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Enhancement of steel beam column connection using Fe based Shape Memory Alloy

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Abstract *Beam column junction in steel moment resisting frames is very critical section in earthquake prone areas. The study of previous earthquakes is the examples showing failure of structures at beam column connections during earthquake event. Different systems are being studied to enhance these connections. Making this connection ductile is one of the research area. In this system ductile connections are used to avoid brittle failure of connection. In this research FeMnAlNi Fe based Shape Memory Alloy (Fe-SMA) is used to make the beam column connection ductile. SMAs have a special property to recover the displacement which is not possible in case of steel material in plastic region. In this research a composite beam of FeSMA and steel is used to control the residual displacement of steel frame. Increasing load and cyclic load analysis is done for steel frame and composite frame in finite element analysis software. The performance of steel and Fe-SMA composite beam is good under cyclic loading and unloading. The recovery of steel and FeSMA composite is 65%.*

Introduction

During last two decades researchers are working to prepare systems which will make any structure earthquake resistant in earthquake prone area. As no bracings are inserted in Moment resisting frames. The beam column junctions of those frames are more prone to damage at seismic event.

1 Performance of Steel Moment Resisting Frame (SMRF) in seismic zones

Steel moment resisting frames suffered damage in the past earthquakes, such as the 1994 Northridge earthquake. Out of 988 damaged buildings made of steel 43.7% buildings were not having bracings. Compared to other frames, the columns of these frames were damaged more. (Miller et al., 2011). To improve resistance to seismic loads, many systems are used in terms of modified connection. Even though these kind of connections improve seismic resistance and decrease damage, recovery of residual displacement is not possible.

Hence the researchers are trying to use more flexible materials like SMA having special properties such as super elasticity, shape memory effect and high damping capacity to improve the seismic performance of steel frames.

2. Improvement of connections

The research today focuses on avoiding or minimizing the damage of the connections. A weak beam and strong column design has been proposed as a solution, which forces the structure to yield at the beams so that the columns remain unaffected by the seismic load. Some researchers are proposing ductile connections by providing yielding members at the connection so that the earthquake loads will be absorbed by the connection and it will regain its original configuration. Some researchers have strategized the strengthening of the connections by using stiffeners or cover plates, etc. A review of the different studies undertaken for performance improvement of moment resisting connections is presented here.

Uang 1991 used the weak beams in moment resisting frame by curtailing beams at some distance from junction of column and beam proposed a RBS-reduced beam section in moment resisting frames. thus the the plastic hinged is forced to be developed at this reduced beam section away from the junction. Because of the yielding of section away from the junction, the damage of connection and columns is avoided. Weak panel zone was proposed by Scott 2002 to get stable hysteretic response for large drifts. This is proposed on the basis of study conducted on 16 different models. Those frames included are of strong, balanced and weak panel zones. The response of those frames under standard quasi static cyclic load is investigated and compared.

It is possible to replace the damaged members, but it is quite tedious. The improvement of the weak members is therefore the better option. To enhance the seismic capacity of these members, many researchers are using new materials and techniques. The use of yield elements, dampers etc. are some of the methods currently under research. The development of systems that minimize structural damage and show minimum residual displacement after it undergo earthquake shocks is needed which will make the structures seismic resistant. NiTi and other Memory alloys have the ability to recover the displacement experienced during earthquake event. Use of those alloys to recover the displacement of structure is one of the latest techniques with a lot of potential.

3 Shape memory Alloys (SMA)

Shape Memory Alloys (SMAs) have very unique properties. One of it is recovery of shape in stress induced Austenite phase. Due to which it comes back to its original shape ones the load is removed this property is called as superelasticity. Another very peculiar property is in temperature induced martensite phase in which the changed shape of the material can be changed to its original shape by applying the temperature this peculiar characteristic is called Shape Memory Effect. The peculiar characteristics of SMA is due to its phase changing property. In martensitic phase the structure is random and in Austenitic phase the structure is crystalline which resist high loads.

