Performance assessment of Shape Memory Alloy plates for recovery of seismic deflections in steel frames

Kamalkishor M Bajoria[1], Rashmi Jadhav[2]

[1] Professor, Indian Institute of Technology Bombay, Mumbai, India
[2] Research scholar, Indian Institute of Technology Bombay, Mumbai, India

ABSTRACT: This paper presents feasibility study of utilizing different types of shape memory alloy (SMA) plates at possible hinge locations of steel frames subjected to seismic loads. Three different plate models are tested for response of steel frames under lateral loading. The performances of two super elastic SMA material plates (Ni-Ti and Ferrous), are compared with steel plates. Finite element analysis using software Ansys is carried out for response of steel plates clamped on all sides for lateral loads using incremental loading. Along with increase in load carrying capacity, both types of SMA plates helped recovery of residual deflection on unloading. Though the load carrying capacity of Ni-Ti SMA plate is more compared to ferrous SMA, the residual deflectiont is completely recovered in both types of SMA plates after unloading. This special characteristic of recovering the residual deflection of ferrous SMA having much lesser cost compared to Ni-Ti SMA, can be used for civil engineering applications. A steel frame is then analysed for lateral seismic load with two types of SMA plates at possible hinge locations and the response is compared with that with a steel plate. Although the introduction of SMA plates at beam-column junction did not result in increase in lateral load carrying capacity, the frames with SMA plates at connections showed excellent recovery compared with that with steel plate.

1 INTRODUCTION

In recent years, there has been an increased interest among researchers to use SMAs in structural engineering applications because of their unique physical and mechanical properties. To make structures seismic resistant, different innovative systems are used in steel frames. For braced frames, the systems may contain components like bracing members in the form of flats, tubes, wire strands, rods or truss members. In case of moment resisting frames, modified connections or other components are used to resist the earthquake loads. Though the load carrying capacity of frames equipped with these modified steel connections can be increased and roof deflection reduced, the recovery of residual deflection remains an issue. Even if the residual deflection remains within allowable range, the repair of members and even replacement of some members is unavoidable. Hence the researchers are trying to use smart materials like Shape Memory Alloys (SMA) having special properties such as super elasticity, shape memory effect (SME) and high damping capacity. Ni-Ti alloys are the most popular SMA having capacity to recover large strains, but they are expensive. Ferrous SMA are now emerging as cost effective options.

In order to reduce residual deformations in steel buildings, several researchers have investigated the applications of Ni-Ti SMAs. Ocel et al.(2004) and Moradi et al.(2014) recovered beam tip deflection up to 76% using Ni-Ti SMA at steel beam column joints. The application of Ni-Ti SMA bars in steel beam column joints showed large energy dissipation when tested for cyclic load. Experimental tests on the cyclic behavior of super elastic Ni-Ti SMA tendons at beam column connections showed appreciable recovery of deformation. An interior beam column steel connection containing super elastic Ni-Ti SMA tendons was able to recover 85% of its deformation after being loaded up to 5% drift (Ellingwood et al. 2010, Speicher et al. 2011). Recovery of deformation upon unloading was observed when Ni-Ti SMA bolts were used in an end plate connection of frame (Ma et al.2007). An experimental study on the cyclic performance of extended end plate connections with Ni-Ti SMA bolts showed excellent re-centering capability with moderate energy dissipation (Fang et al.2014). Due to the re-centering capacity of Ni-Ti SMA, the seismic performance of steel moment frames with Ni-Ti SMA based connections was seen to be improved (Desroches et al.2010). Provision of ferrous SMA plates at the plastic hinge region of the beam showed 90% reduction in residual drift compared to steel beam column connection. The recentering capacity in this case was checked for cyclic loading (Moradi et al. 2015).

