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THE PERFORMANCE OF SEMI-ACTIVE MR DAMPER IMPROVED BY FUZZY LOGIC BASED CONTROLLER UNDER SEISMIC EXCITATION

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Abstract: Control systems play a crucial role in operation of airplanes, robots and new generation of smart automobiles, and improve their performance, safety and robust serviceability. Control systems are useful in structures improving their seismic performance. Although the use of dampers is becoming popular, the main issue with it is that most of such devices are in passive mode, without a control system. Therefore, they may sometimes cause detrimental effects. Magnetorheological (MR) damper is a type of semi-active damper that can produce variable force according to the intensity of the magnetic field that is applied to it. Such magnetic fields can be produced by the DC current that can be provided by batteries. This means that it can be useful in harsh conditions in which the power supply may be interrupted. The capability of variable force production demanding less energy is the major advantage of MR dampers. In this research an intelligent control system based on fuzzy logic method is added to the MR damper system installed on a single story structure. Such a smart system makes the resisting damper force proportional to the magnitude of the earthquake records. Therefore, the damper force can be smartly controlled in real time by changing the applied electricity current to the damper according to the displacement of the structure, caused by an earthquake. The results illustrate that such innovative controllable damper can notably improve the seismic demand of the structure.

Keywords: MR damper, fuzzy logic, mamdani system, seismic loads, energy dissipation

1 INTRODUCTION

Modern civil engineering involves design and construction of complicated structures such as high-rise buildings, bridges with longer spans and infrastructure that requires advanced technics to guaranty safety and good performance of such structures in the condition confronting dynamic loads such as earthquakes. Because the inherent damping of these structures is not sufficient to control their seismic demands including drift and lateral displacements, it is highly demanded to improve the damping characteristic of such structures by installing an additional energy dissipating system that can make the structures more resilient against the effects of earthquake-induced vibrations(FEMA 2003). For more than two decades, structural engineers are utilizing different categories of dampers including active and passive devices to improve the seismic resilience of structures. In recent years, MR dampers have emerged as attractive semi-active energy dissipating devices for vibration control in structures.

A major advantage of this type of damper is that by changing the applied magnetic field (by changing the intensity of the current), the viscosity of MR fluid can be changed quickly, in the order of milliseconds(Henrie and Carlson 2002), thereby making such dampers produce controlled variable damping force. On the other hand, a passive system can produce only uncontrollable passive force, which may or may not be sufficient to dissipate the seismic loads. Another advantage of MR damper is that the viscosity of MR fluid can be adjusted by a small change in the current intensity, which can be supplied by batteries; and therefore, in harsh conditions such as strong earthquakes, the MR damping systems can still remain functional and reliable, while main power supply may fail.

In most of previous researches constant currents or on/off control systems were applied to MR dampers to set them to produce resistant forces and dissipate free vibrations or seismic vibrations of the structures (Dyke et al. 1996, Villarreal et al. 2004) while in recent years the researches are focused on use of MR dampers adjustable by more advanced control systems.

In order to utilize the MR damper properly, it is more efficient to define a control system that makes the damping force adaptive to the earthquake.

In this research, the control system of a MR damper is designed based on a closed-loop controller using fuzzy logic (Mamdani system as reported in Lilly 2011) and the magnitude of the damper force is adaptively controlled in real time by changing the applied current to the damper according to the displacement of the structure, caused by an earthquake. It means that the controller continuously gets the feedback of the system in terms of displacement and adjusts and corrects the damper force during the earthquake event (Lilly 2011, Nise 2011). The novelty of this study is due to the number of far-field earthquakes which are applied to the structure equipped with the MR damper controlled by the fuzzy system to determine the seismic response of the structure.

2 MODELING AND ANALYTICAL PROCEDURE

In this research in order to study the performance of a structure which is upgraded with a controllable MR damper as an external damping system, a dynamic system which contains a 2D single story structure which is equipped with a controllable 200 KN large- scale MR damper (Yang et al. 2002, Yang et al. 2004, Lagaros et al. 2012) is modeled in MATLAB and SIMULINK software.

