NONLINEAR BEHAVIOR OF RC FRAMES STRENGTHENED WITH STEEL GUSSET PLATES AND CURBS

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ABSTRACT

One of the severe deficiencies in RC frame structures making it vulnerable against earthquakes isthe inadequate shear resistance of beam-column joints and low stiffness of frames. To improve the seismic performance of the structure, improving the performance of its joints is essential. A steel curb and gusset plate system is introduced at the beam–column connections to protect the joint panel zone from extensive damage and brittle shear mechanisms, while inverting the hierarchy of strength and stiffness within the beam-column subassemblies and forming a plastic hinge in the beam.

In this paper, the RC frames which were strengthened using this proposed method are investigated under monotonic lateral force using the numerical modelling. After verifying the models, local and global behavior of these frames, such as displacement, strength and ductility factor were studied. Analytical results show that maximum and ultimate lateral force of the strengthened frames has grown up to two times of the ordinary frame, averagely. According to the results, when the number of gusset plate increases, the strenght and stiffness of frames will increase remarkbaly but the ductility factor of frames will decrease relatively. The analytical results also demonstrated the effectiveness of the proposed solution for upgrading of RC frames andthe displacing ofplastic hinges to far from the beam-column joint.

INTRODUCTION

At recent decades, numerous earthquakes have caused severe damage or have led to collapse of old structures. Many existing reinforced concrete (RC) frame buildings were designed and constructed under the old seismic codes and regulations as those details are often not enough for proper seismic behavior, particularly in the beam–column connections,and or the lateral and horizontal displacement of them are not in safe rang.Therefore, these deficient frames often do not the capacity to resist under earthquakes and need to be strengthened. For this purpose, different approaches have been proposed by researchers.

Atfew recent years, adding steel braces to concrete moment resisting frames (MRFs),jacketing with thin plainconcrete or high performance fiber reinforced cementitious composites HPFRCC, flat and corrugated steel plate jacketing, attachment of steel plates, using of FRP composite materialas externally bonded sheets,have used for local and general retrofitting of deficient RC frames. Each of the preceding methods can be used for upgrading and improvingof linear and nonlinear behavior of RC frames such as rigidity, ultimate strength and ductility. Also many researchershave investigated these mentioned methods for upgrading ofbehavior of the deficient RCbeam-column connection experimentally and numerically.

Pimanmas and Chaimahawan(2010)suggested a rehabilitation technique called ‘‘planar joint expansion’’ by expanding the shear area of the joint through the use of on-site cast reinforced concrete. Applying the on-site cast concrete below the beam and application of chemical anchorage are the main restrictions of this technique, which was found to be effective at reducing joint shear stress and improving the bond between the longitudinal beam reinforcement and concrete in the joint region.Shafaeiet al.(2014)studied practical seismic retrofit method named‘‘joint enlargement using prestressed steel angles’’,based on a two-dimensional enlargement of non-seismically detailed external beam–column joints of existing RC structures using steel angles that were mounted using prestressed cross-ties. In this method, the beam–column joint is enlarged by locating stiffened steel angles at the re-entrants corners of the beam-column joint, both above and below the beam, with the steel angles mounted and held in place using high tensile strength bars.

The diagonal metallic haunches aretechniqueswhich are installed locally at the beam–column connection to protect the panel zone and to force a more desirable hierarchy of strength.Several researchers have been investigated thistechnique for rehabilitation of non-ductile beam-column connections of the RC framesat various schemes,experimentally and numerically. Said and Nehdi(2008) proposed this technique as local steel brace members and concludedthat this rehabilitation technique was successful in enhancing the overall performance of the deficient joint and upgrading it towards a close to current standard performance.Pampanin et al. (2006)used the hinged and welded metallic haunches experimentally as seismic retrofit solution (HRS) for existing under-designed RC frame buildings.Those retrofitted specimens displayed asubstantially enhanced response when compared to the non-retrofitted specimens: damage to the joint was eliminated and a flexural plastic hinge formed in the beam at the location of the beam–haunch connection. Those experimental results demonstrated the effectiveness of the proposed solution for upgrading non-seismically designed RC frames. In the design model presented in Pampanin et al.(2006) the stiffness of the connection and the slip between the metallic diagonal plays a central rolein the efficiency of this retrofit solution (Eligehausenet al., 2009). In work of Eligehausenet al. (2009) numerical analyses well agree with the experimental results confirming the reliability of the design approach and the experimental observations.Sharbatdar et al.(2012) used this idea with other schemes that was called"steel prop and curb". They retrofitted the damaged weak exterior RC beam-column connection using this techniqueexperimentally. The main idea of this technique was use of the stiff membersas steel props which acted as a resistant arm and the steel curbs for confiningof the reinforced concrete beam and column. So this diagonal system decreases the forces and damages in damaged panel zone consequently.Emami et al.(2015) and Khalili et al.(2014) made numerical work on abilities of the steel props and curbs method at strengthening of RC frame and investigated the global behaviour of the strengthened frames by this method.Sharma (2013) and Sharma et al.(2013) were carried out experiments to evaluate the performance of so called fully fastened haunch retrofit solution (FFHRS), where the haunch elements were connected to the frame members by using post-installed mechanical anchors. They said FFHRS is clearly sensitive to the performance of anchors used to connect the haunch element to frame members.

