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An innovative experimental method to upgrade performance of external weak RC joints using fused steel prop plus sheets

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Abstract. In this paper, the efficiency and effectiveness of two strengthening methods for upgrading behavior of the two external weak reinforced concrete (RC) beam-column joints were experimentally investigated under cyclic loading. Since two deficient external RC joints with reduced beam height and low strength concrete were strengthened using one-way steel prop and curbs with and without steel revival sheets on the beam. The cyclic performance of these strengthened specimens were compared with two another control external RC beam-column joints, one the standard RC joint that had not two mentioned deficiencies and another had both. Therefore, four half-scale RC joints were tested under cyclic loading.The experimental results showed that these innovative strengthening methods (RC joint with revival sheet specially) surmounted the deficiencies of weak RC joints and upgraded their performance and bearing capacity, stiffness degradation, energy absorption, up to those of standard RC joint. Also, results exhibited that the prop at joint acted as a fuse element due to adding steel revival sheets on the RC beam and showed better behavior than that of the specimen without steel revival sheets. In other words by stiffening of beam, the prop collected all damages due to cyclic loading at itself and acted as the first line of defense and prevented from sever damages at RC joint.

Keywords: RC beam-column joints; strengthening; steel prop and curb; revival sheets; cyclic loading

1. Introduction

In a reinforced concrete moment resisting frame, joint plays a key role, because of its load transferring between beams and columns. Joints resist against applied external loads because of the bending moment encountered at the joint. In concrete structures, load paths are developed in the way loads pass through the beam–column joints and this allows the transfer of the externally applied loads to the basement of the structures (Hadi 2011). It is essential to strengthen the existing structures because of many reasons such as retrofitting of damaged structures under the earthquakes or the need for strengthening or retrofitting undamaged structures, designed based on the previous building codes, upgrading due to mistakes in the design or construction process (Sharbatdar *et al.* 2012a). Sometimes, long after the structure has been completed, it is cleared that

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the contractor has left out some steel or some details are inadequately executed, for example concrete is not the specified (Mahmoud *et al*. 2014). Existence beams with height less than required height is one of design or construction mistakes in RC frames, causing the reduction of bearing capacity and increasing vertical deflection of beams with increasing lateral deflection of those frames and height reduction of beams, reduces beam-column joint common area, shear weakness of panel zone and global infirmity of the structure in seismic loadings. Therefore, these joints of undamaged frames need to be strengthened (Sharbatdar *et al*. 2012a, b).

Several rehabilitation and strengthening methods for RC beam-column joints, including concrete jacketing, steel jacketing and fiber reinforced polymer (FRP) wrapping, etc., have been proposed (Li *et al*. 2013).

Different strengthening techniques in RC joints were introduced such as using concrete jacketing (by Hoffschild *et al*. 1995, Ghobarah *et al*. 1997, Tsonos 2001a, b, Karayannis *et al*. 2008 and Wang and Hsu 2009) and outer steel covers (by Adam *et al*. 2008, Yen and Chien 2010, Hadi 2011). Li *et al*. (2013) used ferrocement cover as jacket in strengthening of weak RC joints. Using concrete jacket and inclined stirrups (Tsonos 2010c, Li *et al*. 2013) and increasing the section area of beam and column and the area of panel zone (Pimanmas and Chaimahawan 2010, Shafaei *et al*. 2014) are some of the newer techniques. Using FRP sheets at different schemes is one of the other strengthening methods in RC concrete joints that have worked by researchers as Prota *et al*. (2001), Antonopoulos and Triantafillou (2003), Abdel-Wahed *et al*. (2005), Anania *et al*. (2005), Li *et al*. (2007), Byong and Ronald (2008), Karayannis and Sirkelis (2008), Amziane *et al*. (2010).

Also using fiber reinforced concrete (FRCC) and high performance fiber reinforced cementitious concrete (HPFRCC) in the panel zone and reducing reinforcement in this zone are some new techniques, were used to improve seismic behavior of RC joints (Shannag *et al*. 2005 and Shakya *et al*. 2012).

Diagonal metallic haunch as rehabilitation technique for beam-column joints was experimentally scrutinized by Pampanin *et al*. (2006). This technique was used to protect the joint panel zone from extensive damage and brittle shear mechanisms, while inverting the hierarchy of strength within the beam–column subassemblies and forming a plastic hinge in the beam far from panel zone. Those experimental results demonstrated the effectiveness of the proposed solution for upgrading non-seismically designed RC joints.

Authors of this paper (Sharbatdar *et al*. 2012a, b), studied the cyclic behavior of damaged RC beam-column joint that was retrofitted using steel prop and curb, experimentally. In pervious study, two half-scale RC joints with the different beam heights were casted and loaded up to their ultimate strength then were retrofitted using high rigidity steel prop and curb. Those results showed that the bear capacity, energy absorption and rigidity of the retrofitted joints relative to undamaged RC joint were increased remarkably. Also because of high rigidity of the props the cracks due to a new lateral loading in the damaged beam-column joint region were minimized and damages were relocated from panel zone to top of the curb of beam.

In this solution, the beam–column joint is stiffened by mounting of the steel curbs on RC column and beam in a span from the beam–column joint, and locating the steel prop between them. In installing process, at first the quartet steel curbs at a definite location are mounted on RC beam and column (rather at above of column and below of beam) member and held in place using high tensile strength bolts. Then the steel prop by locating between them, at above or below the beam story level, is connected to them by high tensile strength bolts. Installation of the steel curbs to RC column is relatively easy but for installation to RC beam only partial slab demolition required to

