ANALYSIS OF HYSTERESIS BEHAVIOR OF EXTENDED END-PLATE CONNECTIONS WITH SUPERELASTIC SHAPE MEMORY ALLOY BOLTS

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Abstract - *Shape memory alloys (SMAs) are nowadays promising candidates for seismic engineering applications because of their ability to undergo reversible deformations and to dissipate energy when subjected to cyclic loading. This paper presents a numerical study of the hysteresis behavior of extended end-plate connections connected using SMA bolts instead of normal high strength bolts in the connections under cyclic loading. The basic concept is to concentrate the earthquake-induced deformation into the connection, such that a 'superelastic' hinge can be formed via the elongation of the SMA bolts. Thirteen models are anlysed in finite element analysis software ANSYS Workbench 16.1. This project focused on the parametric study of superelastic shape memory alloy bolts. An extensive parametric study was conducted on this FE model to investigate the hysteresis behavior of SMA bolt. The effects of change in bolts diameter, bolt pretension and its clearance between the holes in the end plate are elucidated through parametric studies. The SMA connection specimens are shown to have excellent recentring abilities in 65% pretension, 16 mm diameter of bolt and 0 mm clearance between hole in the end plate and column.*

Key Words: Extended end-plate connections, SMA bolts, ANSYS 16.1, Pretension, Bolt diameter, Hole clearance

1. INTRODUCTION

Investigations on moment resisting frames against earthquakes started after the Northridge and Kobe earthquakes, when many steel buildings collapsed due to the fracture of welded regions in their beam-column welding connections. Since then, many studies have been conducted on the behavior and proper design of connections. The most important study was done by FEMA through a project known as SAC. This project involved many investigations and laboratory models, including two main phases of determining the reasons for welding connection rupture and finding the proper substitutive connection for use in earthquake resistant flexural frames. Accordingly, end-plate connections were accepted as the appropriate substitution in the second phase of the project. These new connections have shown proper seismic performance, having sufficient strength, ductility and rigidity (Adey, Grondin et al. 1997). The design strategy of connections with end-plates according to the principle of "strong connection-weak beam" usually results in the formation of inelastic deformations either in the beam (full strength connections) or in the connection (partial strength connections) after an earthquake. Both of these statuses are confronted with high economic costs and considerable difficulties during repair and reconstruction. Investigations have been conducted to overcome the defects resulting from residual deformations. The main aim was to incorporate post-tensioned high-strength bars into the connections in order to provide a self-centring mechanism (Ricles, Sause et al. 2002, Christopoulos, Filiatrault et al. 2002). In this regard, using shape memory alloys in the connections has drawn significant attention. Based on these studies, it can be said that the application of shape memory alloy of nickel-titanium (Nitinol) is the appropriate solution for confronting the relevant difficulties in seismic regions. The capability of shape memory alloys to tolerate cyclic deformations and their moderate energy dissipation during cyclic loading have made them appropriate components against earthquake loads (Lagoudas 2008, Abolmaali, Treadway et al. 2006). Several researches have been conducted on the use of shape memory alloys. Saber Moradi and M. Shahria Alam (2015) [11] studied the feasibility study of utilizing superelastic Shape Memory Alloy (SMA) plates in steel beam−column connections. The proposed connections with SMA plates could return to their original positions, while exhibiting a ductile behavior with good energy dissipation. Furthermore, the occurrence of local buckling in beam flanges was prevented in the new connections with SMA-plates. Wei Wang et.al (2015) [12] studied about a novel connection – integrating superelastic SMA tendons with steel tendons and these connections are proposed between a H-shaped beam to a CHS column. Test results showed that connections equipped with SMA tendons exhibit moderate energy dissipation, double-flag-shaped hysteresis loops and excellent recentering capability after being subjected to cyclic loads up to 6% interstory drift angle. Cheng Fang et.al (2014) [2], In This paper, they presented an experimental study of the cyclic performance of extended end-plate connections connected using SMA bolts instead of normal high strength bolts in the connections. The SMA connection specimens were shown to have excellent recentring abilities and moderate energy dissipation capability with an equivalent viscous damping up to 17.5%. Hongwei Ma et.al (2007) [5] investigated a new connection consisting of an extended end-plate, long shank SMA bolts, continuity plates, beam flange ribs and web stiffeners. They concluded the cyclic elongations of the bolts in the SMA connection compared to the beam local buckling in the traditional connection. Rather than the plastic hinge forming away from the column face in the traditional connection, a superelastic hinge forms just at the beam-to-column interface in the SMA connection with the moment-carrying capacity of bolt cluster controlled below the elastic flexural capacity of the connecting beam. The connection deformations are recoverable upon unloading.

