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NATURAL BEHAVIOUR OF STEEL BRACED FRAMES REINFORCED WITH SHAPE MEMORY ALLOY WIRES

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1. ABSTRACT

Shape memory alloys (SMA) have just recently made their way into structural design, and through studies have proved to be quite effective in increasing a structures strength and performance. Earthquakes are one of the most chaotic natural disasters that occur around the world, significantly impacting infrastructure to the point where cities lose their ability to function as bridges and hospitals are destroyed. The main objective of this paper is to investigate the effectiveness and feasibility of active techniques for seismic retrofitting of structures using pseudoelastic (PE) NiTi SMA wires. Three steel braced frames were designed and constructed; one steel control frame and two SMA frames. A free vibrations test was conducted to determine the natural frequency and damping ratio of the two systems. The tests of the steel and PE SMA frames showed that the stiffness of the brace does not affect the natural frequency of the system but rather, the connection of the system to the rigid floor controls the natural behaviour. Findings of this research are expected to add valuable knowledge to the field of seismic retrofitting of structures and widen the potential applications of the SMA in the structural engineering field.

2. INTRODUCTION

In structural design, the number one priority is the human life factor. The main objective is to create a safe and reliable structure that can undergo the design loads in a given building code. Earthquakes have proved to cause substantial damage and/or collapse of entire buildings, bridges, and ground transportation networks. Earthquakes can cost countries billions of dollars due to the infrastructure repair, demolition and replacement. Recently, seismic design has shifted focus from ensuring moderate ductile behaviour during a strong earthquake to prevent collapse of the structure to focussing on minimizing the amount of damage done to ensure post earthquake functionality. Researchers have investigated the use of smart materials, rocking elements, and isolation devices to minimize damage to structural systems.

This research takes a deeper look into retrofitting steel structures using NiTi shape memory alloy. Recently, this new class of smart materials has been attracting researchers from different fields (Dong et al. 2007, Li et al. 2013). The SMA is a unique class of alloy with the ability to undergo large deformations (up to 8%) and return to its original shape through stress removal. Over the last couple of years, analytical models and studies have been investigated on the idea of utilizing SMA in steel braces (Yang et al. 2010, Haque et al. 2017). This paper explores the concepts of SMA and applications of SMA in steel structures. In this research, pseudoelastic (PE) NiTi wires are placed within a steel brace and experimentally tested under two types of loading conditions: a in-plane free vibrations test and a in-plane quasi-static cyclic loading test. This paper will only discuss the behaviour of the specimens subjected to the in-plane free vibrations test. Overall, this research aims to improve the performance of steel braced frames by dissipating more energy and having the ability to recenter the structure after the load is removed.

3. REVIEW OF SMA IN STEEL STRUCTURES

3.1 SMA

Shape memory alloys are a unique material that can be deformed from either temperature induced (shape memory effect) or stress induced (pseudoelastic effect) (Ozbulut et al. 2011). The pseudoelastic (PE) effect is defined as the ability of the material to undergo hysteretic response when mechanically loaded under constant temperature. The shape memory effect (SME) is defined as the ability of the material to recover its original shape after being deformed in a temperature cycle, however after unloading there is residual strain. Therefore, in order to take full advantage of the SMA's properties, the behavioural characteristics of the PE will be studied.

The unique characteristic of SMA's is that they have different phases based on the induced temperature and mechanical loading. The material can be in two phases, at high temperatures the material is in the austenite phase (A), and at lower temperatures the martensite phase (M). Within the martensite phase, the material is either twinned or detwinned. These different phases are clearly shown in Figure 1, (Abdelrahman, 2017).

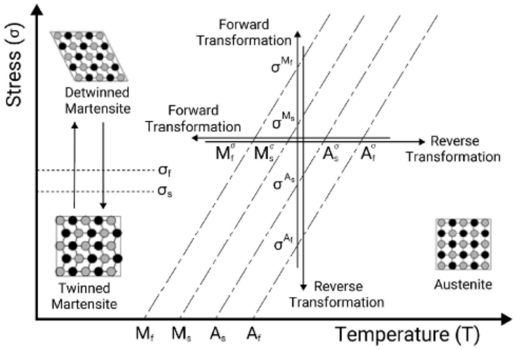


Figure 1: Typical phase diagram of SMA material (Abdelrahman, 2017)

In the stress-free state, the four characteristic phases are as follows: the Martensite start temperature (M_s), the Martensite finish temperature (M_f), the Austenite start temperature (A_s), and the Austenite finish temperature (A_f). The superelastic effect is exhibited when the material is stressed at a temperature greater than A_f. Then the material starts to transform into martensite when it is stressed above M_s and then fully martensite at M_f. When the material is unloaded, it starts to transform back into austenite at A_s and is then in fully austenite when the specimen is unloaded to A_f.