In order to illustrate the performance and efficiency of the damper the inherent damping ratio in this model is assumed 1%.

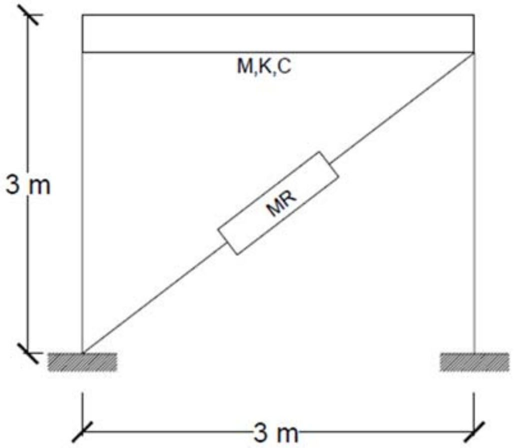

Figure 1: The schematic model of the structure, in which Mass (M) =$\mathbf{4} \times \mathbf{10^5}\ \boldsymbol{kg}$; Stiffness (K)=$\mathbf{1.5} \times \mathbf{10^8}\ \boldsymbol{KN/m}$; Structure inherent damping ratio:$\boldsymbol{C}$=$\mathbf{1.55} \times \mathbf{10^5}\ \boldsymbol{N.s/m}\quad (\boldsymbol{\xi = 0.01})$

In order to simulate the behavior of the MR damper a model which is proposed and formulated by Spencer et al. (1996) is utilized (Dyke et al. 1996, Yang et al. 2002, Yang et al. 2004, Villarreal, Wilson, and Abdullah 2004). This model which is designed based on the Bouc–Wen model can properly illustrate the performance of a MR damper (Yang et al. 2002, Yang et al. 2004, Casciati et al. 2006).

To make the damper behave in a proper way and improve the seismic response of the modeled structure, a closed loop control system is added to the model which adjust the applied electricity current to the damper.

Therefore, the resistant force which is produced by the damper can be continuously controlled (Dyke et al. 1996).

The structure containing an external damping system and subjected to seismic loads can be quite complicated to be modeled and analyzed. The relation between the applied current and the resistant force produced in the damper is non-linear. Therefore, by installing the MR damper on the structure, the whole system becomes more complex. Hence, it is quite difficult to define the mathematical model of such variable and non-linear system accurately (Lagaros, Plevris, and Mitropoulou 2012, Lilly 2011). In that case, the model-dependent controllers may malfunction or even fail.

It is worth mentioning that in complicated dynamic systems in which defining accurate mathematical model is difficult, model–independent control systems can provide a practical solution. In this context, fuzzy logic, that is defined on the human reasoning and works similar to human decision making, can be used as a practical method for designing a control system that is capable of dealing with complex non-linear dynamic systems (Lilly 2011). In this research the Mamdani system is used to design the control unit of the MR damper model. Mamdani system is an intuitive and widely accepted fuzzy system which works based on expert's knowledge (Lilly 2011). Fuzzy control systems in general consist of three stages which are fuzzification, inference mechanism, and defuzzification (Lilly 2011).

In this paper, a fuzzy logic based control technique is proposed, in which the displacement of the modeled structure is converted to fuzzy sets through fuzzification process; and then in fuzzy inference system processes the fuzzified displacement values to determine the fuzzy output based on a set of fuzzy rules that are built upon expert's knowledge. Finally, the fuzzy output is converted to crisp values via defuzzification process. Using centroid defuzzification method, crisp output is calculated from the weighted average of all fuzzy rules involved in finding the fuzzy output. The defuzzified output is the magnitude of electrical current used for driving the MR damper to produce the resistant force (Lilly 2011, Nise 2011). It, means that the fuzzy controller receives the displacement of the structure as a feedback of the system in very short intervals, and based on the feedback, it adjusts the performance of the system continually. This closed-loop process is demonstrated in following block diagram (Figure 2).

