Seismic Behavior of a New Reduced Beam Section Connection by Drilled Holes Arrangement (RBS_DHA) on the Beam Flanges through Experimental Studies

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SUMMARY:
Reduced beam section connection (RBS) is recognized as one of the ductile connections in special steel moment frames. The introduced RBS connections in valid regulations are in reduced cross-section radial form. In order to eliminate flame and expenses and improve existing buildings, utilizing drilled holes in order to reduce beam cross-section is considered. In the present research, we attempt to examine a new reduced beam section connection in the beam flange utilizing ordered drilled holes (RBS-DHA). Carried out experimental studies indicate that the proposed connection is capable of delaying and reducing lateral torsional buckling, and increasing plastic hinge effective lengths relative to the RBS connection with radial shear. In addition, in high rotations, it is found useful in special steel moment frames.

Keywords: new reduced beam section connection, Beam flange drilling, seismic behavior, plastic hinge

1. INTRODUCTION

Since the earthquakes in Northridge (1994) and Kobe (1995) and accession of brittle breakages in connections, various studies were deployed to find the best methods in improving steel connection seismic behavior. A number of these connections have been proposed in FEMA350 [1], which their satisfaction degree had been determined in numerous tests. After the Northridge earthquake, two general concepts were introduced for achieving high levels of ductility and assured operation in connections: connection reinforcement and weakening the beam cross-section related to the connection – in other words, preventing the formation of damage on the face of the column.

In reinforced connections, in most cases, the main objective of reinforcing the beam connection to the column relative to the beam cross-section is to distance the plastic hinge from the column's face, and transfer intense tensions and non-elastic strains inside the beam. However, reinforced connections increase costs, and excess reinforcement leads to new problems including increasing welding processes, and increasing connection resistance, which leads to a stronger panel zone design. Another type of moment connection which provides equal advantages compared to reinforced connections, and may in fact improve some of the weaknesses existent in the latter, is Reduced Beam Sections connection (RBS) which is recognized as dog-bone connection. The concept of RBS was proposed in 1990 by Plumier (Fig. 1.1) [2, 3].

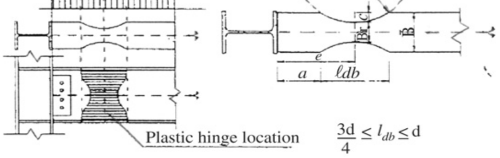


Figure 1.1. The dog-bone conception [2]

After the Northridge earthquake, many studies were carried out in the USA on the seismic behavior of RBS connections [1]. The idea of weakening rests on the method that parts of the beam flange are corrected in a region distant to the column face. Different cuts including constant cut, tapered cut and radius cut are available for reducing the cross-section of the beam flange (Fig. 1.2). The reduced region acts as a ductile fuse. The beam yields at the RBS region and can withstand big strains, and therefore reduces tensions in the beam connection to the column, which has less ductility.

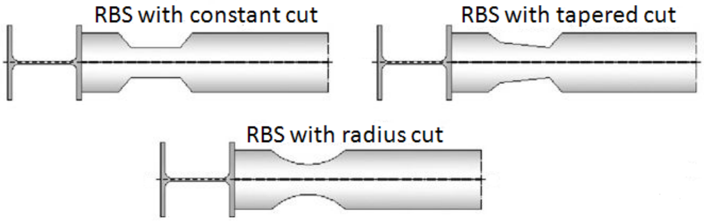


Figure 1.2. Shapes of reduced beam sections

Vast experimental [4-6] and analytical [7-9] tests have examined this solution. After studies carried out in the field of connections with reduced section connection, the RBS connection with radius cut was evaluated to be more suitable [10] and was introduced in FEMA350 and EC8 [11] regulations.

In order to eliminate the effect of heat due to flame cut, reduced costs compared to RBS connections with radius cuts, and improving existing buildings, Yang and Popov proposed using drilled holes for reducing the section [12]. In the report presented by James and Anderson, a connection with reduced section using drilling work was examined, which did not achieve suitable rotation for application in special moment frames, and considering the creation of a fuse in the beam and a strong panel zone, still breakage occurred in the connection from the weld region [13]. In this article, we examine a new reduced section connection using drilled holes with variable diameter and orderly layout in order to achieve desirable operation in special moment frames on IPE profiles.

