Seismic Retrofitting of Moment-Resisting Connections Using Beam Web Opening

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Summary:

The 1994 Northridge earthquake caused widespread damage to steel moment-resisting frames including various brittle fractures in beam to column welded moment connections. To improve the behavior of moment –resisting connections, opening in beam web investigated. Since the ratio of opening diameter to beam depth is a variable parameter in cyclic behavior of connections with opening in beam web, different finite elements models are developed and cyclic load is applied on them and the effects of opening diameter to beam depth ratio are studied on ductility of connections. The results indicate that the seismic energy is dissipated by local deformation in the weakened area of the beam due to the opening in the earthquake action and causes ductile behavior of structure by formation of plastic hinge in beams; preventing the stress and strain demand from exceeding the strength capacity of the connection welds.

Keywords: Beam Web Opening, Reduced Web Beam, Moment-Resisting Connections

1. INTRODUCTION

The 1994 Northridge earthquake caused widespread damage to steel moment- resisting frames including various brittle fractures in beam-to-column welded moment connections. To modify pre-Northridge connections, many investigations have been fulfilled. The modification of the connection is performed by either strengthening the connection or weakening the beam section.

Strengthening of the connection can be achieved by using cover plates and side plates and so on. Weakening the beam section can be prepared either by cutting a portion of the beam flange or the beam web. However, reinforcing of connections are usually more costly and more prolonged than weakening the beam sections because the welding and inspection of welding are difficult and costly. For example in connections with cover plates and side plates as Engelhardt and Sabol (1994 & 1998) discussed, breaking of concrete slabs and the use of additional elements is necessary and costly.

Among the beam weakening methods, the RBS is better accepted but cutting of flange in four locations at each end is costly. This is particularly valid for rehabilitation purposes when the building has floor slabs. In addition cutting of flange decreases the beam stability and increases the probability of beam lateral torsional buckling as Hedayat (2009) suggested.

Opening in beam web is an easy work for fabrication, which turns its application much easier. To reduce the story height as well as making up more free space, web opening beams are used to conduct piping and ductwork.

To investigate the seismic behavior of moment connections with web opening in beam, different models are made and cyclic loads are applied to them. In these models, the ratio of opening diameter to beam depth changes from 0.33 to 0.73 but the location of opening center is supposed to be constant. In these models, Von Mises stress distribution, plastic strain and shear stress are investigated in next to column face and opening location.

2. INTRODUCTION of BEAM WEB OPENING MODELS

A few models with different ratio of opening diameter to beam depth to determine the behavior of connections with web opening in beam are generated. The specifications of models are showed in Fig. 2.1 and Fig. 2.2. Since the point of inflection is assumed in the middle of beam and column, half of the beam length and the column height are considered in connection modeling which are 3.63 and 3 meters respectively. Dimensional specification of each model is presented in Table 2.1 which are

t_{dp}, thickness of double plate

t_{con}, thickness of continuity plate

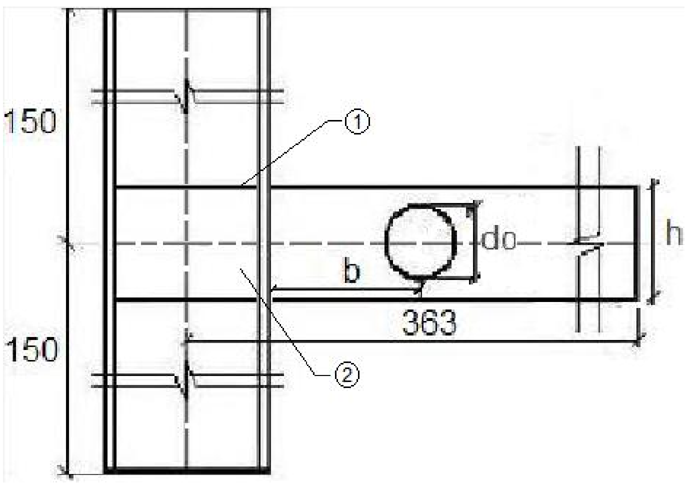
w, width of continuity plate

${d_0}/{h}$, ratio of opening diameter to beam depth

b, distance of opening center from column face

In these models, the ratio of opening diameter to beam depth, ${d_0}/{h}$, changes from 0.33 to 0.73 and the distance of opening center from column face is assumed constant and equal to 350 millimeters.