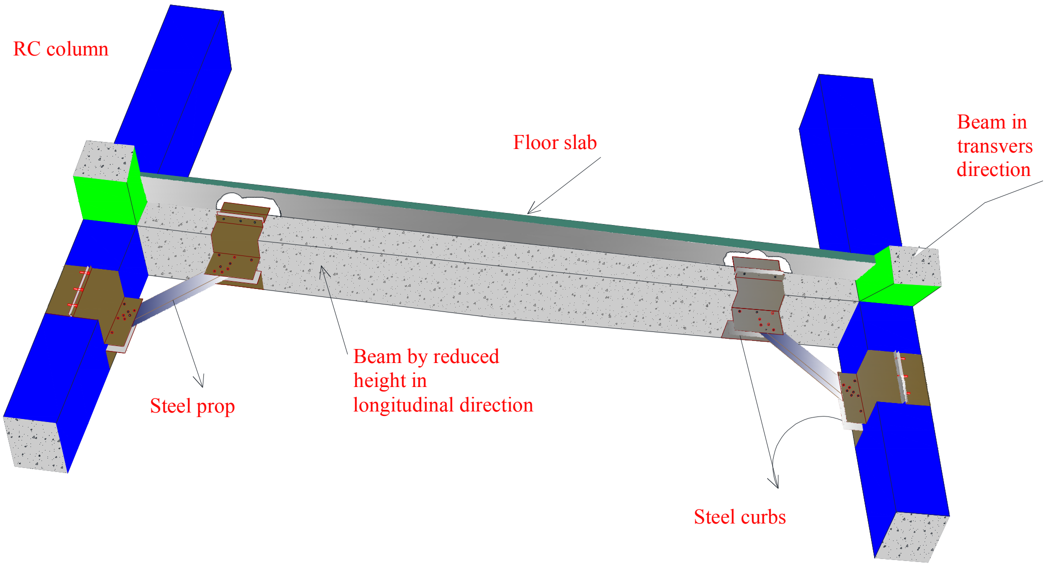


Fig. 1 3D view of suggested solution (one span of frame was shown)

pass it through the slab and tied together. This retrofit solution can be independently applied to 3D-frames in each perpendicular direction (see Fig. 1).

A numerical study were also conducted by Khalili *et al*. (2015) for evaluation influence of the using steel prop and curbs alone, in combination with beam's revival steel sheets and column steel jacketing, on nonlinear performance of the one span and one story RC frames. Those results showed that using of the revival sheet along of beam curbs, causes to more energy absorbed by steel props. In other hand, although by adding the beam revival sheets the ultimate strength of the RC frame don't increase remarkably, but the load carrying mechanism of the RC frame changes.

2. Research significant

In current study, it was supposed that during construction process of RC frame with original height of beam 40 cm, because of limitations in thickness of the roof the height of the beam has been reduced to 30 cm and also the used concrete in construction was been low strength. Therefore this weak RC frames needed to be strengthened. Then the effects of using low rigidity prop alone and in combination with steel revival sheets (two plates which are added to top and bottom of beam with pre-stressed bolts) on the weak RC joints (with reduced beam's height and low strength concrete), and interaction between them, have been investigated under cyclic loading. Increase of the bearing capacity of the weak RC joints was first purpose of these strengthening technique moreover reduction of beam's deflection under service loading. The second and main purpose of this method was that the props before the bar reinforcements of beam were yielded and dissipated the energy of cyclic loading and acted as the first line of defense, so that the RC joint itself acts as the second line of defense. In other words, the innovation of this study is that the prop element play as fuse in the joints and dissipates energy during of the earthquake by its yielding and finally ruptures.

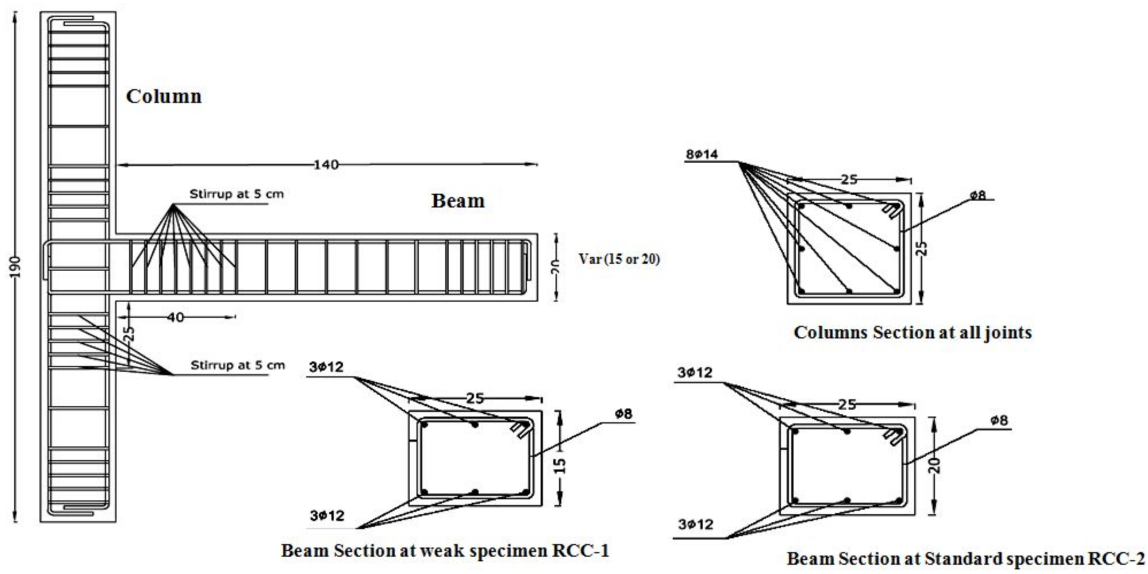


Fig. 2 Sections dimensions and bar arrangements of control specimens of RCC-1 & RCC-2 (in cm)

3. Experimental study

3.1 Details of specimens

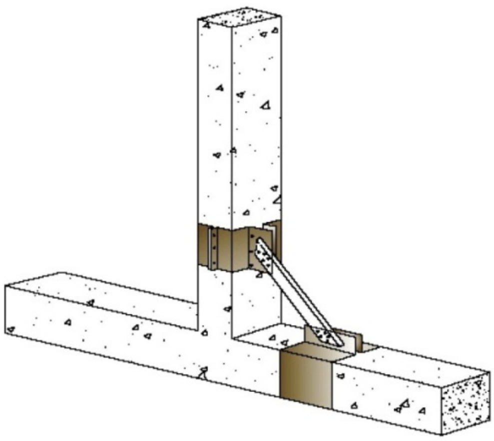
Generally, four half scale RC beam column joints were fabricated and casted. Details of the joints are shown in Fig. 2.

There were three joints with reduced-height beams (by half scale equal 15 cm) and low strength concrete (f'_c = 16 MPa). The first weak specimen was a control weak RC joint with 15 cm- height beam and low strength concrete, named as RCC-1. Two other weak RC joints with the same properties of RCC-1 (reduced-height beams and low strength concrete) were strengthened with two different methods; one was strengthened using one-way steel prop and curb and named as SRCC-1 and the other one was strengthened using one-way steel prop and curb plus two steel sheets on the upper and lower surface of the beam that was named as SRCC-2. The fourth specimen was a RC joint with standard height beam (by half scale equal 20 cm) and common strength concrete(f'_c = 29 MPa) that used as a standard control specimen and named as RCC-2. Columns section and reinforcements at all joints were same.

