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Semi-Active Control of Building Frames subjected to Earthquakes using Smart Tendons composed of Shape Memory Alloys

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Abstract **-** This paper presents a concept for semi-active control of earthquake induced vibrations in building frames based on smart stressing of building frame using shape memory alloys. Smart tendons or cables composed of (Ni-Ti) shape memory alloy (SMA) wires are proposed to be installed externally with building frame elements. In principle, the smart tendons or cables can be designed such that the SMA wires are elongated beyond their plastic limit under the action of earthquake loads on the frame. Upon regulated electrical heating, the Ni-Ti SMA wires will undergo a martensite to austenite phase transformation resulting in large shrinkage strains. The strain energy thus induced can be used to generate a significantly effective control forces in the building frame. The present study proposes the implementation of smart tendons constituted with Ni-Ti SMA wires appropriately connected to building frame members which can be electrically actuated to induced desired variable control forces in building frame. The proof of concept proposed in the present study is theoretically illustrated by numerical simulations of proposed semi-active control scheme in an idealized eight story building frame model

Keywords**:** Structural control, Shape Memory Effect, Smart material, Ni-Ti (Nitinol) Alloy, Super-elasticity

1. Introduction

The past two decades have witnessed intensive research activity in the area of vibration control in civil engineering structures. A number of innovative schemes and devices have been proposed for active, semi-active and passive control of vibrations in building structures. In recent years, the Shape Memory Alloy based control systems have received growing interest in seismic protection of structures [1]. Earlier, shape memory alloys (SMAs) have found successful applications in various engineering disciplines such as aerospace, mechanical and bio-medical engineering. Shape Memory Alloy (SMA) is a smart material, which exhibits two distinct attributes i.e. the shape memory effect in its martensite phase and super-elasticity in its austenite phase, that are particularly desirable from the point of view of structural control.

A review of literature shows quite a few research studies on application of SMAs for passive structural control [2]. Previously reported applications of SMAs in structural base isolation include implementation of SMA bars for base-isolation of highway bridges [3], and SMA wire re-centering devices for buildings [4]. The SMAs have been implemented as passive energy dissipation devices in braces for framed structures [5, 6, 7], in dampers for cable-stayed bridges [8] and in connection elements for columns [9]. Most of the reported research focuses on application of SMAs for passive vibration control of structures, which takes advantage of only the damping property of super-elastic SMAs. The damping property of SMAs in their martensite phase and their unique shape memory effect [10], that offer considerable promise for SMAs as smart materials for developing supplemental damping devices as well as semi-active actuators for structural control, has received little attention thus far.

2. Background

Shape Memory Alloys (SMAs) are materials that have the unique attribute to recover their shape after undergoing large deformations either through heating i.e. the shape memory effect or by unloading i.e. the super-elastic effect. The unique property that is driven by a phase transformation between martensite and austenite phases constitutes the theoretical basis for classifying SMAs as smart materials. When the Ni-Ti SMA in its parental phase (austenite) undergoes large deformations due to applied stresses produced by external loads, the deformations can be recovered or controlled by heating the material above the austenite finish temperature.

2.1. Hysteretic Model of Nickel-Titanium (Ni-Ti) Shape Memory Alloy

The Graesser-Cozzarelli model [11] was extended by Wilde et al. [3] to include the hardening behaviour of SMA materials after the transition from austenite to martensite phase is completed. The extended hysteretic model of Ni-Ti Shape Memory Alloy [3] as well as the constitutive stress-strain-temperature relationship of the Ni-Ti SMA is shown in Figure 1.

2.2. Scope of Present Research

This paper presents an analytical research study based on simulated semi-active structural control systems using smart cables (tendons) composed of Ni-Ti (Nitinol) shape memory alloy (SMA) wires that are externally installed in building frames and can be electrically actuated to induce variable control forces for the reduction of seismic response of the frame. Upon electrical heating, a martensite to austenite phase transformation takes place and the material undergoes large shrinkage strains. The strain energy thus induced can be used to actuate a substantial control force that can be varied by electrical heating, in principle, for semi-active vibration control of building frames subjected to earthquake induced ground excitation. The results of present study indicate that in theory the shape memory effect in Ni-Ti SMA is a viable and effective mechanism for semi-active control of building frames using smart tendons (cables) constituted with SMA wires.

