Design and Performance of Isolators with Shape Memory Alloys

John C. Wilson

Department of Civil Engineering, McMaster University, Hamilton, ON, Canada

Michael Wesolowsky

Sparrow Engineering Ltd., Mississauga, ON, Canada

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ABSTRACT: This paper examines the use of shape memory alloys in seismic isolators. Conventional methods for designing isolators are examined for period shift and damping and are modified to include the peculiarities that occur when shape memory alloys are included as components in the isolator. Limits on forces and displacements are used as constraints in the design of the isolator. Procedures to determine the physical characteristics of the shape memory alloy material are presented for one type of isolator design. A suite of earthquake records are used to examine the performance of the design. It is demonstrated that shape memory alloys can be effectively used within seismic isolators provided adequate damping control is maintained.

1 INTRODUCTION

The paper describes the development of a design procedure for the specification of hysteretic behaviour necessary in a shape memory alloy (SMA) seismic isolation device to meet a set of design constraints (e.g. design forces and displacements). The procedure also determines the damping required from viscous-style supplemental dampers (if necessary) and physical characteristics of the SMA required (SMA length and cross-sectional area) in order to meet target constraints. Individual and mean response quantities from earthquake-induced simulations are presented to draw observations and conclusions regarding the implementation and effectiveness of the design method.

2 SHAPE MEMORY ALLOY ISOLATOR DESIGN PROCEDURE

The following design procedure (Wesolowsky 2006) is based on a single-degree-of-freedom (SDOF) system, although this procedure theoretically also applies to multiple-degree-of-freedom (MDOF) systems, based on the assumption that an isolated MDOF system acts, ideally, as an SDOF. The method described here can be used to specify the hysteretic behaviour necessary for an isolator device, such as the looped-SMA-wire type proposed by Krumme et al. (1995), that could be used to isolate a structure (e.g., bridge or building) from earthquake ground motions. It is assumed that the hysteretic behaviour of the SMA isolator is identical in tension and compression.

1. A linear time-history analysis of the 'non-isolated' elastic system is done to determine the maximum elastic force (F_e) and maximum elastic displacement (Δ_e) caused by the ground motion.
2. The expected hysteretic behaviour (stress-strain) of the SMA is obtained from experimental tests or manufacturers specifications.
3. The hysteretic damping of the SMA material is computed by:

$$\xi_{hys} = \frac{E_D}{2\pi E_{eq} \varepsilon_m{}^2} \tag{1}$$

where E_D is the area (energy dissipated) under the stress-strain curve for one full hysteretic loop of tension and compression, E_{eq} is the equivalent modulus of elasticity which is calculated using the secant stiffness of the maximum stress and strain values, and ε_m is the maximum strain value. This can be seen in Figure 1.

4. Select the target design force (F_d) and displacement (Δ_d) for the isolated system.
5. The resulting equivalent stiffness of the system is calculated by:

$$k_{eq} = \frac{F_d}{\Delta_d} \tag{2}$$

6. The equivalent isolated period is calculated by:

$$T_{eq} = \frac{2\pi}{\sqrt{k_{eq}/m}} \tag{3}$$

where m is the isolated mass.

7. The design spectral displacement (S_D) is read from an appropriately scaled design displacement response spectrum for 5% damping for the period value calculated in Step 6.
8. The equivalent damping required to reduce the design spectral displacement (S_D) to the design displacement (Δ_d) is calculated by:

$$\xi_{eq} = \frac{7}{\left(\Delta_d / S_D\right)^2} - 2 \tag{4}$$

This equivalent damping is the Total Equivalent Damping (TED) and uses a response spectrum correction factor as outlined by Priestley et al. (1996). Equation 4 determines the damping at which an equivalent *linear* SDOF system subjected to design earthquakes will result in the mass achieving the design displacement, assuming an inherent reference modal damping of 5% in the non-isolated system. If the assumed 5% modal damping was subtracted from the equivalent damping calculated by this formula (i.e., with a second term of –7 instead of –2), the difference would be the damping required in the isolator to reduce the spectral displacement associated with a reference damping of 5% to the design displacement. This may not be a conservative assumption because the actual modal damping of many structures, especially bridges, can be substantially lower. Therefore, by using Equation 4 directly (without subtracting the further 5% modal damping), an allowance has been intrinsically incorporated that provides for situations where modal damping may be less than 5%. This is a reasonable and conservative approach.