3.1 Iron based SMA

Two types of iron based SMAs which show characteristics similar to NiTi are discussed here which can be used in civil engineering applications. These are Fe-Ni-Co, Fe-Pt and Fe-Pd are in one category. These category alloy have very high tensile strength of 1200 MPa. Fe-Ni-Co based Alloy is Fe–29Ni–18Co–5Al–8Ta–0.01B (mass %) has recovery strain over 13% at room temperature. (L)

Fe–36Mn–8Al–8.6Ni (mass %) iron based SMAs with superelasticity at room temperature and good ductility. 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. (O)

4 Ferrous SMA in civil engineering

The provision of ferrous SMA plates at the plastic hinge region of the beam showed 90% reduction in residual drift compared to steel beam column connections. The recentering capacity in this case was checked for cyclic loading (Moradi et al. 2015). Rojob and El-Hacha (2015a, 2016) compared the 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) models. Due to the superelastic behavior of Fe-SMA, the beams strengthened with NSM Fe-SMA strips exhibited more ductile behavior. Moreover, NSM CFRP bars require prestressing before use, which is both time and space consuming because space is also a requirement for prestressing.

Cladera et al. (2014) suggested the use of iron-based shape memory alloys in the civil engineering industry, especially Fe–Mn–Si alloys, over NiTi alloys because they exhibit a similar performance while incurring a much lower manufacturing cost. The study also mentions their wider temperature transformation hysteresis and higher elastic stiffness than other SMAs, i.e., Ni–Ti alloys, suggesting that they demonstrate more potential for use in civil engineering applications. The other advantages of Fe SMA are good workability, corrosion resistance and weldability.

Recently, the alloy has been widely used in the form of tendons for repairing existing reinforced structures or for reinforcing new structures.2

5 Details of the study

Most common sections used for steel beams in midrise and low rise buildings are H sections. The composite beams used in this research have upto 4% FeMnAlNi Alloy at the column junction and remaining is steel material. During loading Fe based SMA starts yielding at connection and ones the load is removed the yielding is recovered. For this, comparative analysis of steel and composite beam is done using Ansys. The behaviour of both types of beams under incremental loading unloading cycle and cyclic loading is studied.

5.1 Finite element analysis model

The finite element model of beams are simulated in Ansys software. The element used is solid-185 which supports steel and SMA material. The superelasticity material model is used for SMA material and BISO model is used for simulation of steel material with elastoplastic property. The fine mesh is used at one end where material change takes place and remaining part is meshed with coarse mesh. The end is restrained for rotation and translation. The point load is applied on nodes at other end. The load calculated per step is with FEMA protocol displacement. The load is removed at last step. Same procedure is used for analysis of steel beam and composite beam.

Table 1 Material properties

Steel Properties		FeSMA Properties			
Property		Property		Property	
Young's Modulus (E)	210000 N/ mm^2	Young's Modulus (E)	$9.8E^{10}$ Pascal	SIG-SSA (σsSA)	$2.90E^8$ Pascal
Yield Strength (Fy)	355 N/ mm^2	Poisons Ratio (υ)	0.3	SIG-FSA (σfSA)	$0.9E^8$ Pascal
Poissons Ratio	0.28	SIG-SAS (σsAS)	$3.206E^8$ Pascal	EPSILON	0.36
Density	$7.8e^{-6}$ Kg/mm^2	SIG-FAS(σfAS)	$4.00E^8$ Pascal	ALPHA	0.0

Table 2 Cyclic loading protocol

Cyclic loading protocol provided in FEMA			
Number of Cycles	Peak Deformation Ø (radians)	(Accumulative) Load Steps	Tip Displacements ΔLC (mm)
6	0.00375	12	9.375
6	0.005	24	12.5
6	0.0075	36	18.75
4	0.01	44	25
2	0.015	48	37.5
2	0.02	52	50
2	0.03	56	75
2	0.04	60	100
2	0.05	64	125