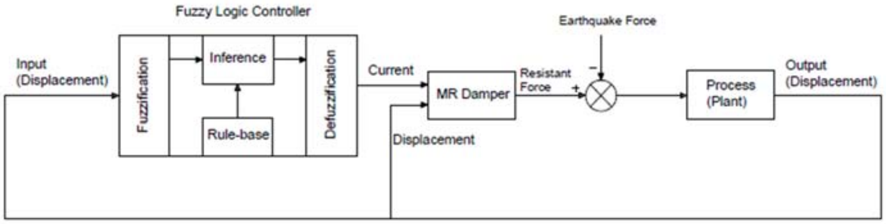

Figure 2: Block diagram of the closed – loop system with fuzzy control

2.1 The equations of motion

In this study the state-space form of dynamic equations is used to analyze the seismic response of the structure equipped with damper (Ogata 1999).

[1] $M\ddot{X} + C\dot{X} + KX = M\ddot{X}_g - f_d$ (General dynamic equation of the system)

[2] $U = \begin{bmatrix} \ddot{X}_g \\ f_d \end{bmatrix}$

Where, $\ddot{X}_g$ is the ground motion acceleration and f_d is the damper force

[3] $q = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} X \\ \dot{X} \end{bmatrix}$

Where q_1 and q_2 are the state variables and $X, \dot{X}$ and $\ddot{X}$ indicate the displacement, velocity and acceleration of the structure, respectively.

$$[4] \quad \dot{q} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} \dot{X} \\ \ddot{X} \end{bmatrix} = \begin{bmatrix} q_2 \\ \ddot{X} \end{bmatrix} = \begin{bmatrix} q_2 \\ -M^{-1}C\, q_2 - M^{-1}\, Kq_1 - M^{-1}\, f_d - \ddot{X}_g \end{bmatrix}$$

Which results:

$$[5] \quad \dot{q} = \begin{bmatrix} q_2 \\ -M^{-1}C\, q_2 - M^{-1}\, Kq_1 \end{bmatrix} + \begin{bmatrix} 0 \\ -M^{-1}f_d - \ddot{X}_g \end{bmatrix}$$

The equation is rewritten as:

$$[6] \quad \dot{q} = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -M^{-1}f_d - \ddot{X}_g \end{bmatrix}$$

Then:

$$[7] \quad \dot{q} = \begin{bmatrix} 0 * q_1 + q_2 \\ -M^{-1}C\, q_2 - M^{-1}\, Kq_1 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -1 & -M^{-1} \end{bmatrix} \begin{bmatrix} \ddot{X}_g \\ f_d \end{bmatrix}$$

The equation is simplified as:

$$[8] \quad \dot{q} = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -1 & -M^{-1} \end{bmatrix} \begin{bmatrix} \ddot{X}_g \\ f_d \end{bmatrix}$$

The output (Y) is:

$$[9] \quad Y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} X \\ \dot{X} \\ \ddot{X} \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ -M^{-1}K\, q_1 - M^{-1}C\, q_2 - M^{-1}f_d - \ddot{X}_g \end{bmatrix}$$

2.2 Earthquake Records

In order to study the performance of such smart dampers, a set of earthquake ground motion records including 44 far-field earthquakes suggested in FEMA P645 have been used in the analysis of a one-storey case study building to study the performance of the damping system. These ground motion records were obtained from the Pacific Earthquake Engineering Research Centre database (PEER 2018).These records are chosen from 14 strong and destructive earthquakes that happened between the year 1971 and 1999 (FEMA 2009).

3 ANALYTICAL RESULTS AND CONCLUSION

The following figures (Figures 3 and 4), illustrate how the proposed fuzzy controller applies the electric current to the damper in accordance to the magnitude of the displacement of the structure caused by the earthquake to control the magnitude of the damper force and reduce the displacement. The following graphs showed in Figure 5, indicate the performance of the smart damping system in reducing the structure's displacement subjected to 44 far-field earthquake records. It can be also observed that within few seconds damper achieves its desired performance, and reduces the displacement efficiently. The bar chart in Fig 6 shows that the designed smart damper has an acceptable performance in reducing the structure's acceleration caused by the earthquake.

