IMPROVEMENT OF KHORJINI CONNECTIONS

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ABSTRACT

The purposeof this researchis tostudy the behaviorof conventional and retrofittedKhorjini connections. Four plates, which were welded between the beams and column, added to the common details of the connection. Two, common and retrofitted, connections were tested under monotonic loading. The tested specimens were modeled by a finite element method, which verified with experimental results. Several models with different size of the connection components were investigated using the verified FEM. The results indicated that a main defect of the conventional connections is severe stiffness deterioration, while Initial stiffness in the improved connections is more than four times the common detailed connections and stiffness deterioration is not a case of concern. Moreover, a great proportion of beam moment in Khorjini connections are carried to the column through beam flange to angle welds. Also, high stress concentration occurs in the elastic phase of the critical weld in a short length of the weld, which yields to stain jump, when the connection fails. However, in the retrofitted connections, added plates transfer a great amount of the connection moment to the column, which yields to a considerable reduction in the maximum plastic strains and von mises stresses in the critical weld. Consequently Retrofitted connections never fails, until beams reach to their ultimate plastic moments.

INTRODUCTION

A special type of steel connections, which has been used for beam-to-column connections in Iranian buildings through past decades is Khorjini connection. In this system, two beams are passed next to the column continously and are connected to the column sides using two angles in the top and bottom of each beam. However the connection is used extensively because of its simplicity and economic advantages, but its performance in the recent severe earthquakes in Iran proved its vulnerability against seismic loads. Following numerous damages in the buildings with Khorjini frames, many attempts were made to investigate and improve the connection behavior. Arbabi (1998), investigated stiffness of the connection.Moghaddam and Alaei (2003) and Mostafaei and Mazroi (2004), experimentally studied the ultimate strength and rotation of the connection. AmiriHormozaki (2012) and Moghaddam and Pirayehgar (2009) surveyed cracking pattern in the connection welds. Specifying weaknesses of the connection, researchers proposed various methods to improve the connection behavior. Karami (1991), tested five improved connections with different details. Mirghaderi and DehghaniRenani (2008), utilizing continuous vertical plates instead of the connection angles, created a ductile rigid connection. Bolted Khorjini connections were tested by Mirghaderi et al. (2007), which indicated its ductility in the moment resisting frames.
In this research program, two Khorjini connections were tested under monotonic loading, one with conventional detailing and another with the proposed details. The experimental results were used for verifying the nonlinear three-dimensional finite element models. The objective of this research is to study the application of the proposed detailing in retrofitting the existing connections.

EXPERIMENTAL PROGRAM AND FEM MODELING

The experimental program consisted of the testing of two exterior connections. The first sample was a conventional Khorjini connection, whereas in the second sample four plates which were placed between web of beams and edges of column flanges and welded to the column flanges' edges and beams flanges and web, were added to the common details, in order to improve connection behavior. Both of the samples consisted of 2INP160 as column and two sections of INP140 profile as beams. Seat angles were L100x100x10 profile, with 12 Cm length, while top angles length were 8 and 12 Cm for common and retrofitted connections, respectively. In order to avoid overhead welding, 5 Cm of the top angles flange, welded to the beams, were cut. Fig. 1 shows the specimens' details.

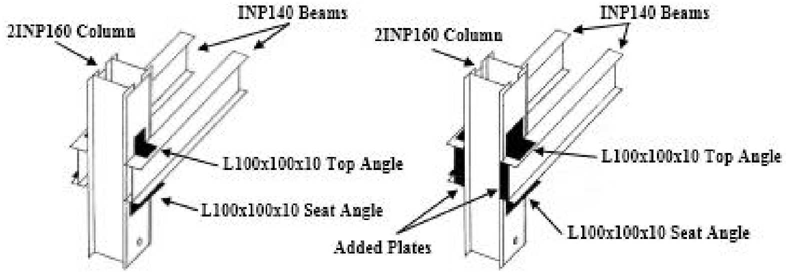

Figure 1. Details of the specimens

The specimens were tested under monotonic loading, as shown in Fig. 2. Vertical loads were applied at the end of the beams by a 300 KN jack. Connection rotation were calculated from the end displacement of the bars that were welded to each beam and column at the connection center.