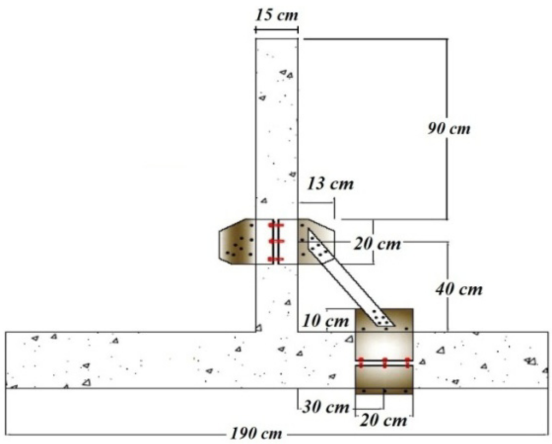
A summary characteristic of tested experimental specimens is presented in Table 1. SRCC-1 and SRCC-2 specimens, strengthened by using two curbs with 20 cm length and 0.5 cm thickness ad a steel prop with sectional area of 2 cm^2 (a box section with 3×2×0.2 cm dimensions). The steel curbs played the role of force transfer from the prop to the beam and column. The erection place of steel curbs center at the beam and the column were 40 cm and 30 cm from the side of beam-column joint. Steel prop were connected to the curbs with five bolts at each end of the prop. Moreover in the SRCC-2 specimen two steel sheets with 30 cm width and 0.5 cm thickness were placed on the upper and lower surface of the beam by six high strength thread bolts. Schematic views of SRCC-1 and SRCC-2 specimens and their dimensions are showed in Figs. 3-4, respectively.

Table 1 Summary characteristic of experimental RC joint specimens

Name	Specimen	Characteristics
RCC-1	Weak control	Weak joint (the beam height = 15 cm , and low strength concrete)
RCC-2	Standard control	Standard joint (the beam height = 20 cm, and medium strength concrete)
SRCC-1	Strengthened-only steel prop	Weak joint with weak beam (the beam height = 15 cm, and low strength concrete), strengthened with a steel prop with sectional area of 2 cm^2 (a box with 3×2×0.2 cm dimensions)
SRCC-2	Strengthened-steel prop and sheet	Weak joint with weak beam (the beam height = 15 cm, and low strength concrete), strengthened with a steel prop with sectional area of 2 cm^2 (a box with 3×2×0.2 cm dimensions) plus steel sheets on the upper and lower surface of the beam with dimensions of 90×30×0.5 cm.

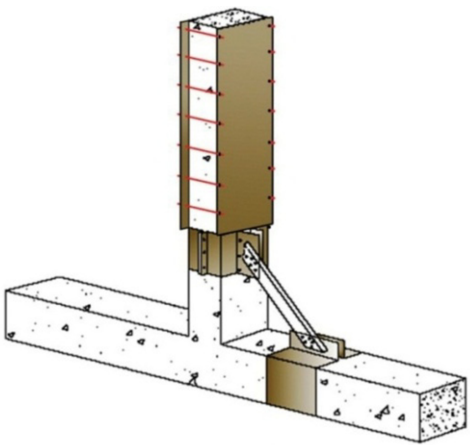


(a) 3D view

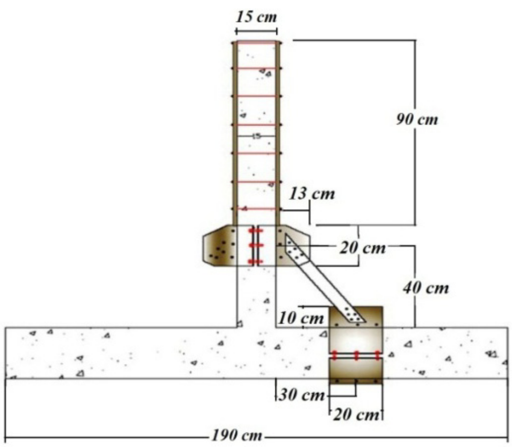


(b) Front view

Fig. 3 Schematic views of SRCC-1 specimen and its dimensions



(a) 3D view



(b) Front view

Fig. 4 Schematic views of SRCC-2 specimen and its dimensions

(a) The prop connection to the curb

(b) Installation of revival sheets

Fig. 5 Views of bolted steel prop and revival sheets

In Fig. 5, the actual condition of steel prop connection to the steel curbs and installation of sheets are showed.

3.2 Material properties

Weakness of some RC frames is due to using low strength concrete, so in order to simulate this condition, average compressive strength of standard cylindrical concrete specimens used in this study at RCC-1, SRCC-1 and SRCC-2 joints was 16 MPa. For standard control joint RCC-2, the average compressive strength of standard cylindrical concrete specimens was 29 MPa. Reinforcements and arrangements at all joints were the same. Properties of reinforcements are presented in Table 2 which shows results of tensile strength tests for the reinforcement specimens.

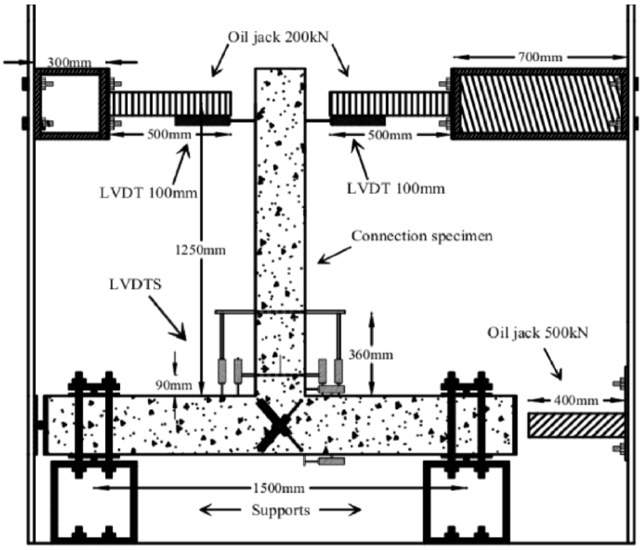
Yielding tensile strength of the steel prop and curb were 300 and 240 MPa, respectively.

