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The beneficial effects of beam web opening in seismic behavior of steel moment frames

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Abstract. Implementation of openings in beams web has been introduced as an innovative method for improving seismic performance of steel moment frames. In this paper, several steel moment frames have been studied in order to evaluate the effect of openings in beams web. The beam sections with web opening have been modeled as a simplified super-element to be used in designing frames and to determine opening configurations. Finite element models of designed frames were generated and nonlinear static pushover analysis was conducted. The efficient location for openings along the beam length was discovered and the effects of beams with web openings on local and global behavioral characteristics of frames were discussed. Base on the results, seismic performance of steel moment frames was improved by creating openings in beams web, in terms of reduction in stress level of frame sensitive areas such as beam to column connections and panel zones.

Keywords: beam web opening, steel moment frame, pushover analysis, finite element method, panel zone.

1. Introduction

Steel frames subjected to seismic loading experience the largest stress and strain demands in their most vulnerable locations i.e. at the beam-column connection where the connection welds and heat-affected zones are located. As it is observed in many earthquakes, one of the major deficiencies in the seismic performance of steel framed structures is the presence of cracks in the beam-column connection followed by a brittle failure (Mahin 1998, Khandelwal & El-Tawil 2007). Presence of these cracks will introduce a large decrease to strength and stiffness of beam-column connection and will decrease the amount of dissipated energy within a loading cycle (Lee *et al.* 2000). Although different methods are introduced in order to strengthen the beam-column connection (FEMA 350 2000), but it should be noticed that improving the quality of the welds and base materials, or increasing the connection strength adequately to promote the development of plastic hinges in the beam away from the connection is expensive (Aschheim 2000).

To solve this problem, a rational way is to shift the location of inelastic flexural deformation of the beam to the zones located at some distance from the beam-column connection. In this regard, some authors have studied intentionally weakened beams by reducing the flange cross section to promote plastic hinging at a location offset from the connection to the column, (Kim & Kim 2009, Han *et al.* 2009). But this approach has its disadvantages (Aschheim 2000): (1) it is relatively costly to cut the

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flange at four locations at each end of the beam; (2) it is not practical to cut the top flanges where floor slabs may be present in the rehabilitation of existing construction; (3) because the plastic hinge zones are set in from the columns, they are subjected to larger deformations to achieve the same displacement of the structure; (4) heavier, more costly beams must be used in order that the cross section having reduced moment capacity provide the system with adequate strength; (5) the removal of flange material reduces the stability of the beam, thereby limiting its deformation capacity; and (6) the asymmetrical removal of flange material, as may happen recognizing the inexactness with which the flange cuts may be executed, may induce instabilities, further limiting the deformation capacity.

Local weakening of the beam by means of web openings is an innovative method which can be used to draw inelastic action away from the welded beam-column connection where brittle failures might initiate. This concept is studied by different researchers. Among the rest, Goel and Itani (1994a, 1994b) and Basha and Goel (1995) presented special truss moment frames (STMFs) with special middle panels. The concept used in STMFs limits inelastic deformation during a severe ground motion, in the special middle panels, while the columns and connections behave elastically except at the base. The STMFs have been adapted by the Uniform building code of the International Conference of Building Officials (ICBO 1997) and by the American Institute of Steel Construction (AISC 1999) and used in several structures. The same concept of STMFs was developed for steel moment frames by Goel and Leelataviwat (1998). In the middle of a special girder of these types of frames, which are called special girder moment frames (SGMFs) in the present work, a special ductile zone is considered to absorb seismic demands. In the work of Goel and Leelataviwat, the special ductile zone consisted of an opening in the beam webs with added web members. Lepage *et al.* (2004) used the reduced web section beams in the lateral resisting system. The reduced zones of the beams were modelled by uncoupled rigid–plastic springs. Yang *et al.* (2009) have demonstrated that the presence of web openings at two ends of a beam will help to the formation of localized plastic hinges in these reduced sections, preventing the connection from entering to the region of plastic rotations. In similar research, Kazemi and Erfani (2007) have concluded that the existence of opening in beams web can improve the seismic behavior of moment frames by bringing the location of plastic hinge from the end connections to the interior parts of the beam. In recent years some other researchers have conducted numerical and experimental studies on the behavior of steel beams with web openings (Kiymaz 2010, Bayramoglu 2012). Beyond the increasing amount of experimental and analytical studies conducted on this issue, application of this system still requires more sophisticated studies on different affecting parameters such as gravity loads, efficient location of web openings and etc.