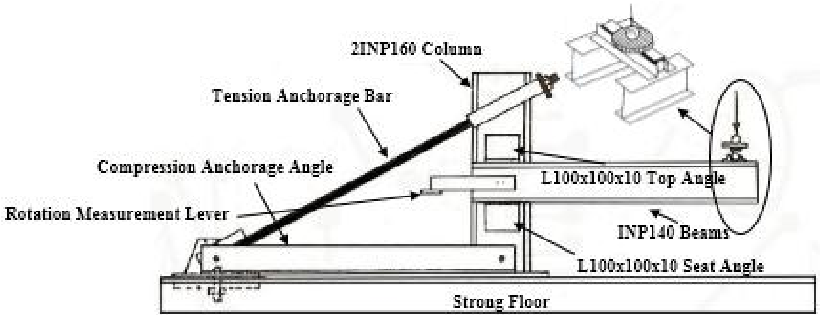

Figure 2. Test setup

Moment-rotation behavior of the specimens are presented in Fig. 3. Initial stiffness of the common detailed specimen was 1800 ton.m/rad and the specimen started to yield at 3.0 ton.m. However initial stiffness of the retrofitted connection was 3100 ton.m/rad and elastic range of the connection considerably increased to 6.5 ton.m. However, cracks occurred in the both angle to column and angle to beam welds, the first specimen failed by opening of the cracks in the angle to clumn welds at a moment of about 60% of the ultimate moment resistance of the connection beams. Since no torsional restraint were used, ultimate strength of the retrofitted connection reached by torsion of the beams at a moment of 75% of the ultimate moment resistance of the connection beams. No damage were seen in the retrofitted connection welds, which proves the added plates advantages in diminishing of high stress and strain concentration in the welds of the connection.

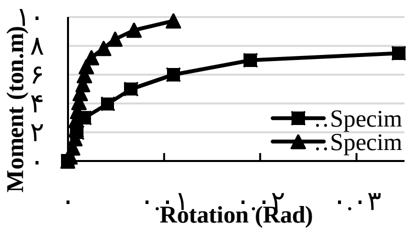

Figure 3. Moment-rotation response of the specimens

The tested specimens were simulated by utilizing ABAQUS 6.11 software. All of the details of the specimens, interactions, boundary conditions and materials were accurately modeled. To decrease the computational costs, half of the specimens were modeled by using the symmetrical situation at the center of the models. The simplified model was checked by a full three-dimensional model, and no significant difference was observed. Following a short parametric study appropriate mesh sizes were chosen for the beam and angles 8-node solid elements (C3D8R). Cracking in the weld material were considered by a Micromechanical method, Void Growth Method (VGM), which is based on the growth and joining of the voids in ductile metals (Kanvinde and Deierlein, 2004 and Chi et al., 2006 and D'Escata and Devaux, 1979). According to the method, 0.1 mm mesh sizes were used for connection welds. The models were analyzed in two steps, first gravity loads was applied and then the beam end was pushed vertically. A Ductile Damage model in ABAQUS 6.11 was used to simulate the behavior of weld material. This model is a phenomenological model for predicting the onset of damage due to nucleation, growth and coalescence of voids and assumes that the equivalent plastic strain at the onset of damage is a function of stress triaxiality and strain rate.

The finite element models of both specimens were verified with experimental results. Moment-rotation behavior of the tests and FEM analysis are demonstrated in Fig. 4. It shows that the FEM results of the models are close to the test results and the initial stiffness of the models and test results are in a good agreement.