In this paper, the steel gusset plates and curbs system for the strengthening of RC frames is suggested and the capability using of this method at developing behaviour of a RC frames is investigated. The steel curbs are erected at top end of the columns and at both end of beams and every gusset plates are located between the curbs of beam and columns. At this research the impact of number gusset plates at every side of connection on nonlinear behaviour of RC framesare studied.

SIMULATION AND VERIFICATION

Two main concrete failure mechanisms are cracking under tension and crushing under compression. For simulations of concrete in ABAQUS, according to its brittle behavior, Concrete Damage Plasticity (CDP) model was used (SIMULIA, 2010). In concrete, according to the modifications, the failure surface in the deviator cross section needs not to be a circle and it is governed by parameter K_c. It is highly recommended to assume $K_c = 2/3$.

The shapes of the plane's meridians change in the stress space. This shape is adjusted through eccentricity (plastic potential eccentricity). Parameter eccentricity (ϵ) can be calculated as a ratio of tensile strength to compressive strength (Jankowiak et al., 2005). The CDP model recommends to assume $\epsilon = 0.1$. σ_{b0}/σ_{c0} (f_{b0}/f_{c0}) is the ratio of the strength in the biaxial state to the strength in the uniaxial state. The ABAQUS user’s manual specifies default f_{b0}/f_{c0}=1.16. Another parameter characterizing the performance of concrete under compound stress is dilation angleΨ, i.e. the angle of inclination of the failure surface towards the hydrostatic axis, measured in the meridionalplane. The other parameters describing performance of concrete are determined for uniaxial stress. Table 1 shows the model's parameters characterizing its performance under compound stress.

Table 1. Suggested parameters of CDP model under compound stress

Viscosity parameter	k_c	Eccentricity (ϵ)	Ψ	f_{b0}/f_{c0}
0.0024	0.6667	0.1	36	1.16

For modeling of concrete 20-node solid element, C3D20R has been used which is a cubic element with 20 nodes. Each node has 6 degrees of freedom; 3 translational and 3 rotational degrees of freedom. For modeling of reinforcements, Truss elements, T3D2 were used. Another material used and modeled in this study is steel. For definition of plastic properties of steel, bilinear stress-strain curve has been used. Defined material has kinematic hardening properties. Also for modeling steel crub and prop and external steel sheets, 8-node Shell element, S8R5 was used.

For verifying performance of elements and behavior of models in program (ABAQUS, 2010), an ordinary RC frame which has been tested under monotonic lateral loading in structural lab of Semnan University, by Hemati(2012) were used.Details of this one bay frame are shown in Fig. 1.

Properties of concrete and steel (reinforcement) used in this frame are presented in Table 2 and Table 3, respectively.

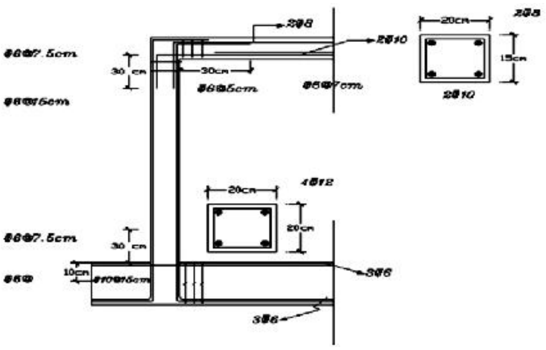

Figure 1. Details of the experimental frame tested by Hemati (2012)