The stress-strain hysteresis of a SMA specimen is shown in Figure 2. This figure shows the superelastic effect of SMAs and clearly demonstrates that the material makes a full recovery with zero residual strain, making it ideal for cyclic loading conditions.

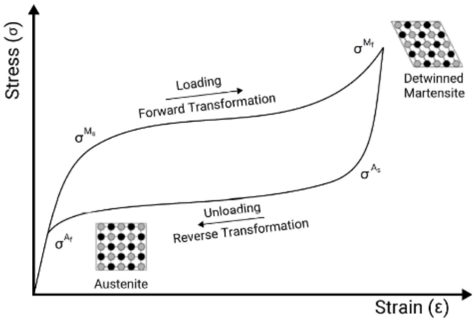


Figure 2: Stress-strain relationship for superelastic SMA material (Abdelrahman, 2017)

1. 3.2 Applications

Over the last decade, a significant amount of research has been done in regard to the use of SMAs for seismic applications. Researchers have investigated SMA-based dampers (Dolce et al. 2007; Ma and Cho, 2008; Shook et al. 2008; Casciati and Favavelli 2008, 2009; Ozbulut and Silwal 2016; Qian et al. 2016), SMA-based structural connections (Speicher et al. 2011; Fang et al. 2014; Oudah, 2014; Wang et al. 2017) and SMA braces (Asgarian and Moradi 2011; Araki et al. 2016; Qiu and Zhu 2017; Cortes-Puentes and Palermo 2018, Sultana and Youssef 2018). The following are some cases that focussed on the use of SMA in steel structures.

Steel braced frames are a very common lateral load resisting system. Results from experimental and numerical studies have shown that braces that incorporate PE NiTi SMA material are very effective in recentering the system as well as dissipating some of the energy. One of the earliest implementations of PE SMA wires in a steel structure was in a European project called ‘The MANSIDE Project’ (Memory Alloys for New Seismic Isolation and Energy Dissipation Devices). Here, the recentering and energy dissipating devices were separated into two groups of wires. The recentering group composed pre-tensioned austenitic PE wires designed within the connection to always remain in tension (Dolce et al. 2000). The dissipating group composed of pre-tensioned austenitic PE wires arranged in a double counteracting system of springs. It was determined that the system had great versatility, where by simply varying the number and/or characteristics of the SMA material, one could obtain a wide range of cyclic behaviours that could suit many different applications.

Haque and Alam (2017), developed a fully buckling restrained piston-based self-centering bracing system that utilizes PE SMA for its self-centering mechanism. Through numerical analysis, four different diameter SMA bars are analyzed: 10mm, 12mm, 16mm and 20mm. When the braced frame system was subject to cyclic loading, all four cases exhibited a symmetric stable hysteresis response, indicating that the bars have not degraded or buckled under the cyclic load. When compared to the steel equivalent frame, after each nonlinear deformation cycle, the bars permanently deform and gaps are generated between the connection points. With every cycle, these gaps become larger, therefore, over time the braces become less effective. This study shows the superb advantages superelastic SMA has over conventional steel.

Recently, Abou-Elfath (2017) investigated the ductility characteristics of a steel buckling restrained brace composed of SMA. The SMA bars were unbonded and placed in grouted tubes so that they would not buckle under the compressive loads. They found that the SMA frame exhibited undesirable strength and stiffness increase after it reached its yield level as the SMA exceeded the maximum allowable drift limit of 5.5%. Their concern by allowing the frame to drift is the potential danger it poses on the other structural members, such as the columns, as they may not be able to recover from such a drift.

4. COUPON TEST OF SMA WIRES

The coupon tests for the NiTi SMA wires were conducted with accordance to ASTM E8-E8M in order to determine the tensile properties of the SMA wires. The average austenite yielding stress was found to be

500MPa and the fracture stress was found to be 1248MPa. Since the PE effect is the focus of this research, the SMA material begins in the austenitic phase; from the tensile test the modulus of elasticity (E_a) was found to be 42GPa.

