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Experimental study of rigid beam-to-box column connections with types of internal/external stiffeners

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Abstract. Box sections are symmetrical sections and they have high moment of inertia in both directions, therefore they are good members in tall building structures. For the rigid connection in structures with box column continuity plates are used on level of beam flanges in column. Assembly of the continuity plates is a difficult and unreliable work due to lack of weld or high welding and cutting in the fourth side of column in panel zone, so the use of experimental stiffeners have been considered by researchers. This paper presented an experimental investigation on connection in box columns. The proposed connection has been investigated in four cases which contain connection without internal and external stiffeners(C-0-00), connection with continuity plates(C-I-CP), connection with external vase shape stiffener (C-E-VP) and connection with surrounding plates(C-E-SP). The results show that the connections with vase plates and surrounding plates can respectively increase the ultimate strength of the connection up to 366% and 518% than the connection without stiffeners, in case connection with the continuity plates this parameter increases about 39%. In addition, the proposed C-E-VP and C-E-SP connection provide a rigid and safe connection to acquire rigidity of 95% and 98% respectively. But C-I-CP connection is classified as semi-rigid connections.

Keywords: box column; rigid connection; continuity plate; vase external stiffener; surrounding external stiffener

1. Introduction

Box-columns, including cold-formed hollow sections and built-up sections fabricated by welding four plates together, are commonly used in rigid orthogonal moment resisting frames. Inherent characteristics of box sections, such as large bending capacity and stiffness around any axis, large torsional stiffness, low sensitivity to local buckling and stable post buckling strength, provide good seismic performance for box-columns. To achieve the aforementioned advantages of columns with box section, providing a proper beam-to-column connection is the first step in proportioning a moment frame with box-columns.

Since 1930, numerous studies have been conducted on rigid connections of I-shaped beam to H- shaped column, but no considerable studies have been done on box columns. Lee *et al.* conducted one of the most valid and inclusive research. (Lee *et al.* 1991a, b, 1993a, b, c, 1994). In their study, angle external stiffeners, triangular plates, T-shape and also continuity plates were studied. The purpose of their paper was to find a proper external stiffener as an alternative for inner continuity plate to satisfy major factors of effective rigid connection. Accordingly, side and intermediate connections were studied. Research team concluded that connection with T-shaped stiffener has the best performance among other connections and is considered as a good substitute for connection with inner continuity plate.

Installing the internal continuity plates is a difficult fabrication task and also a costly procedure, therefore researchers have tried to improve this type of connection not only by improving the connection details in the presence of internal continuity plates, but also by avoiding internal continuity plates and providing new load paths via external features. Rib-reinforced welded connections (Chen *et al.* 2004), column-tree connection with improved details including no weld access hole detail and widened flange of the stub beam detail (Chen *et al.* 2006), and horizontal hunch connection (Tanaka 2003) have recently addressed the improvement of connections with internal continuity plates. Moreover, external T-angle or triangular plate stiffeners for box–columns (Lee *et al.* 1991b, 1993b, Shanmugam and Ting 1995, Shanmugam 1991), T-stiffeners for CFT columns (Kang *et al.* 2001, Shin *et al.* 2004, Shin *et al.* 2008) and stiffening plates around the box–column (Park *et al.* 2005, Kurobane 2001), were employed to provide new load paths for beam to box–column connections by means of external features and eliminating internal continuity plates.

In addition of the force transfer mechanism of the connection is described and a design method is investigated to determine the dimensions of the through plate and other related parts. (Torabian *et al*. 2012, Mirghaderi *et al.* 2010).

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Table 1 The introduction of specimens(Sizes of specimens are in mm)

Row	Specimen(Nick name)	Full name	Address
A	C-0-00	Connection/-/--	Fig. 1
B	C-I-CP	Connection/Internal/Continuity Plate	Fig. 2
C	C-E-VP	Connection/External/Vase Plate	Fig. 3
D	C-E-SP	Connection/External/ surrounding Plate	Fig. 4

An experimental program consisting of two relatively identical cyclically loaded specimens was conducted to evaluate the seismic performance of the connection. The results showed that the specimens reached at least 0.06 rad of the total story drift before experiencing strength degradation.

(Kang *et al.* 2015) In their paper, they compared the previously proposed equations for joint shear capacity, discussed the shear deformation mechanism of the joint, and suggested recommendations for obtaining more accurate predictions. Finite element analysis of internal diaphragm connections to CFT columns were carried out in ABAQUS. Results showed that: (1) shear deformation of the steel tube dominates the deformation of the joint while the thickness of the diaphragms has a negligible effect; (2) in OpenSees simulation, the joint behavior is highly depended on the yielding strength given to the rotational spring; and (3) the axial force ratio has a significant effect on the joint deformation of the analyzed specimen. Finally, modified joint shear force-deformation relations are proposed based on previous theory.

