

Seismic Performance Improvement of Steel Moment Resisting Frame Using Shape Memory Alloy

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Abstract

Shape Memory Alloys have a wide range of applications due to their special properties. The properties like shape memory effect, super elasticity (SE) and high damping are useful to enhance structural behavior and seismic resistance. In this paper, super elasticity effect of two different alloys NiTi and Fe based SMA is used to enhance the structural properties of a steel Moment Resisting Frame and comparison of response of frame with connection of two different alloys is studied.

The finite element analysis of moment resisting frames is done using Ansys-15. The geometry and loading conditions of frames are taken from previous research. For the comparison of structural behavior of the steel frame with Shape Memory Alloy at beam column connection are checked for lateral loading. Also, the response of the frame is checked for time history analysis using past earthquake data. Comparison of the time history analysis response of bare frame (Steel only connections) and frame with SMA at connection suggested excellent performance of frame equipped with SMA.

The main aim of the study is reducing residual displacement of steel frames after earthquake loading. To check the performance of the frame for loading unloading cycle, incremental lateral loading is applied to the frame up to maximum load and then it is unloaded completely. The SMA equipped frame shows almost 85% recovery of the residual displacement. The reduction in residual displacement of the SMA equipped frame is also seen in case of time history analysis. Though Ni-Ti SMAs show a little more recovery in residual displacement, cost comparison shows using Fe based SMA in Civil Engineering industry will be beneficial for the maximum utilization of material with lesser cost.

Keywords: Super elasticity; NiTi SMA; Fe based SMA

Introduction

In recent years, need to strengthen existing structures and using methods to make new structures efficient to withstand all types of loads has become necessary. New innovative materials are being used to make the structures smart. Shape memory alloys like NiTi are materials having unique properties which are used in medical and other industries from long time. Being very costly, these materials are not used in construction industry. But the researchers are now trying to use these materials efficiently to make it suitable for civil engineering application. Also, efforts are made to minimize the cost of material by replacing the costly materials so that it can be produced in mass scale for construction industry. One of the set of these type of materials is Fe based SMAs which are cheaper due to lesser percentage of costly metals like Nickel and Titanium. Suitability of these materials for the earthquake resistant moment resisting frame is checked here.

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 in the range of 4% to 8% compared to traditional steel with 2% recoverable strain known as super elasticity is one of 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 due to its shape memory effect. 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.

History: A Swedish scientist was the first one who discovered pseudo elastic behavior of gold-cadmium SMA in 1932. In 1951 Chang and Read discovered the shape memory effect of the same material gold-cadmium [1]. Though the properties of SMA were discovered in 1932 not much research was done till 1963. In 1963 when Naval Ordnance Laboratory, USA discovered shape memory effect of Nickel-titanium (NiTiNol), the understanding of material properties and the research to use its special properties started flourishing. Many other alloys like Cu-Zn, Cu-Zn-Sn, Ni-Al and Fe-Pt Al were then found to have the SMA properties. The efforts were then taken to exploit the special properties to the application of SMA. As the research was advanced constitutive relationships of SMA were proposed and the use of the material in variety of industries was suggested.

The development of constitutive models for shape memory alloys: The basic approach proposed by Tanaka and Nagaki (1982) on SMA was by using internal variables [2]. The internal variables typically include one or more phase fractions and/or macroscopic transformation

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Received February 02, 2017; Accepted March 24, 2018; Published April 01, 2018

Citation: Bajoria KM, Jadhav RV (2018) Seismic Performance Improvement of Steel Moment Resisting Frame Using Shape Memory Alloy. J Steel Struct Constr 4: 141. doi: 10.4172/2472-0437.1000141

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strains. As a next step the model firstly developed by Tanaka and coworkers (Tanaka and Nagaki, 1982; Tanaka, 1985; Tanaka and Hayashi, 1993; Tanaka and Nishimura, 1994; Tanaka and Nishimura, 1995) was originally conceived to describe three-dimensional problems involving SMAs [2-4], where internal variables are employed to describe the development of the underlying phase mixture. Boyd and Lagoudas (1994) rewrite Tanaka's original model, for a three-dimensional theory, while the relations used to describe phase transformation evolution remain the same as in Tanaka's model [5]. Liang and Rogers (1990) presented an alternative evolution law for the volumetric fraction based on cosine functions. The authors also developed a three-dimensional model, in which they suggest that phase transformations are driven by the associated distortion energy [6].

The revolutionary work was done by Brinson (1993) which is considered as basic framework on which most of the recent models have been proposed to describe SMA behaviour [7]. The authors consider exponential functions to describe phase transformations. Since an exponential function is adopted, there should be an extra consideration for the phase transformation final bounds. An alternative approach to the phase transformation kinetics, in which, besides considering cosine functions, the martensite fraction is split into two distinct quantities, the temperature-induced martensite and the stress-induced martensite was proposed. The authors also consider different elastic modules for austenite and martensite phase.