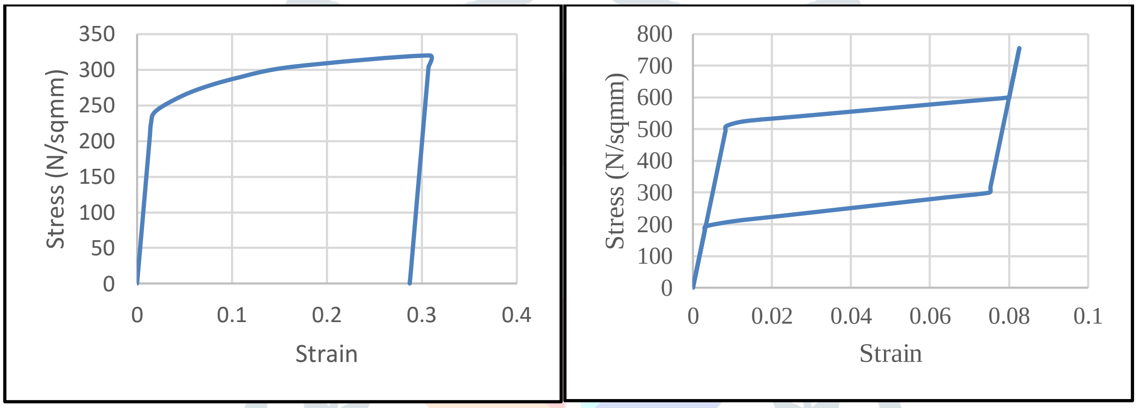


Figure 1 ANSYS Material models a) Bilinear model (BISO) for steel b) Superelastic model (SUPE) for SMA

5.2 Beam details

2m beam length is considered for the analysis.. flange of I section has 150mm X 12mm dimension and web is of 250X10mm. The maximum deflection of cantilever beam is calculated as 30mm using analytical formula

$$Maximum\ deflection = \frac{W*l^3}{3EI}$$

Where, W = 70000 N ; L= 2000 mm ; E = 200000 N/mm2 ; I = 312.81e^5 mm4

The material properties are mentioned in table 1.1..

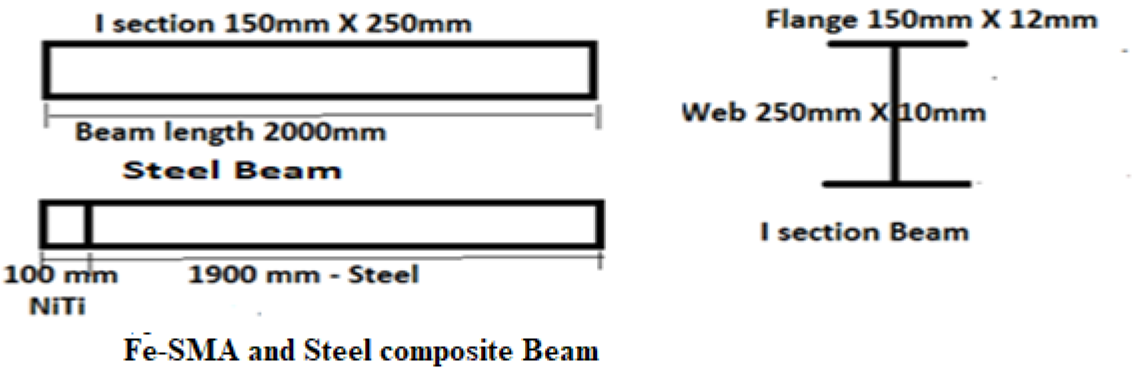


Figure 2 Beam Details a) Steel and FeSMA-Steel composite beam b) I beam cross section

5.3 Beam Analysis

The behaviour of steel beam under incremental loading and unloading is analysed using Ansys. Also cyclic load analysis using cyclic loading protocol as in table 2 is used for comparative analysis The maximum deflection and residual deflection is obtained. The same loading protocol is used for FeMnAlNi (Fe-SMA) and steel composite beam. The maximum and residual displacement is compared.