1.1 Shape Memory Alloys (SMA)

Solid to solid phase transformation is a unique feature of Shape Memory Alloys (SMA) which makes it popular in many areas. Large recoverable strain, super elasticity, and shape memory effect are the characteristics which make SMA an extraordinary material for structures to control seismic response. These materials are also able to come back to its original shape and recover residual strains by transforming their phase using temperature change. Two phases of this material, namely, Austenite and Martensite have two different crystalline forms showing different behaviors. The phase transformation is attained by change in temperature or stress. If the material is in the Austenite state, there is no residual strain, after the removal of the load. However, if it is in the martensitic state, residual strain can be reduced to zero with application of heat.

1.1.1 Nitinol - Ni-Ti SMA

Nickel Titanium (Ni-Ti) is the most commonly used SMA in different scientific and engineering fields. Strong Super Elasticity (SE), Shape Memory Effect (SME) and corrosion resistance are the special characteristics of this alloy, which makes it suitable for specialized use.

Super-elastic Ni-Ti SMA, springs back to its original shape if bent at room temperature. SME is the characteristic by which material returns back to its predetermined shape upon heating at a certain temperature. Phase transformation between two different phases is from Austenite to Martensite and vice versa at different temperatures. Austenite is a stronger phase and stable at high temperature. This phase has relatively stronger resistance to external stresses as it has highly symmetric crystallographic structure. Where as, Martensite is a weaker phase and stable at low temperature. The material can be deformed easily in Martensite phase as it has parallelogram crystalline structure. When Ni-Ti SMA is cold, or below its transformation temperature, it has a very low yield strength and can be deformed quite easily into any new shape which is retained. However, when the material is heated above its transformation temperature, it undergoes a change in crystal structure, causing it to return to its original shape. The material deforms in the martensitic phase , and then springs back to its "remembered" shape in its austenitic form. These alloys exhibit a large recoverable strain of up to 8%.

1.1.2 Ferrous SMA

As the manufacturing and training process of Ni-Ti SMA is expensive, effort has been made to develop other types of SMAs suitable for large-scale Civil Engineering applications (Ozbulut et al. 2011). Although Cu-based SMAs are less expensive, they show poor ductility. As another alternative, low cost ferrous SMAs have been found to be a good candidate for this purpose. Fe-Mn-Si-based alloys exhibit good mechanical properties with a wide transformation hysteresis, good machinability, and weldability, and also good workability compared with properties of Ni-Ti SMA (Alam et al. 2007). Dong et al. (2009) introduced a new ferrous SMA, Fe-Mn-Si, with good shape recovery stress and shape recovery strain, which does not require any training/treatment process. Omori et al. (2011) proposed Fe-Mn-Al-Ni SMAs with good superelasticity and ductility. In contrast to Ni-Ti, these ferrous alloys can exhibit super elastic behavior with no significant sensitivity to temperature. Li et al. (2013) developed a new ferrous SMA with simple manufacturing process and good mechanical behavior, showing SME suitable for smart structural applications. These findings imply that the mass scale production of ferrous SMA with proper characteristics for Civil Engineering applications is possible in future. Superelastic behavior is usually attributed to a thermoelastic martensitic transformation, in which a martensite plate grows and shrinks upon cooling and heating, respectively (Otuska et al. 1998). However, most fe-based alloys, including the Fe-Mn-Al, have a nonthermoelastic martensitic transformation (Omori et al. 2011).The SMA other than Ni-Ti SMA used in this study is Fe-Mn-Al which will be referred as ferrous SMA here onwards.

