Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1007

AN INNOVATIVE SEISMIC PERFORMANCE ENHANCEMENT TECHNIQUE FOR STEEL BUILDING BEAM-COLUMN CONNECTIONS

Tasnim Hassan[1] and Samiuddin Syed[2]

ABSTRACT

An innovative technique for enhancing seismic performance of steel building beam-column connections is proposed in this paper. The novel technique involves heat treating specified sections of beam flanges by exposing these sections to a very high temperature (> 1000°C) for a short duration before slow air cooling. Such a heat treatment process reduces the strength of steel in the heat treated areas of the flange. Consequently, under seismic loading plastic hinge develops at the heat treated beam section (HBS). A connection enhanced by the proposed technique will have the advantages of the reduced beam section (RBS) connection, but the heat treated connection will have better energy dissipation than the RBS connection. In the RBS connection, "weakening" of the beam flanges induces plastic hinge in the beam. In the HBS connection, plastic hinge develops at the heat treated section because of the reduced strength of steel. In the HBS connection, as the beam flange remains intact and inelastic modulus of steel is not altered by heat treatment, the lateral and torsional buckling resistances of the HBS connection will be higher than those of the RBS connection. Consequently, the HBS connection will dissipate a larger amount of energy with a minimum loss of strength or stiffness compare to the RBS connection. This novel seismic performance enhancement technique is validated through finite element analysis, results of which are presented and discussed to demonstrate the potential of the novel HBS connection.

Introduction

A decade of research activities after the Northridge earthquake have developed modified designs of welded steel moment connections (WSMCs) with improved ductility (FEMA-350, FEMA-353, FEMA-355D). The modified design recommendations include removing the backing bar, back gouging and depositing fillet weld in place of the backing bar, using high toughness weld materials, modifying the weld access hole, strengthening the panel zone with continuity and doubler plates, and improving quality assurance procedure (FEMA-350, FEMA-353, FEMA-355D, Stojadinovic *et al.* 2000, SAC/BD-00/01, SAC/BD-00/24, Lee *et al.* 2005, and others). These improvements, however, introduced a new mode of low-cycle fatigue failure

---

[1] Associate Professor, Dept. of Civil, Const. and Env. Eng., NC State University, Raleigh, NC, 27695
[2] Graduate Research Assistant, Dept. of Civil, Const. and Env. Eng., NC State University, Raleigh, NC, 27695

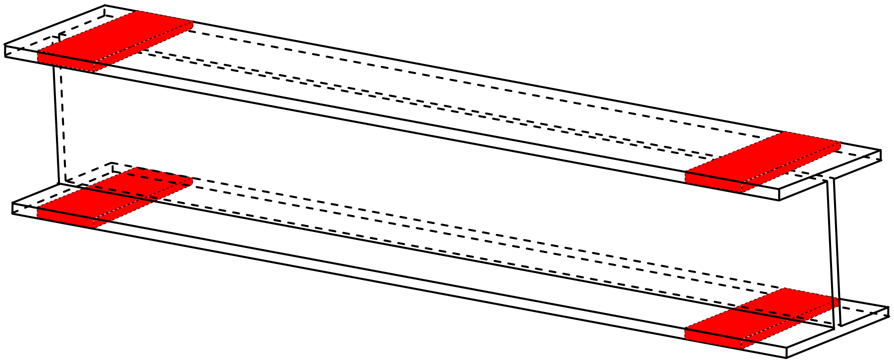
at the beam flange weld toe (SAC/BD-99/23, SAC/BD-00/22, Uang *et al.* 2000, Lee *et al.* 2005, and others). The failure analysis of the post-Northridge connection tests demonstrated a number of cases with fatigue cracks at the beam flange weld toe (SAC/BD-99/23). The European Community research program also demonstrated similar localized low-cycle fatigue failures of the new WSMCs (Chapter 3 in Moazzolani 2000). Connection failures in Japanese tests also occurred due to fracture at the beam flange weld toe (Nakashima *et al.* 1998, see Table 4 in the reference).