3.3 Test set-up

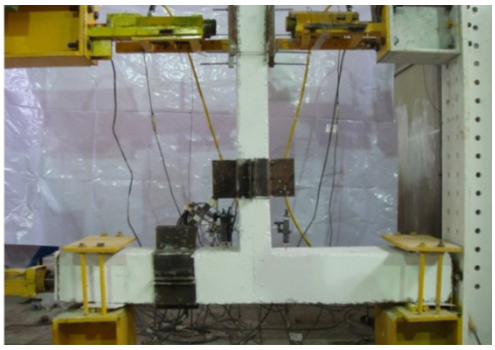
A special set-up for cyclic loading of the joints was designed and fabricated in structural lab, that had two main conditions; (1) two supports were supposed for the column; one hinged and the other rolled (based on the simulation of a moment resistant frame without considering lateral displacement of column under lateral and gravity loads); and (2) two loading conditions were simulated; a cyclic load at the tip of the beam, and a static force as axial load of the column with the constant amount of 15% (170 kN) of ultimate nominal strength of the column. The axial constant load was applied by a 500 kN hydraulic jack to one end of the column. Cyclic loading was applied using two independent 200 kN hydraulic jacks. Each jack could apply only pushing

Table 2 Results of tensile strength tests on the reinforcements

Sample	Rebar diameter (mm)	Yield stress (MPa)	Ultimate stress (MPa)
1	8	398.0	586.0
2	12	433.8	677.1
3	14	510.1	587.6



(a)



(b)

Fig. 6 Schematic and real views of the set-up for experimental modeling

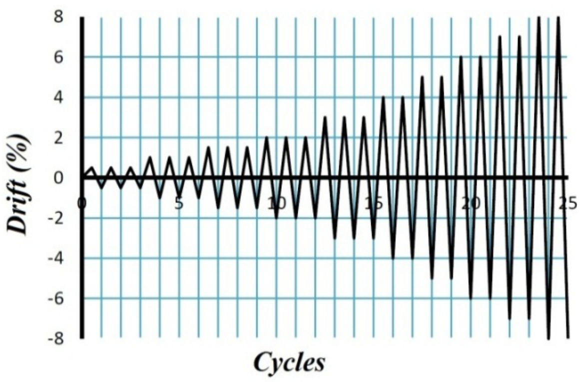


Fig. 7 Loading history (protocol) of joints

loads, so they were set in the way that one pushes the beam up to the objective deflection when the other jack is free, vice versa.

For strain registration of different points in the joint, fifteen strain gages were installed on the reinforcements of the each joint and three other strain gages were installed on the prop.

Schematic and real views of the set-up are shown in Fig. 6.

According to the cyclic nature of earthquake, in this study seismic behavior of RC joints have been investigated under a static cyclic loading condition. For considering seismic simulation, effects of stiffness decline and strength of materials, the cyclic displacement control loading protocol was used. As shown in Fig. 7, loading protocol was based on controlling the displacement of the tip of the beam.

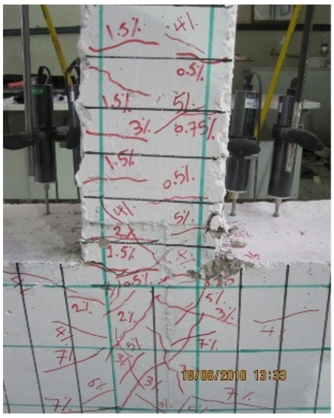
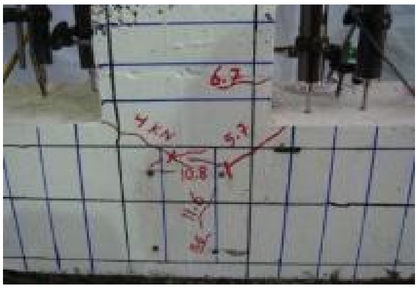
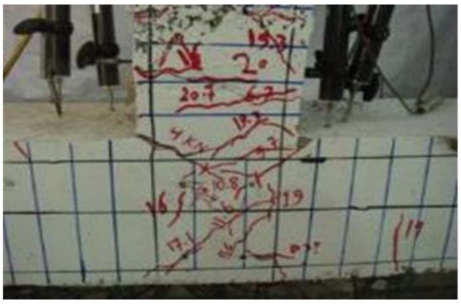


Fig. 8 Status of joint RCC-1 at drift 7%



(a) Drift 0.5%



(b) Front of the joint-drift 7%

(c) Back of the joint-drift 7%

Fig. 9 Flexural and shear diagonal cracks of joint RCC-2 at drift 0.5 and 7%

4. Experimental tests results

For investigating the general behavior of frames, general observations will be explained and then results will be presented quantitatively.

4.1 Observations and general behavior

Flexural cracks in the specimen RCC-1 were initiated on the sides of beam and following forming of diagonal X-shape cracks in panel zone at the drift 3% as shown in Fig 8. Finally the concrete cover was damaged at the end of test.

In the specimen RCC-2 according to Fig. 9(a) initial flexural and shear diagonal cracks were generated at length of beam and beam-column joint at drift 0.5 to 1%. And then these cracks at upper drift of the tip of beam were propagated and deepen at length of beam and panel zone. As shown Figs. 9(b)-(c) at drift 7% by deepening of the flexural and shear diagonal cracks at beam-column joint and around of the panel zone (especially in back of the beam) the test was ended. In

