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دراسة تجريبية لتأثير طرف العامود المصلب على شق اتصال لين لعامود على حرف (I)

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الخلاصة

انفصال طرف العامود من الوصلة يحسن كثير من الوصلات الضعيفة وزيادة ليونة، والقضاء على قوة القص في طرف العامود. في هذه المقالة، التحقيق في السلوك الأهتزازي لهذا الوصل على المقاطع مع أساليب التحليل والاختبار التجريبي مع النظر في العوامل المؤثرة في التصميم. واستخدام طرف العامود المصلب على هذا الاتصال هو مثير للاهتمام بسبب التحسن في السلوك الميكانيكي لهذه الوصلة. وبالنظر في تدابير التصميم، تظهر النتائج وجود انخفاض في قوة هذا الجزء بالمقارنة مع نظيرتها الغير مشقوقة، وتشير إلى انخفاض تدرج الاستطالة في اللحامات طرف العامود. ومقارنات الأداء قد تم اجراءها على الدراسة التجريبية على أساس التناوب الكلي، وأقصى قدر من المقاومة وتبديد الطاقة في العينات. وليونة المقبولة في هذا الاتصال تبين ثبات درجة خاصة من العزم. والمزيد من المشاركة من منطقة لوحة في امتصاص طاقة الاهتزازات ويقلل من ليونة الإجمالية لهذا الاتصال والحد من المقاومة القصوى

Effect of vertical flange stiffener on ductility of slotted web exclusive connection on (I)-shape profiles through experimental investigation

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ABSTRACT

The separation of flange from beam web at slotted web connection improves many weaknesses of connection. Increasing ductility and elimination of the shear force present in beam flanges are benefits of this connection. In this article, the seismic behavior of this connection on IPE cross-sections is investigated with analytical methods and experimental testing, while considering effective factors in design. Using vertical flange stiffener on this connection is strongly impressive in improvement behavior of this connection. Considering design measures, results show no strength reduction in this part, compared to its non-slotted counterpart, and indicate lower strain gradient in beam flange welds. Performance comparisons on experimental study are made based on the total rotation, maximum resistance and energy dissipation of the specimens. Suitable ductility at this connection show that this connection stands in special moment connection class. More participation of panel zone in earthquake energy absorption reduces the total ductility of this connection and its maximum resistance.

Keywords: Ductility; lateral torsional buckling; seismic behavior; slotted web connection.

INTRODUCTION

Observations after the Northridge earthquake (1994) showed that shear forces present in beam flanges were the main cause of brittle fracture in beam flange welding point regions. Existence of this force led to a non-uniform distribution of stress and strain during welding and triaxial stress, while welding beam flanges to columns.

This issue occurred due to the small width of the flange and existent shear force in beam flange was not considered in the design process (Richard *et al.*, 1997a).

In slotted web connections, with improvement of many weaknesses present in moment connections exist in Prior to the Northridge earthquake were introduced by seismic structural design associates (SSDA). They have been classified as special moment connection by the American Institute of Steel Construction (AISC), to meet the Federal Emergency Management Agency (FEMA) regulations (FEMA, 2000). Experimental testing of this connection on a number of W-Sec profiles showed that it behaves suitably toward cyclic loads.

In slotted web connections, the separation of the beam flange from the beam web results in separation of flange force from the beam web, which leads to elimination of shear force in beam flanges and results in a more uniform distribution of stress and strain within the flange weld, thus also eliminatesing lateral torsional buckling along the beam length. With transfer of shear force to beam web, the problem of triaxial stress at beam flange weld was eliminated.

Considering that the main purpose of connections is separation of the plastic hinge from the connection joint, slotted web connection is highly capable of distancing plastic hinges from the column face.

Considering the novel idea of slotted web connections in steel structures, the pivotal objective of this research surrounds identifying the seismic behavior of this connection on semi-wide beam cross-sections. In this study, ductility of slotted web connection is studied in two states; without stiffener and with vertical flange stiffener. The factors concerning this connection, including strain distribution along the weld, plastic hinge transfer method inside the beam and beam buckling were examined and compared with beam to the column direct connection (WUF).