In order to analyze non-linear behavior of connections with web opening in beam, ANSYS finite element software (2009) is applied. The practical element in modeling is SOLID45 element. This element has eight nodes, large deflection capabilityand three degrees of freedom at each node. To simulate the stress-strain behavior of the steel, bilinear model is applied. Parameters of the steel are adopted in bilinear model, i.e., E, $2.1 \times 10^6 \, {kg}/{cm^2}$, F_y,$2400 \; {kg}/{cm^2}$,F_u, $3700 \; {kg}/{cm^2}$. Whereas nonlinear deformations occur near the connected parts and web opening, nonlinear behavior and more refined mesh are applied to these regions. Other parts are assumed with usual mesh and elastic behavior. To perform material nonlinearity analysis, plasticity behavior was based on Von Mises yielding criteria and kinematic hardening was assumed for the cyclic analysis.



1- Continuity plate

2- Web double plate

Figure 1. A connection with web opening in beam (unit in cm).

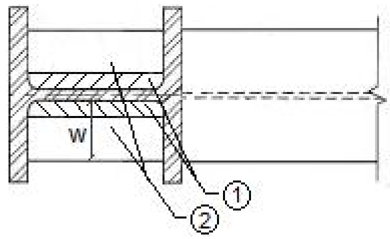


Figure 2. Plan view of connection

Table 2.1. Specifications of Models with Web Opening in Beam

Beam	Column	t_{dp}(mm)	t_{con}(mm)	w (cm)	d(mm)	d0/h	b (mm)
IPE300	IPB260	5	10.7	9.75	100	0.33	350
IPE300	IPB260	5	10.7	9.75	140	0.46	350
IPE300	IPB260	5	10.7	9.75	180	0.6	350
IPE300	IPB260	5	10.7	9.75	220	0.73	350

3.LOADING

Cyclic load was applied according to the SAC loading protocol (1997). The loading consists of stepwise increasing deformation cycles as illustrated in Table 3.1 and Fig. 3.3. The deformation parameter to be used to control the loading history is the interstory drift angle, θ, defined as the beam deflection divided by the beam span.

Table 3.1. SAC Loading History

Load Step	Θ (rad)	δ (cm)	N
1	0.00375	1.36125	6
2	0.005	1.815	6
3	0.075	2.7225	6
4	0.01	3.63	4
5	0.015	5.445	2
6	0.02	7.26	2
7	0.03	10.89	2
8	0.04	14.52	2
9	0.05	18.15	2
10	0.06	21.78	2

