Seismic investigation of longitudinally aligned shape memory alloy-stainless steel reinforced concrete column

Rahul Pardeshi¹, Bhairav Thakur², and Anant Parghi³

¹, ² Research Scholar, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India.
³ Assistant Professor, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India.

E-mail: rahultpardeshi@gmail.com

Abstract: Shape memory alloy (SMA) is a smart material sustain (8~13%) an enormous amount of strain and having an ability to regain parental shape after the removal of an external load and temperature due to its pseudo-elastic (SE) and shape memory effect (SME) properties. The SE and SME properties, lower modulus of elasticity, and higher elastic straining of SMA compared to conventional steel reinforcement makes it predictable for the design of the reinforced concrete (RC) structure. The present research is focused on the seismic investigation of RC columns reinforced with SMA rebar in the plastic hinge region along with stainless steel (SS) in the remaining portion of the column. A nonlinear static pushover seismic analysis is used for the numerical investigation of SMA-SS RC column. The numerical model is validated having 98% accuracy with existing literature results. The impact of various parameters on SMA-SS RC column is evaluated for SMA in the plastic hinge region. The results reveal that an aspect ratio, the yield strength of reinforcement, the compressive strength of concrete and axial load are significantly affecting the lateral strength and the ductility of the column under seismic loading.

1. Introduction

The national development generally depends on infrastructure facilities and the capacity to bear population load. But in the time of natural disasters like earthquakes or storms, this system may get disturb and its speedy repair necessary to make it original to get it into the flow. Generally, the structures have been cracked, buckled, or eventually collapse due to unforeseen huge energy accumulation subjected to earthquake or storm. The researchers are always trying to minimize this energy accumulation by introducing new innovations. The smart structural system through the utilization of smart materials like shape memory alloy (SMA) helps in controlling the structural response via, energy dissipation and optimization of systems. The response and characteristics of structures can be adjusted using a smart structural system through fortifying qualities like external pressure, moisture, magnetic field, and temperature, etc. In finding solutions to global challenges of sustainability of civil structures, the progress of responsive materials plays a vital role in system performance evaluation, restraining damage propagation, damage detection, and repair, etc. [1].

Shape memory alloy is a smart material sustains (8~13%) [2–5] enormous amount of strain and having an ability to regain parental shape after the removal of an external load due to its pseudo-elastic (SE) property [6]. Also, another distinct shape memory effect (SME) property provides a tendency to
reappear an original shape while applying or removing heat. The SE and SME properties in SMA could be utilized to minimize the residual displacement of reinforced concrete (RC) structures subjected to seismic deformation. The behavioral change in the RC structure could be noticeable if the SMA is used as a reinforcement in structure. Lower modulus of elasticity and higher elastic straining with a distinctive yield point of the SMA compared to conventional steel reinforcement makes it predictable for the design of the RC structure.

Crystalline structures or phases of SMA like magneto-strictive or piezoelectric smart materials, changing its states by both external loading and thermal actuation [7]. Two phases of SMA, austenite phases (high temperature and solid material state), and martensite state (cooler and softer material state) are known by high and low temperatures, respectively [6]. The reversible switching of phases of SMA and the related alterations (in thermal, mechanical and electric properties of the material) have been used for inventive applications and improvement in civil engineering structures for making them adaptive or smart structures [6]. Irrespective of unique properties, SMA has an initial high cost (US$20–30/kg [8], US $1250/m length of the bar [9]) restricted its utilization. In India, 20 mm, 1-meter length NiTi rod is net costing to Rs. 20,000/-. Generally, some researchers utilized the SMA in high moment concentrated area like plastic hinge region [10–12].

