A Numerical Study on Application of SMA alloys in Steel Connection

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Abstract

One of construction elements concerning to moment connections is end-plate connection. Since ductility of structural members play an effective role in inhibition of energy resulted from seismic loads, in this study, shape memory alloys have been implemented in bolts of these connections and the influence of this alternative on moment behavior of the connection has been dealt with. This replacement is intended to increase connection ductility and to prevention end-plate connection brittle failure. As a result, it will be investigated that applying shape memory alloys, there will be a steel connection that during inhibition of connection ductility and energy, it will be prevented brittle failure of the bolts and it will be improved connection behavior.

Keywords: moment connection, memory alloys, seismic behavior

1. Introduction

Structure designers have been long ago paid attention using moment frames but after various earthquakes such as Northridge earthquake, field observations indicated that there would be high possibility to occur unpredicted failure in these fasteners. Major observed deteriorations have been resulted from brittle failure in welded beam-to-column wing fastener or in the region heated from welding. Because of this, vast investigations have been performed in order to find guidelines eliminating challenges related to common moment fasteners.

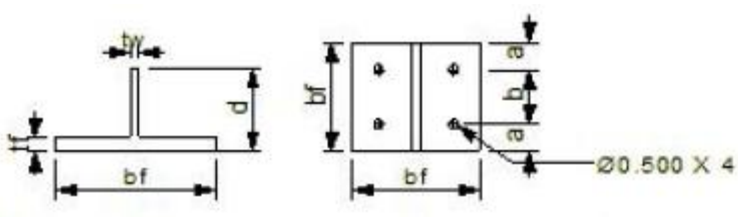
All of the suggested guidelines are directed to create plastic joints in the beam and to keep failure and brittleness away from the fastener place. Applying passive methods to control the structures against the earthquake is mentioned as a suitable replacement for traditional methods. One of the fasteners suggested to resolve the mentioned challenge is a type of fastener in which a plate is welded to the end of beam in the factory and then, in predetermined places bolted in the workplace, is connected to the column by bolt as a result of which structure ductility will be increased.

Investigations in end-plate fastener contexts have been started before 1996 and have still been continued until now. Primitive methods were relied upon static assumptions. As a result of these primitive methods, the thickness of plates as well as diameter of the bolts has been increased. Next investigations were based on using yield lines but recent studies have been based on implementing finite element methods. These methods provide the possibility that more accurate investigations are performed in these subjects. Krishnamurti (1979) implemented finite element method in order to develop empirical relations for end-plate thickness design [1]. Ghasemieh (1983) investigated 8-bolt hardened fastener and also implemented finite element method to develop laboratory tests to analyze mentioned fastener under unilateral loading [2]. Sumner and Muri (2003) presented a comprehensive method to design details of this fastener under earthquake and also the samples constructed by this method were applied cyclic loading according to SAC protocol, some of which were investigated by finite element method and unilateral loading. It was concluded that firstly, this fastener can suitably provide required ductility, resistance and stiffness in moment frames in earthquake-prone areas and secondly, having presented a 3D model, this fastener behavior can be well predicted by finite element method [3].
In the context of the studied performed aimed to review shape memory alloys, it could be said that in 1932, Otsuka, a Sweden scientist, uncovered super elastic behavior of AuCd material [4]. Brono and Volonto investigated the possibility to analytically use above mentioned material by analytical methods and using damage index idea as well as a simplified model of shape memory materials. Obtained results indicate dominance to use foundation isolators of shape memory in order to decrease damages incurred by earthquake on the structures [5]. In a comprehensive laboratory study, DesRoches et al investigated super elastic nitinol material behavior under cyclic loadings in order to review respective capability to use for design and optimization of seismic structures [6]. Abolmaali et al investigated energy attenuation characteristics of t-stub fasteners with steel and shape memory bolts [7].
If memory alloys were used in the bolts of end-plate steel fasteners, then this fastener would be more ductile than ever, would have capability to attenuate more energy caused by earthquake in the structure and would prevent occurring brittle failures in the bolts. The purpose of this paper is to create various models by finite element method including sufficient accuracy to investigate seismic behavior of this fastener and to review the effect of replacing bolt memory alloys in the place of the bolts on respective seismic behavior.
For this, at first, a plate-to-plate fastener as well as an extended end-plate beam-to-column fastener having be constructed by Treadway et al [7] and Sumner [3] and tested under horizontal and cyclic loadings is 3D modeled and analyzed in full scale and comparing this model as well as laboratory results, the accuracy of finite element model is investigated. Then, replacing shape memory alloys in the place of bolts in both type fasteners, it has been investigated the seismic behaviors of these fasteners and comparing common fasteners with alternate fastener, interesting conclusions will be obtained.