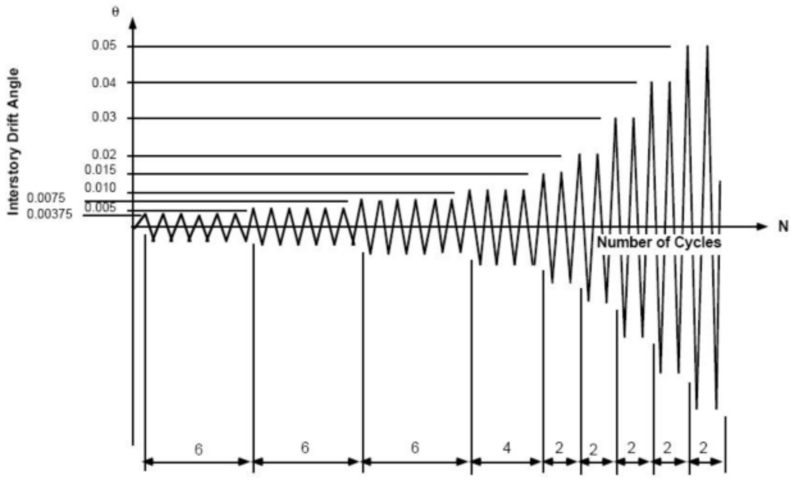


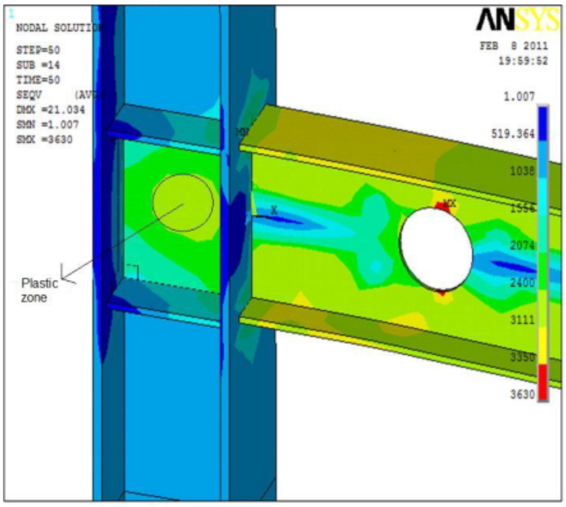
Figure 3. SAC loading history

4. DISTRIBUTION of STRESS and STRAIN IN MODELS WITH DIFFERENT RATIO of OPENING DIAMETER to BEAM DEPTH

Fig. 4.4 and Fig. 4.5 show Von Mises stress and equivalent plastic strain in models at different ratio of opening diameter to beam depth in 0.06 radians interstory drift angle. It can be seen that maximum Von Mises stress occurs in beam web near the opening especially in models with ${d_0}/{h} = 0.46, 0.6, 0.73$ however in model1 with ${d_0}/{h} = 0.33$ maximum Von Mises stress occurs in beam flange near the column flange in connection zone. This subject can be judged from Fig. 4.6 that indicates Von Mises stress distribution in centerline of top flange beam a long beam length (x direction) in 0.04 radians interstory drift angle. Regarding to Fig. 4.6, when the ratio of opening diameter to beam depth reaches to 0.33, maximum Von Mises stress in beam flange takes place near the connection of beam to column. As a result the ratio, ${d_0}/{h} = 0.33$ isn't geometrically suitable ratio for web opening in beam. Also Von Mises stress near the connection of beam to column decreases as the ratio of opening diameter to beam depth increases but Von Mises stress near the opening grows by increasing the ratio of opening diameter to beam depth. Consequently this ratio should be increased to prevent the stress demand near the connection in column face. In addition regarding to Fig. 4.5, maximum equivalent plastic strain appears near opening in beam except model1 with ${d_0}/{h} = 0.33$. As a result beams with ratio of opening diameter to beam depth greater than 0.33 yield ductile behavior by plastic hinge in beam. Also Fig. 4.7 illustrates equivalent plastic strain variation in top beam flange length at column face plane (z direction) at 0.04 radians. It shows that minimum plastic strain takes place in the edge of beam flange. If the ratio opening diameter to beam depth, ${d_0}/{h}$, increases, plastic strain in beam flange reduces in column face. Furthermore the local buckling of beam flange near the opening has occurred in 0.06 radians interstory drift angle as the ratio of opening diameter to beam depth equals to 0.73.

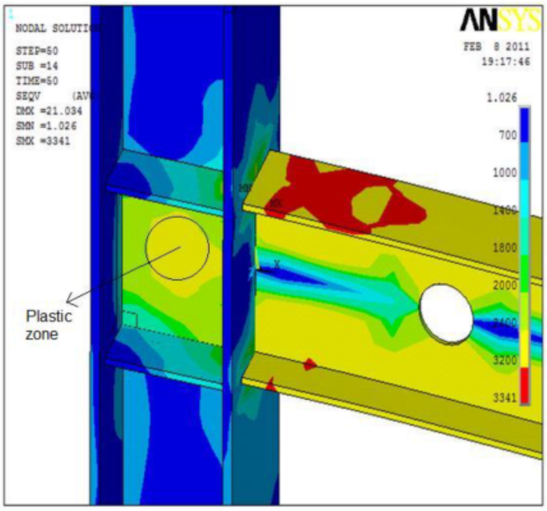
As the ratio of opening diameter to beam depth reduces, the panel zone becomes more plastic and spreads up which is shown in circle in Fig. 4.4.

While ${d_0}/{h}$ changes from 0.46 to 0.6 less Von Mises stress occurs in comparison with the case ratio ${d_0}/{h}$ changes from 0.6 to 0.73. Fig. 4.8 shows Von Mises stress variations in column face along beam web (y direction) at 0.04 radians. It can be seen that Von Mises stress in beam flange is larger than beam web. Therefore opening in beam web conducts forces to beam flange and increases demand on beam flange. For this reason beam flange may not sustain increased demand and may fail in extensive zone. It's recommended that the ratio remains between 0.46 and 0.6.