SPECIAL MOMENT FRAME BASED ON AISC REGULATIONS

Based on AISC regulations, connections fulfilling the following requirements are considered special moment frames (AISC, 2010):

1. Capability of reaching relative ductility, equivalent to 0.04 radians for beam to column connection rotation.
2. Connection moment resistance on 0.04 radian, rotating at column face a maximum 20 percent lower, relative to nominal plastic moment.

The required shear strength of the connection under quake loads is evaluated using Equation 1.

$$V = 2[1.1 R_y M_p]/L_h \tag{1}$$

Where R_y is coefficient of yield stress, M_p is the nominal plastic moment and L_h is the distance between the plastic hinge going on the beam's span. In order to achieve the aforementioned conditions, different connections were should be examined in terms of stability and ductility by means of cyclic loading, according to present procedures and valid regulations (AISC, 2010).

Some of the earthquake energy is wasted in connection by beam, panel zone and column; of which most of the energy waste happens in beam, panel zone and column respectively. The amount of absorbed energy is calculated by the area under the Hystersis curve for every connection element.

A new type of special moment connection is explained below.

SLOTTED WEB CONNECTIONS

The geometry of this connection as presented in Figure 1, consists of two horizontal slots ending in a hole near the connection that separates the beam flange from the beam web,and a shear plate, which is welded to the column along with the beam web. An original and reputed slotted connection introduced in US regulations is in accordance with this model (ICC Evaluation Service, 2002).

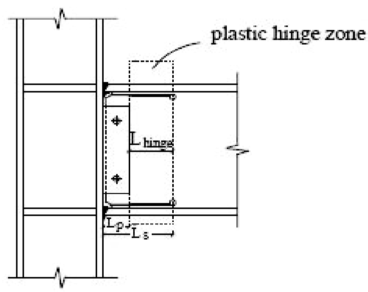


Fig. 1. Slotted web connection (FEMA, 2000)

The basis of designing this connection is the moment diagram (based on ATC-24) demonstrated in Figure 2, which starts from a plastic hinge on start from the beam flange that and continues to the end of the slot, and the beam web yield within the gap between the end of the slot and the plastic shear plate. By writing the balance relation for Sec A-A and Sec B-B, lengths of the plastic hinge and slot are obtained (Richard et al., 1997b).

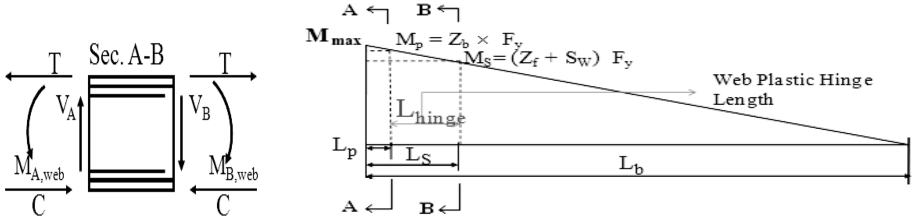


Fig. 2. Moment diagram based on ATC-24 (Richard et al., 1997b)

According to Figure 2, it is obvious that the reduction of moment from inner part of beam to its free part creates a K like border between the elastic and plastic area inside the beam. The length of this region is the same as that of beam plastic hinge.

By writing the equivalent equation between A-A and B-B section (Richard & Allen, 2000 ICC Evaluation Service, 2002), we have

$$M_A = M_B + P_U(L_S - L_p) \tag{2}$$

$$Z_b * F_y = (Z_f + S_W)F_y + P_u(L_S - L_p) \tag{3}$$

On the other hand:

The maximum effective force on beam, which is able to yielding whole of A-A section is calculated with Equation 4. Other effective parameters in determining slot length are: elastic and plastic modules of beam flange and beam web, of which the correlations are as follows (Richard et al., 1997b; ICC Evaluation Service, 2002).

$$P_u = \frac{Z_b F_y}{(L_b - L_p)} \tag{4}$$

$$Z_b = Z_f + Z_W \tag{5}$$

$$Z_f + S_w = Z_b - \frac{Z_w}{3} \tag{6}$$

By substituting correlations 5 and 6 into 3 and simplifying them, the length of plastic hinge can be calculated as in Equation 7.