3. Semi-active Control of Building Frames using Ni-Ti SMA Tendons

The present study proposes the implementation of smart tendons constituted with Ni-Ti SMA wires for semi-active vibration control of building frames subjected to earthquake induced ground excitation. The smart tendons composed of Nitinol SMA wires are appropriately connected to building frame members and can be electrically actuated to induce the desired variable control forces in the building frame. The semi-active control force can be actuated by electrical heating of the Ni-Ti SMA wires comprising the semi-active tendons by a design pulsed current.

3.1. Design Considerations for Semi-active Tendons composed of Ni-Ti SMA

The semi-active control force can be actuated by electrical heating of the Ni-Ti SMA wires comprising the semi-active tendons by a design pulsed current. For purposes of design, the modified version of the analytical model proposed by Wilde [3] for the hysteretic stress-strain relationship of super-elastic Ni-Ti SMA wires illustrated in Figure1 may be employed for predicting the hysteretic force-displacement behavior of SMA wires. Practically, the semi-active tendon would comprise of large number of SMA wires whose numbers are assessed on the basis of maximum control force required during the entire duration of the earthquake ground motion. Theoretically, the control force can be altered based on feedback from sensors for closed loop control by actuating specified number of SMA wires using electrical heating at constant temperature.

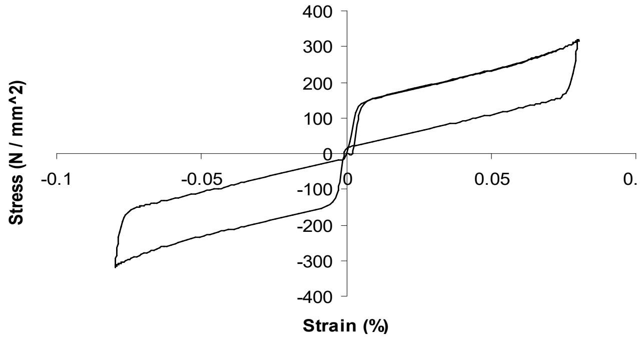
The composition and temperature-dependent properties of nitinol SMA wires that constitute the smart cables are as follows: Percentage of Ni by weight = 55.32, Percentage of Ti by weight = 44.68, Diameter of Nitinol wire = 0.6 mm

Marsenite finish temperature $M_f = 24.6^o$ C, Marsenite start temperature $M_s = 40.2^o$ C

Austenite start temperature $A_s = 53.7^o$ C, Austenite finish temperature $A_f = 74.4^o$ C

3.2. Control Algorithm

Consider a multi degree-of freedom (MDOF) structure with 'n' degrees of freedom, subjected to an earthquake ground acceleration $\ddot{x}_g(t)$. Assuming that the control forces 'f' are adequate to restrict the entire structure within the elastic range, the governing equation of motion is given by Eq. (1) as follows:



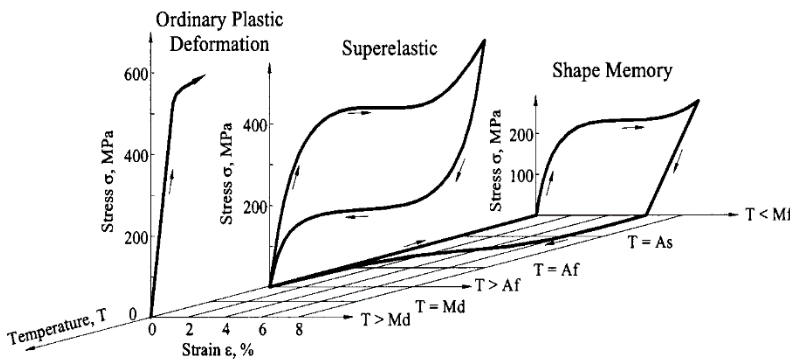


Fig. 1: (a) Super-elastic behavior of Ni-Ti (Nitinol) Shape Memory Alloy (SMA) up to ε_m = 0.08 in Martensite;