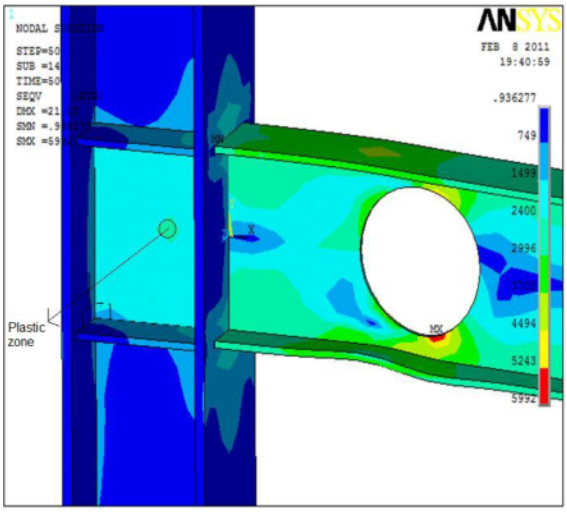
Model2 with ${d_0}/{h} = 0.46, b = 350mm$

$d_0 = 140mm$



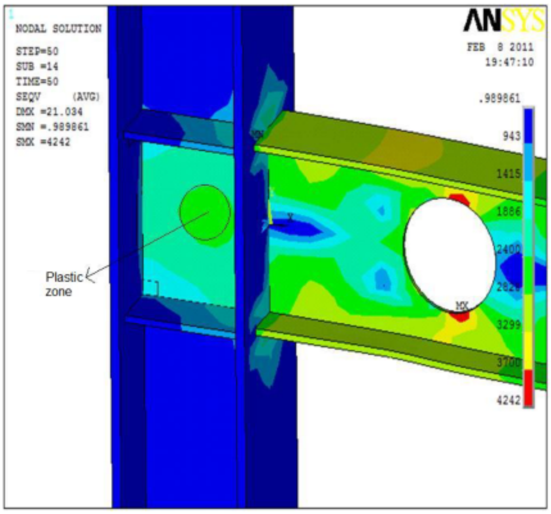
Model1 with ${d_0}/{h} = 0.33, b = 350mm$

$d_0 = 100mm$



Model4 with ${d_0}/{h} = 0.73, b = 350mm$

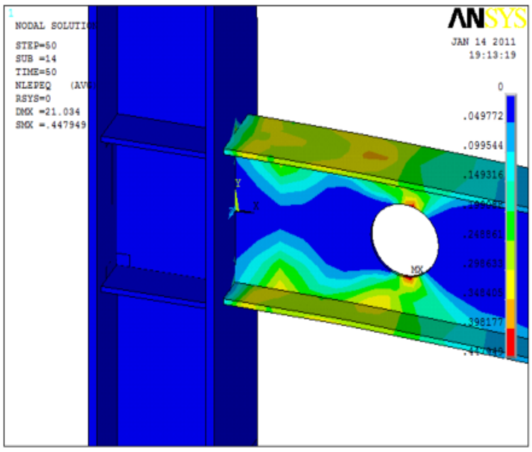
$d_0 = 220mm$



Model3 with ${d_0}/{h} = 0.6, b = 350mm$

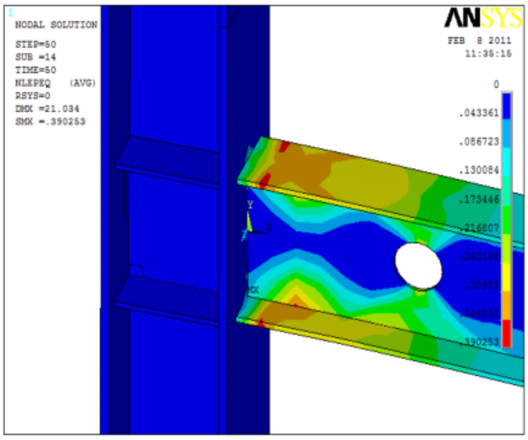
$d_0 = 180mm$

Figure4. Von Mises stress distribution against the ratio of opening diameter to beam depth