$$L_{hinge} = (L_b - L_p)\left[\frac{Z_b - Z_f}{3Z_b}\right] \tag{7}$$

Analytical study of slotted web connections indicate that undesirable ductility is due to rapid buckling of beam flanges, and the resistance decline of this connection compared to its non-slotted counterpart. Thus, in order to improve connection behavior and prevent rapid buckling of flanges, it is suitable to utilize vertical flange stiffeners within the distance between the column face and end of the shear plate. The design of slotted web connection accompanied by vertical stiffeners is demonstrated in Figure 3.

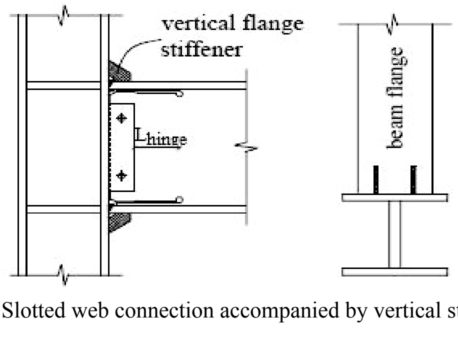


Fig. 3. Slotted web connection accompanied by vertical stiffeners

CONFIGURATION OF MODELS AND LOADING HISTORY

Considering a model of slotted web connections on semi-wide profiles, this article attempts to study its behavior in two states; with and without stiffener on the flange. All models were designed and cyclic loaded according to AISC regulations. Sample configurations are presented in Figure 4 (AISC, 2010).

Steel specifications are based on experimental steel tension tests and steel stress-strain curve (Figure 5) in the finite element method is considered three-line isotropic.

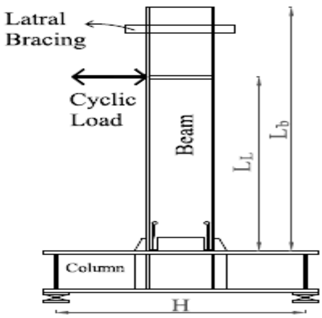


Fig. 4. Sample configurations

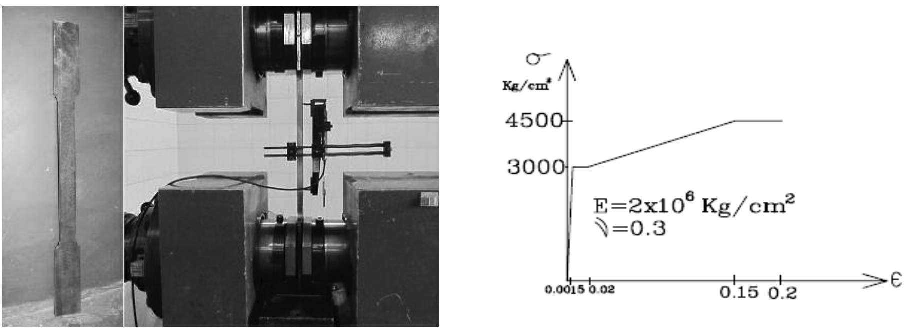


Fig. 5. Steel stress-strain curve

The loading record was selected according to the recommended standard by SAC regulations (SAC, 2000). This record, which is two-sided cyclic multiplier, was applied on the models using displacement control method and based on the overall beam-rotating angle relative to the column. A sample of this cyclic loading is given in Figure 6.

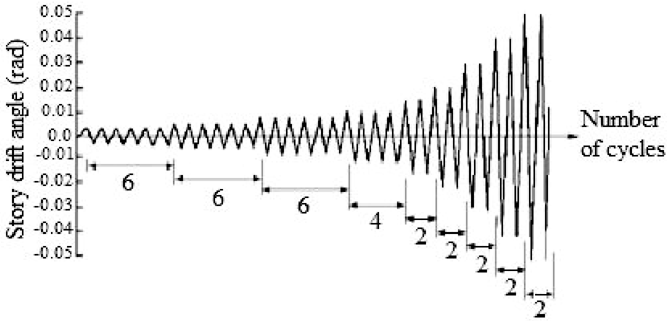


Fig. 6. Loading history (SAC, 2000)

NUMERICAL STUDIES

Modeling

The beam employed in samples was of a semi-wide IPE27 profile loaded within one meter of the column face. In addition, in order to prevent lateral displacement of beam, a lateral bracing was employed. Sample specifications and connection methods according to Figure 4 are given in Table 1.