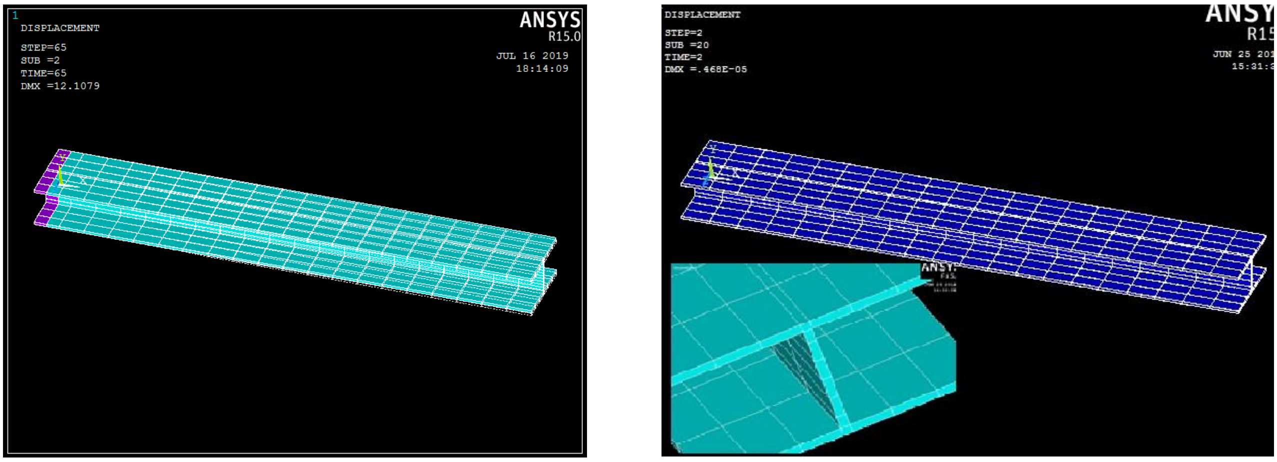


Figure 3 Ansys Beam Modelling a) Fe-SMA-Steel composite beam b) Steel beam cross section and meshed model

6 Analysis Results

The response of Fe-SMA and Steel composite beam and Steel beam is analysed under incremental loading unloading cycle and cyclic loading. Cyclic loading is applied as per cyclic loading protocol provided by FEMA. The analysis of Fe-SMA and Steel composite beam is analysed for different Fe-SMA percentage.

In the case of the steel beam, 30% recovery is seen when the load is removed that is recovery in elastic zone. This shows a 70mm residual displacement. A superelastic hinge is formed in SMA material at peak load, here the strain in SMA is 50-60% more than strain in steel. As the load is removed, due to the special superelastic property of SMA, the strain is reduced to zero but a residual plastic strain is observed in steel due to the residual displacement that remains in steel. The residual displacement observed in the composite beam is in the steel zone. This strain behaviour is shown in fig.4

The strain pattern totally changes when SMA is combined with steel. For steel beam maximum strain location at peak load and residual strain after unloading is same and plastic hinge is located at the maximum strain location. When a composite beam is analysed under incremental loading unloading cycle the maximum strain is observed in the SMA part as if a hinge is formed. While unloading this superelastic hinge recovers the displacement and no strain is remained after unloading in this location. On the other hand, due to the yielding of steel a plastic hinge is developed in the steel part of the beam and due to this residual strain the residual displacement is observed in the composite beam.

For composite beam with 3.3% and 3.75 % FeSMA, the residual displacement is 12mm and 10.6mm which is 62.5% and 66.5% less than the residual displacement of 32.4 mm in steel beam after unloading. The peak displacement in composite beam is 5% less than the peak displacement of steel beam.

3 Conclusion

The comparison of Fe-SMA, and Steel beam analysis under cyclic load is showing maximum recovery upto 89 % . optimum 3.3 % Fe SMA can be used for beam to improve the seismic resistnce capacity.

Table 3 Comparative performance of Steel and Steel-SMA composite Beam for cyclic loading analysis

Load step	& No. of cycles	Cumulative Step No.	Story drift (%)	Force (kN)	Beam tip displacement (mm)		
					Steel	FeSMA - Steel	
						3.3%	3.75%
1	6	1	0.00375	18	7.44	8.07775	8.16
2	6	13	0.005	24.4	10.12	10.9929	11.10
3	6	25	0.0075	36.5	15.07	16.3721	16.54
4	4	37	0.01	48	19.82	21.524	21.74
5	2	45	0.015	73	30.12	33.0427	33.57
6	2	49	0.02	89.5	39.75	65.1651	67.58
7	2	53	0.03	94.5	60.53	69.4717	71.81
8	2	57	0.04	99	80.13	79.9801	81.76
9	2	61	0.05	103.4	100.57	95.4881	96.40
10	1	**65**		**0**	**32.41**	**12.00**	**10.67**
% reduction in residual displacement in steel and Fe-SMA composite beam compared to steel beam						**62.5**	**66.5**