Table 2. Concrete properties used in simulations based on experimental model of Hemati (2012)

Poisson's Ratio (υ)	E_c (MPa)	f_c' (MPa)
0.2	30000	34.49

Table 3. Reinforcement properties used in simulations based on experimental model of Hemati (2012)

Poisson's Ratio (υ)	E_s^t (MPa)	E_s (MPa)	ε_y	ε_u	f_y (MPa)
0.3	6200	200000	0.002	0.15	400

Yield stress for steel curbs and gusset plates, used in this study has been assumed to 300 MPa and their modulus of elasticity 200×10^3MPa. Different mesh sizes were used for calibration of the frame and ultimately, 60×60 mm^2 mesh sizes were chosen (for concrete) because of the accuracy of results. Force-displacement diagram of the experimental and finite element (numerical) models of ordinary RC framesare presented in Fig. 2.Ultimate displacement of verified numerical model, were applied as the same ultimate displacement of experimental model which was 65.61 mm.

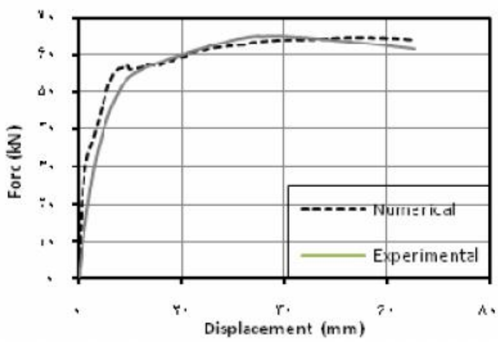

Figure 2. Verification of numerical FE model of ordinary RC frame

Observing the situation of experimental and numerical frame at ultimate displacement, location of cracks and plastic hinges can be investigated. As Fig.3 location of plastic hinges and maximum strains and tensile damage in numerical model can be observed which have a good coincidence with results of experimental model (Fig.4).Directions of cracks are shown with black lines.

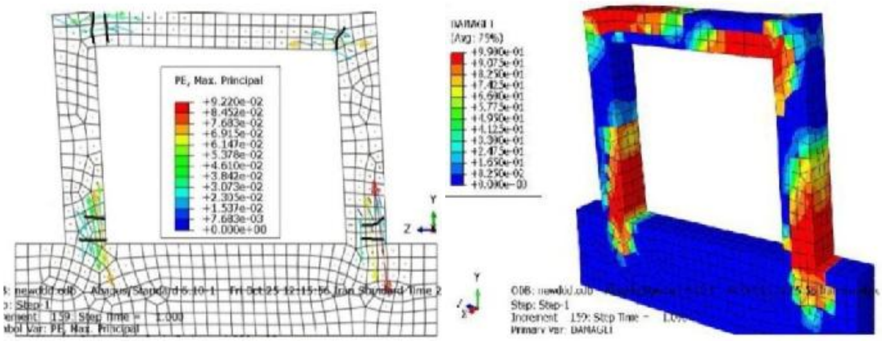

Figure 3. Location of cracks, maximum plastic strains and tensile damage in numerical model

Figure 4.Location of cracks and tensile cracks pattern in experimental model by Hemati (2012)

MODELING AND RESULTS

Fig.5 indicates the proposed strengthening method of frame with steel gusset plate and curbs.For investigating effects of steel gusset plates and curbs on RC frames, threeverified frames were modelled and strengthened by singular, triplet and quintuplet of steel gusset plates at every side of beam-column connections and were then subjected to monotonic lateral loading at top of the frames separately.The dimensionsections of steel curbs weresimilar sections of beams and columns and with length of 200 mm and thickness equal to 5mm. Also the dimensionsections of isoscelestrianglesteel gusset plates were $200\times200\times5$ mm.

