EXPERIMENTAL AND ANALYTICAL EVALUATION OF SEISMIC RESPONSE OF A STEEL STRUCTURE WITH AND WITHOUT SHAPE MEMORY ALLOY DAMPERS

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ABSTRACT

Recently, there has been increasing interest in using super-elastic shape memory alloys for applications in seismic resistant design. Shape memory alloys (SMAs) have a unique property by which they can recover their original shape after experiencing large strain upto 8 % either by heating (shape memory effect) or removing stress (Pseudo-elastic effect). In the present study a new device is made with austenitic SMA wires which dissipate energy when axially stressed in tension. This device uses collets which tightens the grip on the wire. Extensive tests are done on the wires and device at various frequencies and amplitudes of loading. Since this device represents a nonlinear hysterical dynamic system a physically based simplified SMA model considering the residual martensite strain effect is developed. An experimental program of shaking table tests on reduced scale model of a steel structure supporting a tank, is carried out for assessing the capability of SMA wires in dissipating energy. This paper presents a comprehensive overview of the main results of the shaking table tests performed on the steel structure without SMA Dampers and the analysis results for the frame with SMA wires. Initially sine sweep tests are carried out and then the frame is subjected to spectrum compatible earthquake loading with increasing peak base excitation from 0.05 to 0.2 g. Lastly a comparison is made between experimental and analytical response. The addition of dampers in the braces of steel framed structure resulted in significant benefits on its overall seismic behaviour.

INTRODUCTION

Shape memory alloys (Ni- Ti alloys) are unique alloys that have the ability to undergo large deformations, but can return to their undeformed shape by heating (shape memory effect) or through removal of the stress (superelastic effect). Recently there has been increasing trend in using super-elastic shape memory alloy devices based on wires for applications in structural vibration control.

The significant properties of SMAs like Pseudo- elasticity, large ductility, excellent corrosion and fatigue resistance make these alloys attractive material for structural vibration control. Graessar and Cozarelli [1] in 1991, first proposed the use of Nitinol (SMA) as damping materials. They studied the effect of loading frequency and history on the energy dissipation characteristics of SMA wires. They also proposed a one dimensional constitutive model for pseudo-elastic behavior of the model. Later Clark et al [2] and Dolce [3] in 2000 demonstrated the feasibility of the concept of SMA wire device conducting large number of experiments. Researchers have later suggested various applications of SMA dampers in reducing response of structures and carried out analysis of structures with SMA devices. Wilde et al. [4] performed analytical studies to evaluate behaviour of base isolation systems with SMA damper for highway bridges. Dolce et. al. [5] studied the implementation of various states of SMA material for use of special dampers in structures by performing shake table tests. Researchers also have done representative works in thermo-mechanical modeling like Tanaka [6], Liang and Rogers [7], Boyd and Lagoudas[8]. Based on their work, Motahari and Ghassemieh [9] proposed a simple multi-linear model and proved it to be accurate. Recently Andrawes and Des Rosches [10] explored the effect of using different SMA constitutive models on the resulting response of systems using SMAs subjected to seismic loading. They found that the response is more sensitive to cyclic effects in case of earthquakes with long duration or large intensities. Parulekar et al [11] modified an existing thermo-mechanical [9] to incorporate the residual martensite deformation observed in austenitic SMA wires and thus take into account the cyclic effects of SMAs.

This paper presents a new device made with austenitic SMA wires which dissipate energy when axially stressed in tension. This device uses collets which tightens the grip on the wire. Extensive tests are done on the wires and device at various frequencies and amplitudes of loading. A simplified multi-linear SMA model incorporating the residual martensite strains [11] is modified to match the damper device characteristics. An experimental program of shaking table tests on reduced scale model of a steel structure supporting a tank of a heavy water plant is carried out for assessing the capability of SMA wires in dissipating energy. Main results of the shaking table tests performed on the steel structure without SMA Dampers and the analysis results for the frame with SMA wires are presented. Initially sine sweep tests are carried out to evaluate the frequencies and damping. The frame is subjected to spectrum compatible earthquake loading with increasing peak base excitation from 0.05 to 0.2 g. Lastly a comparison is made between experimental and analytical response. The addition of austenite SMA wire dampers in the braces of steel framed structure resulted in about 30 % reduction in seismic response.