5. DESIGN OF SPECIMENS

An idealized framed system consists of a mass concentrated at the roof level, a massless frame that provides stiffness to the system, and a viscous damper that dissipates the vibrational energy of the system. The properties of each structural member are concentrated into three separate components: mass, stiffness, and damping component. A simple, single-degree-of-freedom braced frame was chosen for this study, with the design loads based on the maximum load applied by the actuator. Two specimens were tested in this research: one braced frame with a steel yielding fuse, the other with the PE NiTi SMA fuse. Figure 1 shows the elevation profile of the two frame setups.

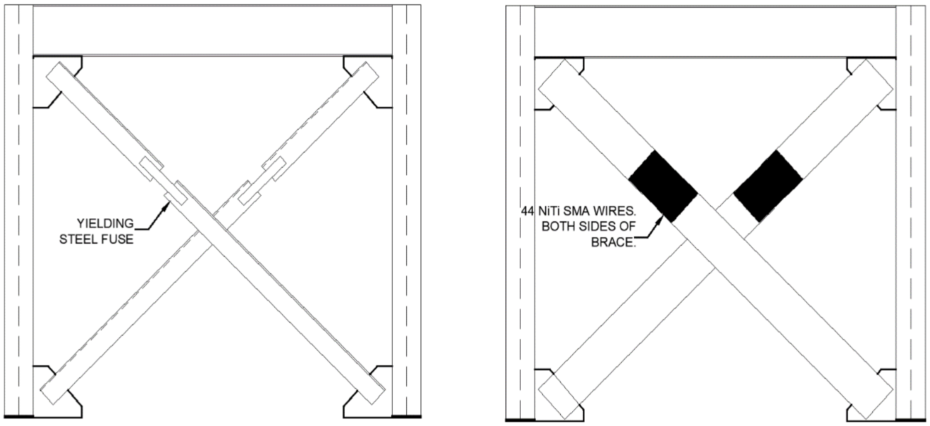


Figure 3: Specimen details

To investigate the potential of PE NiTi wires, the specimens were designed to yield at the same load. By Hooke's law (Eq. 1), the steel and SMA materials may yield at the same load, however their yielding strains will be different.

1. $\sigma = E\varepsilon$

It is the yielding of the material that dissipates the seismic energy; if the specimen is able to yield at a relatively small drift, more energy can be dissipated throughout the excitation. When the maximum allowable lateral load was determined, using Equation 2, the area of each material was calculated based on the yield strength of steel being 350MPa as the yield strength of the SMA was unknown at the design phase.

2. $T_r = \emptyset A F_y$

For the steel frame, a 300x45x6mm (LxWxt) flat bar was used to act as the plastic hinge. For the SMA frame, 88-2mm diameter PE SMA wires were used per brace. The other steel members were designed to remain in the elastic limit when loaded.

6. CONNECTION DESIGN

Lateral load resisting systems (LLRS) are provided in the vertical plane of structures to resist horizonal loads and to ensure lateral stability. There are three primary LLRS: vertical braced frames, rigid frames, and shear walls. For this research, a vertical braced frame was examined. Here, the braced frames had all pinned connections and the columns were only subject to axial loads. As stated before, the objective of this experiment is to ensure a ductile failure, and typically braced frames are more stiff than rigid frames thus limiting their ductility. However, by designing for a pin connection at the foundation level, the system will be able to rotate; furthermore, by implementing a yielding fuse within the cross brace the flexibility of the system is increased. It should be noted that though in design we consider no moment transfer in a pin-pin connection, because the frame is bolted using a plate, there is a partial fixity that causes a small moment transfer. Figure 4 demonstrates the effect when a lateral load is applied to the frame.

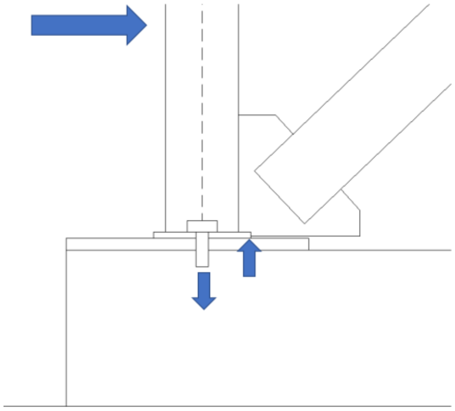


Figure 4: Column to foundation connection

With that said, the connections were mainly designed to withstand the respective shear forces. The beam-column connection was designed to take the self-weight of the beam and the column-foundation connections were designed to take the maximum lateral load the actuator could apply.