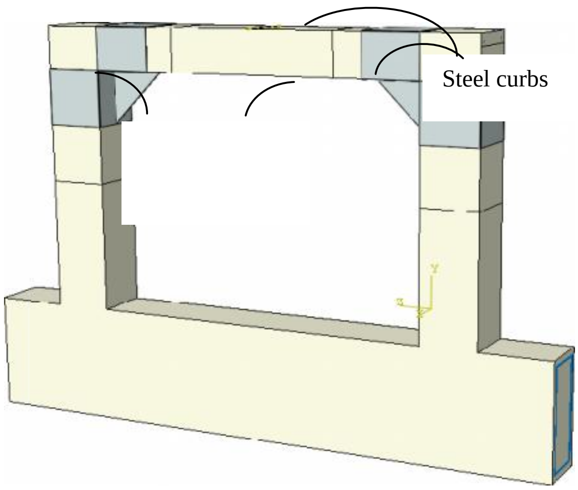

Figure 5.Proposedstrengthening method of frame used in this study

Fig 6.presents Force-Displacement diagrams verified FE models of ordinary RC frame(ORCF) and strengthened RC frames (SRCF)with singular, triplet and quintuplet steel gusset plates and curbs under monotonic lateral loading.The ultimate displacement of numerical modelofstrengthened RC frames were applied when the maximum force 15% decreased.

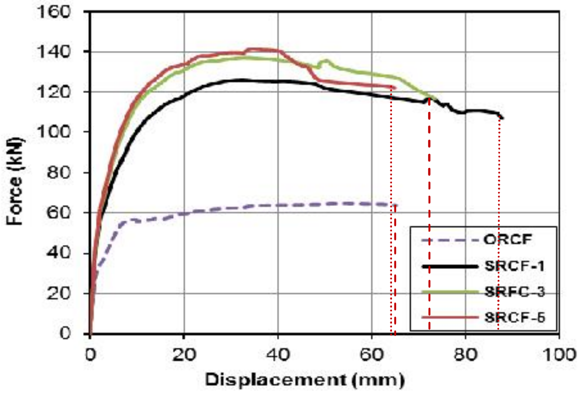

Figure 6. comparsion of Force-displacement diagrams of ordinary and SRCF frames

Maximum strength P_{max} and ultimate strength P_u(corresponding to the $0.85P_{max}$) of eachstrengthened RC frames and the increasing percentage related to ordinary RC frame were given at Table 4. This table and Fig. 7 indicate that load capacity in strengthened frames with gusset plate relative to ordinary frame two time increases averagely. By adding number of gusset plates to frames

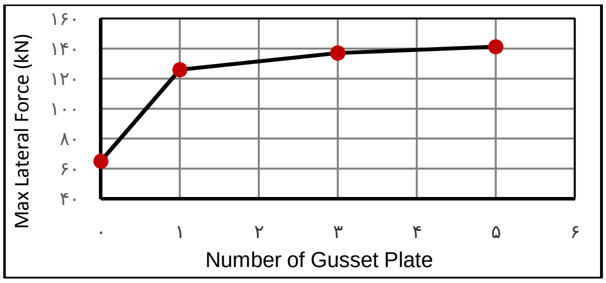

Figure7. Impact number of gusset plate on max lateral force of RC frames

Table 4. Maximum and ultimate strengths of frames

No	frame	P_{max}(kN)	P_u(kN)	increasing relative to ORCF (%)	
				P_{max}	P_u
1	ORCF	64.5	64.8	-	-
2	SRFC-1	126	107.1	95	65
3	SRCF-3	137	116.6	112	80
4	SRCF-5	144	122.2	123	89

and by stiffening of beam-column connection the load capacity (P_{max}andP_u) up to 14% increases but the ultimate displacement due to growing of the damages and consequently decline of the force decreases from 87.7 to 64.9 mm.Location of cracks and tensile cracks pattern in strenghtened frames are presented in Fig. 8. By comparison of figures 8 and 3,are deduced that the proposed strengthening method, steel curbs and gusset plates, can relocate the tensile cracks of beamfrom vicinity of beam-column joint to away of steel curbs and therefore the plastic hinges are formed far from beam-column joints.

