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Seismic Response Control Using Smart Materials

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1. Introduction

Earthquakes are highly destructive natural phenomena resulting in the massive deterioration of civil infrastructure, which becomes highly significant wih increasing urban population. Performance of structural systems needs to be improved recalling the huge loss of life and destruction to constructed facilities caused by various earthquakes. Protection of lifelines and infrastructure facilities are of utmost importance during a seismic event. There have been considerable research efforts in seismic vibration control for the past several decades. Developments of new techniques and new materials, which are not traditionally used in civil engineering structures, offer significant promise in reducing the seismic risk. Smart materials may be described as materials that can sense an external stimulus (e.g:-stress, pressure, temperature change, magnetic field, etc.) and initiate a response. They may belong to one of the four classes namely metals or alloys, polymers, ceramics or composites. Metals and alloys of different metals are considered as classical materials with lot of research activities around the globe . Shape Memory Alloys (SMA) belongs to the class of smart materials which are well known for its peculiar characteristics, which can be stress or temperature, induced. The research area which deals with structural applications of this variety of smart materials are promising (Sreekala& Muthumani, 2009) for structural health monitoring and vibration control.

Nickel Titanium (NiTi) Alloys are well known for its super elastic and shape memory properties and they belong to the class of Shape Memory Alloys (SMA). Presently SMA's are mainly applied in medical sciences, electrical, aerospace and mechanical engineering and also can open new applications in civil engineering specifically in seismic protection of buildings. Super elastic nitinol is found to be very effective for passive vibration control, as it can sustain large amounts of inelastic deformation and recover that deformation at the end of the process with good energy dissipation compared to regular metallic materials.

Various tests are conducted on NiTi wires in CSIR-SERC to evaluate the possibility of using SMA as an energy dissipating material with re-centering capabilities. Ability to sustain and recover large amounts of inelastic deformation during reversed cyclic loading with extra ordinary fatigue resistance make super elastic NiTi suitable candidate for seismic risk reduction. Quasi static and dynamic tests conducted with various parameters like pre strain, amplitudes and frequency for a number of cycles establishes the behavior which is suitable for seismic applications. It is interesting to find that from the quasi-static behavior of the material an optimum value of pre strain, which is material dependent, can be selected and

adopted in vibration control applications. Mathematical models were developed to predict the maximum energy dissipation capability of the material under study. The tests verify the potential of pre-strained NiTi wires as kernel components in seismic protection devices. It also highlights the effects of repeated cycling on pre strained wires, as special devices for passive protection during earthquake are meant for repeated cycling. Various types of vibration control devices can be made with the material used.

The technologies using smart materials are useful for both new and existing constructions. The chapter highlights various structural applications of this class of smart materials available in addition to the suitability of this material for vibration control applications. Protection of structures from damage during earthquakes can be addressed using passive protection devices designed to have maximum energy dissipation capacity with re centering capabilities. Innovative means of structural control scheme can be developed through passive systems, consisting of materials and devices useful in the context of seismic design and retrofit of structures

Ductility and energy dissipation are important parameters to be evaluated and quantified for seismic resistant design of structural components. Equivalent viscous damping is a significant quantity usually employed in earthquake engineering to characterize the dissipation capability of the material under investigation. This parameter expresses the effectiveness of the material in vibration damping. The relevance of the study is made clear with the associated terms in earthquake engineering

2. Properties, which enable SMA for civil engineering application

1. Repeated absorption of large amounts of strain energy under loading without permanent deformation
2. Possibility to obtain a wide range of cyclic behaviour from supplemental and fully re centering to highly dissipating by simply varying the characteristics of SMA components.
3. Strain range of 2 to 10%
4. Extraordinary fatigue resistance under large strain cycles.
5. Their greater durability and reliability in the long run.

2.1 Shape memory alloys in structural control

The existence of SMA property in certain alloys has been known from 1932(when it was first observed in Gold-Cadmium alloy exhibits a rubber like behavior). SMA's have unique properties, which are not present in many materials traditionally used in engineering applications; especially shape memory effect and super elasticity. While shape memory alloys have been commercially available since the 1960s, their application has been limited (Pelton et al., 2000). Early literatures on SMA materials shows successful uses of these for the design of biomedical and clinical devices, particularly for fixing body fractures internally with various 'NiTi' SMA interlocking intramedullary nails(Da et al,2001). Among other designs, research related to the use of SMA materials as micro-pumps, micro-grippers, flexible SMA active catheters, micro nano-tribological devices and SMA thin films for electromechanical system have been increasingly revealed in recent years (Stockel & Melzer, 1995). Those achievements exhibited an excellent reliability and confidence in using these materials for other primarily structural elements. The SMA materials possess many unique mechanical and geometrical properties such as shape memory effects which provide a large recovery strain and force simultaneously, pseudo-elastic behavior upon heating and super-

elastic properties in ambient conditions for specified SMA materials. Birman (1997) and Humbeeck (2001) gave comprehensive reviews on the properties of SMA materials. Based on the studies under MANSIDE project, 1999(Italian Department for National technical services) Ni–Ti SMA's appear to be the best candidates for use in seismic applications. But selection of the SMA wires for energy dissipation with or without pre strain had to be addressed separately (Sreekala et al., 2010). So the need arose for finding the effect of pre strain as well as repeated cycling in the energy dissipation of SMA wires.

2.2 Mechanism behind super elasticity

Super elasticity is related to the isothermal response of SMA specimens to applied mechanical loads. The phase transformations are solid to solid diffusionless processes between a crystallographically more ordered phase, the austenite (A) and a crystallographically less ordered phase the martensite (M). Fig. 1 shows a schematic stress–strain cyclic curve of a super elastic SMA. It is characterized by five branches. Branches 1 and 4 correspond to the elastic deformation of the two stable phases of SMA, respectively, austenite and martensite. Branches 2 and 3 correspond, respectively, to the forward (from austenite to detwinned martensite) and inverse (from detwinned martensite to austenite) phase transformation. Branch 5 corresponds to the onset of plastic deformation of detwinned martensite. In the figure σ_{Fs} and σ_{Ff} represent the critical stresses at which the forward transformation, respectively, starts and finishes, while σ_{Is} and σ_{If} are those at which the inverse transformation, respectively, starts and finishes. Since loading and unloading paths are different from each other, a certain amount of energy is dissipated over the cycle.

3. Research significance

Most of the applications of SMA have focused on developing various types of actuators. However, most of the commercially successful applications - such as couplings, electrical connectors, cardiovascular stents and eyeglass frames - use the full shape- memory effect or the full super elastic cycle only a few times. This indicates that SMA components can be used successfully for several non-actuator applications as well. One such area is the use of SMA components for damage control in structures. The SMA component can undergo finite deformations either due to super-elasticity or due to rearrangement of martensite variants at relatively small stresses. This can be used to prevent permanent plastic deformation due to unexpected loads in the rest of the structure. The ability of the SMA component to recover its original dimensions may be an additional advantage, during the seismic events.

Shape Memory Alloys (SMA) show the potential to eliminate some limitations involved in present technologies, allowing a broader application. The limitations of existing technologies for passive protection devices can be summarized as follows

1. Problems related to ageing and durability (e.g., rubber components)
2. Difficulty in maintenance(those based on fluid viscosity)
3. Installation complexity or replacement and geometry restoration after strong events (those based on steel yielding or lead extrusion)
4. Variable performances depending on temperature(polymer based devices)

The usable strain range in the order of 10% in shape memory alloys provide them very high energy dissipation per unit mass of material. Comparing the well known rubber isolators and steel hysteretic dampers which belong to the class of quasi-elastic devices and elasto-plastic devices respectively, re-centering devices gain the best mechanical characteristics of

both. The shortcomings of the traditional restrainers can potentially be addressed with the use of SMAs (Fig.2). The comparative behaviour of steel, rubber and SMA is given in Fig.2.
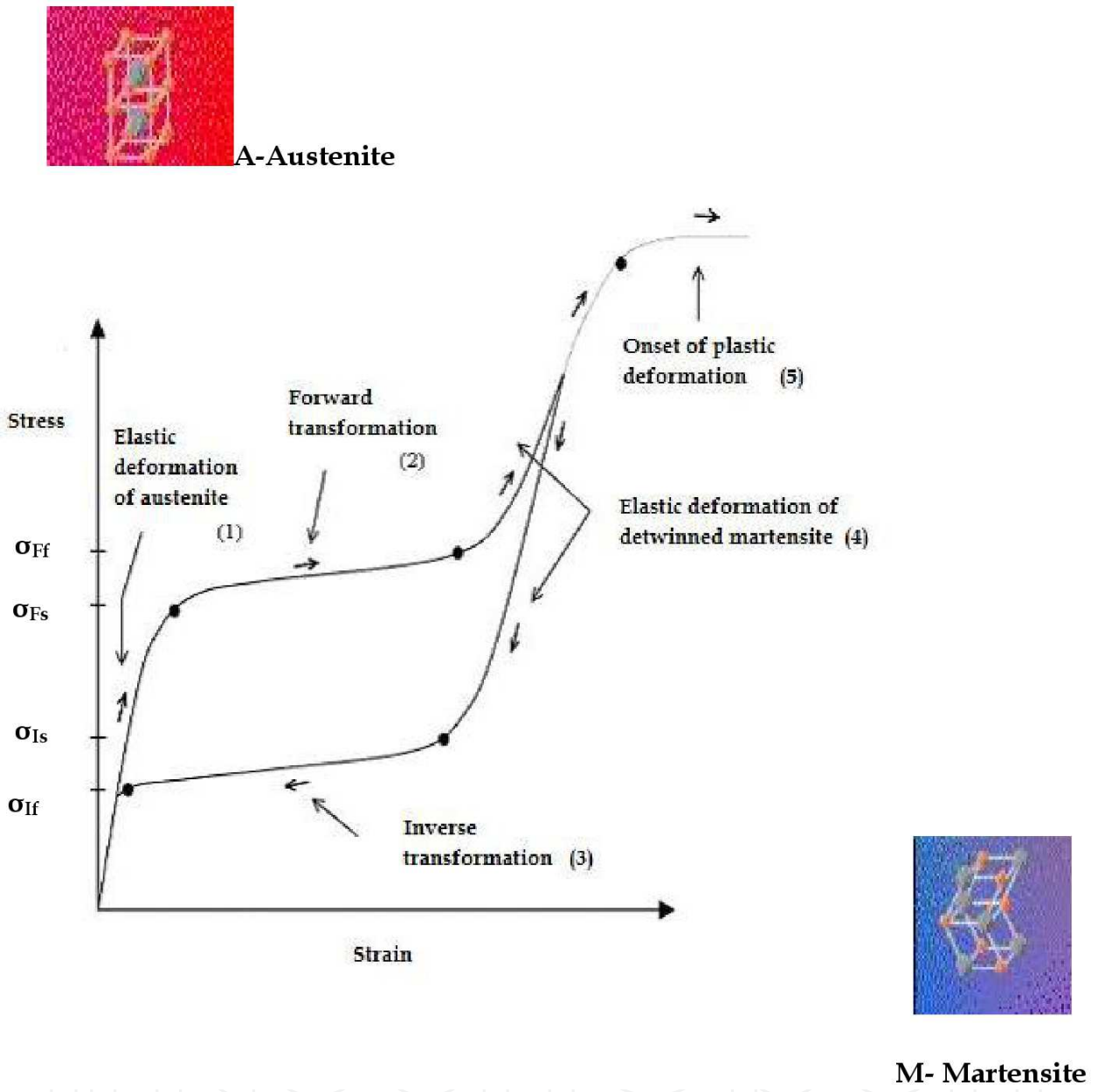
A-Austenite