9. If the equivalent damping (ξ_{eq}) required to control the system displacement calculated in Step 8 is less than the hysteretic damping (ξ_{hys}) of the SMA calculated in Step 3, then the SMA alone provides sufficient damping to control the system response to levels below the design values selected in Step 4. If the equivalent damping in Step 8 is greater than the hysteretic damping in Step 3, then an increase in damping (referred to as supplemental damping, ξ_{sup}) is required. This can be modelled as a viscous damping device acting in parallel to the SMA element. The calculation of this is:

$$\xi_{\sup} = \xi_{eq} - \xi_{hys} \tag{5}$$

The following steps produce the physical characteristics of the SMA material in a Krumme-style isolator required to meet the design specifications. The design procedure assumes a device in which several SMA wires are wrapped around posts to oppose the tensile forces placed on them.

10. The length of wires required in the SMA device is calculated by:

$$L_{SMA} = \frac{\Delta_d}{\varepsilon_m} \tag{6}$$

where Δ_d and ε_m are defined in Steps 4 and 3, respectively.

11. The total cross-sectional area of SMA material needed is calculated by:

$$A_{SMA} = \frac{F_d}{\sigma_m} \tag{7}$$

where F_d is defined in Step 4 and the maximum stress (σ_m) is from Figure 1.

12. The total number of SMA wires required is calculated by:

$$N_{SMA} = \frac{A_{SMA}}{A_1} \tag{8}$$

where A_1 is the area of one SMA wire. The total number of SMA wires required should be rounded up to the nearest even value, which is necessary due to the configuration assumed where the SMA wire is wrapped around anchor posts, providing double the cross-sectional area of a single wire for each complete loop around the posts.

13. The values of L_{SMA} and N_{SMA} provide the physical dimensions of SMA required in the isolator in order to meet the design responses defined in Step 4. The supplemental damping which may be required (Step 9) must also be provided (e.g. by a viscous damper). These values are then used to perform a non-linear analysis of the system in order to verify the adequacy of the isolated system.

Figure 2 shows the hysteretic damping provided by the system shown in Figure 1 at increasing values of maximum strain for five ambient temperatures. Further, the maximum hysteretic damping is achieved at the point in the hysteretic cycle when martensitic hardening is achieved (in this case 0.0738 m/m). The hysteretic damping provided by the SMA that will be used for the design examples will assume an ambient temperature of 10^{o}C, designed to a maximum strain of 0.0738.

3 DESIGN EXAMPLES

Some SMA-modified SDOF systems require supplemental damping in order to control excessive strains, while others are sufficiently served by SMAs alone. This section will demonstrate the application of the design method outlined in Section 2, focusing on two design scenarios: those requiring no supplemental damping, and those requiring supplemental damping. In order to understand the reasons why the modified systems operate differently under excitation by several earthquake time-histories, it is necessary to present the spectral acceleration plots of the earthquakes being considered. The spectral acceleration plots for ten near-field earthquakes (fault-normal components) can be seen in Figure 3, along with the NBCC design spectrum (for a scaling of 40 cm/s pgv) at 5% damping.

3.1 No Supplemental Damping Used

A linear elastic SDOF system has been modelled having a weight of 1500 kN and an elastic period of 0.5 seconds. To illustrate, the SDOF isolator system was excited with the time-history record from the FN10 earthquake, scaled to 40 cm/s pgv. The following steps correspond to the design steps outlined in Section 2 and show the numbers produced by the design procedure:

1. The maximum elastic force (F_e) was determined to be 1176 kN with a corresponding maximum elastic displacement (Δ_e) of 0.048 metres.
2. The hysteretic behaviour is seen in Figure 1 (based on Dolce & Cardone (2001).
3. The energy dissipated (E_D) under the stress-strain curve was calculated to be 35.1 MPa m/m, the equivalent modulus of elasticity (E_{eq}) was calculated to be 10.7 GPa. Thus, the hysteretic damping (ξ_{hys}) of the SMA material was computed to be 9.57%.
4. The target design force (F_d) and displacement (Δ_d) were obtained by dividing the maximum elastic force by a factor of 6 and multiplying the maximum elastic displacement by a factor of 5. These factors were chosen for illustration purposes (see Table 1). This produced a target design force of 196.1 kN and a target design displacement of 0.242 metres.
5. The required equivalent stiffness (k_{eq}) of the system was calculated to be 810 kN/m.
6. The corresponding equivalent isolated period (T_{eq}) was calculated to be 2.73 seconds.
7. The design spectral displacement (S_D) was taken from NBCC (Figure 3) to be 0.239 metres.
8. The spectral displacement (at 5% modal damping) is lower than the target design displacement (Δ_d), but since the assumption has been made that the system will actually have no inherent damping, the equivalent damping required (ξ_{eq}) for an equivalent linear system to result in a spectral displacement of 0.193 metres has been calculated to be 4.84%.
9. $\xi_{eq} < \xi_{hys}$ so no supplemental damping is required.
10. The length of SMA wire (L_{SMA}) required was calculated to be 3.28 metres.

