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A SHAPE MEMORY ALLOY-MAGNETORHEOLOGICAL FLUID CORE BRACING SYSTEM FOR CIVIL ENGINEERING APPLICATIONS: A FEASIBILITY STUDY

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Abstract: The stability of civil infrastructures is one of the main challenges for structural designers, users, and decision makers at the government level. To keep the stability and functionality of the structures against moderate and strong loads, extensive studies have been conducted to develop supplemental structural control systems, particularly bracing system, with the energy dissipation ability.

For instance, bracing systems fitted with friction dampers, and viscous fluids are mounted in structural frames to provide the structural integrity against possible damage. These kinds of bracing systems are passive devices. Furthermore, most of the existing active and semi-active supplemental system integrated with bracing systems are not able to return the system to the initial position (the re-entering ability). Therefore, new hybrid smart structural elements integrated with smart materials, shape memory alloy and magnetorheological fluid, have been developed to improve the structural stability and enhance the re-entering ability of structural elements in infrastructures.

In this study, a hybrid smart bracing system is introduced to partially dissipate the amount of energy and add the re-entering ability to the structure. The new hybrid smart bracing element consists of the shape memory alloy (SMA) wires combined with magnetorheological (MR) fluid damper in its core. This system is able to keep the integrity and enhance the dynamic behavior of civil infrastructure during seismic events.

Simple implementation, easy installation, low operation and maintenance costs, energy dissipation capacity, the re-entering ability, and fast response are counted as the advantages of the present hybrid smart bracing system.

Keywords: stability, civil infrastructure, shape memory alloy, magnetorheological fluid, bracing system, energy dissipation capacity, the re-entering ability

1 INTRODUCTION

During the past decades, the seismic activities put civil infrastructures at risk, injured and lost thousands of lives due to the poor design and/or the lack of strength. Furthermore, failure of civil infrastructures causes decreasing the economic growth and polluting the environment. To keep civil infrastructures healthy and stable, the structural control system should be designed and embedded in civil infrastructures. Nowadays, a wide range of those systems has been installed, including active, semi-active, and passive systems. The Isolation systems (Esteki 2014), the tuned mass damper (Soto and Adeli 2013; Mirzai, Zahrai, and Bozorgi 2017), as a passive structural control systems, active tendon system (Loh, Lin, and Chung 1999), as active structural control systems, and the semi-active tuned mass damper (Hrovat, Barak, and Rabins 1983), semi-active viscous fluid damper (M D Symans et al. 1994), semi-active stiffness control (Michael D Symans and Constantinou 1999) as semi-active structural control systems are some of the examples.

Most of the conventional structural control systems suffer from some disadvantages, including, energy requirement for activation, complicated operational procedure and lack of adaptively for different loading conditions. Recently, rapid advancements in smart materials and structures provided us new features in development of structural control systems with loading adaptively while requiring a minimum amount of energy. In the past years, the magnetorheological fluid (MRF) and the shape memory alloy (SMA) have been attracting the attention for structural control systems (Aryan and Ghassemieh 2017; Zareie et al. 2017b; Zareie et al. 2017a).

Magnetorheological fluid (MRF) is a type of a smart fluid with the ability to change the viscosity under applied the magnetic field. The MRF is made of very small ferromagnetic particles suspended by a fluid, such as the oil. Another component in the MRF is Stabilizer. The stabilizer keeps the thermal properties of the MRF and prevents the settling down of the particles. Nowadays, MRF-based systems are used extensively in many engineering applications such as aerospace, automotive, and particularly civil engineering (Zabihollah et al. 2017; Sarrafan et al. 2011; Naji, Zabihollah, and Behzad 2016). MRF-based isolation systems (Oliveira et al. 2017; Wang et al. 2018; Hapipi et al. 2018; Gu et al. 2017; Cantera et al. 2017), MRF-based damper (Lakhani and Soni 2017; Yoshioka, Ramallo, and Spencer Jr 2002; Iwata et al. 2002; Zamani et al. 2018; Fu et al. 2017) are two common applications of MRF-based systems in civil engineering. Those systems improve the dynamic behavior of the civil infrastructures and keep their stability, by increasing the energy absorption ability and the equivalent viscous damping coefficient of civil infrastructures. They can adjust themselves for various loading conditions while require relatively small amount of energy.