This paper, presents an analytical study in order to assess the effects of openings in beams web on the behavior of steel moment frames. In the first part of study, six models with different opening configurations in their beams web are generated and the efficient location for openings is found using nonlinear pushover analysis. In the second phase, four reference models are analyzed to study the effects of key structural variables such as bay width and gravity loads on the behavior of steel moment frames with openings in their beams web. Based on the results, implementation of openings in beams web can improve seismic performance of steel moment frames considerably.

2. Details of Reference Models

In order to assess effects of openings in beams web, some 2D moment resisting frames are defined in such a way that the results obtained from their modeling and nonlinear pushover analysis can be extended to a broad range of applicable buildings. To do this, different geometric and structural parameters which may affect the behavior of lateral load carrying system are determined based on recommendations of FEMA P695 (2009). The key structural variables considered in this paper and assumptions related to each variable are presented in Table 1.

In this table, two framing systems are considered with respect to gravity loads (namely space frame and perimeter frame). In space frame the effective area used to calculate gravity and seismic loads are identical for all interior and exterior frames. On the other hand, in perimeter framing system, gravity loads are resisted by interior frames where the exterior frames are supposed to carry seismic loads of the entire structure. Using the design variables defined in Table 1, the reference models for implementation in nonlinear pushover analyses are selected as they are displayed in Table 2.

The reference models listed in Table 2 are designed as common special moment frames (without opening in beams web) according to provisions of AISC 360 (2005) and AISC 341 (2005). Sections obtained from design of reference models are summarized in Table 3.

It should be noted that all reference models listed in Table 2 are checked to satisfy different seismic provisions corresponding to special moment frames. As an example, panel zone strength requirements are checked for all beam-column connections and in the case of necessity they are strengthened using additional plate of sufficient thickness. In addition, all beams and columns are checked to meet strong-column-weak-beam criteria.

3. Details of Web Openings

3.1 Modeling of Web Openings

The openings considered in this paper have rectangular shape and are stiffened in both their top and

Table 1 Key structural variables and related assumptions

Structural design variables	Assumptions
Occupancy	Residential
Plan configuration	- One bay (6 m) - Three bay (6 & 9 m)
Elevation configuration	- One story (5 m) - Two story (9 m)
Section Profiles	Wide flange sections
Seismic design category	Category *D* (based on ASCE 7-05)
Framing (Gravity loads)	- Space frame - Perimeter frame

Table 2 Defined reference models

Model name	Number of stories	Number of bays	Bay width (m)	Framing (gravity loads)
TF116SRH	1	1	6	Space frame
TF236SRH	2	3	6	Space frame
TF236PRH	2	3	6	Perimeter frame
TF239SRH	2	3	9	Space frame

Table 3 Sections obtained from design of reference models

Model name	Beams		Columns		
	1st story	2nd story	1st story		2nd story
			Side columns	Mid column	
TF116SRH	W 12×22	-	W 10×45	-	-
TF236SRH	W 16×31	W 14×26	W 8×48	W 10×88	W 8×48
TF236PRH	W 16×31	W 14×26	W 10×88	W 12×106	W 10×88
TF239SRH	W 18×65	W 18×60	W 10×100	W 12×170	W 10×100

bottom sides. Fig. 1 displays a typical opening in the beam web. Dimensions of these openings (width and length of opening) may vary for different beams based on the loads acting on them.