Table 3 General observations of specimens SRCC-1 and SRCC-2

Drift (%)	The specimens SRCC-1	The specimens SRCC-2
0.5%	Flexural cracks were generated at up and down of the beam curb.	Flexural cracks were generated at up and down of the beam curb. Yielding the end of prop at its joint with the curb of the beam.
2.0%	Yielding the end of prop at its joint with the curb of the beam and middle of prop at its web. Yielding of the longitudinal rebar of the beam, first in rebar at the upper edge of the beam's curb, and then rebar of the lower edge of the curb. Shear cracks propagated in the panel zone.	First shear crack (with angle 45°) generated in the panel zone. Yielding the middle of prop at its web. Yielding of the longitudinal rebar of the beam, at the lower edge of the curb.
4.0%	Shear cracks were propagated and more opened in the panel zone. Shear crack (with angle 45°) were generated in the beam, top of the curb. (Fig. 10(a))	Severe damage was not observed at the beam to column joint, yet. More plastic strains were observed in the prop.
5.0%	Flexural cracks were propagated and more opened at top of the beams curb especially. Shear crack (with angle 45°) were extended in the beam, after the curb.	Shear cracks were generated and opened down of the curb and the panel zone. Severe damage was not observed at the beam to column joint, yet. (Fig. 11(a)) Large plastic strains were observed in the flange of the prop at its joint with the curb of the beam. (Fig. 11(b))
6.0%	Shear crack (with angle 45°) extended in back of the beam, top of the beams curb. (Fig. 10(b)) Flexural cracks were propagated and more opened at top of the beams curb especially.	Severe damage was not observed at the beam to column joint, yet. Rupture occurred in the prop at tension at displacement of 65.91 mm, in which the lateral force at the end of the beam was 14.03 kN. (Fig. 11(c))
7.0%	Else shear and flexural cracks weren't propagated at down of the beams curb and damages relocated to top of it. Local buckling in the prop. (Fig. 10(c)) Severe Concrete damages (spalling) were observed at the top of beams curb. (Fig. 10(d))	After rupture of the prop, the joint was loaded up to 7% drift in one direction, in which the lateral force at the tip of the beam was 11.3 kN. While Sever damage was not observed at the length of beams and panel zone (Figs. 11(d) and 11(e))
8.0%	Concrete damages were more severe at the top of beams curb. (Fig. 10(e))	-----

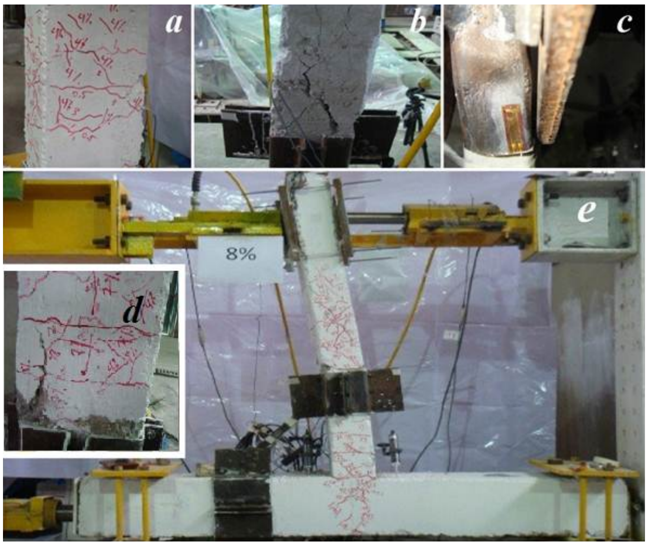


Fig. 10 Different states of the SRCC-1 at during of cyclic loading

the RCC-2 specimen cracks on the beam were flexural and diagonal but in the RCC-1 specimen by decreasing height of beam and due to flexural behavior, the cracks were flexural generally. Also because of weakness of concrete and sliding of the longitudinal bar the depth of cracks in panel zone at RCC-1 relative to RCC-2 were lower while expansion of cracks were more.

General observations results for the specimens SRCC-1 and SRCC-2, in some drifts are presented in Table 3. Figs. 10(a)-(d) show some levels of the loading in the specimen SRCC-1. Figs. 11(a)-(e) show some levels of the loading in the specimen SRCC-2 also.

In the specimen SRCC-1 concrete damage occurred at top edge of the beams curb, but in the specimen SRCC-2 were not seen any severe damage even after rupturing of the prop. But in the specimen SRCC-2 lots of shear cracks with short length and width were seen in the panel zone and down of the beams curb which the joint would able to be rehabilitated and be reused. In the specimen SRCC-2 the prop collected most of failures at itself. In the other word, the prop absorbed the energy of the cyclic loading and prepared enough time and opportunity for the joint to stay non-damaged. According to this observations (Table 3) in the specimen SRCC-2, the prop acts as a fuse and the most of failures concentrates at the prop.

In the previous rehabilitated specimens, tested by authors of this paper (Sharbatdar *et al*. 2012a, b), any damages did not happen in the steel prop and damages were concentrated at the top of the beams curb. By comparison of those specimens with the specimen SRCC-2, lesser damages occurred in the beam of SRCC-2, and most of damages were collected in the prop which the prop needed to be replaced or rehabilitated just. Hence, this would be a great advantage of this study.

4.2 Results and discussion

Maximum strength (peak) P_{max} and ultimate strength (collapse point) P_u of four specimens and the percentage of average increasing to control weak specimen RCC-1 are given in Table 4. P_u, represents the strength corresponding to the maximum displacement prior to failure of the joint or the strength corresponding to the displacement equal to 0.85 P_{max}.

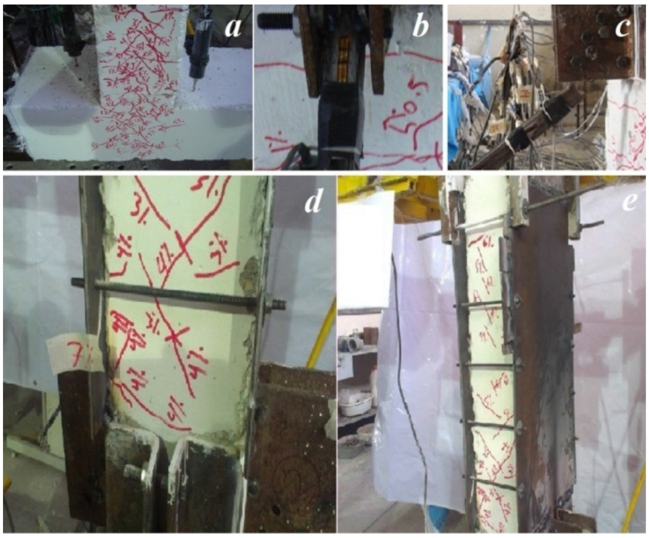


Fig. 11 Levels of the loading in the specimen SRCC-2

Table 4 Maximum and ultimate strength of joints

Name	Positive direction		Negative direction		Average increasing to Con.weak specimen (%)	
	P^{+}_{max} (kN)	P^{+}_{u} (kN)	P^{-}_{max} (kN)	P^{-}_{u} (kN)	$P_{\max}$	P_u
RCC-1	14.67	13.00	16.60	15.60	-	-
RCC-2	20.67	20.67	22.80	22.80	39	52
SRCC-1	24.93	24.93	28.50	27.62	71	84
SRCC-2	25.87	23.99	29.53	25.10	77	72

According to Table 4, the average increasing of the lateral loads $P_{\max}$ and P_u for the specimen RCC-2 compared to RCC-1 are 39 and 52% more, respectively. This is due to reduction of the beam's height and strength of concrete at RCC-1.