1.1 The characteristics of shape memory alloys

Shape memory alloys have two unique specifications, the effect of shape memory and super-elasticity. These two behaviors can be formed by the conversions of the crystalline phase entitled martensite and austenite. When Nitinol experiences deformation at a temperature lower than the austenite phase, residual deformations will be observed after unloading. These deformations are mostly removed by heating the alloy up to a temperature higher than that of the austenite phase. This phenomenon is called shape memory effect. On the other hand, if Nitinol alloy experiences deformation at a temperature higher than that of austenite phase, the created deformations are removed spontaneously after unloading. Changing the crystallographic nature of the martensite phase during these inelastic deformations will cause energy dissipation. This phenomenon is known as super-elastic effect.

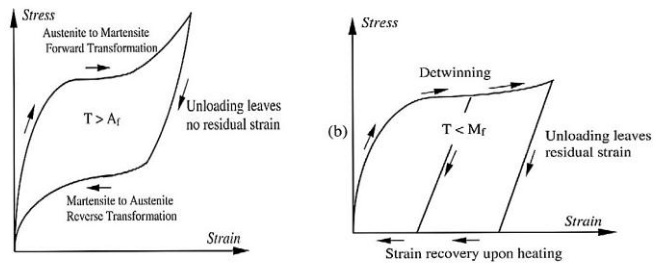


Fig-1: The super elastic & shape memory effect of SMA

1.2 Objectives

The project focused on the parametric study of superelastic shape memory alloy bolts. An extensive parametric study was conducted on FE model to investigate the hysteresis behavior of extended end plate connections with SMA bolt. The selected parameters are effect of change in pretension of bolt, effect of change in diameter of bolt, effect of change in clearance between the hole in the endplate and column.

2. MODELLING AND ANALYSIS

Fig. 2 shows the arrangement of the cyclic loading tests specimen used to model FE model to determine the hysteresis behavior of extended stiffened end-plate steel cantilever beam connection with eight rows of bolts. The model consists of an ISMB-350 steel beam and ISMB-500 for steel column. The lengths of the cantilever beam and column are 1500 mm and 3200 mm respectively. Next, the material properties are defined. Super-elastic behavior is modeled in ANSYS software according to the model presented by Auricchio (2001). In their model, the material has the capability of tolerating large deformations without showing residual deformation in the isothermal situation. Building steel is used for all elements excluding the bolts which are of shapememory alloy bolt that is nitinol. Table 1 shows the material property of connection elements. Table 2 shows the material specifications of SMA bolts.

Table-1: Material property of connection elements

Material	Modulus of elasticity (MPa)	Poisson's ratio	Yielding stress (MPa)	Ultimate stress (MPa)
ST37	200000	0.3	240	370
SMA	42000	0.33	370	500

Table-2: Material specifications of SMA bolts

Starting stress of forward phase transformation (σ_{MS})	360 MPa
Final stress of forward phase transformation (σ_{Mf})	450 MPa
Starting stress of reverse phase transformation(σ_{AS})	280 MPa
Final stress of reverse phase transformation (σ_{Af})	130 MPa
Maximum residual strain (ϵ_L)	0.05

2.1 Boundary Condition, Contact Interactions and Cyclic Loading

The column was considered fixed at the top and bottom. In reality, the connected components are related to each other frictionally. In the software as well, they are connected to each other frictionally with a friction coefficient of 0.2. Moreover, they are totally constrained by bond contact order instead of modeling the welds of sections.