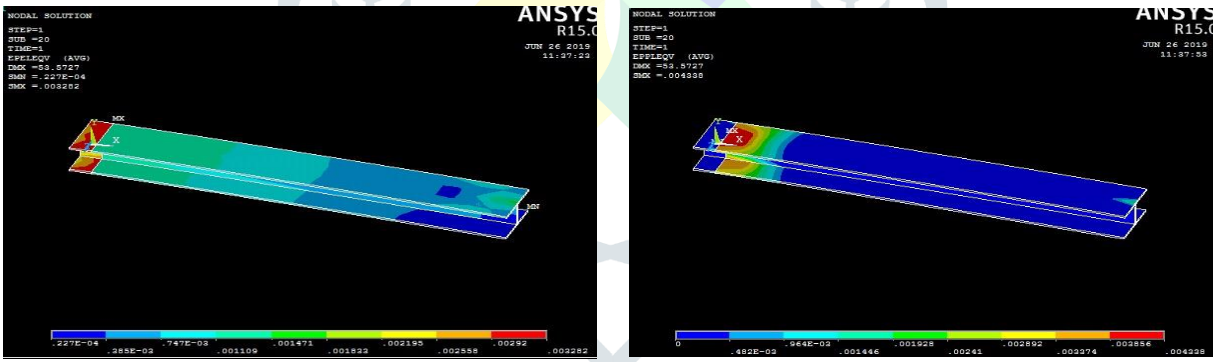


Figure 4 a) Yielding in composite beam during loading at peak load b) Plastic hinge in steel after unloading

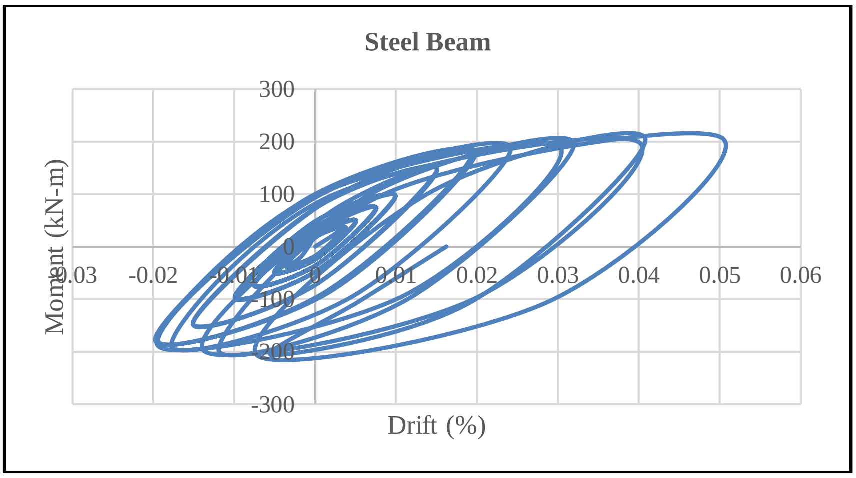
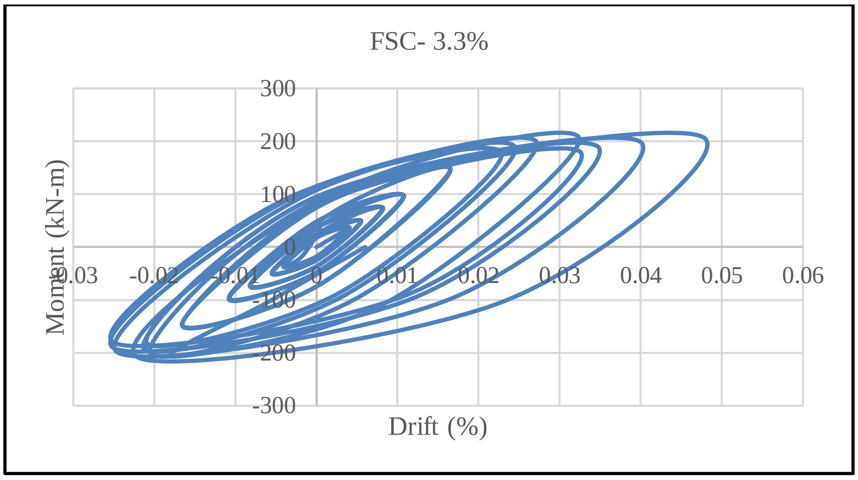