M- Martensite

Fig. 1. Stress-strain curve showing super elasticity of SMA-Schematic sketch describing the phase change with the deformation process and the associated crystal structure

On the one hand, they recover the initial position of the structure, with a good control of the displacements; on the other hand they put a threshold to the force transmitted to the super-structure. The full possibility of designing the mechanical behavior combining the self-centering and the energy dissipation capability, permit to calibrate the desired features and fit the specific needs. The availability of such features opens considerable room for improvement of the structural system design. But the mechanical behavior of SMAs is strongly dependent upon the alloy composition and the thermo-mechanical treatment. Special care should be taken while alloy selection is made.
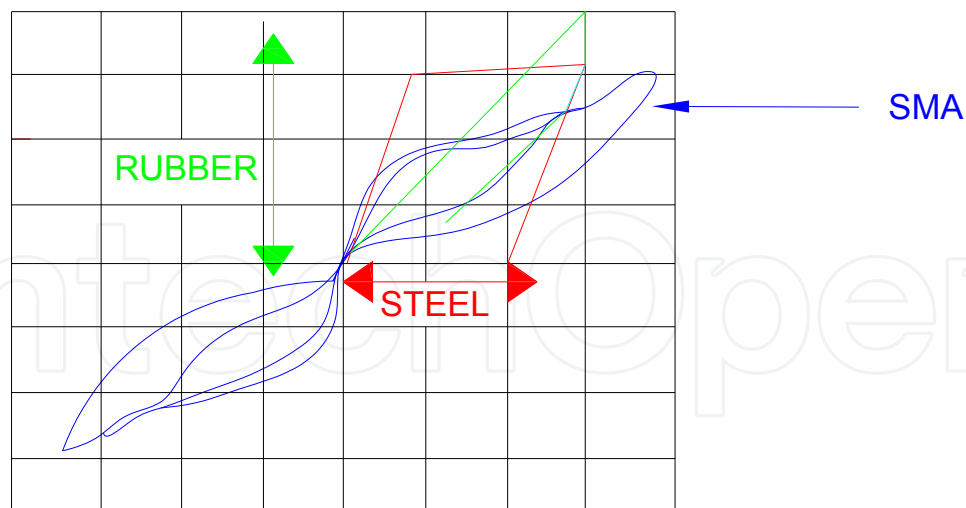
Fig. 2. Comparative behaviour of Steel, Rubber and SMA

4. Experimental investigation and inferences

The experimental tests were carried out on austenite wire samples of 0.4mm diameter and 1.2mm. The wires were available in spool form. The typical photograph of the material – wires in spool form-is shown in fig.3. The compositions of wires were NiTi alloy with 55 % Ni and balance titanium spooled NiTi. The wire selection is made in such a way that Ni-Ti alloy wire with equi-atomic composition possesses better dissipation property and higher resistance to corrosion and fatigue. The material is straight annealed super elastic NiTi wires and has its latent heat and specific gravity 14500 J/kg and 6479.85 kg/m^3 (0.234 lbs/in^3) respectively. The test was carried out under ambient temperature conditions around 27^0 C. Quasi-Static and dynamic tests were conducted to evaluate the super-elastic properties and energy dissipation capabilities under ambient temperature. Dynamic tests were carried out by applying sinusoidal cyclic deformation to wire samples. A displacement controlled test set up was used to perform the tests. The typical test sequence is characterized in terms of number of cycles, strain amplitude and frequency as they could provide very important information regarding earthquake applications.

The test programme on SMA wires of two diameters namely 0.4 and 1.2 mm can be summarized as follows:

1. Quasi-static tests
2. Dynamic tests -frequency of operation 0.5 Hz (sinusoidal cyclic deformation)
   a. Tests to evaluate the number of cycles to failure for a constant amplitude
   b. Variable amplitude tests to evaluate the energy dissipation capability for increased amplitudes.
3. Tests on pre-strained wires –frequency of operation 0.5 Hz .
4. Tests on wires for varying frequencies.

The quasi-static (slow rate) tests were performed till the failure of the specimen. The test was run in a position controlled test set up at constant rate of loading 0.025mm/sec. Fig.4 shows the stress strain curve for quasi-static loading. It is compared with the behavior of the 1mm diameter steel wire which is used for binding purposes in construction A sinusoidal cyclic test on SMA wires was performed for maximum amplitude of 5 mm.

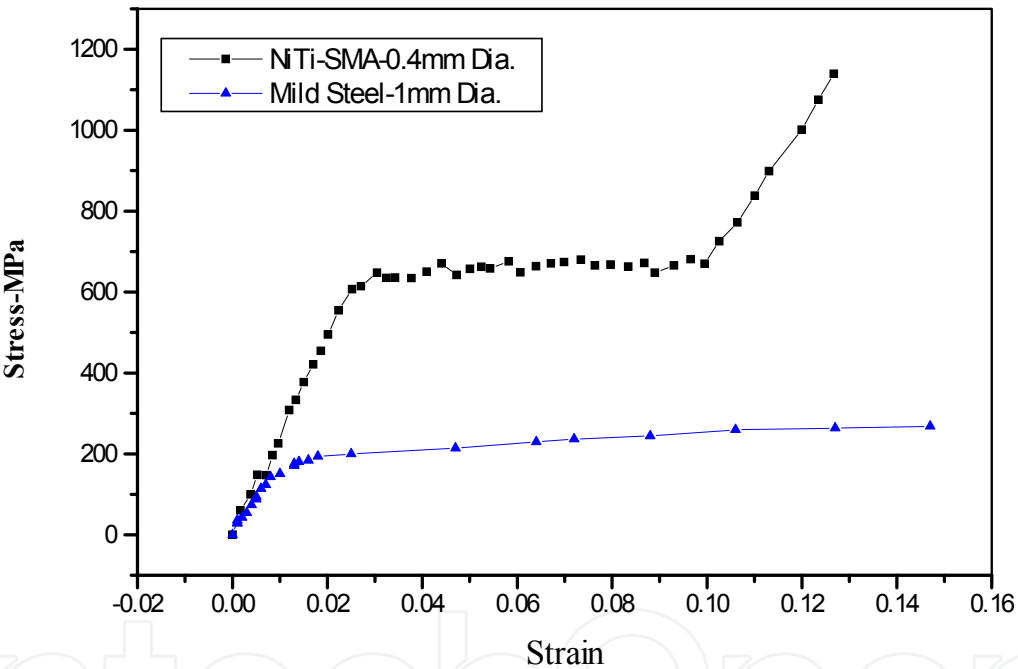Fig. 3. The photograph of the super elastic SMA wire samples (Available in spool form)

Fig. 4. Behaviour of Ni-Ti wires – quasi static tests- Comparison with 1 mm mild- steel binding wire used for reinforcement stirrup tying in structural construction.

The mechanical behavior such as the transformation stress levels, fatigue behaviour and the frequency dependence were found to be similar in both diameter wires. The tests were also carried out with increasing number of cycles to obtain the fatigue characteristics.

Typical load deformation characteristics of 1.2mm diameter wire with 11 mm amplitude are shown in Fig.6. As the displacement amplitude increased as observed in the force deformation behaviour, presence of the martensitic phase -after completion of the phase transformation- provides additional stiffness. Strain hardening is observed towards higher amplitudes which correspond to 8-9% strain in both the wires seen in Fig.4 & Fig.6. The increase in stress levels is quite evident in Fig.6. Here cycling up to 9% strain variation fetches a stress of 830 Mpa.
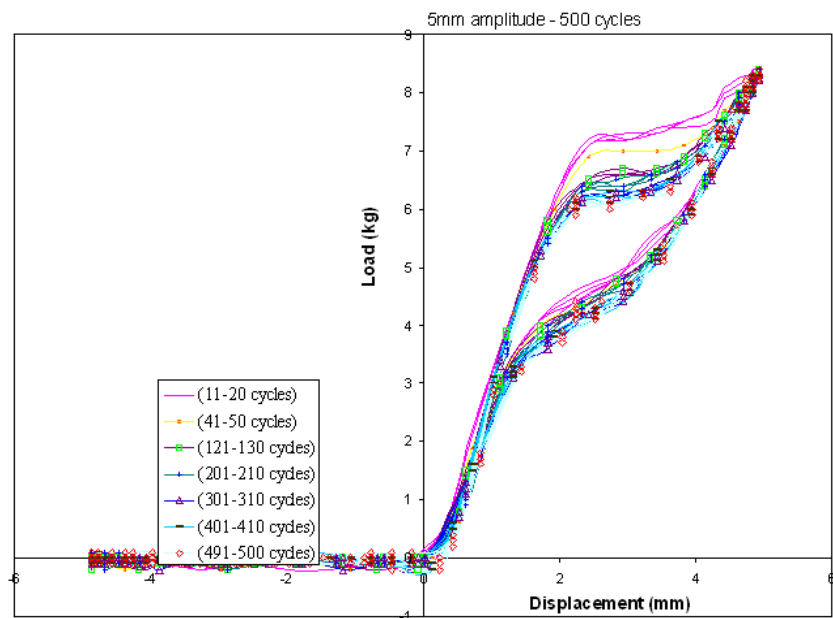
Fig. 5. Load deformation curves for 0.4mm diameter wire with 5mm amplitude (strain variation 3%, maximum stress 650 Mpa)- frequency of loading 0.5 Hz-0.4mm diameter wires
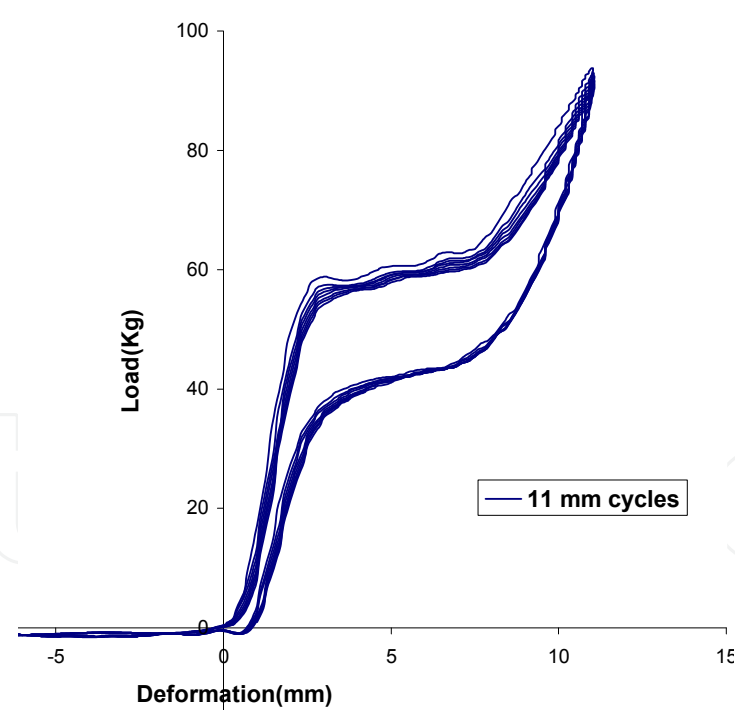