(b) Constituive Stress-Strain-Temperature Behavior of Ni-Ti SMA [3]

$$\mathbf{M\ddot{X}} + \mathbf{C\dot{X}} + \mathbf{KX} = d.f - \mathbf{MI}\ddot{x}_g(\mathrm{t}) \tag{1}$$

In Eq. (1), **X** is the vector of relative displacement, '*f*' is a vector of control force corresponding to n_c number of SMA tendons / dampers. **M**, **C**, and **K** are mass, damping and stiffness matrices of appropriate size,' *d*' represents an $n \times n_c$ location matrix that accounts for the control force location on the structure due to the location of SMA tendons / dampers and *I* is the unity vector.

The governing equation of motion Eq. (1) is a second order non-homogenous ordinary differential equation and may be reduced to a corresponding first order ordinary differential using the state-space formulation [12] that can be conveniently integrated numerically using the state-space block and numerical solver in the Simulink toolbox of Matlab [13]. The state-space formulation of Eq. (1) may be expressed in matrix form as:

$$\dot{\boldsymbol{z}} = \mathbf{A}z + \mathbf{B}\boldsymbol{f} + \mathbf{E}\,\ddot{x}_g(\mathrm{t}) \tag{2a}$$

$$\mathbf{y} = \mathbf{C_o}x + \mathbf{D_o} \tag{2b}$$

in which,
$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\boldsymbol{d} \end{bmatrix} \qquad \mathbf{E} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{1} \end{bmatrix} \tag{3}$$

where **A** is a $2n \times 2n$ system matrix, **B** is a $2n \times n_c$ control matrix , **E** is a $2n \times 1$ location matrix of the external excitation, *z* is a $2n \times 1$ state vector, ***f*** = vector of control forces actuated by the the SMA device and tendons, ***y*** is the vector of measured outputs, $\mathbf{C_o}$ and $\mathbf{D_o}$ are output matrices. For proposed SMA device, the control algorithm is defined by the following function:

$$\boldsymbol{f} = \begin{cases} f_a & strain \leq 4.0\% \\ f_{max} & otherwise \end{cases} \tag{4}$$

in which, $\boldsymbol{f_a}$ is the vector of desired control forces computed using the classical optimal control algorithm [14] with the SMA device as the primary controller. Implementing closed loop control illustrated by the flowchart displayed in Figure 2, the desired digital values of control forces and the corresponding analog current magnitudes for electrical heating of SMA wires required for actuation of the semi-active tendons are obtained for the measured state by the control algorithm [15].

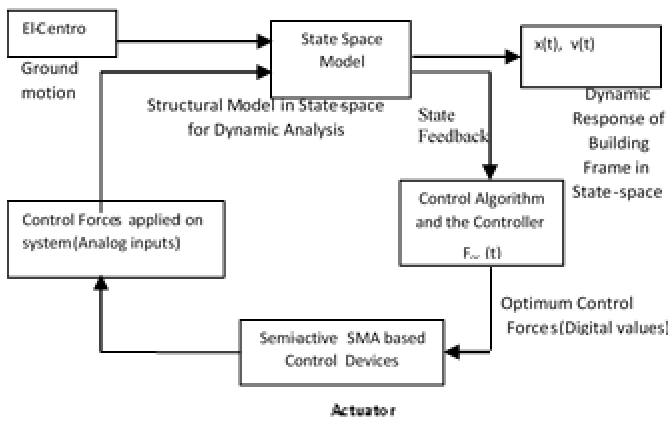


Fig. 2: Flow Chart for Simulation of Structural Control System in Matlab Simulink using Block Diagram Approach

3.3. Case Study for Numerical Simulation of SMA based Semi-active Control

An eight story frame model was considered for numerical simulation of the proposed semi-active control scheme using SMAs in multi-degree-of-freedom structures. The eight story frame model considered in the present study was reported as a benchmark example [14] for comparing the controlled dynamic response with an active mass driver installed at the top (roof) of the frame implementing various control algorithms [14] with reference to the uncontrolled dynamic response.