PSEUDOELASTIC HYSTERISIS

Pseudo elastic effect is the property by which the Shape Memory alloy recovers its initial shape when external load is removed. It occurs in stress induced austenitic to martensitic phase transformation of shape memory alloys. Fig. 1 shows its experimental stress strain characteristics of an austenitic SMA wire stressed uniaxially. On loading the wire (o-a-b-c), when the stress reaches the transformation level σms, transformation from austenite to martensite will be induced and this transformation will continue until all the austenite has been transformed to martensite at almost constant stress level. Upon release of stress during unloading (c-d) martensite unloads elastically down to σas , where it will transform back to austenite(d-e), once again at constant stress level. When this transformation is completed there is final elastic unloading (e-o) of austenite phase. This is called pseudo-elastic (superelastic) effect as there is no permanent deformation though the behaviour is nonlinear. However researchers [12] have observed experimentally that subjecting the austenitic Ni- Ti shape memory alloys to cycles show that some residual martensite remain at the end of the each cycle. This residual martensite progressively increases with cycles for Ni-Ti alloy and tends to reach a value of 0.4 % to 0.5 % asymptotically at about 50 cycles. This is due to the local stress created in particular at the grain boundaries which locally induces martensite and retains it. Thus in Fig. 1, oo′ is the residual martensite which is retained at the end of 50 cycles.

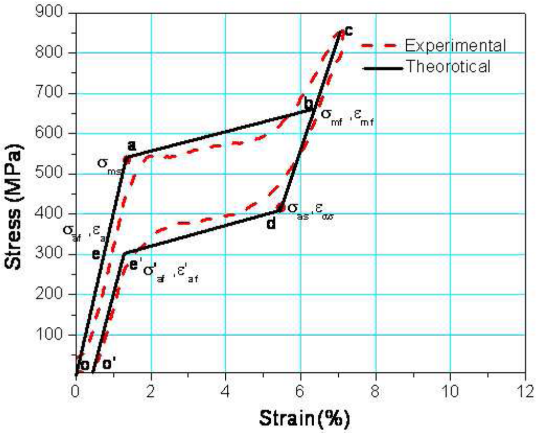
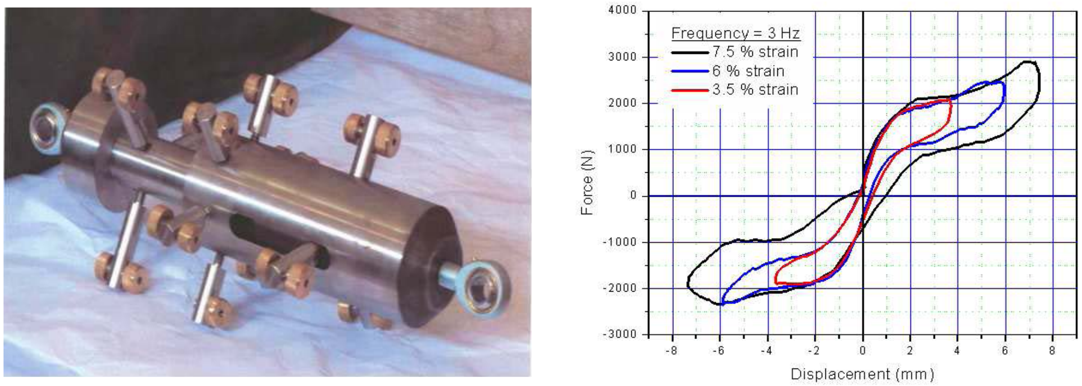