Balpaghol proposed finite element model for analysis of shape memory alloy laminated plates. The model can be used for thin and moderately thick plates [8]. The model is based on first order shear deformation theory. Two-dimensional actuator was proposed which consists of a thin SMA layer perfectly bonded to an elastomer layer. The theoretical modeling of the actuator is based on the first order shear deformation theory and the variable sub-layer model for the two-dimensional martensite transformation. The equations for the static analysis are derived using the minimum potential energy principle. The validation for the static analysis is done by comparing the deflection results of a plate with the theoretical analysis and other finite element models available in the literature. The numerical results demonstrated that the input power, heat sink strength, thermal conductivity and thickness of the elastomer layer play important roles in controlling the time response of the SMA laminated actuator. It is found that decreasing the thickness of the elastomer and increasing the input power accelerate the response of the SMA laminated actuator. Das derived formulation for both the material and geometric nonlinearity for SMA truss member and beam member to investigate pseudo elastic behaviour [9]. The verification was done by numerical analysis of a beam and truss from previous literature. The numerical study showed substantial difference in response of the structure when geometric and material nonlinearity was considered for SMA members.

Types of Shape Memory Alloys

The most widely studied SMAs have been Ni-based, Cu-based, and Fe-based alloys.

Nitinol - Ni-Ti SMA

The most well-known type of NiTi SMA is Nitinol, which was developed in the 1960s by Buhler and Wiley of the USA. Naval Ordnance Laboratory. This equi-atomic alloy consists of approximately 55% nickel and 45% titanium by weight. 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. Whereas, 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%.

Ternary nickel-titanium based shape memory alloys

As NiTi is very costly material, researchers are continuously trying to find other alternatives so that the cost of the alloy can be decreased maintaining the special SMA properties. For this purpose, a third metal is added to NiTi so that percentage of Nickel and Titanium can be reduced. In this effort many researchers tried adding copper, aluminum, cobalt, vanadium, zirconium, niobium, chromium, and iron. But the most common alloys other than NiTi are copper based and ferrous based SMAs.

Copper based shape memory alloys

The most common copper based SMAs include CuZnAl, CuAlNi and CuAlMn, compared to NiTi, the main advantage of these alloys is that they are relatively inexpensive, and that they can be fabricated using conventional metallurgical methods. Copper based SMAs are suitable for use in actuators, safety valves, and pipe couplings.

Iron based shape memory alloys

Although Cu-based SMAs are less expensive, they show poor ductility hence it cannot be used for seismic applications. As another alternative, low cost ferrous SMAs have been found to be a good candidate for this purpose [10]. Most Fe-based alloys, including the Fe-Mn-Al, have a nonthermoelastic martensitic transformation [11].

Two types of iron based SMA are being tested for its applicability in civil engineering applications. Alloys showing similar characteristics of thermoelastic martensitic transformation like NiTi which are Fe-Ni-Co, Fe-Pt and Fe-Pd. The studies showed that Fe-Pt and Fe-Pd cannot have superelastic properties at room temperature. Tanaka et al. presented an alloy having very high tensile strength of 1200 MPa with recovery strain of over 13% at room temperature which is Fe-29Ni-18Co-5Al-8Ta-0.01B (mass %) [10].

Omori et al. proposed Fe-36Mn-8Al-8.6Ni (mass %) iron based SMAs with superelasticity at room temperature and good ductility [11]. Along with these properties it has a recovery strain of over 5% and a fracture tensile strain of 8%. In contrast to Ni-Ti, these ferrous alloys can exhibit behavior with no significant sensitivity to temperature. Li et al. developed a new ferrous SMA with simple manufacturing process and good mechanical behavior, showing SME suitable for smart structural applications [12]. These findings imply that the mass scale production of ferrous SMA with proper characteristics for Civil Engineering applications is possible in future.

The second category of alloys are Fe–Ni–C and Fe–Mn–Si, having shape memory effect but has a larger thermal hysteresis in transformation. These are quite popular in civil applications due to its low cost, good workability, good machinability and good weldability. Dong et al. introduced this new ferrous SMA, Fe–Mn–Si, with good shape recovery stress and shape recovery strain, which does not require any training/treatment process [13].

Characteristic Properties of SMA

Phase transformation

The phase transformation between two different phases is from Austenite phase to Martensite phase and vice versa at different temperatures. Austenite is a stronger phase stable in high temperature. This phase has relatively strong resistance to external stresses, it has highly symmetric crystallographic structure. Whereas Martensite is weaker phase stable in low temperature. The material can be deformed easily in martensite phase as it has parallelogram crystalline structure. When 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 it will retain. However, when the material is heated above its transformation temperature it undergoes a change in crystal structure which causes it to return to its original shape. Four transition temperature characterize the transformation loop martensite start temp MS and the finish temperature MF. Austenite start temperature AS and finish temperature AF. These critical temperature pin point the beginning and end of the forward martensite and the inverse Austenite transformation. The material deforms in the martensitic form, springs back to its “remembered” shape in its austenitic form.