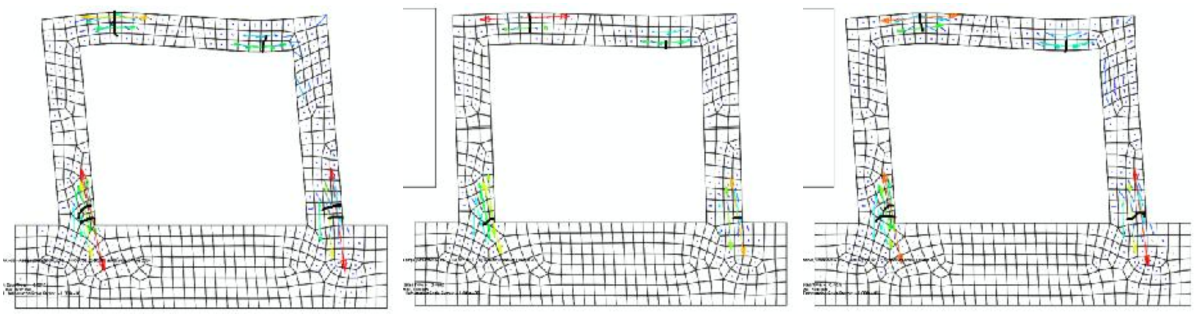
a) SRCF-1 b) SRCF-3 c) SRCF-5

Figure 8. Location of cracks and tensile cracks pattern in strenghtened frames

Fig. 9 indicate thatat ordinary frame, themaximum plastic strain tensileof concrete atRC beam occure adjacent of beam-column joint while at strenghtened frames wereadjacent of steel curbs that show the probability formation of the plastic hingeadjacent of beam-column jointis very low.

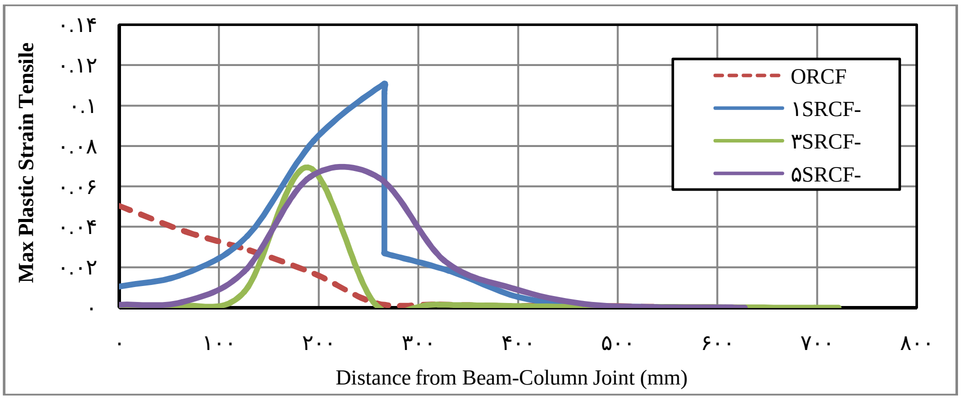

Figure 9. maximum plastic strain tensil of concreteatRC beam of frames

The ductility factor μ is obtained as the ratio between the ultimate displacement (Δ_u) and the yielding displacement (Δ_{yI}); $\mu_\Delta=\Delta_u/\Delta_{yI}$. Determination of such values in the response diagram depends on the used method. Based on the suggestion of Lam *et al.*(2003) in this method the idealization of the force-displacement diagrams is performed by an energy balancebetween the model diagrams and the ideal diagram up to ultimate load (Fig. 10), i.e. the area below the model curve is equal to the area below the ideal elastic-plastic curve. The effective yielding displacement is obtained (Δ_{yI}) by matching area A1 and A2.Idealized diagrams of the ordinary and strengthened frames are presented in Fig. 11.

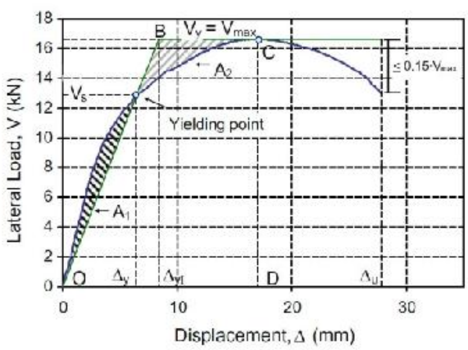

Figure.10Definition of ultimate and ideal yield displacement MBBE(Lam et al., 2003)

In all these diagrams, vertical axis expresses the lateral force, and horizontal axis expresses the lateral displacement of frames, Δ (mm).

