5thSASTech 2011, Khavaran Higher-education Institute, Mashhad, Iran. May 12-14.

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

A. A. Hedayat[1], H. Saffari[2], A. Hadi[3]
[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 Student of Civil Engineering, Shahid Bahonar University, Kerman, Iran, amidhadi@yahoo.com

Name of the Presenter: Amid Hadi

Abstract

The 1994 Northridge earthquake caused widespread damage to moment-resisting frames. Various brittle fractures were found in beam-to-column welded moment connections. So far numerous efforts have been made to find a better connection configuration to improve the behaviour of the post-Northridge moment connections. The improvements are mainly based on the connection reinforcement or the weakening of the beam section. These methods are intended to force the plastic hinge to form away from the column face and consequently increasing the connection ductility. In this study these goals are achieved by creating a sinusoidal void in the beam web. Finite element study was used to investigate the behaviour of connection with such openings. The depth and length of the void are designed as such to cause the shear yielding of the beam web along the beam span and to keep the connection in elastic region. A parametric study was done to realize the effects of length and depth of such openings on the behaviour of connection. Analytical results showed that the presence of sinusoidal void moved the plastic hinge into the beam length and caused an increase in the connection ductility. Normalized moment-rotation curves of various void sizes are presented and their strength and ductility are compared. It seems that in the existing buildings this beam end modification is more economical than the reduced beam section (RBS) connections where the break of concrete slab is needed for top beam flange. In addition in this method the mechanical equipments could pass through the openings.

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

1. Introduction

Based on the seismic design philosophy for steel moment frames, structures are required to remain elastic during small to medium earthquakes. In a large earthquake, such structures should be ductile and safe from collapse. One of the most common methods by which a structure fails under seismic loading is at the connection between beam and column. This type of failure can result in a loss of structural integrity and the collapse of floors, if not whole buildings. The 1994 Northridge earthquake caused widespread damage to steel moment resisting frames including various brittle fractures in beam to column welded moment connections. The Northridge Earthquake prompted the initiation of new research programs that investigated the causes of these fractures and proposed changes to design procedures for more see Mahin (1998) and Miller (1998). Fig. 1 shows the configuration of a typical pre-Northridge connection with A36 beam, A572 column, E70T-4 welds this had very low fracture toughness, backup bars left in place that can create notch effect and increases difficulty of inspection and standard access hole. Typical failure modes are fracture at or near beam flange groove welds. The modified pre-Northridge connections which are now called post-Northridge connections use smooth weld access holes, high fracture toughness weld metal E70-TGK2 and no backing bar at the bottom beam flange. In 2009 a review study was done by Hedayat and Celikag (2009a) on both pre and post-Northridge to collect the most factors that are believed to contribute to the brittle fractures of Northridge connections. This study and also the studies done by other researchers showed that the beam end configuration of post-Northridge connection needs modification to increase its ductility. Modification of a post-Northridge connection can be achieved by either reinforcing the connection or weakening the beam section. Both methods move 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. Strengthening of the connection can be done by using one of the following methods; cover plates see Engelhardt and Sabol (1998), triangular haunches see Chia et al. (2006), straight haunches see SAC (1996), upstanding ribs see Popove and Tsai (1989), lengthened ribs see Chen and Lee (2003) and side plates see 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 see Popove and Yang (1994)) or the beam web (wedge beam connections see Wilkinsona et al. (2006) and Hedayat and Celikag (2010a)) or reduced beam web, RBW, connections with circular voids see Aschheim (2001) and Hedayat and Celikag (2010b), or rectangular voids in beam web see Hedayat and Celikag (2009b).