According to a study by Qiu *et al*. (2013) shear failure and concrete core crushing at plastic hinge region are the two main failure modes of bridge piers, which can make repair impossible and cause the collapse of bridge. To avoid the two types of pier failure a composite pier was proposed, which was formed by embedding high strength Concrete Filled steel Tubular (CFT) column in Reinforced Concrete (RC) pier. The seismic performances of the composite pier were studied through cyclic loading tests.

The experimental results show that the CFT column embedded in composite pier can increase the flexural strength, displacement, ductility and energy dissipation capacity, and decrease the residual displacement after undergoing large deformation. Qin-Ting Wang and Xu Chang in their paper, a numerical study of axially loaded concrete-filled steel tubular columns with T-shaped cross section (CFTTS) based on the ABAQUS standard solver is presented. Two types of columns with T-shaped cross section, the conventional concrete-filled steel tubular columns with T-shaped cross section (CCFTTS) and the double concrete-filled steel tubular columns with T-shaped cross section (DCFTTS) are discussed. The numerical results indicate that both have the similar failure mode that the steel tubes are only outward buckling on all columns' faces (Wang and Chang 2013).

The major objective of the paper presented by (Kwak *et al.* 2013) is to evaluate the behavior and ultimate resisting capacity of circular CFT columns. To consider the confinement effect, proper material models are selected with respect to the confinement pressure. (Huang *et al.* 2008) Proposed a method to estimate the ultimate strength of rectangular concrete-filled steel tubular (CFT) stub columns under axial compression.

Rezaifar and Younesi presented a new beam-to-box column connection with trapezoidal external stiffeners and horizontal bar mats to provide seismic parameters (Rezaifar and Younesi 2016). The proposed connection consists of eight external stiffeners in the level of beam flanges and five horizontal bar mats in Concrete Filled Tube (CFT) columns. The new connection effectively alleviates the stress concentration and moves the plastic hinge away from the column face by horizontal external stiffeners. In addition, the result shows that the proposed connection has provided the required strength and rigidity of connection, so that the increased strength of 8.08% and 3.01% rigidity are compared to connection with internal continuity plates, also the results indicate that this connection can offer appropriate ductility and energy dissipation capacity for its potential application in moment resisting frames in seismic region. As a result, the proposed connection can be a good alternative for connection with continuity plates.

In the present study the experimental investigation of the rigid flexural connection and finding the perfect alternative to connect with continuity plate will be discussed. In this study four models are studied as monotonic and cyclic and compared the effective parameters to identify the rigidity of connection.

2. Experimental program

2.1 Test specimen

In general, four specimens are designed for testing to investigate the seismic behavior of connections as shown in Table 1 and Figs. 1 to 4.

The columns and steel beams were both identical for two specimens. The column was made of four steel plates vertically, seamed by complete joint penetration welds. This is believed to enhance the versatility and practicality of HSS connections due to the wider range and larger size available in tubular sections.

In all of models the height and length of column and beam are chosen as 1500 mm and 1000 mm respectively. In order to build columns, plates with width of 200 mm and thickness of 6 mm are used. Besides, a 150 mm wide and 6 mm thick plate is used for construction of the beam and shear stiffener with 6 mm thickness, 77 mm width and 200 mm length is used in web of the beam. Other details of the models are shown in Figs. 1 to 4.