The opening displayed in Fig. 1 can be structurally modeled as a super-element as it is shown in Fig. 2. This simplified model is composed of two horizontal beam elements in top and bottom, which two vertical rigid elements connect them together and to the rest of beam. The horizontal elements are representative of T-shape sections existing at top and bottom of opening (Fig. 1). The larger flange of these T-shape sections is indeed the flange of main beam where the smaller flange is the stiffener used to prevent the local buckling of the reduced section under compressive loads. Since it is assumed that no gravity loads are assigned to this simplified model, an additional horizontal element is used for distribution of gravity loads along this part of beam (it does not affect shear and bending behavior of super-element).

This simplified model will be used in section 3.3 in order to model reference structures and design T-shape sections in each web opening. For this purpose, internal forces and elastic stiffness of each reference model is calculated using simplified model (for design loads) and compared to the ones obtained from more detailed finite element analysis (see Fig. 10). This revealed the acceptability of proposed simplified model in elastic range (error < 10%).

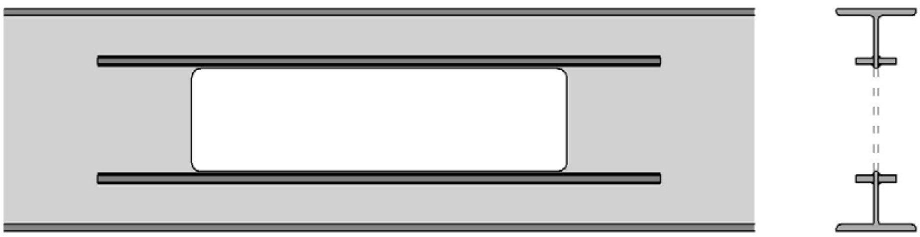


Fig. 1. A typical opening in the beam web

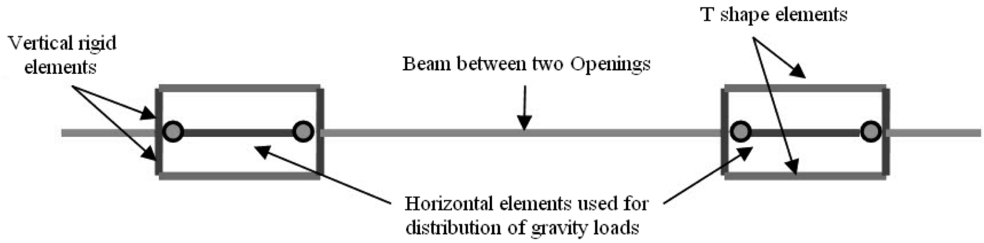


Fig. 2. The simplified model of a beam with two web openings

3.2 location of web openings

The basis of implementing web opening in beams is to create an intentional weak portion which acts as a structural fuse element and prevents excessive forces and stresses that may be imposed on other structural members and connections. This fuse element is intended to yield before any other part of structure and prevent stresses in beam-column connection from reaching intensities that might otherwise cause brittle behavior, fracture, or other undesirable behaviors. Furthermore, this element should be capable of absorbing or dissipating substantial amounts of distortional vibration energy to enhance the displacement capacity of the structure during an earthquake.

Since the location of web openings along the beam will affect structural behavior of these elements, in this section six finite element models with different opening locations and configurations are generated based on the model TF116SRH and their appropriateness is evaluated through nonlinear pushover analysis (Table 4).

Fig. 3 displays the distribution of yielded elements at 2% drift along the beams with web openings at their mid-span (red color indicates yielded elements). As it can be seen from this figure, all four models still experience excessive stress and strain demands at connection area. Hence it can be concluded that the placement of web openings at mid-span is not an efficient method to prevent inelastic flexural deformations from developing in beam-column connection or panel zone.

Fig. 4 displays the distribution of yielded elements at 2% drift along the beams with web openings at two ends. As it is apparent from this figure, in both models inelastic flexural deformations are drawn away from the welded beam-column connection and are concentrated around the web opening. Indeed these web openings act as a structural fuse and regulate the forces and bending moments resisted at the beam-column connection, thereby protecting the beam-column connection from excessive stress and strain demands.

