



Seismic Rehabilitation of Steel Frame Connections Through Asymmetrically Weakening the Beam

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Abstract

Poor seismic performance of steel frame connections were proved after the Northridge earthquake (1994) which led to fundamental change in acceptance criteria of the steel frame connections. New design codes consider the plastic hinge to be located far from the column face to prevent brittle fractures at or near welds. In these cases there is a need to retrofit the existing steel frame buildings which have been designed according to Pre-Northridge seismic codes. In current study, several experimental tests were conducted to investigate the influence of two retrofit techniques on cyclic behavior of a Pre-Northridge connection. The techniques involved intentionally weakening the beam to trigger the plastic hinge to a predefined location in the beam. The retrofit scenario was implemented through reduction and annealing the beam bottom flange. For the Pre-Northridge connection a tear damage mechanism was observed near the welded joint accompanied by a sudden drop in connection strength, while the retrofitted specimens were able to relocate the plastic hinge away from the column face. In reduced specimens, top and bottom flanges of the beam showed local buckling near the joint at the end of loading, however in annealing technique low stress demands in near weld region was resulted. It was concluded that area reduction of the beam would make the connection prone to out of plane buckling.

Keywords Pre-Northridge connection · Seismic rehabilitation · Steel beam to column connection · Reduce beam section (RBS) · Heat treated beam section (HBS)

1 Introduction

Following the Northridge earthquake (1994) a number of welded steel moment-frame buildings were found to have experienced brittle fractures of beam-to-column connections.

Discovery of these unanticipated brittle fractures of framing connections, often with little associated architectural damage to the buildings, was alarming to engineers and the building industry (FEMA-351 2000). This led to a fundamental change in behavior acceptance of moment frame connections. The new aspect of the seismic codes is to

relocate the stress concentrations far from the joint. Different techniques have been proposed to reduce imposed demands on the beam-to-column connections. Two general techniques of “strengthening the joint” and “reducing the beam section” have been thoroughly investigated. The strengthening techniques involve adding rib plates, steel haunch, etc. to the joint while reduction ones include intentionally weakening a portion of the beam and reducing the plastic capacity of the beam section. Reduction of the beam moment capacity provides some advantages such as reduction in shear force in the panel zone, reduction in stress demands in continuity plates and satisfaction of the weak beam-strong column criterion.

From another point of view the existing steel frame buildings which are designed according to Pre-Northridge seismic provisions, need to be retrofitted to prevent the connections from experiencing brittle fracture at or near their welds. Meanwhile the concrete slab in existing buildings presents a problem for economic considerations in seismic retrofit projects. Unless the concrete slab is removed, it is impossible to modify the top flange and its welded joint. Furthermore as the majority of reported damages during past earthquakes

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occurred in the bottom flange of the beam, it is anticipated that modifying only the bottom flange may be sufficient to significantly improve the performance of the steel frame connections. Making a ductile fuse in the beam section through weakening and gaining the most possible plastic behavior from the beam can be a modification program. The asymmetrical retrofitting techniques have received only limited attention in past researches.

FEMA 355 (2000) has reported investigations on different Post-Northridge steel frame connections. The tests included symmetric and some limited asymmetric connections which had been upgraded with strengthening and reduction techniques.

Civjan et al. (2000) investigated the effectiveness of applying a reduced beam section and haunch, in order to retrofit Pre-Northridge steel frame connections. They conducted an experimental test program on 6 large scale steel connections with two specimens retrofitted through RBS technique and four specimens of haunch at both the bottom and top flanges. The most promising technique was haunch with slab effect consideration.

Kim et al. (2004) investigated the influence of slab on retrofitted connections. The retrofitted scheme included three types of no weld access hole, horizontal stiffener and cover plate. Experimental results showed that the techniques were effective in ductility improvement of the frame connections.

Chi et al. (2006) conducted a numerical and experimental research on the application of steel haunch at the beam bottom flange of steel frame connections. The efficiency of this method for a 13 story building in Los Angeles, has been proven.

Judd et al. (2015) investigated a new technique for seismic rehabilitation of Pre-Northridge (PN) connections based on T stub connectors installed on top and bottom flanges of the beam. The finite element simulation conducted in their study revealed that the gravity frame retrofitted through such technique can be utilized in seismic prone regions.

Kim and Lee (2017) conducted an experimental investigation on asymmetrically rehabilitating the Pre-Northridge connections. In their research program welded triangular or straight haunch and heavy shear tab were implemented on the bottom flange or the beam web. Acceptable plastic rotation exceeding 4% inter story drift for the retrofitted connections was resulted.

In this regard the asymmetrical RBS (reduced beam section) technique can be an economic method which is discussed in FEMA 547 (2006). In this standard reduction in bottom flange of the beam is permitted as a method for seismic retrofit of steel frame connections. Other investigation on rehabilitation of steel frame connections are addressed in literature (Tremblay and Filiatrault 1997; Saberi et al. 2016, 2017).

The objective of the present study is to suggest a simple, efficient and economic technique to retrofit the steel frame connections in existing buildings with the least changes. A ductile and seismic structural fuse was implemented in the beam section through weakening to confine the major plastic behavior to the beam. Accordingly weakening the beam section through “reduction” and “annealing” of the beam bottom flange were developed and experimentally validated as two techniques of retrofitting.

2 Introduction to Annealing Process

Annealing is a heat treatment that alters the physical and sometimes chemical properties of a material to increase its ductility and reduce its hardness. It involves heating a material above its recrystallization temperature, maintaining a suitable temperature, and then cooling.

In annealing, atoms migrate in the crystal lattice and the number of dislocations decreases, leading to a change in ductility and hardness. As the material cools it recrystallizes. For many alloys, including constructional steel, the crystal grain size and phase composition, which ultimately determine the material properties, are dependent on the heating, and cooling rate (Verhoeven 1975; Bramfitt 1991). When the material cools *slowly*, the microstructure has an opportunity to coarsen and decrease the strength. This was observed in numerous tensile tests conducted on Iranian steel (St37). On the contrary the “quench” process which comprises of rapid cooling down the temperature increases the material strength, however the rate of cooling would have a crucial effect on post heat mechanical properties.

2.1 Application on Iranian Steel

In order to investigate the effect of the top temperature and the rate of cooling on the steel strength, there is a need to impose a variety of heating scenarios on standard coupon tests.

As previously mentioned the main goal of current research is to propose an economical, easy and effective way for retrofitting frame connections. Based on this goal and given the effect of type and cooling rate on the results, direct fire for the purpose of heating and two cooling scenarios were utilized for tensile tests and also for connection specimens.

In the first scenario, after heating the area up to 900 °C and holding for 15 min, the material is let to be cooled at ambient temperature with “no control = HBS1¹”, and in the second one, it is cooled slowly with “maximum

¹ Heat affected beam section.