2 PRESENT STUDY

2.1 Finite Element Model

3D models are generated, meshed, and analyzed using the finite element software, ANSYS. The plate specimen, having dimensions of 10mm X 100mm X 100mm is used as shown in figure 2. The thickness of the plate is kept lesser compared to other dimensions to check its performance to use as end plate in connection. The material model used for steel is bilinear kinematic hardening model to include material nonlinearity and plasticity as shown in figure 1a. The mechanical properties used for steel are provided in table 1 (Gholami et al. 2013). In ANSYS, the super elastic behavior of SMA is simulated using Auricchio’s model (Auricchio 2001). The material undergoes large deformation without showing permanent deformation under isothermal conditions (ANSYS, Inc. 2012). Figure 1b shows the idealized stress strain diagram of super elastic behavior. The SMA model considered in this study is temperature and rate independent. The mechanical properties for Ni-Ti SMA are taken from available literature shown (Divringi et al. 2012) in table 2. The assumed mechanical properties for ferrous SMA are selected considering the experimental data reported by Omori et al. (2011). The element used is eight noded solid185 for all materials: Steel, Ni-Ti SMA and ferrous SMA as it supports unique properties of SMA. The plate is restrained at all boundaries to resemble the fully welded rigid end plate connection. The frame selected to check the feasibility of use of SMA plate at possible hinge locations, is a simple single story structure with span 1500mm and height 1000mm. The section used for column is rectangualr section 40mm X 30mm and for beam 30mm X 20mm. Extended end plate of 40mm X 30mm with 10mm thickness is used at the beam column connection in all frames for steel connection and SMA connection. The connections are simulated so as to resemble welded connection. Fixed supports were considered for the columns.

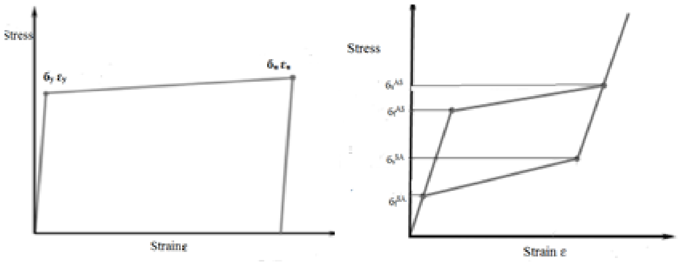

Figure 1. Material models for Steel (kinematic hardening) and Superelastic SMA (SE)

Table 1 . Material properties for steel

Property	Young's Modulus (E)	Yield Strength (fy)	Poisson's Ratio (η)	Density (ρ)
Value	$2.1e^5$	355	0.28	$7.8e^{-6}$
Unit	mpa	mpa	-	Kg/mm^2

Table 2. Material Properties for Ni-Ti SMA (Divringi et al. 2012) and ferrous SMA, (Omori et al. 2011)

Property	Ni-Ti-SMA	Ferrous SMA	Unit
Young's Modulus	$60e^3$	$98e^3$	mpa
Poisson's ratio	0.33	0.36	
Starting stress value for the forward phase transformation	520	320	mpa
Final stress value for the forward phase transformation	600	400	mpa
Starting stress value for the reverse phase transformation	300	290	mpa
Final stress value for the reverse phase transformation	200	90	mpa

2.2 Analysis

Nonlinear static analysis considering large deformation is performed using automatic stepping option. Lateral loads are applied in global X direction in small increments till the maximum load is reached. To check the residual strain after unloading, the plate is fully unloaded after maximum load is reached, using same steps of decrement.

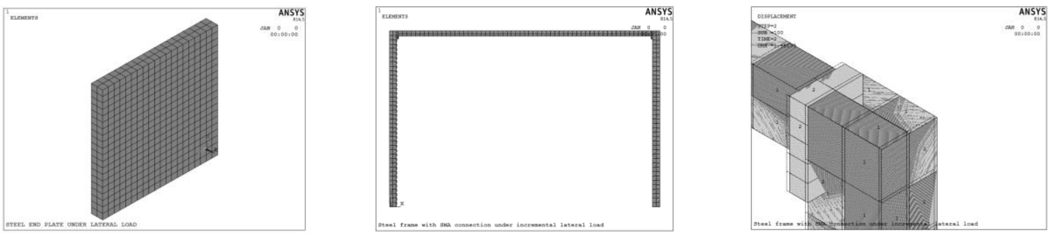

Figure 2. Finite element model (i) Plate, (ii) Simple frame, (iii) Ferrous SMA at connection