Shape Memory Effect (SME)

NiTi alloys return back to their predetermined shapes upon heating. At a certain temperature, SMA wire is stretched to apparent yield so that residual strain remains. Then, heating to a particular temperature causes the residual strain to disappear. This phenomenon is called shape memory effect (SME).

Superelasticity

Super-elastic nitinol springs back to its original shape if bent at room temperature. If NiTi SMA is deformed above Af, the deformation can be recovered spontaneously after unloading; and in addition, the martensite interface motion during inelastic deformation can enable energy dissipation.

Applications of SMA in Industry

Lot of research projects focusing on the use of SMAs for biomedical, aerospace, and commercial industries are undergone during many years. From many decades SMA in medical and other industries is used due to its special characteristics.

SMAs are being used in arterial stents, which are at a lower temperature when inserted into the artery and expand due to body heat. The stents are used to support and enlarge blocked arteries.

They are also being used as orthodontic wire because they provide a constant corrective force on teeth [14]. In the commercial industry, the super elastic properties of SMAs have made them excellent materials to use in eyeglass frames, cell phone antennas and golf clubs [15,16]. The aerospace industry has used SMAs in helicopter blades and aircraft wings to reduce noise and vibrations [17,18].

Properties useful for structural applications

NiTi has been found most appropriate SMA for structural application because of its large recoverable strain, super elasticity and exceptionally good resistance to corrosion. Super elasticity is the distinct property that makes SMA a smart material. A superelastic SMA can restore its initial shape spontaneously even from its inelastic range upon unloading. When SMA specimen is subjected to a cycle of axial deformation within a certain amount of energy without permanent deformation. This results from the phase transformation from Austenite to martensite during loading and the reverse transformation during unloading ensuing a net release of energy. SMA with superelasticity has an advantage over other common metals/alloys in the sense that besides dissipating a considerable amount of energy under repeated load cycles it has a negligible residual strain.

- It can undergo large deformation and recover its original shape by stress removal, thus mitigating the problem of permanent deformation. The constrained NiTi material with residual deformation can generate large recovery force upon heating the material due to its shape memory effect. So, these are regarded as a kind of prospective material to develop actuator with large deformation and force due to shape memory effect.
- Since it is known to have stable super elasticity within a temperature range of approximately 30°c above the reversible transformation temperature, as a self-restoration member in structure if the transformation temperature can be suitably controlled. Also, this makes a candidate material in fire as it shows superelastic behaviour over large strain ranges of up to about 5%, a significant amount of deformation recovery is possible.
- NiTi has shown to develop a flag-shape hysteresis under cyclic axial loading, which can provide both recentering and supplemental energy dissipation to a structural system, resulting in limited inter story drifts and decreases in permanent displacement of the structure. Hence it is used in the bracing system in steel frames.
- In general, it provides several properties ideal for earthquake engineering applications. These properties include repeatable recentering capability, loading plateaus which limit force transfer to other members of the structure at intermediate strain levels, supplemental damping attributed to the flag-shape hysteresis, stiffening at large strain levels due to the formation of stress-induced martensite, and excellent low- and high-cycle fatigue properties. This unique behaviour shows that it can reliably be used to control the response of a structure during seismic events.

NiTi in Civil applications

Graesser and Cozzarelli were the first ones to suggest the use of binary NiTi SMAs as seismic dampers [19]. The effect of loading frequency and loading history on energy dissipation characteristics of NiTi wires were studied for its use as dampers. Inaudi and Kelly used a unidirectional shake table to study a four-story steel-frame model which implemented tuned mass dampers using SMA wires showing its excellent performance. Sabelli used large diameter NiTi superelastic SMA bracing system to minimise the yielding and permanent damage of bracing in concentrically braced frames. The CBF equipped with SMA bracing performed well during seismic events due to its recentering capability and added damping associated with the flag-shape hysteresis

of the large diameter NiTi superelastic SMAs [20]. Barrata and Corbi showed that the performance of structure can be modified with the use of SMA braces by studying their dynamic performance of a portal frame [21]. The results showed that superelastic SMA braces effectively reduced the dynamic response of the frame. Desroches and Smith evaluated the response of concentrically braced frame under LA06 ground motion with NiTi SMA and steel bracings [22]. The CBF with super elastic SMA bracings showed 99% recovery of residual displacement with 79% decrease in maximum roof displacement. The superelastic SMA braces reduced the maximum inter-story drift by 69% compared to the maximum inter-story drift values obtained when conventional steel braces were used. Ocel et al. experimentally compared the effectiveness of using large (1 inch) and mid-size (0.5 and 0.28 inch) superelastic NiTi bars for connections and dampers of frames [23]. The bars were tested for tensile, compressive and cyclic loading. All the bars showed good superelastic behavior under extreme loading similar to the loading experienced during earthquake. Both types of rods showed large recentering under cyclic loading but the midsize rods showed better performance under tensile loading showing residual strain less than 0.75 percent even in case of increased strain cycles compared to 1 percent in case of large size bars. It was also observed that for all cases the equivalent viscous damping remained below 4% suggesting its use in damping applications for extreme loading. The main advantage of using SMA rods is observed in case of its recentering response under compression loading which is not possible in case of steel tension bracing system. This implies that NiTi rods can be effectively used recentering and supplemental damping devices in order to control structural response during extreme loading events. Shape memory effect was studied by Ocel (2004) using temperature for SMA rods at beam column connections [23]. The tendons were able to recover 76% of the beam tip displacement subjected to eight 4% drift cycles. This implies these hybrid connections could be reused following a seismic event, if the tendons can be appropriately heated to initiate the shape memory effect.