The displacement control loading is used. In the finite element software, loading was applied statically to the end of the cantilever beam. Fig. 3 shows the cyclic loading pattern.

2.2Selected Parameters

The dimensions of the beam, column, end-plate and stiffeners are the same in all connections. The first parametric study was change in pretension of bolt. Five different pretensions are selected they are 55, 65, 75, 85, and 95% of tension yield of SMA bolts. In each models have same bolt diameter (16mm) and hole clearance (0mm).
The secondly changed parameter was bolt diameter. 16mm, 18mm, 20mm, 22mm and 25mm were selected. There are five models. In each model have same bolt pretension (65%) and hole clearance (0mm).
Third parameter was the change in clearance between hole in end plate and column. Three different hole clearance such as 0mm, 2mm and 4mm were selected for the study. For this analysis the bolt pretension (65%) and diameter of bolt (16mm) were taken as constant. The analysis was done in ANSYS software.

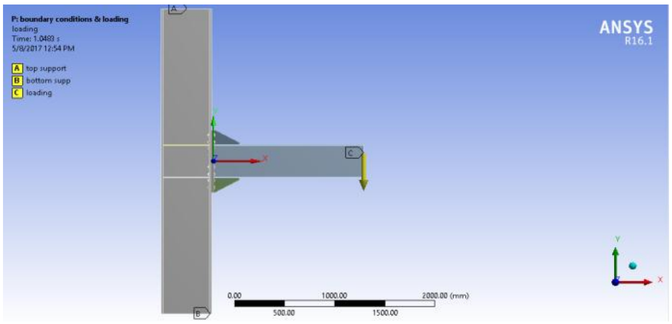
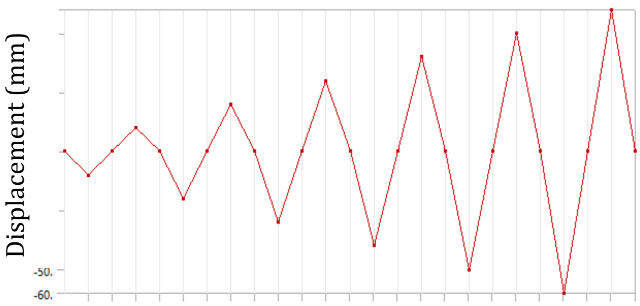


Figure-2: Boundary conditions and cyclic loading



6 number of cycles

Fig-3: Cyclic loading pattern

3. RESULTS AND DISCUSSION

3.1 The Effect of Change in Bolt Pretension

Fig 4 shows the distribution of equivalent von Mises stress for the pretension of bolt and chart 1 shows the moment-rotation response of SMA connection models, in those result shows, when increasing the pretension value of bolt also increasing the moment and stress of bolt. This causes yielding in other elements of the connection, such as beams and stiffners. Therefore, the residual deformations also increase with increasing pre-stressing force. It means that as the pre-stressing increases, lower recentering is observed for the whole connection. After analysing the hysteresis behavior of each pretension value of bolt, the value of pretension above 65% shows the combine behavior of steel and SMA and increasing the pretension from 75% to 95%, increasing steel property in hysteresis behavior of extended end plate connection. The value of the maximum moment is higher in the pretension-65% comparing to that of pretension-55%. That means 65% bolt pretension has more strength than 55% pretension connection. The bolts are modeled with different percentages of pre-stressing for the connections with SMA bolts. Accordingly, the connection with 65% pre-stressing shows the best performance.