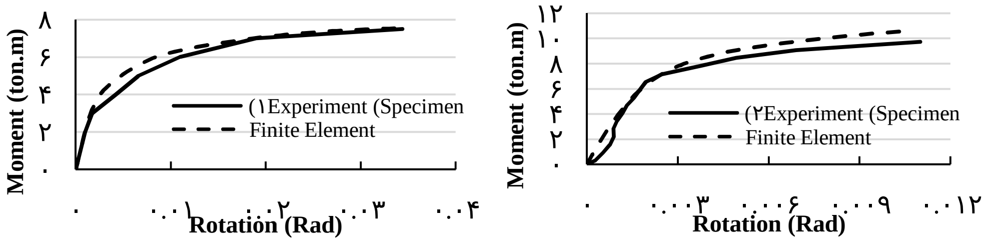

Figure 4. Test and FEM moment-rotation response

CASE STUDY

Various details of common Khorjini connections were simulated using the verified models. In any case, four plates with a thickness of 1 Cm were added to the common detailing, at the edge of the seat angle, to improve the connection behavior. Details of the models have been shown in Table 1.

Table 1. Details of the modeled connections

FEM Models		Beam	Top Angle		Seat Angle	
Common Detailed	Retrofitted		Profile	Length (Cm)	Profile	Length (Cm)
A2	A2-ws	IPE180	L80x80x8	15	L100x100x10	15
A3	A3-ws	IPE180		20		20
A4	A4-ws	IPE180		10		20
A5	A5-ws	IPE180		15		20
A6	A6-ws	IPE160	L60x60x6	15		15
A7	A7-ws	IPE160		20		20
A8	A8-ws	IPE160		10		20
A9	A9-ws	IPE160		15		20
A10	A10-ws	IPE220	L100x100x10	15	L120x120x12	15
A11	A11-ws	IPE220		20		20
A12	A12-ws	IPE220		10		20
A13	A13-ws	IPE220		15		20

The behavior of the retrofitted connections could be influenced by the characteristics of the added plates. Therefore, thickness and distance of the plates were considered in certain models, which has been shown in Table 2.

Table 2. Improved connections by different characteristics of the added plates

FEM Model	Plates Distance (Cm)	FEM Model	Plates Distance (Cm)	FEM Model	Plates thickness (Cm)
A6-10ws	10	A10-10ws	10	A7-0.5ws	0.5
A6-20ws	20	A10-20ws	20	A7-1.5ws	1.5
A6-25ws	25	A10-25ws	25	A7-2.0ws	2.0
A8-10ws	10	A12-10ws	10	A11-0.5ws	0.5
A8-15ws	15	A12-15ws	15	A11-1.5ws	1.5
A8-25ws	25	A12-25ws	25	A11-2.0ws	2.0

MOMENT TRANSFER MECHANISM

In common details of Khorjini connections, moment is carried through shear and torsional mechanisms of the angles. While, as demonstrated in Fig. 5, the added plates which are directly welded to the column, could participate in the moment transfer of improved connections. The connection moment could be written as Eq. (1), where α, β and γ are the ratio of the beam moment that are transferred to column by shear and torsional mechanisms of the angles and the added plates, respectively. Furthermore, *d* is the distance of the added plates and L' is the distance of F_2 reactions.

$$M = \sum_{i=1}^{3} M_i , \begin{cases} M_1 = \sim M = F_1.h \\ M_2 = \quad M = F_2.L' \\ M_3 = ¥ M = F_3.d \end{cases} \tag{1}$$

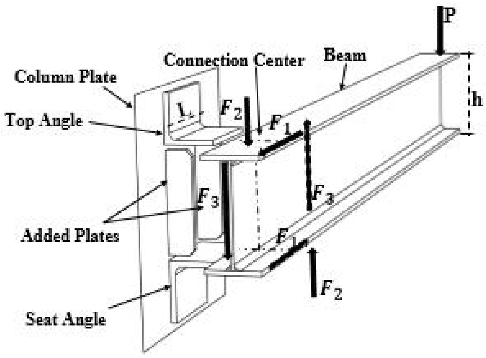

Figure 5. Free body diagram of the beam in the retrofitted connection

As shown in Fig. 6, a great portion of the moment in common Khorjini connections are carried through shear mechanism (86 percent averagely), which causes high stress triaxiality in the vertical welds of the angles to column. However, in the connections improved by welded plates at the edge of the seat angle, up to 66 percent of the connection moment are transferred by added plates and α never exceeds 40 percent.