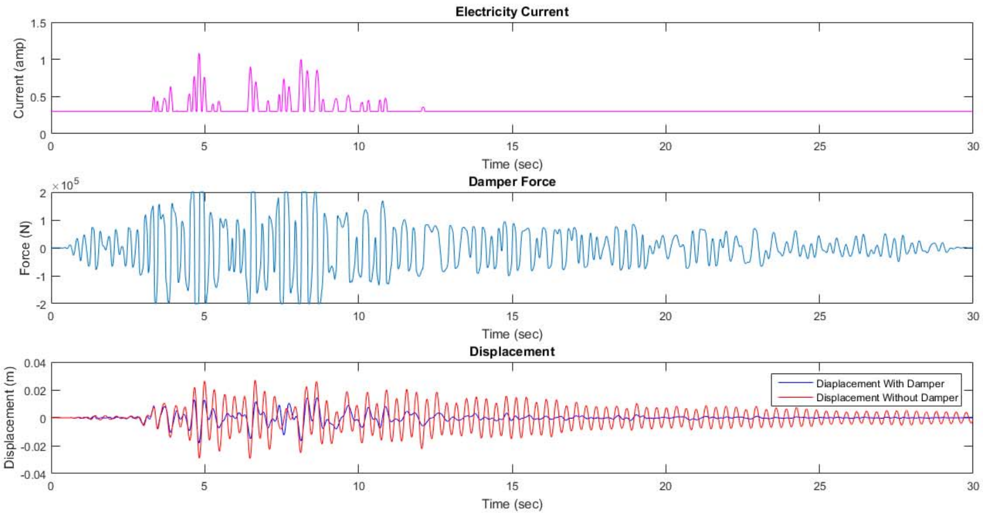

Figure 3: These graphs indicate the driven current to the damper by fuzzy controller, damper resistant force and the displacement of the model vs Time, subjected to Northridge 1994 earthquake records

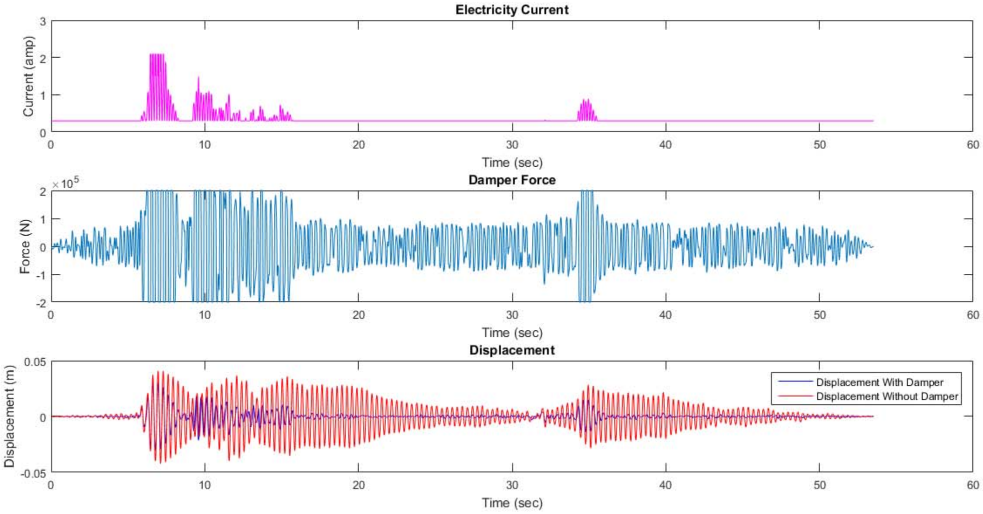

Figure 4: These graphs indicate the driven current to the damper by fuzzy controller, damper resistant force and the displacement of the model vs Time, subjected to Manjil 1990 earthquake records