A schematic of the proposed structural control system implementing the SMA based tendons for semi-active control of the example eight story frame model is illustrated in Figure 3.The proposed semi-active tendons constituted with Ni-Ti SMA wires were assumed to be implemented in alternate floors (story 1, 3, 5 and 7) as well as lower consecutive floors (story 1, 2, 3 and 4) for investigation of the simulated control performance. The dynamic structural parameters specified for the originally reported model [14] were floor mass, m = 245.6 tons; lateral stiffness of each storey k = 3.404× 105 KN/m; and viscous (natural) damping constant of each storey, c = 2937 tons/sec, which corresponds to a 2% damping ratio for the first vibration mode of the entire structure. The angle of inclination of the semi-active tendons with respect to the horizontal is 60 degree. The structural frame model was subjected to the El-Centro (Imperial Valley) earthquake ground motion. The flow chart of the simulation is illustrated using the block diagram approach in Figure 2. The closed-loop control forces in the semi-active tendons were computed using the classical optimal control algorithm [14]. Details of geometric and dynamic properties of the structural frame model as well as the proposed control system, control algorithm and control technology may be found elsewhere [15].

3.4. Results of Simulated Case Study

The comparison of peak values of the dynamic response and control parameters for the eight story frame model with SMA based semi-active tendons installed at alternate floors (story 1, 3, 5, 7) and consecutive floors (story 1,2,3,4) versus the corresponding uncontrolled dynamic response of the structure are summarized in Table 1. For purposes of comparison, the

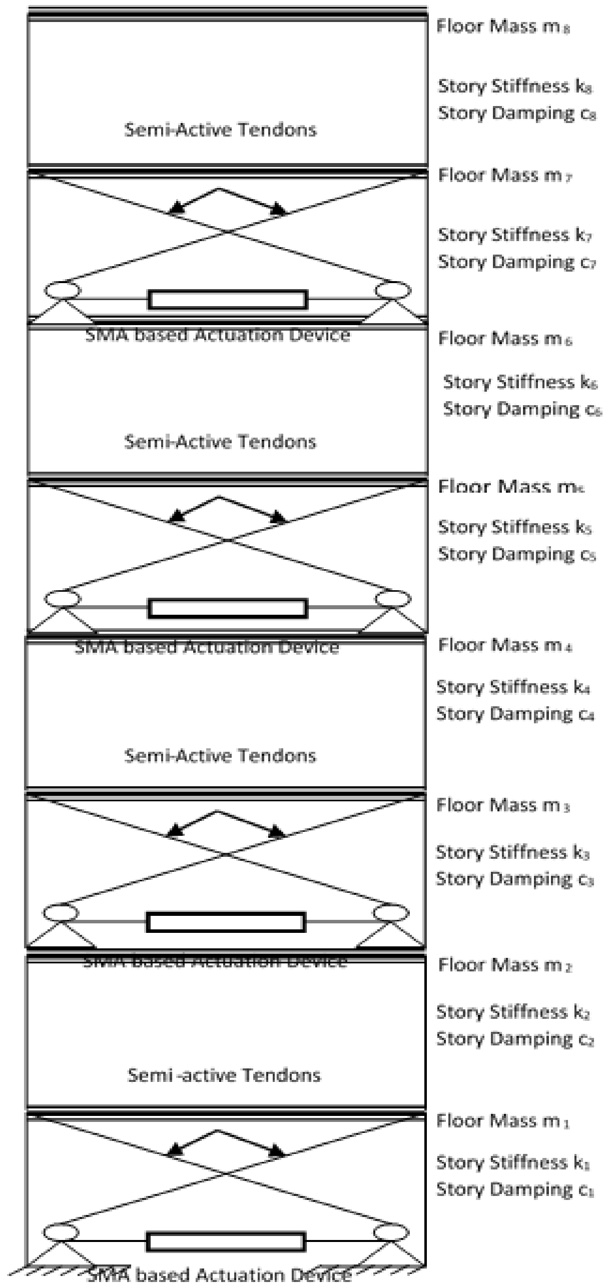


Fig. 3: Structural Control System with SMA based Semi-active tendons and actuation devices installed on alternate floors (story 1, 3, 5,and 7) of the Eight Story Frame Model