The superelasticity of SMAs to recover large strains upon unloading is the unique property which is useful for seismic application. In order to reduce residual deformations in steel buildings, several researchers have investigated the applications of Ni-Ti SMAs. Ocel et al. and Moradi and Alam recovered beam tip displacement upto 76% using Ni-Ti SMA at steel beam column joints [23,24]. 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 [25]. Recovery of deformation upon unloading was observed when Ni-Ti SMA bolts were used in an end plate connection of frame [26]. An experimental study on the cyclic performance of extended end plate connections with Ni-Ti SMA bolts showed excellent recentering capability with moderate energy dissipation [27]. Due to the recentering capacity of Ni-Ti SMA, the seismic performance of steel moment frames with Ni-Ti SMA based connections was improved [28].

Recently SMA was used first time for seismic retrofit and rehabilitation of old structures in Italy. Indiril reported the use of SMA in the façade of the S. Feliciano Cathedral, and the Basilica of S. Francesco in Assisi, for seismic isolation. Desroches et al. used prestressed tie bars containing SMA in the interior corners of bell tower Giorgio Church in Trigano Italy to increase the flexural resistance of the structure affected by Emilia and Modena earthquake on October 15, 1996 [28]. Showing

the success of the retrofitting technic, the structure was intact even after experiencing earthquake of similar magnitude in June 2000.

Ferrous SMA in civil engineering

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 [29]. Rojob and El-Hacha compared strengthening of RC beams with prestressed NSM CFRP rods and self prestressing NSM Fe-SMA strips using small scale (2.0 m long) and large-scale (5.0 m long) beams. Due to superelastic behavior of Fe-SMA the beams strengthened with NSM Fe-SMA strips exhibited more ductile behavior. Moreover, NSM CFRP bars need prestressing before use which is a little time consuming and also need space for prestressing.

Cladera et al. suggested the use of iron-based shape memory alloys especially Fe-Mn-Si alloys in civil engineering industry over NiTi alloys showing similar performance with low manufacturing cost [30]. The paper also mentioned that the wider temperature transformation hysteresis and a higher elastic stiffness than other SMAs, i.e., Ni-Ti alloys show more potential to use these alloys in civil engineering applications. The other advantages of Fe SMA are good workability, corrosion resistance and weldability. Bajoria and Jadhav proposed a FeSMA end plate at beam column junction to control the lateral displacement of frame under seismic loads [31]. The replacement of 40% steel by FeSMA showed excellent performance with almost 90-95% recovery of residual displacement. The comparison with NiTi SMA showed a little difference for recovery implies that cheaper material FeSMA can be used in civil engineering structures. Recently the alloy is widely used in the form of tendons for repairing of existing reinforced structures or for reinforcing new structure.

Present Study

Finite element model

3D models are generated, meshed, and analyzed using the finite element software, ANSYS [32]. The material model used for steel is bilinear kinematic hardening model to include material nonlinearity and plasticity, which is shown in Figure 1a. The modulus of elasticity and Poisson's ratio taken are 210000 mpa and 0.3, respectively. The mechanical properties used for steel are provided in Table 1. In ANSYS, the super elastic behavior of SMA is simulated using Auricchio's model [33]. The material undergoes large deformation without showing permanent deformation under isothermal conditions [32]. 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 in Table 2. The assumed mechanical properties for ferrous SMA are selected considering the experimental data reported by Omori et al. [11]. The element used is eight node Solid 185 for all materials Steel, Ni-Ti SMA and ferrous SMA as it supports unique properties of SMA (Figures 1 and 2).

The structures chosen to verify the finite element results and also to examine the new application of SMA-plates are taken from past research [25]. The simple connection consists of mild Steel and SMA plate for three story Moment Resisting Frame. The three-story structure consists of 9 m span and 3.9 m story height for all floors [34,35]. The supports are fixed supports and connections are simple end plate connections. All the details of the frame are shown in Table 2 (Figure 2).