In the specimen SRCC-2 the average maximum strength ($P_{\max}$) of the joint increased up to 6% compared to the specimen SRCC-1 but this strength declines after failure of the prop and the average ultimate strength P_u decreased up to 12%. This reduction is because of adding the beam's revival sheets and elimination of the prop from bearing system of the joint consequently. In the specimen SRCC-2 the prop element lost its load bearing capacity because of rupture, while the rest of the joint remained undamaged, which obviously shows the absorption of damages in the prop .

In all states, bearing capacity of strengthened joints were more than the weak and standard control joints that show performance of the steel prop at increasing bearing capacity of joints. For example, the average increasing of the lateral loads $P_{\max}$ and P_u for the specimen SRCC-1 relative to RCC-1, are 71 and 84% and for specimen SRCC-2, are 77 and 72% respectively. Also by comparison of the average increasing of the lateral loads $P_{\max}$ and P_u for the specimens SRCC-1 and SRCC-2 with RCC-2, are detected that this two strengthening methods of weak joints provide the request bearing capacity of a standard RC joint as RCC-2 .

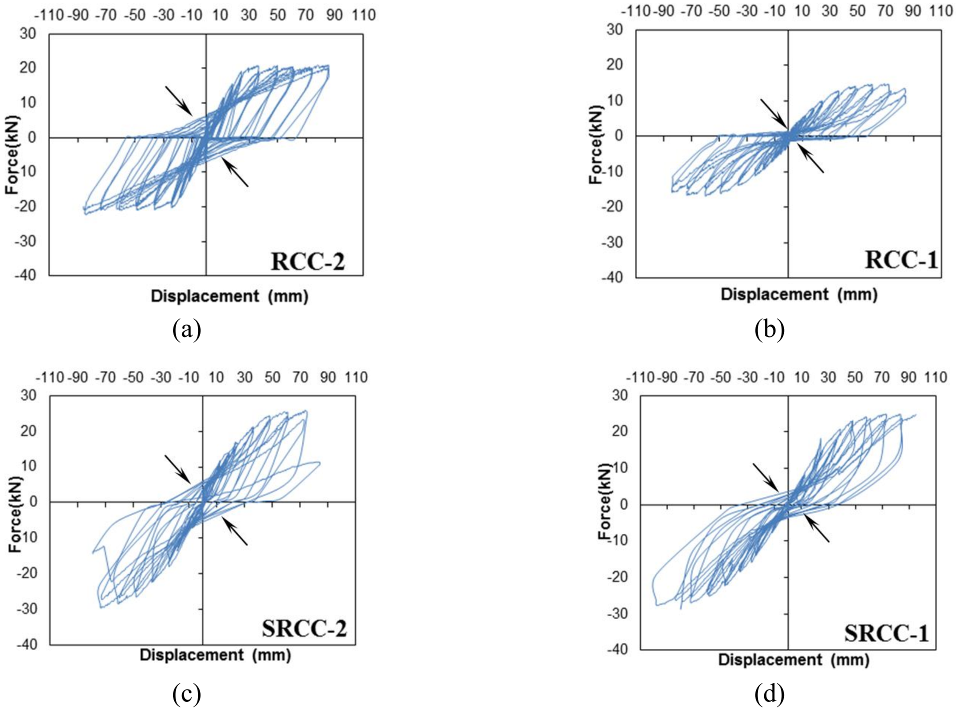


Fig. 12 Hysteresis load-beam tip displacement curve for all the specimens

Hysteresis load-beam tip displacement curves of all specimens were plotted at Fig. 12.

According to Figs. 12 and 17, in the specimen SRCC-2 the areas under hysteresis loops are more than the specimen SRCC-1. For instance this value for joint SRCC-2 is 55, 65, 41 and 50% more relative to specimen SRCC-1 at drifts 3, 4, 5 and 6% respectively which indicates in the specimen SRCC-2 more energy is absorbed. This would be because of the plastic behavior of the prop in this specimen. Also the pinching of hysteresis curve was reduced because of yielding and reaching higher strains in the prop and decreasing the number and width of flexural cracks. In the specimen RCC-2, the area under hysteresis loops are more than the specimen RCC-1. This shows that in the specimen RCC-2 more energy is absorbed. This could be because of the increasing 25% height of beam and higher strength of concrete (approximately twice) in this specimen compared to the specimen RCC-1. Also the pinching of hysteresis curve was reduced relative to weak cast specimen RCC-1 because of increasing approximately twice the strength of concrete and prevention of the beams longitudinal bars from sliding.

In Fig. 13, hysteresis load-displacement curve of the tip of the beam for the specimens SRCC-2 and RCC-2 are compared. This figure presents that by adding the steel prop and curb plus the beam's revival sheets to weak reinforced concrete joints (with low strength concrete and decrease of beam's height), that can act as a standard reinforced concrete joints approximately and provide those request criteria to the desired limit by upgrading its properties (stiffness and strength). The Pinching of two specimens almost are similar.

Hysteresis envelop curves of specimens are plotted and compared in Fig. 14 .This figure shows that the variation rates and increasing of load capacity in the strengthened specimens are like each other. The specimen SRCC-2 has an obvious fall at its end (displacement 72 mm) due to rupture of

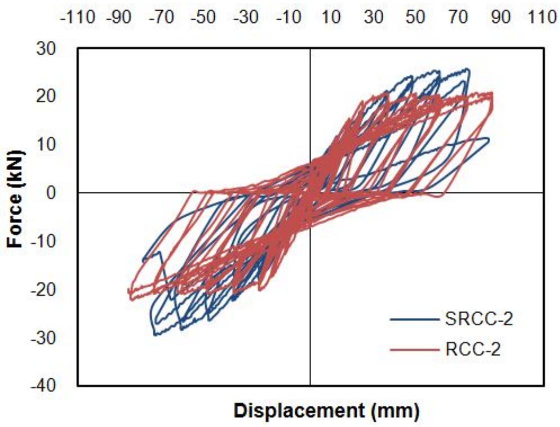


Fig. 13 Comparison of hysteresis load-beam tip displacement curve of SRCC-2 and RCC-2