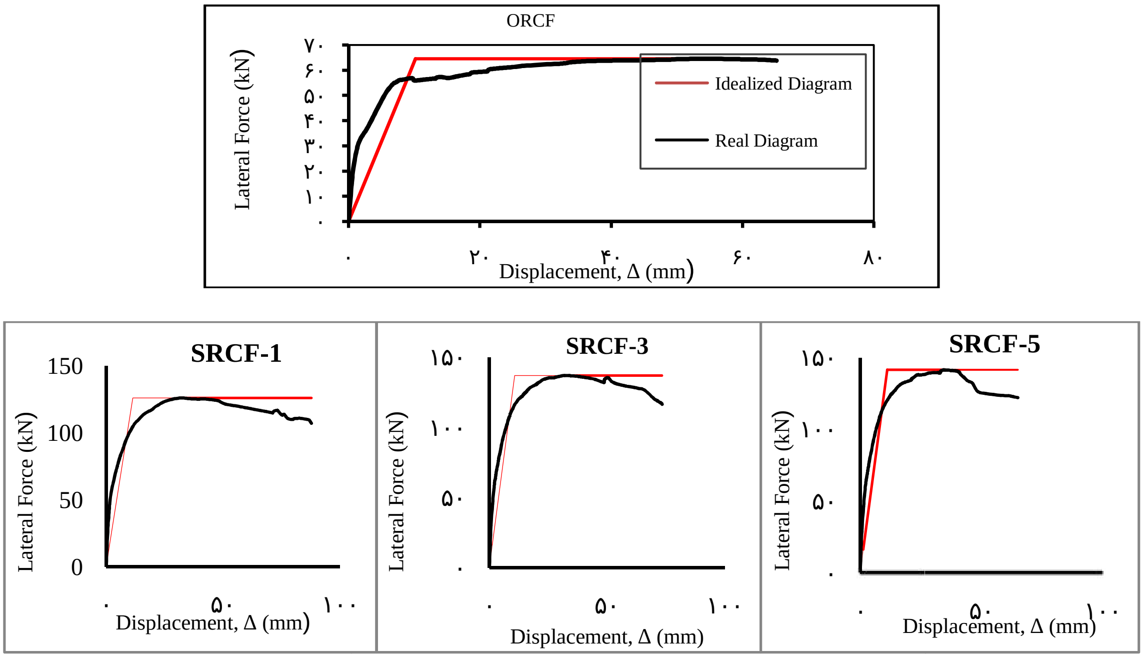

Figure. 11 Idealized diagrams of the ordinary and strengthened frames

Yield displacement (Δ_{yI}), ultimate displacement (Δ_u) and ductility factor (μ) for all frames are presented in Table 5.This table and Fig. 12 show that ductility factor at of the strengthened frames SRCF-1 and SRCF-3are7% and 21 more than ORCF respectivelybut in SRCF-5 about 11% decreases. Generally, according to obtained results the ductility factor at strengthened frames decreases by increasing number of gusset plate relatively.

Table 5. Ductility factor for the ordinary and strengthened frames

NO	Frame	Δ_{yI}	Δ_u	μ
1	ORCF	10.21	65.61	6.43
2	SRCF-1	11.30	87.70	7.76
3	SRCF-3	10.70	73.38	6.85
4	SRCF-5	11.09	64.93	5.85

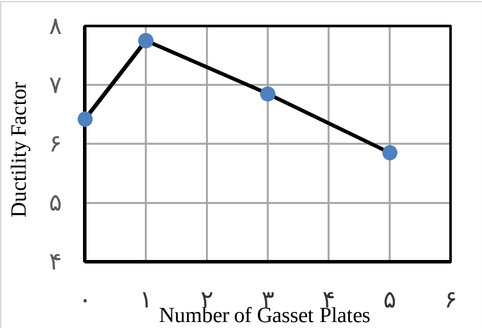

Figure.12Impact number of gusset plate on the ductility factor of RC frames

CONCLUSIONS

In present study by using the numerical method, the RC one bay frames were strengthened using proposed method of steel curb and gusset plates. The main results can be summarized as:

- This proposed strengthening method increased remarkably the strength, stiffness and ductility factor of frames but by adding five gusset plates decreased the ductility factor relatively.
- Maximum and ultimateStrength of the strengthened models using the steel curbs and with one, three and five gusset plates has grown up to 95, 112,123and 65, 80, 89 percentagemore than of the ordinary frame, respectively.
- In strengthened RC frames, when the number of gusset plates increased, the maximum and ultimatestrength of frames increasedup to 14% but the ultimate displacement due to growing of the damages and consequently decline of the force decreased from 87.7 to 64.9 mm.
- Ductility factor of the strengthened frames with one and threegusset platesup to 21 and7% increasedrelative to the ordinary frame, respectively.When the number of gusset plates increases, the ductility factor of frames decreasedrelatively.
- This proposed systemcould severely decrease the maximum plastic strain tensile of concrete adjacent of joint and relocated the damages and plastic hinges to vicinity of steel curb.

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