

Behaviour of steel reduced beam web (RBW) connections with drilled voids

A. A. Hedayat¹, H. Saffari², A. Eghbali³

¹ **Assistant Professor of Civil Engineering, Islamic Azad University, Kerman, Iran, amirahmad1356@yahoo.com;**

² **Associate Professor of Civil Engineering, Shahid Bahonar University, Kerman, Iran, hsaffari@mail.uk.ac.ir;**

³ **Graduate Students of Civil Engineering, Shahid Bahonar University, Kerman, Iran,**

Eghbali.afsaneh@gmail.com

Paper Reference Number: 20

Name of the Presenter: A. Eghbali

Photograph of Presenter

Abstract

The 1994 Northridge earthquake caused widespread damage to moment-resisting frames. Various brittle fractures were found in beam-to-column welded moment connections. This prompted the initiation of new research programs to investigate the causes of these fractures and to propose the necessary changes in design procedures. In recent years a variety of approaches have been proposed by researchers to improve the ductility of post-Northridge connections. The improvements are mainly based on reinforcing the connection or weakening of the beam end. These methods are intended to force the plastic hinge to form away from the face of the column, to avoid premature fractures at this region. Providing circular voids at vicinity of the beam end is one of the solutions to reach adequate ductility in post-Northridge connections in the case of using deep beams. However, in this method the presence of circular void causes a significant reduction in the beam shear capacity and initial rotational stiffness of the beam. Hence, in this study to prevent the detrimental effects of big voids, a number of drilled voids are created in the beam web. A parametric study has been done to find out the best configuration of these voids. Finite element results have shown the adequacy of this method to increase the connection ductility without significant reduction in the connection strength. This type of modification can be easily applied to existing buildings with no need to break of the concrete slab as it is the case for reduced beam section (RBS) connections.

Key words: Ductility, Plastic hinges, Post-Northridge connection, Reduced beam web, Strength.

1. Introduction

Seismic design of welded steel moment frame (WSMF) construction is based on the assumption that, in a severe earthquake, frame members will be stressed beyond the elastic limit. Inelastic action is permitted in frame members (normally beams or girders) because it is presumed that they will behave in a ductile manner thereby dissipating energy. It is intended that welds and bolts, being considerably less ductile, will not fracture. Thus, the design philosophy requires that sufficient strength be provided in the connection to allow the beam and/or column panel zones to yield and deform inelastically. From 1988 to 1994 the Uniform Building Code or UBC (ICBO 1994) prescribed a beam-to-column connection that was deemed to satisfy the above strength requirements. This connection type is known as Pre-Northridge connection (Fig. 1). A lot of tests have been done until 1994 to investigate the ductility level of the Pre-Northridge connections (Chen et al. 1981, Carpenter et al. 1973, Popov et al. 1969, Popov et al. 1970, Popov et al. 1972, Popov et al. 1973). Most of these tests were successful, with a number of specimens sustaining total

rotation larger than 0.04 rad. Despite of the design expectations and successful tests, the 1994 Northridge earthquake caused widespread damage to moment-resisting frames. The Northridge Earthquake prompted the initiation of new research programs that investigated the causes of these fractures and proposed changes to design procedures. In 2009 a detailed study was done by Hedayat et al. to collect the most factors that are believed to contribute to the brittle fractures of Northridge connections which were identified from other sources [e.g. Mahin, Miller]. The modified pre-Northridge connections which are now called the post-Northridge connections use smooth weld access holes, high fracture toughness weld metal E70-TGK2 and no backing bar at the bottom beam flange [SAC]. However, post-Northridge connections did not achieve 3% plastic rotation as required by the seismic codes. As a result further modifications were applied on post-Northridge connections. These modifications were achieved by either reinforcing the connection or weakening the beam section. Both methods keep the plastic hinge away from the face of the column and reduce the stress levels in the vicinity of the complete joint penetration (CJP) flange welds. To enhance the ductility of post-Northridge connections, two different modification methods can be used, strengthening of the connection or weakening of the beam section.

