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Investigating the Behavior of Reinforced Concrete Frames Using Superelastic Nitinol

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ABSTRACT: Buildings in regions of high seismicity are susceptible to severe damage and potential collapse due to large lateral displacements. The basic philosophy in seismic design of noncritical conventional reinforced concrete structures is to allow for yielding of steel to dissipate energy while encountering damage to unconfined concrete and permanent deformation due to plastic hinging.The target performance is to maintain structural integrity and avoid collapse. In accomplishing the performance objective, severe damage to structural components may occur, and the structure might not be serviceable after the earthquake. In this paper the response of RC frames using smart bars under static lateral loading has been numerically studied, using Finite Element Method. The material used in this study is Superelastic Shape Memory Alloys (SMAs) which are unique materials that have the ability to undergo large deformations, but can return to their undeformed shape by the removal of the stress. If such materials can be used as reinforcement in plastic hinge regions of frame elements, they will not only experience large inelastic deformations during strong earthquakes, but can also potentially recover their original shape. This behaviour will allow mitigating the problem of permanent deformation. Since Young's Modulus of this material is much lower than that of conventional steel reinforcement, it is not feasible and economical (due to relatively high price of Shape Memory Alloys) to replace the total steel with SMA bars. Therefore, different quantities of steel and smart rebars have been used for reinforcement. The behaviour of these frames has been compared with that of ordinary RC frames designed according to ACI code.
Key words: Shape Memory Alloys, Reinforced Concrete Frame, Residual Displacement, Lateral Stiffness

1 INTRODUCTION

Buildings and bridges in high seismic regions are prone to severe damage and collapse during earthquakes due to large lateral deformations. In particular, beam-column elements in reinforced concrete (RC) frames are extremely vulnerable and are considered the weakest link in such a structural system. Current seismic deign practice for reinforced concrete frames generally relies on yielding of steel to dissipate energy under strong earthquakes. This leads to large permanent displacements and makes the structure susceptible to severe damage. In standard structures, damage to plastic hinges is accepted to allow for energy dissipation. Consequently, during large-scale earthquake events, severe damage of infrastructure occurs resulting in the collapse of buildings, closing of bridges, unattainable post-disaster rescue operations, and overall substantial economic losses. Frame plastic hinges that can dissipate energy without experiencing severe damage and permanent deformation would alleviate these problems. Shape Memory

Alloys (SMAs) are a novel functional material which can exhibit little residual strains under cycles of loading and unloading even after passing the yielding zone. They have the ability to remember a predetermined shape even after severe deformations which enable them to be widely used in numerous applications in the area of "smart materials" or "intelligent materials"[1-3].

In 1965, shape memory alloys (Nitinol) which derived from Nickel and Titanium were first patented by Buehler and Wiley [4] in Naval Ordnance Laboratory. Depending on the temperature or stress, SMA can be austenite, martensite or the mixture of them. Indeed, these alloys are particularly useful when large deformation and recovery of the shape is observed under a small rate of stress or temperature. Shape memory alloys may have different kinds of shape memory effect. The two most common memory effects are the one-way and two-way shape memory. One of the commercial uses of shape memory alloy involves using the pseudo-elastic properties of the metal during the high temperature (austenitic) phase. This is the result of pseudoelasticity that the martensitic phase is generated by stressing the metal in the austenitic state and this martensite phase is capable of large strains. With the removal of the load, the martensite transforms back into the austenite phase and resumes its original shape. In this study this property is used.

SMA's high strength, large energy hysteretic behaviour, full recovery of strains up to 8%, high resistance to corrosion and fatigue make them strong contenders for use in earthquake resistant structures. In particular, Ni-Ti alloy has been found to be the most promising SMA for seismic applications. Then, results of analysis using ANSYS software are presented and discussed.

2 RESEARCH SIGNIFICANCE

The seismic design of structures has evolved towards a performance-based approach in which there is need for new structural members and systems that posses enhanced deformation capacity and ductility, higher damage tolerance, decreased residual crack size, and recovered or reduced permanent deformations. The use of superelastic SMA as reinforcement instead of steel in the hinge to dissipate adequate seismic energy, but could also restore the original shape of such structures after seismic actions. The objective of this study was to investigate the effectiveness of reinforced concrete frames with SMA reinforcement in plastic hinges in reducing permanent residual displacements and damage due to earthquakes. The reduction in damage and residual displacement would substantially improve serviceability of concrete buildings after strong earthquakes, which would lead to improved emergency response and economic recovery.