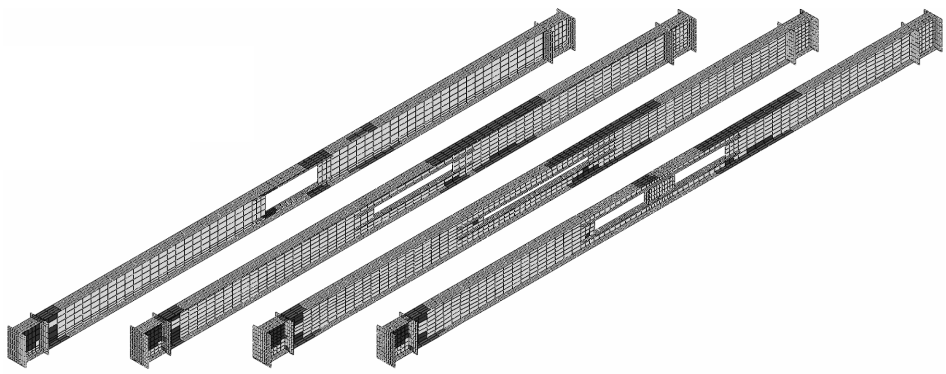
3.3 Finite Element Modeling

In order to design T-shape sections in each web opening, the reference structures are modeled in SAP 2000 software using the simplified link element shown in Fig. 2. The height of these sections and width of smaller flange (stiffener) is selected in such a way that each section comply with the design provisions of AISC 360 (2005), including buckling criteria, shear design and axial-flexural interaction. The general configuration of web openings obtained from this procedure is summarized in Table 5.

After designing T-shape sections, a detailed two-dimensional finite element model is generated for

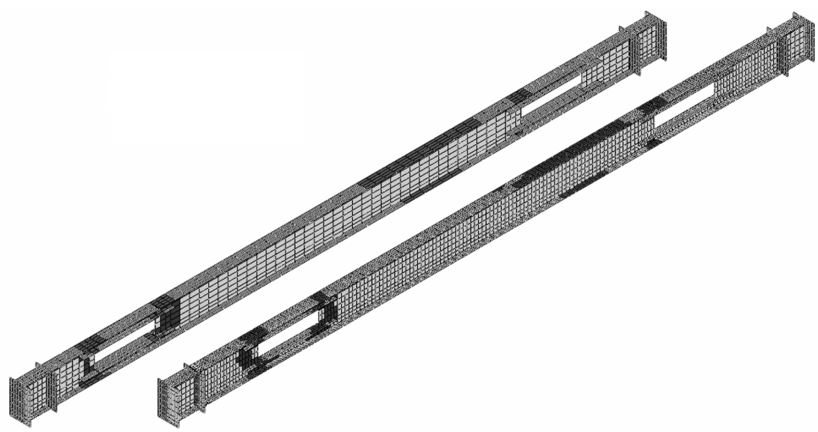
Table 4 Details of openings used to find the efficient location of openings

Location	Model No.	Number of openings	Distance from center of opening to the middle of span (mm)	Length of opening (mm)	Width of opening (mm)	Width of stiffener (mm)
Mid-span	1	1	0	600	218.694	51.181
	2	1	0	900	124.968	51.181
	3	1	0	1200	93.726	51.181
	4	2	450	600	156.21	51.181
Two ends	5	2	2100	600	187.452	102.362
	6	2	1950	600	187.452	71.6534



Model No. 1 **Model No. 2** **Model No. 3** **Model No. 4**

Fig. 3. Distribution of yielded elements in beams with openings at mid-span (drift 2%)



Model No. 5 **Model No. 6**

Fig. 4. Distribution of yielded elements in beams with openings at two ends (drift 2%)

each reference structure. In these models all structural sections are meshed using 4-node shell elements with elastic-perfectly plastic material prosperities. Fig. 5 displays finite element model used in nonlinear pushover analysis of reference structures with web openings.

Presence of openings in beams web can have a considerable effects on local and global behavioral characteristics of steel moment frames. Effects of implementing web openings on local and global behavioral characteristics steel moment frames is evaluated and discussed in the following sections.