11. The total cross-sectional area (A_{SMA}) was calculated to be 0.000248 m^2.
12. Assuming an SMA wire diameter of 0.002 metres, the total number of SMA wires required (N_{SMA}) was calculated to be 79, rounded to 80 in order to assume that the SMA device being considered uses looped wires around posts (40 wires x 2 effective areas - similar to the device proposed by Krumme et al. (1995)).

Figure 4 shows the hysteretic behaviour of the SDOF system modeled with the SMA behaviour derived above, with the elastic system included for comparison. The design 'envelope' showing the design force and displacement is also shown (green line). In this case it is clear that the design method produces isolated forces and displacements that are at the edge of the design envelope. The spectral acceleration plot for FN10 shown in Figure 3 indicates that FN10 appears below the NBCC design line at 2.73 seconds, signifying that the earthquake should induce responses that are below design values, assuming that the system had an equivalent period of 2.73 seconds. This assumption is not exactly true, as the equivalent stiffness of the system (and therefore period) does shift throughout the hysteretic cycling. During the strong motions, the equivalent period will vary (at constantly changing intermediate values) between the elastic period of 0.5 seconds and the isolated equivalent period of 2.73 seconds. This explains why the response is at the edge of the design envelope, as Figure 3 indicates that FN10 does exceed the NBCC spectrum between 1.4 and 2.0 seconds.

The corresponding force and displacement time-histories can be seen in Figure 5. Figure 5 emphasizes the reduction in force experienced by the system as a result of the SMA isolator (as well as the increase in displacement). It is clear from both the force and displacement responses that the isolated system responds with an equivalent period of approximately 2.5 seconds during the phase of greatest motion (3-10 seconds). After that point, the isolated response shows an equivalent period closer to 1.0 seconds as the system is not strained to the martensitic hardening level.

Figure 6 shows the hysteretic behaviour for a SDOF system having an elastic period of 0.6 seconds, subjected to earthquake FN2 at a scaling of 40 cm/s. Through the steps outlined in Section 2, it was determined that an equivalent period of 2.4 seconds with no supplemental damping would be sufficient to control the response of the system ($F_e/4$, Δ_e*4). Figure 6 demonstrates that not only is the design envelope exceeded, but the maximum elastic force is also surpassed (by the SMA) at strains that would induce martensitic plasticity.

The reasons behind excessive response can be seen in Figure 7, which shows the force and displacement time-histories of the system. During the time range of strong motion (5 – 15 seconds) the isolated system is oscillating through a range of equivalent periods that coincide with the strongest spectral acceleration exhibited by FN2 (see Figure 3). In the period range of 1.1 – 2.4, FN2 produces spectral accelerations that mainly exceed the NBCC design spectrum. As the SMA transitions from its austenitic form towards the martensitic hardening strain, it absorbs large amounts of energy from the earthquake ground motion from these high-spectral periods, thus pushing it past the martensitic hardening point into the fully martensitic range. At this point, the system's equivalent stiffness increases, thus keeping the SMA responding at close to a 2 second equivalent period (see Figure 7). Figure 3 demonstrates that at this period range, the spectral accelerations are greater than code values. This is one drawback of a hysteretic system that exhibits large-strain hardening, as a traditional lead-rubber type isolator would continue upon a relatively low-stiffness plateau, thus further elongating the equivalent period into a range which is not greatly affected by the earthquake. Since several of the near-field earthquakes exceed the NBCC code for longer period values, this problem occurs for other earthquake responses, and should be considered when designing any SMA isolator for near-field motions.