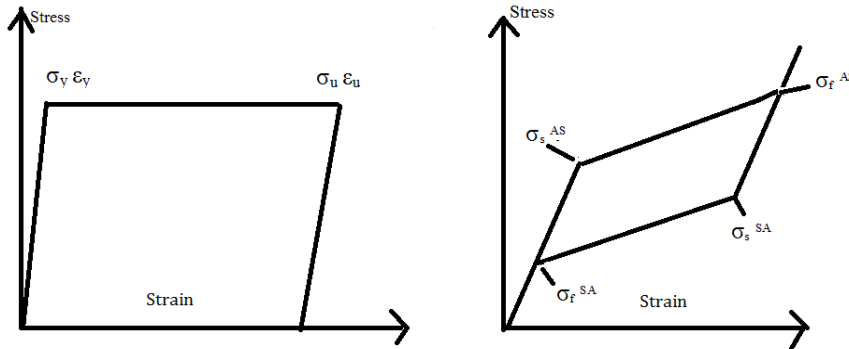


Figure 1: (a) Material model for steel, (b) SMA material model for Fe SMA and NiTi SMA.

Steel Properties			
Property	Structural steel	Mild steel	Units
Young's Modulus (E)	2.10E+11	2.10E+11	Pascal
Yield Strength (Fy)	355	250	N/ mm ²
Poissons Ratio	0.28	0.28	
Density	7.80E-06	7.80E-06	Kg/mm ²
SMA Properties			
Property	Nitinol – NiTi	Fe based SMA FeMnAlNi	Units
Young's Modulus (E)	6.70E+10	9.80E+10	Pascal
Poissons Ratio (u)	0.33	0.3	
SIG-SAS (σsAS)	3.66E+08	3.21E+08	Pascal
SIG-FAS (σfAS)	4.22E+08	4.00E+08	Pascal
SIG-SSA (σsSA)	2.11E+08	2.90E+08	Pascal
SIG-FSA (σfSA)	1.41E+08	9.00E+07	Pascal
EPSILON	0.07	0.36	m/m
ALPHA	0	0	

Table 1: Material properties.

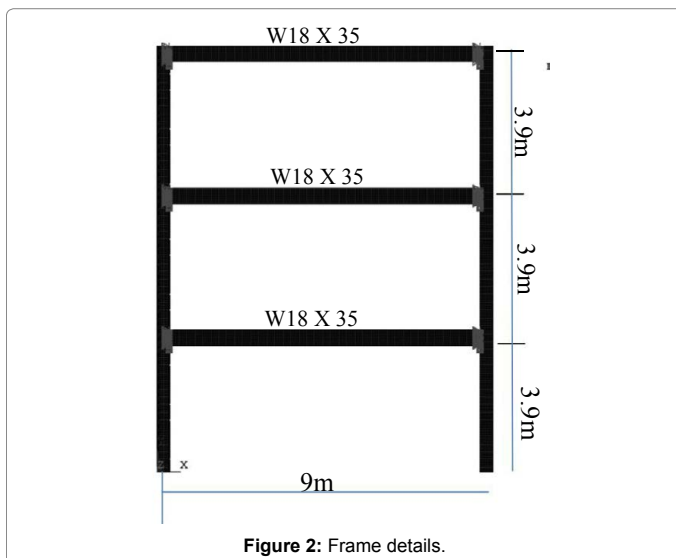


Figure 2: Frame details.

One Bay Three Story Frame		
Geometry	Number of Floors	3
	Span	9 m
	Floor Height	3.9 m
Column	Level 1,2 and 3	W14 x 74
Beam Sections	Level 1,2 and 3	W18 X 35
End Plate full depth	10 mm X 440 mm X 150 mm	

Table 2: Frame details.

frame the force is removed in the same decrement till zero, to study the residual displacement and behavior of the frame for loading unloading cycle [36-38].

The maximum displacement observed in case of frame with traditional steel connection is 302.6 mm and the residual displacement is 105.61 mm. Also the maximum strain is 0.00234 at maximum stress 469 N/mm² and 0.011 at residual stress 402 N/mm². The maximum roof displacement of frame with Fe-SMA connection is reduced by 12% and that for frame equipped with NiTi SMA connection by 25% compared to traditional steel frame connection which is 266.6 mm and 226.46 mm respectively [39,40]. The performance improvement of frame equipped with SMA connection is seen more prominently in case of residual displacement, the residual displacement observed in case of frame with Fe-SMA connection is 67.44 mm and that for NiTi SMA connection is 49.65 mm. This shows excellent performance of SMA showing 36.7% and 56% reduction in residual roof displacement 105.6 of frame equipped with steel end plate after loading unloading cycle in case of SMA equipped frames. The SMAs show excellent performance

due to its super elasticity property, reducing residual strain by 80.9% in case of Fe-SMA and 90.8% in case of NiTi SMA [41].