2. RECOMMENDED CONNECTION DESIGN METHOD AND MECHANISM (RBS-DHA)

The main idea in the connection design process is creating a plastic hinge simultaneously in the reduced section of the beam flange, and utilizing all of the reduced section to expand the plastic flange, which leads to an increase effective length of the plastic flange compared to the RBS connection with radius cut (Fig. 2.1). On the other hand, in the proposed connection, considering the more uniform distribution of plastic strains in the length of the reduced region compared to the RBS connection with radius cut, leads to delayed lateral torsional buckling and prevention of instability. In order to achieve a simultaneous plastic hinge, the reduce section in the beam flange must reach a specific percentage of the plastic moment of the beam. This can be obtained using Eqn. 2.1:

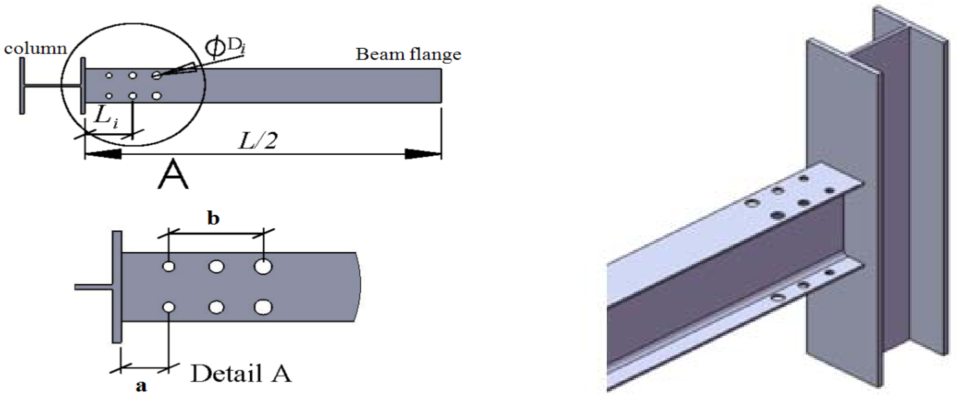


Figure 2.1. Proposed connection details

$$\frac{M_1}{Z_1}=\frac{M_2}{Z_2}=\frac{M_3}{Z_3}=\frac{M_i}{Z_i} \tag{2.1}$$

In Eqn. 2.1, M_i is a reduced moment for designing holes in the considered section for creating fuse in the beam which is obtained through Eqn. 2.2 and 2.3, (Fig. 2.2). Z_i is the basis of the beam's plastic cross-section in the reduced region, which is obtained through Eqn. 2.4.

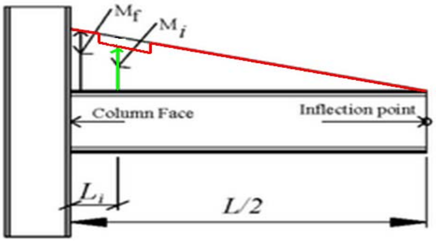


Figure 2.2. Reduced section profile seismic moment

$$M_i=\alpha M_{pr}\left(\frac{L/2-L_i}{L/2}\right) \tag{2.2}$$

$$M_{pr}=C_{pr}\,R_y\,Z_b\,F_y \tag{2.3}$$

$$Z_i=Z_b-2\,D_i\,b_f\,(d_b-b_f\,) \tag{2.4}$$

In equation 2, α is the coefficient of transfer for the plastic hinge with a recommended value of 0.85 to 0.9. Considering the applied momentum in the non-reduced section in the face of the column (Eqn. 2. 3), and the basis of the beam's section in the reduced region, and the slope of the seismic moment applied to the beam, the holes can be designed based on Eqn. 2.5.

$$D_i=\frac{Z_b\left[1-\alpha\left(\frac{L/2-L_i}{L/2}\right)\right]}{2b_f\,(d_b-b_f\,)} \tag{2.5}$$

In the above equations, L is the beam's span length, and Li is the considered section's distance for drilling and reduced section from the column's face, D_i is the hole diameter in the considered location for reduced section, and d_b is the beam height, while b_f is the beam flange width. The distance of the first hole from the column face (α) is specified in Fig. 2.1, and determined based on Eqn. 2.6. In addition, the plastic hinge length (b) can be obtained using Eqn. 2.7.

$$0.5b_f \le a \le 0.75b_f \tag{2.6}$$

$$b \ge 0.75\,d_b \tag{2.7}$$

The minimum length of the plastic hinge is considered $0.75d_b$, which this length can be considered longer, if the reduced section of the beam does not exceed 50%, so that lateral torsional buckling is prevented. The closest hole to the column face for improving the creation of the plastic hinge should be designed in a manner that its effect is tangible in the traction flange. According to conducted studies, a minimum of three rows for holes with a length of $0.75d_b$ are recommended, which in experimental models, samples were designed identical to these specifications. The remaining design procedure and required controls are the same as the RBS connection with radius cuts in ANSI/AISC 358-05.