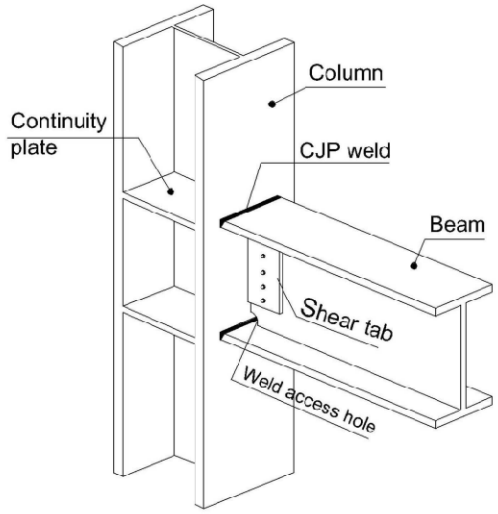


Fig 1: typical pre-Northridge connection

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. In RBW connections proposed by Aschheim (2001) and Hedayat and Celikag (2010a) the beam web is penetrated by a single or a number of circular voids. This study aimed to increase the ductility of post-Northridge connections by modifying the beam end configuration (BEC) at the vicinity of the column face. The proposed BEC which is based on the weakening of the beam section method can easily be applied to new and existing buildings .A sinusoidal void is penetrated on the beam web to keep away the plastic hinge away from column face. In this process, using finite element models a parametric study was carried out to find the best configuration for this opening.

Generally, for building construction, RBW connections seems to be more suitable since ducts and pipes can be passed through the voids and as a result the building height can be reduced.

2. Finite element analysis

2.1. Finite element modeling

Three pre-tested non-modified post-Northridge connections utilized by Stojadinovic 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 Stojadinovic et al. (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, where as 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 Stojadinovic et al. (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 Stojadinovic et al. (2000). The results agreed suitably with the experimental results. For instance, Fig. 2 shows comparison for specimen SAC3 under cyclic and monotonic loading.

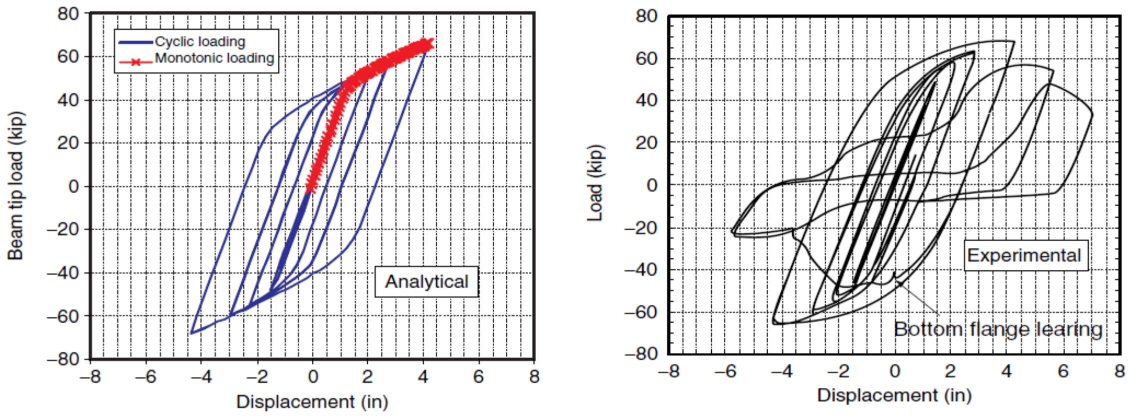


Figure 2: Comparison between analytical and experimental results for specimen SAC3 (a) Analytical; (b) Experimental (Hedayat and Celikag (2009b))

3. Research Methodology

Design criterion used in this study is similar to the one was used by Aschheim (2001) and Hedayat and Celikag (2010). In this criterion, a sinusoidal opening (Fig. 3) is provided in the beam web to cause the beam web to yield in shear at void area when the maximum normal stress developed at flanges at column face is limited to a nominal target value, f_s, which is less or greater than the yield stress of material ($f_s = \alpha . f_y$ where f_y is material yield stress and α is a multiplier). Based on this definition, the void height (a) can be calculated using equation 1. The middle of void is located at a distance equal to (Sc) which is obtained using equation 2. In depth (H_t) away from the column face is:

$$a = H_t - 2\sqrt{3}.\alpha.S_b / (t_w.L_b) \quad (1)$$

$$S_c = b_{sh\text{-}p} + b + w/2 \quad (2)$$

In these equations S_b, t_w, L_b, H_t, $b_{sh\text{-}p}$ are the beam section elastic modulus, the beam web thickness, the span length, overall beam depth and width of shear plate respectively.