However, the MRF-based bracing systems are not able to move back to the initial position. To provide the moving back option to MRF systems, two solutions could be considered, including push (pull) back by applying the external excitation or combined with other smart system and materials, such as shape memory alloy (SMA) with recovery ability, as the optimized solution. SMA is a type of alloy, which is able to return to the pre-defined shape after experiencing large deformation due to the superelasticity (SE) or the shape memory effect (SME) (Song, Ma, and Li 2006). In the SE, the recovery occurs with removing the external excitations, and in the SME, the residual strain (deformation) eliminates by applying heat. The contrast between SE and SME in civil engineering application shows that SE is much in demand rather than SME. It is mainly linked to the simplicity of the use and no need for the external heat. SMA-based applications are used solely, such as SMA-based damper, SMA-based bars or integrated to other applications, like isolation system, to enhance the dynamic behavior of civil infrastructures (Zhang and Zhu 2007; Savi,

Pacheco, and Braga 2002; Sun and Rajapakse 2003; Tu et al. 2011; Jennings and van de Lindt 2014). In spite of those advantages in SE of SMA-based applications, the functionality of SMA, including recovery ability and energy dissipation capacity are the only function of applied loads. On other hands, the outputs of the systems are not controllable.

In order to develop a smart system with controllable energy absorption capacity and recovering ability, a combination of the SMA and MRF is suggested. In this study, the SMA-MRF bracing system, as the structural control systems is designed to implement in buildings. To find the effect of the suggested smart system, it has been integrated into the idealized frame. The time-history displacement, the maximum displacement, and the root-mean-square displacement have been obtained to illustrate the improvement in structural response.

2 THE MRF-SMA CORE BRACING SYSTEM

The SMA-MRF core bracing system is composed of an MRF-based damper in the core of the bracing system and four SMA-wires, as displayed in Figure 1. Two cylinders are used to hold the SMA wires, as illustrated in Figure 2. One cylinder (inner cylinder) is connected to the bottom of the MRF-based damper and another cylinder (outer cylinder) is attached to the top of the MRF-based damper. Two ends of two SMA-wires are gripped to the inner cylinder and other two ends are secured to the outer cylinder. This arrangement is used to provide the resistive force under tension by the SMA and MRF core ($F_{SMA-MRF}$). Likewise, the other two wires, are secured to the outer cylinder and inner cylinder; this set up generates the resistive force under the compression ($F_{SMA-MRF}$). This mechanism is shown in Figure 3. On the other hand, while the external loading applied to the bracing system, the system supplies a resistive force regardless of the direction of loading.

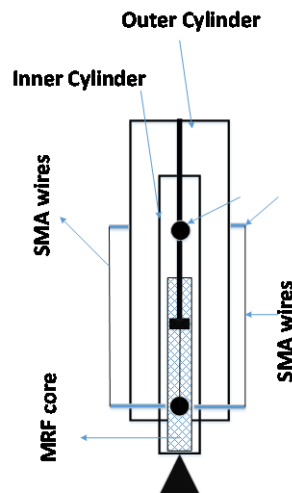


Figure 1. The conceptual design of the SMA-MRF core bracing system

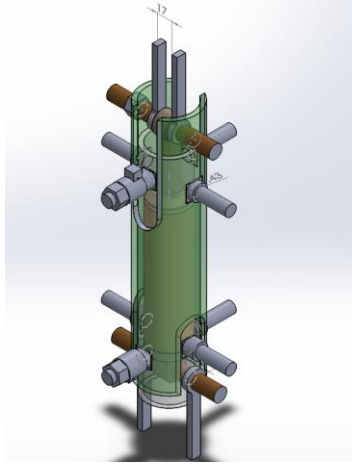


Figure 2. The Conceptual 3D design of the bracing system

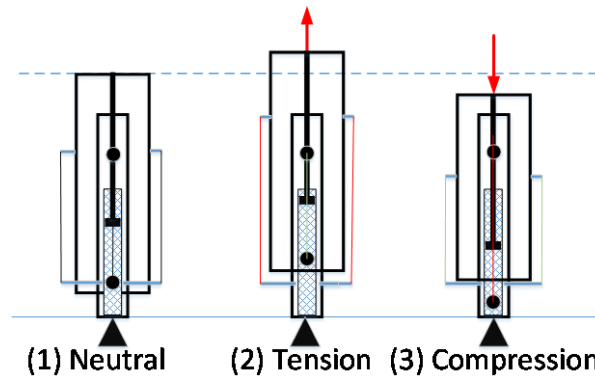


Figure 3. The schematic diagram of the working mechanism in the SMA-MRF core bracing system