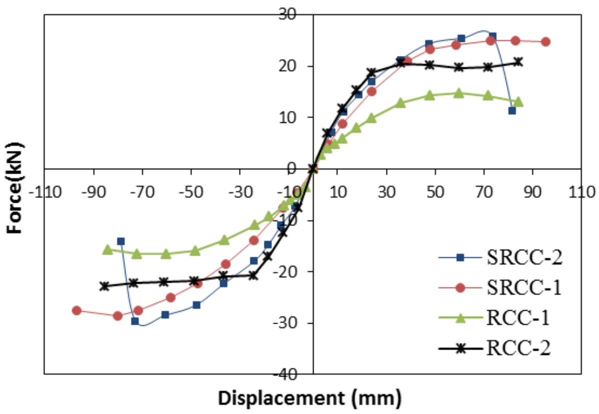


Fig. 14 Hysteresis envelop curves of the specimens

the steel prop. In specimens SRCC-1 and RCC-2 no strength degradation was observed up to drift 7% at the end of test. But force degradation of the specimen RCC-1 begun at drift 5%. By decreasing of 45% concrete compression strength and 25% beam's height, the Stiffness and strength of the specimen RCC-1 relative to RCC-2 were reduced remarkably. As shown in Table 4, and Figs. 12-14, due to the performance of lateral support of the steel prop and curb the bearing capacity in the strengthened specimens were increased remarkably compared to the weak specimen RCC-1 and standard specimen RCC-2.

4.2.1 Stiffness

Stiffness slope at the each loading cycle could be obtained from the line connecting the negative and positive maximum loads at each loop. Stiffness of the specimens versus drift in every cycle is shown in Fig. 15. Initial and ultimate stiffness of the specimens were presented at Table 5.

The lowest and highest stiffness variations of the specimens are those of the specimens SRCC-1 and RCC-2 joints, respectively. Ultimate stiffness of the specimens SRCC-2 and RCC-1 are equal and in the specimens SRCC-1 and RCC-2 are also. Due to lateral support performance of

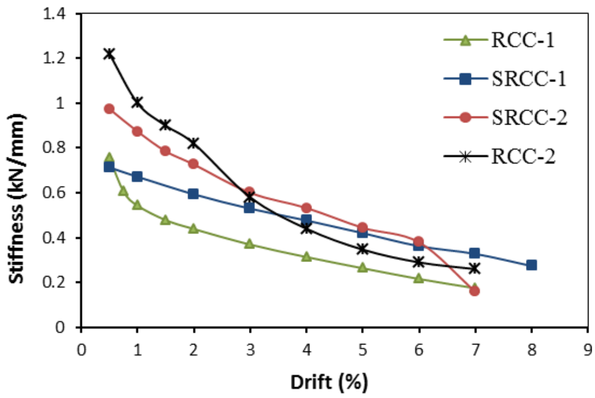


Fig. 15 Stiffness of the specimens versus drift for the all specimens

Table 5 Stiffness variations of the all specimens

Name	Initial stiffness	Ultimate stiffness	Stiffness variations
RCC-1	0.76	0.17	0.59
RCC-2	1.22	0.26	0.96
SRCC-1	0.76	0.27	0.44
SRCC-2	0.97	0.18	0.81

two strengthening systems SRCC-2 and SRCC-1, that initial and ultimate stiffness were more than weak joint RCC-1 and after drift 3% it can be said that they had higher stiffness relative to RCC-1 and RCC-2.

As it is observed in Fig. 15 and Table 5, initial stiffness of the specimen SRCC-2 is more than the specimen SRCC-1 and RCC-1, but its domain of variation are 84% and 37% more, respectively. This is a weakness for this specimen. More initial stiffness of the specimen SRCC-2 proves that in this specimen, a better control of beam's deflection under service loading is available. In another word more initial stiffness in this strengthening combination, leads to a reduction in the beam's deflection under service loading. Both specimens SRCC-1 and SRCC-2 reach the same stiffness at drift of 6% and after that the specimen SRCC-2 experienced a sever stiffness decline (more than 16% decline in a cycle) which is because of arriving the ultimate capacity of the prop that led to its rupture.

By decreasing of 45% concrete compression strength and 25% beam's height, initial stiffness from 1.22 in RCC-2 arrive to 0.76 in RCC-1 and ultimate stiffness and stiffness variations were increased up to 53% and 63%, respectively. Although initial and ultimate stiffness of the standard specimen RCC-2, were 26% and 44% more than SRCC-2, respectively but stiffness variation of SRCC-2 is 19% lower.

Fig. 16 shows the stiffness decline curve for all specimens. As that indicate in the specimen SRCC-2 at drift of 6%, the prop got out of load carrying, consequently the stiffness decline curve to up jumped suddenly. The stiffness declines of the strengthened specimens (especially SRCC-1) were lower than RCC-1 and RCC-2 at all drift. In the specimen RCC-2 the stiffness decline up to drift 3% is lower than RCC-1 but then a few increased up to drift 7%.