Table 1. Sample details

Sample	**Connection method**	**Element**	**Cross-section**	**Steel grade**	**H (cm)**	**L_L (cm)**	**L_b (cm)**	**Double Plate (mm)**
SW1	Slotted Web	Beam	IPE27	ST37	--------	100	130	
		Column	IPB24	ST37	100	-------	-------	2 PL 6
SW2	Slotted Web with flange stiffener	Beam	IPE27	ST37	--------	100	130	
		Column	IPB24	ST37	100	-------	-------	2 PL 6
WUF	Beam with out Slotted Web	Similar to the two previous samples for comparison in section (1-3)						

Examination of finite elements of model was carried out using ANSYS software (ANSYS, 1992). 3D elements were employed for connection modeling, and Solid45 elements and suitable Hex meshes were utilized for meshing. Figure 7 depicts a sample meshed connection.

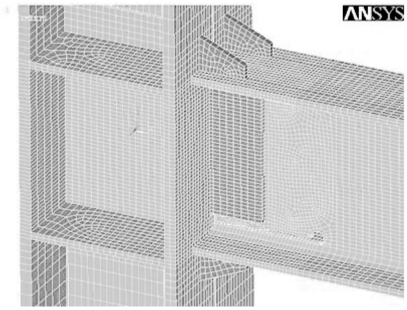


Fig. 7. Numerical model shape in mesh mode at SW2

HYSTERETIC RESPONSE AND ANALYSIS

It is evident that hardness of flange near the connections due to added stiffeners prevents rapid buckling of beam flanges and improves connection ductility. Utilizing stiffeners, existing heavy strain in flanges that lead to flange buckling can be controlled and reduced. Strain distribution chart along the length of the beam is depicted in Figure 8, for two slotted samples. In slotted web connections, separation of the web and flange leads to their independent buckling and prevents lateral torsional buckling in the beam.

Von Mises stress distribution and shear stress distribution at this connection, are demonstrated in Figure 9.

The Hysteresis graph for two slotted samples is demonstrated in Figure 10. As specified in both graphs, in the slotted non-stiffener connection, the sample has experienced force reduction in 0.03 rad rotation, due to rapid buckling in flanges. The maximum force is around 17 tons and reaches 20.5 tons in non-stiffener and stiffener models respectively.

Independent buckling of flange and web in this connection eliminates the lateral torsional buckling phenomenon (Figure 11).

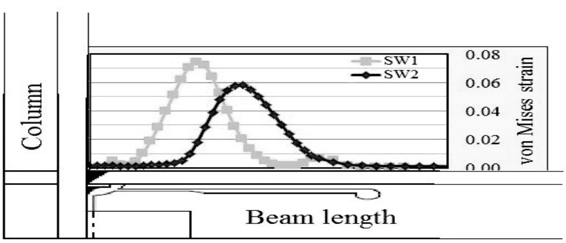
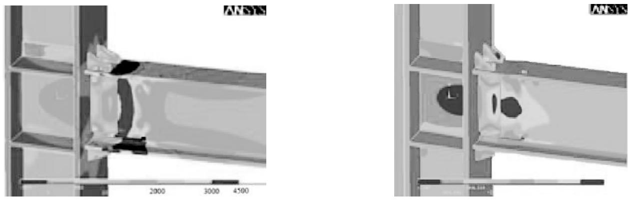


Fig. 8. Strain distribution on the flange within the length of the beam



(a) (b)

Fig. 9. Stress Distribution in slotted web connection a) von Mises b) shear stress