2. Finite element method description and model verification

Firs model is Treadway's consisting two T-stubs which are connected to each other by 4 bolts. First model fitting dimensions are selected exactly equal to laboratory dimensions (Figure 1). Because there are two orthogonal axes, it has just modeled a quarter of the whole

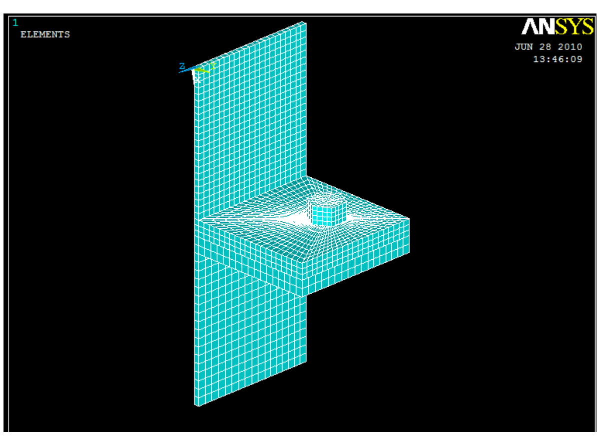
fastener. Bolt geometry includes three masses, body, head and nut which head and nut are located in the front of first plate and behind of the other, respectively.
Mesh scheme is produced in two separate models by 3D software elements, SOLID185 and SOLID45 in which the size of elements is smaller at bolt openings. In order to model the contact in end-plate beam-to-column fastener and the contact of bolt details with analogous details, Target170 and Contact174 have been used.



characteristics	d(in)	tw(in)	tf(in)	bf(in)	L(in)	a(in)	b(in)
WT 4*12 d1	3.965	0.245	0.4	6.495	5.512	1.250	3.995

Figure 1: Details of fastener modeled by finite element method [64]

The loading has been the same as SAC protocol [7] as shown in **Figure 2** in this Figure, mesh scheme of the model has been also illustrated. Loading the model is performed via applying a displacement on the beam free end until the respective rotation of each loading cycle is achieved. Structure rotation equals beam free end displacement divided by the horizontal distance from beam to column centerline. It should be noted that each loading step is applied on finite element model for just one time.



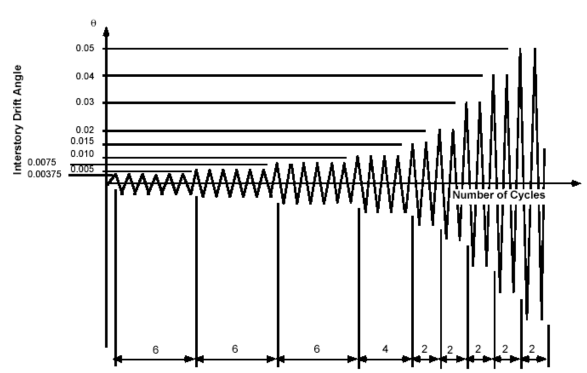


Figure 2: Finite element model mesh scheme and loading reconstructed from Treadway test

For the column and beam, yielding and final stresses are 53ksi (364MPa) and 70.7ksi (488MPa), respectively. In order to introduce the materials implemented in the bolts, yielding and final stresses are 90ksi (621MPa) and 110ksi (760MPa), respectively.

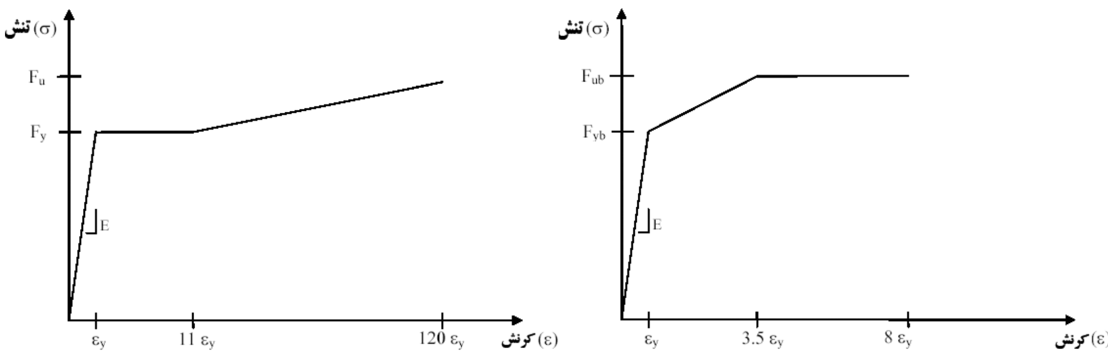
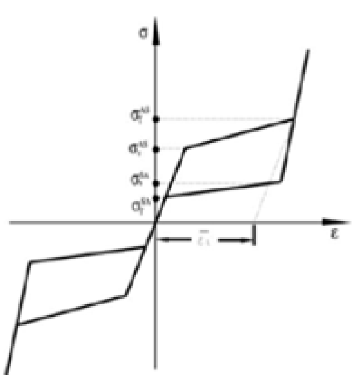