7. TEST PROGRAM

An in-plane free vibrations test was carried our on each specimen. The test was carried out with no vertical loads applied to the specimens. A cable was fastened to a cap plate on the loading beam and then attached to a lateral actuator. The actuator was pulled back horizontally in the in-plane direction to create a small displacement, but small enough as to not cause the system to yield. The cable was then cut, releasing the frame to vibrate freely.

8. RESULTS

A free vibrations test on a structure is when it is disturbed from its static equilibrium state and is then allowed to vibrate without any external dynamic excitations. From this test, the natural vibration frequency and damping ratio are determined.

Figures 5 and 6, show the basic setup for the free vibrations test for the specimens.

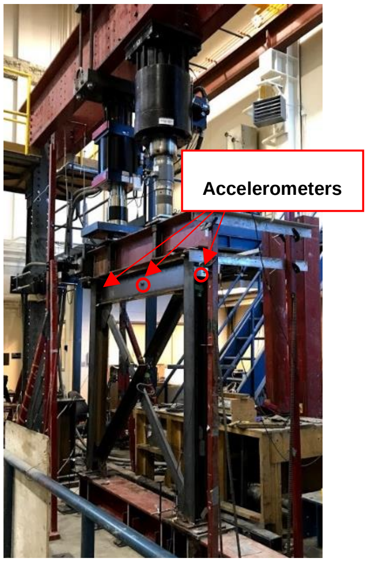


Figure 6: Accelerometer set up on specimens

Figure 5: Frame to actuator connection detail

2. 8.1 Data Acquisition

During the free vibrations test, the displacement of the top of the frame was measured using 2 laser-based displacement transducers, both aligned in the in-plane direction. Three high accuracy accelerometers were mounted on the frame. Two were placed on each column to measure the in-plane vibration (accelerometers #1 and #3), and the other was placed on the cross beam to measure the out-of-plane vibration (accelerometer #2). Data was acquired at a frequency of 2000Hz during the free vibrations test.

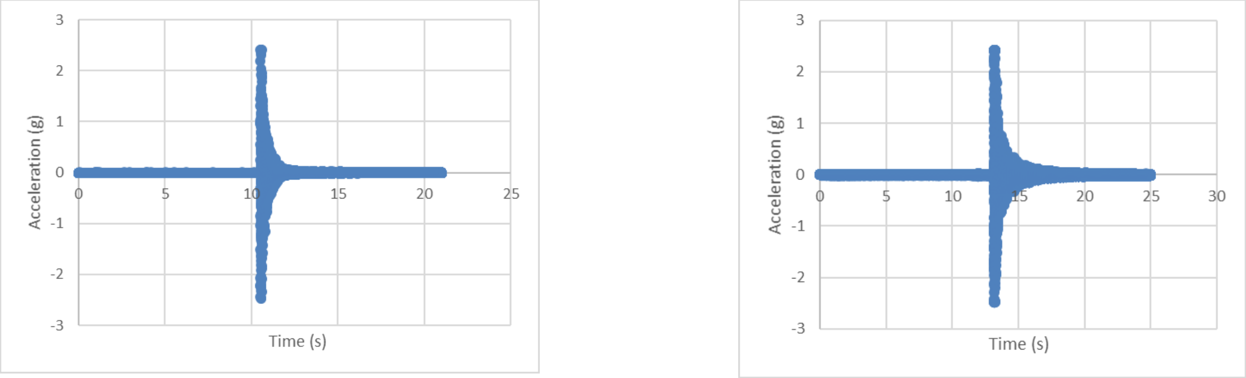
3. 8.2 Frequency analysis

A viscous-based free vibrations analysis was used to determine the natural frequency of the system as the yielding of the fuse acts as a damper, shortening the natural frequency and lengthening the natural period from the undamped period to a damped period, Equation 3. However, when the damping ratio is less than 20%, as most structures are, these effects can be neglected (Chopra 2012), therefore, $T_D = T_n$ and $\omega_n = \omega_D$.

3. $$T_D = \frac{T_n}{\sqrt{1-\zeta^2}}$$

Where ζ is the viscous damping ratio; T_D is the damped period; T_n is the natural period; ω_n is the natural frequency; and ω_D is the damped frequency.