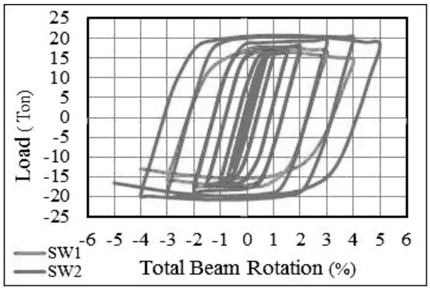


Fig. 10. Hysteresis behavior in slotted web connections

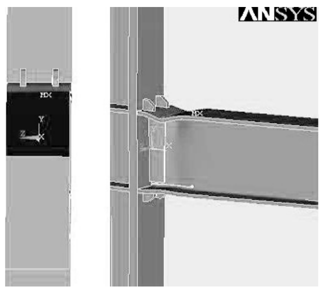


Fig. 11. Elimination of lateral tortional buckling

STRAIN GRADIENT IN BEAM FLANGE WELD

In order to examine the effect of creating a slot on strain gradient reduction in beam flange welds, strain distribution and rupture index were calculated for the width of of the beam flange at connection region. The comparison dealing with slotted web connection and non-slotted web connections is given in Table 1. Rupture index was calculated using Equation 8 (EL-Tawil *et al*., 1999; Kim *et al*., 2002) and is normally compared between connections with specific displacements and required numerical convergence.

$$RI = \frac{\varepsilon_p/\varepsilon_y}{\left(exp(-1.5\frac{\sigma_m}{\sigma_{eff}})\right)} \tag{8}$$

In this equation, ε_p, ε_y, σ_m and σ_{eff} are strain equivalent to plastic rotation, yield strain, hydrostatic pressure stress and von Mises stress, respectively.

The chart in Figure 12 shows that the existence of a slot under the flange leads to reduced stress concentration in the middle of the weld and more uniform strain distribution on the width of flange. In addition, in the slotted connection sample, the existing stiffener on the flanges provides further reduced strain values. Figure 13 represents reduced rupture criteria on high welds in slotted connections, in a way that slotted web connections with stiffener have a lower and near zero criteria value.

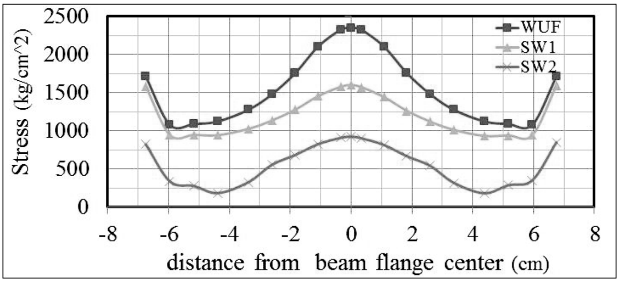


Fig. 12. Von Mises stress distribution on the flange weld in the elastic range

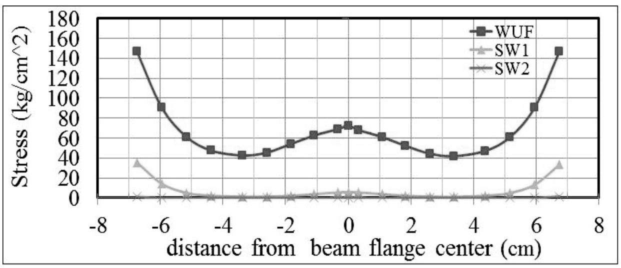


Fig. 13. Comparison of rupture Index in the flange weld

EXPERIMENTAL STUDIES

A more precise evaluation of behavior of slotted web connection was followed by testing two experimental samples. Study of the ductility of slotted web connection was carried out on two selected models of slotted web beams with flange stiffeners, with different columns.

The beam profile was from Isfahan Iron Foundry, and average tension test results are given in Figure 5. Considering the configuration of models as demonstrated in Figure 14, specifications of the two samples are given in Table 2. Sample configurations in the experiment are demonstrated in the figure below. Cyclic loading records are based on SAC regulations (Figure 6), which was applied to the beam at a distance of one meter from the column face. In order to prevent outer plan instability in experimental samples, a lateral bracing was installed at a suitable place on the beam.