The three moment resisting connections prequalified for simplified moment connections (SMFs) and Intermediate moment connections (IMFs) by the AISC 358 standards (AISC 2005a) are the reduced beam section (RBS), bolted unstiffened extended end plate (BUEP) and bolted stiffened extended end plate (BSEP) connections. These connections are shown to improve seismic performance over older connection details (Engelhardt *et al.* 1998, 1999, SAC/BD-00/17, Adey *et al.* 2000, SAC/BD-00/21, Roeder 2002, and others). However, these connections are expensive compared to, for example, welded unreinforced flange bolted web (WUF-B) connections. Moreover, similar to WUF-B connections the prequalified connections also demonstrated a verity of failure modes. For example, RBS connections demonstrated lateral and torsional buckling of beam, column twisting, and beam web buckling (Uang and Fan 2001, Chi and Uang 2002, Roeder 2002, Zhang and Ricles 2006). The extended end plate connections demonstrated fracture of end plates or stiffener near welded joints (Adey *et al.* 2000, SAC/BD-00/21, Guo *et al.* 2006).

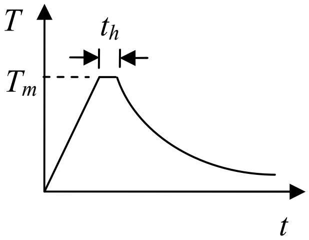
With the current state of the modified connections, it is not guaranteed that surprises similar to the Northridge and Kobe earthquakes would not be repeated in the future. According to the SEAoC committee, the weld interface and low-cycle fatigue failure mechanisms are needed to be understood towards developing fully rational design guidelines (SEAoC 2002). This recommendation has not drawn much attention probably because of the complexity involved. Also, addressing such an extensive problem could not be achieved in a short period of time. Until such rational design guidelines become available, developing seismic performance enhancement techniques for improving ductility of existing WSMCs is more attractive and feasible approach. A number of enhancement techniques, such as, RBS, slotted web, reduced web, welded flange plate and others are proposed to enhance the seismic performance of the steel building connections. Among these, the RBS connection is the most popular because of its seismic performance and cost effectiveness. The proposed HBS connections will have the advantages of the RBS connections but the earlier is anticipated to have better energy dissipation than the latter. The proposed technique and its analytical validation are presented below.

The Proposed Seismic Performance Enhancement Technique

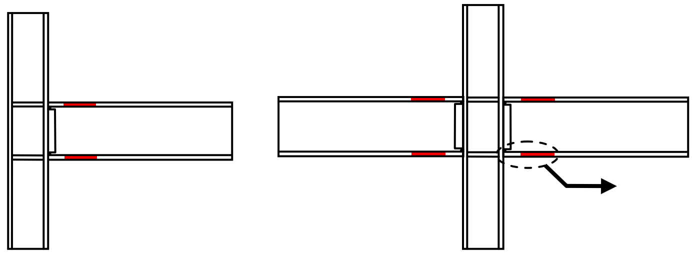
The proposed technique involves heating specified beam flange areas (highlighted red in Fig. 1a) to a temperature, T_m, above 1000^{o}C and maintain the peak temperature for certain duration of time, t_h, before slow air cooling as shown in Fig. 1b. Finite element analysis demonstrated that the beam does not distortion at the end of the heating and cooling processes. Examples of exterior and interior building connections with the proposed HBS are shown in Figs. 1c and 1d, respectively. The proposed high temperature heat treatment will reduce the strength of steel in the heat treated areas of the flanges (discussed later). Consequently, under seismic loading “plastic hinge” will develop at the HBS which is away from the weld. This will result in reduced stresses near the weld and increased ductility capacity of the connections.



(a) Heat treatment of the flanges at the fabricator’s shop

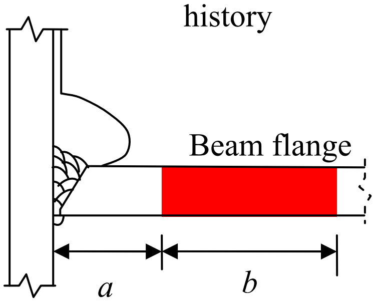


(b) Heat treatment temperature history



(c) Exterior connection with heat treated sections

(d) Interior connection with heat treated sections



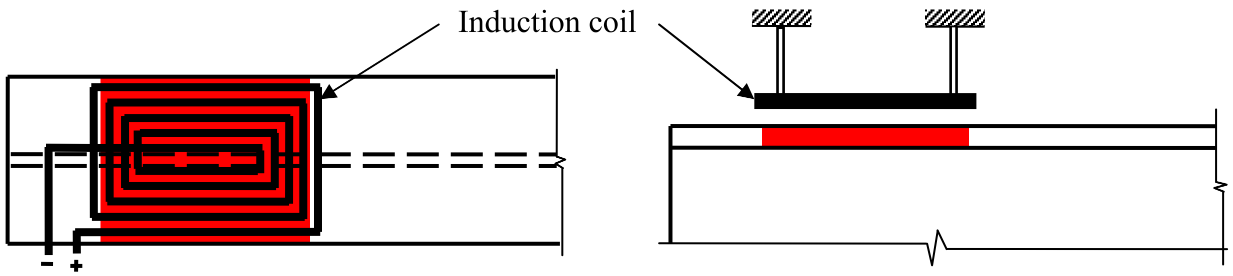
(e) Bottom beam flange with heat treatment dimensions

