Seismic Behavior Studies of Welded Flange Plate in Steel Structures Connections

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SUMMARY:
Since the Northridge earthquake, great deal of theoretical and experimental researches on steel structures behaviors, have been carried in order to study the cause of connections' brittle failures, observed in numerous welded connections, and to find ways to improve their ductility. Having compared 'pre-Northridge' connections, using steel moment connections reinforced with welded flange plate (WFP) have shown noticeable improvements in steel structural connections' performance. This paper discussed an investigation trend to improve the connection seismic performance. The significance of welding details on the behavior of welded beam to box column moment resisting connections has been the incentive to focus on welding type, back up bars, fillet reinforcement, electrode toughness and material properties. Considering the identified parameters, the nonlinear finite element results have led to a better understanding of the retrofitted connections behavior and improvement of connection details under seismic loading conditions.

Keywords: Seismic behavior, welded flange plate, steel structure, material properties

1. INTRODUCTION

Following the Northridge earthquake, a great number of steel moment-frame building were found to have experienced brittle fractures of beam-to-column connections. In typical pre-Northridge welded moment connections, a bolted shear tab is commonly used to transfer the shear force and a complete joint penetration (CJP) groove weld was employed to join the beam flange to column flange. The beam-to-column interface is the critical section that has maximum flexural moment when moment frames are subjected to earthquake-included force. Therefore, typically, brittle fractures initiated at the CJP groove weld between the beam bottom flange and column flange. In many cases the brittle fractures initiated within the connections at very low level of plastic demand, and in some cases, while the structures remained essentially elastic [1-4].

Numerous studies have been undertake to improve the behavior of pre-Northridge moment connections and developing repair techniques and new design approaches to minimize damage to steel moment-frame buildings in future earthquake. The improvement is based mainly on strengthening the connection [5-8] or weakening the beam [9] to reduce stress levels within the vulnerable region near the column face and forces the large stresses and inelastic strains further into the beam. Steel moment connections reinforced with flange plates (WFP) have been widely used since the Northridge earthquake all around the world. This research has been conducted in order to develop improved details for retrofitted proposed connection through investigating the effect of following parameters on seismic behavior of WFP connections.

(1) Welding detail (Weld type, electrode toughness, back up bar, fillet reinforcement): (2) Material properties (St37, St52)

2. FINITE ELEMENT ANALYSIS

Nonlinear finite element analysis was performed to investigate stress and strain distribution and hysteretic behavior of the connections. The symmetry in the plane of beam to column web was such that only half of the specimens were modeled and analyzed to reduce computational effort. A vertical displacement history was imposed at the free end of the beam using the displacement-control method in accordance with FEMA [1].Table 2.1 presents the material properties adopted for the analytical study [10].

Table 2.1. Material properties used for analytical models.

Test coupon	F_y(MPa)	F_u(MPa)	$\frac{F_y}{F_u}$	Elongation (%)
Beam web (St37-2)	334	464	0.71	30
Beam flange (St37-2)	311	438	0.71	26
Column plate & Bottom flange plate	320	460	0.69	27
Top flange plate	267	424	0.63	27
Electrode E6013	460	522	0.88	4
E7018 Electrode	540	627	0.86	16

The result of finite element analysis was compared with the experimental result [10] in terms of moment and story drift angle relations to verify the analytical model. Fig 2.1 shows the detail of experimental specimen. According to figure 2.2, the results are consistent well with each other.