3.2 Supplemental Damping Used

Figure 8 shows the hysteretic behaviour for a system having an elastic period of 0.5 seconds, subjected to earthquake FN7 at a scaling of 40 cm/s. Through the steps outlined in Section 2, it was determined that an equivalent period of 1.41 seconds with 24.9% supplemental damping would be sufficient to control the response of the system ($F_e/4$, Δ_e*2). In this case, due to the high spectral responses expected for FN7 (see Figure 3) through the range of equivalent periods that were exhibited by the system (<1.41 seconds), the system was once again pushed past its design values for the same reasons outlined for Figure 6. One of the major differences between this case and that shown in Figure 6 is the tight restrictions on the isolated target displacement (multiplication factor of 2 instead of 4). This requires a considerably higher value of supplemental damping in order to force the expected spectral displacement to a lower value. Since the overall damping of the system is greater, the ability of the system to control excessive movement is improved over a non-supplementally damped scenario.

4 MEAN RESPONSES FROM SEISMIC SIMULATIONS

A series of SDOF systems having elastic periods between 0.3 and 1.4 seconds have been considered for a comparison of the mean responses to a set of near-field earthquake records, all scaled to a pgv of 40 cm/s. This range of elastic periods has been chosen to encompass the range of periods where the input earthquake records exhibit strong motions which often exceed NBCC design values.

Six isolation cases have been considered for each elastic-period SDOF system, with different combinations of force division and displacement multiplication factors (see Table 1). These factors were chosen to provide a series of isolated equivalent periods for the purpose of comparing across a range of possible isolator designs. For design purposes, the maximum elastic responses were computed for each record in the set of ten, and then averaged in order to determine the elastic responses required for Step 1 of the design procedure. This allowed for one single isolator design for all earthquakes for each of the six cases.

Figure 9 shows a comparison of the elastic forces and displacements across all periods with the target values chosen for the isolator force and displacement for the near-field earthquakes. Since some of the six cases considered have either identical force division and displacement multiplication factors, some of the lines shown in Figure 9 are identical, most notably for the force division factor. Figure 9a shows a local peak around 0.8 seconds. A similar peak can be seen in Figure 9b.

5 SUMMARY

The key points in this study are:

1. Depending on what elastic characteristics are exhibited by the SDOF system, there are several possibilities of SMA-based isolator design specifications that could be appropriate, based on the required target displacements and forces. Care must be taken to ensure that the required supplemental damping is possible from commercially available dampers and the required physical dimensions of the SMA material meet geometric constraints within the physical framework of the system being isolated.
2. For near-field earthquakes, even though the SMA provides maximum damping at the point where martensitic hardening occurs, it may be more conservative to design for a lower maximum SMA strain that may have a similarly high damping capacity (see Figure 2). This reduces the possibility of cycling into the martensitic range (where the equivalent period of the system decreases) when an isolated system is adversely affected by long period pulses that are characteristic of near-field motions.
3. Although not discussed here for reasons of space limitations, the design procedure is generally sufficient to specify system behaviour for far-field earthquake motions, as they do not exhibit long-period pulses.

6 REFERENCES

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Table 1 Six isolation cases considered for mean response study.

Case	Force Division Factor	Displacement Multiplication Factor
1	4	2
2	6	3
3	8	4
4	4	4
5	6	5
6	8	6

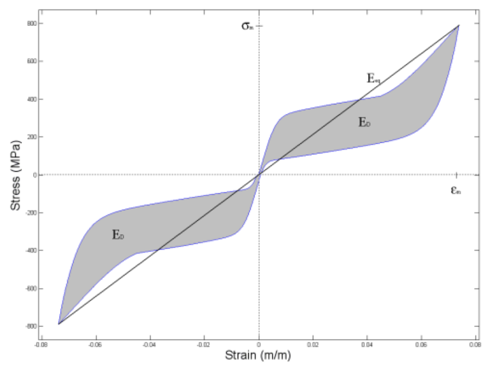

Figure 1 Expected SMA hysteretic behaviour demonstrating the energy dissipated (E_D) and the equivalent elastic modulus (E_{eq}).