4. Results and Discussions

4.1 Effect of web opening on local behavior of structure

In this section, effects of web opening are evaluated on behavioral characteristics of beam-column connection and panel zone. To do so, three models with web openings (different configurations of

Table 5 General configuration of web openings

Model name		First Story (points 4, 5, 6)			Second Story (points 1, 2, 3)		
		Length of opening (mm)	Width of opening (mm)	Width of stiffener (mm)	Length of opening (mm)	Width of opening (mm)	Width of stiffener (mm)
TF236SRH	Config. (1)	900	176.53	63.881	900	201.93	70.231
	Config. (2)	900	211.836	95.882	900	242.316	105.347
	Config. (3)	600	211.836	63.881	600	282.702	70.231
TF236PRH		900	247.142	63.881	900	282.702	70.231
TF239SRH		900	277.368	96.012	900	280.416	96.393

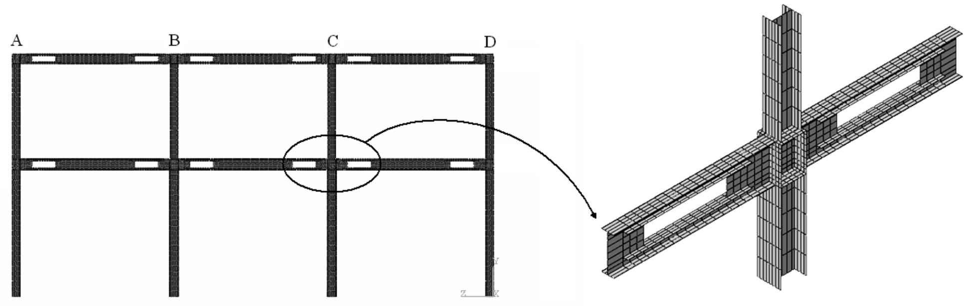


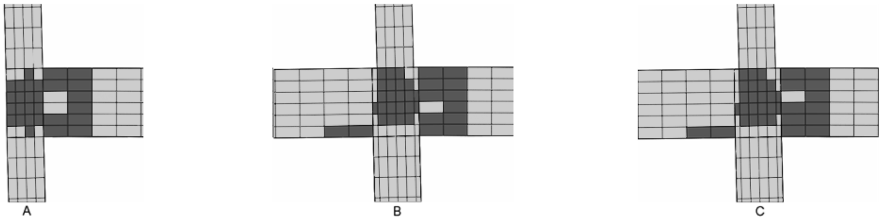
Fig. 5. Finite model of reference structures with web openings

model TF236SRH) and one model without web opening (model TF236SRH) are analyzed using nonlinear static analysis (pushover) and results are compared. Fig. 6 displays the distribution of yielded elements at 2% drift for six connections with and without web openings (red color indicates yielded elements). As it is clear from Fig. 6(a), in the first set of connections (which does not have web openings) nearly all panel zone area has yielded. In the second set (Fig. 6(b)), a plastic hinge forms at some distance from the beam-column connection preventing the connection area from yielding.

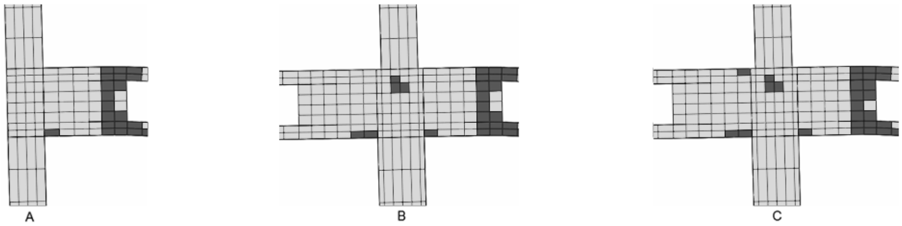
As a further comparison, the maximum plastic strain at panel zone area is plotted versus roof rotation angel in Fig. 7. According to this figure it is clear that web openings improve deformability of steel moment frames by shifting inelastic flexural demands to the beam, away from the beam-column connection.