3 RESULTS AND DISCUSSION

3.1 Results for plates

The performance of Ni-Ti SMA and Ferrous SMA plates under incremental lateral loading are compared with steel plate under same loading and boundary conditions. The maximum load carried by steel plate is 100 kN, whereas for ferrous SMA and Ni-Ti SMA, it is 150kN and 170kN, respectively. The load carrying capacity for ferrous SMA is increased by 50% and Ni-Ti SMA is increased by 70% compared to Steel plate. The residual deflection is almost zero in case of both types of SMA, 0.000173mm for ferrous SMA and 0.0000101mm for Ni-Ti SMA.

Table 3. Comparative results of Steel and SMA plates

Material	Max Load (kN)	Max Deflection (mm)	Residual Deflection (mm)	Recovery of deflection (%)	Increased load carrying capacity (%)
Steel Plate	100	1.043	0.983	5.3	-
Ni-Ti-SMA plate	100	0.905	$1.56e^{-8}$	100	-
Ni-Ti-SMA plate	170		$0.101e^{-4}$	100	70
Ferrous SMA plate	100	0.515	$4.76e^{-8}$	100	-
Ferrous SMA plate	150	0.568	$1.73e^{-4}$	100	50

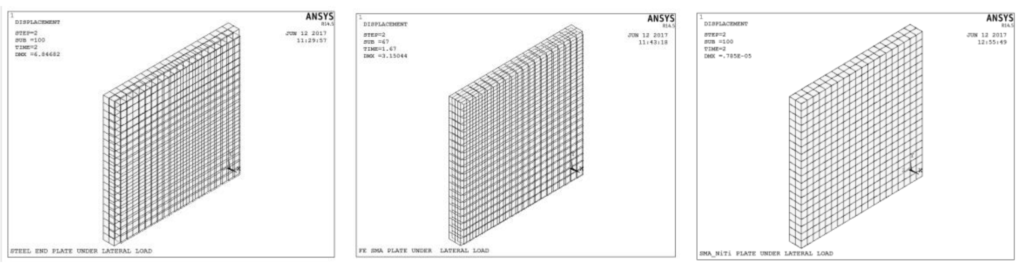

Figure 3. Deflection of plates under lateral load (i) Steel plate, (ii) Ferrous SMA plate, (iii) Ni-Ti-SMA plate

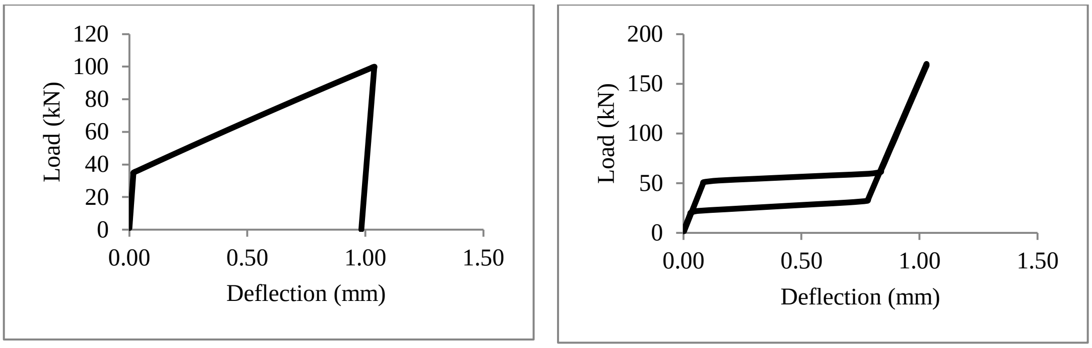

Figure 4. Load bearing capacity of plates (i) Load deflection curve for steel plate after loading unloading cycle (ii) Load deflection curve for Ni-Ti SMA plate after loading unloading cycle