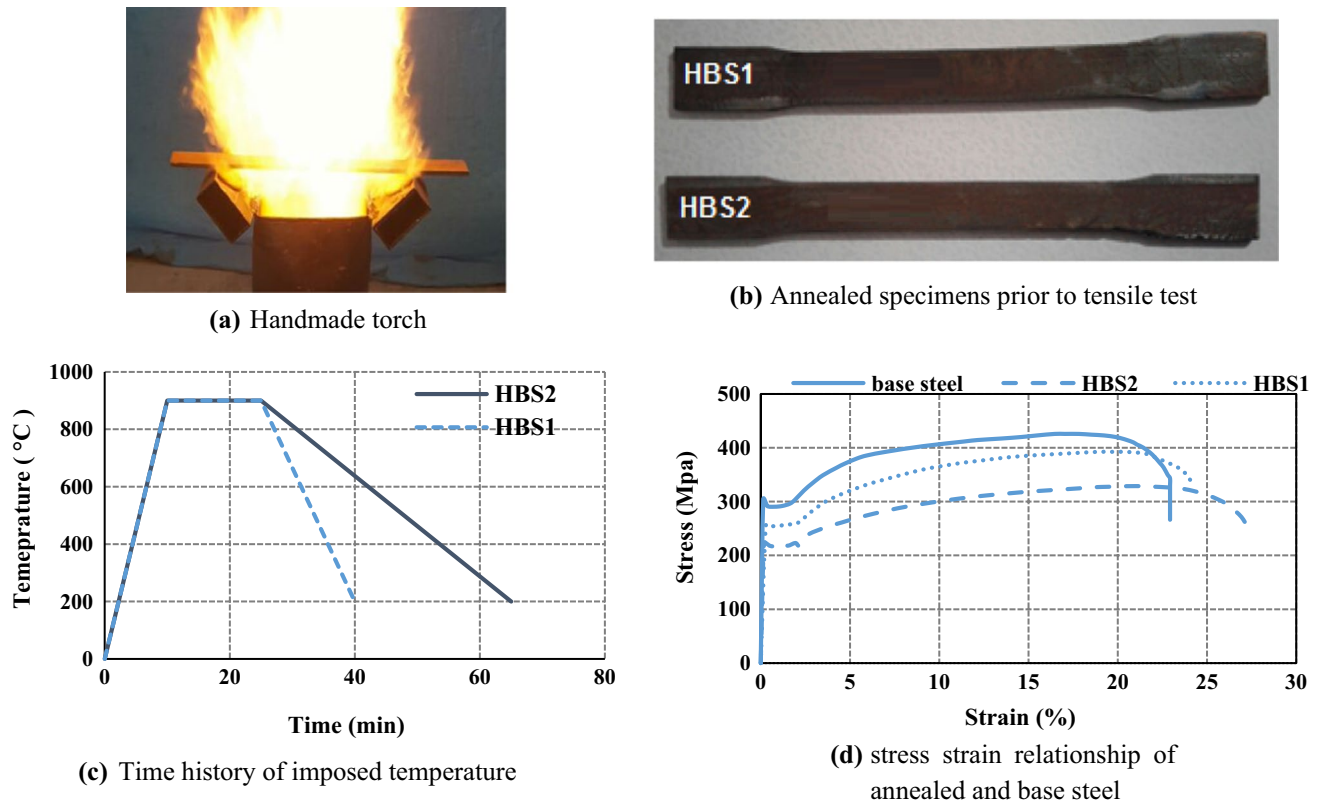


Fig. 1 Annealing results of Iranian steel

control = HBS2". It is worthy to mention that HBS1 can be the most quickly "annealing" technique which is available in situ with fire and HBS2 is the slowest possible one.

Details of annealing tests and a comparison of the post fire mechanical properties for dumbbell specimens is presented in Fig. 1. In this figure temperature histories for two HBS schemes are shown. As can be seen, cooling rate had significant influence in stress strain relationship. For HBS1 and HBS2 the yield strength degradation was 17% and 31% also the ultimate strength degraded by 11% and 23% respectively. Annealing process had increased ultimate strain for HBS1 and HBS2 by 7% and 18% respectively. This increase in ductility of the tensile coupons can be predicted to have a good effect on relocation of plastic hinge in moment frame connections. So in a similar manner to the RBS, the HBS scenario can provide a ductile seismic fuse through weakening. Also, since the cross section of the bottom flange in beam is not altered, the buckling resistance of the connection retrofitted through heat process remains similar to that of the beam section before heat induction. Another advantage of asymmetrical HBS is convenience so that the technique can be easily and economically applied by an installed torch on the bottom flange.

3 Experimental Program

3.1 Pre-Northridge Specimen

A series of five sub assemblages were tested to investigate two retrofit techniques based on beam weakening. The connections represent a corner beam to column connection according to the substructure suggested in SAC Joint Venture (2000). The specimens included one Pre-Northridge (Reference) connection and four retrofitted connections. The reference connection was designed and constructed according to AISC (2011) requirements for WUF (welded unreinforced flange) connections and was chosen to be representative of typical building construction in common use prior to the Northridge Earthquake (1994) associated with some improvements such as strong panel zone and removal of backing bars (as opposed to Pre-Northridge).

Considering the capacity of the utilized hydraulic jack, moment demand at column center line as well as shear force demand was calculated and the beam section was chosen. Meanwhile considering a free span of the column as 1.6 m it was designed and controlled for lateral bracing regulations (unbraced length). The column panel zone

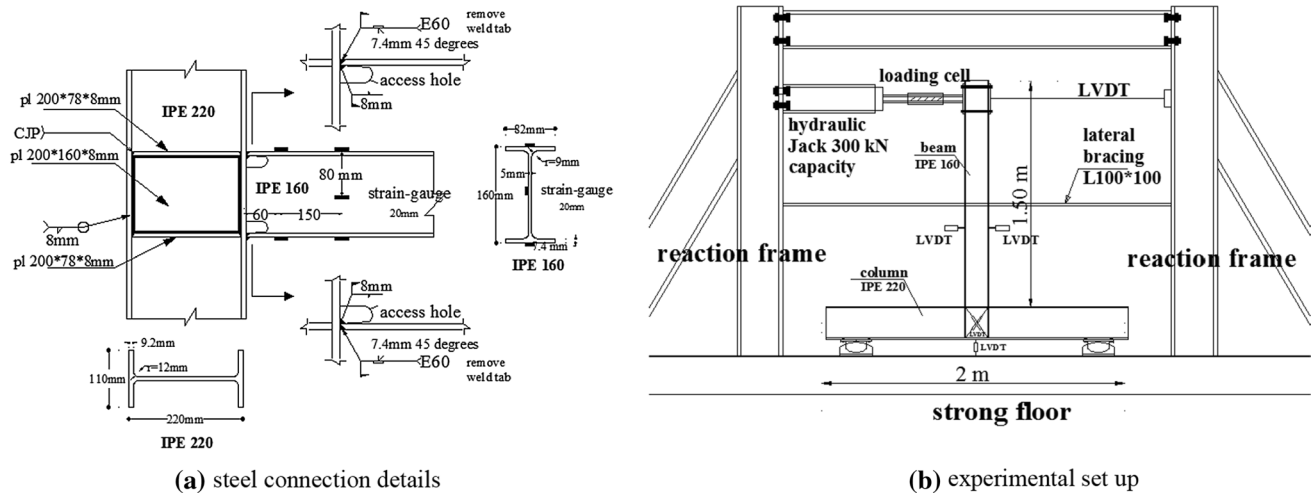


Fig. 2 Details of experimental program

was reinforced with two 8 mm doubler plates to promote strong panel zone behavior and ensure that most of the inelastic action was obtained from the beam (see Fig. 2a). Accordingly, large plastic rotation demands can be applied on the beam which allows better evaluation of the ductility and energy dissipation of the specimens. Meanwhile four continuity plates with 8 mm thickness were designed and added to the column web along the beam flanges. In this way the column flanges were prevented from local buckling. Groove welds and fillet welds were used to connect the doubler plates and continuity plates to the column respectively.

3.2 Experimental Set Up

The test set up and instrumentations used for application of cyclic loading are shown in Fig. 2b. In this figure the column is in horizontal situation and the beam is vertical. The test set up was designed to provide expected boundary conditions for subassemblies which comprises of two pinned supports for the column. The standard cyclic loading was applied to the beam tip with a hydraulic jack until failure.

A calibrated load cell in the hydraulic jack provided readings of force response during the experiments. The loading capacity of the jack was 30 tons with 30 cm stroke capability. The overall out of plane displacement of the beam was constrained using a lateral support installed in the mid-height of the beam. The lateral bracing met the requirements of AISC (2011) for WUF connections. Six LVDTs² were placed on the connection components to monitor displacements of the beam tip, beam mid height, panel zone diagonals and

column midpoint. The loading protocol used in cyclic tests was in accordance with the standard provided by AISC (2011). In this loading scenario, the rotation applied to the beam tip starts from 0.00375 radians and gradually continues to 0.06 in totally 34 cycles.

3.3 Retrofit Schemes

The retrofit techniques were applied on the beam bottom flange through “reduction” and “annealing” scenario.

3.3.1 Annealing Scenario

3.3.1.1 Basis of the Technique The purpose of this scenario is to create a softer and more ductile material in the beam section to change the damage mechanism of the steel connection. Accordingly the two investigated annealing methods (HBS1 and HBS2) were implemented on the beam. The annealing retrofit technique utilizes a similar ‘fusing’ mechanism similar to that of the reduction technique. The material strength reduction is achieved through “annealing” of the beam flange in a portion relatively far from the column face.

Similar to the annealing scenarios applied on coupons, the two annealing schemes were utilized and named as R-HBS1 and R-HBS2. Details are presented in Fig. 3.

3.3.1.2 Thermal Analysis One of the important issues in annealing scenario is heat transfer. It is obvious that when the steel (as a conductive material) is heated in a portion, the temperature will distribute to other parts. It’s needed to investigate the heat transfer during the annealing process to determine the exact influenced area. In this research the finite element simulation was utilized to exactly define the

² Linear variable displacement transducer.