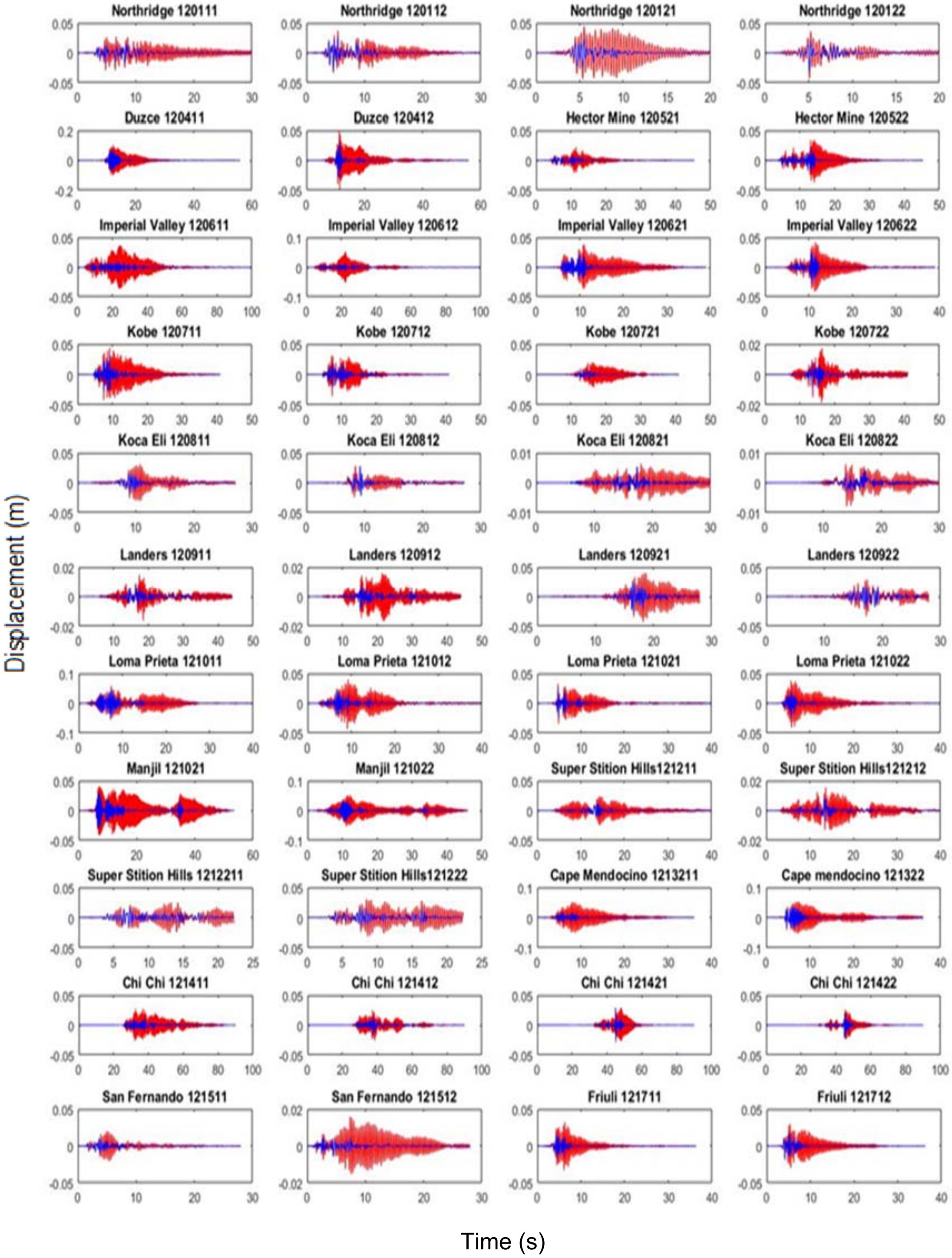

Figure 5: These graphs indicate the reduction of structure displacement, due to the presence of smart MR damper, subjected to the 44 earthquake records