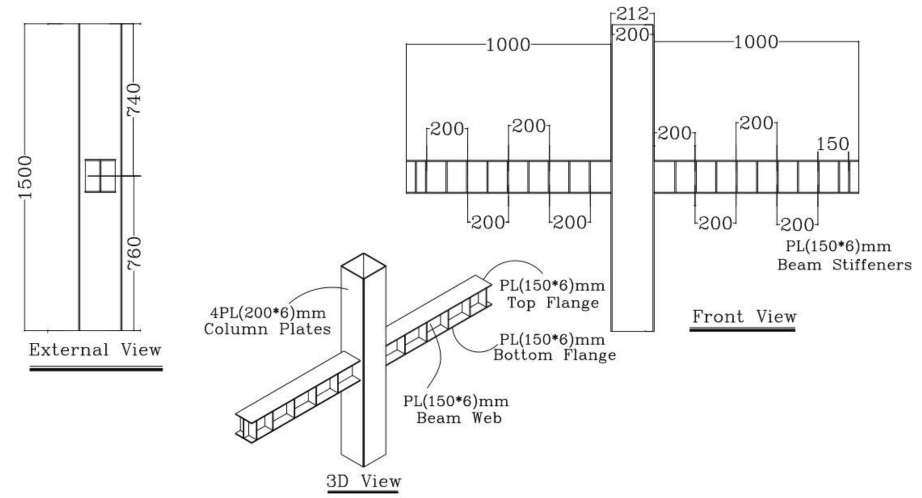


Fig. 1 Details Model C-0-00

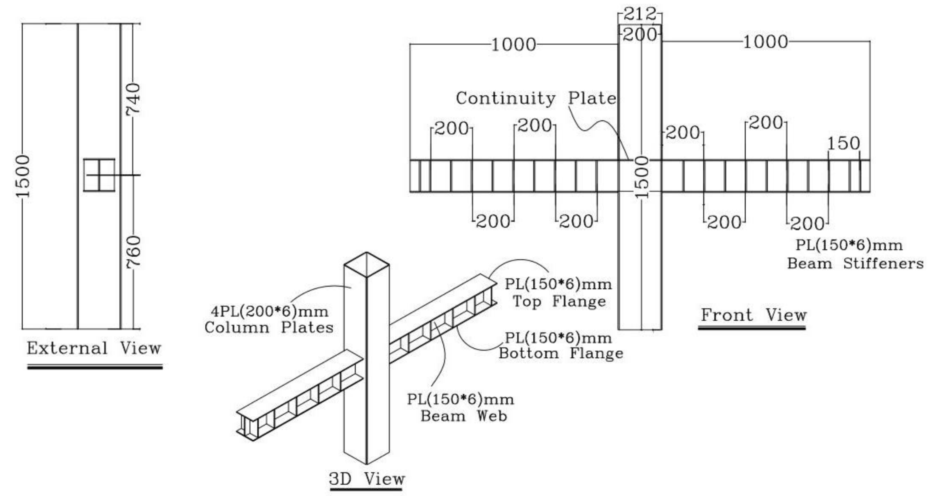


Fig. 2 Details Model C-I-CP

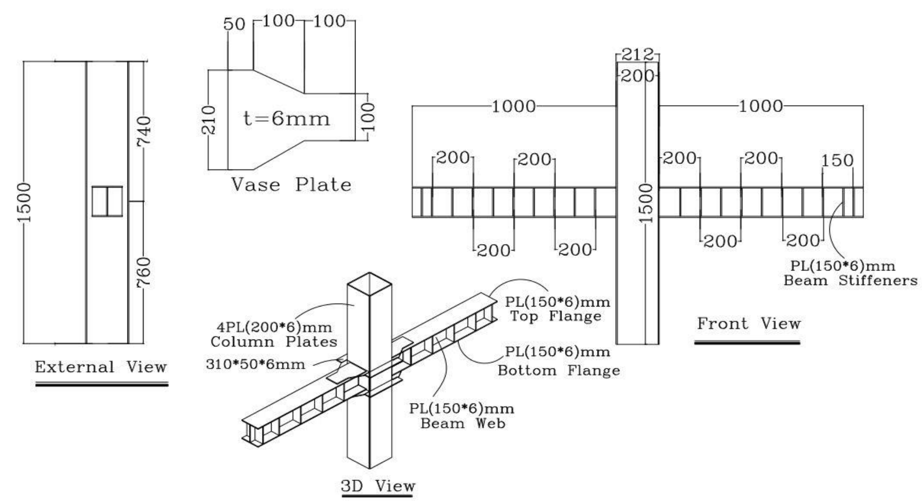


Fig. 3 Details Model C-E-VP

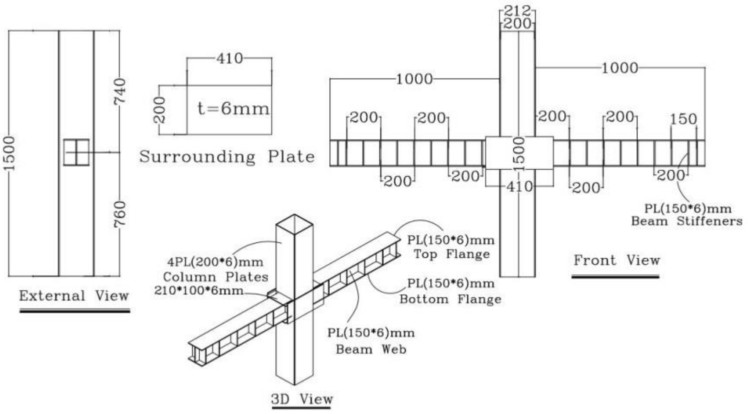


Fig. 4 Details Model C-E-SP

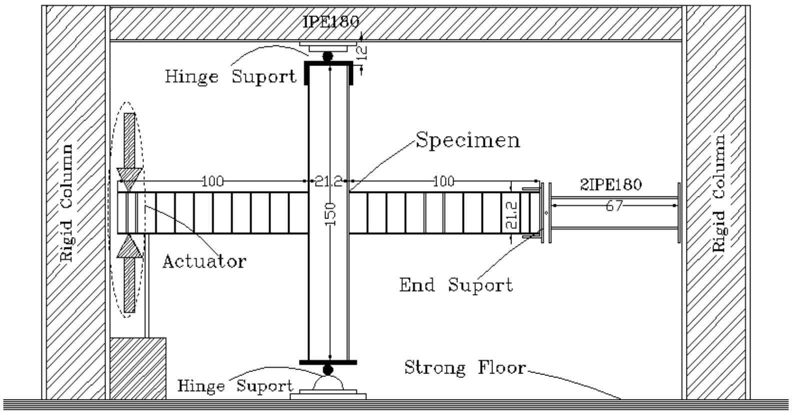


Fig. 5 Test set-up

Fig. 6 Instrumentation of the test specimens

2.2 Material properties

The selected steel is the type of mid steel construction, i.e., ST37. The steel elasticity modulus is 2×10^5MPa and its yielding stress is 240MPa and steel Poisson ratio is considered 0.3 after that the tensile test of plate is obtained (Table2).

Table 2 Material properties

Elasticity module (MPa)	yielding stress (MPa)	ultimate stress (MPa)	Poisson ratio
1.95×10^5	281.5	423.6	0.29

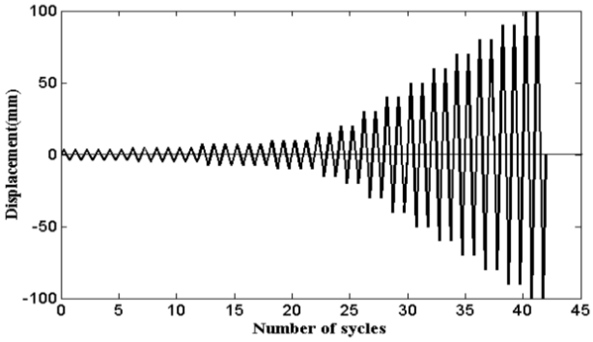


Fig. 7 Time history diagram of loading, SAC97 (Clark 1997)

2.3 Test setup and instrumentation

All specimens in this study consist of a column with net height of 150 Cm and beam length of 100 Cm on each side, accordingly, the height of the experiment setup including up and down supports is intended to be 200 Cm and the total length of setup is considered 300 Cm (See Fig. 5). In this study, hinge connections are considered to be boundary conditions for up and down of column and the right beam. The end of left beam is loaded by actuator.

Strain gauges are used to determine the strain in the surrounding area of panel zone and internal/external stiffeners in different points, in addition all supports in Figs. 5 and 6 are hinged. The overview of test and how to loading is shown in Fig. 6.

2.4 Loading history

Cyclic loads, simulating seismic load effects, were applied vertically at the beam tip using the loading sequence proposed by SAC97 (Clark 1997) for qualifying beam-to-column moment connections (See Fig. 7).

Loading was applied by controlling the actuator displacements following the loading history, which consisted of gradually increasing deformation cycles. Quasi-static testing provided an opportunity to monitor the behavior of connection and capture all probable events.