The RC columns are the most susceptible member of a structural system and agonize substantial deformation during an earthquake. The severe damage generally noticed in the plastic hinge region of the column since it experiences huge lateral deformation [13]. So, this area of the plastic hinge is important from the point of view of seismic performance assessment. The present research is focused on the seismic investigation of RC columns reinforced with SMA rebar in the plastic hinge region along with stainless steel (SS) in the remaining region of the column. The nonlinear seismic analysis was used for the numerical investigation of SMA-SS RC column. The numerical model was validated with existing literature results. The impact of various parameters on SMA-SS RC column in the plastic hinge region was evaluated. The parameters like an aspect ratio, the yield strength of reinforcement, the compressive strength of concrete and axial load affecting the lateral strength, failure mode, and the ductility of SMA-SS RC column under the seismic loading were evaluated.

2. The Geometry of Longitudinally Aligned SMA-SS RC Column
In this study, the longitudinal aligned SMA-SS rebar RC column was configured such as the SMA employed in the plastic hinge region and SS bar longitudinally aligned in remaining portion using a mechanical coupler. The geometry, reinforcement details, and material properties of SMA-SS rebar RC column were particular from Billah and Alam (2012) [14]. Figure 1 described the detailed geometry and rebar details having 450 mm × 450 mm cross-section with 8 numbers of 20.6 mm diameter SMA rebar and 8 numbers of 19.5 mm diameter SS rebar. Paulay and Priestley (1992) equation (Eq. 1) was used to calculate the length of the plastic hinge ($L_P$) region.

$$L_P = 0.08\, L + 0.022\, f_y\, d_o$$

(1)

Here, $L$ is the column height (mm), $f_y$ is the yield strength of the rebar (MPa), and $d_o$ is the rebar diameter (mm). For the total height of the column (3200 mm), the $L_P$ was calculated as 468 mm using the above equation. For this research study, particularly the NiTi SMA rebar was used. The SMA and SS were longitudinally aligned using a mechanical coupler.

3. Constitutive modelling of different materials
The constitutive modeling approach was adopted to describe the material properties and their unique nature in finite element analysis software [16]. Mander et al (1988) [17] nonlinear concrete model was adopted for the numerical modeling of concrete. The uniaxial bilinear stress-strain model was adopted for modeling of SS reinforcement. Whereas, Auricchio and Sacco’s (1997) [18] super-elastic shape-memory alloys model [16] has been adopted for the numerical modeling of SMA rebar.
4. Finite element analysis
The aim of research was to develop a fiber-based numerical model that should be proficient to predict the non-linear seismic behavior of SMA-SS RC column in terms of base shear force and displacement distribution. The Seismo struct fiber element-based software [16] was employed for modeling and non-linear static pushover seismic analysis. The rectangular columns were model as an inelastic beam-column element using a force-based modeling approach. The single barrel screw lock mechanical coupler developed by Alam et al. (2010) modified by Billah and Alam (2012) have been employed here to joint longitudinally aligned SMA and SS rebar. In modeling, it has been implemented at the base of the column by using a rotational spring zero length element as shown in Figure 2(c). The stress-slip behavior of the SMA bar inside the mechanical coupler has been used to model the bond-slip behaviour of rebar within the coupler. This bond-slip behaviour was used to define the joint element for modeling of rotational spring. The definition of joint element through moment rotation relationship has been incorporated in software through a modified Takeda hysteresis curve. The behaviour of curve has been characterized through five different parameters and their respective values have been defended through moment rotation relationship of a hybrid combination of SMA-SS rebar. The adapted FE model of the column is presented in Figure 2(a). A constant axial load of 400 kN was applied at top of the column to simulate the gravity load.