Fig. 6. Load-deformation curves for 1.2 mm diameter wire with 11mm amplitude cycles (strain range 9%, max. stress 830MPa)- frequency of loading 0.5 Hz Cycles (strain range 9%, max. stress 830MPa)

The various parameters and the testing scheme are selected in a way to understand the behavior of the material during earthquakes. Initially a sinusoidal cyclic test on SMA wires was performed for constant amplitude of 5 mm [Fig.7(a)- 7(d)]. Usually earthquake

vibrations are dynamic- reversed cyclic in nature which consists many number of cycles. The tests were also carried out with increasing number of cycles to obtain the fatigue characteristics. Further tests were carried out with increasing amplitude from 5 mm to 11 mm [i.e increasing the total strains from 4% to 9%, Fig.7 (e)]. Strain measurements were based on the actuator displacement as the wires were having very smooth oxide finish surface
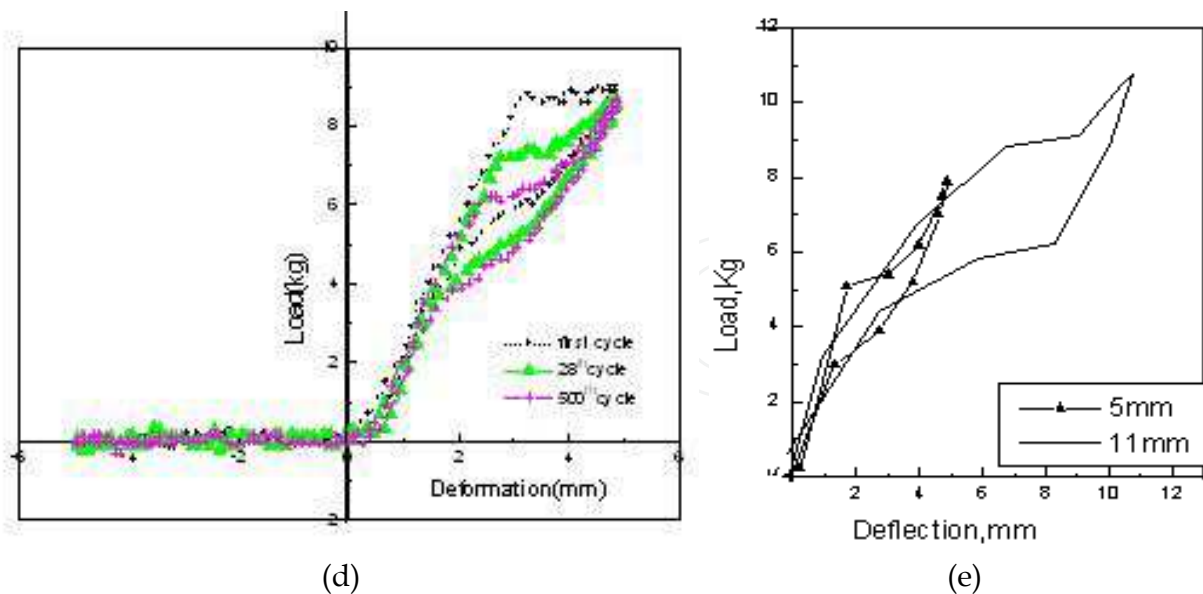

(a)

(b) Initial 28 cycles

(c) Subsequent cycles

(d)   (e)
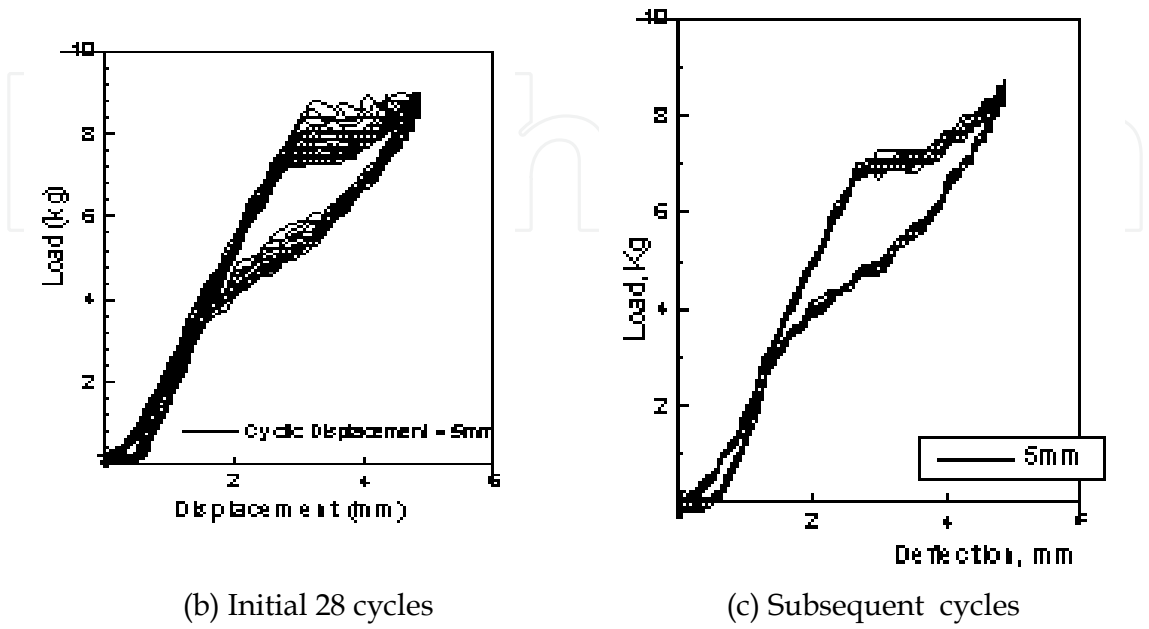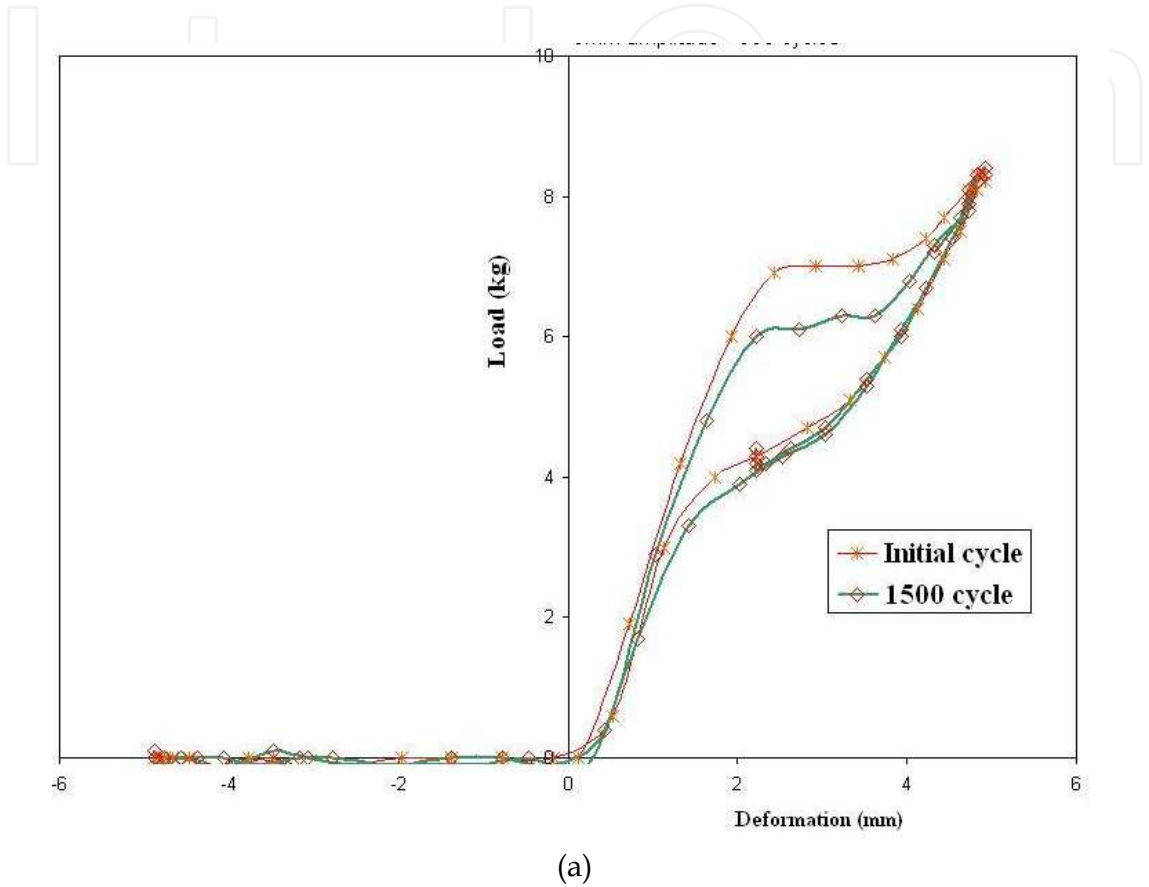
Fig. 7. (a) to (d) Cyclic tests on non pre-strained wires cycling for +/- 3 percentage strain variation (5mm amplitude). (e) Effect of increasing the amplitude beyond 1500 cycles.

Due to the repeated cyclic deformation of the same amplitude it is observed that the hysteresis loops translate downwards and narrows (Fig.7a-7d). Consequently the stress levels for the transformation decreases. Energy dissipation capacity under constant amplitude loading remained same up to 500 cycles, 20% reduction was observed in the next 500 cycles and around 30% reduction towards the failure from the initial value. Effect of increasing the amplitude beyond 1500 cycles can be observed in figure.7e.

4.1. Effect of pre-strain

The effect of pre-strain was found out by imposing pre-strain amplitude in the wire. The wire is held at that point of pre-strain and reversed-cycling performed for various amplitudes (Fig.8b). Like wise for various pre strain values the dynamic tests were performed by giving sinusoidal deformation to the wire samples (Fig.8a). These tests help to simulate the characteristics of earthquake loading and understand the behaviour of the material. The frequency dependence on loading is also investigated during the experiment (Fig.9). The frequency of loading was varied from 0.5 Hz to 3 Hz, at intervals of 0.5 Hz, since most of the earthquake applications come within this range. Table.1 gives the test programme for the nitinol wire and the parameters evaluated in the study are tabulated. Temperature variation during cycling was observed using a thermocouple for quite a few cycles.