Table 1 also includes the peak displacement response and control force for the originally reported multi-story frame model with an active mass driver (AMD) installed at the roof [14]. Figure 4(a) displays the comparison of time-histories of controlled and uncontrolled dynamic displacement response of the eight floor (top floor) of the frame model for various simulated control systems considered in the present study. Figure 4(b) illustrates the dynamic time histories of the simulated control forces actuated by the semi-active tendons installed at alternate floors for the control system with SMA based semi-active control devices installed at stories 1, 3, 5 and 7.

Table 1: Comparison of Dynamic Response and Control Force Parameters for the Eight Story Frame Model [14] with Ni-Ti Shape Memory Alloy based Semi-active Tendons

Control System	Maximum Displacement at top floor (m)	Maximum Velocity at top floor (m/s)	Maximum Control Force (KN)				
			Floor No.				
			1 / 1	3/ 2	5 / 3	7 / 4	Total
Uncontrolled	0.171	1.06	-	-	-	-	-
Frame with SMA based Semi-Active Tendons at Floors 1,3,5,7	0.0627	0.57	74	214	327	398	1013
Frame with SMA based Semi-Active Tendons at Floors 1,2,3,4	0.0819	0.68	121	239	350	450	1161
Frame with AMD at roof	0.0431	0.3912	-	-	-	-	1774

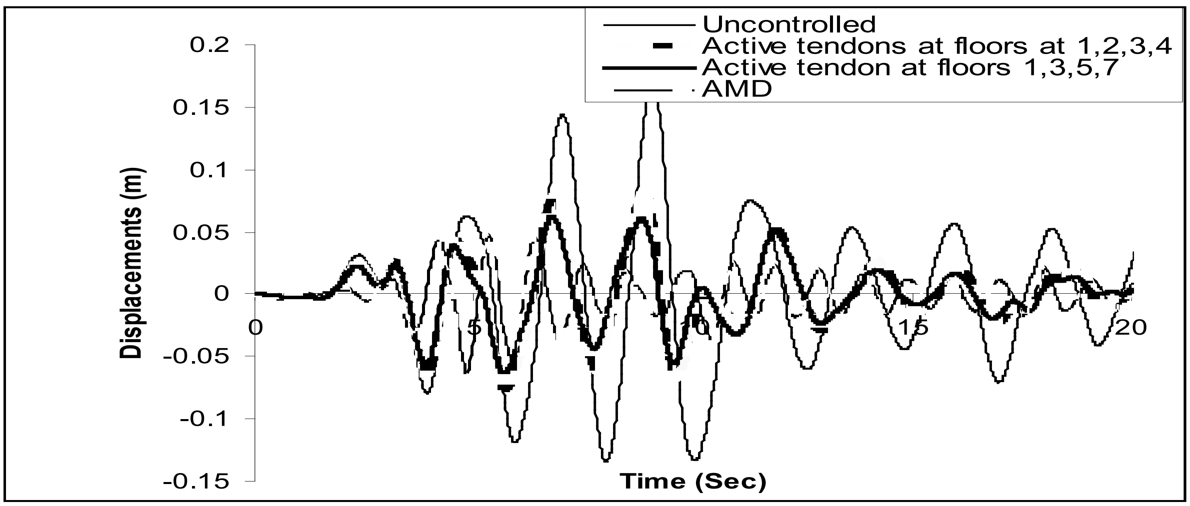


Fig. 4(a): Time-histories of Displacements (in metres) at Eighth floor of the Eight Story Frame Model [14] subjected to El-Centro earthquake ground motion with various simulated Control Systems considered

4. Practical Implementation Issues

The practical implementation issues involved in bundling of wires, electrical heating of wires and thermal insulation of the bundles for application of the proposed semi-active structural control technology using Ni-Ti shape memory alloys will need to be resolved in the design stage. The present section of the paper addresses the practical design and implementation [16] of the proposed conceptual scheme for semi-active structural control of building frames using Ni-Ti SMA based tendons.