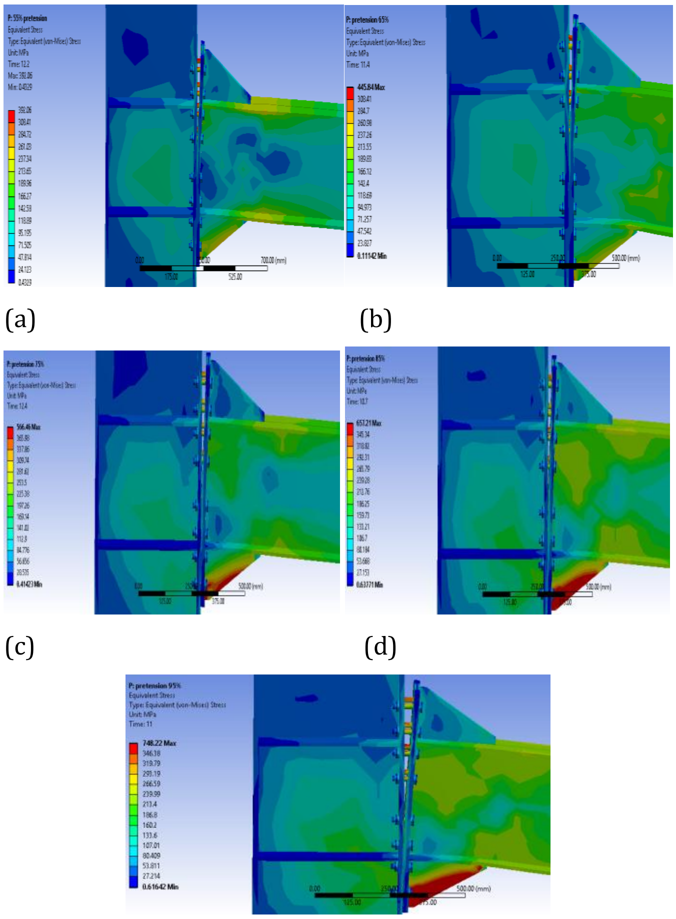
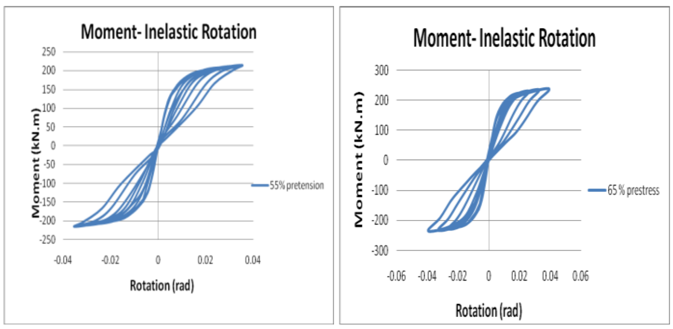


Fig-4: Distribution of equivalent von Mises stress for the connections: (a) 55%, (b) 65%, (c) 75%, (d) 85%, (e) 95%