5. Discussion of test results

Quasi-static tests of the wire clearly shows the super elastic property of the SMA wire. Fig.4. presents the stress strain curves obtained under quasi-static loading using a hydraulically driven test system (instron make). The shape of the stress strain curve exhibits some of the fundamental characteristics of SMA. Test result shows the super elastic property of the SMA wires in the strain range 2% to 10 %. The initial elastic to plateau transition, that is the

transition from linearly elastic to super-elastic occurs at a stress of approximately 597 MPa. The yield stress of 597 Mpa and ultimate stress of 1100 Mpa is comparable with the idealized behavior of SMA (Dolce, 1994).
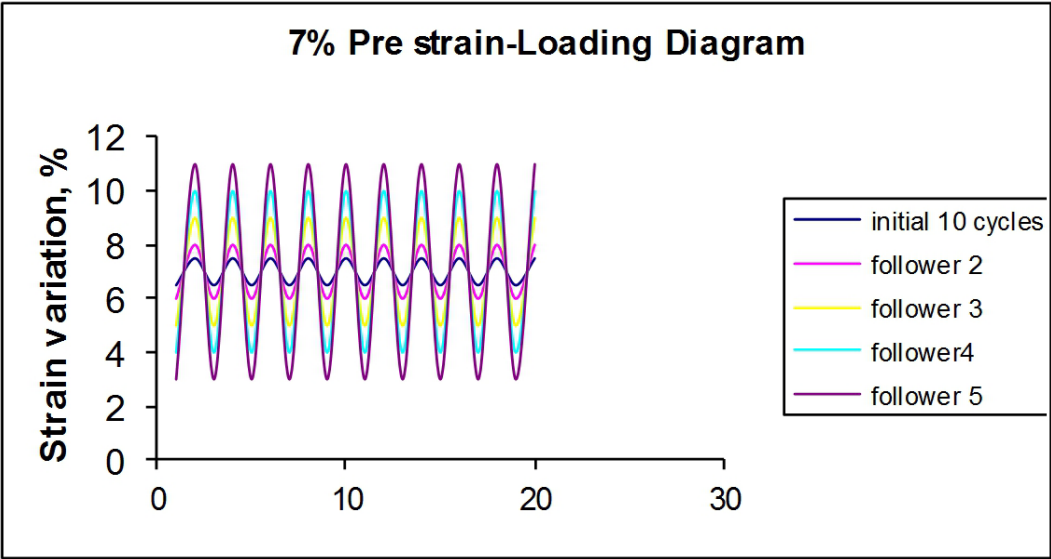
(a)
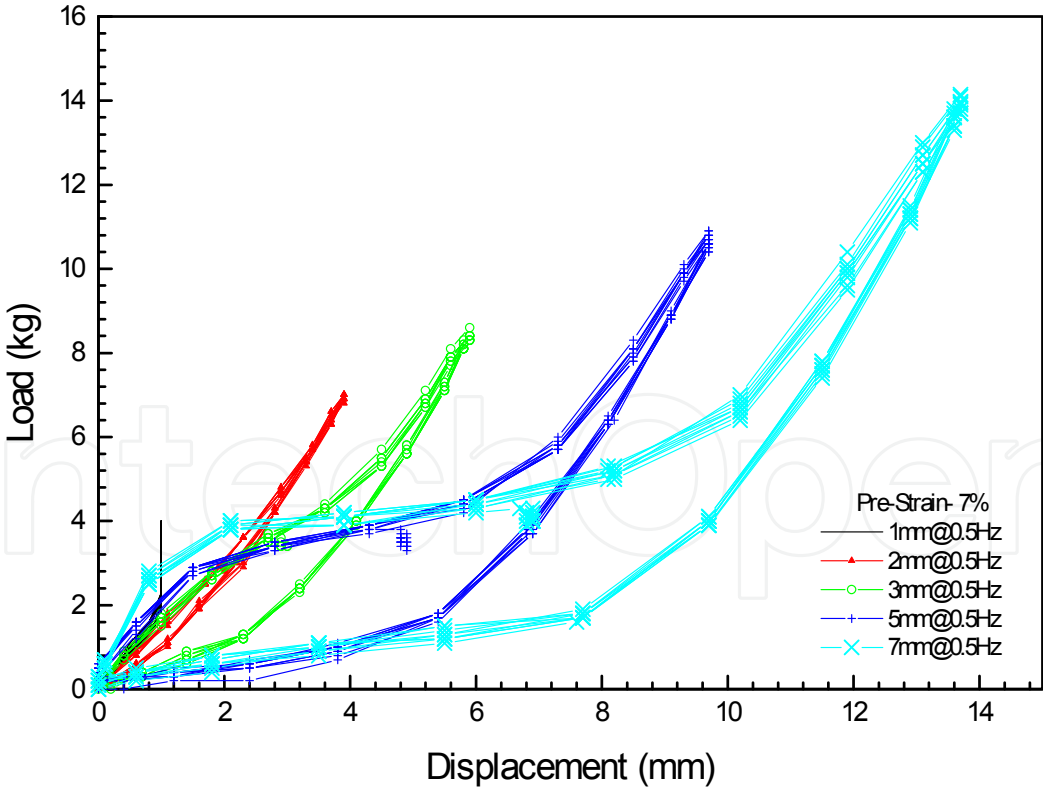
(b)

Fig. 8. Typical sketch showing the loading and the hysteretic curves obtained at 7% pre-strain –variable amplitudes.

If the material is unloaded after being loaded into the super elastic region, the unloading portion of the stress strain curve does not follow the loading portion, but follows a lower path back to the origin which indicates the transformation of stress induced martensite back to the austenite (Fig.5,6). This makes the hysteretic energy dissipation which is an important parameter to be assessed for earthquake applications and hence in passive control devices. The super elasticity based applications take advantage of the following features 1) the possibility of recovering large deformations 2) the existence of a transformation stress plateau, which guarantees constant stress over non-negligible strain intervals. The frequency dependence on loading is also investigated during the experiment (Fig.9). The frequency of loading was varied from 0.5 Hz to 3 Hz, at intervals of 0.5 Hz, since most of the earthquake applications come within this range. It is interesting to note that the number of cycles for the same amplitude is not sensitive to the frequencies in the range 0.5-3 Hz as observed in both the diameter wires.
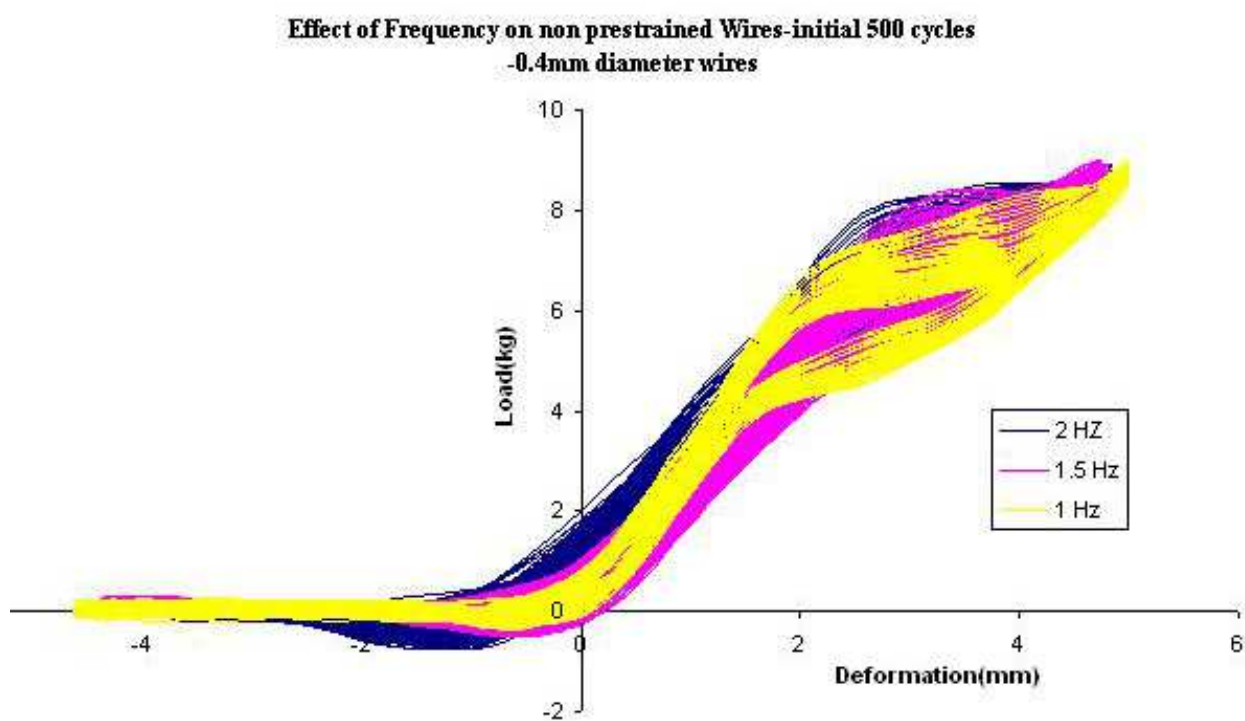

Fig. 9. Typical Cyclic behavior (tension compression tests) of non pre-strained wires for varying frequencies.

It is reported in the literature that the effect of frequency is negligible in the energy dissipation in the range of interest 0.5 - 3 Hz for seismic applications (Cardone et al,1999) . But it is observed from the test that the dissipated energy during the sinusoidal loading at 0.5 Hz is 25 % more than the energy dissipated at 1Hz to 3Hz, which is almost a constant value. Effect of increasing the amplitude beyond 1500 cycles can be observed in figure.7e. The high fatigue resistance combined with negligible residual deformation, observed in SMA material help to reduce the post earthquake repair costs, if dampers are made out using these.
It is found from the experiment that the hysteresis loops narrow and translate upwards when there is an increase in strain amplitude, while the branches of the curve relevant to the

phase transformations harden, thus yielding an increase in the stress levels (Sreekala et al,2008). This trend is observed in the case of cycling around 7% pre-strain, as the strain reaches to 10% the end of the transformation range (Fig.8). This phenomenon is related to the elastic deformation of the de-twinned martensite found at the end of the phase transformation. This is true for pre strained wires as well as without pre strained. It is a favorable aspect in seismic applications as the system stiffens rather than softening, if the expected design seismic action is exceeded, thus ensuring a good control of displacements.