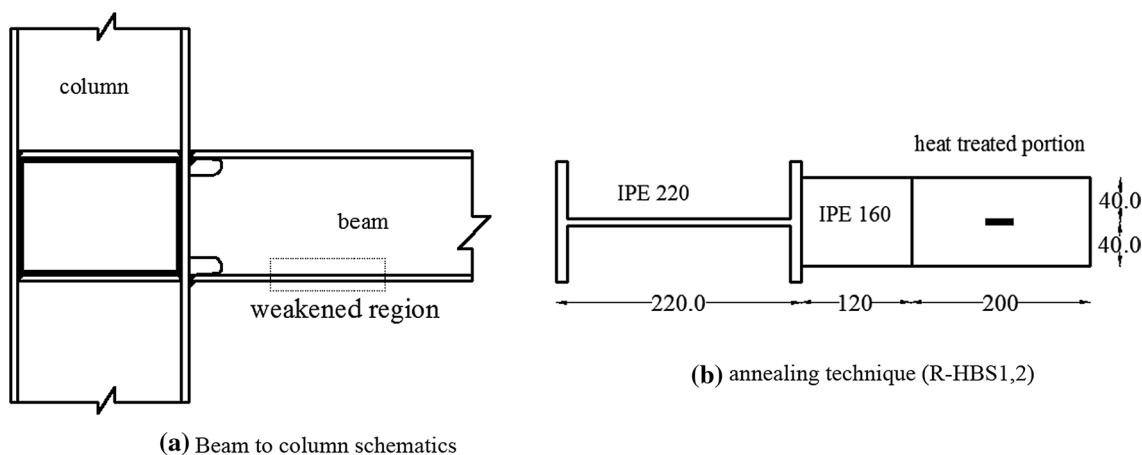


Fig. 3 Annealing retrofit technique

“target” and the “influenced” area in heat induction process. Fourier heat conduction equation represents a three dimensional heat flow in a solid body which is given in Eq. 1.

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + Q = \rho c_p \frac{\partial T}{\partial t} + \frac{E\alpha}{1-2\nu} \left(\frac{\partial \epsilon_x}{\partial t} + \frac{\partial \epsilon_y}{\partial t} + \frac{\partial \epsilon_z}{\partial t} \right) \quad (1)$$

In which k is thermal conductivity, Q is generated heat energy, ρ is density, c_p is specific heat, T is temperature, E is modulus of elasticity, α is coefficient of linear expansion, ν is poisson’s ratio, ϵ is mechanical strain, t is time, x, y, z are Cartesian coordinates.

The boundary condition for solving Eq. 1 is given in Eq. 2 and is valid at the surface.

$$-k \frac{\partial T}{\partial n} = h(T - T_{am}) \quad (2)$$

In which h is surface coefficient of heat transfer, n is coordinate normal to surface. However, for solving the heat flow equation numerically, in the thermal finite element analysis it is assumed that the material is homogeneous and isotropic throughout the cross section and the material coefficients are known as functions of temperature (Quayyum 2014). For a body subjected to cooling in the atmosphere with no sharp variation in the time temperature history, the coupling effect of temperature and strain can be neglected. Hence, the 2nd term in the right hand side of Eq. 1 can be neglected. Furthermore, $Q=0$ since there is no heat generated in the body. These assumptions simplified Eq. 1 as follows:

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + Q = \rho c_p \frac{\partial T}{\partial t} \quad (3)$$

After discretization over the region, the heat-conductivity equation can be reduced to the following matrix equation.

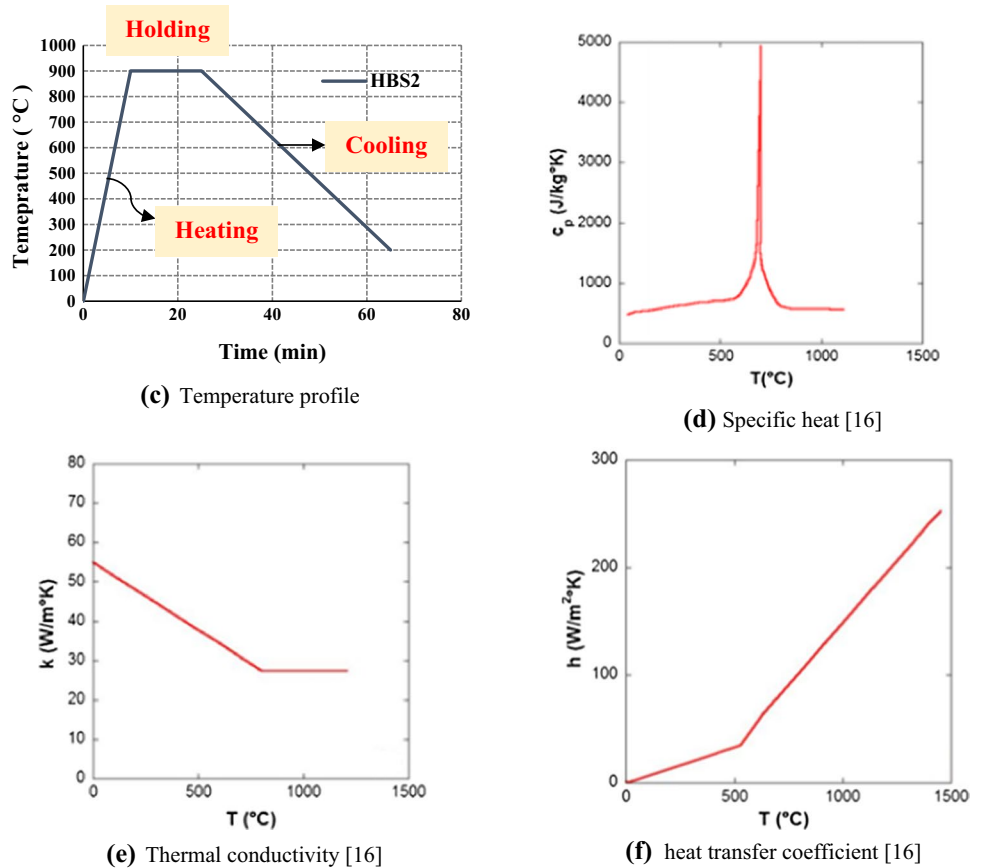
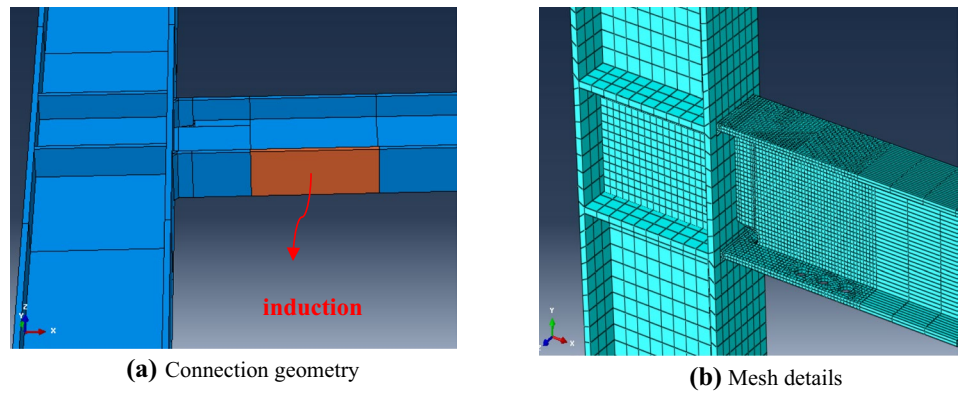
The material coefficients that are required to solve Eq. (4) are density, thermal conductivity, specific heat and surface coefficient of heat transfer (Quayyum 2014).

$$[C]\{\dot{T}\} + [K]\{T\} = \{Q\} \quad (4)$$

where $\{T\}$ is the vector of nodal temperatures, $[C]$ is the heat-capacity matrix, $\{K\}$ is the heat conductivity matrix, $\{Q\}$ is the vector of heat energy which is zero for this case. A three dimensional finite element model was constructed in ABAQUS/PRE (1997). The welding geometry was tied to column flange considering a complete joint penetration (CJP). The column panel zone plate as well as the continuity plates were geometrically merged to the nearest nodes. All of the connection components have been modeled using neat transfer element type with Six-node hexagonal temperature degrees of freedom. Mesh size of the components were 3, 1.5, 1 cm for the panel zone, far from the joint and near the joint respectively. Details of the numerical modeling are presented in Fig. 4. The temperature time history was in accordance with the HBS2 annealing scheme and was applied in the same geometry as the R-HBS2 retrofitting program. Thermal properties of the constructional steel as temperature dependent parameters including specific heat, thermal conductivity and heat transfer coefficient are also shown in this figure. A total time of 90 min was considered for heat transfer analysis.