3 MODELING

To study the effect the SMA-MRF based bracing system, a one-story frame, as presented in Figure 4, with two massless columns ($m = 0, 4EI_c$), and the rigid frame ($2m, EI_\infty$) with the height of h and the bay length of L is considered. According to these assumptions, it is assumed that the frame is the one-degree of freedom system (Chopra 2001).

The equation of motion of the frame is given by (Chopra 2001).:

$$[1] 2m\ddot{u} + ku = -2m\ddot{u}_g(t)$$

where $2m$ and k are the mass and the stiffness of the frame, respectively. \ddot{u} and \ddot{u}_g denote the acceleration of frame and the ground acceleration, correspondingly (Chopra 2001).

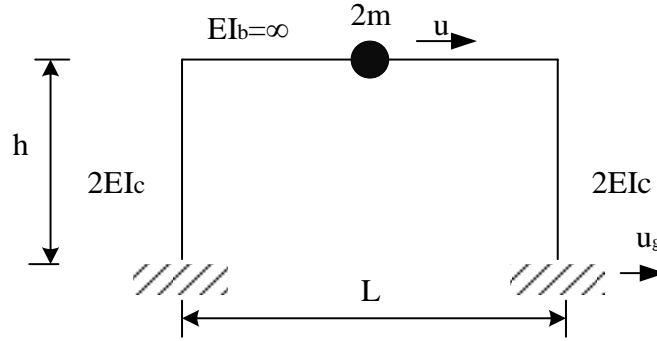


Figure 4. The one-story model of the frame

By inserting the SMA-MRF core bracing system into the frame, as shown in Figure 5, Eq.1 is modified to:

$$[2] 2m\ddot{u} + ku = -2m\ddot{u}_g(t) - F_{SMA-MRF}$$

where $F_{SMA-MRF}$ is the resistive force of the SMA-MRF based bracing system.

With respect to the mechanism of the bracing system, $F_{SMA-MRF}$ is expressed by:

$$[3] F_{SMA-MRF} = F_{MRF} + F_{SMA}$$

where F_{MRF} and F_{SMA} are the force supplied by the SMA wires and the MRF core, respectively.

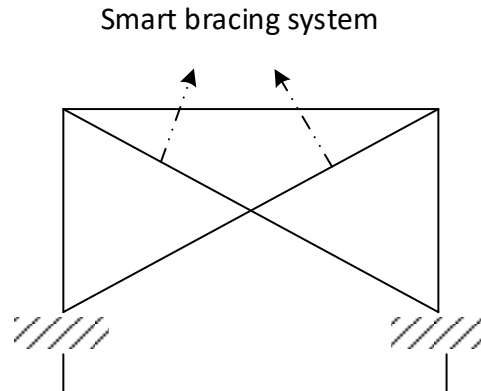


Figure 5. The fame with the x-bracing system

3.1 The SMA modeling

The first main components of the bracing system are the SMA wires. The resistive force supplied by SMA wires is given by:

$$[4] F_{SMA} = \sigma A$$

where σ and A denote the stress in SMA wires and the cross-section, respectively.

The stress is given by (Zuo et al. 2009):

$$[5] \sigma(\varepsilon) = E(\varepsilon - \varepsilon^T)$$

where E , ε , and ε^T represent the Young modulus, the strain, and phase transformation strain, correspondingly.

The Young modulus is defined by:

$$[6] E = E_A + \zeta(E_M - E_A)$$

where ζ is the phase transformation strain. The terms E_A and E_M denote Young modulus in the Austenite phase and the Martensite phase.

3.2 The MRF core modeling

The core of the bracing system is the MRF-based damper. The force of damper is a function of the applied magnetic field and basic viscosity of the MRF in the damper. This force is given by (Unsal 2006; Yang et al. 2002):

$$[7] F_{MRF} = F_\tau + F_\mu$$

where F_τ is the uncontrollable force, as a result of a friction force and a plastic viscous force. F_μ is the controllable force and its magnitude is a function of the varied viscosity of MRF.