3 CHARACTERISTICS OF MATERIALS

3.1 Concrete

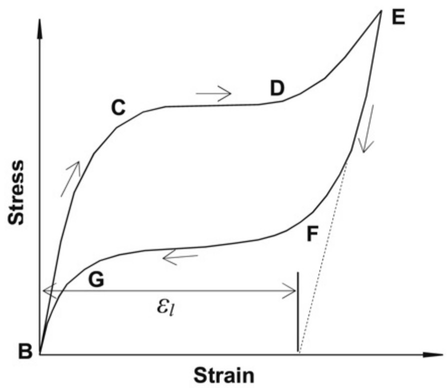
The modeling of concrete considers cracking, crushing failure modes and nonlinear behavior. The compressive strength of concrete is 27.5 MPa and its tensile strength is 3.5 MPa. The elastic modulus and Poisson's ratio are 21 GPa and 0.2, respectively as shown in Table 1. The concrete material model in the ANSYS software predicts the failure of brittle materials by using the model of Willam and Warnke [5].

3.2 Reinforcement

Bilinear stress-strain curve has been used for modelling of steel behaviour. The values of elastic modulus and Poisson's ratio of steel are 200 GPa and 0.3, respectively. Additionally, the steel is assumed to have yield strength of 450 MPa as shown in Table 1.

3.3 Shape Memory Alloy

Since most civil engineering application of SMA are related to the use of bars and wires, one-dimensional phenomenological models are often considered suitable. Several researchers have proposed uniaxial phenomenological models for SMA. The superelastic behaviour of SMA has been incorporated in a number of finite element packages, e.g. ANSYS 10.0, ABAQUS 6.4 and SEISMOSTRUCT 4.0.2 where the material models have been defined using the model of Auricchio et al., Auricchio and Taylor, and Auricchio and Sacco, respectively. In order to model SMA in ANSYS software [6, 7], the predetermined nonlinear model, which is provided in material library, has been used here. Fig. 1(b) shows the 1D-superelastic model used in ANSYS 10.0 where SMA has been subjected to multiple stress cycles at a constant temperature and undergoes stress induced austenite-martensite transformation. The parameters used to define the material model (Fig. 1) are yield stress, f_y (point C); maximum stress up to the superelastic strain range, f_{P1} (point E); first stage of unloading stress, f_{T1} (point F); second stage of unloading stress, f_{T2} (point G); superelastic plateau strain length, ε_l; moduli of elasticity, E_s and E_a; and the ratio of f_y under tension and compression, α. Considered values of above parameters are shown in Table 1.



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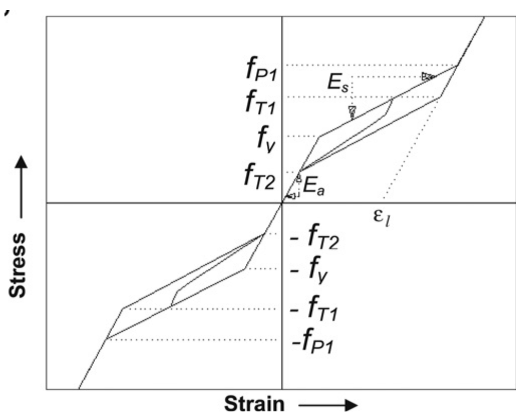


(b)

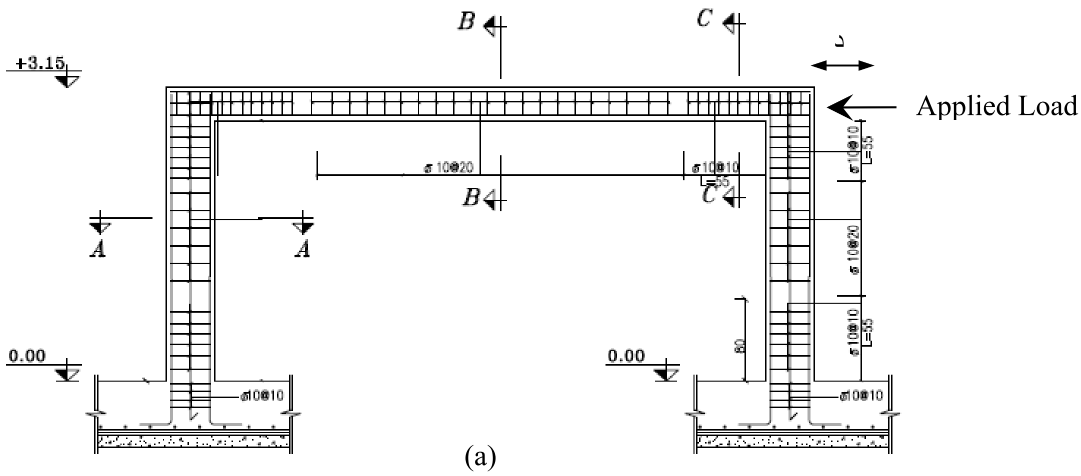
Fig. 1. (a) Typical axial stress-strain diagram of SMA, (b) 1D model of SMA incorporated in FE packages