Results of heat transfer analysis are depicted in Fig. 5. Nodal temperature distribution during three phases of heating, holding and cooling for R-HBS2 scenario proved the following important points; (1) After 10 min of increasing time, the target area (200 mm × 80 mm) experienced 900 °C uniformly, (2) A hold time of 15 min can help the temperature to be uniformly distributed along the thickness of the bottom flange, (3) after the cooling phase ($t = 70$ min) terminated, the maximum temperature

Fig. 4 Finite element modeling details



was approximately 302 °C and decreased to 148 °C at the end of loading ($t = 90$ min); at this temperature mechanical properties of steel would not be altered which proved that the target and influenced regions don't differ so much in area. These regions are shown in Fig. 6, and (4) the bottom welding was not affected during heat induction. These results are important to determine the influence heat loading on the built structure.

3.3.2 Reduction of the Bottom Flange Section

A portion of the beam bottom flange near the column is weakened in reduction scheme so that plastic hinging can be predicted to occur at the designated location. Introducing a “ductile fuse” with a reduced beam flange width near the beam-column connection has little effect on frame lateral stiffness, but the flange force that is transmitted to the connection is reduced. The retrofit technique was

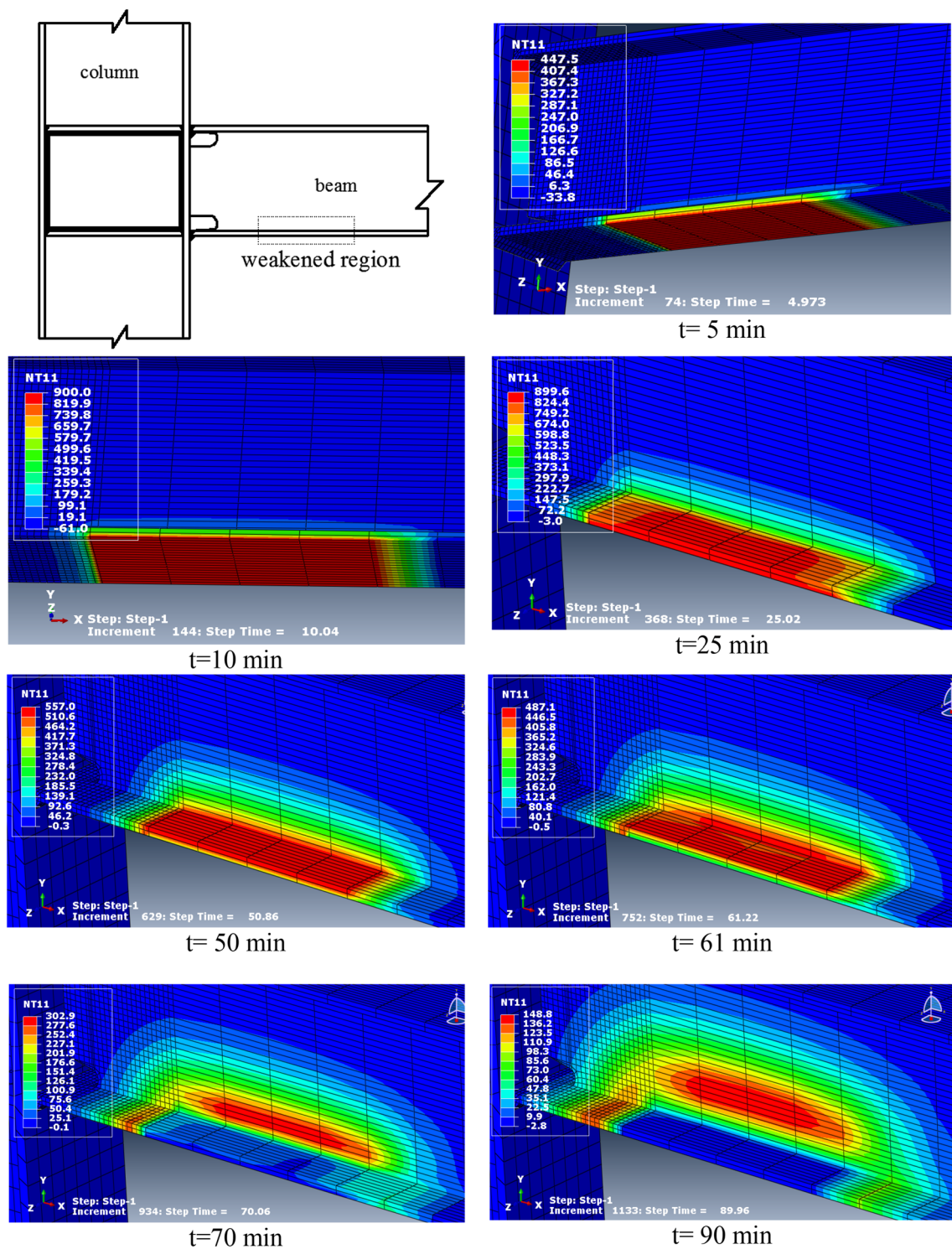


Fig. 5 Heat induction analysis results (nodal temperature in °C)

applied only on the bottom flange in which 20 and 50% of the flange section was reduced by drilling. Regarding the fact that the building had already been constructed, for the purpose of rehabilitation, it seems that the only practical method to reduce the section is by a magnet or drill device.

Details of drilling are shown in Fig. 7. Diameter of drilled holes are 1 cm and 2 cm and a region of 140 × 80 mm which is 80 mm far from the column face was considered as an area of plastic hinge location. A similar configuration for drilled flange connections was investigated by

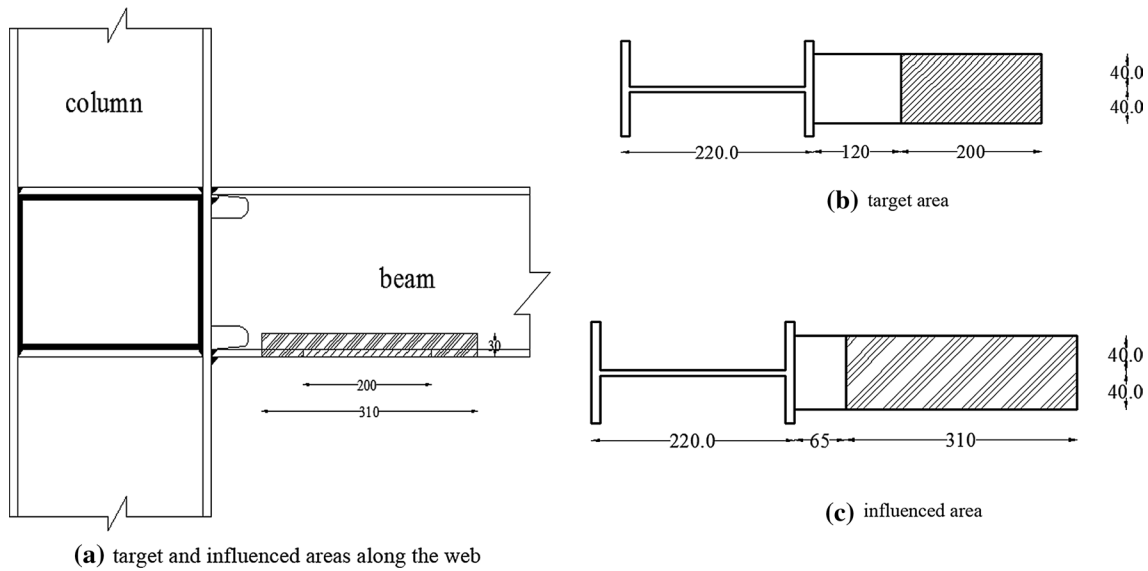


Fig. 6 Heat distribution effects in annealing process

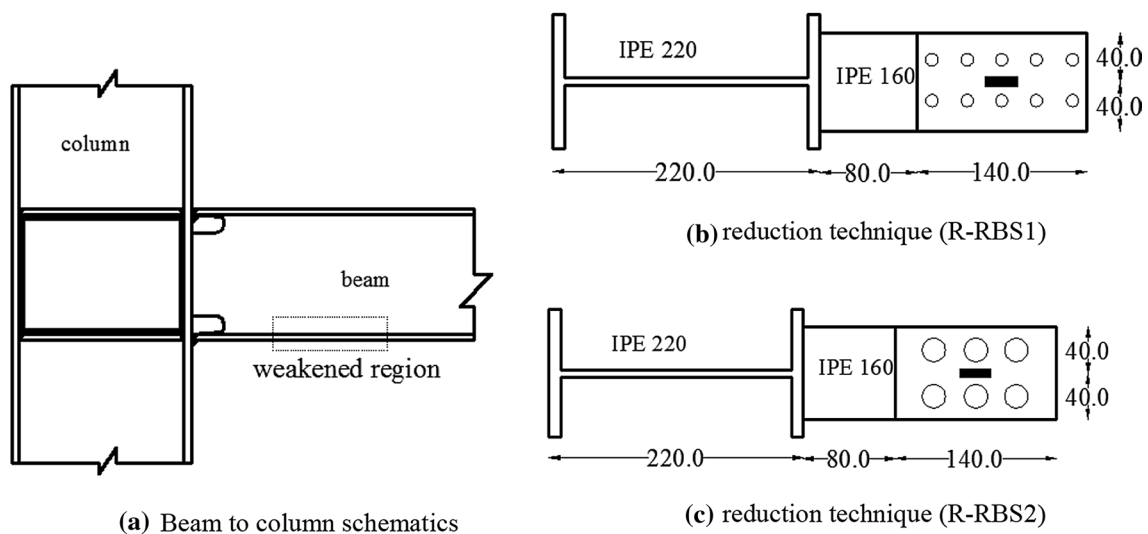


Fig. 7 Reduction of the bottom flange

Atashzaban et al. (2015). They have numerically investigated several drilling configurations for both flanges of the beam.