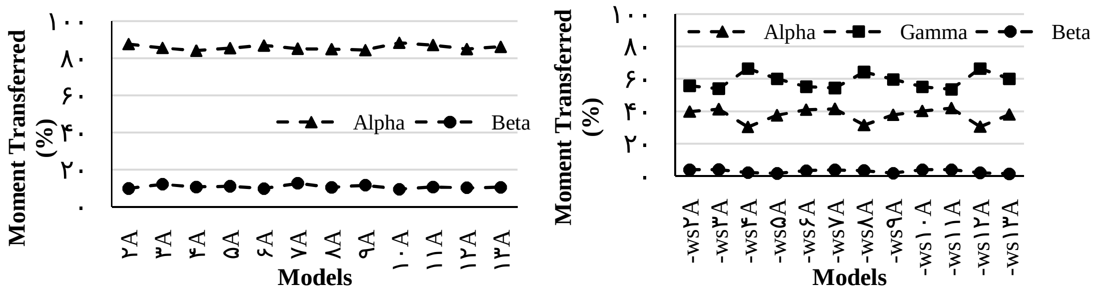

Figure 6. Moment transfer mechanism in the conventional and improved connections

Distance of the plates is a vital parameter in the moment distribution. As illustrated in Fig. 7, by increasing the distance from 10 to 25 Cm, angles portion (α+β) falls from 50 percent to less than 30 percent, while the plates portion (γ) increases from 50 percent to more than 70 percent. Although the thickness of the plates is an effective parameter in the moment distribution, but it is not as magnificent as the distance.

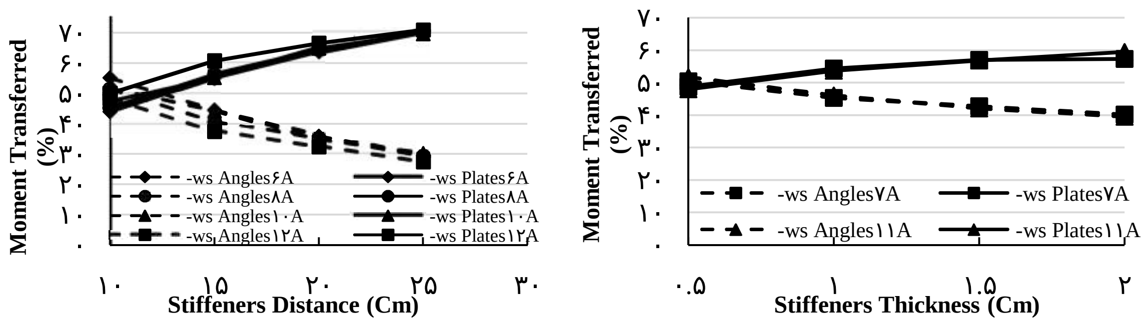

Figure 7. Effect of the added plates properties in the moment distribution

INITIAL STIFFNESS

The added plates influence on initial stiffness and rigidity of the analyzed connections is demonstrated in Fig. 8. Initial stiffness of the retrofitted connections is about four to six times the corresponding common ones. Connections rigidity are calculated based on the Beam Line Method for a 4.0 m length beam. Rigidity less than 90 percent, through with high stiffness deterioration which were observed in the analytical results, indicates semi-rigid behavior of the common connections. But improved connections rigidity never goes less than 90 percent and the connections maintain their stiffness until beams fail, which proves rigid behavior of the connections. According to the results, as beam height increases, more distance is needed for the plates to have a rigid connection.

