Analysis, Design, and Construction of SMA-Reinforced FRP-Confined Concrete Columns

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ABSTRACT: Reinforced concrete (RC) columns are designed to withstand severe earthquakes without collapse, but damage to concrete and yielding of reinforcing steel bars are allowed. The combination of concrete damage and large residual displacements may significantly affect the bridge serviceability because the bridge has to be decommissioned for repair or even total replacement. The damage to bridges can be minimized using advanced materials and novel technologies. Of different types of advanced materials, shape memory alloy (SMA) and fiber reinforced polymer (FRP) are the focus of the present study. SMA-reinforced FRP-confined concrete columns were developed in the present study as a novel column concept in which the expected damage and residual displacements are negligible. A comprehensive parametric study was carried out to establish the performance of the proposed columns. Drift ratio rather than displacement ductility was utilized as a new seismic design parameter suited for displacement-based design method. Detailed analysis, design, and construction guidelines were proposed for this type of novel columns to facilitate field deployment. A summary of the findings and design and construction guidelines is presented in this manuscript.

1 INTRODUCTION

Reinforced concrete (RC) columns are currently designed to withstand severe earthquakes without collapse, but damage to concrete and yielding of reinforcing steel bars is tolerated. In general, minor to moderate concrete damage can be repaired after severe earthquakes. However, columns with significant damage such as core concrete failure or reinforcement fracture are usually replaced. Furthermore, yielding of reinforcement can result in large permanent lateral deformations. The combination of concrete damage and the large residual displacement may significantly affect the bridge serviceability because the bridge has to be decommissioned for repair or even total replacement. Any disruption in bridge functionality will cause significant economic and social burden to the public, and owners and affects the emergency response operation.

Seismic damage to bridges can be minimized using advanced materials [e.g. shape memory alloy (SMA), fiber reinforced polymer (FRP), ultra-high performance concrete (UHPC)] and novel technologies (e.g. rocking mechanism)].

Of different types of advanced materials, SMA and FRP are the focus of the present study. Superelastic (SE) SMA has been incorporated in critical parts of RC members in lieu of steel reinforcement to minimize residual displacements (Ayoub et al., 2003; Saiidi and Wang, 2006; Youssef et al., 2008; Saiidi et al., 2009; Cruz and Saiidi, 2012; Nakashoji and Saiidi, 2014; and Tazarv and Saiidi, 2014). FRP has been used in many forms, the most common of which is FRP fabrics wrapped around RC sections to improve confinement and to reduce concrete damage. More than 25 national and international design guidelines, codes, and specifications are available for FRP such as ACI 440.2R-08 (2008).

SMA-reinforced FRP-confined concrete columns were developed in the present study as a novel column concept in which damage and residual displacements are expected to be negligible. A comprehensive parametric study was carried out to establish the performance of the proposed columns. Drift ratio rather than displacement ductility was utilized in the present study as a new design parameter suited for displacement-based design method. Detailed analysis, design, and construction guidelines were proposed for this type of novel columns under NCHRP 12-101 (2017) to facilitate the field deployment. The main findings and a summary of the design and construction guidelines are presented herein.

2 PROPOSED NOVEL COLUMN CONCEPT AND APPLICATION

The proposed novel column consists of NiTi SE SMA as main longitudinal reinforcement and conventional concrete confined with an FRP jacket (Fig. 1) and will be referred to as SMA/FRP column. The column is potentially superior to conventional steel-reinforced concrete columns in terms of seismic performance since SE SMA minimizes the column lateral residual displacements and FRP jacket eliminates the concrete damage after strong shaking.

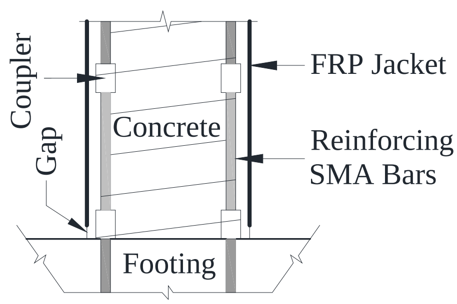


Figure 1. Plastic Hinge Detail for Proposed Columns.

SMA longitudinal bars are used only in column plastic hinges to minimize the cost. The SMA bars are connected to steel bars outside plastic hinges using mechanical bar splices. The column is encased with a hard FRP tube or wrapped with FRP fabrics with fibers confining concrete and providing shear strength for the column.