4 Experimental Results

4.1 Load Displacement Relationship

Figure 8 shows the moment at column center line versus beam total rotation relationships for all specimens. The behavior of the improved specimens in tension and

compression, especially in plastic excursions, are different and the ultimate rotation is different in these two zones. As can be seen the specimens which experienced a tear damage mechanism (Reference and R-RBS2) showed a sudden drop in hysteresis curves. Other specimens (R-RBS1, R-HBS1 and R-HBS2) showed wide hysteresis loops and stable inelastic behavior. In these specimens gradual strength degradation was observed due to buckling which can satisfy AISC (2011) acceptance criteria to confirm that the flexural capacity of the specimen at the column face was not less than 80% of the beam plastic moment at 0.04 rad.

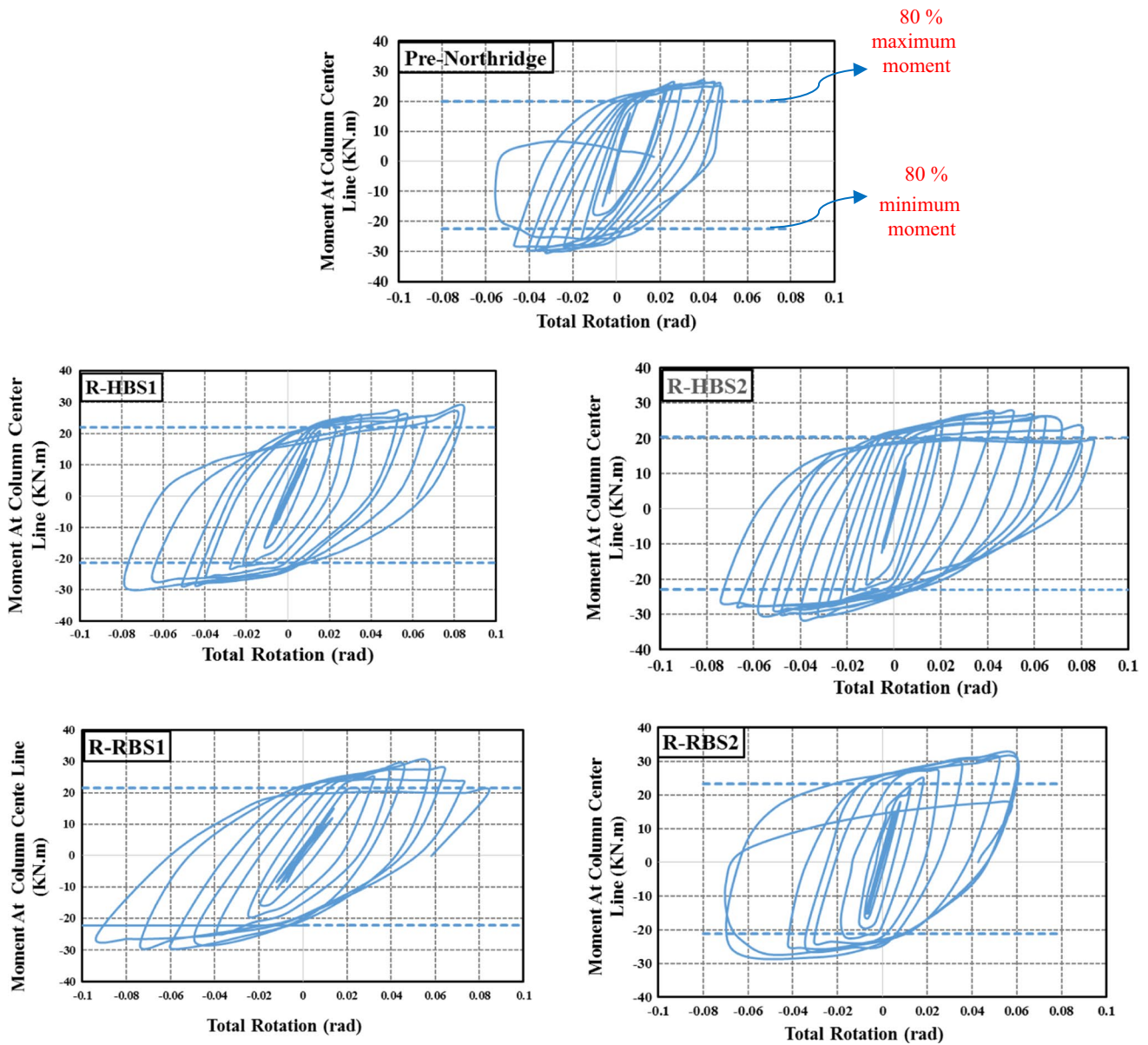


Fig. 8 Hysteresis curve for specimens

To get insight into the cyclic behavior of the reference and retrofitted connections, the envelopes of hysteresis curves are presented in Fig. 9 separated for “buckling” and “tear or brittle fracture” damage mechanisms. These two mechanisms occurred after yielding and resulted in gradual and sudden strength degradation respectively.

4.2 Test Observations

4.2.1 Pre-Northridge Specimen

During the cyclic loading, yielding initiated at total rotation of 0.0011 rad when the plastic paint cover with low

resin began to fall down from some portions of the bottom and top flange. Beam flange yielding, without local buckling or fracture, resulted in negligible degradation of structural strength. By increasing the loading amplitude, yielding extended into other regions of the flange and the web. At story drift of 3.5% local buckling in the bottom flange was observed. By increasing the number of inelastic cycles, in plane deformation of the bottom flange was measured as 4 cm. This in plane buckling resulted in near weld damage. First cracks in the bottom flange HAZ³ region originated at story drift of 4.5%. At story

³ Heat affected zone.