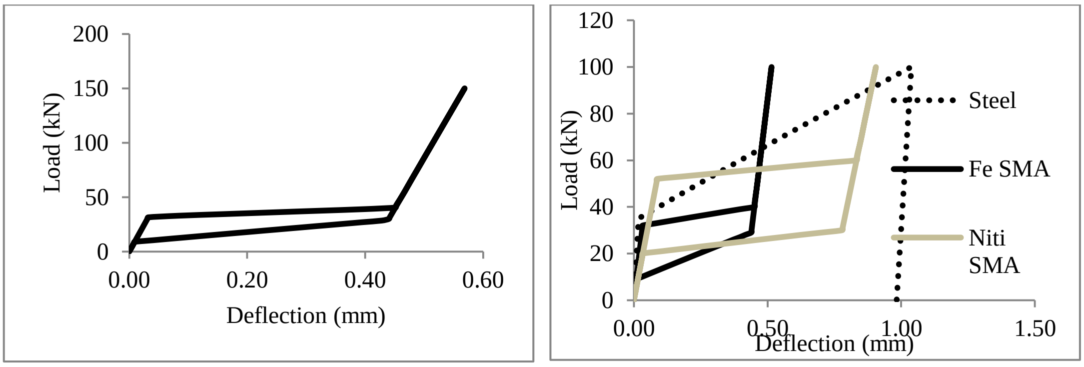

Figure 5. Load bearing capacity of plates (i) Load deflection for ferrous SMA plate after loading unloading cycle (ii) Comparative curve of load deflection for all plates with different material after loading unloading cycle

3.2 Results for single story frame

In case of single story simple frame, the load carrying capacity is not increased when SMA connections are used, compared to frame with steel connection but almost 90% residual deflection is recovered compared to residual deflection of frame with steel connection. The maximum lateral load of the frame was 80N for all types of connections. The maximum roof deflection for frame with steel connection is 30.78mm and residual deflection is 9.74mm. For frame with ferrous SMA connection, maximum deflection is 29.73mm and on unloading, the residual deflection is 1.47mm. Similarly, for Ni-Ti SMA, the maximum roof deflection is 26.24mm and residual deflection is 0.0871mm at the end of loading unloading cycle. The recovery of residual deflection of ferrous SMA connection is 84.9%, and for Ni-Ti SMA, it is 99.11%.

Table 4. Comparative results of single story frame with steel, Ni-Ti SMA and ferrous SMA end plates

End plate material	Max Load (N)	Max Deflection (mm)	Residual Deflection (mm)	Recovery of deflection (%)
Steel connection	80	30.78	9.74	67.74
Ni-Ti SMA connection	80	26.24	0.0871	99.11
Ferrous SMA connection	80	29.73	1.47	84.9

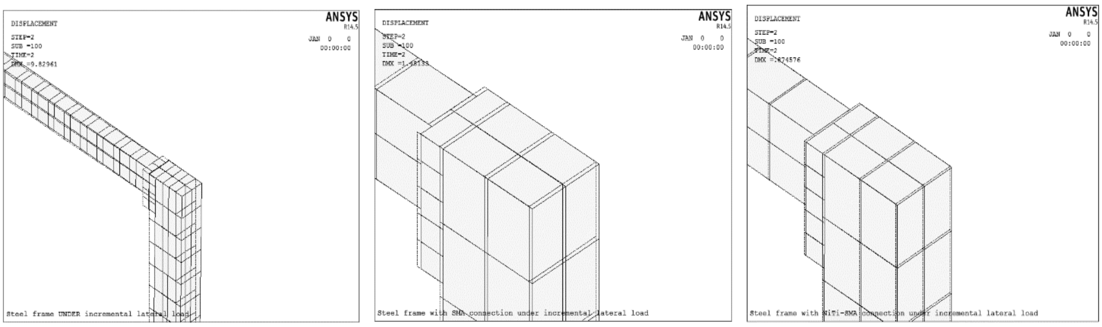

Figure 6. Deflection of connections after loading unloading cycle (i) Steel connection (ii) Ni-Ti SMA connection (iii) Ferrous SMA connection