5. Validation of Numerical Results
Billah and Alam (2012) carried experimental investigations through a pull-out test to ascertain the slippage of SS rebar and SMA rebar inside the mechanical coupler in the form of a stress-slip behavioural graph [14]. Where they used five sharp ended screws and mechanical coupler for connecting longitudinally aligned SMA and SS rebars. The stress-slip behavioural graph of the SMA
bar inside the mechanical coupler has been used to model the bond-slip behaviour (rotational spring) of rebar within the coupler. The same modeling approach has been validated here with the analytical investigation of pushover analysis carried by Billah and Alam in 2012 with present research works result. Figure 3 and Table 1 show the performance results of nonlinear static pushover numerical investigation of the column and results of experimental-analytical investigation of Billah and Alam in 2012 [14]. The respective values of maximum base shear and its conforming displacement were calculated as 80.28 kN and 96 mm for SMA-SS RC column whereas, experimental-analytical result was 82 kN and 84 mm. The numerical results agree with the existing literature with an accuracy of about 98%.

### Table 1. The Comparative Performance of SMA-SS RC Columns

| Column type                          | Concrete cracking | Steel yielding | Concrete crushing |
|--------------------------------------|------------------|----------------|-----------------|
|                                       | Base shear (kN) | Δ (mm)         | Base shear (kN) | Δ (mm)         | Base shear (kN) | Δ (mm)         |
| Numerical Investigation              | 23.32            | 3              | 76.34           | 57             | 77.46           | 168             |
| Experimental-Analytical Investigation | 30.17            | 3              | 63.68           | 60             | 75.14           | 171             |

Note: Δ - Corresponding displacement in mm

**Figure 3.** Base shear Vs. displacement - validation of numerical results

6. Parametric investigation of longitudinally aligned SMA-SS RC Column

In previous sections, numerical FE models have validated for SMA-SS reinforced concrete rectangular column using a fiber modelling approach with literature [14]. In this section, for parametric investigational study, total twelve different column models with four variable parameters have been used. The variable parameters are an aspect ratio (l/d), the compressive strength of concrete (f<sub>c</sub>), the yield strength of (f<sub>y</sub>) and axial load P (%) as shown in Table 2. The numerical models are named as P-1-5.5, P-2-7.5, P-3-9.5, P-1-35, P-2-45, P-3-55, P-1-250, P-2-450, P-3-650, P-1-5, P-2-7.5, P-3-12.5. For example, column P-1-5.5, P-2-7.5 & P-3-9.5 are defined as column models with aspect ratio 5.5, 7.5 and 9.5 respectively. Whereas column P-1-35, P-2-45, P-3-55 are defined as column models with the compressive strength of concrete (f<sub>c</sub>) 35 MPa, 45 MPa and 55 MPa respectively. Yield strength of (f<sub>y</sub>) of 250 MPa, 450 MPa and 650 MPa are considered for defining column P-1-250, P-2-450, P-3-650. Axial load P (%) with 5, 7.5 and 9.5 are selected in column P-1-5, P-2-7.5, and P-3-12.5 respectively.
Table 2. Parametric details of longitudinally aligned SMA-SS RC columns

| Parameters                  | Column Id | Aspect ratio (l/d) | P (%) | L (mm) | f’c (MPa) | fc (MPa) | D (mm) |
|-----------------------------|-----------|--------------------|-------|--------|-----------|----------|--------|
| Aspect ratio (l/d)          | P-1-5.5   | 5.5                | 10.0  | 2475   | 38.3      | 402      | 450    |
|                             | P-2-7.5   | 7.5                | 10.0  | 3375   | 38.3      | 402      | 450    |
|                             | P-3-9.5   | 9.5                | 10.0  | 4275   | 38.3      | 402      | 450    |
| Compressive strength (f’c) | P-1-35    | 7.1                | 10.0  | 3200   | 35        | 402      | 450    |
|                             | P-2-45    | 7.1                | 10.0  | 3200   | 45        | 402      | 450    |
|                             | P-3-65    | 7.1                | 10.0  | 3200   | 55        | 402      | 450    |
| Yield strength (f_y)        | P-1-250   | 7.1                | 10.0  | 3200   | 38.3      | 250      | 450    |
|                             | P-2-450   | 7.1                | 10.0  | 3200   | 38.3      | 450      | 450    |
|                             | P-3-650   | 7.1                | 10.0  | 3200   | 38.3      | 650      | 450    |
| Axial load (P) %            | P-1-5.5   | 7.1                | 5.0   | 3200   | 38.3      | 402      | 450    |
|                             | P-2-7.5   | 7.1                | 7.5   | 3200   | 38.3      | 402      | 450    |
|                             | P-3-12.5  | 7.1                | 12.5  | 3200   | 38.3      | 402      | 450    |