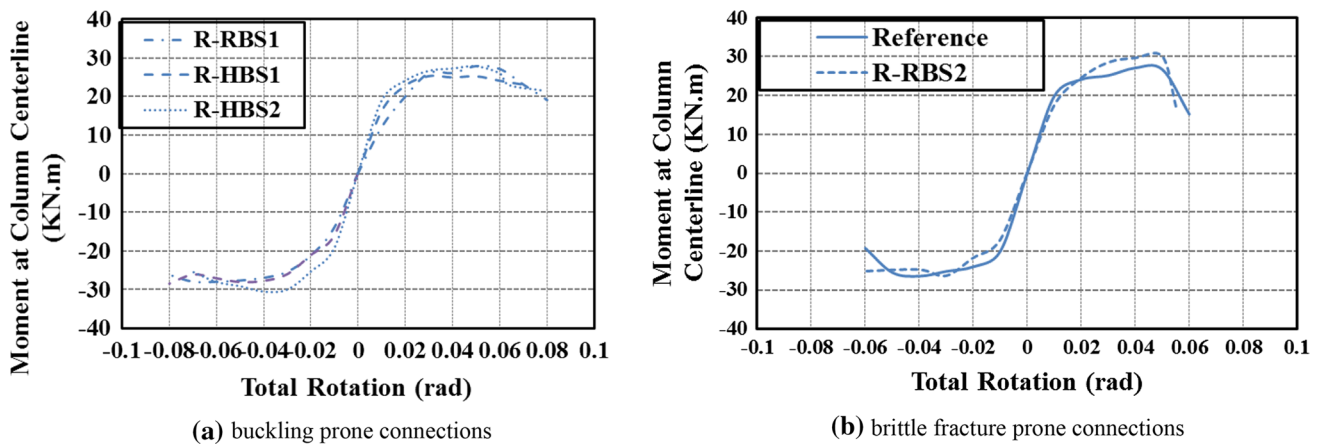


Fig. 9 Envelope of moment-rotation hysteresis curve of the specimens

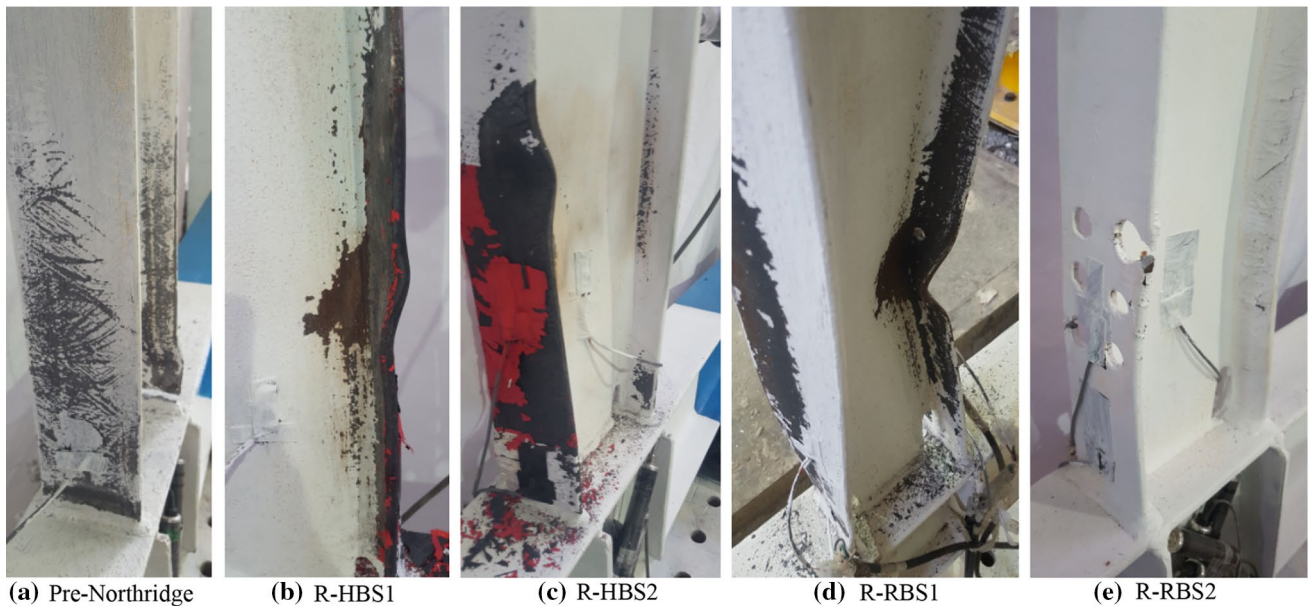


Fig. 10 Location of plastic hinge in specimens after the cyclic tests

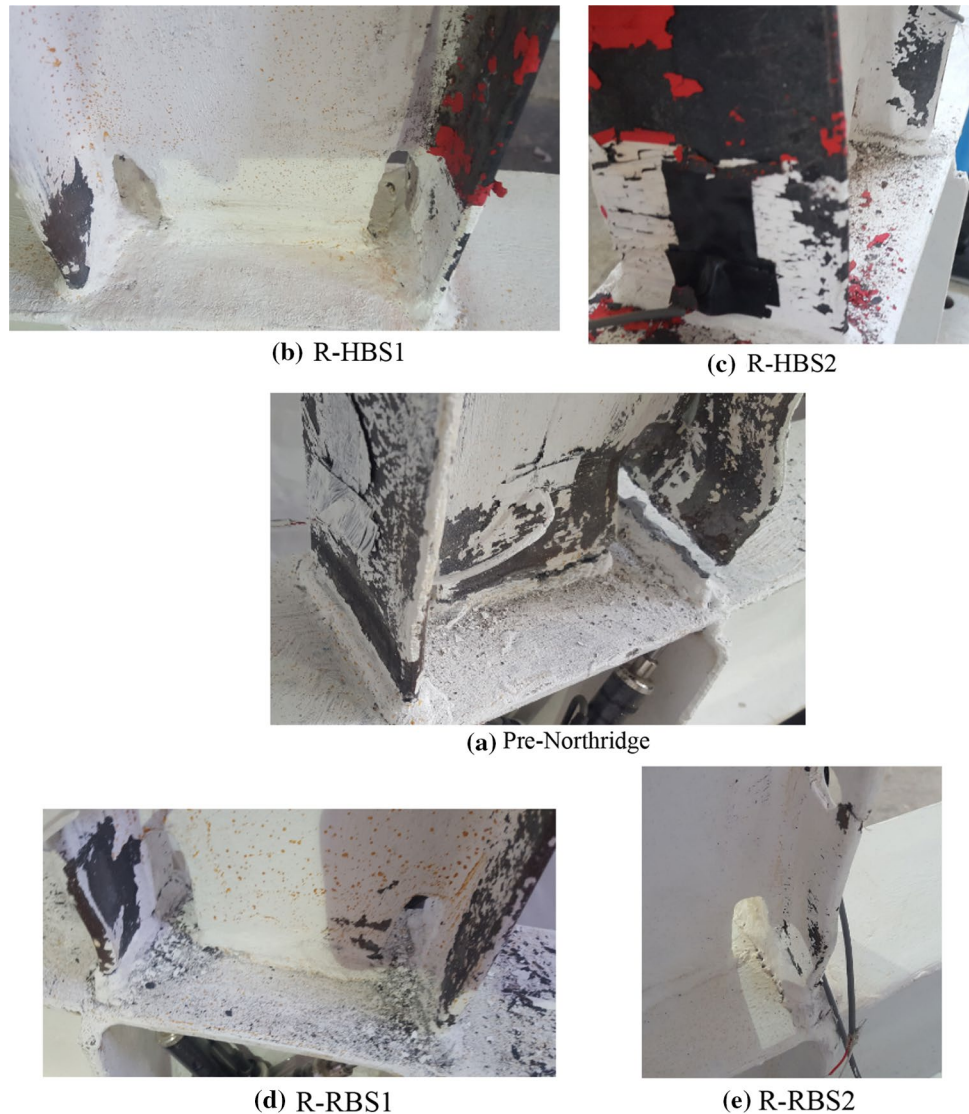
drift of 5.5% local buckling and tear in HAZ region of the flange and the web resulted in significant strength loss and the test was terminated. The overall damage mechanisms are presented in Fig. 10a and damages near the welds in Fig. 11a at the end of experiment. After the elastic region, the rotational stiffness of the connection decreased by 78%. The amount of energy dissipated by this connection was 26.58 kJ which the contribution of the column and the connection panel zone was not considerable. According to FEMA 351 (2000), in order to

design this connection, the location of the plastic hinge should be considered at the column face.

4.2.2 R-HBS1 Specimen

Results of the cyclic test on the connection retrofitted through “heat induction with no control” are shown in Figs. 10b and 11b. This connection began to yield at 0.013 rad rotation, and by continuing the cyclic loading, yielding extended to whole the annealed region (red colored region in the figure) and some regions near the welding

Fig. 11 Damage mechanisms near the welds in specimens



region. The test was terminated at 0.064 rad rotation due to 20% strength reduction. As can be seen, just yielding with no local buckling at regions near the column face was observed. The rotational stiffness reduced after yielding by about 98% in tension and 91% in compression excursions. Note that in this case, the top and bottom flange positions to spring LVDT is contrary to that of other connections, and the compression region represents the bottom flange behavior. The amount of energy dissipated by this connection was 39.76 kJ, which like other connections, largest contribution belonged to the beam.

4.2.3 R-HBS2 Specimen

This connection was asymmetrically retrofitted through annealing with maximum control in cooling regime. Results of the cyclic tests are shown in Figs. 10c and 11c. At the rotation of 0.01 rad the connection yielded in some regions

of the annealed portion of the beam. Significant loss in strength was not observed until the rotation of 0.078 radians. In this rotation the bottom flange showed local buckling in a distance of 27–34 cm from the column face. Yielding extended to other regions of the beam. Results of the cyclic test showed that there was a 98% reduction in rotational stiffness in tension and 93% in compression excursions. The amount of dissipated energy was 47.93 kJ. This amount of dissipation comes from the plastic behavior of the beam. It can be concluded that annealing of the beam material increased ductility of the beam and helped the connection to dissipate energy much more than other connections.