SMA-reinforced FRP-confined concrete bridge columns are recommended for sites in which the 1-*sec* period acceleration coefficient, S_{D1}, is greater than 0.3, which is equivalent to the seismic design category (SDC) C or D according to AASHTO SGS (2011). NiTi SE SMA stress-strain material relationship is based on the model proposed by Tazarv and Saiidi (2014). FRP confined concrete properties are determined according to the model presented in ACI 440.2R-08 (2008). FRP jacket is not extended into the column adjoin members. A 50-*mm* gap is provided as shown in Fig. 1.

3 ANALYSIS OF PROPOSED NOVEL COLUMN

General analytical methods to obtain the seismic demands of SMA/FRP column are according to AASHTO SGS (2011). However, some parameters need modifications as discussed herein.

3.1 Effective Section Properties

The effective moment of inertia (I_{eff}) is used for modeling of the SMA-reinforced FRP-confined concrete columns. I_{eff} may be estimated using the chart in Fig. 2, or the slope of $M - \emptyset$ curve between the origin and the first SMA bar yield point may be used.

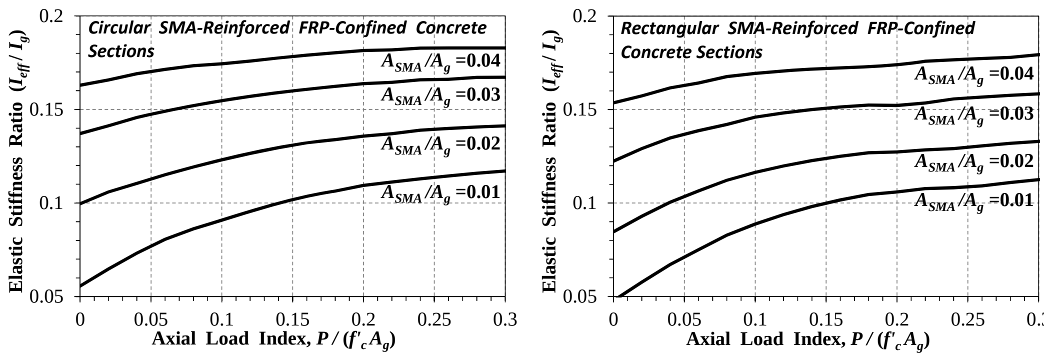


Figure 2. Effective Moment of Inertia for SMA/FRP Columns.

3.2 Damping Ratio

For elastic and nonlinear dynamic analyses of SMA-reinforced FRP-confined columns, a damping ratio of 3.2% is recommended rather than 5% used for RC columns. The lower damping ratio accounts for the lower hysteretic damping in columns with flag-shaped behavior that could result in higher displacement demands. The proposed damping ratio was derived form a statistical analysis of hysteretic damping for self-centering columns by Dwairi et al. (2007), Priestley et al. (2007), and Billah and Alam (2015).

3.3 Displacement Ductility versus Drift Ratio

Displacement ductility in current codes is defined as the ratio of the peak displacement to the idealized yield displacement (AASHTO SGS, 2011). The ductility of SMA reinforced columns based on this definition may be misleading because the yield strain of SMA bars is five times higher than that of steel bars resulting in a higher idealized yield displacement, thus lower calculated displacement ductility even though the displacement capacity of a SMA-reinforced column may substantially exceed that of a comparable conventional column. “Drift ratio”, the ratio of column lateral top displacement to the column height, is proposed as an alternative measure to estimate the deformation capacity and demand of novel columns including SMA-reinforced FRP-confined concrete columns.

Because current bridge seismic codes utilize displacement ductility rather than drift ratio in design, it is important to determine the relationship between ductility and drift ratio so that displacement ductilities for conventional columns in current codes can be translated to drift ratios that may be utilized in novel column design. An extensive parametric study of more than 690 conventional RC columns was conducted to establish a relationship between the displacement ductility and drift ratio for these columns. Figure 3 shows the condensed result of the parametric study. Equation 1 relates the drift ratio to the ductility for different aspect ratios.

$$\delta = 0.26(A_r)^{0.81}\mu - 0.18(A_r)^{0.57} \quad \text{(Eq. 1)}$$

where A_r is the column aspect ratio (Fig. 4). For single column bents, the aspect ratio is defined as the ratio of the column height to the column side dimension parallel to the loading direction. For multi-column bents, the aspect ratio is the ratio of a portion of the column length (length of column from point of maximum moment to the point of contraflexure) to the column side dimension parallel to the loading direction. The full column length is used if one end of the column is pinned.