Figure 1. Heat treatment of steel building beam-column connections for seismic performance enhancement

In the RBS connections, “weakening” of the beam flanges induces plastic hinge away from the welds. The plastic hinge in the HBS connections develop at the heat treated beam section because of the reduced strength of steel. As the inelastic modulus of steel is not altered by the heat treatment (demonstrated later) and as the beam cross-section remains intact in the HBS connections, the lateral and torsional buckling resistance of HBS connections will be higher than those of the RBS connections. Consequently, HBS connections are anticipated to dissipate larger amount of energy with a minimum loss of strength or stiffness compare to RBS connections. The degree of seismic performance enhancement of the HBS connections will primarily depend on the parameters “a” and “b” of the heat treated flange section (see Fig. 1e), T_m and t_h of the heat treatment temperature history (see Fig. 1b), and cooling conditions adjacent to heat treated areas during heat treatment. Research will be needed to optimize all these parameters. Other advantages of the proposed method are: i) the condition for satisfying the uniform building code requirement of “strong column-weak beam” is enhanced because of the reduced strength of HBS steel, ii) HBS connections will not rely on panel zone yielding for ductility, and iii) for new constructions the proposed heat treatment can be performed at the fabricators’ shop before shipping the beams to the construction site.

Induction Heating for the Proposed Heat Treatment

Induction heating process may precisely heat electrically conducting materials. It is a clean, fast and repeatable process which can be automated. The process induces eddy currents within the material to produce heat. The basic components needed for an induction heating system are AC power supply, induction coil, and coil cooling system. One of the many induction coil design options which can be used for beam flange heat treatment is shown in Fig. 2 (Bausch, 2008). Note in Fig. 2b that no contact is required between the flange section to be heated and the coil. Using a cooling system, heat treatment can be restricted to a specified flange area, which will be essential for seismic performance enhancement of connections. For providing flexibility to the induction coil for using to different size beams, coil can be designed with L and U type connectors for easy dismantling and reassembling to different sizes. The cost of an induction coil system for simultaneous heat treatment of both flanges of a plastic hinge section is around \$237,000. If the whole heat treatment process is compared to the RBS fabrication process (thermal cutting, grinding, rounding, etc.), it can be realized that the labor cost for HBS will be cheaper than that for RBS, and quality assurance and quality control for HBS will be simpler than that for RBS.