Strengthening of the connection can be done by using one of the following methods; cover plates [Engelhardt and Sabol 1998], triangular haunches [Chia et al.], straight haunches [SAC 1996], upstanding ribs [Popove and Tsai], lengthened ribs [Chen and Lee] and side plates [Engelhardt and Sabol 1994]. Weakening the beam section can be done either by cutting a portion of the beam flange (reduced beam section, RBS, connections) or the beam web (wedge beam connections [Wilkinson et al., Hedayat et al.] or reduced beam web, RBW, connections [Aschheim, Hedayat et al.]). All of these modifications can be used for new or existing buildings. However, strengthening of connections are usually more expensive and more time consuming than weakening the beam sections as the former need welds which are difficult and costly to make and inspect.

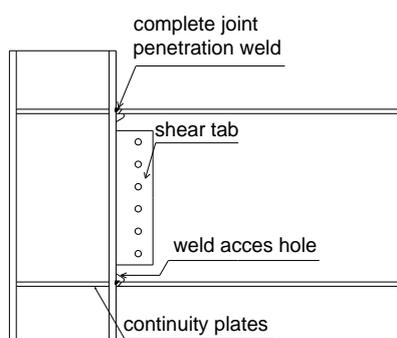


Fig 1: typical pre-Northridge connection

Among the beam weakening methods, the RBS is better known. However, this type of connection becomes relatively costly due to the cutting of flanges at four locations at each end, especially in the presence of floor slabs for rehabilitation purposes. Also in these connections the cutting of flanges reduces the beam stability and increases the probability of beam lateral torsional buckling. However, in RBW connections where the reduction is made in the beam web, such problems are much less. In RBW connections proposed by Aschheim (2000) and Hedayat et al. (In Press) the beam web was penetrated by a single or multi circular voids (Fig. 2). In the study done by Hedayat et al. (In press) it was shown that the connection can reach the desired ductility (4 percent total rotation) when a relative

big void is created at the beam web. This causes a remarkable reduction in the connection strength and initial rotational stiffness. Hence, this study aimed to propose a new beam end configuration (BEC) to increase the post-Northridge connection strength, ductility and initial rotational stiffness simultaneously. The proposed BEC is based on the weakening of the beam section method. In this method, instead of creating a big void at the beam web, numbers of small drilled voids were created at the beam web which was named drilled beam web (DBW) connection. The finite element method was used to model a pre-tested post-Northridge connection. In order to verify the accuracy of modelling, the analytical result was compared to the experimental one. This was followed by the application of the proposed beam end configuration on the connection. Strength, ductility and initial rotational stiffness of the modified connections were investigated with respect to various voids details.

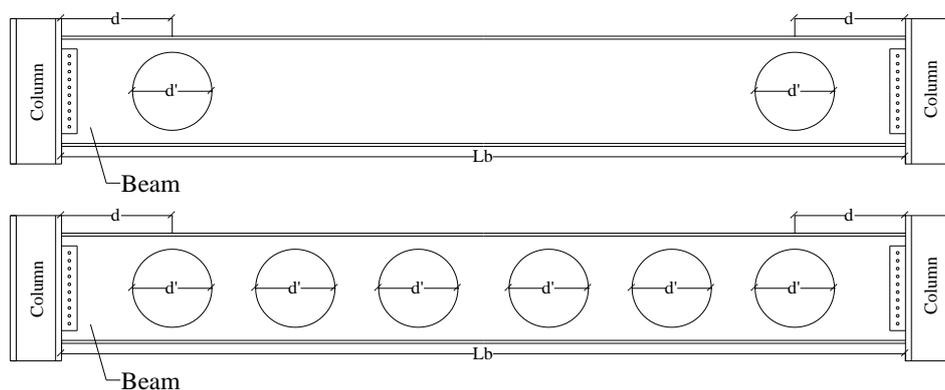


Fig 2: RBW connection with single and multi circular voids (Aschheim, 2000)