3. Experimental results

3.1 General observations

The displacement applied from actuator to the specimen increases 33% and 50%. the decussate and tolerable force in connection with continuity plates(C-I-CP) in all steps is more than C-0-00 connection and as the lateral displacement increases its rate increases as well. According to experimental observations, C-0-00 connection was allocated to the most ultimate tensile and compression capacity therefore this parameter is more than about 42% of the C-E-VP connection, 272% of the C-I-CP connection and 417% of the C-0-00 connection. The C-E-VP connection has an initial rigidity more than other models and its implementation is much simpler and easier than C-I-CP models and C-E-SP specimen, but C-E-SP Offers better load transfer flows than the C-E-VP, therefore this connection can bear higher load.

3.2 Load-Displacement curves

Fig. 9 shows the Force-Displacement curves of all specimens. According to Fig. 8(a), C-0-00 specimen has lower ultimate strength and initial stiffness (The first part of the curve slope) than the C-I-CP specimen due to the large deformation of compressive and tensile flanges of column under load and the lack of appropriate load transmission of beam to column. Therefore, in all points for the identical displacement, less load bearing capacity. The use of continuity plates(C-I-CP specimen) can improve the performance of this connection, but according to Figs. 8(c) and 8(d), the use of external stiffeners(C-E-VP, C-E-SP) improves the connection’s behavior in terms of strength, rigidity and energy dissipation compared to the C-I-CP connection.

As shown in Fig. 8(d), C-E-SP specimen has a very high load-bearing capacity than the C-E-VP and finally compared to all other specimens, C-E-SP specimen is more sloping in the first part of the curve which represents that this connection is more rigid.