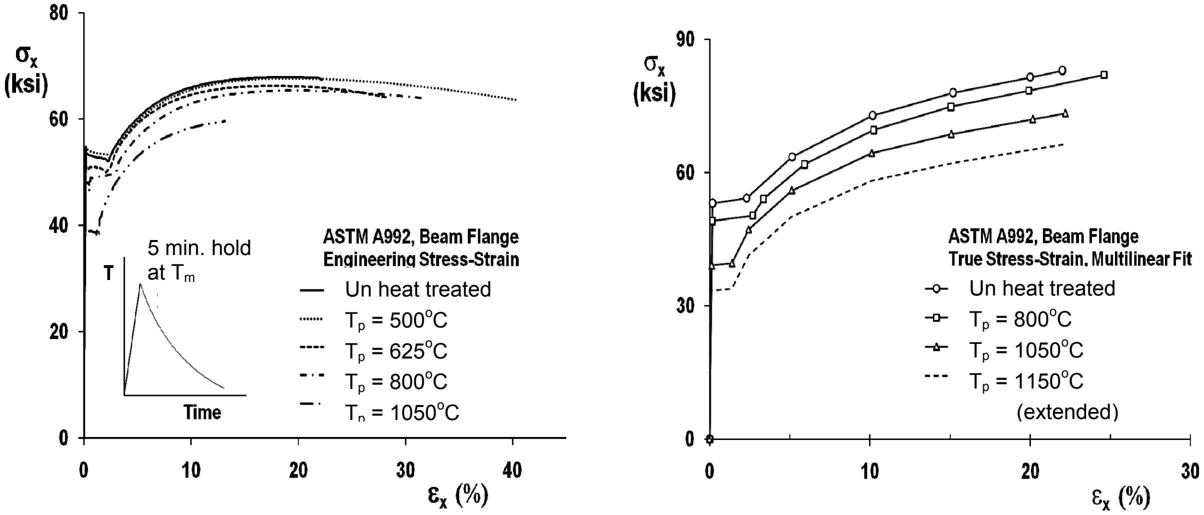
(a) Top view of the beam

(b) Side view of the beam

Figure 2. Induction coil design for heat treating beam flanges (Bausch, 2008)

Analytical Validation of the HBS Seismic Performance Enhancement Technique

For determining material parameters of constitutive models used in the finite element analysis, a set of monotonic tension and cyclic tests of beam flange steel coupons (ASTM A992), heat treated by different maximum temperatures with a 5 minutes hold were conducted (see the inset in Fig. 3a). The stress-strain responses from the monotonic tension tests are shown in Fig. 3a. It is observed in this figure that as the maximum temperature of heat treatment increases both the yield and ultimate stresses of the beam steel gradually decreases by downward shift of the stress-strain curves. The reduction in yield stress by heat treatment with maximum temperature 1050^{o}C is about 30%. It is also important to note in Fig. 3a that the inelastic modulus of the beam flange steel is not altered much by the heat treatment process. These two observations were instrumental in developing the proposed seismic performance enhancement technique as discussed earlier. Multilinear fits of monotonic stress-strain curves as shown in Fig. 3b were performed to determine the parameters of the multilinear model in ANSYS 11.0. To perform finite element simulation for 1150^{o}C heat treatment temperature, the model parameters were extended to this temperature through curve fitting of the recorded yield and ultimate strengths as a function of maximum temperature. The parameters obtained from the multilinear stress-strain fit were used for simulating the monotonic moment-rotation responses of WSMCs by ANSYS 11.0 finite element software package.

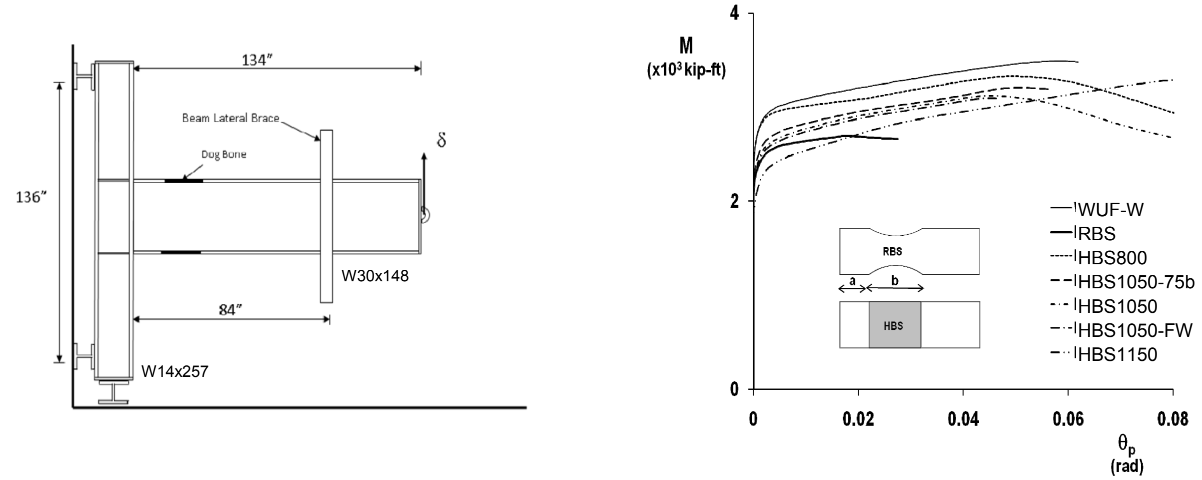


(a) Tension test of heat treated beam flange steel coupons

(b) Multilinear fit of stress-strain curves for finite element analysis

Figure 3. Influence of heat treatment on ASTM A992 steel and multilinear fit for ANSYS 11.0 multilinear model parameter determination