Table 2. Experimental sample specifications

Sample	**Element**	**Cross-section**	**Steel grade**	**H (cm)**	**L_L (cm)**	**L_b (cm)**	**Sheet dimensions (cm)**	**Doubler Plate (mm)**
Sample 1	Beam	IPE27	ST37	-------	100	130	W63x19x1 F63x22x1.5	1 PL 8
	Column	Plate girder	ST37	63	-------	-------		
Sample 2	Beam	IPE27	ST37	-------	100	130	--------------	-----------
	Column	IPB24	ST44	126	------	-------		

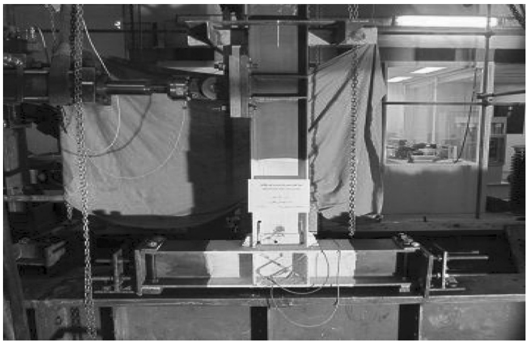


Fig. 14. Experimental sample configurations

TEST RESULTS

In every loaded structure, changes can be investigated from two aspects; changes in surface shape and internal shape. These changes accompany different elastic, elastoplastic and plastic stages after structure rupture. Experimental samples are coated with lime, so that the state of yield and method of plastic hinge creation can be tentatively investigated.

By applying loads, lime is poured from the front of the flange stiffener and extended to the end of the slot. In addition, the front part of the shear plate in the beam web enters the nonlinear range shown in Figure 15, a. By continually adding more load to the beam, the beam flanges gradually start to buckle, independent of the buckling of web connection, and within this period, yield continuous to progress from the beam web to the end of the slot. After flange buckling, with the web connection entering the nonlinear range, the web connection buckles and a wave appears in the length of the slot. The independent buckling of the flange and web connection eliminates the lateral torsional buckling mode (Figure 15, b).

(a) (b)

Fig. 15. Yield of beam flange and web & beam flange buckling

Proceeding from a 0.04 rad rotation of the samples from the end of the slot in the rounded shape location, due to intense increase in stress fractured in this region (Figure 16). Cyclic loading results for the test samples are given in Figure 17. The panel zone cyclic behavior of experimental samples are shown in Figure 18.

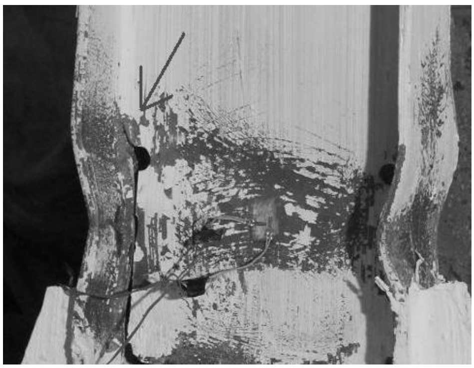
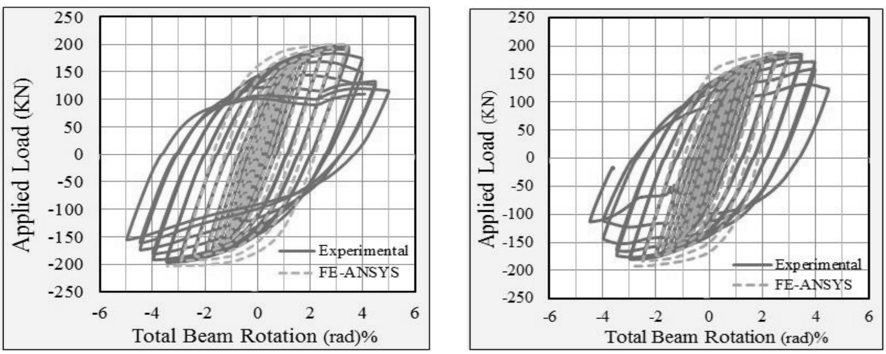
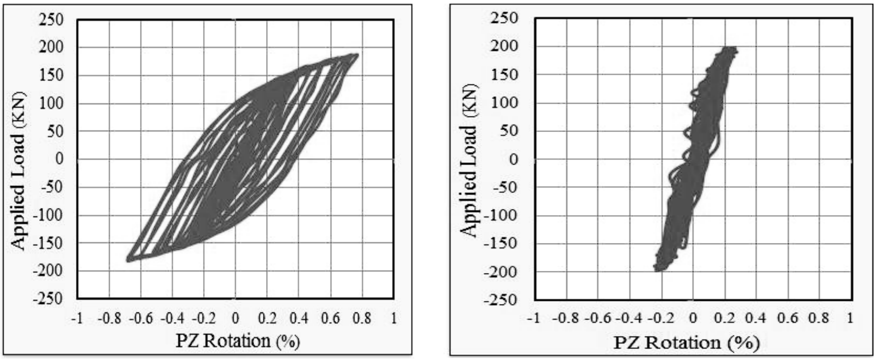