The response of three story frame for earthquake acceleration is studied using Time history analysis with el centrino earthquake acceleration data [42]. The time period is 31.22 seconds with 0.3188 g peak ground acceleration the time step considered is 0.02 seconds. The maximum roof displacement of three story frame under acceleration is 130.36 mm and residual roof displacement is 46.3 mm. The residual strain observed is 0.0017 mm/mm for time history analysis of frame with traditional steel connections. The maximum roof displacement

of three story frame with Fe SMA connection under acceleration is 138.48 mm and residual roof displacement is 27.53 mm and residual strain 0.0058 mm/mm is seen for time history analysis [43,44]. 36.71% reduction in residual displacement is seen in case of frames equipped with Fe SMA under earthquake acceleration. 72.5% reduction in residual displacement is seen in case of frames equipped with NiTi SMA under earthquake acceleration. The maximum roof displacement seen in this case is 143.2 mm and residual roof displacement is -6.7 mm also residual strain observed is 0.0058 mm/mm (Tables 3 and 4) (Figures 3-7).

Connection Material	Max Load (kN)	Max Disp (mm)	Decrease in max disp (%)	Residual Disp (mm)	Decrease residual disp (%)	Residual Strain (mm/mm)	Decrease in residual strain (%)
Steel	600	302.6	-	105.6	-	0.011	
Fe-SMA	600	266.6	12	67.4	36.7	0.0021	80.9
Ni-Ti SMA	600	226.46	25	49.5	56	0.00002	90.8

Table 3: Comparative performance of connections under incremental lateral loading unloading cycle.

Connection Material	Residual disp (mm)	Decrease in residual disp (%)	Max disp (mm)	Max acl	Decrease in max acl (%)
Steel	46.3	-	130.36	2919.17	-
Fe-SMA	27.5	36.71	138.48	2126.54	27
Ni-Ti SMA	-6.7	72.57	143.2	2476.34	15.2

Table 4: Comparative performance of connections of time history analysis.

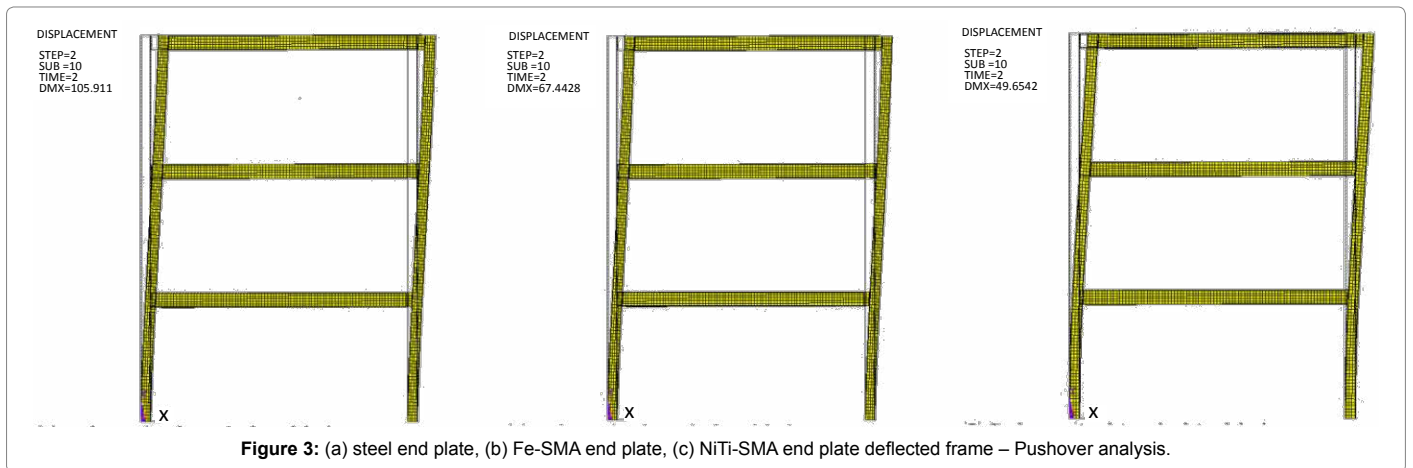


Figure 3: (a) steel end plate, (b) Fe-SMA end plate, (c) NiTi-SMA end plate deflected frame – Pushover analysis.