Based on the results of the numerical simulation of the structural control system with SMA based semi-active tendons installed on alternate floors of the eight story frame model subjected to EL-Centro earthquake ground motion, the number of SMA wires n(t) required to actuate the desired peak values of control forces computed for the semi-active tendons at levels 1, 3, 5 and 7 of the structural model considered in the simulated case study are 2000, 4200, 6500 and 8000 respectively. Figure 4(c) shows the temporal variation in the number of SMA wires n(t) that need to induce actuation in order to generate the desired or computed control forces in the SMA based semi-active tendons installed at alternate floors 1, 3, 5 and 7 of the eight story frame model subjected to El-Centro earthquake ground motion. The (-) sign that prefixes n(t) on negative y axis of the graph physically signifies that the wires are bundled in the counteracting tendons that actuate control forces in the negative transverse horizontal direction of the frame model. Since the diameter of an individual wire is 0.6 mm and each wire can actuate a maximum force W_o = 50 N approximately and assuming that a maximum of 500 wires can be bundled in a single SMA tendon and the tendons are thermally independent of each other, in principle, each tendon comprising a group of 500 wires can actuate a maximum semi-active control force of 25 kN approximately.

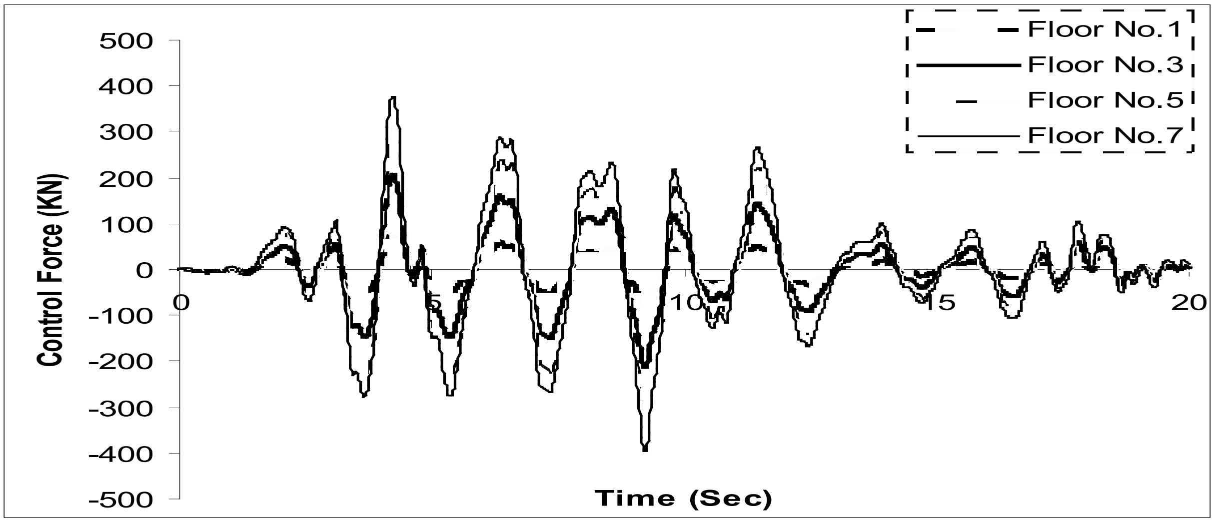


Fig. 4(b): Time-histories of Simulated Control Forces (in kN) computed for actuation in the Semi-active Tendons at Alternate Floors 1, 3, 5 and 7 of the eight story frame model subjected to El-Centro earthquake ground motion