Fig. 16. Fracture at end of the slot



(a) Sample 1 (b) Sample 2

Fig. 17. Cyclic behavior of experimental samples



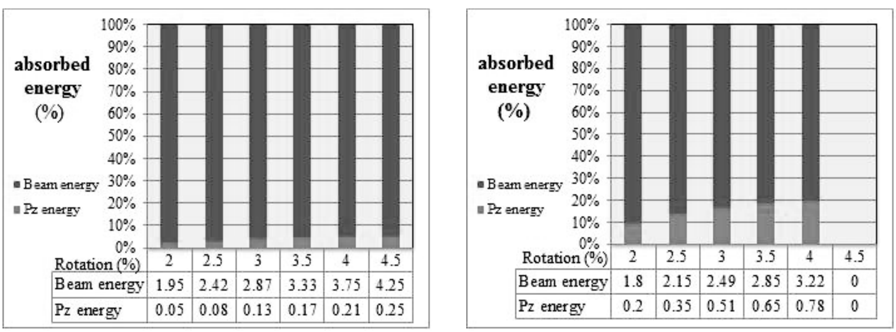
(a) Sample 1 (b) Sample 2

Fig. 18. Panel zone Cyclic behavior of experimental samples

The above graphs show that both samples have displayed desirable ductility and have endured an overall 0.04 rad rotation in more than $0.8M_p$ capacities, which indicate placement of slotted web connections with vertical stiffeners in the special moment connections class. Considering utilization of Iranian semi-wide (IPE) profiles in design of this connection, its ductility and suitable seismic behavior indicate the suitability of such profiles for this application.

The energy dissipation capacity of a connection is calculated based on the area under the hysteresis load-deflection curve, which indicates how effectively a connection withstands earthquake loading.

The amount of absorbed energy in beam and panel zone in two samples is presented in Figure 19. By comparing this graph with final results as shown in Table 3, it can be found that in samples where the panel zone has a higher share of participation in energy waste, it has tolerated less resistance and showed less ductility. Beam plastic rotation demands are smaller in connections with weak panel zones and The potential for brittle fracture is therefore greater in such connections if there are flaws or other irregularity at the beam-column interface. (EL-Tawil *et al.*, 1998)



(a) Sample 1 (b) Sample 2

Fig. 19. Percentage of absorbed energy at beam and panel zone

Table 3. Final sample results

Sample	Maximum force (KN)	Final rotation (rad)	Panel zone rotation (rad)
1	200	0.05	0.0025
2	185	0.04	0.0078

STRAIN UNIFORMITY IN THE FLANGE WIDTH (STRAIN GAUGE)

Evaluation of uniform distribution in the width of beam flanges in experimental samples was carried out by placing three strain gauges in a cross-section of the beam flange in one of the studied experimental samples. The location of these three strain gauges is on the width of the flange in front of the vertical stiffeners. Figure 20 demonstrates the location of the strain gauges.