4 EARTHQUAKES

In order to apply the ground motions (GMs) to the introduced frame, three GMs including Christchurch, Imperial Valley, and Parkfield are chosen and scaled to 1:2. The properties of the GMs are given in Table 1.

Acceleration time history of Christchurch, Parkfield, and Imperial Valley are shown in Figure 6, Figure 7, and Figure 8, respectively.

Table 1 Selective ground motions and characteristics in three tectonic environments(Pieper 2018)

Earthquake	Year	Site	Mw	R(km)	Vs30(m/s)
Christchurch,NZ	2011	Resthhaven	6.2	5	141
Imperial Valley, USA	1979	E.C.A.-3	6.5	13	163
Parkfield, USA	2004	P.F.Z.-1	6	3	178

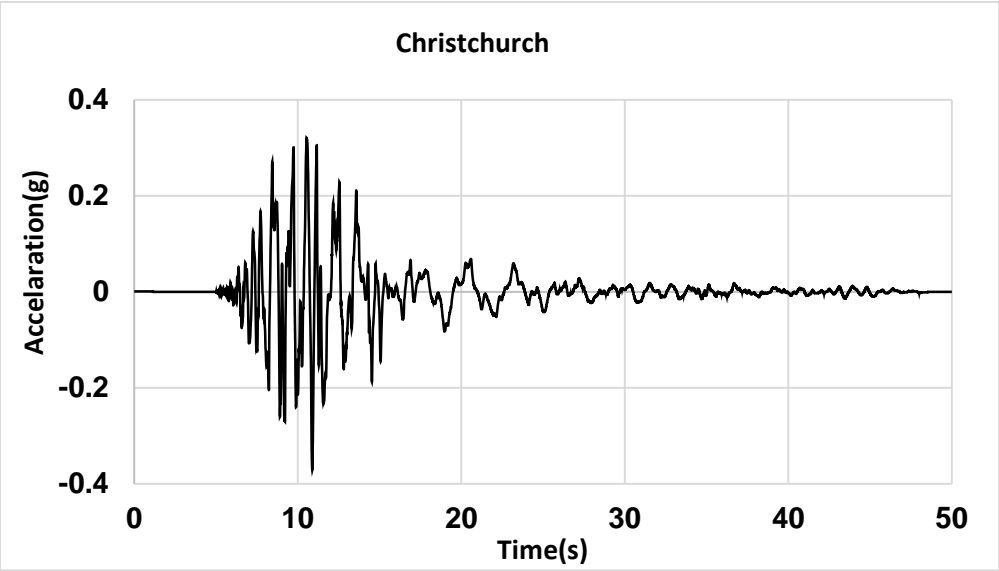


Figure 6. Acceleration time history of the Christchurch earthquake at the Resthaven station

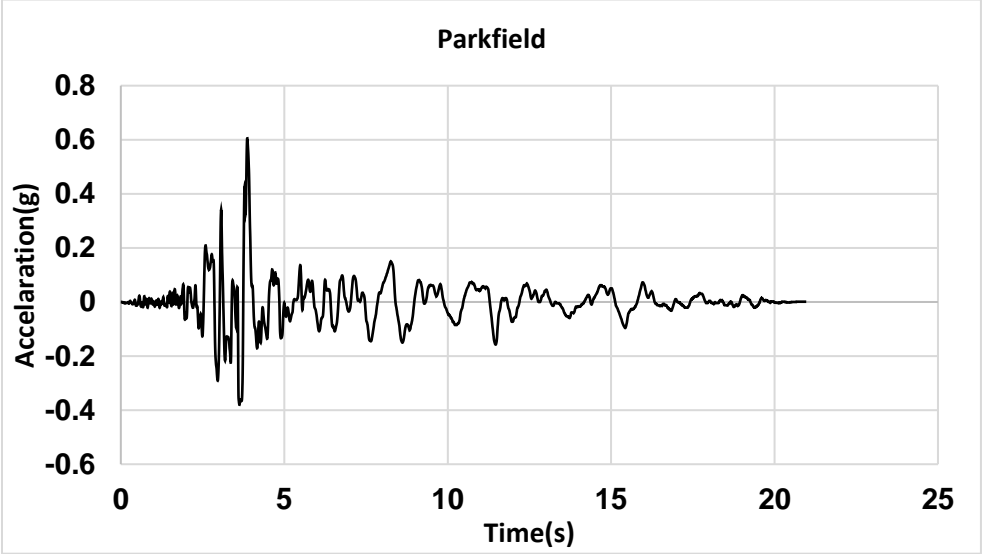


Figure 7. Acceleration time history of Parkfield earthquake at the P.F.Z.-1 station