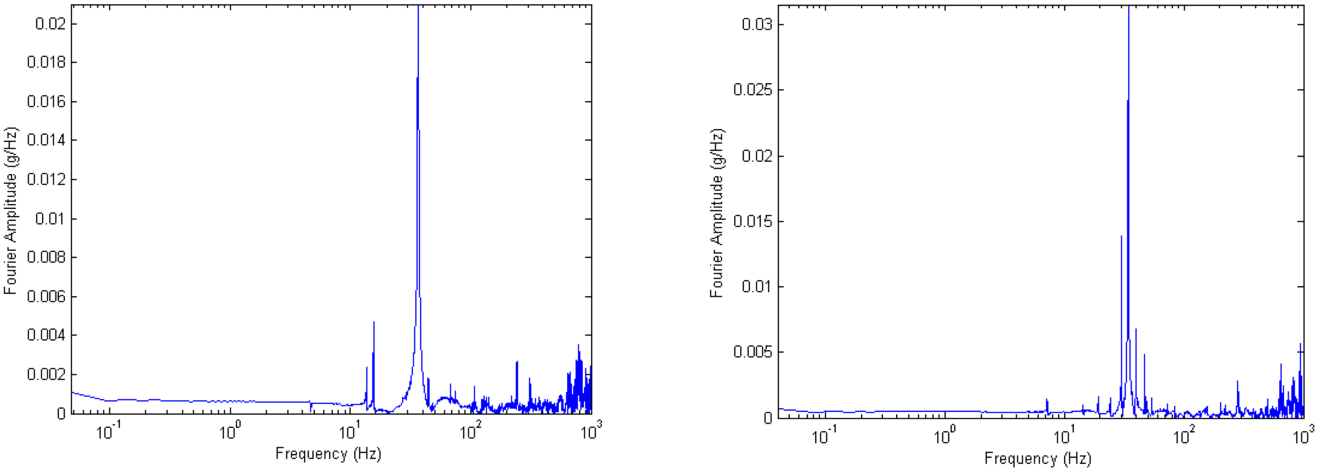
From the free vibrations test, the following results were obtained.



Steel Frame Accelerometer Data

SMA Frame Accelerometer Data

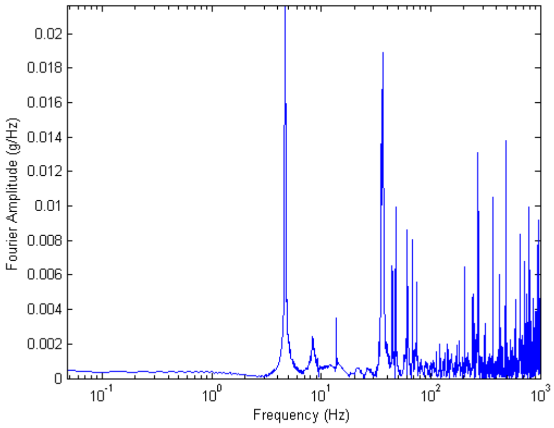
Figure 7: Accelerometer versus Time data for specimens



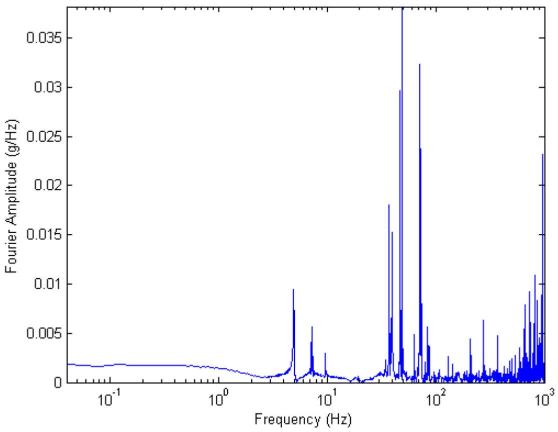
Steel Frame In-Plane Natural Frequency

SMA Frame In-Plane Natural Frequency

Figure 8: In-Plane Natural Frequency results for specimens



Steel Frame Out-of-Plane Natural Frequency



SMA Frame Out-of-Plane Natural Frequency

Table 1: Summary of results

	In Plane Frequency	Out of Plane Frequency	Damping ratio
Steel Frame	35Hz	39Hz	1.3%
SMA Frame	35Hz	46.8Hz	1.0%

The in-plane free vibrations tests revealed some important information regarding the design of the braced systems. Typically, braced systems are a superposition of two different systems: one being a rigid frame that supports the vertical loads, and the second is a vertical bracing system that is regarded as a pin-connected truss that resists the lateral forces. Therefore, the lateral stiffness of the braced frame can be estimated as the sum of the lateral stiffness of the individual braces as seen in Equation 4 (Chopra 2012).

