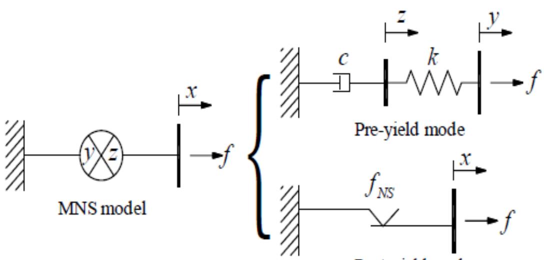

Fig. 10 Maxwell Non-Linear Slider Model

Comparing Displacement of the structure for varying current, it is found that displacement is reduced for 1A. Base shear is constant from 1A to 2A with little variation [19]. Analysis with MNS MR Damper performance shows that response reduction is higher when current varies from 1A to 2A and 1.5A shows more displacement when compared to 1A and 2A. (Fig. 11 and Fig .12).

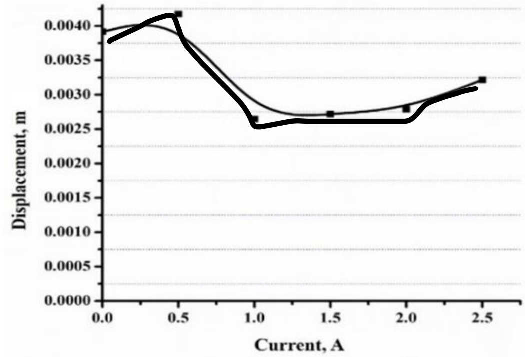

Fig. 11 Displacement distribution of Maxwell Non-Linear Slider Model under varying current from 0A to 2.5A

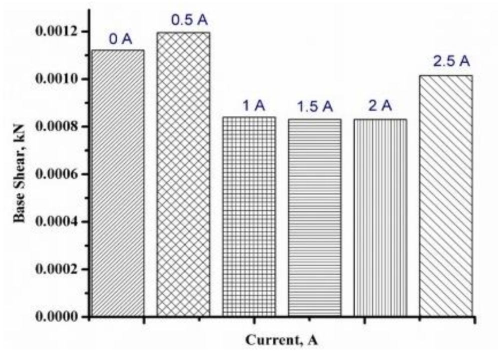

Fig. 12 Comparison of base shear using Maxwell Non-Linear Slider Model under varying current from 0A to 2.5A

4. Results and Discussion

The results are obtained in terms of displacement, Inter storey drift and Base shear for the RCC benchmark building. Time History Analysis using SAP 2000 is done for varying models of MRD for different ground motion data. Analysis results include the performance of MRD under three different numerical models Kelvin Voight model, Hyperbolic Tangent model and Maxwell nonlinear slider model [20]. Each model is analysed for varying current and exponential value. Each model shows good performance when the exponential value is varied according to the performance of MRD. Kelvin Voight model and Hyperbolic Tangent models show good performance when exponential value is reduced and Maxwell Nonlinear Slider model show response reduction in the exponential value of α=0.5.

4.1. Displacement

Table 6. Percentage of Reduction Displacement in Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider model compared with bare frame model for El Centro 1940 earthquake

Models	KV Model	HPT Model	MNS Model
% Reduction	35%	71%	79%

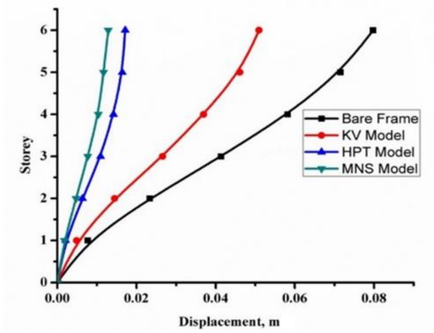

Fig. 13 Displacement distribution of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for El Centro 1940 earthquake

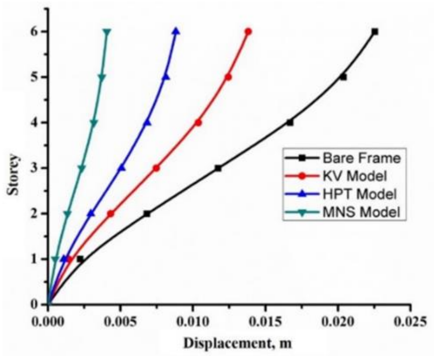

Fig. 14 Displacement distribution of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for Northridge earthquake

Table 7. Percentage of Reduction Displacement in Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider model compared with bare frame model for Northridge earthquake

Models	KV Model	HPT Model	MNS Model
% Reduction	38%	61%	78%

Lateral Displacement of G+5 RCC Building shows better performance with MRD compared to bare frame for varying ground motion shows in Fig. 15, Fig. 16 and Fig. 17. For Elcentro ground motion, displacement percentage reduction of KV model, HPT model and MNS each model is 35%, 71%, 79% respectively. During Seismic application of Northridge MRD shows 38%, 61% and 79% and Imperial Valley 20.36%, 49% and 69% for KV model, HPT model and MNS model respectively shown in table 6, table 7, table 8.