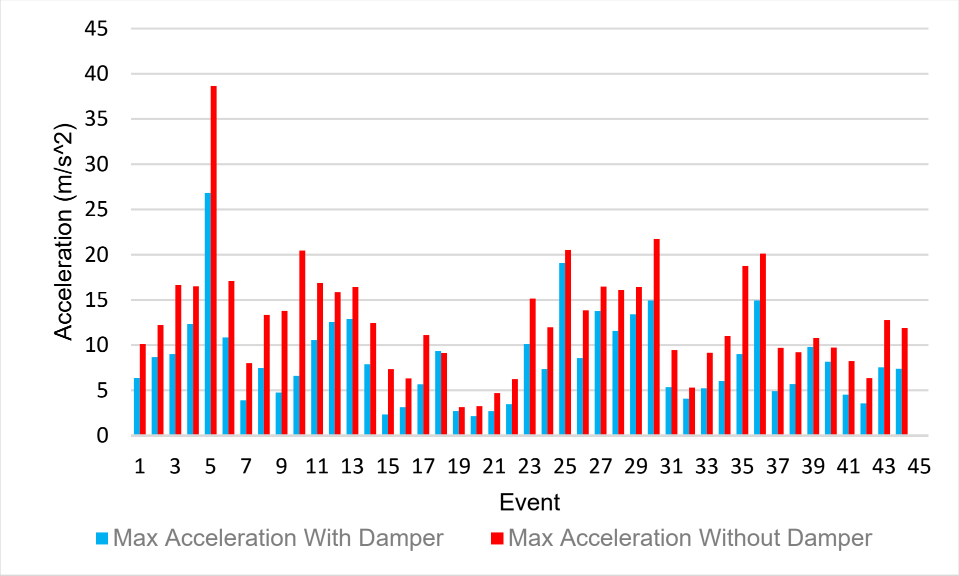

Figure 6: The maximum acceleration with damper vs the maximum acceleration without damper

In this paper considering the formula shown in Eq. (1) for the energy of the earthquake waves in two different conditions: structure with damper and without damper, are compared in Figure 7. It shows that the proposed system can dissipate the energy of earthquake waves significantly.

[10] $E=\int_0^t |D(t)|^2 \, dt$ (Oppenheim et al. 1998)

Where E is the wave energy, D is the displacement of the structure and t is the earthquake time.

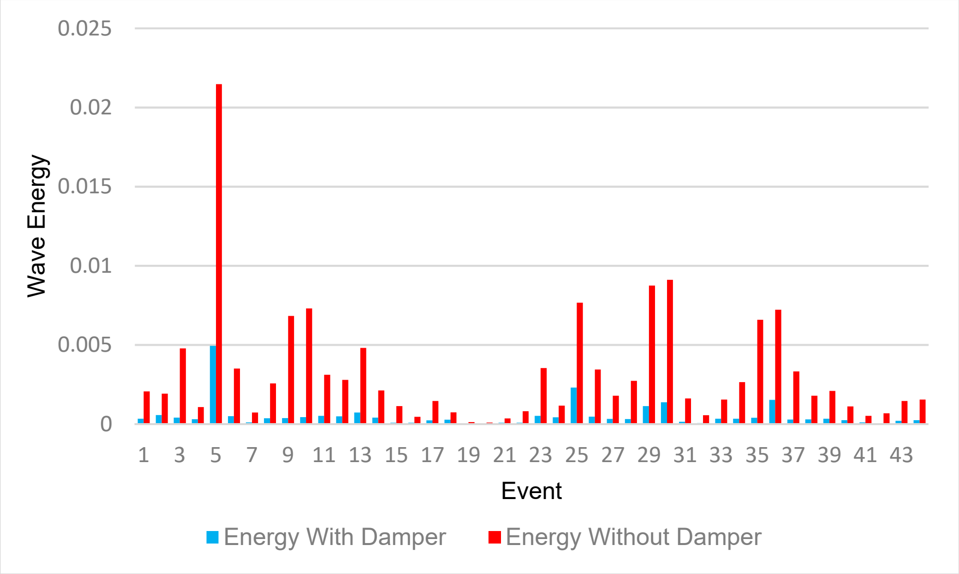

Figure 7: The bar chart illustrates the energy damping effect of the smart MR damper subjected to earthquake records