7. Results and discussion
The RC column incorporating SMAs rebar’s in plastic hinge region along with SS rebar in the remaining portion has been modelled using the Seismo struct FE software [16].

Table 3. Parametric Investigation of Different Columns

| Parameters                  | Column Id | First cracking of the concrete | First yielding of steel | First crushing of the concrete | Maximum base shear (kN) | Δ (mm) |
|-----------------------------|-----------|---------------------------------|-------------------------|-------------------------------|------------------------|--------|
|                             |           | Base (mm) | Δ (mm) | Base (mm) | Δ (mm) | Base (mm) | Δ (mm) | Base (mm) | Δ (mm) |
| Aspect ratio (l/d)          | P-1-5.5   | 35.58     | 2.5   | 105      | 37.5   | 112      | 100    | 113.55    | 220    |
|                             | P-2-7.5   | 21.96     | 3     | 71.95    | 60     | 71.65    | 189    | 75.52     | 96     |
|                             | P-3-9.5   | 21.19     | 8     | 52.94    | 88     | 43.79    | 324    | 54.79     | 128    |
| Compressive strength (f’c) | P-1-35    | 25.72     | 3     | 75.98    | 54     | 77.37    | 174    | 80.34     | 93     |
|                             | P-2-45    | 23.43     | 3     | 76.93    | 54     | 79.05    | 153    | 81.53     | 78     |
|                             | P-3-55    | 26.86     | 3     | 79.85    | 54     | 82.19    | 147    | 83.89     | 96     |
| Yield strength (f_y)        | P-1-250   | 25.90     | 3     | 60.68    | 33     | 56.92    | 249    | 68.68     | 78     |
|                             | P-2-450   | 25.76     | 3     | 80.26    | 72     | 79.02    | 162    | 81.10     | 96     |
|                             | P-3-650   | 28.00     | 5.2   | 80.35    | 109.2  | 78.19    | 169    | 80.49     | 101.4  |
| Axial load (P) %            | P-1-5.5   | 21.89     | 3     | 69.19    | 54     | 77.42    | 171    | 78.54     | 300    |
|                             | P-2-7.5   | 21.95     | 3     | 72.93    | 54     | 77.85    | 168    | 78.72     | 120    |
|                             | P-3-12.5  | 25.64     | 3     | 80.08    | 54     | 78.44    | 168    | 83.53     | 84     |

Note: Δ- Corresponding displacement in mm

A non-linear static pushover analysis has been performed for all models to compare the behaviour of columns. The value of base shear and displacement at which first cracking, first yielding, and first crushing occurs in pushover analysis for each model are considered for the brief study. Table 3
showing these values, and maximum value of base shear and corresponding displacement of above mentioned different configurational columns. Figure 4 to Figure 7 displayed the results of nonlinear seismic pushover analysis in terms of base shear vs. displacement conforming to different parameters namely, an aspect ratio, the compressive strength, the yield strength, and axial load, respectively. As described in Table 3, the value of base shear for column P-1-5.5 found to be maximum for the lower value of aspect ratio. Furthermore, as shown in Figure 4, base shear decreases with increases in aspect ratio. The compressive strength parameter does not make much difference in base shear for different values of $f_c$. The lower value of yield strength for column P-1-250 affects by 15% less value of base shear as compared to the higher yield strength column. Axial load, $P$ (%) variation affects result by approximately 6% from lower value axial load to higher value axial load for column P-2-7.5 to P-3-12.5. Form Table 3 it is concluded that variation in aspect ratio makes much difference in the maximum value of base shear as compared to other parameters.