According to the Force-Displacement curves of specimens, in C-I-CP and C-E-VP specimens maximum bearable load is in 30 mm but in C-E-SP this value is in 50 mm, which shows that this specimen has a high configurability.

3.3 Seismic parameters

3.3.1 Ultimate strength

In Force-Displacement curves the ultimate strength is in fact the peak of Force-Displacement curve of specimens shown in Figs. 9 and 10 for each specimen.

According to Fig. 10, ultimate strength of connection with continuity plates is 27.8kN, which is an increase of 39.2 percent over C-0-00 connection. On the other hand, the use of vase stiffener causes 162.6 percent increase of ultimate strength than the base model design codes (C-I-CP model). Besides, C-E-SP specimen with the ultimate strength of 103.38kN has the best performance among all studied specimens and is a good alternative for connection with continuity plate.

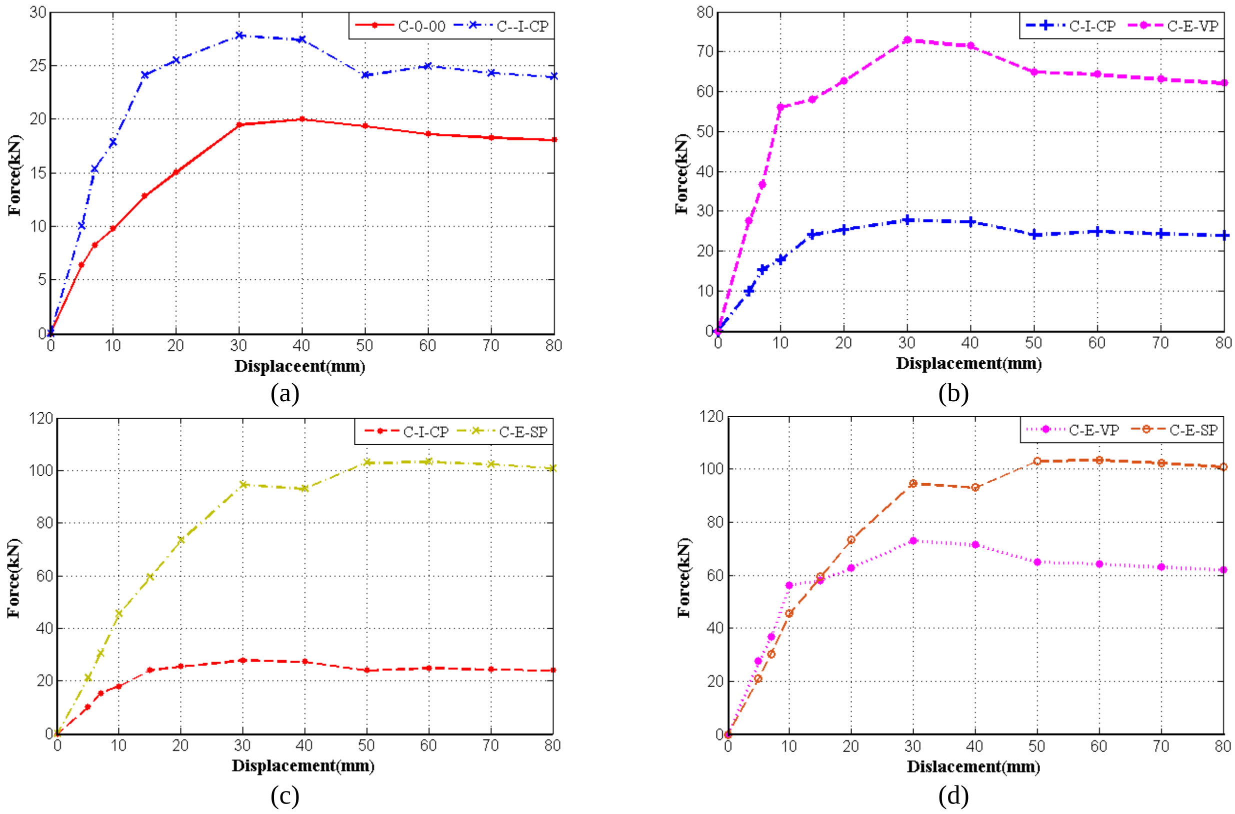


Fig. 8 Force-Displacement curves of specimens

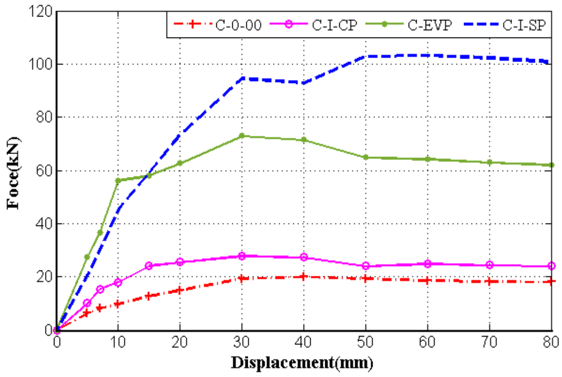


Fig. 9 Force-Displacement curves of all specimens

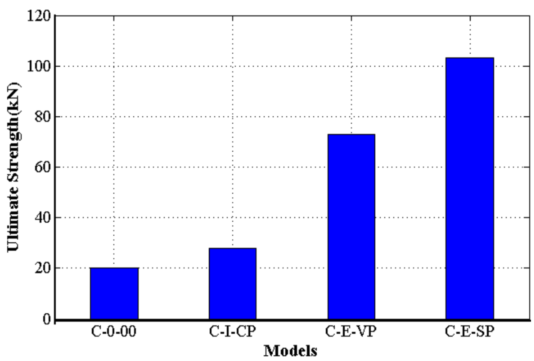


Fig. 10 Bar charts ultimate strength of Specimens

3.3.2 Ductility and rigidity

Strength, rigidity and ductility are important parameters in study of connection behavior. Ultimate strength is the peak of force-displacement curve and ductility is the ability of a member or structure in deformations after yielding and rigidity is the property of a structure that it does not bend or flex under an applied force. Rigidity as follows is the ability of load bearing by connections. Ductility parameter of connections is defined by Eq. (1) and Fig. 11 and the rigidity parameter is defined by Eq. (2) and Fig. 12.