In addition to improved behavior of panel zone area, application of web openings has considerable effect on decreasing the maximum moment resisted by beam-column connection. Fig. 8 displays the distribution of plastic strain at 4% drift, near two beam-column connections with and without web openings.

As it is apparent from Fig. 8, the location of maximum demand for inelastic deformations in right beam-column connection is shifted from column edge in Fig. 8(a) to the location of web opening in Fig. 8(b). It should be noted that the maximum value of plastic strain at the left connection is nearly ¼ times the same quantity at the right connection. This is due to the counteracting effect of gravity loads on seismic induced moment of left beam-column connection which prevents the formation of plastic hinge at location of web opening. The improved behavior of beams with web opening can be better seen in Fig. 9 which displays the ratio of maximum end moment to plastic moment capacity for two beams



(a) Model TF236SRH without web openings



(b) Model TF236SRH with web openings (Config. 2)

Fig. 6. Effect of web opening on distribution of yielded elements around the connection

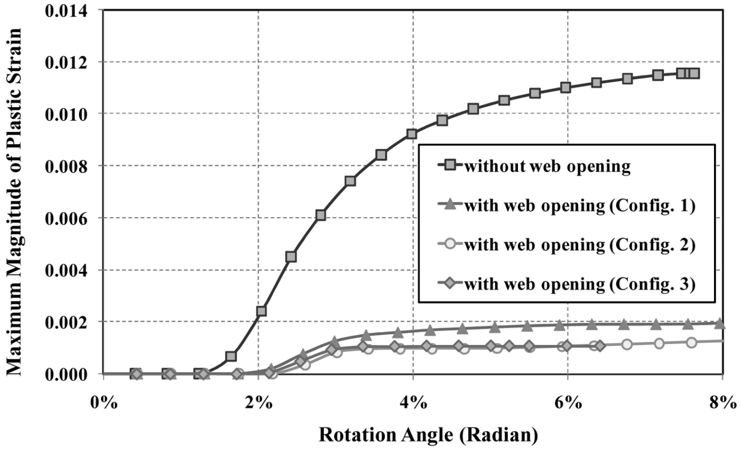
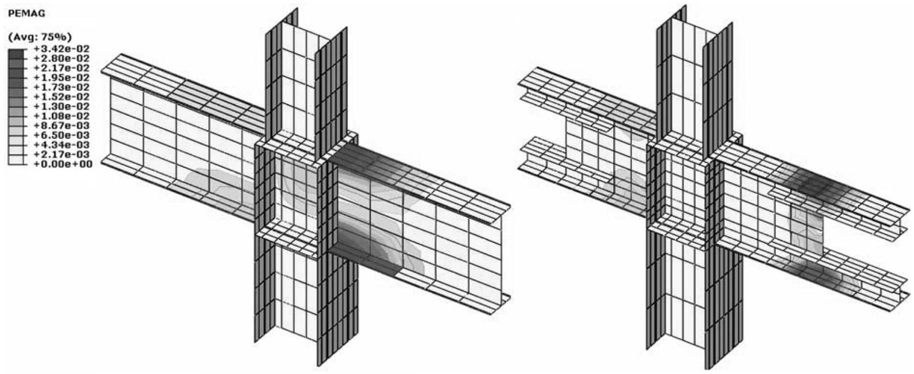


Fig. 7. Maximum plastic strain at panel zone area versus roof rotation angel

with and without web openings. Reduction of maximum end moment in beam with web opening indicates the reduced demand for inelastic deformation at beam-column connection.

4.2 Effect of web opening on global behavior of structure

Although presence of web openings at beam elements has beneficial effects on local behavior of structure, it will not be useful if it has adverse effects on global behavioral characteristics of structure e.g., load carrying capacity, stiffness degradation and etc.