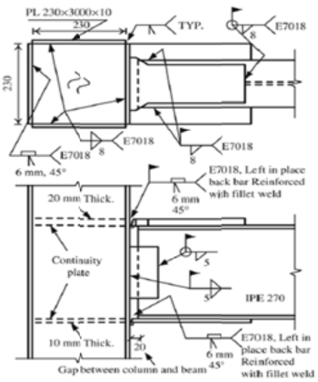


Figure 2.1. Detail of experimental specimen

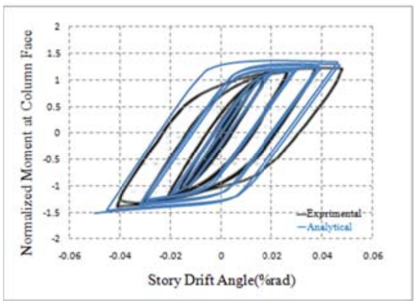


Figure 2.2. Combined plot of experimental and analytical results

3. EFFECT OF WELDING DETAILS

Damage in the weld is the most common cause of brittle failure in these connections; premature fractures can occur due to potential weld defects. In order to study the effect of welding detail include weld type, electrode toughness, backup bar and fillet reinforcement on connection seismic performance, six specimens were modeled and analyzed. The specimens comprised an IPE270 for beam and Plates 230×3000×10 mm for box column [10] and designing procedure conducted in accordance with FEMA [1]. Table 3.1 and Figure 3.1 illustrated the welding details of specimens. Different weld types used to join the flange plate to box column, furthermore notch tough E7018 and non notch tough E6013 welding electrodes were used to evaluate the electrode toughness effect on the welded connection's performance.

Table3.1. Welding details of the specimens

Specimen	Welding type joining the top/bottom flange plate to column		Electrode
	Top	Bottom	
RC1	SFW	DFW	E6013 E7018
RC2	SBBW (with backup bar)	SBBW (with backup bar)	E6013 E7018
RC3	SBBW (with backup bar)	DFW	E6013 E7018
RC4	SBBW (with backup bar)	DBBW	E6013 E7018
RC5	SBBW (with backup bar)	SBBW (without backup bar)	E6013 E7018
RC6	SBBW (with backup bar)	SBBW (without backup bar & reinforced with fillet weld)	E6013 E7018
DFW=Double Fillet Weld			
SFW=Single Fillet Weld			
DBBW=Double Bevel Butt Weld			
SBBW=Single Bevel Butt Weld			