Table 1. Material Properties

Material	Property	Value
Concrete	Compressive strength (MPa)	27.5
	Strain at peak stress (%)	0.2
	Tensile strength (MPa)	3.5
Longitudinal steel	Yield strength (MPa)	450
	Ultimate strength (MPa)	650
	Young's modulus (GPa)	200
Transverse steel	Yield strength (MPa)	450
	Ultimate strength (MPa)	650
SE SMA	Modulus of elasticity, ESMA (GPa)	60
	fy as in Fig. 1(b) (MPa)	520
	fP1 as in Fig. 1(b) (MPa)	600
	fT1 as in Fig. 1(b) (MPa)	300
	fT2 as in Fig. 1(b) (MPa)	200
	ε1 as in Fig. 1(b) (%)	7.00

4 CHARACTERISTICS OF FINITE ELEMENT MODEL

A one-story one-span frame as shown in Fig.2 (a) is designed under ACI 318-05 considerations for a seismic design category of "D". The columns have a length of 3.0 m and are rectangular in cross section with dimensions of 40 cm by 40 cm. The beam has a length of 5.0 m and is rectangular in cross section with dimensions of 30 cm by 40 cm. A gravity load of 46 kg/cm (1.2D+1.6L) is applied on the beam. SMAs can be specified for SOLID185 element [8]. LINK8 element has been used here for longitudinal and shear reinforcements in the frame. Furthermore, hexahedral-shaped elements have been used to mesh the model. The amounts of reinforcements are shown in Fig.2. The arrangement and replacement of smart rebar are shown in Fig. 2 (e). In order to confine the concrete, maximum amount of shear reinforcement has been used for stirrup modelling which corresponds to ACI code and prevents brittle shear failure [9]. In this paper, response of a frame under cyclic lateral load is studied. The lateral load was applied to the frame in X-direction, as shown in Fig.3. Loading process was carried out based on displacement control with the maximum displacement of 0.2 m.



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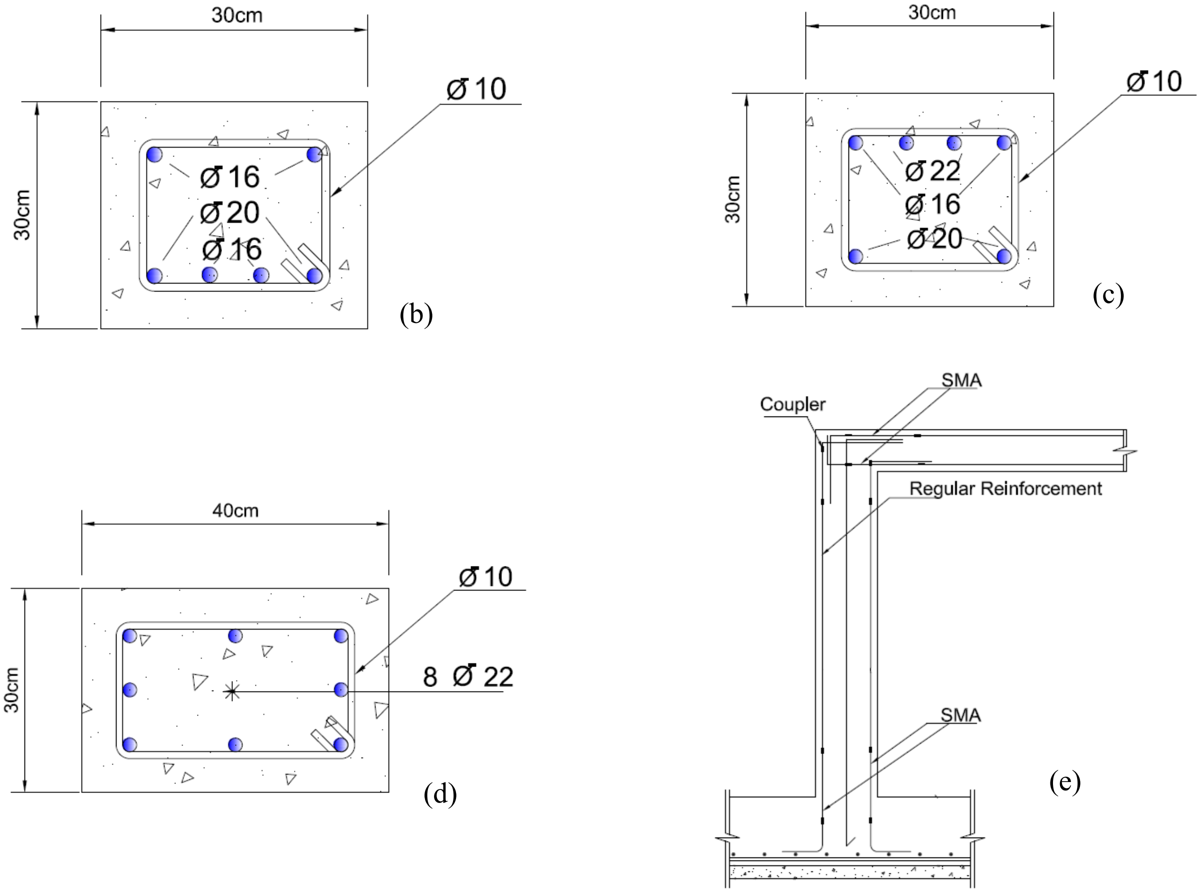