Figure 3: stress-strain curve for the steel implemented in the bolt and also the beam, the column and the plate (right to left)

For the bolt steel, orthotropic coefficient of thermal expansion have defined equal to 1.2×10-6 just in line with the bolt axis. In order to consider pre-stress loading of the bolts, uniform negative heating is applied on their bodies before applying the displacement in the beam ending. The reason for defining coefficient of thermal expansion just in one direction is that resulted from thermal loading, after that, bolt diameter wouldn't be decreased caused by temperature decline. The second model is that of Sumner in which one of unhardened 4-bolt fasteners having been investigated in VPI University by him have modeled in ANSYS and then has been analyzed under SAC protocol loading the same as laboratory model. Behavior model of shape memory materials has been selected to illustrate the behavior of NITI-made bolts. ANSYS implements Auricchio behavior model [9] to define reciprocating materials in constant temperature conditions. Auricchio model advantages the Drager-Prager criterion and internal variable formulation in order to optimize solution algorithm which it can be used in classic computational tools like finite element method. For super elastic memory materials in constant temperature conditions, stress-strain curve has been illustrated utilizing Auricchio model in the Figure below. Referring to the values obtained from DesRoches tests [6] for memory materials with large diameters, parameters used in Figure below have been illustrated and have been used to simulate memory material in modeling the bolts (Figure 4).



deffinition	value
martensite dominate stress	
(MPa) : beginning stress σ_s^{AS}	375
(MPa) : finalstress σ_f^{AS}	430
reverse-fase converter	
(MPa) : beginning stress σ_s^{AS}	208
(MPa) : finalstress σ_f^{AS}	138
max. reversible stress	0.09

Figure 4- the assumptions used in modeling behavior of shape memory alloys

2. Comparison the results obtained from finite element model with laboratory results

In Figure 5, load versus displacement curve has been illustrated in Treadway model in both laboratory and finite element models.

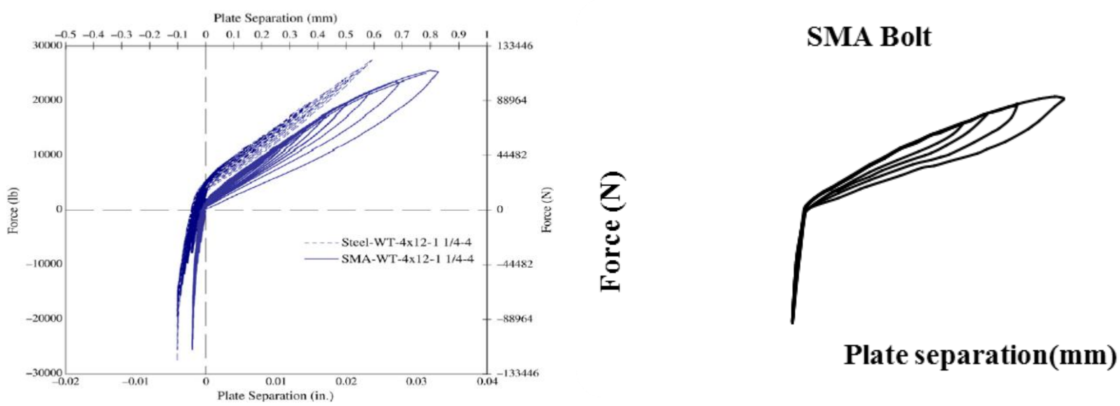


Figure 5: Comparing load-displacement curve for finite element model with Treadway laboratory results

In Figure 6, moment versus rotation curve has been also illustrated in Sumner model in both laboratory and finite element samples. The applied moment equals to shear at the beam free end multiplied at the distance from beam free end to column centerline. The results of these two curves have been shown in Table 1 for comparison.