Fig. 1 Pseudo-elastic Hysterisis of SMA wire

SMA DAMPER DEVICE

Energy dissipation device was designed making use of the energy dissipation properties of Ni- Ti wires. The wires are austenitic wires which give the energy dissipating as well as the recentering property. The device as shown in Fig. 2a consists of two concentric pipes which will move mutually. Three studs are attached to inner pipe at angles 120° apart at two locations. Six studs are attached to outer pipe in the centre equidistant (100 mm) from the studs attached to the inner pipe. Super-elastic SMA wires having length 100 mm are attached between these two studs. However to get a good stroke length of the damper the length of the wires can be increased. In order to get a good grip on the wires and prevent slipping of the wires during tensile tests they were fixed to the studs using collets. Thus the damper consists of 6 wires each of 1.2 mm diameter connected to studs. The testing of the damper for tension compression sinusoidal loading was done at room temperature of 35°C. First the tests were carried out on wires (Fig. 1) and then the damper device was tested. It is observed from the figure that the wires can be used effectively for energy dissipation upto a strain of 8%. During testing of the damper one end of the damper is fixed and other end is connected to an actuator. When the damper is loaded, at a time three of the wires are in tension and three are slack. The wires, which will be in tension dissipate earthquake energy and less energy will be transmitted to the structural system. Thus two independent groups of wire loops will act as energy dissipating group. Testing has been carried out on SMA Damper with 3 nos. of 1.2 mm dia wires in tension and 3 wires becoming slack at a time.

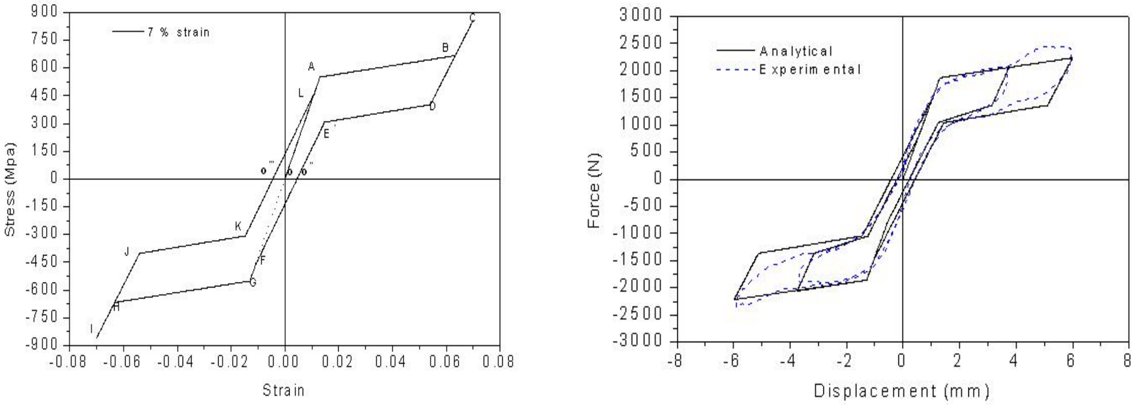


a. Schematic b. Force displacement relation

Fig. 2 Shape Memory alloy Damper Device

Tests have been carried out by increasing the loading rate from quasistatic conditions (0.01 Hz) to the loading rate of predominant earthquake frequencies (0.1Hz-5 Hz.). Combined graphs showing one cycle for 3 Hz loading rate with increasing amplitude are shown in Fig.2b. It is observed that with change in amplitude for same frequency, the stress at austenite start transformation (σ_{as}) remains the same while the unloading paths are different at different amplitude of loadings.

THERMO-MECHANICAL MODEL WITH CYCLIC EFFECTS



a. Theoretical Stress strain curve b. Comparison of theoretical and Test F-δ

Fig. 3 Multi-linear Model of SMA damper device

Thermo-mechanical model based on the original work of Boyd and Lagoudas [8] which is modified [9] to give multi-linear stress train relationship is used in the present study. This model is simple and has ability to capture the cyclic loading effects on SMAs in addition to sub looping behavior resulting from incomplete phase transformation cycles. The uniaxial themo-mechanical behavior of SMAs can be described by constitutive relation

$$\sigma = E(\xi)\varepsilon - \alpha(\xi)E(\xi)(T - T_s) - E(\xi)\xi\varepsilon_l \quad (1)$$