Constant amplitude tests for many cycles for varying frequencies indicated that there is slight variation in the shape of the loops. Different heat exchange modalities with ambient temperature, at different strain rates are the causes of these effects from quasi-static to dynamic range (0.5-3 Hz). As strain rate increases, the heat-exchange condition increasingly digresses from the isothermal one. The latent heat of transformation causes the specimen to self-heat and then increase its average temperature during test. At the same time, during each loading cycle, the specimen temperature oscillates around an average value, according to the sinusoidal variation of strain. The temperature variation is found to be 9^0c.While the instantaneous temperature of the wire oscillates around the ambient temperature (27^0c) with excursions of the order of 9^0c, the average temperature remains practically unchanged during all the loading history equal to the ambient temperature.

As a result of the self heating (cooling) there occurs instantaneous increase (decrease) of the stress required for transformation. It is observed from the test that the dissipated energy during the sinusoidal loading at 0.5 Hz is 25 % more than the energy dissipated at 1Hz to 3Hz, which is almost a constant value. The hardening of the transformation branches, the narrowing of the cycle, apparent change in the shape of the loop resulting in a reduced energy loss all of which are associated with slight temperature variation due to different heat exchange modalities are caused by the stabilization of the material due to repeated cyclic loading(Fig.10). Possible increase of average temperature during cycling at higher strain rates produces an upward translation [Miyazaki et al,1986b].

Stabilization of the material behavior due to repeated cyclic loading also can be observed from the shape change of the loops in the tests on non-pre strained wires (Fig.10). The effect of pre-strain is found at 2.5% pre strain applied in the form of deformation to the sample, on two cyclic strains namely 4 % and 6 % (Fig.11.).

The figure reveals the fact that the hysteresis loops translate upwards as it near the transformation stress level. The comparison between the energy dissipation capability at various pre strain under different amplitudes, namely 3mm and 7mm is shown in Fig.12.

It is interesting to find that the quasi-static curve serves as the envelope curve in this process and as and when the stress reaches the transformation stress level, as marked in fig.12, further stiffening happens in the material. This is an added advantage for seismic applications that the material gets stiffen, rather softening to have good control of displacements. Fig. 12 also shows the hysteresis curve for the wire pre strained at 6% and cycled between 2 % and 10% along with other strain variations.

Tests on wires pre strained to different levels, indicated a particular value of pre-strain, from which cycling in the pseudo-elastic range fetches maximum energy dissipation (Fig.8.). The equivalent viscous damping expresses the effectiveness of the material in vibration damping. It is calculated based on the average energy dissipated per cycle and the damping values observed are also found to be significant. Looking into 6% pre strain one can see the higher equivalent damping values. Cyclic variation of 4% strain on either direction at 6% pre strain gives higher equivalent damping due to higher energy dissipation (Table.1). An
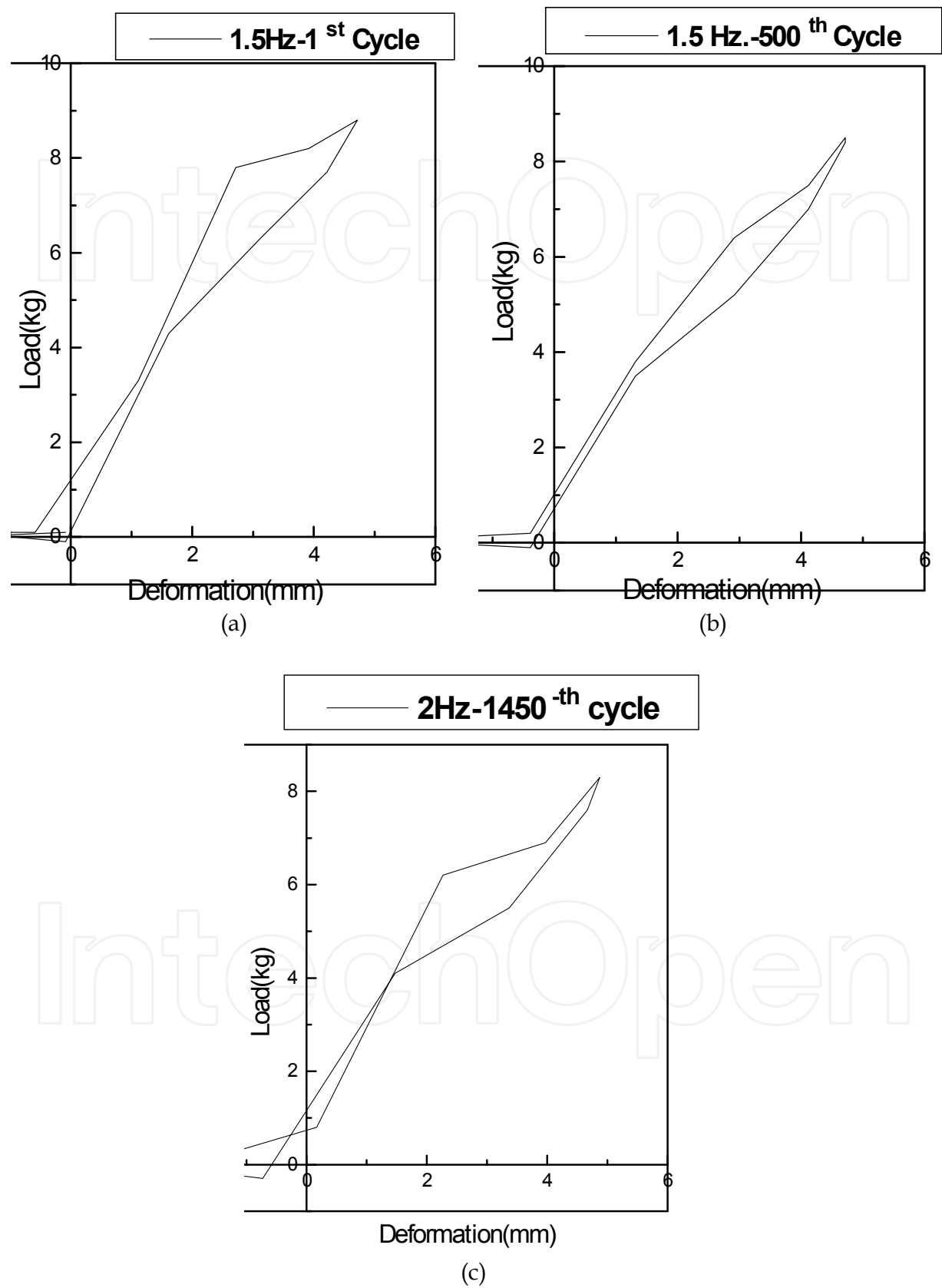
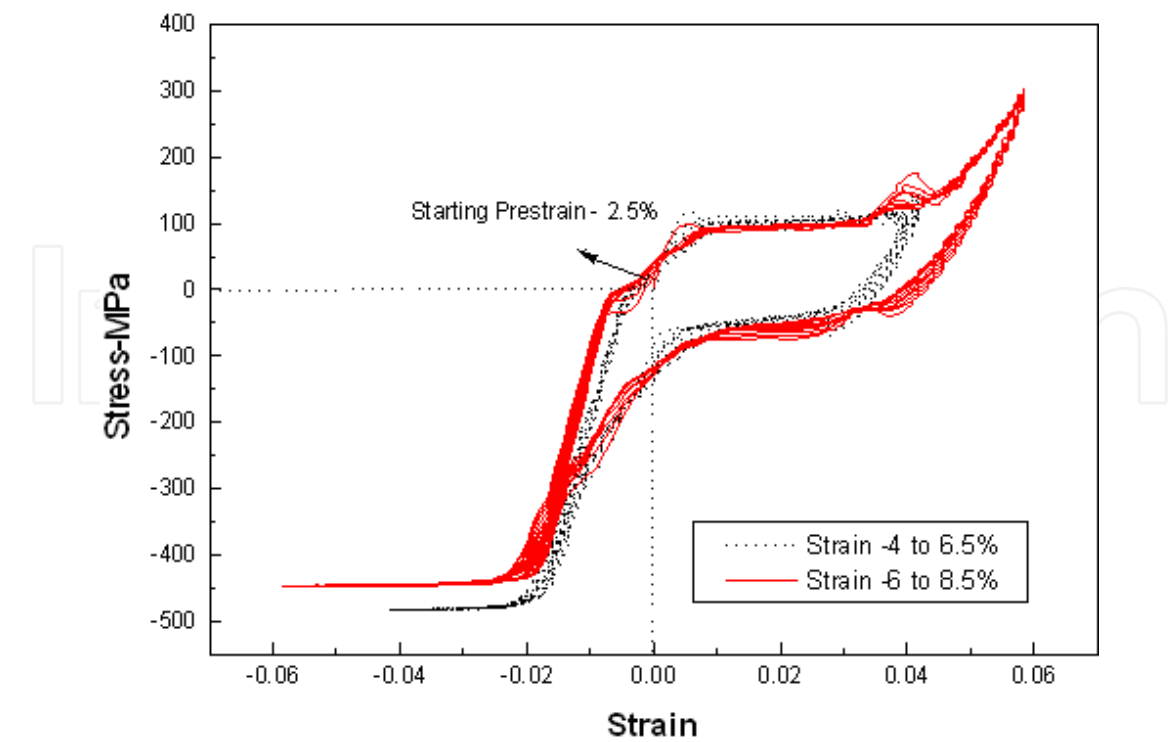Fig. 10. (a) to (c) Changes in the shape of the curve during varying frequencies.