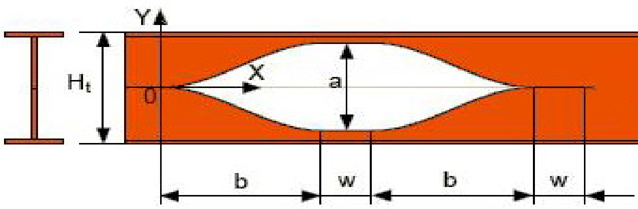


Fig 3: Sinusoidal void format with parameters

4. Parametric Study

Fig. 3 shows the parameters used to model a sinusoidal opening in the beam web. The void height (a) is determined using equation 1 which is a function of parameter α. Hence, the optimum void height was obtained by doing a parametric study on parameter α (Table 1). The total void length is comprised of three portions, two sinusoidal portions of length "b" and a flat portion of length "w". The total void length was defined to be β times of the void height (L_h=2b+w=β.a). To create the void, the sinusoidal cut of the web follows equation 3. Table 1 summarizes all parameters used in this study to modify the BEC of specimen SAC3.

$$y = a/4 - \sin(\pi(x/b + 3/2)) + a/4 \quad (3)$$

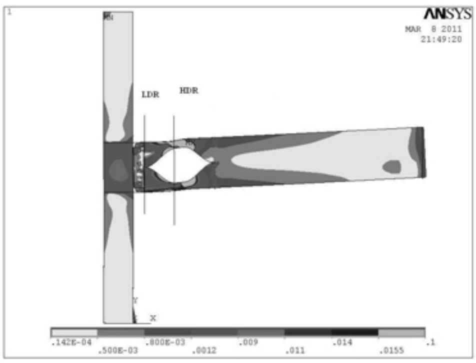
No.	Specimens	α	β	a(mm)	b(mm)	w(mm)
1	SAC3-SIN1	1.2	1.93	460	396	100
2	SAC3-SIN2	1.3	1.5	445	290	100
3	SAC3-SIN3	1.4	2	435	385	100
4	SAC3-SIN4	1.6	2	410	360	100
5	SAC3-SIN5	1.6	2.5	410	460	100

Table 1. Geometric parameters.

5. Finite element Results and Discussion

4.1 Effect of void

Hereafter, for simplicity, a post-Northridge connection with the proposed BEC is named as a modified specimen. Fig. 4 shows the typical deformation shape of a modified specimen. The presence of sinusoidal void divides the beam into two regions: low and high deformable regions (LDR, HDR). Due to the geometry of the void, the LDR has a limited vertical deflection at its end when compared to the other region. The HDR is located far away from the face of the column and provides the required connection rotational capacity (Fig. 4). Normalized moment (M/Mpb) versus rotation curves of a typical modified specimen are shown in Fig. 5. As this figure shows the presence of sinusoidal void caused a reduction in the connection initial rotational stiffness at the void center (HDR region) when is compared with the non-modified specimen. However, at the column face level (LDR), the initial rotational stiffness is increased compared to the non-modified specimen. It means that the rotational stiffness of this type of connection is a combination of these two extreme rotational stiffnesses. Also Fig. 5 indicates increase in the connection ductility at both HDR and LDR regions when is compared to the non-modified one. Despite the connection strength (M/M_{pb}) decreased at HDR, it is still greater than the minimum required by seismic codes (M/M_{pb}=0.85). Fig. 6 shows the Plastic equivalent strain PEEQ distribution for the modified specimen SAC3. There is a significant reduction of PEEQ at the weld access hole region and column panel zone. However, a remarkable PEEQ concentration is obvious at void area which means the movement of plastic hinge into the beam.