(a) Without web opening (b) With web opening (Config. 2)

Fig. 8. Distribution of plastic strain at middle connection of first story (drift 4%)

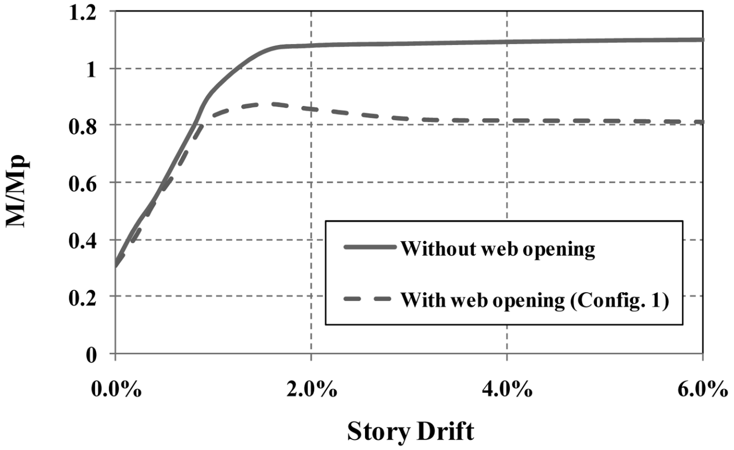


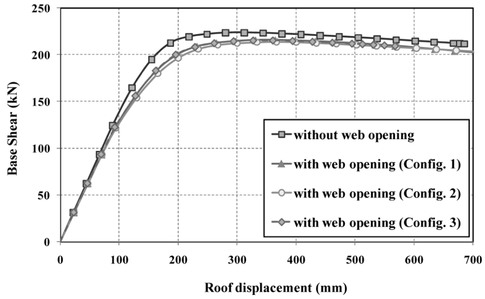
Fig. 9. Effect of web openings on reduction of M/M_p

Fig. 10(a) displays the lateral force versus roof displacement for one ordinary moment frame and three other structures with web openings in their beams (based on model TF236SRH). As it can be seen from this figure, introduction of openings to beams web has negligible effect on reduction of load carrying capacity which is in average about 4%.

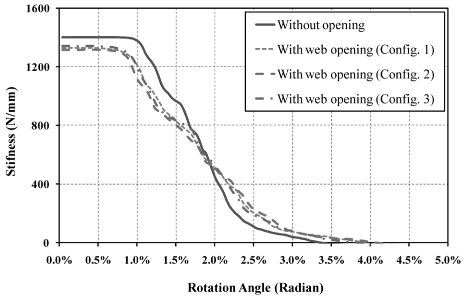
Fig. 10(b) displays another characteristic related to global behavior of structure. In this figure lateral stiffness of models are plotted versus their roof rotation. According to Table 6, the elastic stiffness of models with opening in their beams web is about 5% below the elastic stiffness of ordinary moment frame. But due to their slow stiffness deterioration in the inelastic range, they preserve more stiffness during inelastic deformations compared to the ordinary model (the negative sign shows increase in stiffness).

4.3 Effect of gravity loads on behavior of proposed system

The ratio of seismic loads to gravity loads in perimeter frame (TF236PRH) is almost three times the



(a) Lateral force- Roof displacement



(b) Lateral stiffness-Roof rotation

Fig. 10. Effects of web openings on global behavior of structure

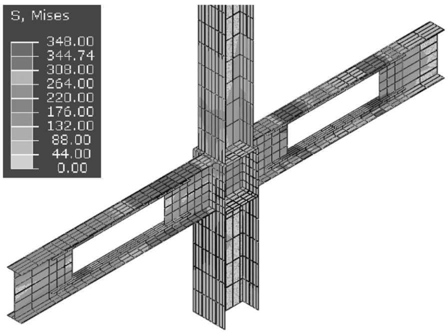
Table 6 Stiffness degradation of models with respect to ordinary moment frame