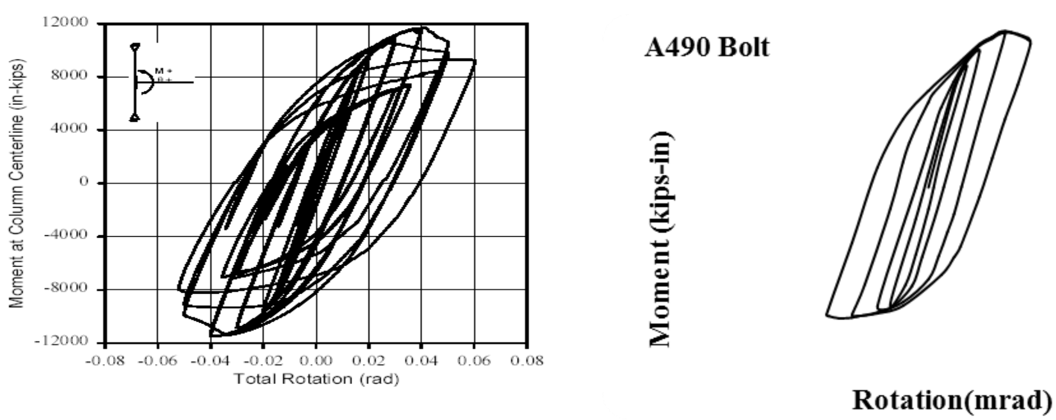


Figure 6: Comparing hysteresis diagram of finite element model with Sumner laboratory results.

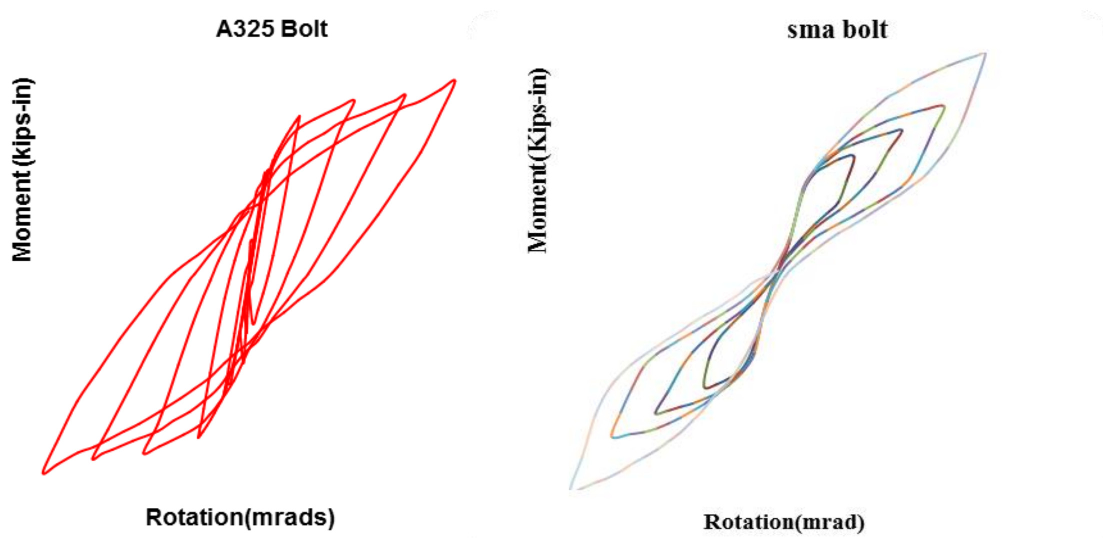
Table 1: Comparing the results of both finite element model and laboratory sample.

Plastic rotation (rad)	Max.incured (K.in) moment	Respective yield moment (K.in)	Respectiveyield (rad)rotation	
0.035	11200	8100	0.011	Finite element mod
0.038	11703	8600	0.014	Laboratory sample

As it can be seen, model accuracy is suitable except for structure plastic rotation. The reason for this accuracy decline in plastic rotation is that after column web shear yielding and forming plastic joint in laboratory sample because of local buckling in the beam web and wing, structural capacity is declined and in spite of sustained moment decrease, the structure still sustains much more rotation until it is failed caused by lateral torsional buckling of the beam but in the finite element sample, it is no longer modeled any lateral torsional buckling of the beam. Therefore, in this stage, the model will be unstable as a result of over-plasticity in the fastener opening of the model. Considering models constructed in the software and observing suitable consistence with laboratory results, the accuracy of model has been validated and it can be concluded that the models has sufficiently been validated to continue the investigations.