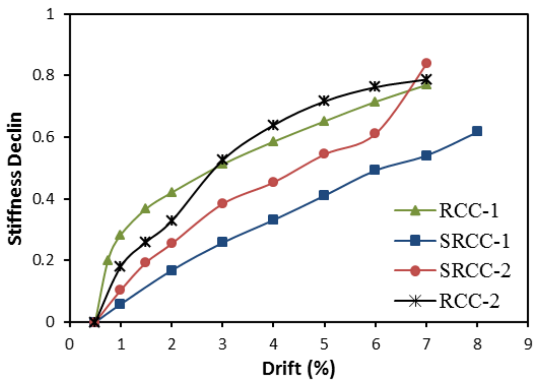


Fig. 16 Stiffness decline curve for all specimens

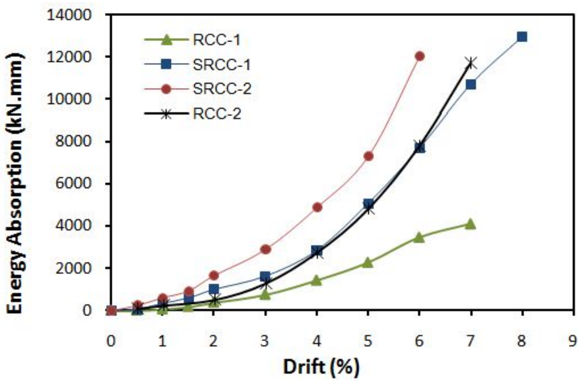


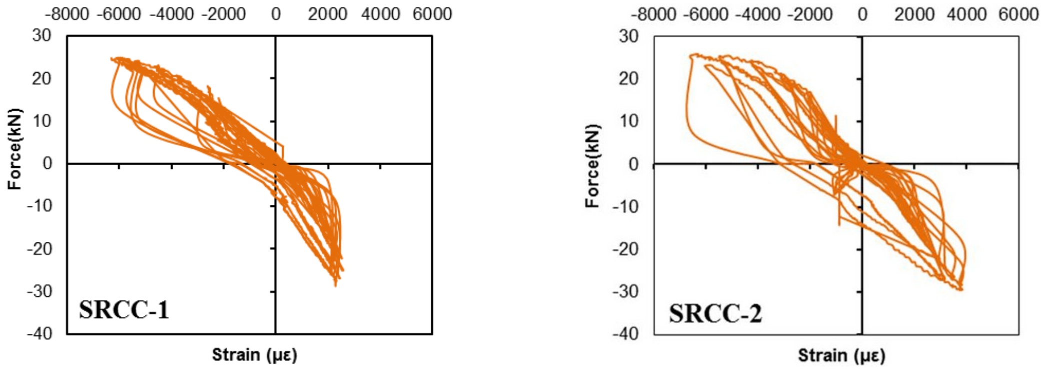
Fig. 17 Energy absorption for the all specimens

4.2.2 Energy absorption

Energy absorption could be obtained through summation of hysteresis loop area at the drift in which the load is not less than 0.85 maximum loads (0.85 P_{max}). Energy absorption for the specimens is shown in Fig. 17. This figure indicates that by decreasing of 45% concrete compression strength and 25% beam's height, the absorbed energy decreases severely (up to one third. The absorbed energy of the strengthened specimens (especially SRCC-2) was more than the specimens RCC-1 and RCC-2 at all drifts that this consequence indicates the high performance of the strengthening system (particularly in the specimen SRCC-2). The absorbed energy of SRCC-2 was equal to RCC-2 (12000 kN.mm) at end of tests and almost three time of that RCC-1 .

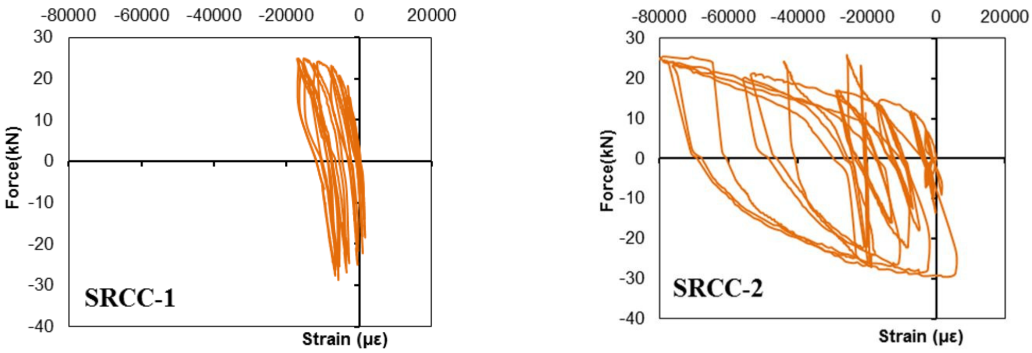
As shown in Fig. 17, the energy absorption of the joint SRCC-2 with beam strengthened using steel sheets is 1.5 time more than that specimen SRCC-1 up to drift 6%. This shows that the prop yielded earlier in that strengthening method due to higher rigidity of beam and more energy were absorbed at the joints.

Figs. 18-19 present the hysteresis force-strain curve of the middle and end of props at its joint with the curb of the beam in the specimens SRCC-1 and SRCC-2, respectively. In these curves horizontal axis is strain ($\times 10^{-6}$) and vertical axis is lateral force on the beam tip. As it is completely clear in Figs. 18-19, in the specimen SRCC-2 the hysteresis curve is wider, which means that in this specimen, the prop has absorbed more energy and has acted as a fuse in the joint.



(a) (b)

Fig. 18 Hysteresis force-strain curve of the middle of props in the specimens SRCC-1 and SRCC-2



(a) (b)

Fig. 19 Hysteresis force-strain curve of the top of props in the specimens SRCC-1 and SRCC-2

In Fig. 19 the maximum strain of the prop increased up to 15000×10^{-6} means that in this specimen in addition to its greater energy absorption, the prop has beard a greater amount of load and moment. In both specimens SRCC1 and SRCC-2, the props yielded, while in the previous rehabilitated specimens of authors of this paper (Sharbatdar *et al*. 2012a, b), the props never yielded. In another comparison, in both specimens SRCC1 and SRCC-2, the props yielded sooner (i.e.,in smaller drifts), and absorbed the damages, especially in the specimen SRCC-2 in which the prop yielded in the first loading increment.

5. Conclusions

In this study, two strengthening methods were introduced for upgrading the behavior and performance of weak RC joint (low strength concrete and/or the reduced beam's height) that were low rigid steel prop and curb with and without steel revival sheets. Strengthened joints along standard and weak control RC joints were subjected to lateral cyclic loading and axial constant load, and then results and observations were compared. A summary of conclusions are: given at the following:

- By decreasing of 45% concrete compression strength and 25% Beam's height of the joint the maximum strength, initial rigidity and energy absorption, were reduced 28, 38 and 65%,respectively also the pinching of hysteresis loops was increased severely.
- Unlike strengthening method of steel prop alone, using the added steel revival sheets led to more force transfer and earlier yielding of the prop before longitudinal bar of beam and the prop act as fuse element in joint finally.
- Adding steel revival sheets to the steel prop and curb had rarity effect on the peak strength of joint relative to steel prop alone and curb specimen but increased the absorbed energy 50% up to drift 6%.
- In the specimen with steel prop alone, the damages were occurred at top of the beams curb while in the specimens along steel revival sheets due to more rigidity of beam were concentrated at steel prop mostly.
- The maximum strength, ultimate rigidity and energy absorption of strengthened weak joints with and without steel revival sheets were 77, 6 and 200% and 71, 59 and 225% more relative to weak control joints, respectively.
- The pinching of hysteresis loop at the strengthened weak joint with beam's steel revival sheet was same the standard RC control joint but its absorbed energy up to drift 6% was 1.5 times more.
- Comparing the basic performance factors of the strengthened joints with standard control joint it can be concluded that the strengthened weak joint with beam's steel revival sheet, approach the performance of weak joint to standard joint and even better because of created fuse element.

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