2. Finite element analysis

Three pre-tested non-modified post-Northridge connections utilized by Lee et al. (2000) were modeled using the general purpose finite element program ANSYS (2007). Pre-tested specimens included specimens SAC3 (beam: W24x68; column: W14x120), SAC5 (beam: W30x99; column: W14x176) and SAC7 (beam: W36x150; column: W14x257). As stated by Lee and Stojadinovic (2000), specimens SAC3, SAC5 and SAC7 represent three conventional specimen sizes, small, medium and large respectively which were also tested in Phase 1 of SAC Steel Projects (1996). This was the reason of selecting these specimens. To perform material nonlinearity analyses, plasticity behavior was based on the von-Mises yielding criteria and the associated flow rule. Isotropic hardening was assumed for the monotonic analysis, whereas kinematic hardening was assumed for the cyclic analysis as used by Mao et al. (2001) and Ricles et al. (2003). A bilinear material response was used for base metals based on the material properties given by Lee and Stojadinovic (2000), whilst for weld metals, a multilinear material response based on material property given by Mao et al. (2001), Ricles et al. (2003) was used. Accurate prediction of large deformations at the void area after yielding was achieved via the consideration of the geometric nonlinearities through a small strain, large displacement formulation. The monotonic analyses were conducted by applying a monotonic vertical displacement load to the beam tip until achieving more than 4% total rotation at column web center, whereas the load history recommended in Reference FEMA 350 (2000) was utilized for cyclic analyses. In order to model the global model two different shell elements, SHELL43 (one layer element) and SHELL181 (multilayer element) were used. Multilayer shell elements are well suited to model the local bending behaviour. In the case of using SHELL181, each element was separated into five layers across the thickness. In order to verify the

accuracy of the modeling, Hedayat and Celikag (2009b) prepared finite element models for specimens SAC3, SAC5 and SAC7 of the experimental study conducted by Lee and Stojadinovic (2000). The results agreed suitably with the experimental results. For instance, Fig. 2 shows comparison for specimen SAC7 under cyclic and monotonic loading.

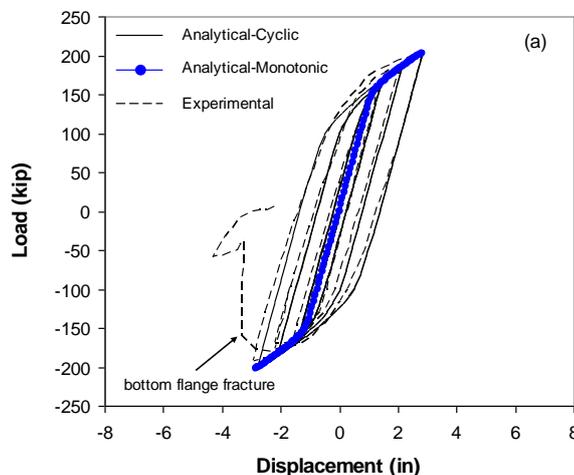


Fig 3: Comparison between analytical and experimental results for specimen SAC7 (Hedayat and Celikag (2009b))

3. Proposed beam end configuration and design parameters

Figure 4 shows the proposed BEC. The reason of proposing the DBW connection can be explained as follow:

Figure 5 shows the normal strain distribution of a typical RBW connection in presence of a big void size at the web area. This figure clearly shows that for the second part of beam which is located between the beam tip and the void center, there is only one neutral axis which is located at the mid beam depth. However, for the first part of the beam which is located between the void center and the column face, there are two neutral axes. It indicates that creating a void at the beam web, divides the beam into two beams. In fact, the moment of inertia of the beam at the void area (I_{void}) is not equal to the moment of inertia of the beam (I_{beam}) minus the moment of inertia caused by the circular opening ($I_{void} \neq I_{beam} - t_w \cdot d^3 / 12$, d' is circular void diameter). It might be one of the reasons of why early beam flange fracture appears at the beam flanges at void area and why this type of connections has low connection rotational stiffness. The reason of the creation of two neutral axes at the beam web area in presence of large void size might be because of the improper transformation of shear forces from the top beam flange to the bottom beam flange at void area. It can be considered as lake of shear studs in composite roofs where the absence of the shear studs causes non-integrity between the concrete slab and the steel beam, in which the moment capacity of the composite roof is less than what was expected. Therefore, in order to have proper transformation of shear forces from the top beam flange to the bottom beam flange at void area and consequently increase in the beam section elastic modulus at the void area, drilled beam web connection was proposed. Figure 6 shows the shear strain distribution along the beam web height of a typical DBW connection. This figure shows significant shear strain concentration at beam web between the drilled voids and significant reduction in shear strain concentration at vicinity of the beam flanges. This caused a reduction in the von-Mises strain at beam flanges and consequently delayed the beam flange fracture at void area. However, this delay can promote beam flange fracture at another critical location, weld access hole, WAH, region.

Therefore, the diameter, number and clear distance between the drilled voids can play an important role on connection strength and ductility.

Hence, a parametric study was done for DBW specimen SAC7. Clear distance between drilled voids was kept as a constant ($CD=10$ mm). Drilled voids diameter was selected as a variable. Totally two parameters were defined, α and β . Total distance between the first and last drilled voids in the horizontal, L_{hv} , was selected to be proportional to the total distance between the first and last drilled voids in the vertical direction, L_{vv} ($L_{hv}=\alpha.L_{vv}$). Parameter β is the ratio of the drilled void diameter, d_v , to the clear distance between drilled voids, CD ($\beta=d_v/CD$). Table 1 summarizes all parameters used in this study.