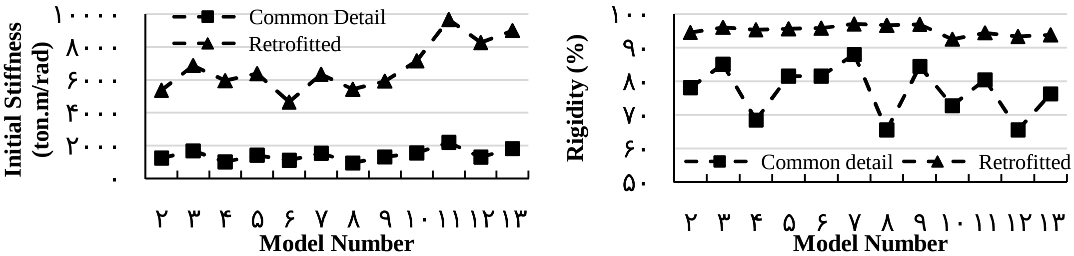

Figure 8. Initial stiffness and rigidity comparison

Analytical results showed that the horizontal displacement of the connection angles could be related to the measured rotation of the connection by ª coefficient, $(¢_{top} + ¢_{bot})/h = ª¯$, where $¢_{top}$ and $¢_{bot}$ are horizontal displacements of the top and bottom angles and h is the beam height. Also horizontal displacement of an angle, loaded by F_1, at its edge, has given by Eq. (2), where (b/l), t and E are width to length ratio and thickness of the angle's flange and steel modulus of elasticity, respectively and C is a constant.

$$¢ = C.F_1 (b/l)^a / Et^b \tag{2}$$

Since the connection stiffness is defined by $M/¯$, using equations (1) and (2), a general equation could be reached. Consequently, nonlinear regression of the analytical results, leads to Eq. (3) and Eq. (4), for the initial stiffness of the common and retrofitted connections, respectively:

$$K = 0.197Eh^2 \left(\frac{b_{beam}}{b_{top}}\right)^{0.573} \Bigg/ \left(\left(\left(\frac{b}{l}\right)^{1.192} \cdot \left(\frac{1}{t}\right) \right)_{top} + \left(\left(\frac{b}{l}\right)^{1.430} \cdot \left(\frac{1}{t}\right) \right)_{bot} \right) \tag{3}$$

$$K = 0.208\Psi Eh^2 \left(\frac{b_{beam}}{b_{top}}\right)^{0.253} \Bigg/ \left(\left(\left(\frac{b}{l}\right)^{0.661} \cdot \left(\frac{1}{t}\right)^{0.467} \right)_{top} + \left(\left(\frac{b}{l}\right)^{1.101} \cdot \left(\frac{1}{t}\right)^{0.747} \right)_{bot} \right) \tag{4}$$

b_{beam} and b_{top} are beam flange and top angle flange dimensions and indexes *top* and *bot* stand for the top and bottom angles and all parameters are in SI. Also Ψ accounts for the added plates characteristics and according to the analyzed models it is proposed by Eq. (5), where T is the plate thickness and D is the ratio of the plates distance to the length of the seat angle.

$$\Psi = 0.992(T^{0.249} D^{0.455}) / h^{0.019} \tag{5}$$

CRACKING STRENGTH

Experimental and Analytical results indicated that in the common detailed connections, critical weld, vertical weld of the top angle to column, at the face of the beam flange is the failure spot of the connections. As illustrated in Fig. 9, the connections always fail before beam and cracking moments range from 0.35 to 0.9 times the beam plastic moment. However cracking moment is in a regular relation with the connection features, but cracking rotation is a complex quantity and could not be easily predicted. Unlike the conventional, retrofitted connections never fail, if the plates be placed in the right position. The distance of the plates have a great influence in the cracking behavior of the connections and plates should be placed in a distance more than the length of the seat angle. Regarding this criterion, beams always reach their plastic strength, before the failure of the connection welds.