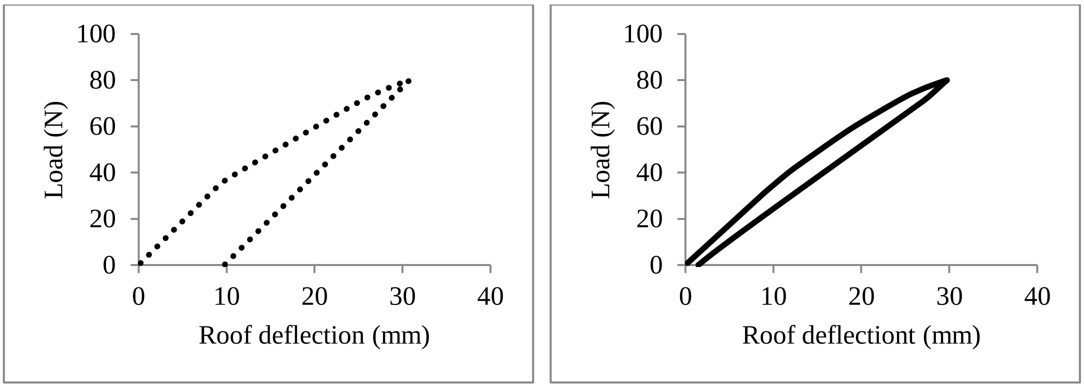

Figure 7. Load bearing capacity of frames (i) Load Deflection for frame with steel end-plate for loading unloading cycle (ii) Load deflection for frame with ferrous SMA end plate for loading unloading cycle

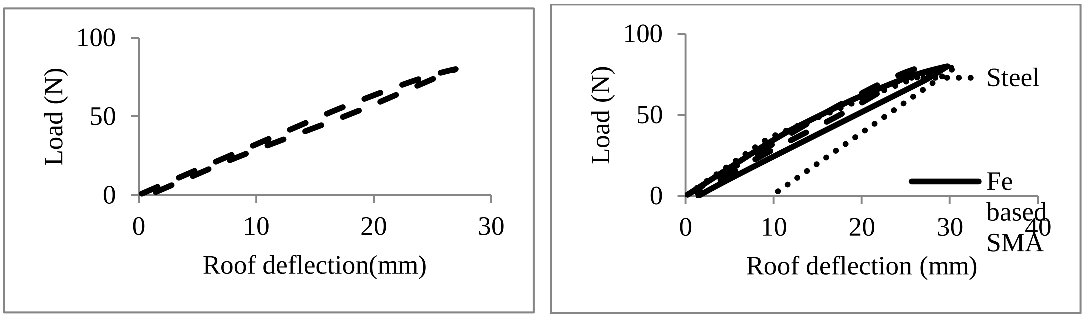

Figure 8. Load bearing capacity of frames (i) Load deflection for frame with Ni-Ti SMA end plate for loading unloading cycle (ii) Comparative load deflection of all frames with different material end plates for loading unloading cycle

4 CONCLUSIONS

The load-carrying capacity is increased by 50% and 70% for ferrous SMA and Ni-Ti SMA, plates respectively, compared to a steel plate along with recovery of residual deflection upto 90% compared to steel plate. When Ni-Ti SMA is used at connections of steel frame in the form of extended end plate, the recovery of residual deflection is almost 99%. Though the load carrying capacity is not increased when Ni-Ti SMA and ferrous SMA plates are used in steel frames the recovery of residual deflection is almost 90% which is not possible in case of steel connection. The reason behind no change in load carrying capacity even when both types of SMA is used at connections may be the composite action of steel and SMA where steel starts yielding earlier compared to SMA. Only 4% increase in recovery of residual deflection of frame provided with Ni-Ti SMA connection is found when compared to ferrous SMA connection. This implies that ferrous SMA material can be used for improving steel frame performance instead of costlier Ni-Ti SMA material for civil engineering use where mass quantity is needed.