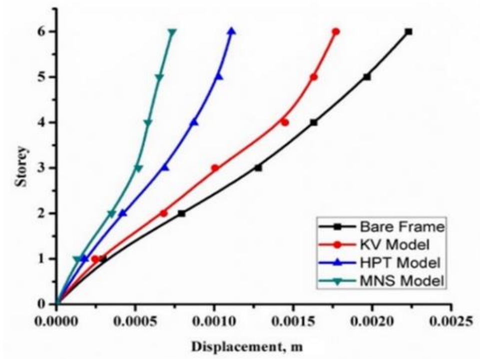

Fig. 15 Displacement distribution of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for Imperial Valley earthquake

Table 8. Percentage of Reduction Displacement in Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider model compared with bare frame model for Imperial Valley earthquake

Models	KV Model	HPT Model	MNS Model
% Reduction	20.36%	49%	69%

4.2. Inter Storey Drift

This paper presents the study of inter storey drift of G+5 RCC Building with and without MRD. Story Drift of structure with MRD under three models for optimum current is analysed and studied.

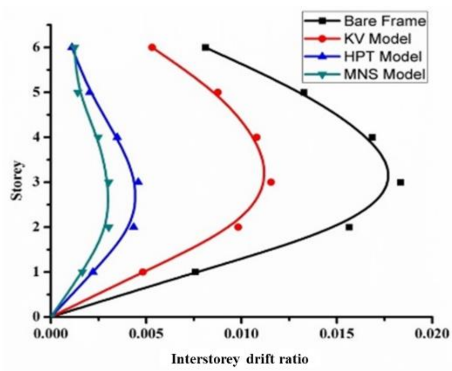

Fig. 16 Distribution of interstorey drift ratio of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for El Centro 1940 earthquake

Comparative analysis of the storey drift for models of MRD shows MNS model and HPT model show maximum reduction in drift of the structure. All three model shows the drift within the limit. Kelvin Voight model shows least response reduction compared to other two models shown in Fig. 18, Fig. 19 and Fig. 20.

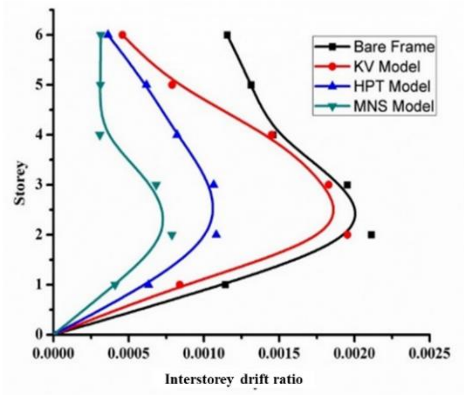

Fig. 17 Distribution of interstorey drift ratio of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for Imperial Valley earthquake

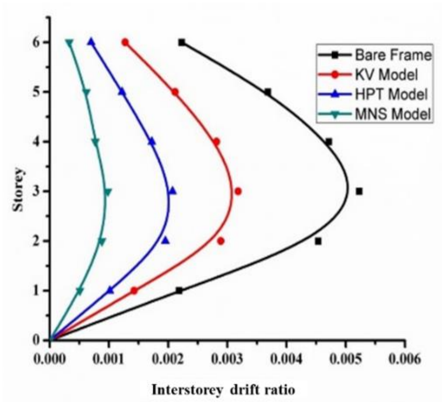

Fig. 18 Distribution of interstorey drift ratio of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for Northridge earthquake

4.3. Base Shear

Base shear is the maximum lateral force occurs at the base of the building. Base shear maxima or minima will depend upon the soil condition, fixidity condition, probability of ground motion, ductility, strength and weight of the building and natural period. When the natural period of the structure is higher, flexibility of the structure will be also higher. Flexible structure will experience low acceleration compared to stiffer building [21-22]. When the flexibility of the structure is increased it will show low base shear compared to stiffer building. At the same time flexibility of the structure should be within limit to reduce the lateral displacement of the structure. MRD shows good performance in both displacement reduction and base shear reduction with lower lateral displacement.