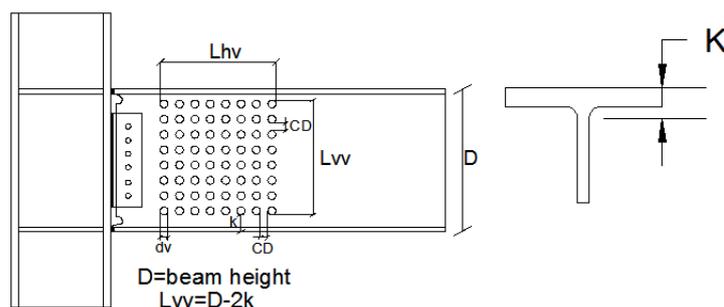


Figure 4: Proposed BEC, drilled beam web (DBW) connection

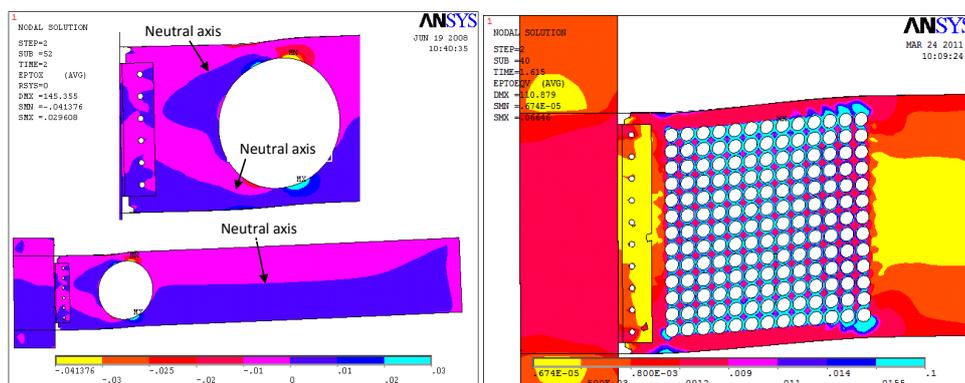


Fig 5: Effect of a circular void on location of neutral axis of the beam

Fig 6: Typical Shear strain distribution in a DBW connection

4. Finite element results and Discussion

4.1. Failure modes

Based on the finite element results, generally, there are two failure modes for the proposed BEC, beam flange fracture either at WAH region or at void area (Figure 7). The location of beam flange fracture depends on the parameters α and β and consequently depends on the energy dissipation capacity of the void area. By increasing parameters α and β and increase in void energy dissipation capacity, strain concentration decreases at WAH. As a result, it promotes the beam flange fracture at void area which is a desirable failure mode. The presence of drilled voids caused the plastic equivalent strains move into the beam length and plastic hinge formed away from the column face.

Specimens	α	β	d_v (mm)	CD (mm)	L_{hv} (mm)	$L_{vv}=D-2k$ (mm)
SAC7-DBW1	0.5	3	30	10	630	630
SAC7-DBW2	1	3	30	10	630	630
SAC7-DBW3	1.5	3	30	10	630	630
SAC7-DBW4	1	5	50	10	650	650

Table 1. Geometric parameters

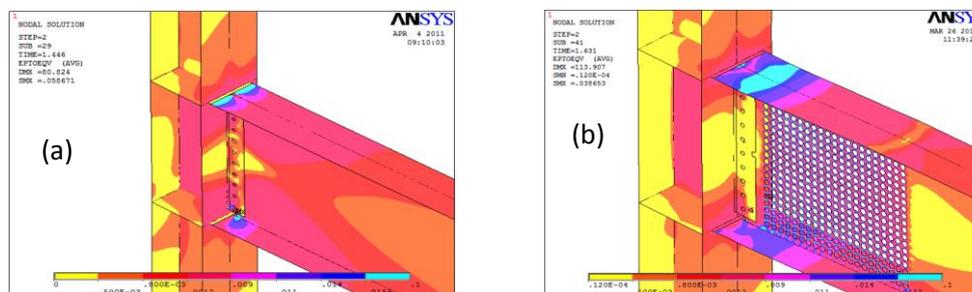


Fig 7: Different failure modes for a typical DBW connection: (a) beam flange fracture at WAH region; (b) beam flange fracture at void area

4.2. Effect of drilled voids and parameters

Figure 8 compares the normalized moment-rotation curves of all DBW specimens (Table 1) and unmodified specimen SAC7. As this figure shows, the presence of drilled voids caused a little reduction in the connection initial rotational stiffness (IRS) when is compared to the unmodified specimen SAC7. For instance, the ratio of the IRS of specimen SAC7-DW2 to the IRS of specimen SAC7 is only 0.96 which is enough close to 1. However, It is not the case for the DBW connections with circular voids (Figure 2) where circular voids caused a relative significant reduction in the connection IRS (between 25 to 40 percent, depends on the void size).

Ductility of a connection can be represented by the connection total rotation measured at the column web center (θ_{cwc}). Based on the most of seismic codes the minimum required value for this parameter is 4 percent. θ_{cwc} for specimen SAC7 is 2 percent which is too low. As figure 8 shows, the presence of drilled voids increased the connection ductility and ductility increased by increase in parameter α . θ_{cwc} for DBW connections presented in Table 1, for α equal to 0.5, 1 and 1.5 are 2.54, 3.15 and 3.54 percent respectively. Parameter β represents the variation in voids diameter. Two different values for parameter β were used, 3 and 5. Figure 8 shows that the DBW connection with smaller value of β ($\beta=3$) has higher ductility. Connection strength can be evaluated by the ratio of the connection moment at failure time to the beam plastic moment capacity (M/M_{pb}). The minimum required strength for a connection used in a seismic region is 0.85. Figure 8 shows that the presence of drilled voids reduces the connection strength. However, in all cases the ratio of M/M_{pb} is greater than 1.3 and it increases by increasing parameter α .