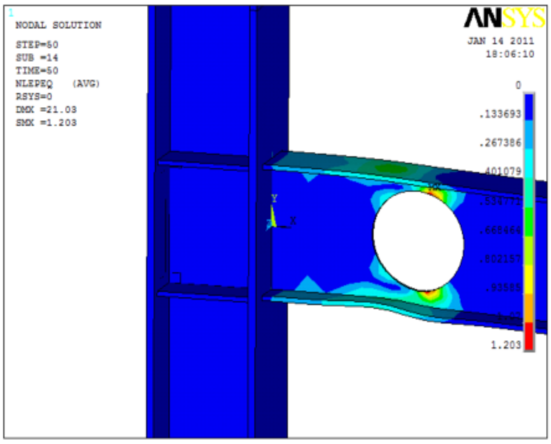
Model2 with $^{d_0}/_{h} = 0.46, b = 350mm$

$d_0 = 140mm$



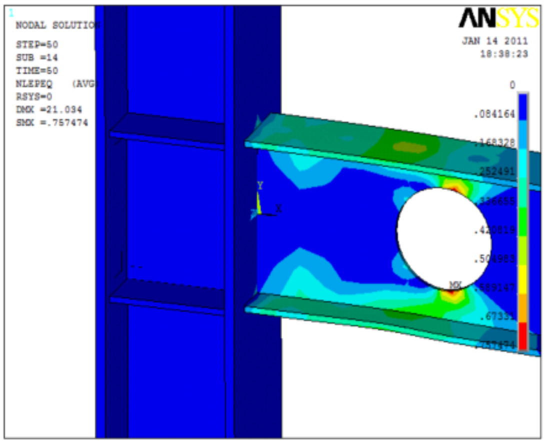
Model1 with $^{d_0}/_{h} = 0.33, b = 350mm$

$d_0 = 100mm$



Model4 with $^{d_0}/_{h} = 0.73, b = 350mm$

$d_0 = 220mm$



Model3 with $^{d_0}/_{h} = 0.6, b = 350mm$

$d_0 = 180mm$

Figure5. Equivalent plastic strain distribution against the ratio of opening diameter to beam depth

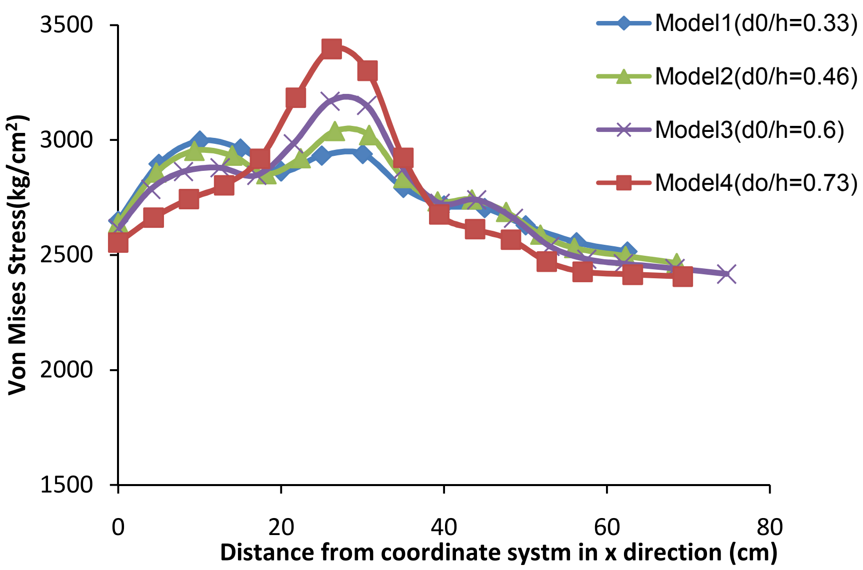


Figure6. Von Mises stress distribution in centerline of top flange beam in, x, direction