For El Centro 1940 all three models shows response reduction in base shear with least lateral displacement. Percentage of Base shear reduction for El Centro 1940 is 28%, 56%, 61% respectively for KV model, HPT model and MNS model respectively. MRD under the application of Imperial valley and Northridge shows 62%, 68%, 81% and 28%, 56% and 81% for KV model, HPT model and MNS model respectively shown in Fig. 22, Fig. 23 and Fig. 24. Among all models MNS show higher potential of response reduction shown in table 9, table 10 and table 11 [23-25].

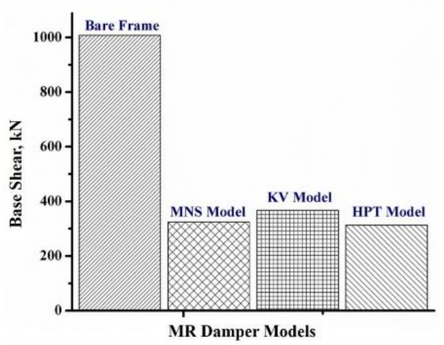

Fig. 19 Base shear comparison of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for El Centro 1940 earthquake

Table 9. Percentage reduction of base shear in Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider model compared with bare frame model for El Centro 1940 earthquake

Models	KV Model	HPT Model	MNS Model
% Reduction	28%	56%	61%

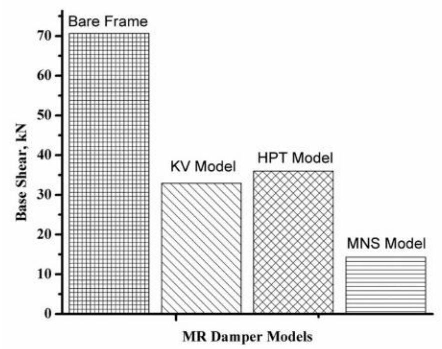

Fig. 20 Base shear comparison of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for Imperial Valley earthquake

Table 10. Percentage reduction of base shear in Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider model compared with bare frame model for Imperial Valley earthquake

Models	KV Model	PT Model	MNS Model
% Reduction	62%	68%	81%

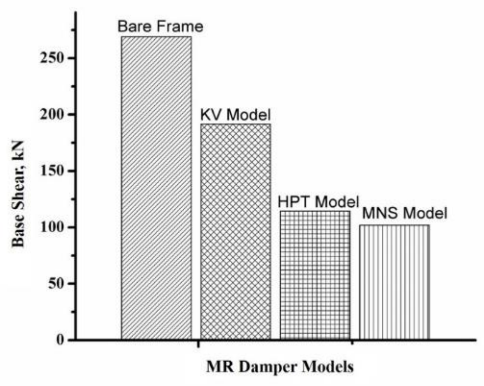

Fig. 21 Base shear comparison of Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider and Bare frame model for Northridge earthquake

Table 11. Percentage reduction of base shear in Kelvin Voight, Hyperbolic Tangent, Maxwell Non-Linear Slider model compared with bare frame model for Northridge earthquake

Models	KV Model	PT Model	MNS Model
% Reduction	28%	56%	61%

5. Conclusions

The results show that the response of the structure is reduced in higher percentage when it relates to magnetorheological damper. The Large scale 200KN MR Damper (MRD) for three proposed numerical models were investigated. For various currents and various earthquakes numerical models were analyzed. Numerical models of MR Damper are studied under varying current and exponential value. Parameters were studied using SAP2000 software which involves displacement, base Shear, and interstorey drift.

- In Kelvin Voight model reduction in damping property such as damping exponential shows the response reduction where the higher damping exponential shows no response reduction.
- In Hyperbolic Tangent model even with low exponential value, increase in current shows lower stiffness. Reduction in displacement and other seismic response parameter found to be occur under limit at 0.5A.
- In Maxwell Non-Linear slider model response reduction is found to be higher at the value of 1A to 2A, where 1A shows maximum reduction.
- Each Parametric model shows variation in response reduction based on the variation in excitation.
- G+5 RCC building shows maximum response reduction when connected with MRD modelled with MNS model.
- Base Shear of MNS and HPT are more or less equal for Elcentro earthquake input Data.
- Base Shear of HPT MRD is higher than the other two models for Imperial Valley input data.
- The reduction in base shear El Centro seismic excitation is 28%, 56%, 61% respectively for KV model, HPT model and MNS model respectively.

- For the seismic excitation of Imperial valley and Northridge shows 62%, 68%, 81% and 28%, 56% and 81% for KV model, HPT model and MNS model.
- This result helps the research working on MR Damper to select the model for their analytical investigation
- The future work can be extended for steel buildings subjected to various earthquakes with self-powered MR Damper configuration and optimal positioning of MR Damper

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