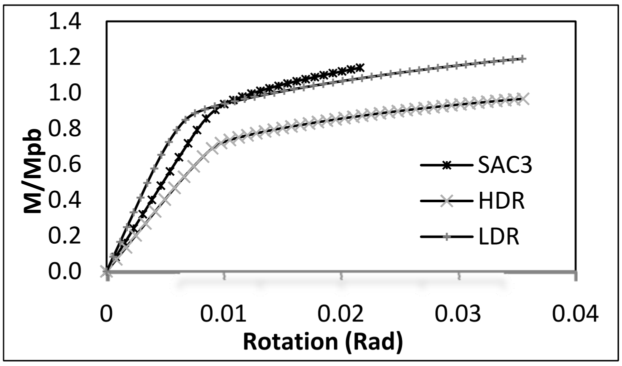


Fig 4: Typical deformation shape **Fig 5: Normalized moment-rotation curves**

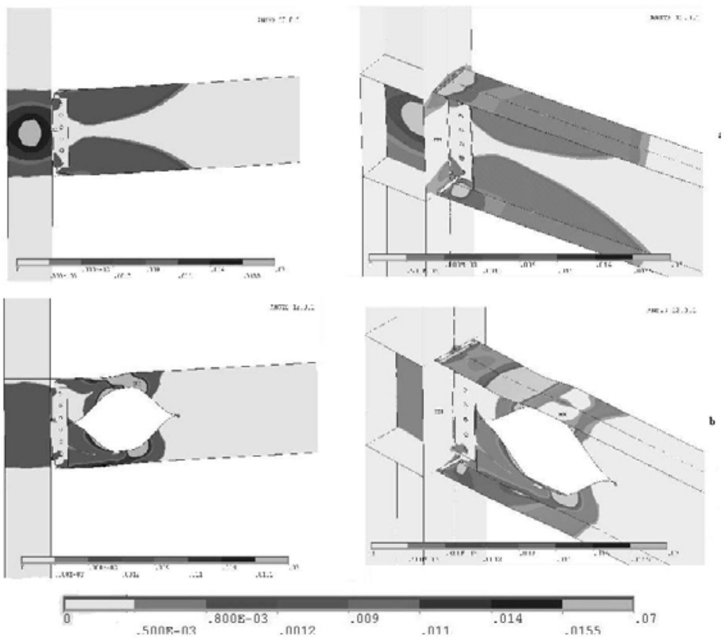


Fig. 6: Plastic equivalent strain (PEEQ) distribution of specimen SAC3: (a) Unmodified; (b) Modified

4.2 Failure Mode

The presence of a sinusoidal void at the beam web increases the level of both shear and normal strains at column face and especially at void area. Hence, in this study, it was assumed that the fracture of materials happens when the von-Misses strain reaches the ultimate strain of materials based on the material properties stated by Stojadinovic et al. (2000). Depending on the geometry of the proposed BEC, three failure modes might be observed for a modified specimen:

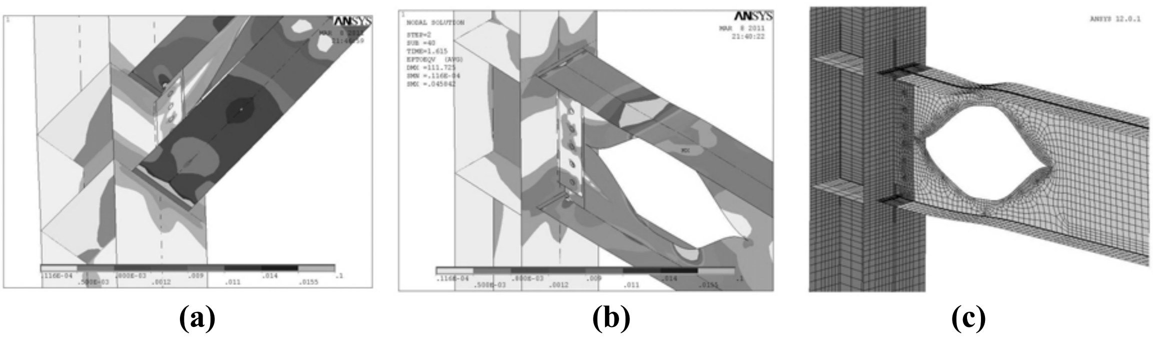
1. Beam flange fracture at the weld access hole (WAH) region (Fig. 7a). This happens when the HDR is not able to absorb a suitable amount of seismic energy to avoid the strain concentration at the WAH root.
2. Beam flange fracture at the middle of void (Fig. 7b). This happens for big values of parameter α or void height (a).
3. Excessive buckling of the T-section formed at the top and bottom of the void (Fig. 7c). This happens when the total length of sinusoidal void is too big compared to its height.