It is considered that based on Hook's law, the elastic range of stress and strain have a direct relation with each other. Therefore, strain gauge values in the elastic range are considered acceptable. Strain gauge values in the elastic range are depicted in Figure 21.

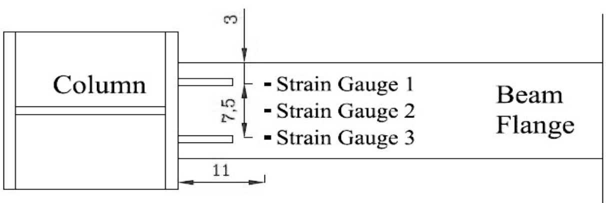


Fig. 20. Strain gauge figure (sample 1)

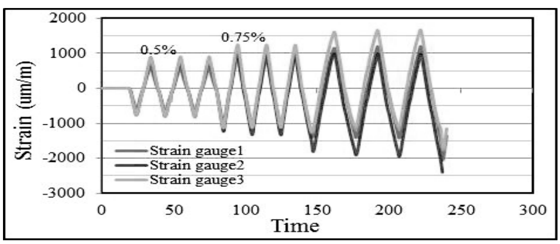


Fig. 21. Strain gauge results

According to the chart, strain distribution in the elastic range is identical on the flanges for all three strain gauges. This indicates uniform stress distribution on the flange width. Entrance of the strain gauges to the nonlinear started by the strain gauge no. two followed by strain gauges number one and three.

CONCLUSION

1. Utilizing vertical stiffeners on beam flanges in slotted web connections is considered necessary due to their special nature, to prevent early buckling of beam flanges and to improve connection resistance and ductility.
2. Slotted web connection on semi-wide cross-sections with rotation endurance of more than 0.04 rad provide suitable ductility, and is considered as a special moment connection according to AISC regulations.
3. Sample with more dissipated energy in panel zone endures 0.01 rad less rotation, and an 8% decline has been observed in connection resistance. Existence of a weaker panel zone increase relative to structural displacement and increase the Pi Delta effect.
4. Creating a slot in beam web eliminates shear force in beam flanges, and produces uniform distribution of strain in beam flanges weld.
5. Independent buckling of flange and web in this connection eliminates the lateral torsional buckling phenomenon.

REFERENCES

Richard, R.M., Allen, C.J., & Partridge, C.E., 1997a, “Proprietary Slotted Beam Conections Designs”, Journal of modern Steel Construction.

Richard, R.M., Allen, C.J., and Partridge, C.E., 1997b, “Steel Frame Stress Reduction Connection”, United State Patent Application Publication.

EL-Tawil, Sh., Mikesell, T., Vidarsson, E., & Kunnath, S. K., 1998, “Strength and Ductility of FR Welded-Bolted Connections”, SAC Steel Project. Report. SAC/BD98/01.

ICC Evaluation Service, INC, 2002, “Slotted Web Beam-To-Column Steel Moment Frame Connection”, Division: 05-Metals, Section: 05120-Structural Steel, California.

Federal Emergency Management Agency (FEMA), 2000, “Seismic Design Criteria for Steel Moment-Frame Structures”, FEMA 350 and 355D.

American Institute of Steel Construction, INC., 2010, “Seismic Provisions for Structural Steel Buildings”, AISC/ANSI 341-10.

Department of Civil & Env. Engineering, Stanford University (SAC), 2000, “Development of Loading Histories For a Testing of Steel Beam-to-Column assemblies”. SAC Background Report SAC/BD-00/10.

ANSYS, User’s Manual, 1992, Theory, Swanson Analysis Systems, Inc, Vol. IV.

EL-Tawil, S., E. Vidarsson, T. Mikesell and S. K. Kunnath, 1999. "Inelastic Behavior And Design of Steel Panel Zones." Journal of Structural Engineering 125(2): 183-193.

Kim, T., A. Whittaker, A. Gilani, V. Bertero and S. Takhirov, 2002. "Cover-Plate and Flange-Plate Steel Moment-Resisting Connections." Journal of Structural Engineering 128(4): 474-482.

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