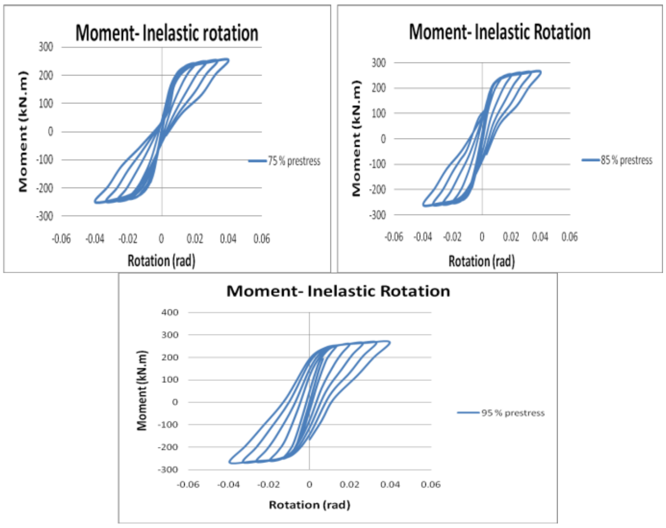


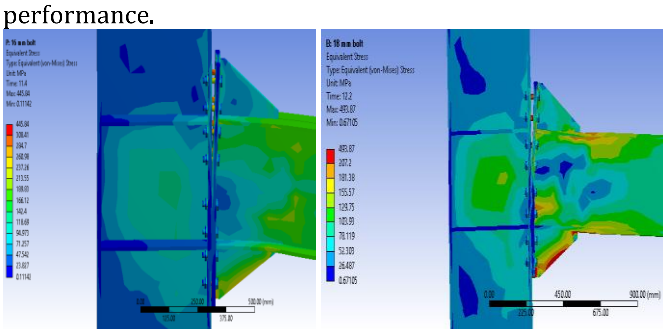
Chart-1: Moment-rotation response of each bolt pretension of SMA connections models

Table-3: The maximum rotation- moment and stress of each pretension of bolt

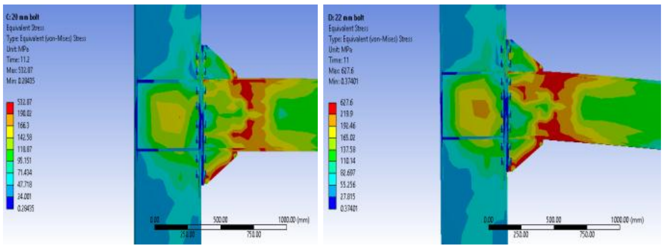
Bolt pretension	Maximum rotation (rad)	Maximum moment (kN.m)	Maximum stress (MPa)
55% pretension	0.0355	215.27	392.06
65% pretension	0.0393	237.64	445.84
75 % pretension	0.0395	252.91	566.46
85 % pretension	0.0395	263.34	657.21
95 % pretension	0.0395	269.2	748.22

3.2 The Effect of Change in Bolt Diameter

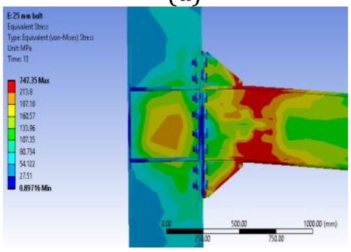
After analyzing the hysteresis loop & stress diagram of each connection, the elastic hinge is developed in the 16mm and 18mm diameter of bolt connection. The change of diameter of bolt from 20 to 25 mm gets more strength than end plate because the diameter of bolt is greater than end plate thickness thus bolt is strong and end plate is weak. Therefore plastic hinge is formed in the region of beam near to the end plate. The bolts are modeled with different value of diameter. Table 4 shows, with increasing diameter of bolt, the moment is also increase. The moment of connection from 20 to 25mm is the plastic moment of beam. Accordingly, the connection with 16mm bolt diameter shows the best performance.



(a) (b)



(c) (d)



(e)

Fig-5: Distribution of equivalent von Mises stress for the connections: (a) 16mm, (b) 18mm, (c) 20mm, (d) 22mm and (e) 25mm bolt diameter