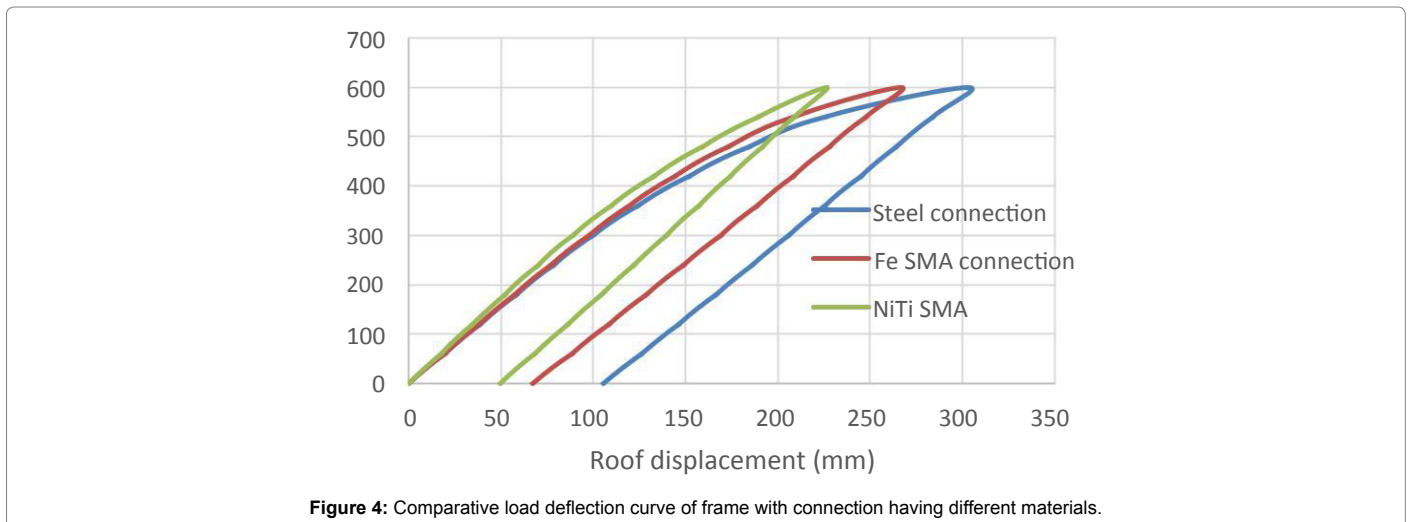


Figure 4: Comparative load deflection curve of frame with connection having different materials.

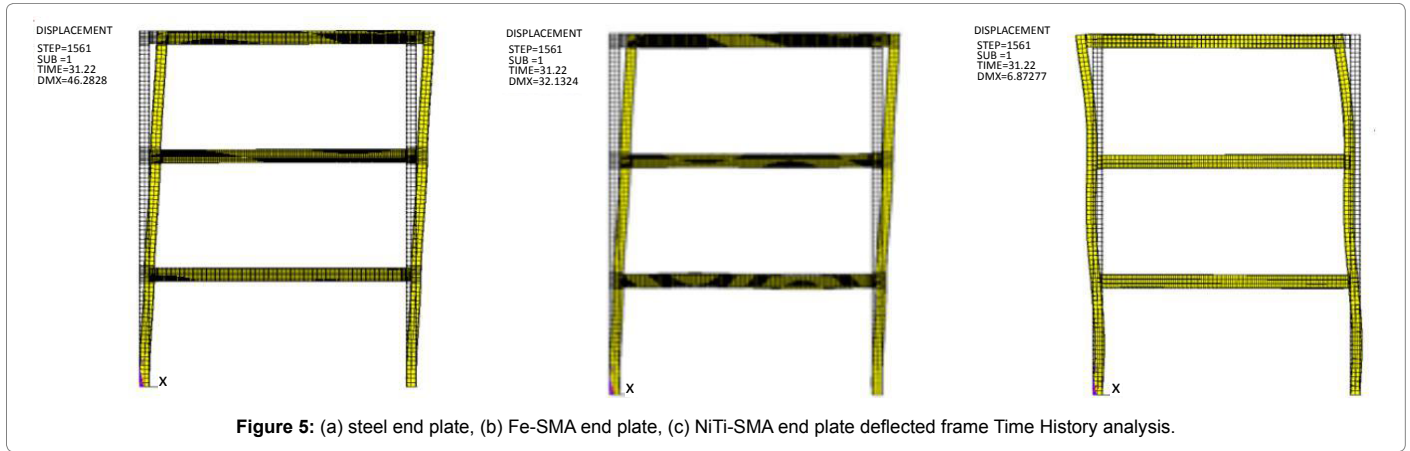


Figure 5: (a) steel end plate, (b) Fe-SMA end plate, (c) NiTi-SMA end plate deflected frame Time History analysis.