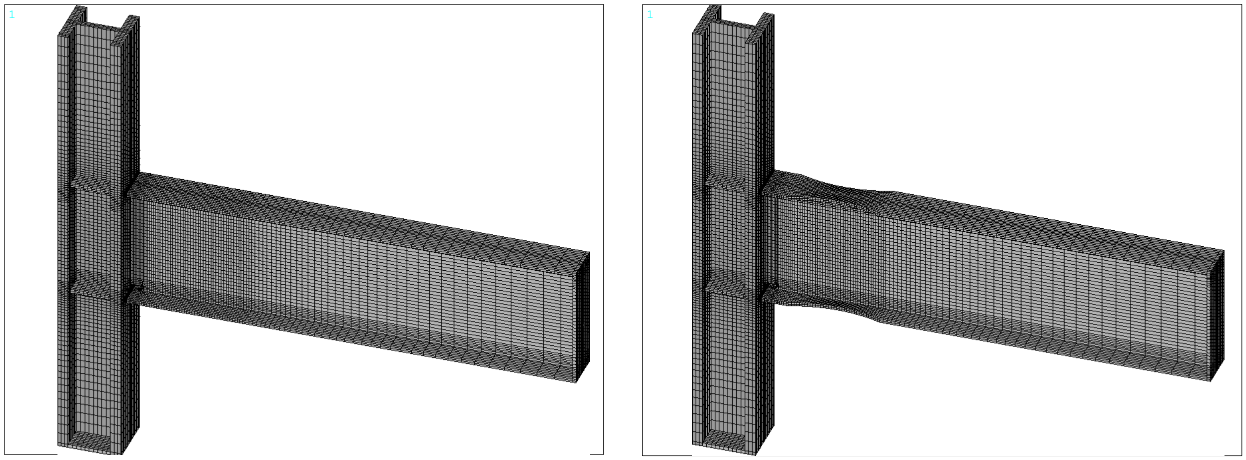
Specimen geometry, beam and column size, and boundary conditions of Englehardt et al. (1998) test set up (Fig. 4a) were used for developing finite element mesh and analysis model (see Fig. 5). Dimensions of the heat treated flange section (see Fig. 1e and the inset in Fig. 4b) were kept the same as those of the RBS in Englehardt et al. (1998). Finer mesh size determined using convergence analyses was used in the RBS are HBS areas, and kept the same in the WUF-W mesh for the corresponding area (see Fig. 5a). The monotonic, moment-inelastic rotation simulation responses of WUF-W, heat treated WUF-W (WUF-WH), and RBS connections are shown in Fig. 4b. It is observed in this figure that as the peak heat treatment temperature increases from room temperature (WUF-W) to 800°C (HBS800) to 1050°C (HBS1050) to 1150°C (HBS1150) the connection moment capacity gradually decreases. If the moment-rotation responses of WUF-W and RBS are compared to those of HBS1050 or HBS1150, the potential of HBS connection in enhancing ductility of beam-column connections can be realized. Note also in Fig. 4b that the degradation of RBS started around 0.02 radians, whereas that for HBS1050 started around 0.05 radians. Also, stiffness of HBS1050 connection before degradation is higher than that of RBS connection. The better degradation and stiffness properties of the HBS connection compare to that of the RBS connection is because of the fact that the RBS flanges were weakened whereas the HBS flanges remained intact. The enhanced behavior of HBS can also be attributed to the fact that the heat treatment process does not alter the inelastic modulus of the monotonic stress-strain curve much. Simulations of connections with a different heat treatment length (75% of b, HBS1050-75b) and full web depth heat treatment in addition to its flanges (HBS1050-FW) shown in Fig. 4b demonstrates that the influences of these parameters are small.



(a) Engelhardt *et al* (1998) RBS test set-up considered for the simulation study