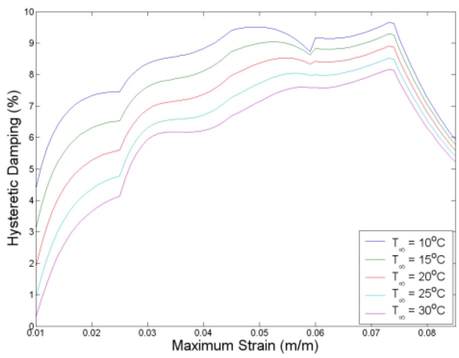

Figure 2 Equivalent hysteretic damping provided by the system shown in Figure 1 at increasing values of maximum strain for five ambient temperatures.

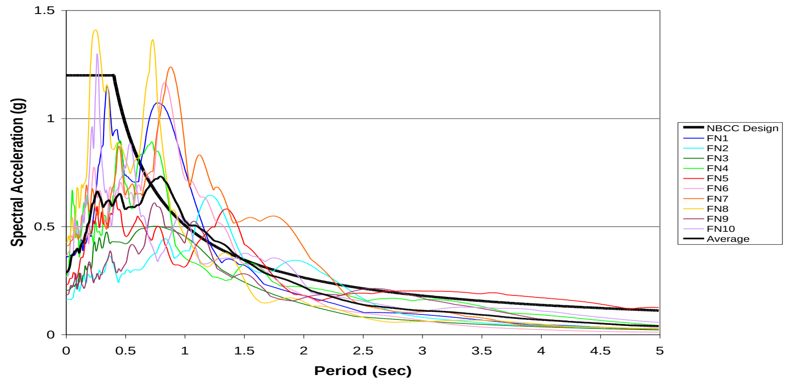

Figure 3 Spectral acceleration plots for the ten near-field earthquakes (fault-normal components), along with the NBCC design spectrum for a scaling of 40 cm/s pgv at 5% damping.

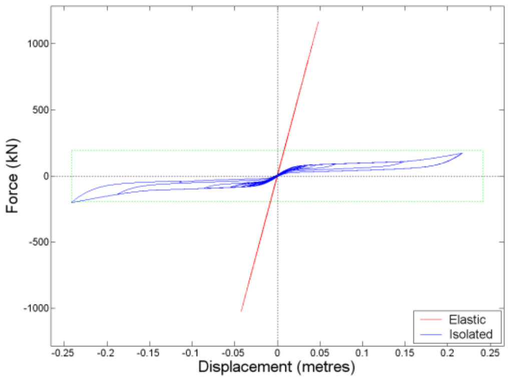

Figure 4 Hysteretic behaviour for the SMA-isolated system having an elastic period of 0.5 seconds subjected to earthquake FN10. The green line represents the design envelope.

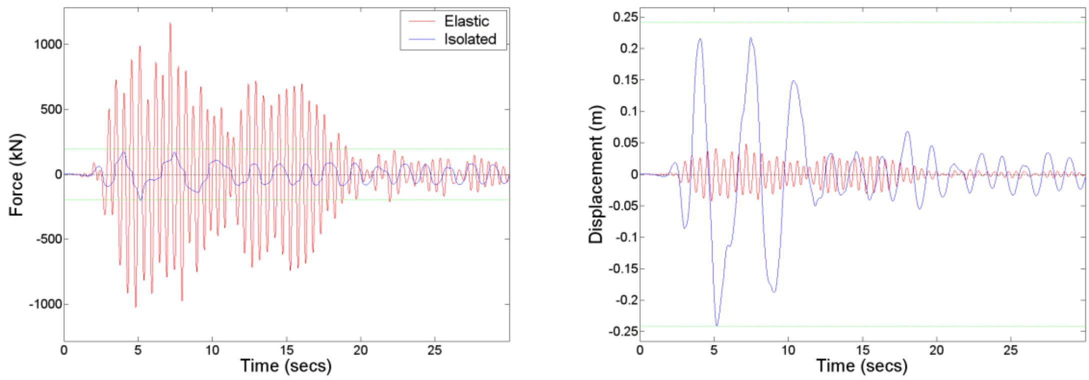

Figure 5 Force time-history (left) and displacement time-history (right) for the SMA-isolated system having an elastic period of 0.5 seconds subjected to earthquake FN10.