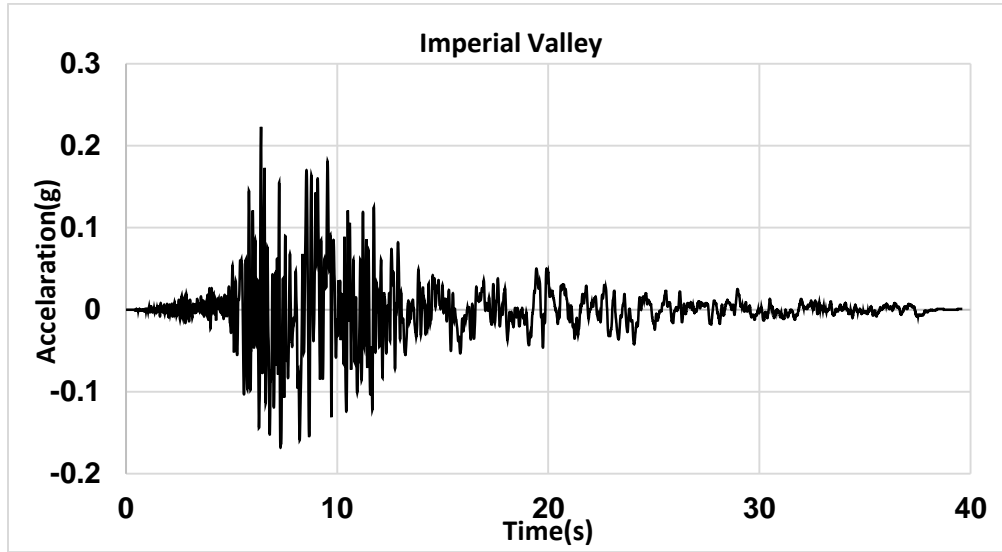


Figure 8. Acceleration time history of the Imperial Valley earthquake at the E.C.A.-3 station remarkable

5 NUMERICAL MODELING

In order to model and analyze the frame equipped with the SMA-MRF bracing system, the OpenSees (the Open System for Earthquake Engineering Simulation), is used. A frame with the height of 3657 mm and the bay length of 7314mm is considered. The weight of the frame is about 100kN. The Young modulus and the moment of inertia of each column are about 206.84 kN/mm² and 133.19×10⁶ mm⁴, respectively.

5.1 The MRF damper

Table 2. The properties of the MRF damper

PHYSICAL PROPERTIES	Value
Stroke (mm)	74
Extended Length (mm)	248
Body Diameter(mm)	42.1
Shaft Diameter(mm)	10
Tensile Strength(N)	8896 max
Damper Forces (N) ,Peak to Peak, 5 cm/sec @ 1 A	>2447
Damper Forces (N) ,Peak to Peak, 20 cm/sec @ 0 A	<667
Operating Temperature(°C)	560
Input Current, Continuous for 30 seconds(A)	1 max
Input Current, Intermittent(A)	2 max
Input Voltage(V)	12 V