From Figure 4, it can be observed that the SMA-SS RC column flexural performance was significantly affected by the aspect ratio. Results from Table 3 reveals that the aspect ratio of 7.5 shows 38.28, 31.52 and 36.23% lower cracking, yielding and crushing base shear values, correspondingly revealed to those for an aspect ratio of a 5.5. For the aspect ratio of 7.5, crushing, yielding and cracking displacements increase by 47.09, 37.5 and 16.67%, correspondingly revealed to those having the aspect ratio of 5.5. According to the results presented in Figure 4 the aspect ratio of 5.5 expresses the lower deformability and higher stiffness respect to the aspect ratio of 7.5. The aspect ratio of 9.5 shows 3.5, 26.42 and 38.88% lower cracking, yielding and crushing base shear values, correspondingly revealed to those for an aspect ratio of 7.5 (see Table 3). For the aspect ratio of 9.5, crushing, yielding and cracking displacements raise by 41.67, 31.82 and 62.5% as shown in Table 3, correspondingly revealed to those for an aspect ratio of 7.5. According to the results presented in Figure 4, the aspect ratio of 7.5 expresses the lower deformability and higher stiffness respect to the aspect ratio of 9.5.

Results from Table 3 reveals that 45 MPa concrete raises pier yield and crushing base shear capacity by 1.23% and 2.15% respectively while cracking base shear capacity declines by 8.9% relative to 35 MPa concrete. Results also revealed a higher displacement for crushing by low strength concrete. There was no difference observed in 35, 45 and 55 MPa concrete yield and cracking displacement. The result shown in Figure 5demonstrates that the stiffness of all columns is quite identical until the concrete is cracked. The 35 MPa column shows comparatively lower stiffness than 45MPa concrete once concrete cracked and a similar observation was also seen in the case of 45 and 55MPa concrete. Results from Table 3 reveals that 55 MPa concrete raises 12.77, 3.65 and 3.82 % pier cracking, yielding and crushing base shear capacities, relative to 45 MPa concrete, respectively.
The significant performance of SMA-SS RC column has been seen from Figure 6, due to the influential effect of yield strength of longitudinal reinforcement on the flexure. The high yield strength (450 MPa) rebar expresses the higher-crushing and yielding base shear of 27.96 and 24.39%, and larger yield displacement by 54.17% and lower crushing displacement by 34.94%, correspondingly associated to 250 MPa yield strength (see Table 3). There is no difference in the cracking and yield base shear for 450 MPa and 650 MPa yield strength. For the yield strength of 650 MPa, cracking, yielding and crushing displacements increase by 42.31, 34.06 and 4.14% as shown in Table 3, correspondingly associated with those for the 450 MPa yield strength.

It can be found from Table 3 that the yielding and crushing base shear rises by 5.13 and 0.5 % with an axial load of 7.5 % relative to that of 5 %. Figure 7 further indicates, the crushing displacement for 7.5% axial load decreases by 1.75% compared to 5% axial load, and with 7.5 and 5% axial loads, yielding and cracking displacements are the same. Table 3 further indicates that the cracking, yielding and crushing base shear rises by 14.39, 8.93 and 0.75 % relative to that of 7.5% axial load at 12.5% axial load and with 12.5% and 7.5% axial load, cracking yielding and crushing displacements are the same. It is clear from Figure 7 that the 5% axial load pier has a higher deformation relative to the column of 7.5, 12.5% axial load.