(b) Moment-inelastic rotation simulations of WSMCs

Figure 4. WSMC and its monotonic response simulations for various conditions

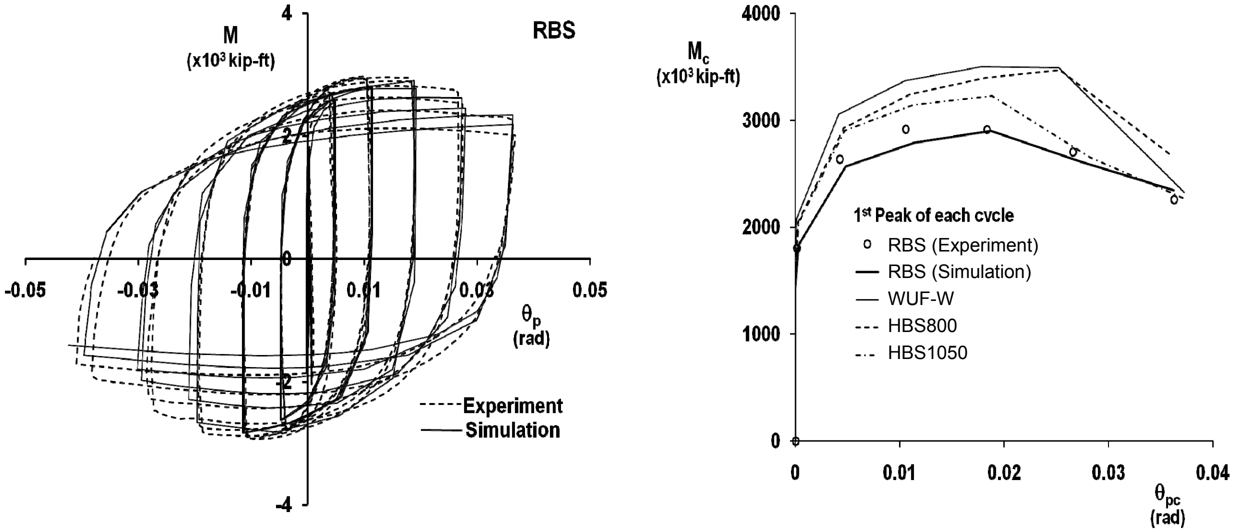


(a) WUF-W connection finite element mesh used in the simulations

(b) RBS connection finite element mesh used in the simulations

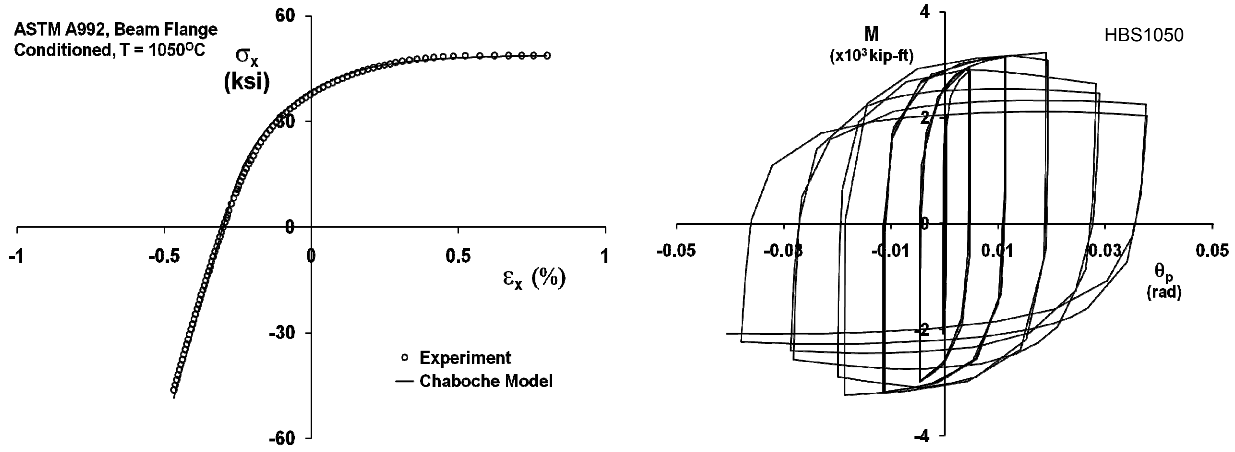
Figure 5. Finite element mesh used in the simulations with ANSYS 11.0

The finite element analysis scheme used in the WSMC seismic response simulation was first evaluated by comparing against the RBS experimental response from Engelhardt et al. (1998) as shown in Figs. 6a, b. Figure 6a is showing the moment-inelastic rotation hysteretic response obtained by prescribing the incremental, simulated seismic loading cycle, and Fig. 6b the 1st peak envelope of the responses in Fig. 6a. As mentioned earlier, the test set up and specimen geometry of Engelhardt et al. (1998), as shown in Fig. 4a, was considered in the simulations. Seismic response simulation for the RBS connection using the multilinear model



(a) Moment-inelastic rotation response of RBS

(b) Moment-inelastic rotation envelopes of various WSMCs



(c) Fitted ASTM A992 beam flange steel hystersis curve for determining Chaboche (1998) model parameters