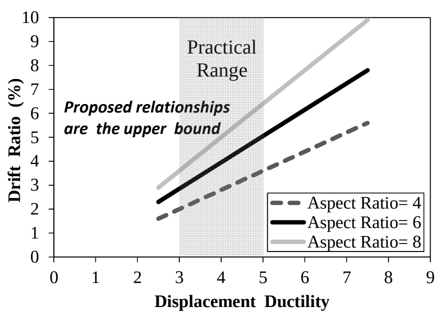
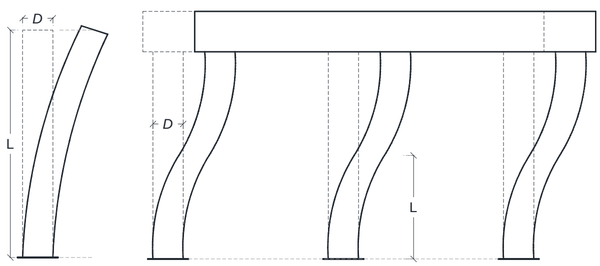


Figure 3. Drift-Ductility Relationship.



(a) Single Column

(b) Multi-Column Bent

Figure 4. Aspect Ratio Definition.

3.4 Column Force Demand

Columns is designed to resist all internal forces developed during an earthquake or those associated with a collapse mechanism.

3.4.1 Moment Demand

The column design moment is the smaller of that obtained from (a) the demand at the design level earthquake, and (b) the idealized plastic capacity of the column cross section. The column design moment obtained from (a) and (b) is increased to the column failure moment (M_u) when the column failure moment is greater than 1.2 times the idealized plastic moment ($M_u \geq 1.2M_p$).

3.4.2 Shear Demand

The column shear demand is the smaller of that obtained from (a) the demand at design level earthquake, and (b) the shear associated with 1.2 times the plastic moment calculated using the idealized method. The column shear obtained form (a) and (b) is increased to the shear associated with 1.44 times the idealized plastic moment when the calculated failure moment exceeds $1.2M_p$ ($M_u \geq 1.2M_p$). All possible plastic hinge locations should be considered in the determination of shear forces using (b).

3.4.3 Column Adjoining Member Force Demand

Column adjoining members (e.g., footings, cap beams, and connections) are designed to resist the overstrength plastic hinging moment, see sections 3.4.1 and 3.4.2, and the associated forces (e.g., shear and overturning axial forces) in an essentially elastic manner. This design approach is known as capacity design and is outlined in the AASHTO SGS.

3.5 Residual Drift Ratio

The residual drift ratio of SMA-reinforced FRP-confined concrete columns is insignificant for all practical cases due to the superelastic effect of reinforcing SMA bars ($\delta_r \leq 1.0\%$).

Figure 5 shows the residual drift-peak drift relationship for all practical SMA-reinforced FRP-confined concrete columns. The analytical results are shown up to the failure point (drift capacity) of each column. It can be seen that the residual drift ratios for all columns are less than 1.0%. The left cluster of the data (solid black lines), mid-cluster of the data (solid gray lines), and the bottom-right cluster of the data are respectively for columns with aspect ratios of four, six, and eight. The residual-peak drift relationships measured in a conventional RC bridge column test (dashed grey line) as well as an SMA reinforced steel-confined concrete column test (dashed black line) are also shown in the figure.

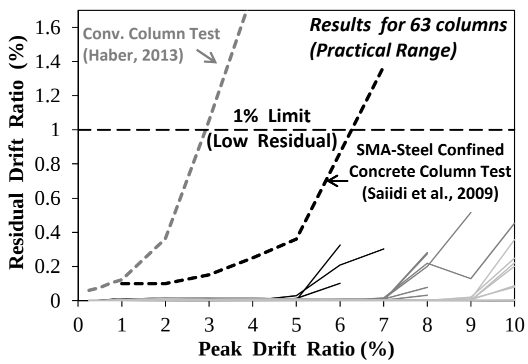


Figure 5. Residual drifts for all practical SMA-reinforced FRP-confined concrete columns.

4 DESIGN OF SMA/FRP COLUMN

Several parameters need to be considered for successful design of SMA-reinforced FRP-confined concrete columns. A review of critical parameters is presented herein.