Figure 6 Comparative cyclic load analysis of beam



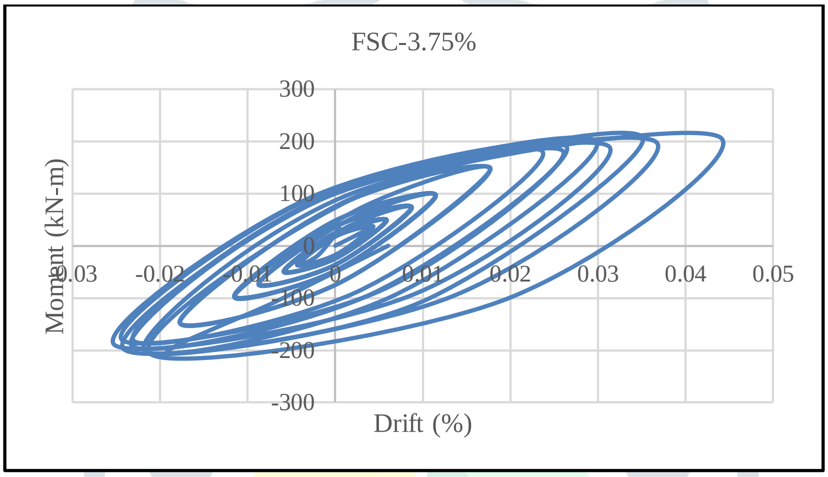


Figure 5 Moment and drift relation for beams a) Steel b) 3.3% FeSMA c) 3.75 FeSMA

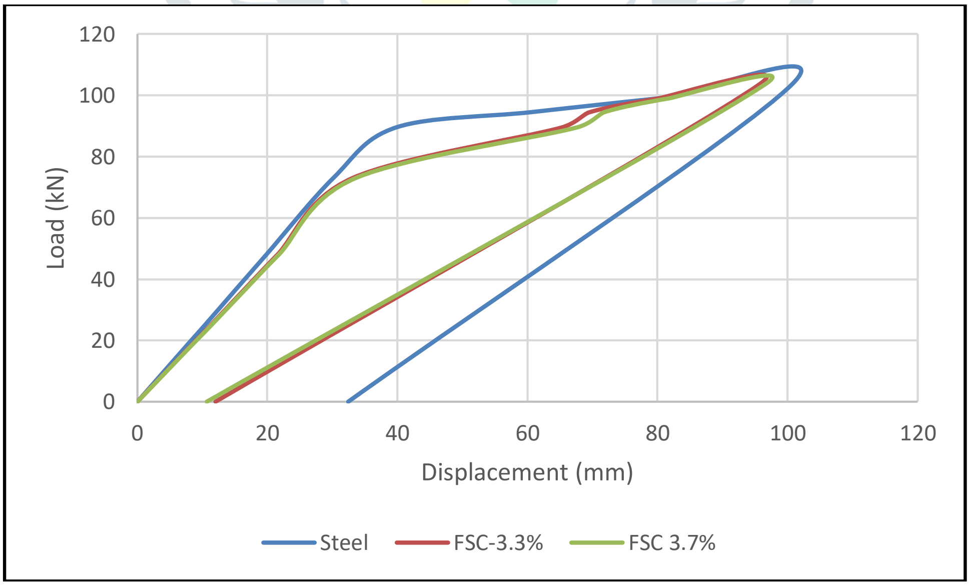


Figure 6 Comparative load displacement of steel and composite beam under cyclic loading analysis at each step

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