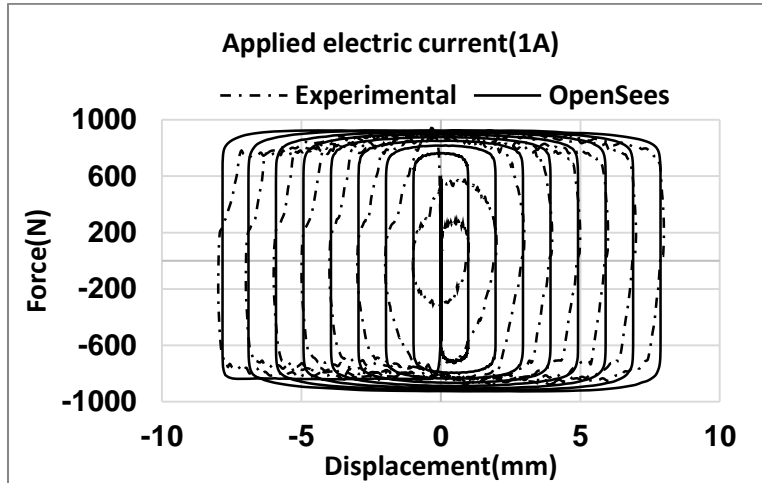


Figure 9. The force-displacement of the MRF damper under 1A electric current

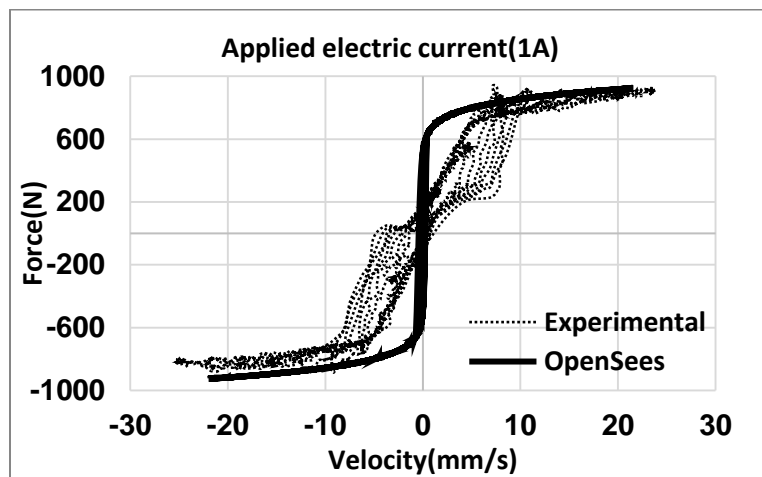


Figure 10. The force-velocity response of the frame with 1A electric current

To simulate the dynamic behavior of the core, the MRF damper manufactured by Lord® is chosen. The characteristics of the damper are given in Table 2.

To use the numerical model of the MRF damper, the force-displacement (see Figure 9) and hysteresis responses (see Figure 10) of experimental and numerical results are obtained and compared together. It is noted that both numerical and experimental results are in a reasonable range. In order to use the MRF damper in the bracing system, the maximum force of numerical damper under 1A electric current changes to 30.5 times greater than the maximum force of the original damper.

5.2 The SMA-wire

The SMA wire in the bracing systems, NiTi, as SMA, manufactured by Confluent Medical Technologies company, is modeled and verified in the OpenSees. The properties of SMA are given in Table 3.

To model the SMA wire in OpenSees, the hysteresis response of the numerical and experimental results are found and presented in Figure 11. where one may realize a good match between the results.

The SMA wire in the bracing system has the length of 1635.72 mm. The area of the SMA wires are computed by:

$$[8] A_{wire} = \frac{cof}{2} \left(\frac{\max(F_{MRF})}{\sigma_{ms}} \right)$$

where the cof , $\max(F_{MRF})$, and σ_{ms} are 3, 25KN, and 500 MPa, respectively.

Table 3. The specifications of the SMA

PROPERTIES	Value
Melting point (°C)	1310
Density (g/cm ³)	6.5
Electrical resistivity (μohm-cm)	82
Coefficient of Thermal Expansion(°C)	11 x 10 ⁻⁶
Modulus of Elasticity(GPa)	41
Ultimate Tensile Strength(MPa)	≥1070
Total Elongation	≥10%