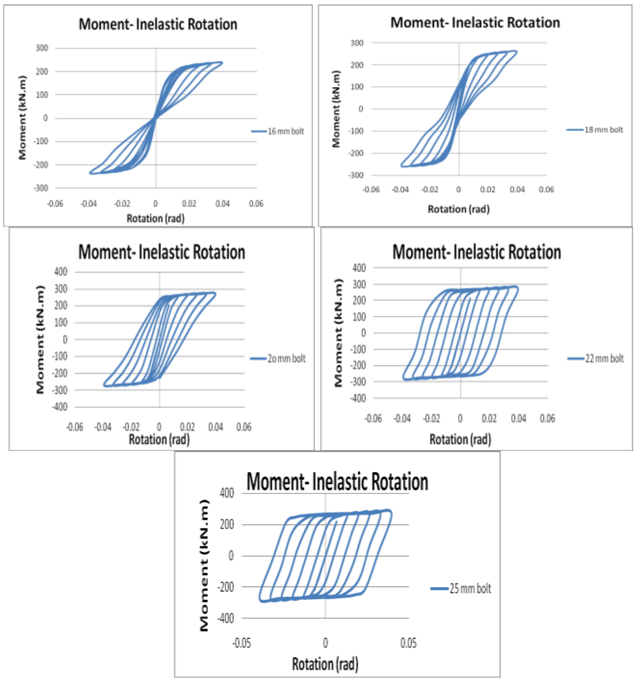


Chart-2: Moment-rotation response of bolt diameter of SMA connections models

Table-4: The maximum rotation- moment and stress of each diameter of bolt

Bolt diameter (mm)	Maximum rotation (rad)	Maximum moment (kN.m)	Maximum stress (MPa)
16 mm	0.0395	237.64	445.84
18 mm	0.0395	261.84	493.87
20 mm	0.0400	271.55	532.87
22 mm	0.0399	273.82	627.6
25 mm	0.0399	274.14	747.35

3.3 The Effect of Change in Clearance between Hole in End Plate and Column

After analysing the hysteresis loop & stress diagram of each connection, the deformations are mostly controlled by SMA bolts through super-elastic behavior. Maximum moment is developed in the 0mm hole clearance. So that connection has more strength compared with other connections. Table 4.3 shows the maximum rotation- moment and stress of each hole clearance.

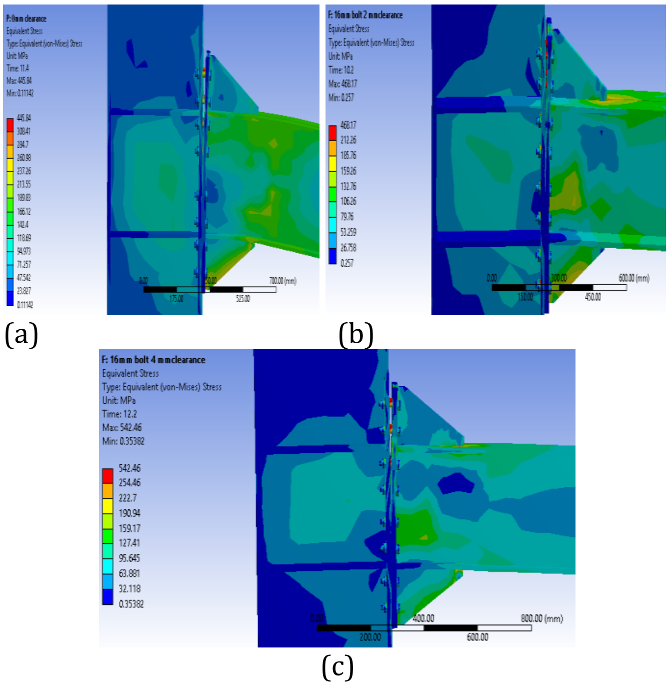


Fig-6: Distribution of equivalent von Mises stress for the connections: (a) 0mm, (b) 2mm and (c) 4mm hole clearance