Fig. 11. Effect of pre-strain on the energy dissipation (1.2 mm diameter wires)- frequency of loading 0.5 Hz
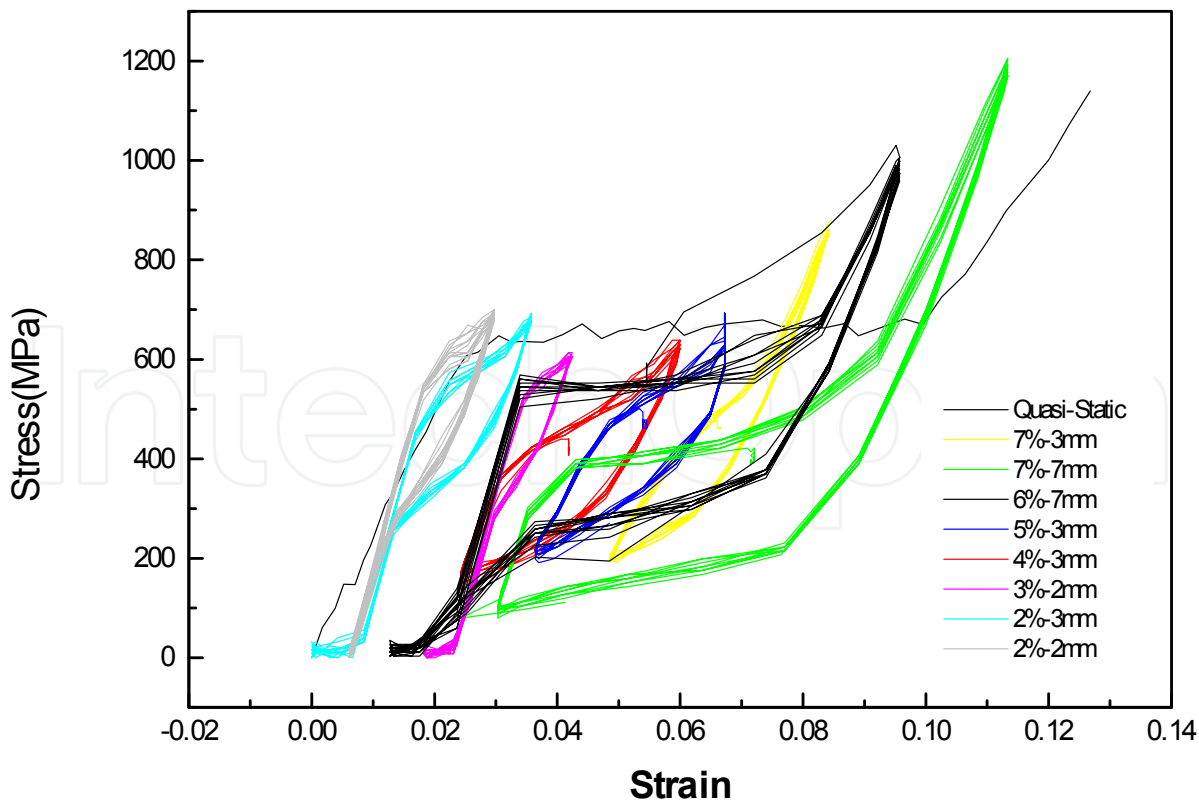

Fig. 12. Cyclic behavior of pre strained wires for varying pre strains. [The legend denotes pre strain %-reverse displacement cycles from that prestrain (mm)]

average equivalent damping ratio of 16% was realized during the test [Sreekala et al, 2008]. It is found to be nearer to half the super-elastic range obtained from quasi-static tests. Results indicate that if the super elastic wires have to play an energy-dissipating role, cycling around the threshold pre-strain value within this range is desirable [Sreekala et al,2010]. In this case the energy dissipation is dependent on the strain value in the super-elastic range from where cycling the entire range fetches maximum, as seen in figure 4.

For wires without pre strain, the equivalent damping ratio observed is in the order of 3%. This is because during cycling, the reverse direction (compressive region) does not contribute for the energy dissipation in non pre-strained wires. Tests on virgin wires shows lesser damping and energy dissipation capacity and these results can be compared with those under MANSIDE project. The design of the SMA based devices can be made by choosing the mechanical properties such as transformation stress levels/ plateau strength as design variables. Fig.14 shows the hysteretic behaviour of the different types of devices that can be developed using the properties of the SMA material. A variety of hysteretic behaviour can be obtained from the material tested and its application can be made suitable for seismic devices like re-centering, supplemental re-centering or in the case of non re-centering devices. These results reveal the suitability of using pre strained SMA wires in vibration control applications, especially for Non Re-Centering Devices-NRCD as seen in Fig.14. Normally pre straining of wires in vibration control devices requires highly skilled labour and maintenance becomes a difficult procedure. As far as the numbers of cycles are concerned, pre strained wires also goes beyond 900 cycles under constant amplitude loading. e.g.:-in 6% pre strained wire, under the maximum pseudo-elastic range goes up to 940 cycles before failure. No reduction in the energy dissipation is observed up to 30 cycles, but towards the failure 30 % reduction is observed as in non-pre strained wire. Usually for seismic applications, the numbers of cycles to be considered are less than 500 cycles as per various codal spectrums for seismic design in different countries. Table 1 summarizes the number of cycles, energy dissipation capacity per cycle, the strain variation and the equivalent damping. These results reveal the suitability of using SMA wires in seismic vibration control applications.

The usable strain range of the order of 10% in the alloys provide them very high energy dissipation per unit mass of material. Re-centering devices gain the best mechanical characteristics of both quasi-elastic devices (e.g., rubber isolators) and elasto-plastic devices (e.g., steel hysteretic dampers). On the one hand, they recover the initial position of the structure, with a good control of the displacements; on the other hand they put a threshold to the force transmitted to the super-structure. The full possibility of designing the mechanical behavior combining the self-centering and the energy dissipation capability, permit to calibrate the desired features and fit the specific needs. The availability of such features opens considerable room for improvement of the structural system design. Fig 7 indicates the various device options for passive vibration control using this material. But the mechanical behavior of SMAs is strongly dependent upon the alloy composition and the thermo-mechanical treatment. Special care should be taken while alloy selection is made.

6. Equivalent viscous damping

Some significant quantities usually employed in earthquake engineering to characterize the dissipation capability of the material under investigation are equivalent viscous damping, secant stiffness and energy loss per cycle. The equivalent viscous damping expresses the

effectiveness of the material in vibration damping. It is calculated based on the average energy dissipated per cycle. It is calculated as
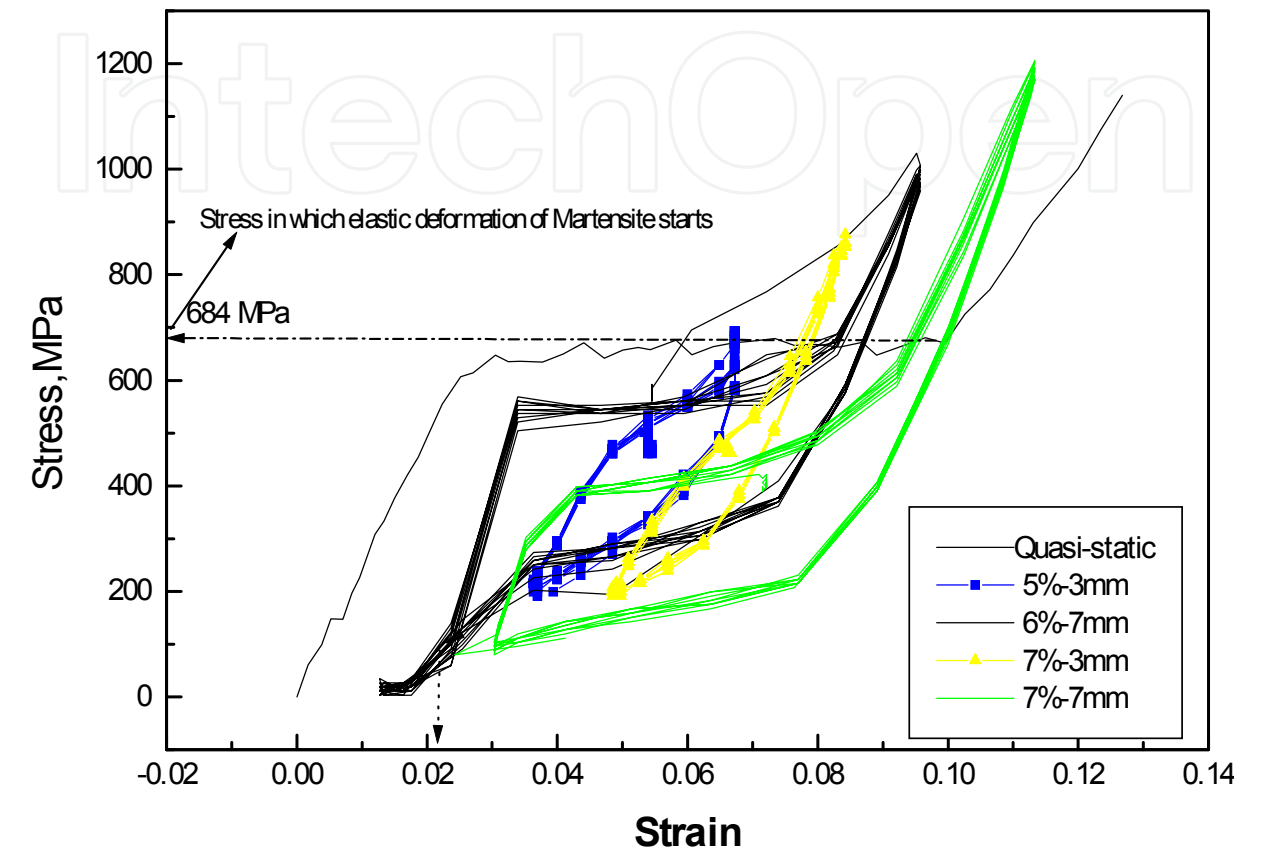
$$\xi_{eq.} = W_D / (2\Pi \, K_S \delta^2) \tag{1}$$

Fig. 13. Cyclic behavior of pre strained wires –maximum energy dissipation when pre-strained almost at the middle of the pseudo-elastic range. [The legend denotes pre strain %-displacement cycles (mm)]
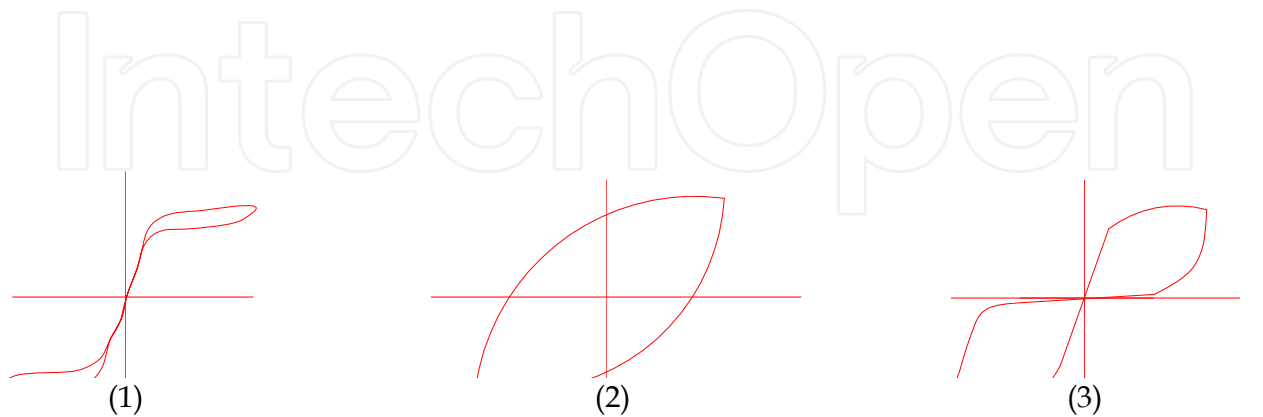

Fig. 14. Load –deformation behavior (Hysterisis curves) for various types of   Devices based on SMA, SRCD-Supplementary Re-Centering Device, NRCD-Non Re-centering Devices, and RCD-Re-centering Devices

where W_D is the energy loss per cycle and δ is the maximum cyclic displacement under consideration. The secant stiffness (K_s) is computed as

$K_s \quad = (F_{max} - F_{min}) / (\delta_{max} - \delta_{min})$ where F_{max} and F_{min} are the forces attained for the maximum cyclic displacements δ_{max} and δ_{min}. The associated energy dissipation and the equivalent viscous damping calculated are included in Table.1.