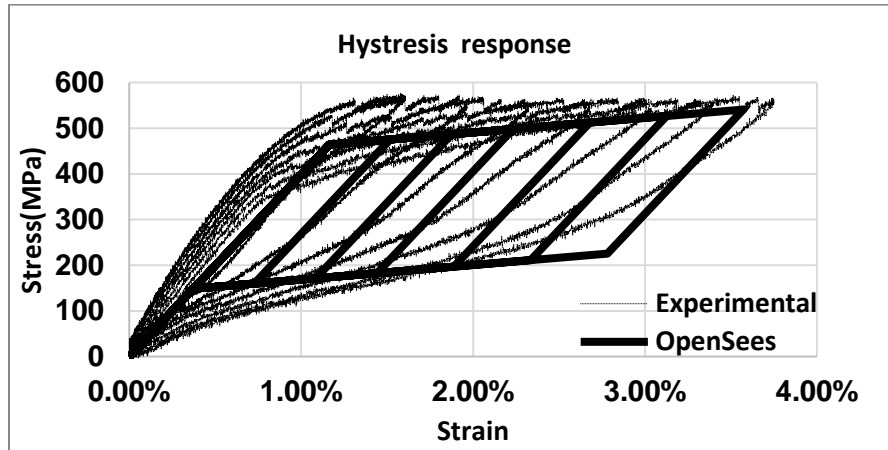


Figure 11. the Hysteresis response of the frame of the SMA specimen

6 RESULTS

The dynamic behavior of the introduced frame without structural control system under three scaled GMs are investigated and shown in Figure 12. It is noted that the maximum displacement under Christchurch Parkfield and Imperial Valley are about 37mm, 48mm, and 16mm, respectively.

To study the effect of the structural control system on the structural behavior of the frame, the time-history analysis of the frame under the Imperial Valley GM is presented in Figure 13. It is observed that the control system reduces the displacement sharply contrast to the frame without a structural control system. It is mainly due to the effect of stiffness of the SMA and the structural damping effect of the MRF-core of the suggested system.

Figure 14 presents the maximum displacement of the frame under the Imperial Valley, the Christchurch and Parkfield GMs. By inserting the SMA-MRF (0A) into buildings, the peak displacement drops about 59%, 10%, and 50%, respectively. By energizing the SMA-MRF (1A), it decreases by about 6 %, 30% and 62% under the same GMs, compared to the inactive structural control system. The contrast between the two states of the suggested systems, reveals by setting the variable viscosity of the MRF core, the maximum displacement of the frame.

The other studied parameter is the root-mean-square (RMS) displacement of the frame under GMs. A contrast of the RMS displacements of the frame is illustrated in Figure 15. It is found that the RMS values for the frame are approximately 3.06 mm, 2.43 mm, and 1.6mm under the Christchurch, the Parkfield, and Imperial Valley GMs. It decreases to 1.01 mm, 1.76 mm and 0.38 mm with a frame with SMA-MRF (0A). By implementing the SMA-MRF(1A) into the frame, the RMS displacement significantly decreases and reach to 0.68 mm, 1.08 mm, and 0.14 mm subjected to same GMs.

The structural dynamic analysis of the frame proves the remarkable enhancement in the frame's response obtained with the SMA-MRF bracing systems, compared with frame without the bracing system