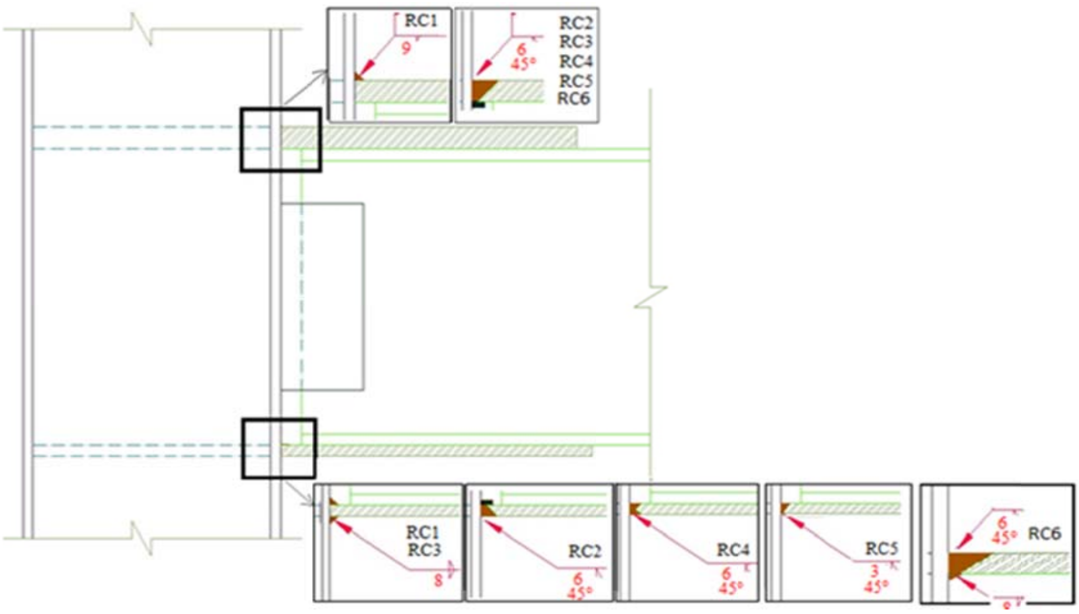


Figure 3.1. Geometry and weld types employed to join the flange plate to column

3.1. Specimen RC1

RC1 is a specimen with outdated old detail of a welded connection, that a single fillet weld and a double fillet weld were used to join the top and bottom flange plate to column respectively. According to figure 3.2, maximum stress concentration occurred in single fillet weld joining the top plate to the column flange, using each types of electrode, E7018 or E6013.

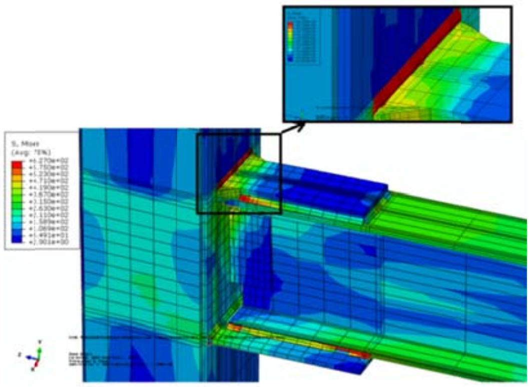


Figure 3.2. The von Mises stress distribution in specimen RC1

Figure 3.3 presents the normalized plastic strains on the top beam flange, top flange plate and upper continuity plate of specimen RC1 at story drift angle of 4% rad.

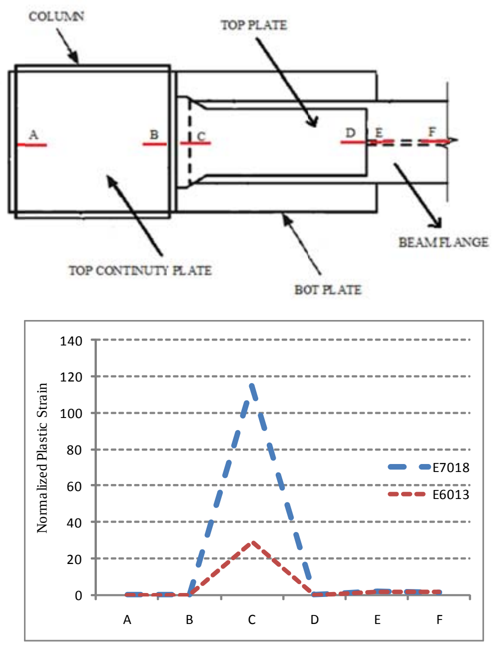


Figure 3.3. Strain response for specimen RC1

On the bases of figure 3.3, the maximum plastic strains occurred in the beam to column connection area, caused intensive plastic deformation of weld and prevent formation of plastic hinge in the beam. As a result the connection was not able to show suitable ductile behavior as indicated in figure 3.4.

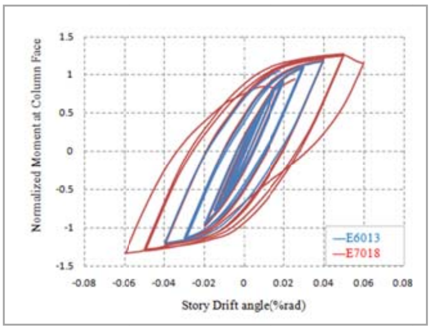


Figure3.4. Plots of cyclic response of specimen RC1

3.2. Specimen RC2

This specimen consists of welding detail: both top and bottom plate joined to the column flange with single bevel butt weld and back up bars.

Based on the analytical result, using each type of electrode E6013 or E7018, the connection showed a reliable behavior. The primary objective of reinforcing connection using flange plate is relocating the plastic hinge away from the column face into the beam flange, immediately beyond the nose of the flange plate which occurred in this specimen as shown in figure 3.5.