In Fig. 11, Δ_w is the displacement corresponding to stress working and V_w is the base shear corresponding to stress working and $\Delta_s = Y\Delta_w = 1.4\Delta_w$ (For earthquake loading $Y = 1.4$ (AISC-ASD 1989)), $\Delta_y = \Omega\Delta_s$ (Ω is overstrength factor), $\Delta_{max} = C_d\Delta_s = 5.5\Delta_s$ (For special moment resisting frame system (ASCE7 2010)), $V_e = RV_s = 8V_s$ (V_e is the maximum base shear and R is behavior factor), $V_s = YV_w = 1.4V_w$, $V_y = \Omega V_s$

$$\mu = \frac{\Delta_{\max}}{\Delta_y} \tag{1}$$

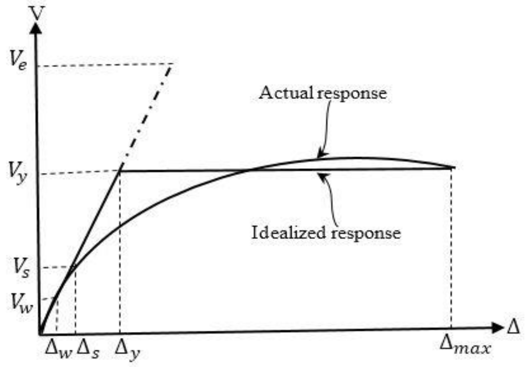


Fig. 11 Actual and ideal response curves of connection

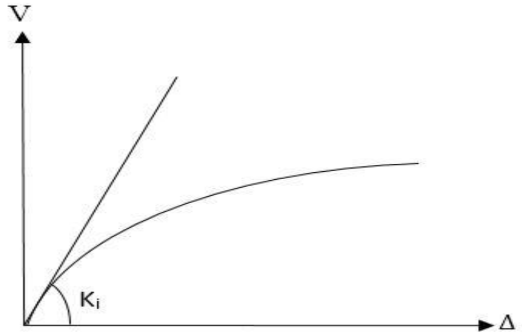


Fig. 12 Determination of stiffness

Where μ is the ductility index. $\Delta_{\max}$ and Δ_y are shown in Fig. 11.

$$R = \frac{K_i}{K_{total}} \times 100 \tag{2}$$

Where R is the rigidity, K_i is the stiffness and $K_{total} = \sum \frac{3EI}{L^3}$; EI is the flexural rigidity of each member of the connection and L is the length of each member.

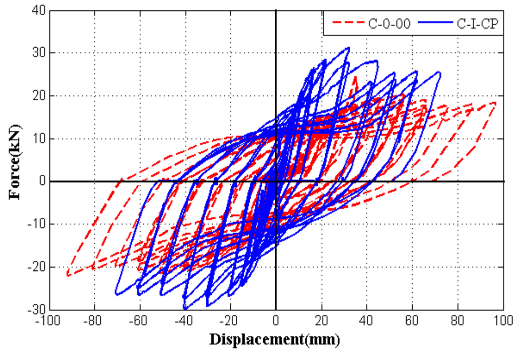
According to table3, C-E-SP and C-E-VP specimens by acquiring over 90% rigidity are classified as rigid connections and connection with continuity plate with 88.54% rigidity is a semi-rigid connection. Studies show that the use of external stiffeners is to increase the rigidity of connections by strengthening the area around the panel zone, but reduces the ductility parameter of connections. C-I-VP connection with a 10% increase of ductility than the C-0-00 connection has the best behavior among all models.