As mentioned above, DBW connection with biggest value of parameter α ($\alpha=1.5$) has the highest ductility. However it is less than the minimum required ductility (4 percent). Parameter α equal to 1.5 means a long drilled web and its expense is 1.5 times as what is for a DBW specimen with α equal to 1. Hence, from economical point of view, DBW connection with α equal to 1 seems to be more desirable. It should be noted that the biggest void size can be drilled by most of fabricators is around 1.25 inches (30 mm) which is corresponded to β equal to 3. Based on this discussion, it might be concluded that from the practical and economical points of view, 1 and 3 are the optimum values for parameters α and β respectively. However, the ductility of DBW connection with these parameters (Specimen SAC7-DW2) is 3.15 percent which is less than 4 percent. Hence, in

order to increase the connection ductility, a circular void was added to the specimen SAC7-DW2 (Figure 9). To avoid the web buckling, the clear horizontal distance between the circular void and the drilled void was selected $D/5$ where D is overall beam depth. The diameter of circular void was selected to be equal to the summation of diameter of all small drilled voids in a vertical line. It should be noted that in this specimen the circular void has a negligible effect on the connection rotational stiffness. Because, it is located at a distance which is enough away from the column face. Figure 8 compares the ductility and strength of specimens SAC7-DW2 with and without a circular void. As this figure shows this specimen could easily reach to the minimum required ductility and its strength is big enough ($\theta_{CWC}=0.04$, $M/M_{pb}=1.34$).

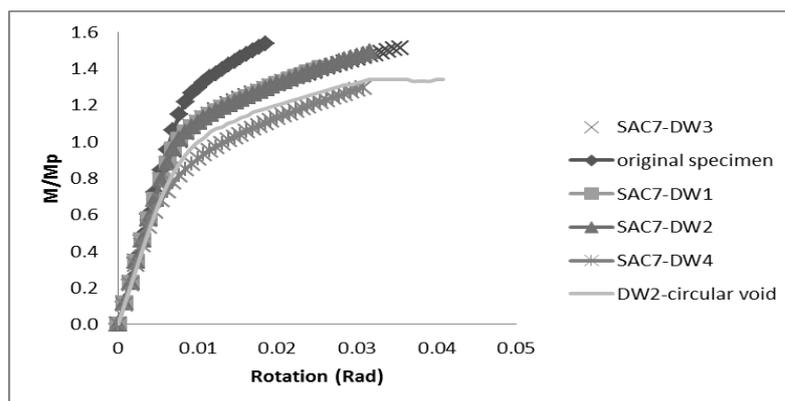


Fig 8: Normalized moment-rotation curves

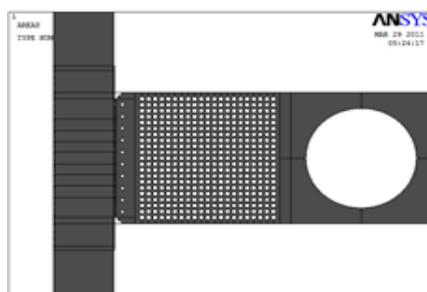


Fig 9: DBW connection with a circular void

5. Conclusion

The 1994 Northridge earthquake caused widespread damage to moment-resisting frames. Various brittle fractures were found in beam-to-column welded moment connections. So in recent years a variety of approaches have been proposed by researchers to improve the ductility of post-Northridge connections. These methods are intended to force the plastic hinge to form away from the face of the column, to avoid premature fractures at this region. One of the methods is weakening of the beam end. This study was based on this method. For this purpose, a number of drilled voids were created at the beam web at the vicinity of column face. Finite element results showed that the drilled voids increased the connection ductility with just negligible reduction in the connection initial rotational stiffness and strength. From the practical and economical points of view, 1 and 3 were the optimum values for parameters α and β respectively. However, results showed for the very deep beam specimen SAC7, drilled voids were not as much as effective to reach the minimum required ductility, 4 percent. Adequate connection strength, ductility and

rotational stiffness were easily obtained by adding a circular void to the DBW specimen. This void was located $D/5$ away from the last column of drilled voids and its diameter was equal to the summation of the diameter of all small drilled voids in a vertical line. This BEC can easily be applied to the new and existing buildings.