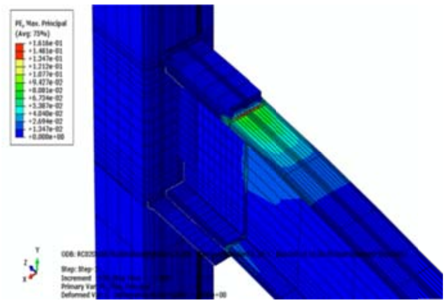


Figure3.5. The plastic strain distribution in specimen RC2

The hysteresis behavior of the specimen is shown in figure 3.6 represents that, the connection is capable of reaching more than 6% radians of story drift angle without strength degradation. Moreover, on the basis of figure 3.6, using E7018 instead of E6013 makes no significant improvement in strength and ductility of connection.

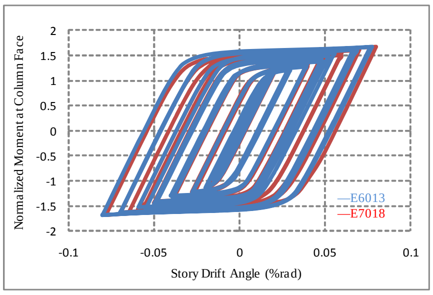
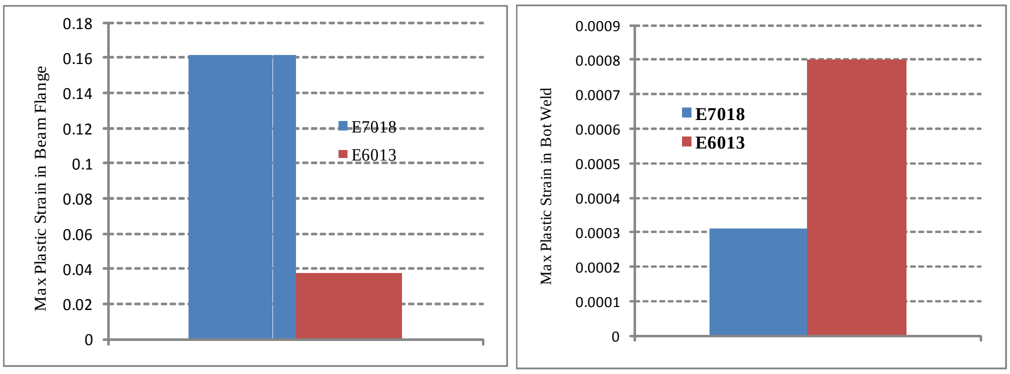


Figure3.6. Plots of cyclic response of specimen RC2

However investigating the strain concentration in beam flange and weld, which joining the bottom flange plate to column as shown in figure 3.7 present that, using E6013 will lead to reduction of inelastic deformation in beam flange; while, the strain in weld increased extensively. Therefore, using a high toughness weld metal and back up bar, will cause developing stable inelastic behavior in beam flange that will dissipate a large portion of energy absorbed from the earthquake and prevent brittle fracture of critical sections near the column face and weld joint.



(a) (b)

Figure3.7. Maximum plastic strain: (a) beam flange (b) bottom weld

3.3. Specimen RC3

This specimen is identical to RC2, except welding the bottom plate to column with a double fillet weld (DFW). According to the finite element result, using DFW weld caused large stress concentration in weld. As long as the maximum plastic strain measured in DFW weld, is considerable in comparison with the maximum plastic values in beam flange as shown in figure 3.8, it is required to control the welding process carefully, because occurring any imperfection in welding process will lead to plasticization of weld before forming a plastic hinge in beam and failure of connection.