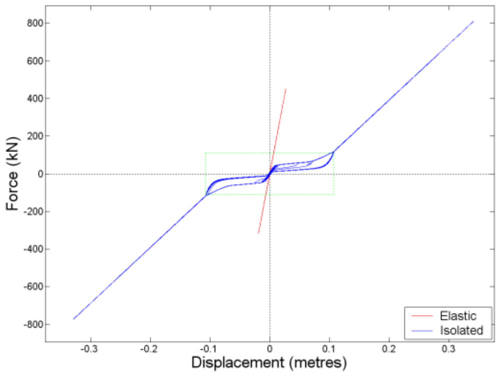

Figure 6 Hysteretic behaviour for the SMA-isolated system having an elastic period of 0.6 seconds subjected to earthquake FN2. The green line is the design envelope.

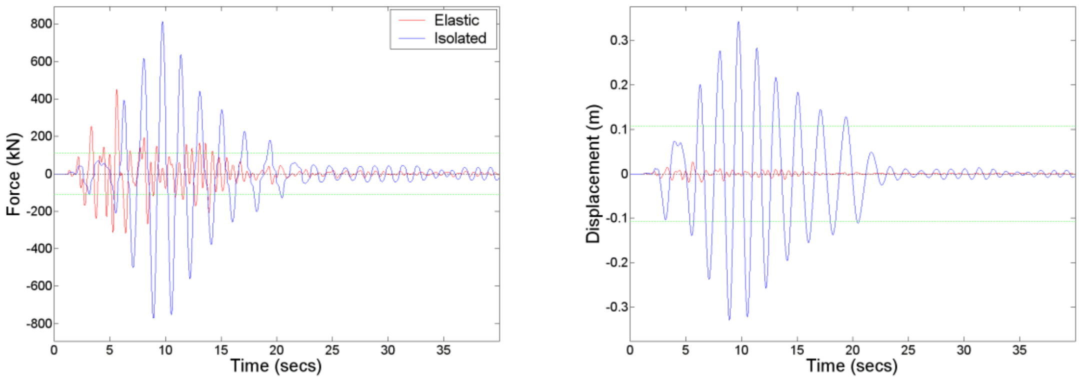

Figure 7 Force time-history (left) and displacement time-history (right) for the SMA-isolated system having an elastic period of 0.6 seconds subjected to earthquake FN2.

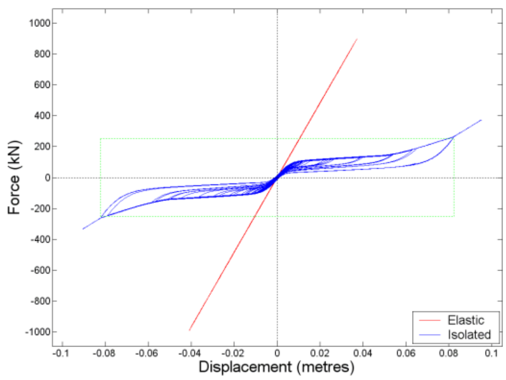

Figure 8 Hysteretic behaviour for the SMA-isolated system having an elastic period of 0.5 seconds subjected to earthquake FN7. The green line is the design envelope.

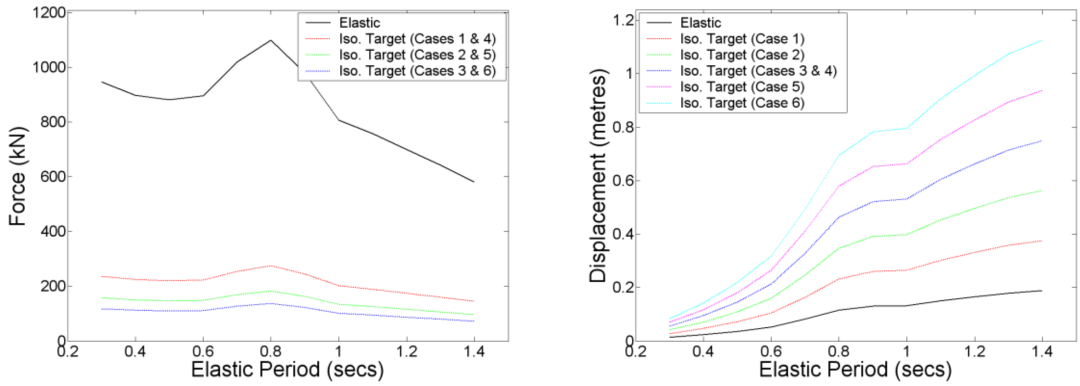

Figure 9 Elastic and target isolated forces (left) and displacements (right) for the SDOF systems.