Where σ,ε,T,T_s are the stress, strain, temperature and start temperature of transformation for a mixture of austenite and martensite material. E and α are the effective Young's Modulus and effective coefficient of thermal expansion attributable to transformation. ε_l denotes the maximum residual strain which is material constant and ξ denotes the volume fraction of the martensite phase. The model used in the present study is proposed by Motahari and Ghassemeih [9] in which the evolution equation enforces linear relationship between stress and strain. This model is modified to take into account residual martensite strain of 0.45 % in the stress strain relation path when the pseudo-elastic wire is unloaded.

Considering isothermal process ($T=T_s$) for super-elastic behaviour and using Eq. 1

$$\sigma = E(\xi)\varepsilon - E(\xi)\xi\varepsilon_l \quad (2)$$

Now considering E_A and E_M Effective Young's moduli of austenite and martensite state respectively the subsequent equation is good approximation for polycrystalline SMAs [9]

$$E(\xi) = E_A + (E_M - E_A)\xi \quad (3)$$

Where function $\xi = f(\varepsilon)$ will be such that

$$\sigma = E(\xi)\varepsilon - E(\xi)\xi\varepsilon_l = a\varepsilon + b \quad (4)$$

Where a and b can be obtained enforcing the model to pass though finish critical stresses and strains.

The critical stresses (σ_{Ms},σ_{Mf} ,σ_{As} and σ_{Af}) and strains (ε_{Ms},ε_{Mf},ε_{As} and ε_{Af}) are obtained using the stress strain relationship obtained from wire tests. Using Fig. 1, the transformation critical stresses are obtained as σ_{Ms}= 551 MPa, σ_{Mf} =667 MPa, σ_{As}=402 MPa and σ_{Af}=288.1 MPa whereas the critical strains are obtained as ε_{Ms}=0.013, ε_{Mf}=0.064, ε_{As}=0.054 and ε_{Af}=0.0068. The residual matrensite strain, ε_{ir} is obtained from tests on wires as 0.0045 and hence the values of σ'_{Af} and ε'_{Af} are obtained as 299 MPa and 0.0113 respectively. The Young's Moduli E_A = 42308 MPa, E_M=28571 MPa and the maximum residual strain value, ε_l =0.04 is also obtained from the uniaxial tests in wires. The transformation temperatures for the SMA considered in present study are M_f=-80°C, M_s= -60°C, A_s= -25°C and A_f= -8°C. The tests on SMA wires have been carried out at room temperature hence T_s=35 °C. The stress strain relation ship of the simplified model of damper device considering the effect of residual martensite strain is shown in Fig. 3a. The stress strain relations for path OA,AB,BC,CD,DE' and E'O'' are explained in [11]. For the complete stress strain relation ship of the SMA damper device subjected to cyclic loading. It is essential to define the stress strain path when the damper will undergo compression load. During compressive load another set of three wires go in tension according to the design of the damper. Thus, when the load becomes negative during unloading i.e. Path O″F (see Fig. 3a), stress strain relation ship will be equivalent to that of unloading in elastic austenitic with reduced modulus of Elasticity, equivalent to 80 % of initial modulus E_A and with residual martensite strain (Path E′O″)

Path O″F

$$\sigma = \frac{\sigma'_{Af}}{\varepsilon'_{Af} - \varepsilon_{ir}}(\varepsilon - \varepsilon_{ir}) \quad (5)$$

Where σ'_{af} and ε'_{Af} are the stress and the strain corresponding to austenite finish states taking into account the residual strain.