Table 3 Ultimate strength and ductility of Specimens

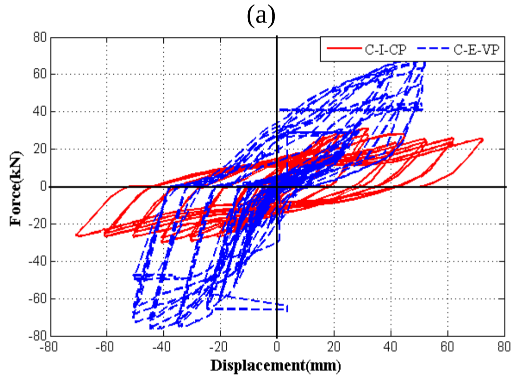
Specimens	Rigidity	Increment	Ductility	Increment
C-0-00	75.26	0	7.27	0
C-I-CP	88.54	+17.65	8.00	+10.04
C-E-VP	95.01	+26.24	4.70	-21.59
C-E-SP	97.87	+30.04	3.20	-42.23

3.4 Hysteresis curves

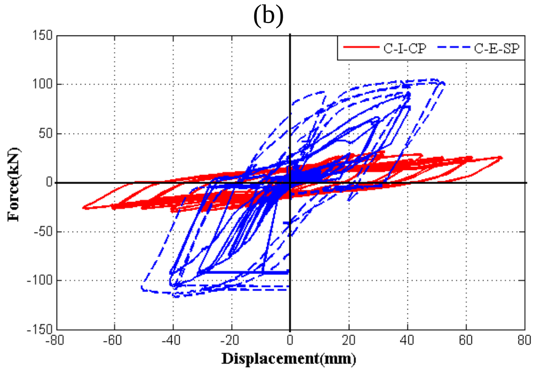
The specimens are placed under cyclic load according to SAC97 loading protocol. Loads are gradually increased so that failure happens in specimens. The comparison of these curves is presented in Fig. 13.



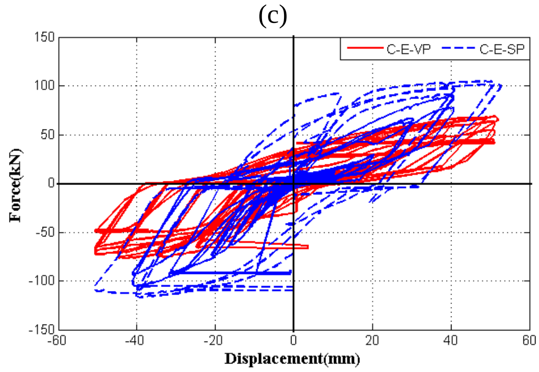
(a)



(b)

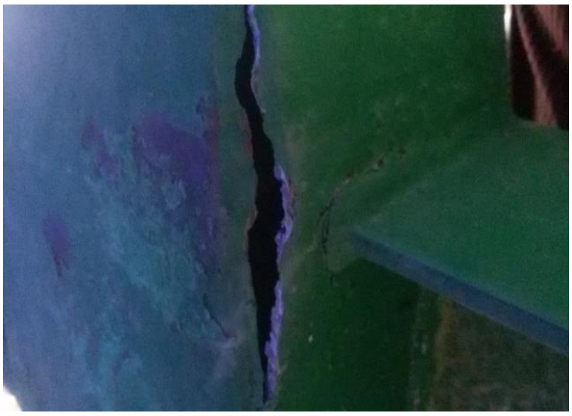


(c)



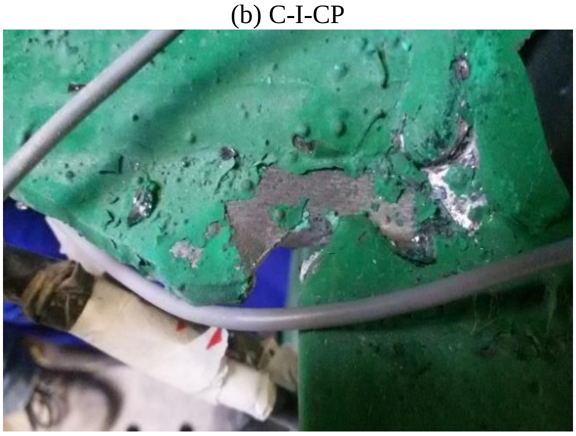
(d)