5 REFERENCES

Alam MS, Youssef MA and Nehdi M 2007, Utilizing shape memory alloys to enhance the performance and safety of civil infrastructure: a review. *Canadian Journal of Civil Engineering* 34(9): 1075–1086.

ANSYS, Inc. 2012, ANSYS mechanical APDL (Release14.0). Canonsburg, PA: ANSYS, Inc.

Auricchio F., 2001, A robust integration-algorithm for a finite-strain shape-memory-alloy. *International Journal of Plasticity* 17(7): 971–990.

DesRoches R. and Smith B. 2004, Shape memory alloys in seismic resistant design and retrofit: a critical review of their potential and limitations. *Journal of Earthquake Engineering* 8(3): 415–429.

DesRoches R., Taftali B. and Ellingwood BR., 2010, Seismic performance assessment of steel frames with shape memory alloy connections. Part I—analysis and seismic demands. *Journal of Earthquake Engineering* 14(4): 471–486.

Dong Z., Klotz UE., Leinenbach C., et al. 2009, A novel Fe-Mn-Si shape memory alloy with improved shape recovery properties by VC precipitation. *Advanced Engineering Materials* 11: 40–44.

Ellingwood BR., Taftali B. and DesRoches R. ,2010, Seismic performance assessment of steel frames with shape memory alloy connections. Part II—probabilistic seismic demand assessment. *Journal of Earthquake Engineering* 14(5): 631–645.

Fang, C., Yam, M. C. H., Lam, A. C. C., Xie L.,2014, Cyclic performance of extended end-plate connections equipped with shape memory alloy bolts, *Journal of Constructional Steel Research*, 94, 122–136

Gholami M., Deylami A. and Tehranizadeh M., 2013, Seismic performance of flange plate connections between steel beams and box columns. *Journal of Constructional Steel Research* 84: 36–48

Li K, Dong Z, Liu Y, et al., 2013, A newly developed Fe based shape memory alloy suitable for smart civil engineering. *Smart Materials and Structures* 22(4): 1–6.

Ma M., Wilkinson T. and Cho C., 2007 Feasibility study on a self-centering beam-to-column connection by using the super elastic behavior of SMAs. *Smart Materials and Structures* 16(5): 1555–1563.

McCormick J., Aburano H., Ikenaga M., et al., 2008, Permissible residual deformation levels for building structures considering both safety and human elements. In: Proceedings of the 14th world conference on earthquake engineering, Beijing, China, 12–17 October

Moradi, S., Alam, M. S., 2014,Feasibility study of utilizing superelastic shape memory alloy plates in steel beam-column connections for improved seismic performance. *Journal of Intelligent Material Systems and Structures*, 463-475

Moradi S., Alam S., Feasible Application of Shape Memory Alloy Plates in Steel Beam-Column Connections, Structures Congress 2015

Ocel J., DesRoches R., Leon RT., et al.,2004, Steel beam column connections using shape memory alloys. *Journal of Structural Engineering*: ASCE 130(5): 732–740.

Omori T., Ando K., Okano M., et al. ,2011, Superelastic effect in polycrystalline ferrous alloys. *Science* 33: 68–71.

Ozbulut OE., Hurlebaus S. and DesRoches R. ,2011, Seismic response control using shape memory alloys: a review. *Journal of Intelligent Material Systems and Structures* 22(14): 1531–1549.

Roeder CW. ,2002, Connection performance for seismic design of steel moment frames. *Journal of Structural Engineering: ASCE* 128(4): 517–525.

Song G., Ma N. and Li H., 2006,Applications of shape memory alloys in civil structures. *Engineering Structures* 28(9): 1266–1274.