4. $k_{brace} = \frac{AE}{L} cos^2(\theta)$

However, from the test results, both frames have the same natural frequency. This suggests that the fixation at the columns dominates the rigidity of the system rather than the stiffness of the braced members. The PE SMA brace is approximately 24% less stiff than the steel brace, it would be expected for the frequency of the PE SMA brace to be higher than the steel brace. However, because of the partial fixity, the frames behave more like a rigid frame than a pin-connected truss frame. Therefore, the stiffness of the braces does not affect the in-plane natural behaviour of the frame.

It should be noted that the out-of-plane frequencies are different for the different systems. In the out-of-plane direction the stiffness of both systems is less as it is the weak axis, thus giving a higher frequency. Reasons for the systems having different out-of-plane frequencies is due to the difference in plastic hinge, one being steel, the other PE NiTi SMA. Furthermore, the steel bracing member for each system is different. For the steel braced frame, a L102x102x6.4 angle is used and for the PE SMA brace, a 200x6mm plate is used. The angle in the steel frame, increases the out-of-plane stiffness of the system compared to using a 6mm thick plate, thus having a lower frequency than the SMA frame.

4. 8.3 Damping ratio analysis

In structures, there can be several energy dissipating mechanisms acting simultaneously, and typically they are idealized by equivalent viscous damping. There are some cases where it may be more appropriate to use the Coulomb damped method of analysis when Coulomb frictional forces are utilized. However, in the case of a steel braced frame, using the equivalent viscous damping method is sufficient.

For an underdamped single degree of freedom (SDOF) system, the equation of motion is of the form:

5. $u(t) = e^{-\zeta\omega_n t}(Acos\omega_D t + Bsin\omega_D t)$

Where A and B are real-valued constants determined from the initial conditions of the system.

The important effect of damping is the rate at which the free vibration decays. For lightly damped systems, such as the steel braced frame, the damping ratio can be determined from the following equation:

6. $\zeta = \frac{1}{2\pi j}\ln(\frac{\ddot{u}_i}{\ddot{u}_{i+j}})$

Where $\ddot{u}_i$ and $\ddot{u}_{i+j}$ are peaks of the acceleration-time graphs.

In this study for damping analysis, the acceleration-time relationships were used to determine the damping ratio of the systems. It was found that the steel braced frame had a slightly larger damping ratio than the PE SMA frame, with it being 1.3% and the PE SMA frame being 1.0%. The slight variation in damping ratio suggests that like the natural frequency, the stiffness of the system as a whole is dominating the behaviour of the natural system as opposed to the plastic hinge affecting the behaviour.

9. CONCLUSION & FUTURE RESEARCH

Though structures are designed in accordance to the capacity design standards and are safe, with a small probability of collapse during the earthquake ground motion, they can still sustain extensive damage with repair costs of about one-third of the building replacement value (Ramirez et al. 2012). This paper looked at the advantages of using smart material such as NiTi SMA for minimizing damage done to a structure. A steel braced frame with a steel yielding fuse and a PE NiTi SMA fuse was designed, built and tested under a in-plane free vibrations test. From this experiment, the following were observed.

- The two specimens, though with different materials acting as the plastic hinge, their natural frequency was the same. Suggesting that the end conditions dictate the behaviour of the frame.
- The damping ratios of each specimen are very close, further suggesting that the braces do not contribute to the lateral stiffness of the system.
- The out-of-plane frequencies of the systems are different mainly due to the different bracing members used in the design.

The next phase of this research is to examine the quasi-static cyclic behaviour of both specimens to investigate the hysteresis response. The hysteresis response will give a clear indication of the PE SMA frames self-centering capability as well as the amount of energy it is able to dissipate. Findings of this research are expected to add valuable knowledge to the field of seismic design and retrofitting of buildings and widen the potential applications of the SMA in the structural engineering field.

10. ACKNOWLEDGEMENTS

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