During further unloading Path FG,

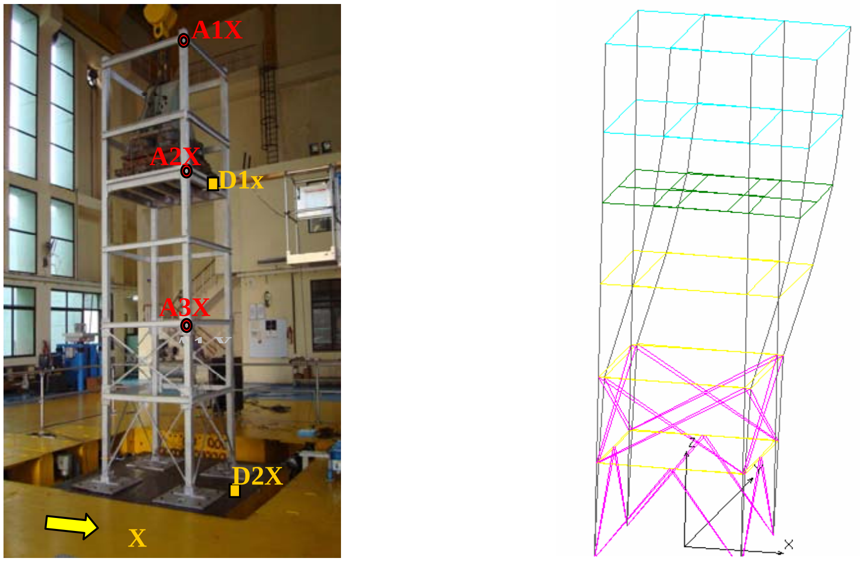
$$\sigma = E_A\varepsilon \quad (6)$$

Where E_A is the initial elastic modulus of austenite. For further unloading the (Path GH) stress strain characteristics will be similar to Path AB.

The load deflection characteristics of SMA damper device consisting of 3 wires of 1.2 mm diameter loaded in tension is obtained. Using stress strain relations for different paths [11] and the critical stress and strains obtained from the wires characteristics, the force displacement characteristics of the damper device is obtained. This theoretical force displacement characteristic is compared with that obtained from the load deflection characteristics by experiments [Fig. 3b] for 3.75 % and 6 % strain. The analytical model shows the residual deformation in the hysterisis loop when the load is less than austenite finish state. This model is an improvement of the models proposed in literature [2,9,10] where the force displacement characteristics shows same linear path for loading and unloading when the load is less that Austenite finish state. The force displacement characteristics of the analytical model thus very well predict the energy dissipated in SMA wires than the previous models mentioned in literature. It is observed that the theoretical load deflection characteristic is higher than experimental in some parts while it is lower in some other parts. However considering the overall area of energy dissipation the theoretical and experimental results are in good agreement.

EXPERIMENT ON STEEL STRUCTURE

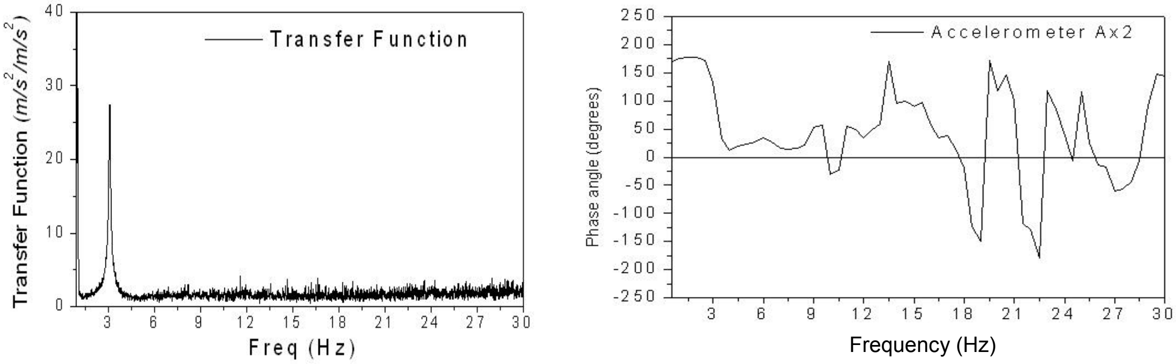
A six storeyed steel structural model shown in Fig. 4a is tested on shake table. The structure consists of rolled steel members having sections of different shapes and sizes. Mass of 6.0 tons representing the mass of a tank is placed on the 4th storey in form of plates and the total mass of the structure is 6.9 tons. The structure is a 1:3 scaled model of a dump tank and its supporting structure of heavy water plant, Kota. The frequency of the prototype structure is about 1.02 Hz. The frequency of 1: 3 scaled model obtained by FE analysis is 3.1 Hz and the mode shape is shown in Fig. 4b.