4.2.4 R-RBS1 Specimen

In total rotation of 0.013 radians first signs of yielding appeared at the weakened region in bottom flange of the beam. By continuing the loading, the white wash of areas

Table 1 Test results

Group	Specimen	M_{\max}^a	M_{\max}/M_p^b	Satisfaction of FEMA requirements	θ_y^c	θ_u^d	K_y^e negative excursions (kN m/rad)	K_y^e positive excursions (kN m/rad)	E^f (kJ)
Reference	Reference	-28.05	0.94	-	0.011	0.055	2400	2400	26.58
Retrofitted	R-HBS1	-26.46	0.99	Ok	0.013	0.065	1310	1430	39.76
	R-HBS2	-28.35	1.19	No	0.01	0.078	3142	2494	47.93
	R-RBS1	-27.32	0.99	Ok	0.013	0.064	1071.4	1071.4	42.44
	R-RBS2	28.78	1.14	No	0.014	0.05	2231.3	2440	28.01

^aMoment at the column face

^bPlastic moment of the beam

^cElastic total rotation

^dUltimate total rotation

^eRotational stiffness at yield point

^fTotal dissipated energy

of the beams in two flanges was separated from the surface of the steel. In 0.06 rad rotation, in plane and out of plane buckling (lateral torsional damage) occurred at a distance of 18 cm from the connection. In this case, out of plane buckling was recorded as high as 4 cm in the weakened area. At 0.064 rad the test was terminated due to significant loss in flexural strength (more than 20% reduction of flexural strength). As can be seen in Figs. 10d and 11d, at the end of loading regime near weld regions yielded and at the top flange of the beam local buckling was observed. The whole energy dissipation of this connection was calculated as 44.42 kJ and the contribution of the column and the panel zone in energy dissipation was negligible. Since the rehabilitation method was applied asymmetrically and only on the bottom flange, there was a difference between cyclic behavior in tension and compression zones. In this connection in the positive zone (tensile excursions) after the yielding point, the rotational stiffness decreased by 92% and in the negative zone (compressive excursions) the decline was 83%. Considering the location of the displacement meter (LVDT), it can be concluded that weakening the connection in the bottom flange has reduced the elastic stiffness in tension. In compression, the connection can still sustain loading, and this is due to the spread of failures in the bottom flange. This is an important aspect of asymmetrically retrofitting.

4.2.5 R-RBS2 Specimen

At a rotation of about 0.014 radians, yielding in the weakened region of the bottom flange was observed. The failure modes of this retrofitted connection is shown in Figs. 10e and 11e. As the loading continued, bottom flange and the web near the weakened region yielded. At total rotation of 0.05 rad the test was terminated. At this rotation a tear

damage mechanism occurred around the third hole. Local buckling in the bottom flange of the beam near the column face was a disadvantage of this technique. The initial rotational stiffness of the connection decreased by 87%, in tension and in compression by 94% after yield. The overall dissipated energy resulted from plastic behavior of the connection was 28 kJ, of which the beam made the major contribution in energy dissipation.

4.3 Global Response of the Specimens

The response of the specimens was analyzed by data measured by instrumentation during the tests and equations proposed by Popov et al. (1985). Results are briefly summarized in Table 1. In FEMA 547 (2006) for the acceptable utilization of the reduced beam section method for the bottom flange, the condition 1.05 is considered. This means that the maximum moment ratio does not exceed 1.05 over the plastic moment in the weakened area. The plastic moment capacity was calculated assuming that the plastic hinge would form at the narrowest (in reduction method) and the weakest (in the annealing method) section of the beam. As can be seen in the table, two improved connections satisfy this condition.

Since the improvement was done only in the bottom flange, the rotational behavior of the connection was different in tension and compression. The most considerable difference in the rotational stiffness of the connection between the two tension and the compression excursions was associated with R-HBS2 specimen. In retrofitted connections plastic action was totally confined to the beam. Among the specimens the most ductility of the R-HBS2 specimen has led to the most amount of energy dissipation. The dissipated energy was calculated based on the area under hysteresis curves until 80% reduction in strength.

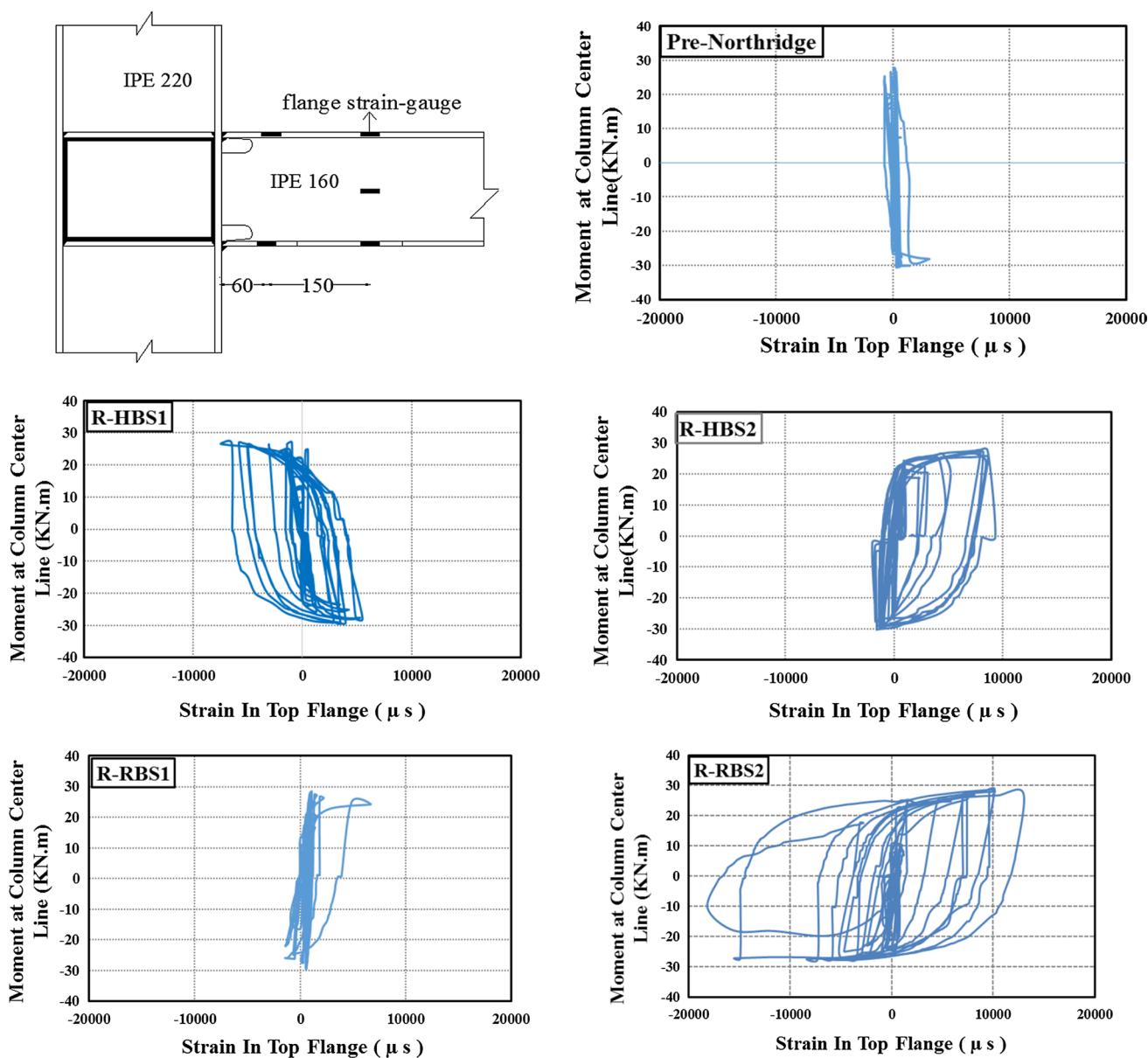


Fig. 12 Strain gauge values based on a distance of 21 cm on the top flange

It can be concluded that by application of a ductile fuse in the beam section, the frame connection can experience a “buckling” failure mode and this is accompanied by more energy dissipation by the connection. In this way the frame can deform laterally in a plastic manner. The connections R-RBS1, R-HBS1, R-HBS2 represented a qualified plastic behavior for special moment resisting frames (SMRFs) which can withstand over 0.03 radians in plastic cycles.

4.4 Strain Gauge Values

4.4.1 Top Flange Strain Gauges

Among the issues considered in choosing the appropriate rehabilitation method, the reaction of the top flange plays an important role. The current rehabilitation methods was applied only on the bottom flange, however the top flange is buried in concrete in real cases. The concrete slab would be effective in providing lateral bracing for the top flange so that lateral-torsional buckling would not occur under positive bending. But the top flange local buckling still would be developed under negative bending. The longitudinal strain

was considered as the basis of comparison between methods of retrofitting at a distance of 21 cm from the column face (see Fig. 12).