Fig. 2 (a) designed frame under ACI considerations (b) middle section of beam (c) section of beam near connection (d) column section (e) arrangement of SMA in the frame

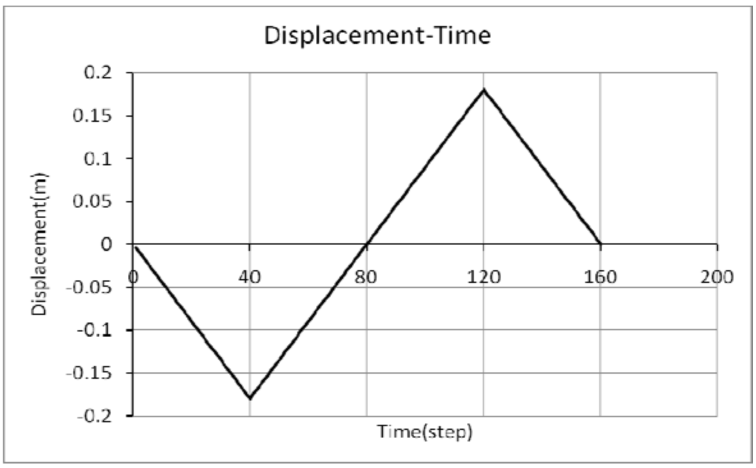

Fig. 3 Loading process

5 RESULTS OF ANALYSIS

Fig.4 shows hysteresis curve of shear force versus displacement for concrete frame. The displacement of the models is measured at the top corner of the frame. This figure indicates that increase in the ratio of smart rebar, reduces the area of the hysteresis P-Δ curves. This is due to smaller area under stress-strain curve of smart rebar compared with that of ordinary reinforcement. As indicated in Fig.4 with stars, Residual Drift is the permanent lateral drift when the lateral load is zero. The values of residual drifts are available in table 2.