As shown in Figure 8, at the lower aspect ratio, the range of ductility is wider. The level of ductility decreases as the aspect ratio increases. Here, aspect ratio, yield strength, and axial load, are found to be significant on the ductility. Among them, the aspect ratio and yield strength have been responsive influential factors on the ductility of the longitudinally aligned SMA-SS RC column. With the axial load level, the impact of axial load on ductility is not important, the ductility decreases. Atalay and Penzien (1975), and Sheikh and Khoury (1993) also reported that increasing the axial load can reduce the displacement ductility of the column. The change in the compressive strength of concrete does not make any difference in the ductility of SMA-SS RC column.
8. Conclusions
In this study, the inelastic pushover analysis was carried out on corrosion-free SMA-SS RC column for seismic investigation of RC column reinforced with SMA rebar in plastic hinge region along with SS in another region of the column. The results of the parametric analysis on SMA-SS RC column are demonstrated in terms of base shear and displacement. Based on the numerical investigation the resulting conclusions are extracted:

- The yield strength of rebar and axial load, the aspect ratio, and compressive strength have a significant impact on the crushing and yielding base shear of SMA-SS RC column.
- The compressive strength of concrete does not have a significant impact on the yield and crushing drift; However, it shows some contribution to the seismic performance of SMA-SS RC column in the yielding and crushing base shear.
- The variation in aspect ratio makes much difference in the maximum value of base shear as compared to other parameters.
- The reinforced SMA columns demonstrated adequate ductility prior to failure.
- The aspect ratio, yield strength, and axial load, are found to be significant on the ductility. The change in the compressive strength of concrete does not make any difference in the ductility of SMA-SS RC column.

References
[1] Maghsoudi A A, Maghsoudi M and Haghighi H 2018 Amirkabir J. Civ. Eng. 49 233–6
[2] Forrest B T and El-hacha R 2019 Struct. Anal. Hist. Consr. 18 1931–9
[3] Maruyama T and Kubo H 2011 Woodhead Publishing Limited 141–59
[4] Tanaka Y, Himuro R, Sutou Y, Omori T and Ishida K 2010 Science 80 327 4
[5] Logoudas D C 2008 Shape memory alloys modeling and engineering applications ed D C Logoudas (TX, USA: Springer International Publishing)
[6] Janke L, Czaderski C, Motavalli M and Ruth J 2005 Mater. Struct. 38 578–92
[7] Callister Jr. W D 2007 Materials Science and Engineering 7th Ed.: An Introduction vol 26
[8] Chang W-S and Araki Y 2016 Proc. Inst. Civ. Eng. - Civ. Eng. 169 87–95
[9] Pareek S, Suzuki Y, Araki Y, Youssef M A and Meshaly M 2018 Eng. Struct. 175 765–75
[10] Gencturk B and Hosseini S F 2014 10th U.S. National Conference on Earthquake Engineering (Earthquake Engineering Research Institute, Anchorage, AK)
[11] Nakashoji B A 2014 Seismic performance of square Nickel-Titanium reinforced ECC columns with headed couplers (University of Nevada, Reno)
[12] Saidi M S, O’Brien M and Zadeh M S 2009 ACI Struct. J. 106 69–77
[13] Bae S and Bayrak O 2008 ACI Struct. J. 105 290–300
[14] Billah A H M M and Alam M S 2012 Constr. Build. Mater. 28 730–42
[15] Paulay T and Priestley M J N 1992 Seismic Design of Reinforced Concrete and Masonry Buildings, ISBN: 978-0-471-54915-4
[16] SeismoStruct 2018 SeismoStruct - A computer program for static and dynamic nonlinear analysis of framed structures
[17] Mander J B, Priestley M J N and Park R 1988 J. Struct. Eng. 114 1804–26
[18] Auricchio F and Sacco E 1997 J. Intell. Mater. Syst. Struct. 8 489–501
[19] Alam M S, Youssef M A and Nehdi M L 2010 Mater. Struct. 43 91–107
[20] Atalay M and Penzien J 1975 The seismic behavior of critical regions of reinforced concrete components as influenced by moment, shear and axial force
[21] Sheikh S A and Khoury S S 1993 ACI Struct. J. 90 414