3. Investigating the effect of replacing memory alloys in the bolts on the seismic behavior

In order to investigate the effect of replacing high resistance regular bolts with memory alloy bolts, applying modifications in Sumner fastener, connection failure region has been



transferred to the bolt region under dynamic loading such that implementing mentioned replacement, maximum respective effect can be observed. In Figure 7, it can be seen hysteresis diagrams related to two discussed connections.

Figure 7: Comparing hysteresis diagram in common high-resistance bolt fasteners with memory alloy bolt fasteners.

Table 2: Comparing hysteresis diagram in common high-resistance bolt fasteners with memory alloy bolt fasteners.

Plastic (rad) rotation	Max.incured (K.in) moment	Respective yield moment (K.in)	Respectiveyield (rad)rotation	
0.035	11000	6100	0.015	Sumner Finite element mode with A325
0.053	12000	3800	0.009	Sumner Finite element mode with SMA

In Table 2, it can be observed a summary of the results obtained from hysteresis diagrams. As it can be observed from above diagrams, replacing bolt material characteristics, the fastener with memory alloy bolts can sustain less moment under the same rotations. As it can be seen in the diagrams, fastener behavior in the second state has become more ductile and residual deformations has become much less after finishing each cycle. Memory alloys applied in the bolts can make the fastener behavior more ductile and attenuate much more energy. In fact, although yielding and final resistance of these bolts is less than high resistance bolts implemented in common end-plate moment fasteners, because of ductile behavior and high reversible strains, this material has had considerable influence on behavior of mentioned fasteners. In Sumner model, in torsion 0.05rad, the reversible rotation of fastener reaches 0.047rad which is 94 percent of total rotation. In rotation 0.063rad, the reversible rotation of fastener becomes 0.057rad which is 91 percent of total rotation. In fact, in this fastener, maximum inelastic rotation is 83 percent of maximum rotation indicating high ductility, while in Sumner laboratory fastener with regular high resistance bolts, when the fastener has compensated just 50 percent of its rotation and sustained large reversible deformations, stress in the bolts has reached its yielding limit and the bolts have failed. In order to verify above mentioned results, it can be observed Von Mises stresses of above fastener in Figure 8.

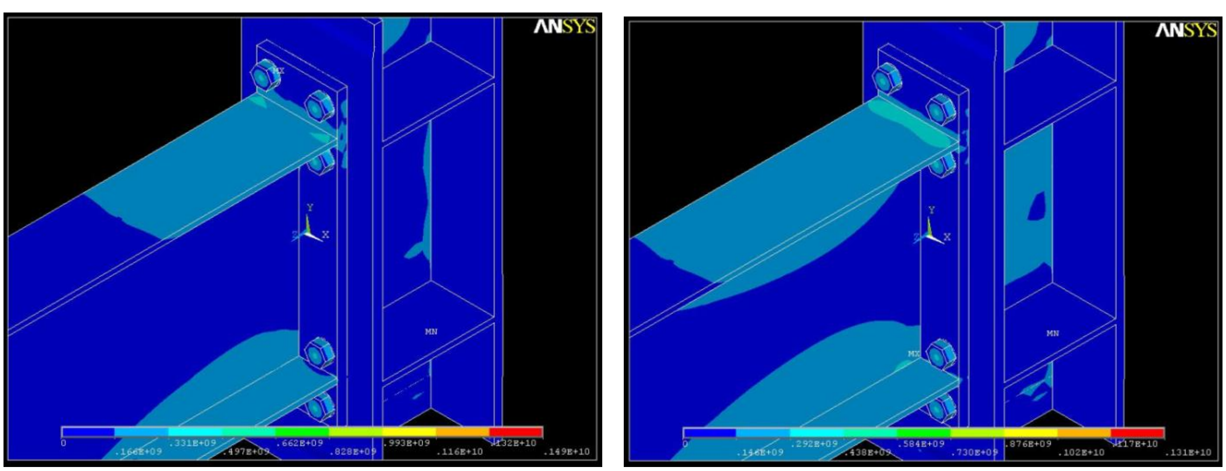
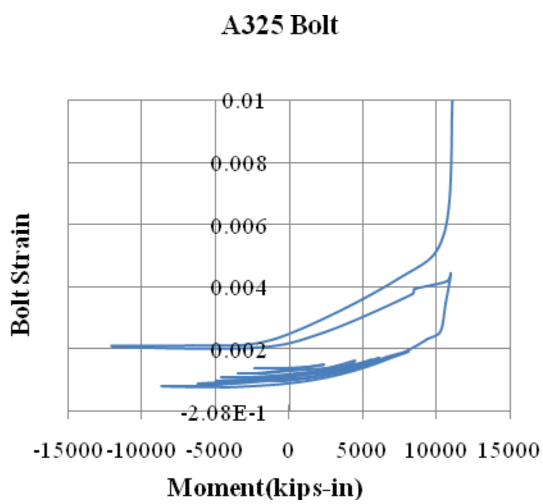