The displacement of the system under three scaled ground motions

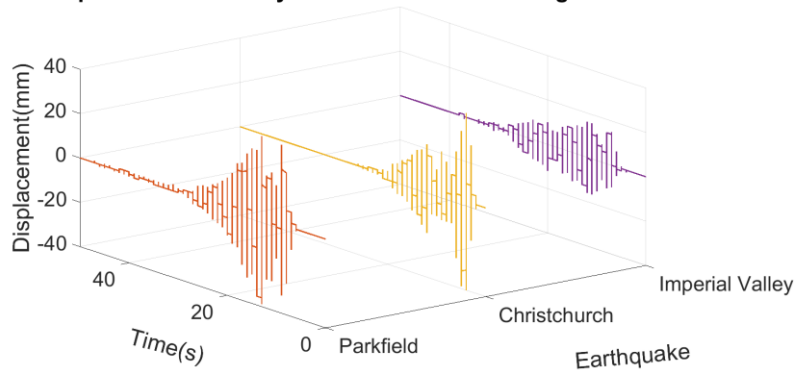


Figure 12. The displacement of the frame without the bracing system

The displacement of the system under the scaled Christchurch GM

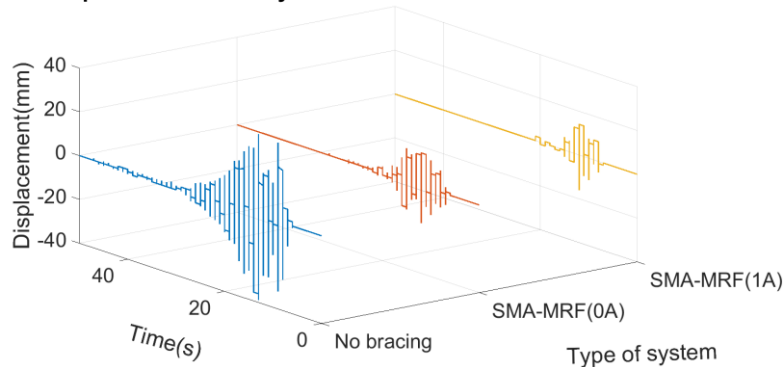


Figure 13. The displacement of the frame with and without bracing system

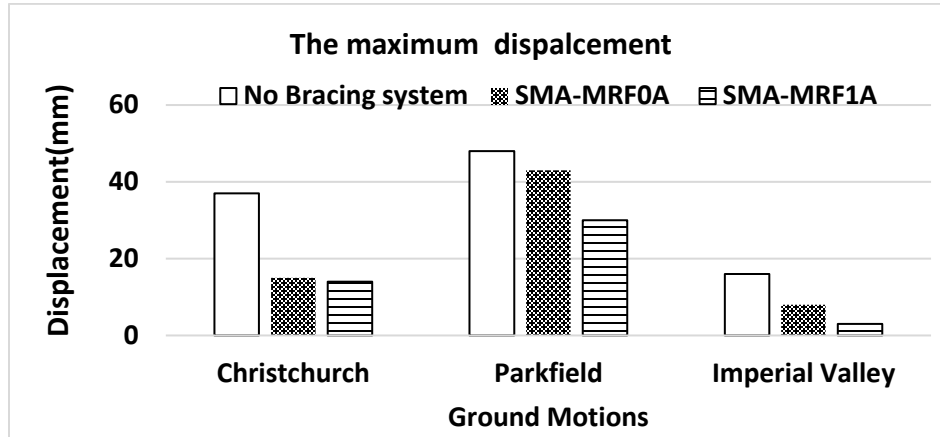


Figure 14. The maximum displacement of the frame under simulated GMs

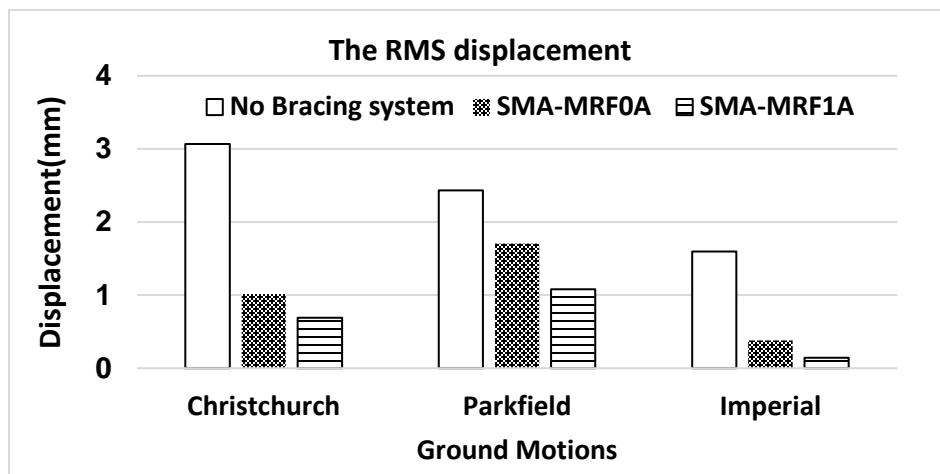


Figure 15. The RMS displacement of the frame under simulated GMs

7 CONCLUSION

In this study, the conceptual design of the SMA-MRF based bracing system is presented to take advantage of the SMA-based system and the MRF-based system and overcome the disadvantages found in each component. The proposed system works under tension and compression loading.

The suggested system is installed in the simplified frame and subjected to the three simulated earthquakes. The main outcomes of the research are as follows:

1. The maximum and the RMS displacement have been remarkably reduced by the frame equipped with the SMA-MRF-based bracing system.
2. The contrast between active (0A) and inactive (1A) of the SMA-MRF-based system, the effect of the active structural control system is much rather than the inactive system.

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