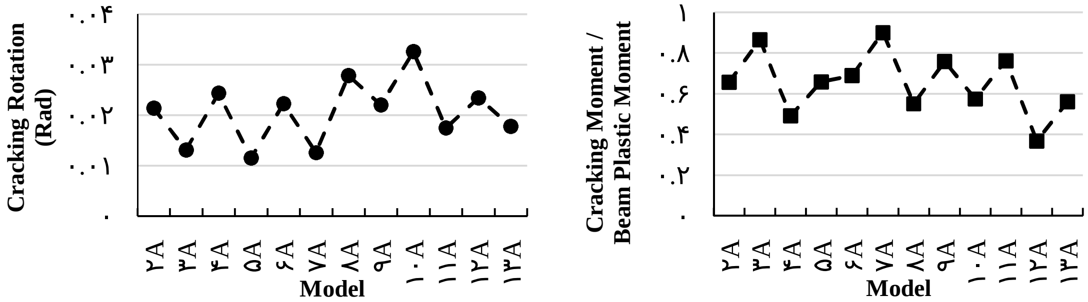

Figure 9. Cracking rotation and moment of the common detailed connections

STRESS AND STRAIN IN THE CRITICAL WELD

Stress distributions in the critical weld are compared in Fig. 10, for one of the analyzed models, where *Fyw* stands for the weld yield stress. Analysis showed the same distribution, with different magnitudes, for other models. Also, maximum von mises stresses in the critical welds are compared for all of the common and retrofitted connections in Table 3. It is observed that for the common detailed connections, in the beginning of loading stresses are concentrated in a limited length of the weld. But at the moment of rupture, stresses are more uniformly distributed, which yield to a great reduction in stress concentration and the weld fails at a critical stress of about 1.6 times the weld yield stress. However, the added plates have a remarkable effect in diminishing stress concentration. In the best case, the critical weld maximum stress, in elastic phase, decreases to 36 percent of the corresponding connection without plates. However, as beam height increases, the influence of the plates in reduction of the maximum stresses slightly decreases, but the weld maximum stress, at the failure load of the corresponding non-retrofitted connection, in many cases, never goes beyond 1.2 times the weld yield stress.

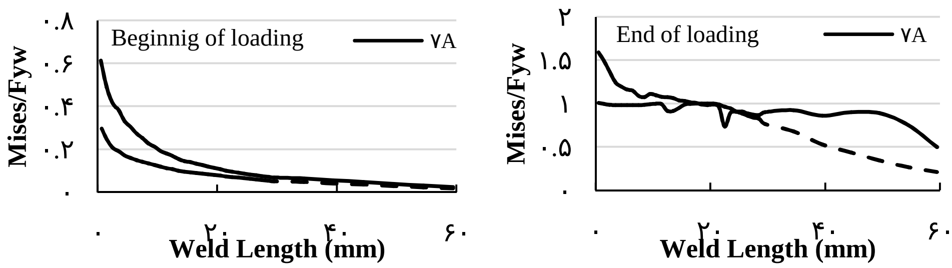

Figure 10. Comparison of von mises Stresses distribution in the critical weld

Table 3. Maximum von mises stresses in the critical welds as a ratio of the weld yield stress

Model Number	Beginning of Loading (Elastic Behavior of the Weld Material)			End of Loading (Failure Displacement of the Common Detailed Connection)	
	Displacement Applied (mm)	Common Detailed	Retrofitted	Common Detailed	Retrofitted
2	2.6	1.00	0.98	1.60	1.34
3	2.6	1.00	0.79	1.53	1.03
4	2.6	0.98	0.95	1.65	1.50
5	2.6	0.99	0.85	1.56	1.14
6	2.0	0.99	0.67	1.58	1.14
7	1.5	0.61	0.31	1.59	1.01
8	1.5	1.00	0.36	1.60	1.18
9	1.5	0.81	0.30	1.59	1.04
10	1.5	0.90	0.72	1.61	1.59
11	1.5	0.85	0.67	1.56	1.28
12	1.5	0.99	0.67	1.55	1.49
13	0.75	0.51	0.31	1.57	1.44

