Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

PERFORMANCE ASSESSMENT OF RC BEAM-COLUMN JOINT REINFORCED WITH DIFFERENT SUPER ELASTIC SHAPE MEMORY ALLOY TYPES

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Superelastic Shape Memory Alloys (SE SMAs) are smart materials that have the ability to undergo large inelastic deformation upon stress removal (superelasticity) or heating (shape-memory alloy effect). If such smart materials can be used in the plastic hinge regions of reinforced concrete (RC) beam-column joints as reinforcement, they can undergo large deformations during an earthquake and can return to their undeformed/ original shape after the earthquake. This paper represents the seismic performance of beam-column joint reinforced with three different types of SMA (e.g Ni-Ti, Cu-Al-Mn, Fe based) and compared the result with regular steel-RC beam-column joint. An analytical investigation has been considered to evaluate the seismic performance of smart RC beam-column joint and regular steel-RC joint under reversed cyclic loading. The performance of the beam-column joint is compared in terms of load-story drift ratio and energy dissipation capacity. All SMA-RC beam-column joints show nearly 40-60% higher displacement than steel-RC joint before yielding. Among three types of SMA Ni-Ti dissipate 24% higher energy than any other types of SMA.

Keywords: Super-elasticity, Plastic hinge, Load-storey drift, Energy dissipation.

1 INTRODUCTION

The overall behavior of reinforced concrete moment resisting frame in recent earthquakes all over the world has highlighted the poor performance of the beam-column joint. Beam-column joints are more susceptible to failure than any other members of the building due to severe damage to the joint zone. Steel is being used as reinforcement around the world, but lack of corrosion resistance makes steel vulnerable for long time use. On the other hand, earthquake energy is dissipated through yielding of reinforcement causes permanent deformation of the reinforcement. To address this problem of deteriorating civil infrastructures, researchers are seeking new material, which has enhanced deformation capability and ductility. One of these innovative materials is shaped memory alloy (SMA), which remembers the “Parent” shape.

SMA has introduced a new era for the improvement of the overall performance of concrete frames. An experimental study conducted by Nehdi *et al.* (2011) found that longitudinal SMA bar experienced very negligible residual strain compared to steel. Less residual strain helps material undergo large deformation without permanent damage under cyclic load. In particular, SMAs have distinct thermomechanical properties, including superelasticity, shape-memory alloy effect, and hysteretic damping. These properties can be effectively utilized in the beam-column joint under reversed cyclic loading. A study by Abdulridha *et al.* (2013) shows that under cyclic loading, the recovery of post-yield deformation of the SMA beam is almost 78% higher than conventionally reinforced beams. Due to the high superelastic property of SMAs, it can be used in the beam-column joint for significant energy dissipation during a seismic event. In this article, it is proposed to use superelastic SMAs in conjunction with steel-RC beam-column joint. Here the beam-column joint is reinforced with three different types of SMAs (Ni-Ti, Fe-based, and Cu-based) in the plastic hinge region and compare the results with steel-RC beam-column joint. In this study, four beam-column joints have been designed and analytically investigated using finite element software SeismoStruct (2015). The prime objective of this study is to investigate the behavior of Steel-RC and SMA-RC beam-column joints under cyclic load in terms of load-story drift ratio, and energy dissipation capacity.