References

- ICBO (1994), Uniform Building Code, *International Conference of Building Officials (ICBO)*, Whittier, CA.
- Chen, W.-E, and Patel, K. V. "Static behaviour of beam-to-column moment connections." *J. Struct. Div.*, ASCE, 1981, 107(9), 1815-1838.
- Carpenter L. D., and Lu L.-W (1973). "Reversed and repeated load tests of full-scale steel frames." Tech. Rep. Steel Res, for Constr. Bull No. 24, *American Iron and Steel Institute, Washington, D.C.*
- Popov, E. P., and Pinkney, R. B., (1969), "Cyclic yield reversal in steel building connections." *J. Struct. Div.*, ASCE; 95(3), 327-353.
- Popov, E. P., and Stephen, R. M., (1970), "Cyclic loading of full-size steel connections." Tech. Rep. UCB/EERC-70/3, Earthquake Engrg, Res. Ctr., University of California, Berkeley, Calif.
- Popov, E. P., and Stephen, R. M., (1972), "Cyclic loading of full-size steel connections." Tech. Rep. Steel Res. for Constr. Bull. No. 21, American Iron and Steel Institute, Washington, D.C.
- Popov, E. P., and Bertero, V. V., (1973), "Cyclic loading of steel beams and connections." *J. Struct. Div.*, ASCE; 99(6), 1189-1204.
- Amir A. Hedayat and M. Celikag, "Fracture Moment and Ductility of Welded Connection", Proceedings of the *Institution of Civil Engineers Structures and Buildings* 162 December 2009 Issue SB6 Pages 405–418.
- Mahin, S.T. (1998). Lessons from damage to steel buildings during the Northridge earthquake, *Engineering Structures*, 261–270.
- Engelhardt MD, Sabol TA. (1994). Testing of welded steel moment connections in response to the Northridge earthquake. American Institute of Steel Construction.
- Engelhardt MD, Sabol TA. (1998). Reinforcing of steel moment connections with cover plates: Benefits and limitations. *Engineering Structures*. 20(4_6), 510_520.
- Chia B, Uang C-M, Chen A. (2006). Seismic rehabilitation of pre-Northridge steel moment connections: A case study. *Journal of Constructional Steel Research*. 62, 783_92.
- Aschheim M-A (2000). Moment-resistant structure, sustainer and method of resisting episodic loads. United State Patent, Patent number: 6,012,256.
- Amir A. Hedayat and Murude Celikag, "Wedge Design: Reduced Beam Web (RBW) connection for seismic regions". *Advances in Structural Engineering* Vol. 13 No. 2 2010.
- Amir A. Hedayat, Murude Celikag, "Reduced beam web (RBW) connections with circular openings", Nova Science Publishers, Inc., New York, USA.
- Wilkinson S, Hurdman G, Crowther A. (2006). A moment resisting connection for earthquake resistant structures. *Journal of Constructional Steel Research*. 62, 295_302.
- Lee H., Stojadinovic B., Goel S. C., Margarian A. G., Choi J., Wongkaew A. at al. (2000), Parametric Tests on Unreinforced Connections. SAC/BD-00/01, Volume I – Final Report.
- Ricles J-M, Mao C, Lu L-W, Fisher J-W. (2003). Ductile details for welded unreinforced moment connections subject to inelastic cyclic loading. *Engineering Structures*. 25:667_80.
- SAC. (1996). *Experimental investigations of beam_column subassemblies*. Report no. SAC 96-01. SAC joint venture, Sacramento, Calif.
- FEMA350 (2000), *Recommended Seismic Design Criteria for New Steel Moment Frame Buildings*.