a. Test model b. FE Model showing mode shape (Freq=3.1 Hz)

Fig. 4 Model of the steel structure

The instrumentation carried out for the tests is shown in Fig.4a. Three accelerometers A_{1x}, A_{2x} and A_{3x} are situated on top floor, 4thlevel (mass level) and 2nd level as shown in the Figure. Laser displacement transducers D_{1X}` and D_{2X} are placed on the frame at level 4 and at the table respectively. The relative displacement between the mass and the table is measured by the transducers. Sine sweep tests are carried out on the structure. The input acceleration is 0.05g peak sine sweep acceleration at the rate of 1 octave per minute in X direction. Transfer function is obtained as shown in Fig. 5a. It is observed from the figure that resonance occurs at 3.05 Hz frequency and the amplitude of transfer function is 27 and the damping is obtained as 2 %. The plot phase angle with frequency is shown in Fig. 5b.



a. Transfer function v/s Frequency b. Phase angle v/s Frequency

Fig. 5 Experimental Frequency response functions

The model is then subjected to spectrum compatible time histories with peak acceleration increasing from 0.05g to 0.2g. The response spectra for the test time histories are shown in Fig. 6. The spectra are plotted for damping of 2 % which is obtained from the experiments. Time history analysis is carried out for the steel structure for the spectrum compatible time history of 0.05g to 0.2g PGA with increment of 0.05g. The analysis results are compared with the test results. The first fundamental frequency of the structure is 3.1 Hz with 96% mass participation in the first mode. Thus the structure can be idealized as a single degree of freedom system. The comparison of test and analysis displacement time histories at the mass level (displacement transducer D1X) of the frame is shown in Fig. 7 for 0.1g PGA. It is observed from the figure that the analysis and test response are in good agreement with each other. The displacements and accelerations obtained at various floors of the structure in linear analysis at 0.1g peak base acceleration are obtained from the analysis of single degree of freedom system by multiplying the displacement and acceleration obtained at the mass with the spatial representation vector $\{\phi\}$.