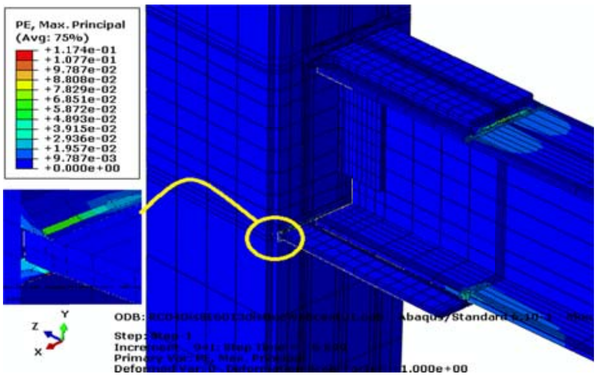


Figure3.8. The plastic strain distribution in specimen RC3

Based on the hysteresis curve of the specimen, using E7018 electrode was led to increase of story drift angle and connection’s strength 25% and 7.2% respectively.

Quite similar to the specimen RC2, using E7018 instead of E6013, increased plastic strain values in beam flange and substantially decreased the plastic deformation in bottom weld.

3.4. Specimen RC4

This specimen consists of welding detail: top plate welded to the column flange with single bevel butt weld and back up bar and a double bevel butt weld (DBBW) used to join bottom plate to column.

Comparing plastic strains distribution of specimens RC2, RC3 and RC4, it was found that the magnitude of plastic strain in beam flange of specimen RC4 is smaller than RC2 and RC3; however flange plate underwent larger plastic deformation. On the other hand, flange plates of RC4 perform a higher portion in dissipating the earthquake loading in compare to specimens RC2 and RC3 as shown in figure 3.9.

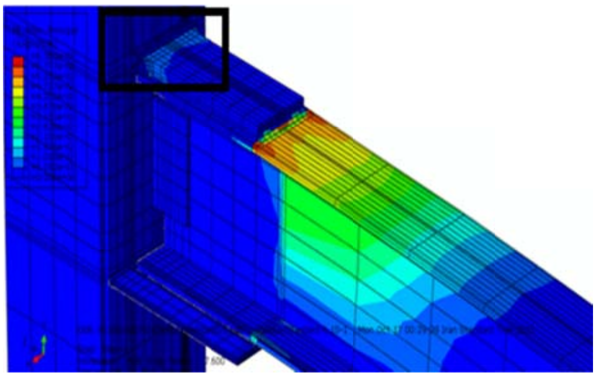


Figure3.9. The plastic strain distribution in specimen RC3

Based on the hysteresis curve of the specimen, using E7018 electrode was led to increase story drift angle and strength of connection 26.8% and 7.2% respectively. Using E6013 instead of E7018, increased plastic strain values in bottom weld 2.5 times and decreased the plastic deformation in beam flange.

3.5. Specimen RC5

This specimen consists of welding detail: top plate welded to the column flange with single bevel butt weld and back up bar and a single bevel butt weld with weld root without backup bar used to join bottom plate to column. Based on the finite element result, the plastic hinge formed in beam flange away from the column face and specimen underwent large plastic deformation. Comparing hysteresis response of RC5 with RC2 revealed that, eliminating backup bar in specimen RC5 decrease connection's strength 2.7%, using E7018, and strength and ductility of connection decreased 9.2% and 30.2% respectively, using E6013.

3.6. Specimen RC6

According to FEMA [1], when using single-bevel groove weld, remove backing after welding, back gouge and reinforce with $\frac{5}{16}$" minimum fillet weld. Analytical model of this specimen was analyzed while backup bar removed and a fillet reinforcement weld was used. Based on The analytical results, this specimen showed a ductile behavior as well as specimen RC2. Similar to specimen RC2, using E7018 instead of E6013 makes no significant improvement in strength and ductility of connection while strain measured in weld reduced 39.7% and the beam flange plastic strain increased 27.5%.

Therefore, in spite of insignificant effect of electrode type on strength and ductility of the specimen, the electrode toughness has direct effect of strain distribution on critical region of the connection.

Tables 3.2 and 3.3 summarize data from hysteresis response of specimen RC1-RC6.