Model name	Yield initiation displacement, δ_y (mm)	Decrease in stiffness with respect to model TF236SRH (%)				
		$\delta \leq \delta_y$	$1.5\delta_y$	$2.0\delta_y$	$2.5\delta_y$	$3.0\delta_y$
TF236SRH-Config. (1)	89.7	5.39	14.48	-11.78	-84.27	-81.11
TF236SRH-Config. (2)	82.5	6.11	17.71	-15.76	-98.36	-95.34
TF236SRH-Config. (3)	85	4.48	13.44	-12.59	-69.96	-85.51
Average	85.7	5.33	15.21	-13.41	-84.19	-87.32

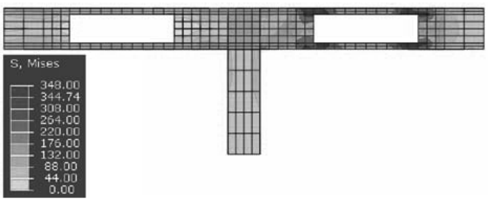
same ratio for space frame (TF236SRH). Fig. 11 displays distribution of Von-mises stresses at two connections of perimeter frame (drift 2%). As it is apparent from this figure, increasing the ratio of seismic loads to gravity loads in perimeter frame does not have adverse effect on fuse action of web openings. In this model, like space frames formation of plastic hinge at location of web opening prevents the connection area from yielding. This provides the perimeter frame with the same ductility and displacement capacity as the previously studied space frames.

4.4 Effect of bay width on behavior of proposed system

Despite the previously studied parameters, increasing the bay width of structure has adverse effect on

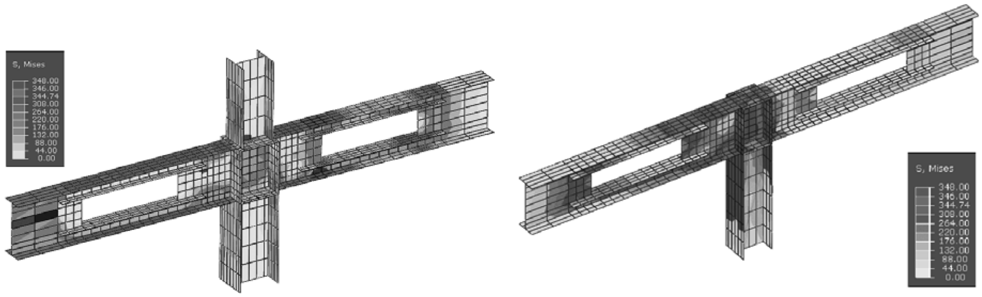


(a) Middle connection at first floor



(b) Middle connection at second floor

Fig. 11. Stress distribution at connection area for model TF236PRH (drift 2%)



(a) Middle connection at first floor (b) Middle connection at second floor

Fig. 12. Stress distribution at connection area for model TF239SRH (drift 2%)

behavior of beams with web openings. Fig. 12 displays distribution of Von-mises stresses at two connections of model TF239SRH which its bay width is 1.5 times the bay width of previously studied models. According to this figure, application of web openings in beams of a structure with large bay width can't improve seismic behavior of beam-column connection or prevent panel zone area from yielding.

5. Conclusions

Effects of openings in beams web on the behavior of steel moment frames is studied in this paper. Based on the results, Implementation of web openings at two ends of a beam is an efficient method to prevent inelastic flexural deformations from developing in beam-column connection or panel zone. Also it is found that the presence of web openings at beam elements has negligible effect on reduction of global stiffness and strength. In other words, introduction of openings to beams web doesn't have adverse effect on global behavioral characteristics of structure.

In structures with medium bay width, web openings act as a fuse element and prevent beam-column connection from excessive forces and stresses. Based on distribution of yielded elements around connection, it can be said that the beam sections with web opening yield before any other part of structure and prevents connection and panel zone from yielding. Also it is observed that the fuse action of web openings is not sensitive to the ratio of seismic loads to gravity loads and hence alteration of this ratio in perimeter frame does not have adverse effect on ductility and displacement capacity of proposed system. Generally, it can be said that application of openings in beams web is an efficient method which can be used to shift the location of inelastic flexural deformation of the beam to the zones located at some distance from the beam-column connection.

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