(d) Simulated seismic response of HBS1050 connection

Figure 6. Seismic response simulation for WSMCs under various conditions by ANSYS 11.0

in ANSYS 11.0 was found unsatisfactory. Hence, the advanced, non-linear kinematic hardening model of Chaboche (1989) in ANSYS 11.0 was used. Readers are referred to Rahman et al. (2008) for a detailed discussion on the Chaboche model and its parameter determination methodology. For Chaboche model parameter determination, stable hysteresis loops obtained from single amplitude, strain-controlled cycle were fitted as shown in Fig. 6c. The same finite element meshes (see Fig. 5a, b) used for the monotonic response simulations also were used for seismic response simulations. The moment-inelastic rotation simulation of the RBS connection obtained using ANSYS 11.0 and its Chaboche model is compared to the corresponding experimental responses in Figs. 6a, b. These comparisons validate the ANSYS simulation scheme used. Moment-inelastic rotation hysteresis response simulation of HBS1050 connection shown in Fig. 6d seems reasonable. All the 1st peak envelopes from simulations of various connections are compared to the experimental RBS envelop in Fig. 6b. This comparison demonstrates the potential of the proposed HBS technique in enhancing seismic performance of WSMCs. By increasing the peak heat treatment temperature, the seismic performance of HBS connections can be enhanced further. This novel technique will be validated through a systematic experimental study support by the NSF-NEES program.

Conclusions

A novel technique for enhancing seismic performance of WSMCs is proposed in this paper. The application potential of the technique is demonstrated through monotonic and seismic response simulations of WSMCs under various conditions. The novel technique involves heat treating specified sections of beam flanges by exposing these sections to a very high temperature (> 1000oC) for a short duration before slow air cooling. Such a heat treatment process reduces the strength of steel in the heat treated areas of the flange. Consequently, under seismic loading plastic hinge develops at the heat treated beam section (HBS). A connection enhanced by the proposed technique will have the advantages of the reduced beam section (RBS) connection, but the former will have better energy dissipation than the latter connection. The finite element analysis scheme developed for WSMC response simulations was validated by comparing the simulation and experimental responses of RBS. Both monotonic and seismic response simulations of the heat treated WUF-W connection demonstrated that as the maximum heat treatment temperature increases the moment-inelastic rotation response of the connection gradually softens. Comparison of the RBS and HBS connection simulations demonstrated that the seismic performance of these two connections is comparable. In fact, the HBS connections are anticipated to be seismically more ductile compare to the RBS connections because the earlier connections would be more resistant to torsional or lateral buckling than the latter connections. According to AISC 341, Appendix P (AISC, 2005b), full-scale test results demonstrating seismic performance of a connection will be needed to prequalify a connection for SMFs and IMFs. Hence, a systematic set of full scale, exterior beam-column connection tests will be conducted in the near future. This test program is supported by the NSF-NEES program. The test program will allow validation of the novel HBS technique, as well as, development of a rational application methodology of the technique.

References

Adey, B.T., Grondin, G.Y., and Cheng, J.J.R., 2000. Cyclic Loading of End Plate Moment Connections, *Canadian Journal of Civil Engineering* 27, 683-701.

AISC, 2005a. Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications, *American Institute of Steel Construction 358*, AISC 358-05.

AISC, 2005b. Seismic provisions for Structural Steel Buildings, *American Institute of Steel Construction 341*, AISC 341-05.

Bausch, R., 2008. Private Communications on Induction Coil Design, Ameritherm, Inc.

Castiglioni, C.A., 2005, Effects of the Loading History on the Local Buckling Behavior and Failure Mode of Welded Beam-to-Column Joints in Moment-Resisting Steel Frames, *Journal of Engineering Mechanics*, 131, 568-585.

Chaboche, J.L., 1989. Constitutive Equations for Cyclic Plasticity and Cyclic Viscoplasticity, *International Journal of Plasticity*, 5, 247-302.

Chi, B., Uang, C.-M., 2002. Cyclic Response and Design Recommendations of Reduced Beam Section Moment Connections with Deep Columns, *Journal of Structural Engineering*, 128, 464-473.

Engelhardt, M.D., Winneberger, T., Zekany, A.J., and Polyraj, T.J., 1998. Experimental Investigation of Dogbone Moment Connections, *Engineering Journal*, 35, 128-139.