The effect of pre-strain is found at 2.5% pre strain applied in the form of deformation to the sample, on two cyclic strains namely 4 % and 6 % (Fig.11.). An increase in the energy dissipation can be observed as the cyclic strain amplitude increases. The energy dissipated during cycling in pre-strained wires is considerably high compared to non-pre strained wires as observed from the experiment. It is interested to observe that (Fig.13) leaving the flat plateau; the response follows the elastic curve below 2% strain as obtained from the quasi-static test. Hence the quasi- static behaviour gives the envelope curve for the cyclic actions and a variety of hysteretic behaviour suitable for seismic devices can be obtained with pre straining effect [Sreekala et al, 2010].

7. Modeling the maximum energy dissipation for the material under study

It is observed from the experiment that the wires pre strained to the middle of the strain range gives the maximum energy dissipation(fig. 8). The behaviour can be predicted using the following mathematical expressions.

$$\sigma = E\left[\varepsilon - |\varepsilon|\{1 / \left(\frac{\sigma - \beta}{Y}\right)^n\} + \sigma_*\right] \tag{2}$$

$$\varepsilon = \left[\frac{\sigma}{E} + |\varepsilon|\{1 / \left(\frac{\sigma - \beta}{Y}\right)^n\} - \frac{\sigma_*}{E}\right] \tag{3}$$

σ_* denotes the stress in the pre strained wire at the beginning of the cycling. Here β can be expressed as

$$\beta = E\alpha\{\ \varepsilon^{in} + f_T|\varepsilon^c|erf(\alpha\varepsilon)\left[u\left(-\varepsilon\dot{\varepsilon}\right)\right]\ \} \tag{4}$$

β denotes the one dimensional back stress, Y is the "yield" stress ,that is the beginning of the stress- induced transition from austenite to martensite, n is the overstress power. In equation (4) the unit step function activates the added term only during unloading processes. In the descending curve it contributes to the back stress in a way that allows for SMA stress-strain description. The term with (.) shows the ordinary time derivative.

$\alpha = \dfrac{E_y}{\left(E - E_y\right)}$ is a constant controlling the slope of $\sigma - \varepsilon$, where E is the elastic modulus of austenite and E_y is the slope after yielding.

Inelastic strain, ε^{in} ,is given by

$$\varepsilon^{in} = \varepsilon - \frac{\sigma}{E} \tag{5}$$

The error function, erf(x) ,and the unit step function, u(x) are defined as follows.

$$erf(x) = \frac{2}{\sqrt{\Pi}} \int e^{-t^2} dt \tag{6}$$

$$u(x) = 1 \ , \ x \geq 0 \tag{7}$$

$$u(x) = 0 \ , \ x < 0 \tag{8}$$

The basic expression obtained here for pre-strained wires is a modified form of the model suggested by wilde et al, [12] which is used for predicting the tensile behaviour of SMA materials. This mathematical expression describes the mechanical response of materials showing hysteresis.

$$\dot{\sigma} = E\left[\dot{\varepsilon} - \left| \dot{\varepsilon} \right| \left(\frac{\sigma - \beta}{Y} \right)^n \right] \tag{9}$$

where σ is the one dimensional stress and ε is the one-dimensional strain, β is the one dimensional back stress , E elastic modulus , Y the yield stress and n the constant controlling the sharpness of the transition from elastic to plastic states.

The modified Cozzarelli model suggested by Wilde et al represents the hardening of the material after the transition from austenite to martensite is completed. Here in this case for pre strained wires for maximum energy dissipation, the hardening branch has not been considered which requires additional terms containing further unit step functions. The model is rate and temperature independent. The requirement of zero residual strain at the end of the loading process motivated the selection of the particular form of back stress through the unit step function. The coefficients f_t, and c are material constants controlling the recovery of the elastic strain during unloading. Since the stress and strain were found to be independent of the rate, the time differential can be eliminated. Hence equation (2) and (3) can be used for predicting the behaviour after many cycles by appropriately changing the values of 'n' and the starting stress value which follows the trend as in fig. 15. The material constants for the wires tested were obtained as

f_t = 0.115, C =0.001, n = 0.25,   α = 0.055. Using Equations (2) and (3) the curves are fitted. Fig. 15 gives the fitted curve for the maximum energy dissipation for the material tested.

8. Various seismic response mitigation strategies

Earthquake engineering has witnessed significant development during the course of the last two decades. Seismic isolation and energy dissipation are proved to be the most efficient tools in the hands of design engineer in seismic areas to limit both relative displacements as well as transmitted forces between adjacent structural elements to desired values. Parallel development of new design strategies (the seismic software) and the perfection of suitable mechanical devices to implement the strategies (the seismic hardware) made it possible to achieve efficient seismic response control. An optimal combination of isolator and the energy dissipater ensures complete protection of the structure during earthquake. Energy dissipation and re-centering capability are the two important functions to cater this need.

Most of the devices now in practice have poor re-centering capabilities. Instead of using a single device a combination of devices can provide significant advantages
The chart shown below Fig.18 illustrates the various seismic response mitigation strategies.
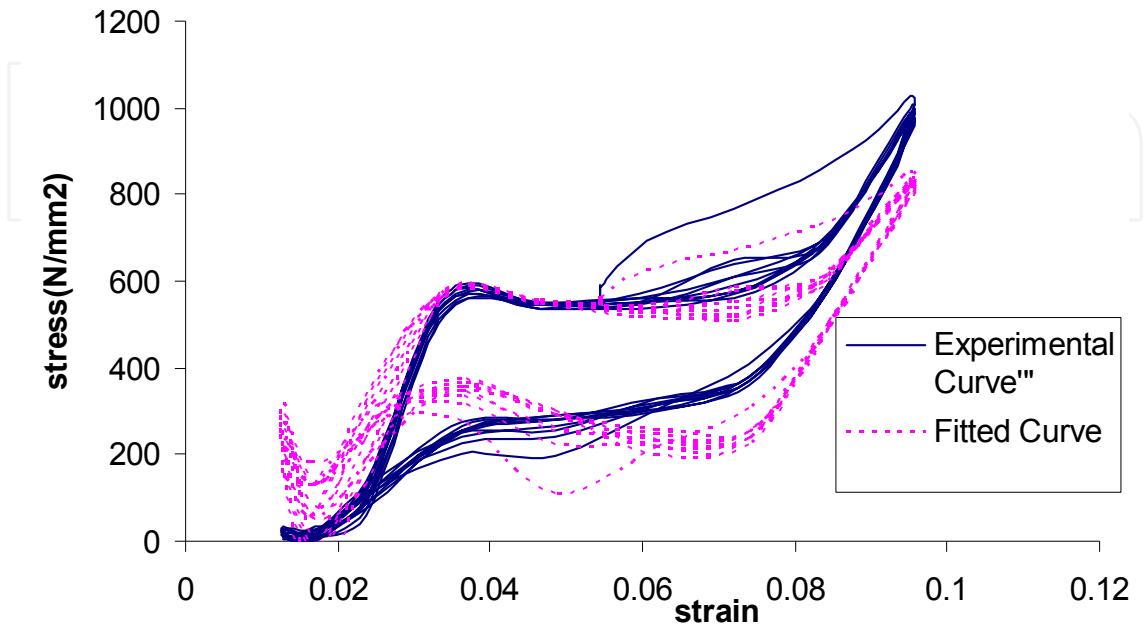

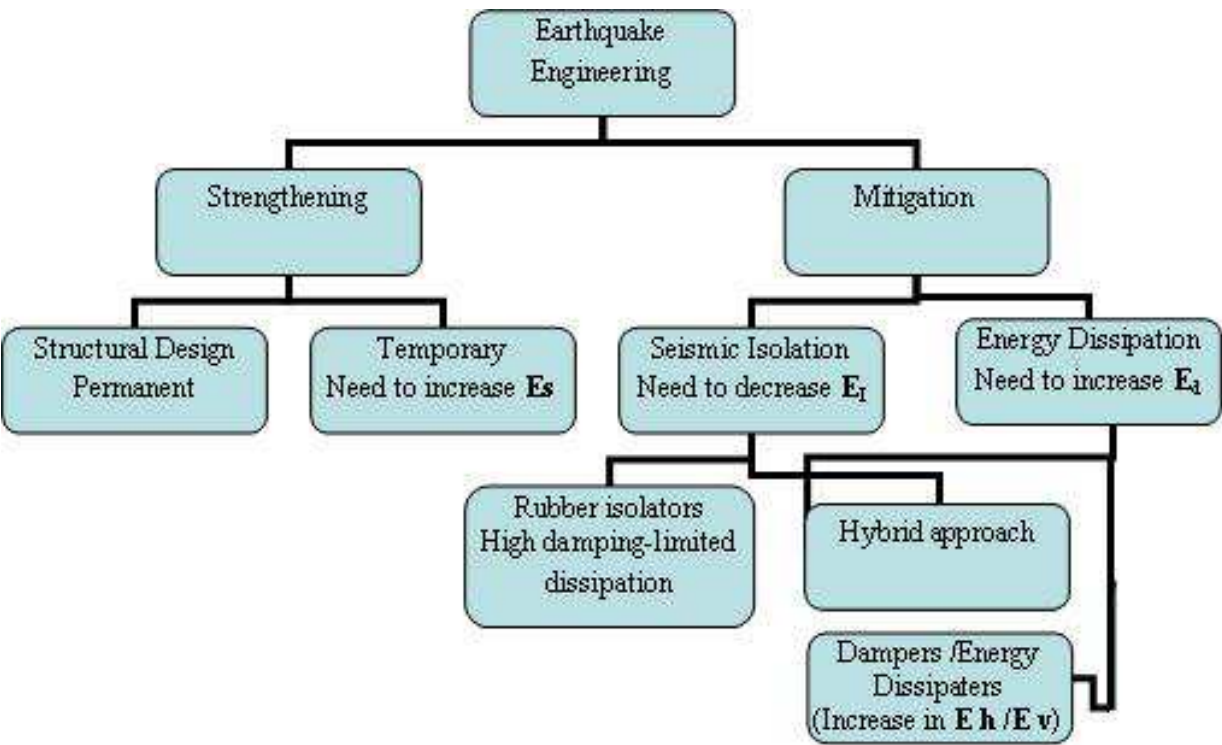Fig. 15. Cyclic behaviour of prestrained wires –maximum energy dissipation obtained and the fitted curve.