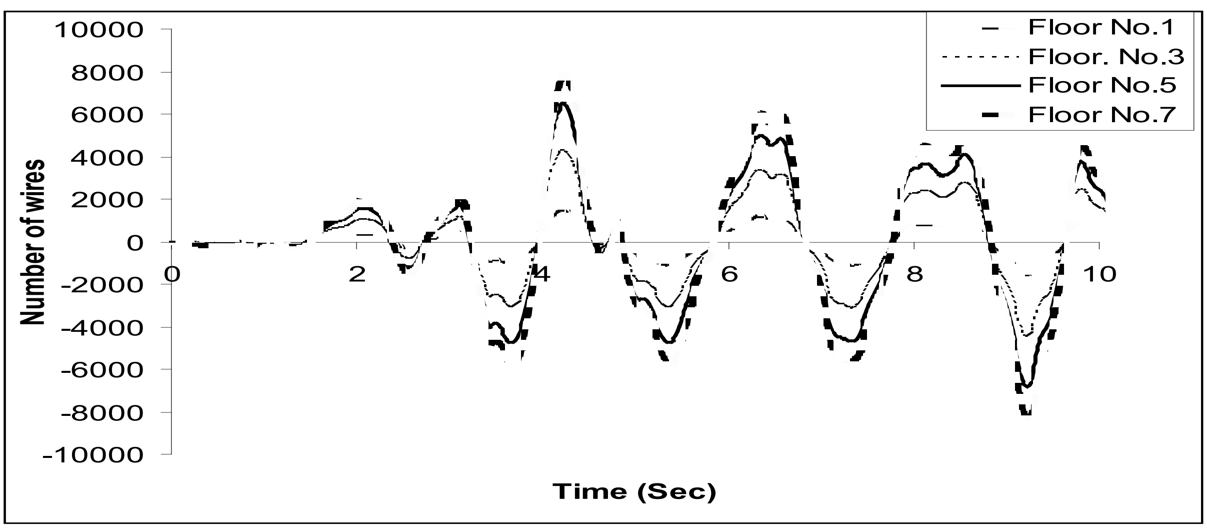


Fig. 4 (c): Temporal variation of the number of SMA wires to be actuated to induce the computed control forces in the semi-active tendons installed at alternate floors 1, 3, 5 and 7 of eight story frame model under El-Centro earthquake

Theoretically, therefore, as an example, the maximum tendon force of 25 kN may be considered as the incremental control force in the control algorithm for conceptual design of the proposed control technique. In order to refine the continuity of the semi-active control force, the SMA device may be supplemented with tendons constituted of smaller groups of 100 wires bundled in a single tendon, as an example, wherein each such tendon is capable of actuating 5 KN force. Thus, in principle, a sufficiently refined piece-wise continuous incremental control force may be achieved by providing and selectively actuating a combination of SMA tendons with different force capacity ratings. Therefore, for the above-mentioned case study, fifteen tendons constituted of 500 SMA wires each and five tendons comprising of 100 SMA wires each may be implemented in the SMA device to achieve a reasonably acceptable incremental control force of 5 kN (least count for actuation of analog force) and a peak control force of 400 kN by electrically heating appropriate and optimal combination the SMA tendons.

5. Conclusions

The results of the present study indicate that the shape memory effect and super-elasticity in Ni-Ti shape memory alloys (SMAs) is conceptually an effective mechanism for semi-active control of building frames using smart cables constituted with SMA wires The results of numerical modeling and simulation of the building frame with the smart cables or semi-active tendons composed of Nitinol (Ni-Ti) SMA wires lead to the following specific interpretations:

1. The proposed semi-active control technique implementing the SMA based tendons is, in theory, distinctly effective in the response reduction of building frame. Results of the simulated case studies presented in the paper demonstrate that the peaks displacement is reduced by 63.3% and 52.1% for the tendons are placed at odd floors 1,3,5,7 and at consecutive floors 1,2,3,4 respectively in comparison to the reduction of 74.7% in the case of AMD at top floor. In comparison, the peak velocity is reduced by 46.2% and 35.9% with the SMA based semi-active tendons placed at odd floors (stories 1,3,5,7) and at consecutive floors (stories 1,2,3,4), respectively as compared to 63.1% in the case of AMD at top floor.
2. The arrangement of Ni-Ti SMA based semi-active tendon at the alternate floors results in superior control effectiveness in comparison to the arrangement of the semi-active tendons at lower consecutive floors as the former arrangement reduces the maximum displacement of the top floor of the eight story frame model considered in the simulated case studies to 0.0627 m as compared to 0.0819 m in case of the latter arrangement.