4.1 Analytical Plastic Hinge Length and Drift Capacity

The analytical plastic hinge length of SMA-reinforced columns may be estimated using

$$L_p = 0.08L + 0.022 f_{ye} d_{bl} \geq 0.044 f_{ye} d_{bl} \quad \text{(Eq. 2)}$$

where f_{ye} (*MPa*) is the expected austenite yield strength of the longitudinal column reinforcing SMA bars and d_{bl} (*mm*) is the nominal diameter of longitudinal column reinforcing SMA bars. Nakashoji and Saiidi (2014) utilizing all available test data showed that the plastic hinge length of SMA-reinforced columns can be conservatively estimated using the equation presented in AASHTO SGS (2011).

Either moment-curvature or pushover analyses may be used for the estimation of a SMA-reinforced FRP-confined concrete column displacement capacity. However, a pushover analysis is preferred since it includes the entire bridge model, frame actions, and geometric nonlinearities.

The recommended minimum drift ratio capacity for SMA-reinforced FRP-confined concrete columns is listed in Table 1. The drift ratios correspond to the minimum displacement ductility capacity for conventional columns. Columns should be designed to provide at least this level of drift ratio.

Table 1. Minimum Bridge Column Drift Ratio Capacity Requirements

Member	Conventional Columns	Novel Columns	
Single- or multi-column bents	$\mu_c \geq 3$	Aspect Ratio 4: Aspect Ratio 6: Aspect Ratio 8:	$\delta_c \geq 2.0\%$ $\delta_c \geq 2.85\%$ $\delta_c \geq 3.60\%$

Note: "δ_c" is the drift ratio capacity (%) and "μ_c" is the displacement ductility capacity
Use linear interpolation for intermediate aspect ratios

4.2 Axial and Shear Capacities

The axial and shear capacities of SMA-reinforced FRP-confined columns within the plastic hinge can be be calculated according to ACI 440.2R-08 (2008). The moment capacities should be calculated using a moment-curvature analysis incorporating the aforementioned material models for SMA and FRP-confined concrete.

5 DETAILS OF SMA/FRP COLUMN

5.1 Reinforcement Details

The area of longitudinal reinforcing SMA bars (A_{SMA}) in SMA-reinforced FRP-confined concrete columns should satisfy:

$$0.01A_g \leq A_{SMA} \leq 0.04A_g \quad \text{(Eq. 3)}$$

where A_g is the gross area of member cross-section (mm^2). NiTi SE SMA bars are available in all sizes.

5.2 Splicing of SMA Reinforcement

The incorporation of SMA bars only over partial length of columns should be permitted and is recommended to save cost. The length of SMA bars shall not be less than the analytical plastic hinge length and 75% of the largest column cross sectional dimension (0.75*D*). Tazarv and Saiidi (2016) showed that mechanical bar splices used in the column plastic hinges could reduce the displacement ductility capacity of the column. Equations presented in the study should be used for the design of columns with mechanical bar splices in their plastic hinges.

5.3 Maximum Axial Load

The axial load acting on a SMA/FRP column including gravity and seismic demands (P_u) where a pushover analysis is not performed should satisfy:

$$P_u \leq 0.15f'_c\,A_g \quad \text{(Eq. 4)}$$

where A_g is the gross area of member cross-section (mm^2) and f'_c is the nominal concrete compressive strength (MPa). A higher axial load value may be used provided that pushover analysis including the $P-\Delta$ effect is performed to compute the maximum drift capacity of the column.

5.4 *Maximum Aspect Ratio*

The aspect ratio of SMA/FRP columns should not exceed eight. Columns with larger aspect ratios may fail at relatively low drift ratios due to the $P - \Delta$ effect.

6 CONCLUSIONS

Novel columns with improved seismic performance are emerging mainly because conventional RC columns may need repair or total replacement after an earthquake, which can cause a significant economic and social cost to public. A novel bridge column incorporating NiTi superelastic SMA bars and conventional concrete confined with fiber reinforced polymer (FRP) jacket was proposed in the present study. More than 750 pushover analyses were performed to establish the column behavior and to develop design, construction, and analysis guidelines. A summary of the findings and guidelines was presented. The proposed novel column is a viable alternative to conventional RC columns with insignificant residual displacements and minimal damage after severe earthquakes.

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