As another criterion that can be used to visualize the effect of the MR damper in the system is the probability of exceedance of the median values of the dynamic response. By taking account of the results of dynamic structural analysis; the probability curves for maximum displacement demand are drawn and Fig. 8 shows the maximum probability of displacement in two conditions with damper and without damper. Here, the standard normal cumulative distribution function (CDF) is fitted to the cumulative distribution of maximum displacement of model for 44 selected far-field earthquakes (Baker 2015). It can be observed in Fig. 5 that the median of the data in the system with damper is approximately 40% less than the system without damper.

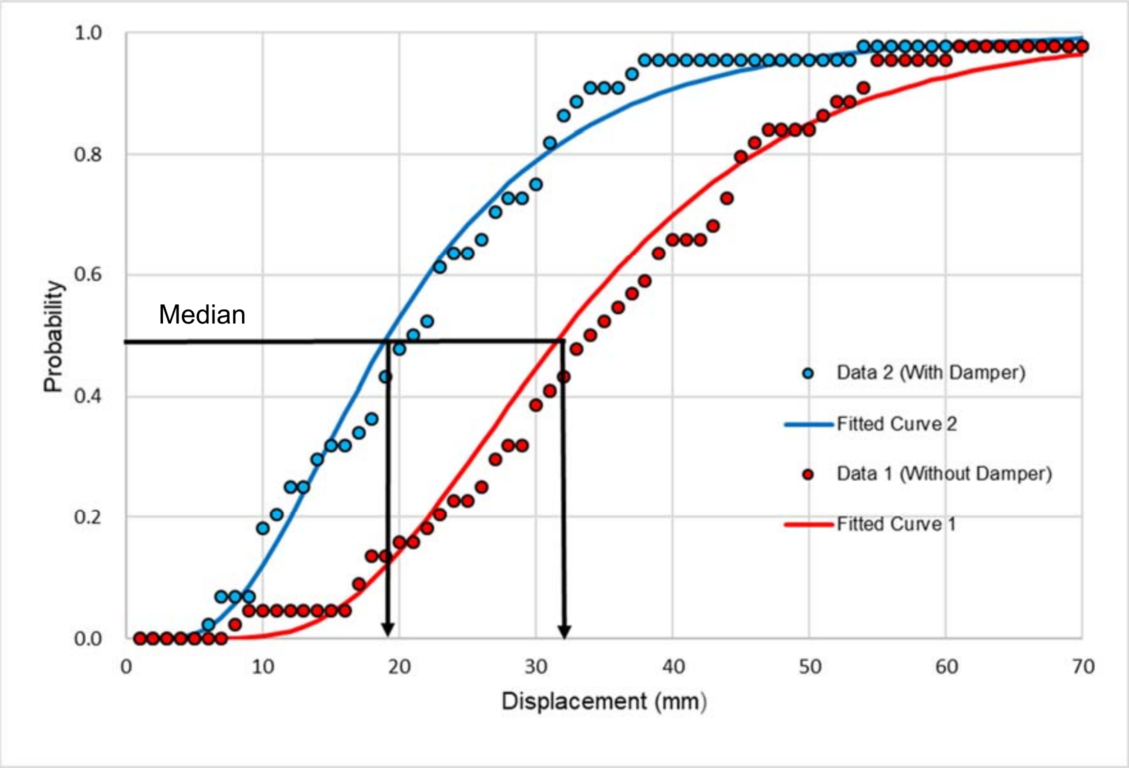

Figure 8: Median response of the system subjected to the earthquake records

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