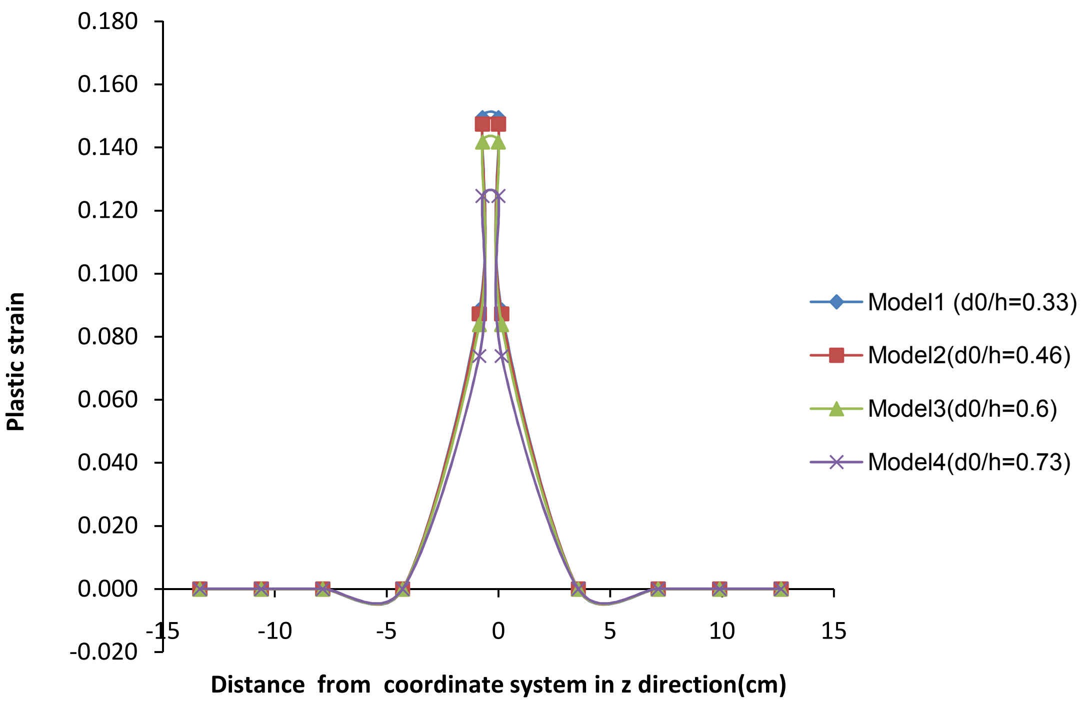


Figure7. Equivalent plastic strain variation in top flange in z direction in column face

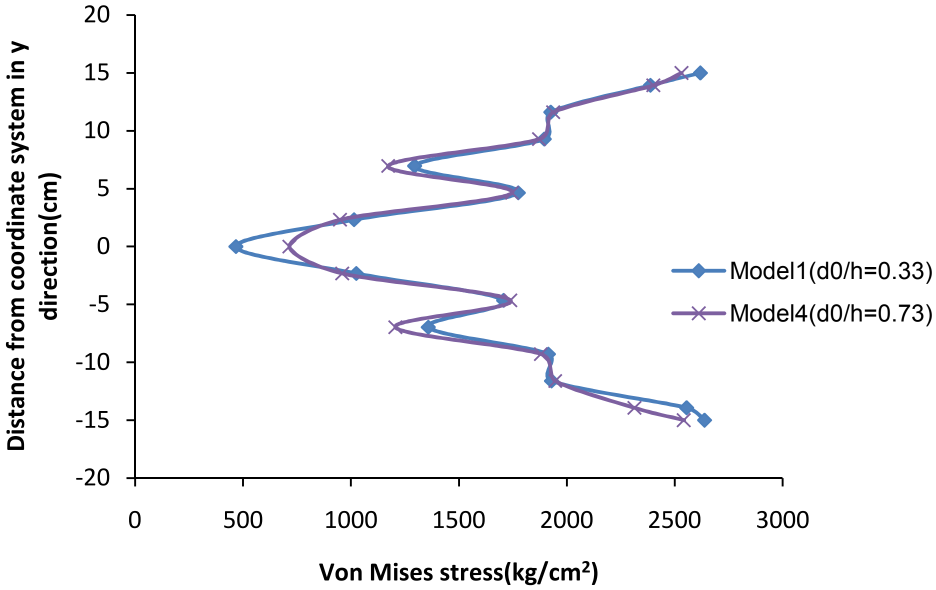


Figure8. Von Mises stress variations in column face in y direction at 0.04 radians

5. CONCLUSION

Finite element studies are carried out to investigate the seismic behavior of connections with opening in beam web. The results indicate that the seismic energy is dissipated by local deformation in the weakened area of the beam due to the opening in the earthquake action. Also plastic deformations take place in the web opening of beam if the ratio opening diameter to beam depth is greater than 0.33. As the ratio of opening diameter to beam depth reduces, the panel zone becomes more plastic and spreads up. Also opening in beam web conducts forces to beam flange and increases demand on beam flange. For this reason beam flange may not sustain increased demand and may fail in extensive zone.

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