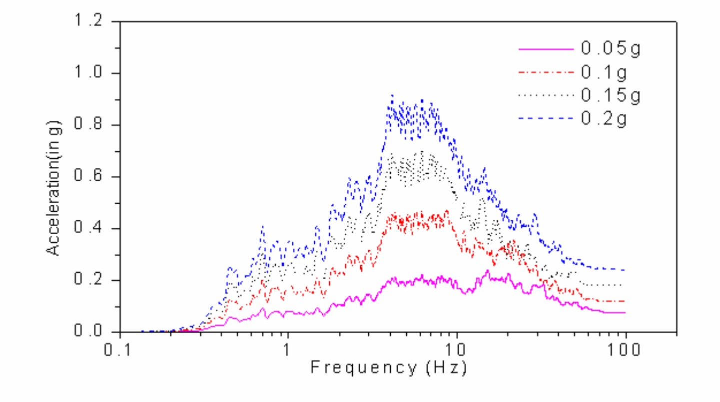


Fig. 6 Response spectra for 2% damping

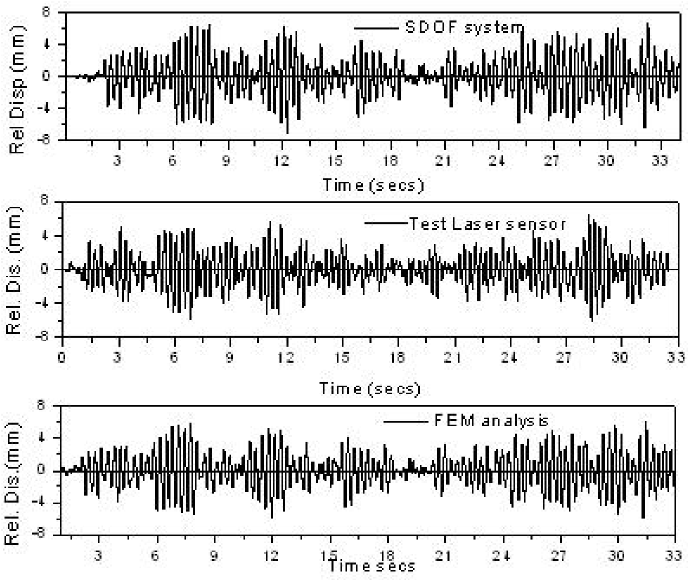


Fig. 7 Comparison of test and analysis displacement time histories for 0.1 g Peak acceleration at mass level

NONLINEAR ANALYSIS OF FRAME WITH SMA DEVICE

The SMA damper consisting of 4 wires of 1.2 mm dia. acting simultaneously in tension are to be placed on either side of the steel frame. Thus at a time 8 wires (4 on either side of the frame) will be in tension with its force and displacement required for martensitic transformation as 4950 N and 1.3 mm respectively. The structure can be idealized as a single degree of freedom system connected with SMA damper. as shown in Fig. 8. The equation of motion for such a case is written as

$$m\ddot{x}(t)+kx(t)+c\dot{x}(t)+F_{SMA}(t)=-m\ddot{x}_g(t) \tag{7}$$

Where m is the mass attached to the structure, c is the damping coefficient, k is the stiffness of the structure, $x(t), \dot{x}(t), \ddot{x}(t)$ are the displacement velocity and acceleration of the structure at the lumped mass and $\ddot{x}_g(t)$ is the base acceleration. $F_{SMA}(t)$ is the force exerted on the structure by SMA damper. Stress strain relations of SMA damper can be used to describe the F_{SMA} when the damper has complete and incomplete phase transformations. Nonlinear time history (TH) analysis is performed for the structure with damper, for the spectrum compatible earthquake time history having peak ground acceleration (PGA) 0.05g,0.1g,0.15g and 0.2g. The reduction in the response of the structure with damper for 0.1g PGA is shown in Fig. 9a. Fig. 9b shows the force displacement characteristics of the damper.

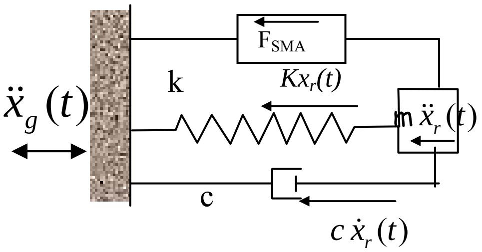
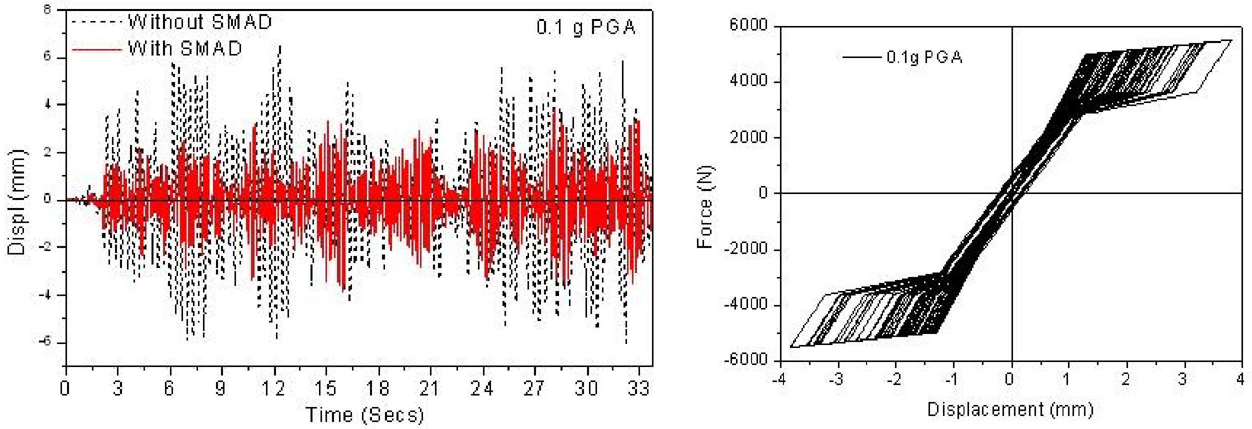