Fig. 16. Various seismic response mitigation strategies

Sl.no:	Nature of Test	Pre- strain in the wire	Cycling Strain range (%)	Average energy dissipated per cycle X10^{-2} J	No: of cycles	Equivalent viscous damping
1		7%	6.5-7.5	00.30	10	0.02
			6.0-8.0	00.60	10 [a]	0.02
			5.0-9.0	06.70	10 [a]	0.06
			4.0-10.0	18.60	10 [a]	0.07
			3.0-11.0	33.00	10 [a]	0.09
			1.3-12.0	-	-	-
2	Dynamic Tests	6%	2-10	33.80	10	0.16
				27.00	50 [a]	0.11
				21.00	500 [a]	0.09
3		5%	4.5-5.5	00.50	10	0.04
			4.0-6.0	04.60	10 [a]	0.13
			3.0-7.0	07.70	10 [a]	0.12
4	Freq. of operation 0.5 Hz. (Sinusoidal cyclic)	4%	3.5-4.5	00.33	10	0.02
			3.0-5.0	05.40	10 [a]	0.16
			2.0-6.0	10.35	10 [a]	0.16
5		3%	2.5-3.5	01.01	10	0.05
			2.0-4.0	01.91	10 [a]	0.04
6		2%	1.5-2.5	01.50	10	0.10
			1.0-3.0	04.40	10 [a]	0.10
			0.0-4.0	05.10	10 [a]	0.07
7		Nil	-3 - +3	07.30	25.	0.03
			-3 - +3	06.40	328 [a]	0.03
			-4 - +4	05.10	560 [a]	0.04
8		Nil	-3 - +3	05.60	1500	0.03
			-7 - +7	10.90	140 [a]	0.045

Table 1. Evaluated parameters of the Nitinol wire.

[a] - denotes the number of cycles which are followed by the cumulative previous cycles.

From this diagram it is clear that for seismic mitigation, a combination of Seismic isolation and Energy Dissipation is beneficial. Seismic Isolation can be implemented as explained below:

- Through the reduction of the seismic response subsequent to the shift of the fundamental period of the structure in an area of the spectrum poor in energy content
- Through the limitation of the forces transmitted to the base of the structure. A high level of energy dissipation also characterizes this approach. So it represents a combination of the two strategies of seismic mitigation. Isolation systems must be capable of ensuring the following functions:
  1. transmit vertical loads,
  2. provide lateral flexibility,
  3. provide restoring force,
  4. provide significant energy dissipation.

In each device, the constituent elements assume one or more of the four fundamental functions listed above. Some of the cases hybrid systems prove to be very much beneficial. For example, the strategy need to be adopted in suspension bridges is that of isolation and energy dissipation as the vertical cables did not provide energy dissipation characteristics. Hence dampers need to be provided and the hybrid system provide adequate protection during seismic response. The Table 2 below provide various energy dissipators/dampers along with their principle of operation

Classification	Principles of operation
Hysteritic devices	Yielding of metals Friction
Visco elastic devices	Deformation of visco elastic solids Deformation of visco elastic fluids Fluid orificing
Re centering Devices	Fluid pressurization and orificing Friction spring action **Phase transformation of metals (Shape memory alloys belong to this category)**
Dynamic vibration absorbers	Tuned mass dampers Tuned liquid dampers

Table 2.Various energy dissipation devices/damper

Fig. 17. Example of Composite Rubber/SMA spring damper

The unique constitutive behaviors of Shape Memory Alloys have attracted the attention of researchers in the civil engineering community. The collective results of these studies suggest that they can be used effectively for vibration control of structures through vibration isolation and energy absorption mechanisms. Possible applications of SMA based devices on Various structures for vibration control is shown in Fig.18,

For the analysis of structures, an equivalent Single Degree Of Freedom (SDOF) system can be utilized. The following mechanical model can represent the behavior of the energy dissipating system (Fig.19a). If re centering device is utilized the hysterisis should be adequately represented using mathematical models.
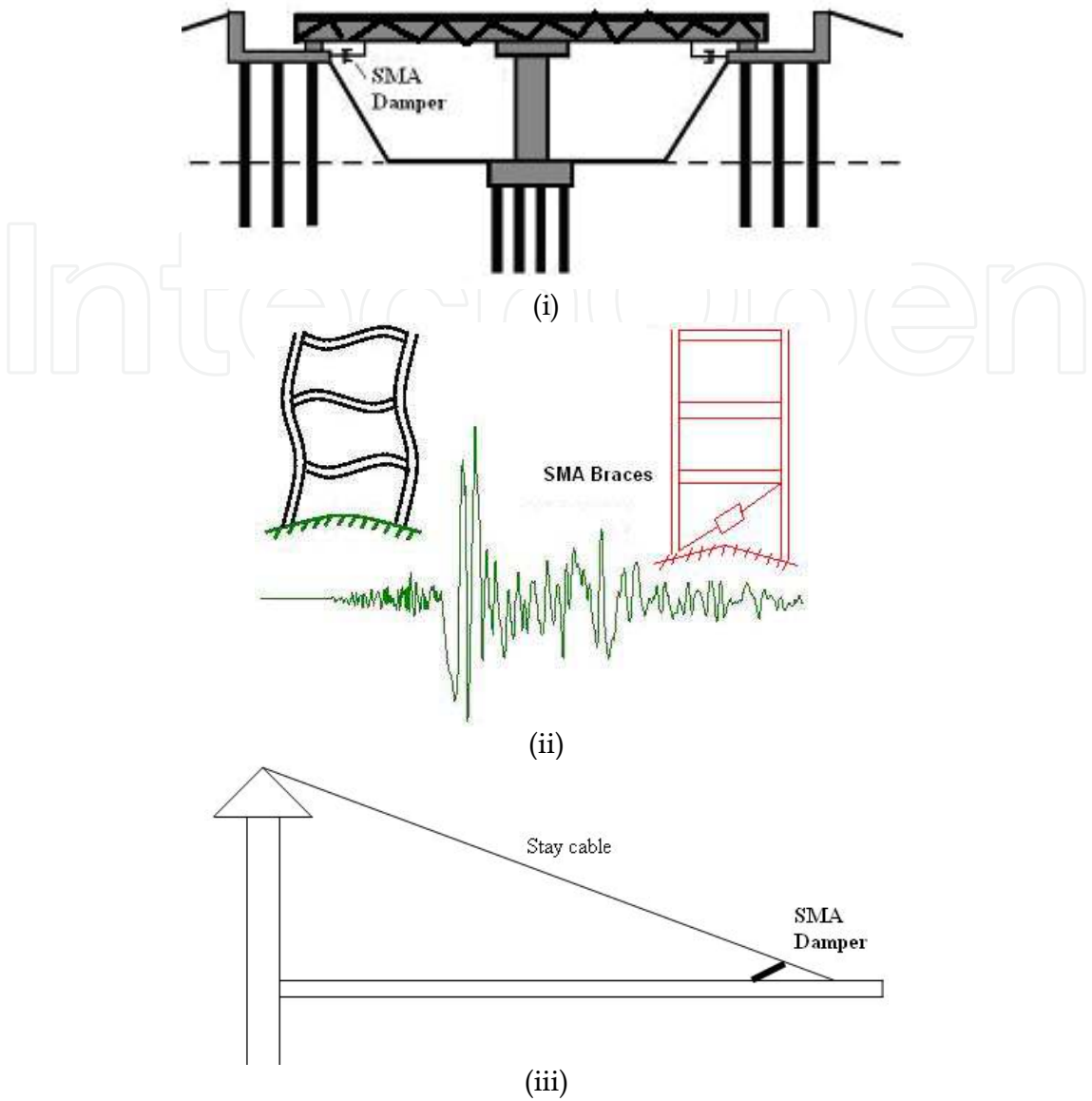
(i)

(ii)

(iii)

Fig. 18. Possible Applications of the Devices (i) Restrainers in Bridges (ii) Diagonal braces in buildings (iii) Cable stays (iv) combination of isolators and dampers in bridges
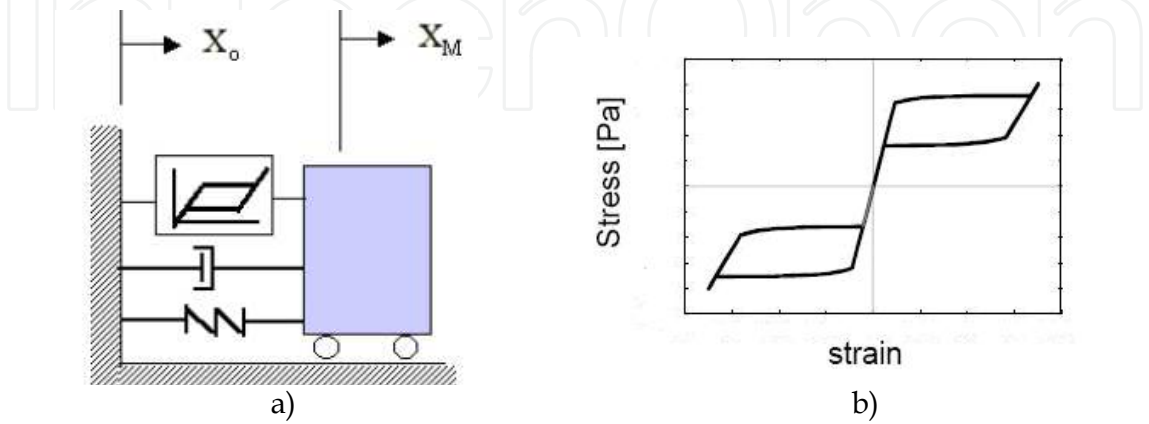

Fig. 19. a) Equivalent mechanical model of the SDOF scaled structure
b) The hysterisis /energy dissipation behavior of the re-centering device

9. Conclusion

There have been considerable research efforts in seismic response control for the past several decades. Due to the distinctive macroscopic behaviour like super elasticity, Shape Memory Alloys are the basis for innovative applications such as devices for protecting buildings from structural vibrations. Super elastic properties of Nitinol wires have been established from the experiments conducted and the salient features to be highlighted from the study are

- The material's application can be made suitable for seismic devices like recentering, supplementally recentering or in the case of non-recentering devices, as a variety of hysteretic behaviors were obtained from the tests.
- Cyclic behavior of the non pre strained wires especially energy dissipation capability, equivalent viscous damping and secant stiffness are not very sensitive to the number of cycles in the frequency range of interest (0.5- 3Hz.) as observed from constant amplitude loading.
- Pre-strained super elastic wires shows higher energy dissipation capability and equivalent damping when cycled around the midpoint of the strain range obtained from quasi-static curve. It is found from the experiment that the pre strain value of 6 %, with amplitude cycles which covers 2-10% gives higher energy dissipation.
- For possible application of vibration control devices in structural systems, a judicious selection of the wire under tension mode can be selected between pre strained and non-pre strained wires. However application of pre strained wires in the system provides excellent energy dissipation characteristics but it requires skilled and sophisticated mechanism to maintain/provide the required pre strain.
- The mathematical model predicts the maximum energy dissipation capability of the material namely pre strained nitinol wires under study.
- The test results shows immense promise on SMA based devices which can be used for vibration control of variety of structures(New designs and restoration of structures). SMA structural elements/devices can be located at key locations of the structure to reduce the seismic vibrations.

10. Acknowledgment

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