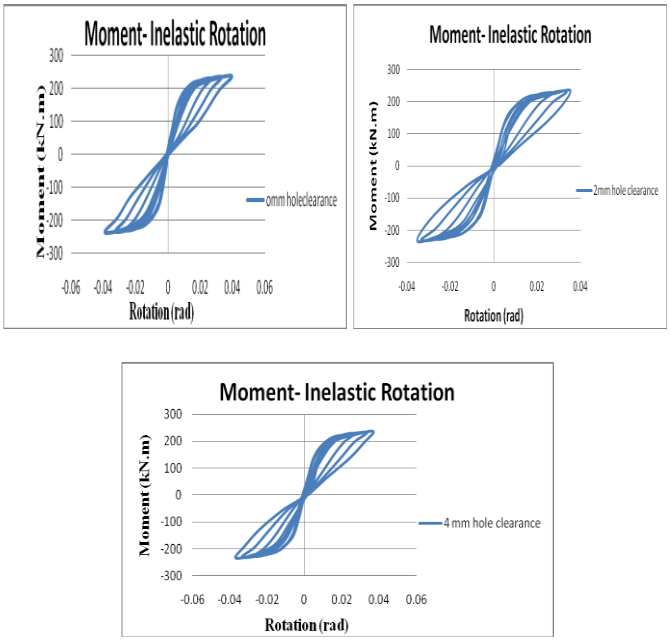


Chart-3: Moment-rotation response of hole clearance of SMA connections models

Table-5: The maximum rotation- moment and stress of each hole clearance

Hole clearance	Maximum rotation (rad)	Maximum moment (kN.m)	Maximum stress (MPa)
0mm	0.0395	237.6368	445.84
2mm	0.0352	235.7064	468.17
4mm	0.0370	235.9861	542.46

4. CONCLUSIONS

The following conclusions may be drawn from the parametric study conducted on extended endplate cantilever beam connections with SMA bolt subjected to cyclic loading by using finite element analysis software ANSYS Workbench 16.1.

•Increasing the pretension force of the bolts in the last loading step results in increasing resultant moment of all bolts (moment of connection), bringing the plastic moment of beam. This causes yielding in other elements of the connection, such as beams and stiffeners. Therefore, the residual deformations also increase with increasing pre-stressing force. It means that as the pre-stressing increases, lower recentering is observed for the whole connection. It should be mentioned that the recentering capacity is very high for SMA- 65 % pretension

•After analysing the hysteresis behavior of each pretension value of bolt, the value of pretension above 65% shows the combine behavior of steel and SMA and increasing the pretension from 75% to 95%, increase steel behavior in hysteresis loop of extended end plate connection with SMA bolts. In the connection with 75% to 95 % pretension, the bolts of the connections experience rupture in the cyclic loading and stiffners get deformation

•In SMA connections, generally increase with increasing pre-stressing force. The ascending trends of recentering capacity are continued up to 65% pretension of bolt. The value of the maximum moment is higher in the pretension-65% comparing to that of pretension-55%. That means 65 % bolt pretension has more strength than 55% pretension connection.

•Accordingly, the connection with 65% pre-stressing shows the best performance in recentering and strength. This causes the improvement of performance and reduction of repairing costs after earthquake or loading.

The following conclusions are drawn from the change in prestress of SMA bolt.

•After analyzing the hysteresis loop of each diameter of SMA bolt connections, the elastic hinge is developed in the 16mm and 18mm diameter of SMA bolt connections. Because end plate is rigid.

•The change of diameter of bolt from 20 to 25 mm gets stronger than end plate because the diameter of bolt is greater than end plate thickness thus bolt is strong and end plate is weak. So that connections of bolt does not get any stress and deformation. Therefore plastic hinge is formed in the region of beam near to the end plate. So those connections show the steel hysteresis loop.

•The rigid behavior of the end-plates is show to encourage a reliable recentring mechanism of the SMA connections, the use of thick end-plates is recommended. Of course, the influence of thin end-plates is of great interest in future studies.

•When increasing diameter of bolt, the moment is also increase in the connections. The moment of connection from 20 to 25mm is the plastic moment of beam.

•The connection with 16mm bolt diameter shows the best performance in recentering.

The following conclusions are drawn from the change in diameter of SMA bolt.

•After analysing the hysteresis loop of each hole clearance connections, the deformations are mostly controlled by SMA bolts through super-elastic behavior. Maximum moment is developed in the 0mm hole clearance. So that connection has more strength compared with other connections.

•The connection with 16mm bolt diameter shows the best performance in recentering.After completion of each parametric study in end-plate connections with SMA bolts, in which 65% of pretension, 16 mm diameter of SMA bolts and 0 mm hole clearance have good recentering capacity and strength.

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