2 DETAILS OF SPECIMENS

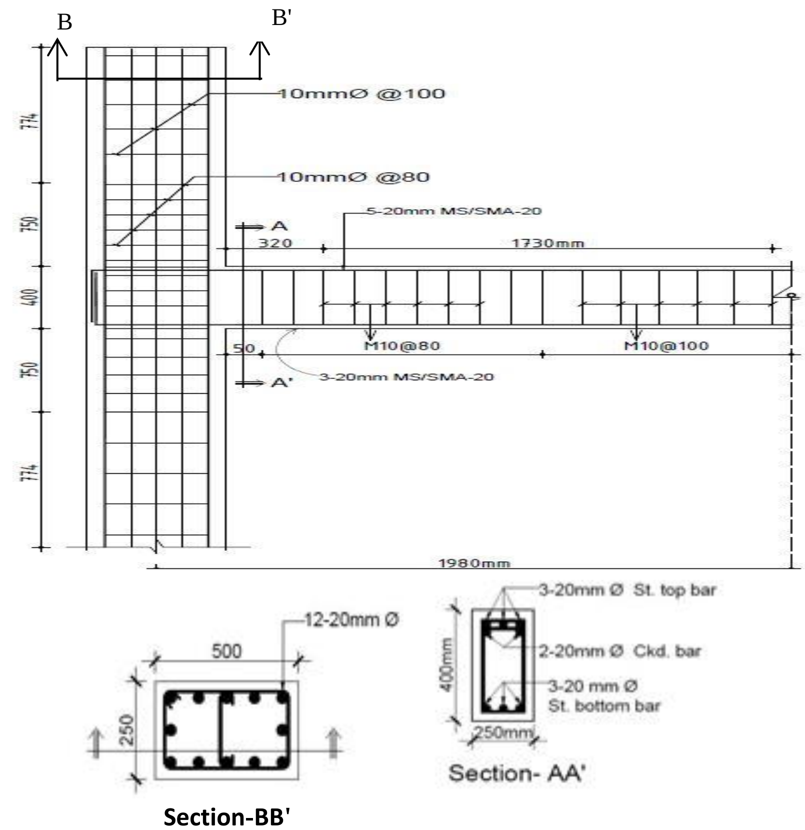
In this study, a seven-story RC moment resisting frame building is considered. The exterior beam-column joint is isolated from the building at the points of contra-flexure from the mid-height of the second floor to mid-height of the third floor. The cross-section of the column is 250 mm by 500 mm and reinforced with 12-20 mm diameter longitudinal bar. Cross section of the beam is 250 mm by 400 mm and longitudinal reinforcement is similar for all types of joint except SMA is used only in the plastic hinge region for three joints while the other joint is fully reinforced with steel. The detailing of reinforcement of the joint is shown in Figure 1. The beam-column joints are designated as steel-RC (reinforced with regular steel), SMA-RC-1 (reinforced with SMA-1), SMA-RC-2 (reinforced with SMA-2), SMA-RC-3 (reinforced with SMA-3). SMA-RC-1 is reinforced with 8-20 mm SMA-1 bars, SMA-RC-2 reinforced with 8-16 mm SMA-2 bars, SMA-RC-3 reinforced with 8-28 mm SMA-3 bars. Material properties used for three different types of SMA are shown in Table 1.

Table 1. Properties of different types of SMA (Billah *et al.* 2016).

SMA Types	**Alloy**	**ε_s (%)**	**E (GPa)**	**f_Y (MPa)**	**f_{P1} (MPa)**	**f_{T1} (MPa)**	**f_{T2} (MPa)**	**Reference**
SMA-1	$NiTi_{45}$	6	62.5	401.0	510	370	130	Alam *et al.* 2008
SMA-2	FeNCATB	13.5	46.9	750	1,200	300	200	Tanaka *et al*. 2010
SMA-3	CuAlMn	9	28	210	275	200	150	Shrestha *et al*. 2013

f_y (austenite to martensite starting stress); f_{P1} (austenite to martensite finishing stress); f_{T1} (Martensite to austenite starting stress); f_{T2} (martensite to austenite finishing stress); ε_s (superelastic plateau strain length).

In the SMA-RC beam-column joints, SMA is used only in the plastic hinge region of the beam. Rest of the part is detailed with regular steel. The plastic hinge region was calculated using Paulay and Priestley (1992) equation. The plastic hinge length is found to be 320 mm from the face of the column for the RC beam-column joint.



Concrete	
Compressive strength (MPa)	35
Tensile strength (MPa)	3.5
Steel	
Yield strength (MPa)	413.7
Strain hardening parameter	0.005
Modulus of elasticity (GPa)	200

Figure 1. Reinforcement details of beam–column joint and material properties.

3 MOMENT-CURVATURE RELATIONSHIP

The sizes of the rebar are selected in such a way that the axial forces developed in the rebar are almost the same. Figure 2 shows the moment-curvature graph for all types of beam-column joint. From the moment-curvature graph, it is observed that all the beam-column joints have similar stiffness and comparable moment capacity.