The response reduction resulting from the proposed SMA based semi-active control scheme with classical optimal control algorithm (LQR control) is proportionate to applied control forces as well as comparable to the response reduction achieved by the active mass driver (AMD) in the benchmark example [14] implementing optimal closed loop control.

References

[1] Yunfeng, Z, and Songye Z. (2008). "Seismic Response Control of Structures with Superelastic Shape Memory Alloy Wire Dampers". *Journal of Engineering Mechanics, ASCE*. 134(3). 240-251.

[2] Song G., Ma N. and Li H.N. (2006). "Applications of shape memory alloys in civil structures". *Journal of Engineering Structures, Elsevier*. 28. 1266-1274.

[3] Wilde K, Gardoni P. and Fujino Y. (2000). "Base isolation system with shape memory alloy device for elevated highway bridges". *Journal of Engineering Structures, Elsevier*. 22(3). 222-229.

[4] Dolce M., Cardone D. and Marnetto R. (2001). "SMA re-centering devices for seismic isolation of civil structures". *Proceedings of SPIE*. 238(49). 4330.

[5] Dolce M., Cardone D. and Marnetto R. (2000). "Implementation and testing of passive control devices based on shape memory alloys". *Earthquake Engineering and Structural Dynamics, Elsevier*. 29 (7), 945-968.

[6] Han Y.L., Li Q.S., Li A.Q., Leung A.Y.T. and Lin P.H. (2003). "Structural vibration control by shape memory alloy damper". *Earthquake Engineering and Structural Dynamics, Elsevier*. 32. 483-494.

[7] Saadat S., Noori M., Davoodi H., Zhou Z., Suzuki Y. and Masuda A. (2001). "Using NiTi SMA tendons for vibration control of coastal structures". *Journal of Smart material and structures*.10. 695-704.

[8] Li H., Liu M. and Ou J.P. (2004). "Vibration mitigation of a stay cable with one shape memory alloy damper". *Journal of Structural Control and Health Monitoring*. 11. 1-34.

[9] Tamai H. and Kitagawa Y. (2002). "Pseudoelastic behavior of shape memory alloy wires and its application to seismic resistance member for building". *Journal of Computational Material Science*. 25. 218-27.

[10] DesRoches R., McCormick J. and Delemont M. (2004). "Cyclic properties of superelastic shape memory alloy wires and bars". *Journal of Structural Engineering, ASCE*. 130(1). 38-46.

[11] Graesser E. J. and Cozzarelli F. A. (1991). "Shape memory alloys as new materials for aseismic isolation". *Journal of Engineering Mechanics, ASCE*.117(11). 2590-2608.

[12] Madan, A. (2006). "General Approach for Training Back-propagation Neural Networks in Vibration Control of Multi degree-of-freedom Structures". *Journal of Computing in Civil Engineering*, *ASCE*, 20(4). 247 - 260.

[13] The MathWorks, Inc. (2011). MATLAB software and Simulink Toolbox, Natick, Massachusetts, USA.

[14] Soong T.T. (1990). "*Active Control of Structures – Theory and Practice*". Longman Scientific and Technical.

[15] Gupta, V. K. (2016). "Structural control of building frames subjected to earthquake ground excitation using semi-active tendons of shape memory alloys". Ph.D Thesis, Department of Civil Engineering, IIT Delhi.
[16] Soong, T.T., Reinhorn A. M. and Chu, S.Y. (2005). "*Active, Hybrid and Semi-active Structural Control – a Designand Implementation Handbook*". John Wiley & Sons.