As can be seen, in the reference specimen, the highest longitudinal strain was 0.0032. However the minimum value was 0.0058 and belonged to R-HBS1. This can be interpreted as more use of beam ductility capacity in retrofitted connections. The softer specimens may be more likely to get inelastic longitudinal strains at a given inter-story drift. During the 1994 Northridge earthquake, beam damage was most commonly detected at the bottom flanges, although some

instances of top flange failure were also reported. There are several reasons for this. First the composite action induced by the presence of a floor slab at the girder top flange tends to shift the neutral axis of the beam towards the top flange. This results in larger tensile deformation demands on the bottom flange than on the top. In addition, the presence of the slab tends to reduce the chance of local buckling of the top flange. The bottom flange, however, being less restrained can experience buckling relatively easily (Civjan et al. 2000).

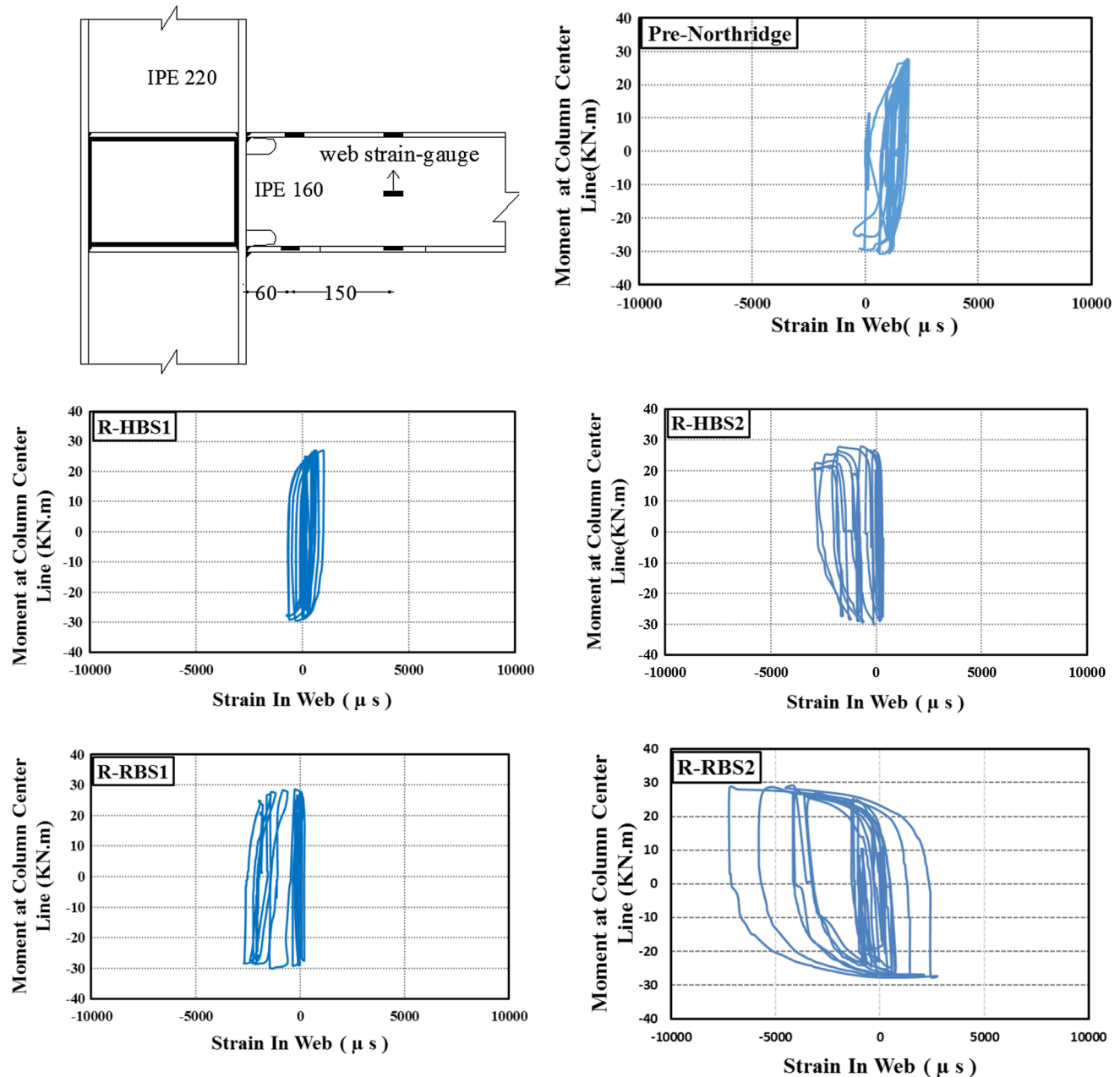


Fig. 13 Strain gauge values based on a distance of 21 cm on beam web

4.4.1.1 Web Strain Gauges It was observed that as a result of retrofitting the reference connection, local buckling of the beam web was drastically reduced. In reference specimen the brittle fracture initiated from the beam flange propagated to the beam web. The two weakening techniques reduced the risk of brittle fracture at the beam web and relocated the plastic hinge far from the column face. The longitudinal strains of the beam web were compared at a distance of 21 cm from the column face in Fig. 13. When the material is removed and the cross sectional area of the bottom flange is reduced, the neutral axes moves towards the top flange. Hence it is expected that the “reduced” specimens show more strains in beam web than the other specimens. Results revealed that the highest values belonged to R-RBS2 specimen which included the most area reduction in its bottom flange. Meanwhile the beam flange contribution in plastic behavior of the connection was larger than the beam web which emphasized the importance of flange modification in retrofit projects.

5 Comments on Asymmetrical HBS Concept

The asymmetric rehabilitation method through reduction in beam flange is permitted by FEMA 547 (2006). The design engineer should consider the ease of utilization of the method as well as the effectiveness. “Heating or annealing” methods, especially those consisting of cooling in the environment, are much more convenient and more efficient than reduced beam section technique. This method can help plastic hinge to relocate far from the column face. In order to better control the temperature and prevent damage to roof components near the heating area, it is suggested that appropriate ceramic blankets be used in these areas and safety cases be intended in the field. By using thermal elements or thermal pads, instead of direct fire, the yielding tension of steel can be reduced to 40% in the heated area but in this case, the cost and history time of heating the beam will be greatly increased.

6 Conclusion

New seismic design codes consider the plastic hinge to be located far from the column face to prevent brittle fractures at or near welds. In these cases there is a need to retrofit the existing steel frame buildings which have been designed according to Pre-Northridge seismic codes.

Proposition of a suitable technique to retrofit the steel frame connections in existing structures with the least changes has always been a concern to civil engineers. In this paper, two general retrofit techniques were investigated for a Pre-Northridge connection. These two methods

were implemented through weakening the bottom flange of the beam. One rehabilitation scheme included drilling holes (reduction) in the bottom flange while the other was conducted through a controlled heat induction process (annealing). Therefore, the beam section was reduced in the first method, but in the second method, a softer and more ductile area was created in a portion of the beam bottom flange. Four rehabilitated specimens and a Pre-Northridge (reference) one were investigated under cyclic loading. Based on the results of laboratory tests, the following conclusions can be drawn:

- The Pre-Northridge specimen showed local buckling near the column face which led to a tear in the HAZ (heat affected zone) area of the beam welding. Significant strength degradation of the beam caused a fracture that initiated at near the welding and propagated rapidly into the bottom flange. This connection didn't show qualified plastic behavior for special moment frames and represented the least energy dissipation among the specimens.
- The two simplest techniques of annealing were applied through direct fire on standard tensile specimens. The techniques included a scenario with “no control = HBS1” and “maximum control = HBS2” in cooling down regime. For HBS1 and HBS 2 the yield strength degradation for Iranian steel (st37) was 17% and 31% also the ultimate strength degraded by 11% and 23% respectively. Annealing process had increased ultimate strain for HBS1 and HBS2 by 7% and 18% respectively.
- A three dimensional finite element model was constructed in ABAQUS to investigate the heat transfer process in annealing scenario prior to experimental tests. Based on numerical results of nodal temperature distribution, two sections of “target” and “influenced” were defined. Heat analysis revealed that the annealing history could generate a uniform nodal temperature along the thickness of the bottom flange and the welding was not affected by annealing. Not a major difference between target and influenced area was observed.
- The two annealing scenarios were then applied on the Pre-Northridge connection in bottom flange of the beam to implement a ductile fuse. At the end of cyclic tests, in both specimens local buckling was observed only in the annealed region. In this technique, beam area near the column face showed only yielding with no local buckling which was an advantage to reduction technique. Another advantage of this technique was the out of plane buckling resistance. This subject has also been discussed for symmetrical HBS frame connections by Morrison et al. (2015).

- Lateral torsional buckling of the weakened region and local buckling in the beam near the column face was observed in both specimens retrofitted through section reduction technique, at the end of loading. It was revealed that the reduction in bottom flange with 20 mm diameter holes led to a tear damage mechanism while in 10 mm holes reduction scheme, buckling damage mode was observed.

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