Following high stress concentration at the beginning of loading, strain jump at the end of loading causes failure of the conventional connections, which is shown in Fig. 11 for two of the FEM models. At the first 5 mm of the weld length, above the beam flange, plastic strain severely increases and strain jump occurs, while added plates reduce strain jump considerably.

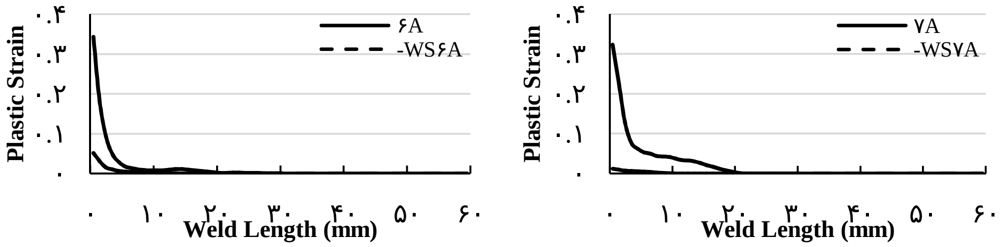

Figure 11. Comparison ofplastic strains distribution in the critical weld

The critical welds maximum Plastic strains are compared in retrofitted and common detailed connections, at the failure load of the common detailed connections and maximum plastic strain of each connection has been shown in Table 4. Results show that, the added plates reduce the maximum plastic strains up to 96 percent and in some cases the plastic strain of the critical weld approaches to zero. However the advantages of the retrofitting decrease slightly with increasing the beam height, but its effects are always remarkable in preventing from strain jump.

Table 4. Comparison of the maximum plastic strains in the critical welds

Model Number	Failure Displacement of the Common Detailed Connection		Model Number	Failure Displacement of the Common Detailed Connection	
	Common Detail	Retrofitted		Common Detail	Retrofitted
2	0.378	0.110	8	0.372	0.058
3	0.235	0.026	9	0.357	0.028
4	0.447	0.193	10	0.501	0.474
5	0.278	0.047	11	0.334	0.088
6	0.343	0.051	12	0.329	0.222
7	0.324	0.012	13	0.332	0.163

CONCLUSIONS

In this investigation, two exterior Khorjini connections were tested under monotonic loading. First specimen was a conventional Khorjini connection, while in the second specimen, four plates, welded to the column flanges' edges and beam flanges and web, were added to the common details of the connection to improve its performance. Verifying the FEM models, conventional and retrofitted connections with different details simulated and the following conclusions were observed:

- Experimental results showed that, conventional Khorjini connections failure occurs with rupture of the connection weld, while the added plates could effectively prevent from that and increase the improved connection strength considerably.
- Added plates substantially decrease torsional mechanism proportion in the moment transfer. In the common detailed connections averagely 86% of the beam moment are transferred by the torsional mechanism, while in the improved connections, this portion could reduce to less than 30% and more than 70% could be transferred by added plates.
- Initial stiffness of the improved connections increases more than four times, while stiffness deterioration decreases and connection rigidity goes beyond 90%. As a result semi-rigid behavior of the common Khorjini connections, changes to rigid. Also appropriate relations, according to the connection features, are proposed for initial stiffness of common and retrofitted Khorjini connections.
- High strain jump in the critical weld, which is a result of high stress concentration in low displacements, causes failure of the conventional connections at a moment of about 0.35 to 0.9 times the beam plastic moment. However, added plates have a great influence in balancing the stresses and plastic strains in the critical weld. High stress concentration in the critical weld considerably decreases and strain jump diminishes and in many cases approaches to zero.

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