4 FINITE ELEMENT MODELING

Nonlinear models of the steel-RC and SMA-RC beam-column joints are developed using SeismoStruct (2015). Fiber modeling technique has been used to represent the distribution of material nonlinearity along the length and cross-section of the beams and columns. Beams and columns are divided into four and two elements, respectively, in the longitudinal direction, and each element, in turn, is subdivided into 200 × 200 fiber elements in the transverse direction. One of the longitudinal elements of the beam represents the plastic hinge region at the beam-column joint. A constant axial load of 1112 kN is applied at the top of the column and reversed cyclic loading is provided at the tip of the beam. A detailed description of finite element modeling approach can be found in Nahar (2018). For validation two beam-column joint one is reinforced with regular steel and another with SMA in the plastic hinge region with a dimension of 250 mm x 400 mm is developed. Reversed cyclic loading is applied at the beam tip and the result is compared in terms of load-story drift ratio and energy dissipation capacity. Ultimate beam tip load is 12% and 6% higher for steel-RC and SMA-RC joint comparing to the result found in the experimental works performed by Alam *et al.* (2008). Energy dissipation capacity is 5.5% higher for both types of the joint while compared with the experimental results by Alam *et al.* (2008). From this validation results, it can be concluded that FE modeling using Seismostruct can predict the experimental results with reasonable accuracy. Moreover, previous studies have also demonstrated the accuracy of the FE program to predict the seismic behavior of SMA-RC bridge pier and SMA-RC frames (Alam *et al*. 2012, Billah and Alam 2012, Billah and Alam 2016).

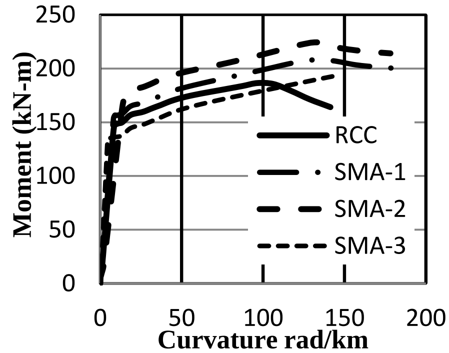


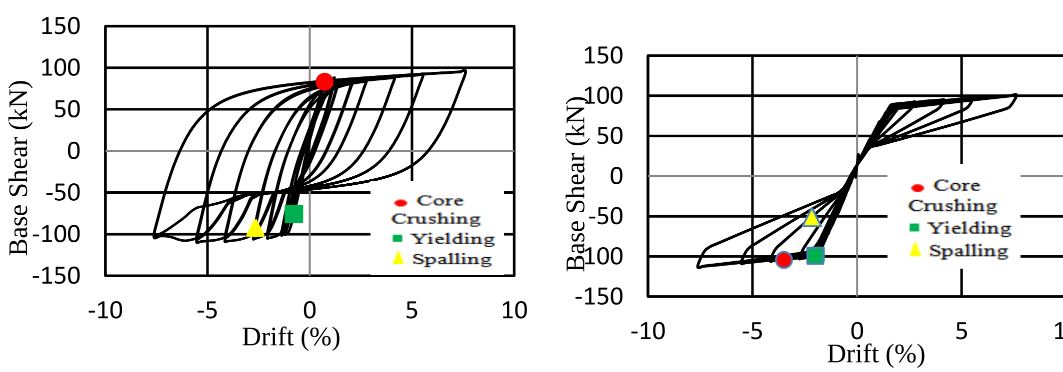
Figure 2. Moment-curvature relationships for steel-RC, SMA-RC-1, SMA-RC-2, SMA-RC-3, beam-column joint.