Engelhardt, M.D., 1999. The 1999 T.R. Higgins Lecture: Design of Reduced Beam Section Moment Connections, *Proc. 1999 North American Steel Construction Conference*, AISC, Chicago 1-1-1-29.

FEMA-350, 2000. *Recommendation and Seismic Design Criteria for New Steel Moment-Frame Buildings*, prepared by the SAC Joint Venture for the Federal Emergency Management Agency, Washington, DC.

FEMA-353, 2000. *Recommended Specifications and Quality Assurance Guidelines for Steel Moment-Frame Construction for Seismic Applications*, prepared by the SAC Joint Venture for the Federal Emergency Management Agency, Washington, DC.

FEMA-355D, 2000. *State of the Art Report on Connection Performance*, prepared by the SAC Joint Venture for the Federal Emergency Management Agency, Washington, DC.

Guo, B., Gu, Q., Liu, F., 2006. Experimental Behavior of Stiffened and Unstiffened End-Plate Connections under Cyclic Loading, *Journal of Structural Engineering*, 132, 1352-1357.

Han, S.W., Kwon, G.U., Moon, K.H., 2007. Cyclic Behavior of Post-Northridge WUF-B connections, *Journal of Constructional Steel Research*, 63, 365-374.

Lee, D., Cotton, S.C., Hajjar, J.F., Dexter, R.J., 2005. Cyclic Behavior of Steel Moment-Resisting Connections Reinforced by Alternative Column Stiffener Details, I. Connection Performance and Continuity Plate Detailing, *Engineering Journal*, 4th Quarter, 189-213.

Mazzolani, F.M. (Editor), 2000. *Moment Resistant Connections of Steel Frames in Seismic Areas, Design and Reliability*, E&FN Spoon.

Nakashima, M., Suita, K., Marisako, K., Maruoka, Y., 1998. Tests of Welded Beam-Column Subassemblies. I. Global Behavior, *Journal of Structural Engineering*, 124, 1236-1244.

Rahman, S.M., Hassan, T., Corona, E., 2008. Evaluation of cyclic plasticity models in ratcheting simulations of straight pipes under cyclic bending and steady internal pressure, *International Journal of Plasticity*, 24, 1756-1791.

Roeder, C.W., 2002. Connection Performance for Seismic Design of Steel Moment Frames, *Journal of Structural Engineering*, 128, 517-525.

SAC/BD-99/23. *Failure Analysis of Welded Beam to Column Connections*, by Barsom, J.M. and Pellegrino, J.V.

SAC/BD-00/01. *Parametric Tests on Unreinforced Connections*, By Lee, K.H., Stojandinovic, B., Goel, S.C., Margarian, A.G., Choi, J., Wongkaew, A., Reyher, B.P., and Lee, D.-Y.

SAC/BD-00/17. *Behavior and Design of Radius Cut Reduced Beam Section Connections*, by Engelhardt, M.D., Venti, M.J., Fry, G.T., Jones, S.L., Holliday, S.D.

SAC/BD-00/21. *Cyclic Testing of Bolted Moment End-Plate Connections*, by Sumner, E.A., Mays, T.W., Murray, T.M.

SAC/BD-00/22. *Cyclic Response of RBS Moment Connections: Loading Sequence and Lateral Bracing Effects*, by Yu, Q-S, Gilton, C., Uang, C-M.

SAC/BD-00/24. Development and Evaluation of Improved Details for Ductile Welded Unreinforced Flange Connections, by Ricles, J.M., Mao, C., Lu, L.-W., Fisher, J.W.

SEAoC, 2002. *Commentary and Recommendations on FEMA 350*, Structural Engineers Association of California Seismology Committee.

Stojadinovic, B., Goel, S.C., Lee, K.-H., Margarian, A.G. and Choi, J.H., 2000. Parametric Tests on Unreinforced Steel Moment Connections, *Journal of Structural Engineering*, 126, 40-49.

Uang, C.-M., Yu, Q.-S., Noel, S., Gross, J., 2000. Cyclic Testing of Steel Moment Connections Rehabilitated with RBS or Welded Haunch, *Journal of Structural Engineering*, 126, 57-68.

Uang, C.-M., Fan, C.-C., 2001. Cyclic Stability Criteria for Steel Moment Connections with Reduced Beam Section, *Journal of Structural Engineering*, 127, 1021-1027.

Zhang, X. and Ricles, J.M., 2006. Experimental Evaluation of Reduced Beam Section Connections to Deep Columns, *Journal of Structural Engineering*, 132, 346-357.