Table3.2. Summery analytical data using E6013

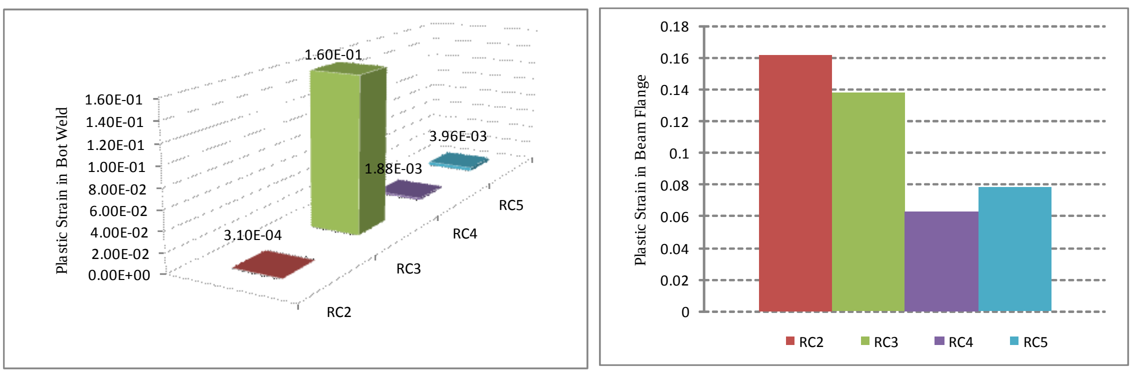
Result	RC1	RC2	RC3	RC4	RC5	RC6
Δ_m(mm)	103	207.2	153.9	152.1	144.4	208
$\frac{\Delta_m}{h}$ (%)	3.4	6.9	5.1	5.07	4.8	6.93
M(N.mm)	1.76×10^8	2.51×10^8	2.3×10^8	2.3×10^8	2.28×10^8	2.48×10^8
$\frac{M}{Z\sigma_y}$	1.17	1.6	1.53	1.53	1.52	1.65
θ_p^m(%)	3.96	8	5.91	5.85	5.55	8

Table3.3. Summery analytical data using E7018

Result	RC1	RC2	RC3	RC4	RC5	RC6
Δ_m(mm)	155.8	208	208	208	208	208
$\frac{\Delta_m}{h}$ (%)	5.2	6.93	6.93	6.93	6.93	6.93
M(N.mm)	1.92×10^8	2.53×10^8	2.48×10^8	2.48×10^8	2.46×10^8	2.48×10^8
$\frac{M}{Z\sigma_y}$	1.27	1.68	1.65	1.65	1.64	1.65
θ_p^m(%)	5.99	8	8	8	8	8

Δ_m=maximum beam displacement; h=story height; M=maximum moment at column face; Z=plastic section module for beam; σ_y= yield stress of beam flange; θ_p^m=maximum beam plastic rotation.

As long as using E7018, all specimens expect RC1 showed similar strength and ductility, maximum plastic strains measured in beam flanges and bottom weld of specimens, displayed in figure 3.10 to reach better understanding of connections seismic performance.



(a) (b)

Figure3.10. Max plastic strain of specimens; (a) bottom weld (b) beam flange

On the basis of nonlinear finite element result, specimen RC2, showed the most reliable seismic behavior among the other specimen. As shown in figure 3.10, in this specimen, connection ductility supplied just thorough forming the plastic hinge in beam flange and therefore the plastic strain measured in bottom weld is less among other specimens.

4. EFFECT OF MATERIAL PROPERTIES

To study the effect of beam, column, and continuity plate and flange plate material properties, on connections performance, three connections modeled and analyzed. The geometry and welding details of these specimens is similar to RC2.