Figure 8: Illustrating Von Mises stresses in fasteners with memory alloy bolts and fastener with regular high resistance bolts, respectively.

In this section, behavior of the bolts is discussed during loading steps. Figure 9 shows internal bolt strain versus applies moment diagram related to above fastener.



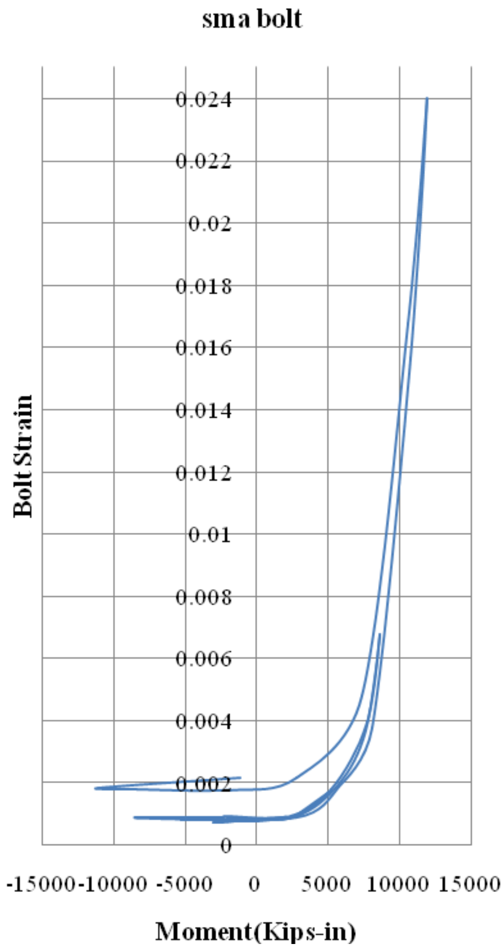


Figure 9: Strain diagram of memory alloy bolts and that of regular high resistance bolts (right to left).

As the diagrams show, laboratory model has a good consistence with Sumner laboratory sample. In the first model in primary loading cycles, strains remain the same as pre-stressed strain and increasing applied moment, bolt strains also increased while it could be no longer observed any reversibility. This event shows that bolt in the fastener has been failed and it is indicated to this case in the Sumner thesis, but in the model in which material characteristics of the bolts has replaced memory alloys, it can be observed that in comparison with regular high resistance bolts, the bolts have sustained more strains at similar moments. As it has been seen, these strains have suitable reversibility and 92 percent of final strain of the bolt has been compensated in the reversible cycle, of course, it has been observed no failure in the bolt at this time. If the beam were no longer failed during connection at this time, the bolts still would have sufficient resistance in order to sustain much more moments. Considerable increase in fastener ductility and much more quantities of energy attenuation have been resulted to failure area to be made more far away from the bots without using any high resistance bolts.

4. Conclusions

In both samples of fasteners with high resistance regular bolts, it has been observed failures of fastener because of bolt failures, but applying memory alloy bolts, failure area has been made away from the bolts and this time the failure has been occurred in the beam. Ductility increase is the other influence of this replacement such that in the fastener, final rotation and plastic rotation have in average increased 24 and 50 percent, respectively. Although moment absorption has increased 9 percent, fastener ductility has considerably increased. Compensating about 90 percent of applied rotation sustained by the fastener indicates the energy quantities attenuated without significant persistent deformation. It is interesting that in both fastener, replacing memory alloys, fastener failure has no longer occurred and the beam at the fastener has been correctly achieved its yielding limit and converted to a plastic joint. This conclusion is obtained when little decline in stiffness, considerable increase in ductility and high reversible behavior in the bolts has been observed in the bolts.

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