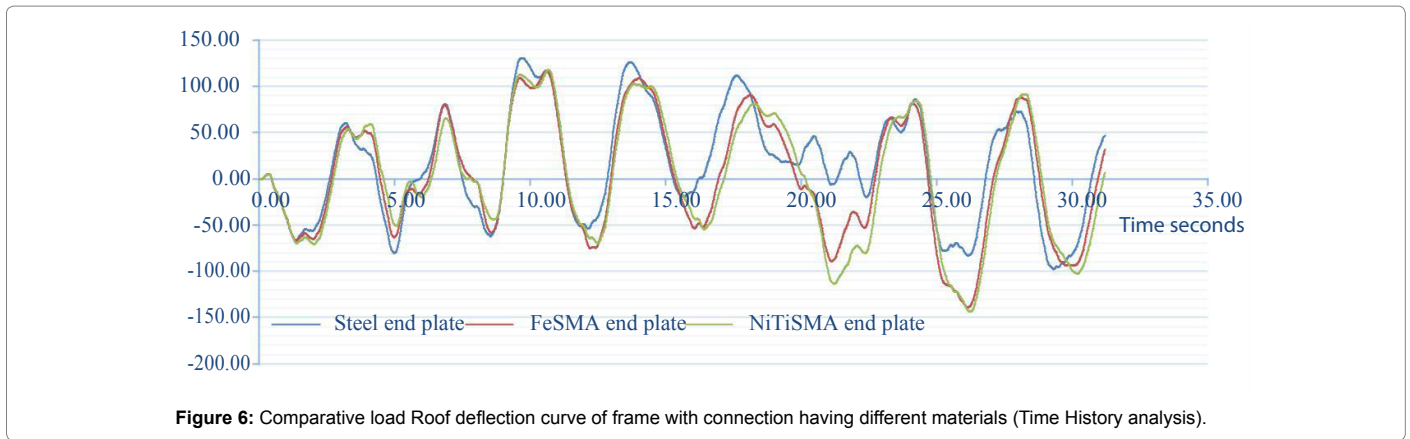


Figure 6: Comparative load Roof deflection curve of frame with connection having different materials (Time History analysis).

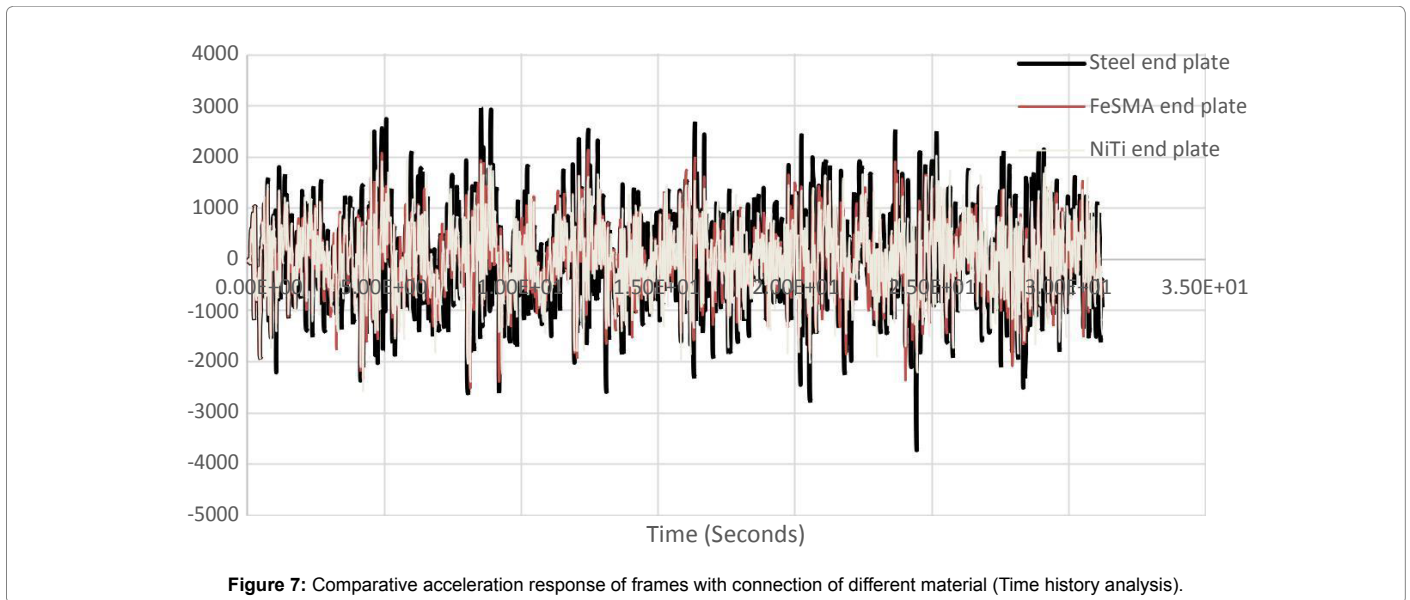


Figure 7: Comparative acceleration response of frames with connection of different material (Time history analysis).

Conclusion

Introducing SMA plate at connection between Beam and Column shows almost 90% recovery of residual displacement of the Structure after loading unloading cycle of lateral load in moment resisting frame in case of incremental lateral loading analysis. The load carrying

capacity is not increased when Ni-Ti SMA and ferrous SMA plates are used in steel frames though the recovery of residual displacement is seen. 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. 35% increase in recovery of residual deflection and is seen in

frame provided with Ni-Ti SMA connection compared to ferrous SMA connection.

To cross check the results, the behavior of frame under el Centrinno earthquake data is studied which shows 36.71% and 72.5% decrease in residual roof displacement for Fe SMA and NiTi SMA equipped frame respectively compared to traditional steel connection. It is observed that the results obtained using time history analysis and coefficient method shows similar behavior of frame.

Introducing NiTi SMA connection shows better improvement in recovery of displacement when compared to Fe SMA connections but at the cost of expensive material. Hence the results signify that Fe-SMA can be used for improved response of structure under earthquake load with lesser cost.

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