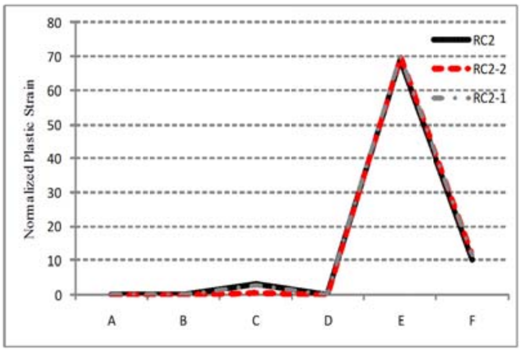
Specimen RC2-1: The ST52 steel material was utilized for column, the welding electrode is E7018.
Specimen RC2-2: The ST52 steel material was utilized for column, continuity plates and flange plates, the welding electrode is E7018.
Specimen RC2-3: The ST52 steel material was utilized for column, the welding electrode is E6013.

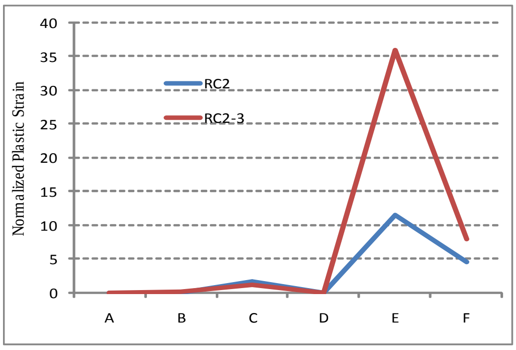
Table 4.1 presents the hysteresis response of the specimens under cyclic loading.

Table 4.1. Summery analytical data

Results	RC2-1	RC2-2	RC2-3
Δ_m(mm)	208	208	208
$\frac{\Delta_m}{h}$(%)	6.93	6.93	6.93
M(N.mm)	2.54×10^8	2.54×10^8	2.53×10^8
$\frac{M}{Z\sigma_y}$	1.69	1.69	1.68
θ_p^m(%)	8	8	8

Figure 4.1 (a & b) compare the strain distribution in story drift angle of 8% in specimens RC2-1 and RC2-2 with specimen RC2 (welding electrode E7018) and specimen RC2-3 with RC2 (welding electrode E6013) to study the effect of material properties on strain distribution in critical regions of specimens.





(a) (b)

Figure 4.1. Comparing strain response of specimen RC2-1, RC2-2 and RC2-3 with RC2

Based on the finite element results, using high strength steel (ST52) increased the connection's strength, maximum 0.8% radian, however utilizing ST52 steel material for column, continuity plates and flange plates was led to reducing plastic deformation of weld joint or increasing the plastic strain in beam flange as shown in figure 4.1.

5. CONCLUSIONS

This paper has been conducted in order to study the effect of welding details and material properties on cyclic behavior of moment-resisting connections. The following conclusions can be pointed out from the analytical analysis.

- Of all parameters examined in this study, the weld electrode type had the most significant effect on the performance of welded flange plate connections. Using high toughness electrodes prevent stress concentration at weld joint and develop stable inelastic behavior in the beam flange.
- Using welding detail similar to specimen RC1, will lead to plasticization of weld and connection's brittle fracture which is not recommended.
- Utilizing single bevel but weld and backup bar for joining the flange plates to column similar to specimen RC2, effectively improves the connection's behavior by increasing strength and ductility of the connection.
- In the case of using electrode E6013, utilizing the welding detail similar to specimens RC2 and RC6 is strongly recommended, which lead to improvement of connection's hysteretic response.
- It is critical to control the welding process precisely in the case of using double fillet weld for joining the flange plate to column, as existing any imperfection in welding process will lead to plasticization of weld before forming a plastic hinge in beam and failure of connection.
- Due to economic considerations, using high strength steel is not recommended as it can increase the connection's strength, maximum 0.8% radian and did not have a significant effect on seismic performance of connections.
- Eliminating backup bar based on the FEMA recommendation did not have a significant effect on connection performance.

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