5 RESULTS AND DISCUSSIONS

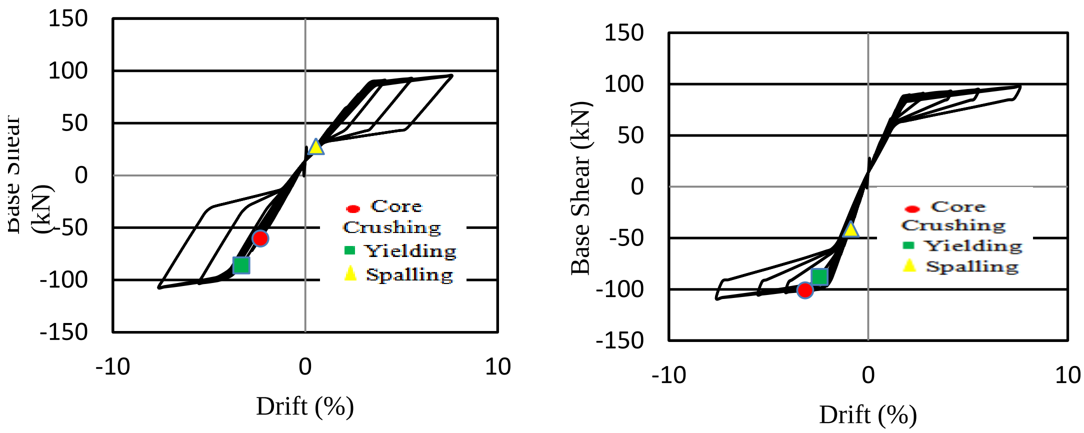
5.1 BeamTip Load Versus Story Drift

Figure 3 illustrates the story drift relationship of the beam–column joint with beam tip load. All of the beam-column joints show drifts up to 7%. At 3% story drift, Ni-Ti SMA carry 4 to 8% higher load than SMA-RC-2 and steel-RC joint respectively.

In this study, three performance criteria namely core crushing, yielding and spalling are considered and noted in the figure. All SMA-RC beam-column joints show higher drift before yielding, For Fe-based SMA, i.e., SMA-RC-2, core crushing drift occurs earlier before yielding of reinforcement due to its high yield strength than any other SMAs. At 3% collapse drift defined by Kircil and Polat (2006) SMA-RC-1 carry 5% to 6% higher load than the other two types of SMA.



(a) Steel-RC (b) SMA-



(c) SMA-2 (d) SMA-3

Figure 3. Beam tip load-story drift relationship for (a) steel-RC, (b) SMA-1, (c) SMA-2, (d) SMA-3, beam–column joint.

5.2 Cumulative Energy Dissipation Capacity versus Story Drift

Figure 4 shows the plot of cumulative energy dissipation versus story drift for the four types of the beam–column joints considered in this study. From the figure, it is evident that energy dissipation capacity is higher for the RC-beam–column joint than any other SMA-RC joint due to its larger hysteretic loop. At 4% collapse drift the RC beam-column joint can dissipate 49 kNm of energy, which is almost 65% greater than any other SMA-RC joint.

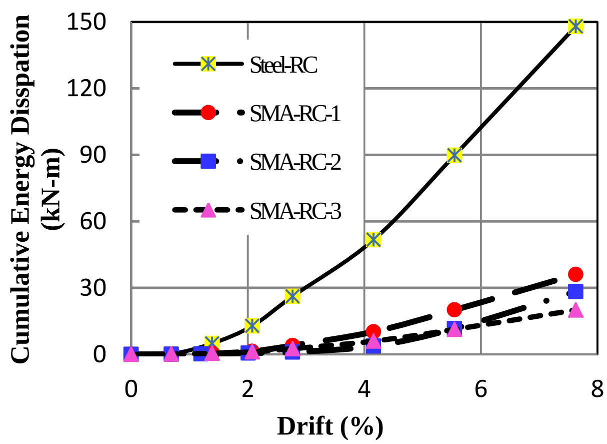


Figure 4. Cumulative energy dissipation-story drift relationships of specimens.

6 CONCLUSIONS

This paper presents a comparative numerical study to investigate the cyclic behavior of Steel-RC and SMA-RC beam-column joints in terms of load-story drift ratio and energy dissipation capacity and shows the potential of using SMA rebars in the plastic hinge region of the RC beam-column joints. The key findings from the current study are summarized below:

- All SMA-RC beam-column joints show similar load carrying capacity compared to steel-RC joint, however, Ni-Ti based SMA carry 7% higher load than any other types of joint at 6% drift ratio.
- The load carrying capacity of SMA-RC beam-column joint is 21-35% higher than steel-RC joint before yielding of reinforcement due to SMAs large superelastic property.
- Although Fe-based SMA dissipates less energy compared to other types of SMA at the lowest drift, however, it can dissipate a significant amount of energy at higher drift.
- Due to the inelastic property of SMA and notably higher load carrying capacity of SMA-RC joint compare to the steel-RC joint before yielding provides a better solution against permanent deformation during seismic events.

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