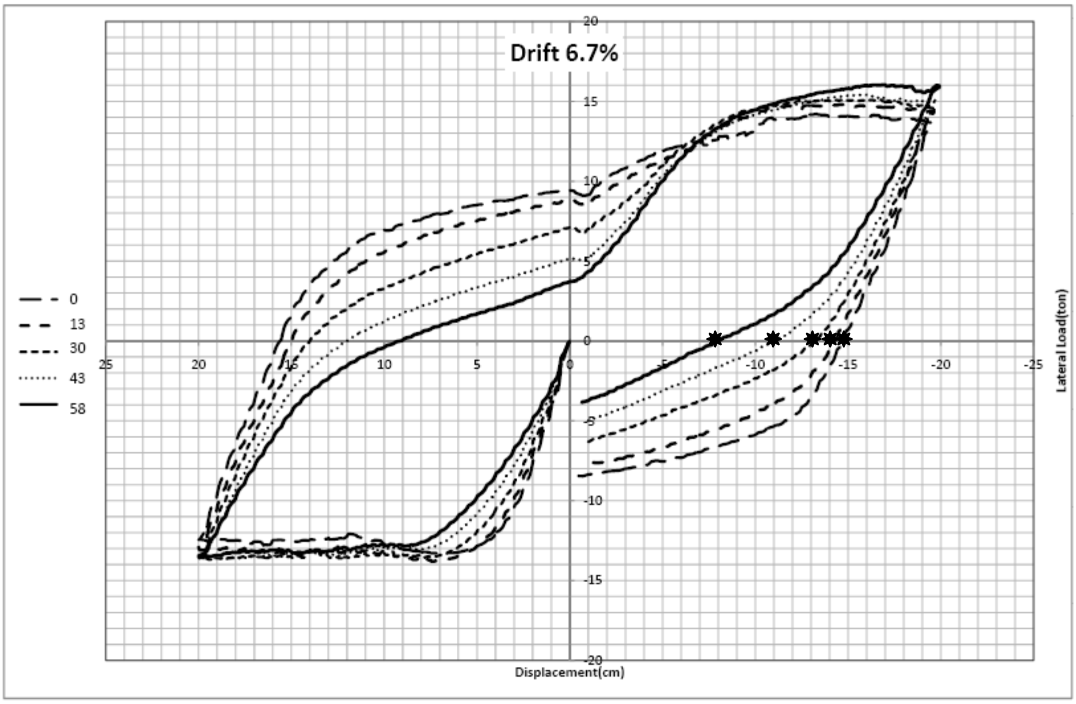

Fig. 4 . Hysteresis curve of shear force versus displacement for models

Residual displacements of the models are given in Table 2. Smart rebars reduces residual displacement. In the third column of this table, reduction of residual displacement due to SMA to that of without SMA is expressed as a percentage. For higher ratio of smart rebars, higher residual displacement is reduced. At the end of the loading, SMA rebars tend to return to the zero strain. Therefore, they create recovery forces which lead into both closing of concrete cracks and reduction of residual displacement.

Table 2. Results due to the various details of smart rebars

Specimen Lable	Ratio of smart bar (R)	Residual displacement (cm)	Reduction of residual displacement (%)	K (ton/cm)	Percentage of stiffness reduction (%)	Percentage of the reduction of area of P-د curves(%)
RC1	0.00	14.87	0.00	5.15	0.0	0.0
SMAC1	0.13	14.49	2.6	4.85	5.7	12.1
SMAC2	0.30	13.49	9.3	4.47	13.2	23.6
SMAC3	0.43	11.18	24.8	4.01	22.0	35.2
SMAC4	0.58	8.21	44.8	3.51	31.9	45.7

Table 2 contains the stiffness of the models for each ratio of smart rebar. According to this table, smart rebar causes reduction of stiffness in frame before cracking and higher ratio of smart rebar provides higher percentage in stiffness reduction. Since the elastic modulus of SMA is much less than that of steel, both modulus of equivalent section and stiffness decreased by replacing steel with smart rebars. In fact, smaller amount of elastic modulus of SMA than steel (60 GPa vs. 200 GPa) is a disadvantage of these materials in addition to its relatively high price.The moment of inertia of the section is computed by Mechanics of Material's formulas, the reinforcement is transmitted to concrete ($n=\frac{E_c}{E_s}\approx 8$) and then the lateral stiffness is computed.

The slope of load-displacement curve has been used as the lateral stiffness of the models after cracking.

The hysteretic load-displacement curves of SMAC3 and SMAC4 exhibited better performance compared with that of RC1 and SMAC1 in terms of residual displacements remaining in the joint after unloading. The flag-shaped stress-strain hysteresis of superelastic SMA bars produced flag-shaped hysteretic load-displacement curves in the SMAC frame elements. Although the steel –RC frame dissipated a relatively higher amount of energy compared to that of SMACs because of its large hysteretic loops, SMAC1 and SMAC2 performed better because of their capability in recovering post-elastic strain, which makes them very attractive in highly seismic regions where the frame can dissipate significant amounts of energy and remain functional even after a strong earthquake.

Excessive lateral displacement and residual displacement have been identified as the major causes of failure of buildings and bridges during earthquakes. SMAs are unique materials that can recover strains almost fully even after large inelastic deformations. If SMA can be used as reinforcement in frame elements, it can initiate major progress in seismic design whereby the repair cost can be substantially reduced and the structure may remain serviceable even after a severe earthquake. The developed numerical model can be used to simulate the behaviour of superelastic SMA-RC multi-story concrete frames with high degrees of redundancy.

6 CONCLUSIONS

1. Replacing steel bars with SMA bars reduces the area of the hysteresis P-Δ curves.
2. Using smart rebar reduces the residual displacement of the frames after lateral cyclic loading.

3. Increase in the ratio of smart rebar reduces lateral stiffness of the frame in first steps.
4. Increase in the ratio of smart rebar slightly increases lateral stiffness of the frame in last steps.
5. Even though SMA reduces residual displacements in RC frames due to its recoverability, it reduces energy absorption capacity of the structure.

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