Fig. 13 Compare the hysteresis curves of specimens

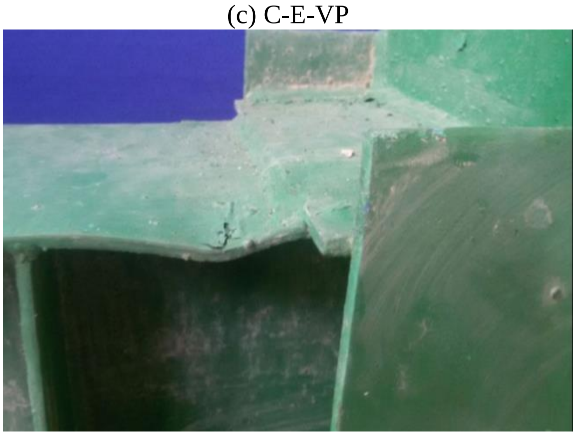


(a) C-0-000

(b) C-I-CP



(c) C-E-VP



(d) C-E-SP

Fig. 14 Failure mechanism of specimens

According to Fig. 13(a), the use of continuity plate in panel zone increases the strength of connection due to the increase in connection rigidity (peak point of curves), but decreases the ultimate displacement of connection. Fig. 13(b) shows that the use of vase stiffener instead of continuity plate increases the ultimate strength of connection considerably.

Connection with Surrounding plate(C-E-SP), has wider hysteresis curve than other connections and dissipates more energy, (See Fig. 13(d)) and it also has the maximum strength. As it can be seen from Fig. 13(c) the C-E-SP connection is more rigid than the other connections and it has higher peak point.

3.5 Failure mechanism

The failure mode of specimens is shown In Figs. 14(a) to 14(d). According to Fig. 14, failure in C-0-00 and C-I-CP specimens happens in column flanges but in specimens with external stiffener it happens in beam, therefore specimens with internal stiffener experience collapse sooner.

In C-0-00 and C-I-CP specimens the plastic hinge occurs in panel zone but in C-E-VP and C-E-SP specimens it happens far from panel zone, therefore this connection moves plastic hinge into the beam and provides the idea of weak beam-strong column.

3.6 Stiffness degradation

The stiffness degradation and its degradation rate in connection are very important. A number of connections have high initial stiffness but over time and increased load, it leads to deterioration that is not suitable. For investigation of this parameter in this section, stiffness degradation curves of all models are shown in Fig. 15.

According to Fig. 15, initial stiffness of C-E-VP specimen is more than other specimens but the rate of reduction is greater than all specimens. Fig. 16 shows that C-0-00 connection has low stiffness and rate of reduction.

For displacements greater than 30 mm all specimens have almost identical stiffness.

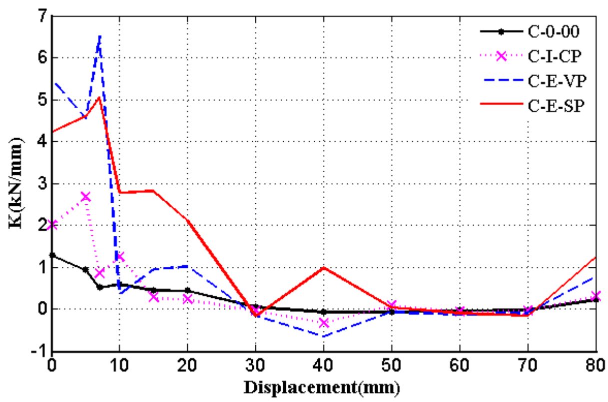


Fig. 15 Stiffness deterioration curve

4. Conclusions

Results of the investigation show that the use of continuity plate can improve the connection performance, but it is not approved due to the operational constraints. In addition, in this connection the plastic hinge happens in panel zone that violates the idea of weak beam-strong column and on the other hand has lower ultimate strength than the model with external stiffeners. Connections with external stiffeners provide the seismic parameters of connections and are classified as rigid connections according to this research. In addition, these connections (C-E-VP and C-E-SP) dissipate energy of earthquake as well.

The results show that connections with vase plate and surrounding plate have a wider hysteresis curve and they have more energy dissipation ability. Failure mechanism of specimens shows that in connections with continuity plate and connections with hollow section column will fail sooner than beam, which represents the non-satisfaction of weak beam-strong column idea and connections with external stiffeners by tightening up around the panel zone resolve this problem. According to higher initial stiffness and maximum load than the other specimens (C-0-00 and C-I-CP), they are suitable for load transfer.

According to the conducted studies it is concluded that connections with external stiffeners provide all necessary parameters for the rigid connection and are as good alternative for connection with continuity plate. Connection with vase plate (C-E-VP) is the desirable connection for authors and designers due to the easer assembly than the C-E-SP connection.

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