Fig.8 SDOF system with SMA Damper

It is seen in the figure that the damper goes in the nonlinear deformation with peak displacement of 3.75 mm at 0.1g PGA. Moreover, the force displacement characteristics of the damper shows the residual martensite strain effect. Graph of reduction in peak response displacement of the structure with SMA damper for 0.05g,0.1g,0.15g and 0.2g is shown in Fig. 10. For higher excitation if the damper undergoes nonlinear displacement of greater than 6.4 mm (i.e. higher than complete martensite transformation strain, ε_{Af} of 6.4 %) the wires will go in martensitic hardening of the SMA. As the load increases further the pure martensite follows the elastic response with modulus E_m. Fig. 10 shows that at 0.15g peak base excitation the peak response displacement of structure with damper is 6.8 mm and thus the wires undergo maximum strain of 6.8 %. It is observed experimentally that the maximum strain taken by SMA wires is about 10 % and hence the damper designed can be used for peak base excitation of 0.2g. However for higher excitation damper should be designed for better stroke by increasing the length of the wires used. It is also observed from Fig. 10 that the reduction in response for 0.05g, 0.1g, 0.15g and 0.2g is 39 % ,43% ,31 % and 0.22 % respectively. Thus higher excitation (greater than 0.15g) the damper undergoes martensite hardening and the effectiveness of damper decreases. Moreover for higher excitation the increase is strain energy effect also decreases the damping given by the SMA damper. Hence, it is essential that the no of wires should be increased to maintain the effectiveness of damper subjected to higher excitation.



a. Displacement response at mass point b. Force Displacement characteristic of damper

Fig. 9 Response of structure with SMA damper device

CONCLUSIONS

The mechanical behavior of super-elastic shape memory alloys suits the optimal requirements of a seismic control device. SMA wires were tested for various parameters and their suitability was made use in conceptual design of SMA damper device. SMA damper is thus designed and cyclic testing is carried out on the device to prove its effectiveness in energy absorption capacities. In the present work, existing multi-linear thermo-mechanical model is validated to capture the behavior of the newly proposed device. Moreover the effect of residual martensite strain which is observed in austenite SMA wires stressed in tension is also incorporated in the model. The experimental

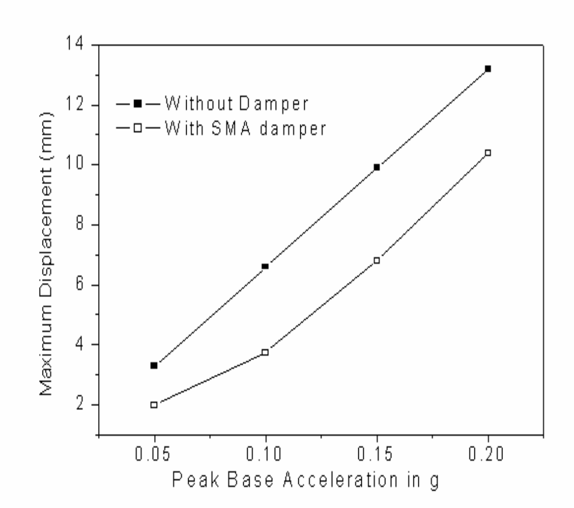


Fig. 10 Comparison of peak response with and without SMAD

and theoretical characteristics of SMA damper are found to be in good agreement. Experimental verification of steel framed model is done by conducting shake table tests. FE analysis and analysis with equivalent SDOF system is also performed and the analysis and test results shows good comparison. The structure is analyzed with SMA dampers and average reduction in response of the steel structure is about 35 %.

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