4.3 Effect of parameter α

By reducing parameter α, void height (a) increases. This causes a reduction in strain concentration at column face level and consequently increases strain level at void area. This caused an increase in the connection ductility. However, excessive reduction in parameter α, causes a significant reduction in the connection rotational stiffness. It also moves the location of beam flange fracture inside of the beam from the WAH region to the middle of the void. Fig. 8 compares the moment rotation curves of modified specimens presented in Table 1.

4.4 Effect of parameter β

To create sinusoidal void, the length w is taken as a constant. Hence, by decreasing the parameter β, the total void length (L_h) decreases. This causes the length of energy dissipation region reduces which leads to increase in the strain concentration at WAH region. For big values of parameter β, a long T-section creates at the void region. In this case, for the small value of parameter α, slender T-sections form which finally causes an early failure of connection either due to the flange fracture at the middle void or excessive T-section buckling. The highest connection strength and ductility achieves at an appropriate combination of parameters α and β. Fig. 8 compares the moment-rotation curves of modified specimens with different values of parameter β. As this figure shows the best value of parameter β is 2.5 which caused a 87.2 percent increase in connection ductility. Table 2 summarizes the strength and ductility of modified specimens presented in Table 1.



(a) (b) (c)

Fig 7: Different failure modes of a modified specimen; (a) Fracture at weld access hole region; (b) Fracture at beam flange; (c) Excessive buckling of the beam flange

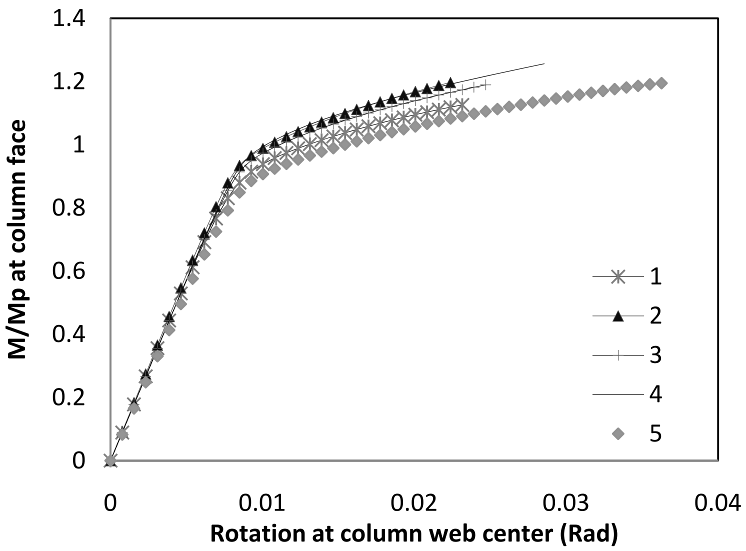


Fig 8: Effect of parameters α and β on moment rotation curve

No.	Specimens	α	β	M/Mpb	Θ (radian)
1	SAC3-SIN1	1.2	1.93	1.126	0.0231
2	SAC3-SIN2	1.3	1.5	1.197	0.0224
3	SAC3-SIN3	1.4	2	1.189	0.0247
4	SAC3-SIN4	1.6	2	1.256	0.0286
5	SAC3-SIN5	1.6	2.5	1.194	0.0363

Table 2. Modified specimens results.

6. Conclusion

This study was aimed to introduce a new beam end configuration (BEC) which can easily be applied to the beams of new and existing buildings to increase the strength and ductility of post- Northridge connections. RBW connections are a new beam-to-column joint of MRFs, and it not only improves aseismic behavior of connection, but also increases the function of the building. This goal was achieved by opening a sinusoidal void at the beam web. The opening size, a, and opening Length, L_h, are the main design parameters for web opening connections. Due to the geometry of the sinusoidal void, most of the deformations are concentrated around the RBW areas. Analytical results showed that the proposed BEC can reduce the stress concentration and plastic strain demand at beam flanges at the WAH region. Beam web void caused extensive yielding of the modified web area which consequently moved the plastic hinge in the beam away from the column face. The best results were obtained when parameters α and β are equal to 1.6 and 2.5 respectively. This modification caused an 87.2 percent increase in the connection ductility for specimen SAC3. However, from the ductility point of view it is not enough. Since based on most of seismic codes a connection is acceptable if it sustains at least two complete displacement cycles with a plastic rotation of 0.03 radian (or total rotation of 0.04 radian).

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