3. EXPERIMENTAL SAMPLES

In order to examine the seismic behavior of the proposed connection, two similar samples were examined. The IPE270 profile with ST37 steel was utilized for the beams, and SM400 type was employed for the columns.

The design of hole diameters in this experimental model was based on Eqn. 2.5, and the coefficient of transfer (α) was considered 0.87. Likewise Fig. 3.1 and 3.2 demonstrate the overall diagram of the beam and column. Fig. 3.3 depicts details of the reduced section beam and the column section. All figure are based on the millimeter unit. In designing and examining the panel zone, the coefficient of shear force in the panel zone (V_{pz}) on shear resistance of the panel zone (R_v) was used.

$$R_v = 0.6 F_y d_c t_p \left[1 + \frac{3 b_{cf} t^2_{cf}}{d_b d_c t_p} \right] \tag{3.1}$$

$$V_{pz} = \frac{M_f}{d_b} - V_c \tag{3.2}$$

In the Eqn. 3.1 and 3.2, F_y = yield stress of PZ material, M_f = moment of the face column, V_c= shear force of the column. d_c, d_b, b_c, t_p, and t_{cf} are column depth, beam depth, column flange width, PZ thickness, and column flange thickness, respectively.

Table 3.1. Design of connection panel zone for experimental samples

Regulation	R_y	M_f (t.m)	V_{pz} (t)	Ø	R_{v1} (t)	R_{v2} (t)	V_{pz} / R_{v1}	V_{pz} / R_{v2}
AISC	If 1.3	14.34	30.25	1	64.9	39.6	0.47	0.76
AISC	If 1.5	16.54	35.01	1	64.9	39.6	0.54	0.88

In Table 3.1, the coefficient related to the panel zone resistance was examined in both samples. R_y is obtained from Eqn. 3.1, and R_{v1} is related to the first experimental sample, which was reinforced using an 8mm plate on the panel zone. R_{v2} corresponds to the second experimental sample without reinforced panel zone. V_{pz} is the shear force in the panel zone, which was calculated using Eqn. 3.2.

In the panel zone, displacement gauges were installed to control changes in panel zone shape, and strain gauges were installed to further examine formation of plastic hinges in the reduced section region.

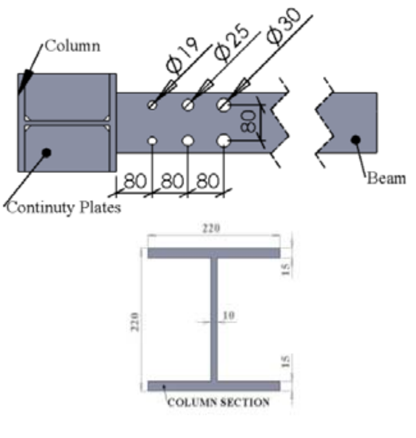


Figure 3.1. Reduced section details in experimental samples and column section

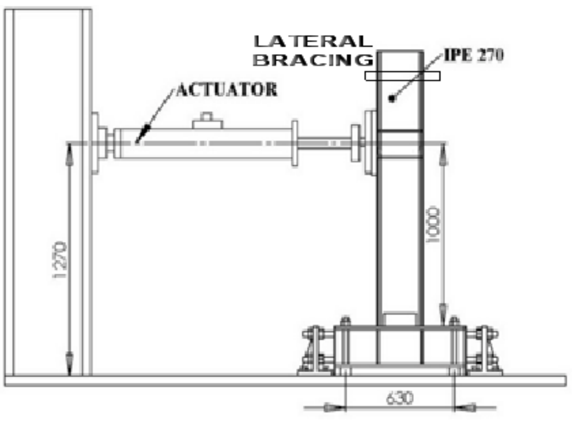


Figure 3.2. Laboratory setup

Figure 3.3. experimental sample in laboratory frame

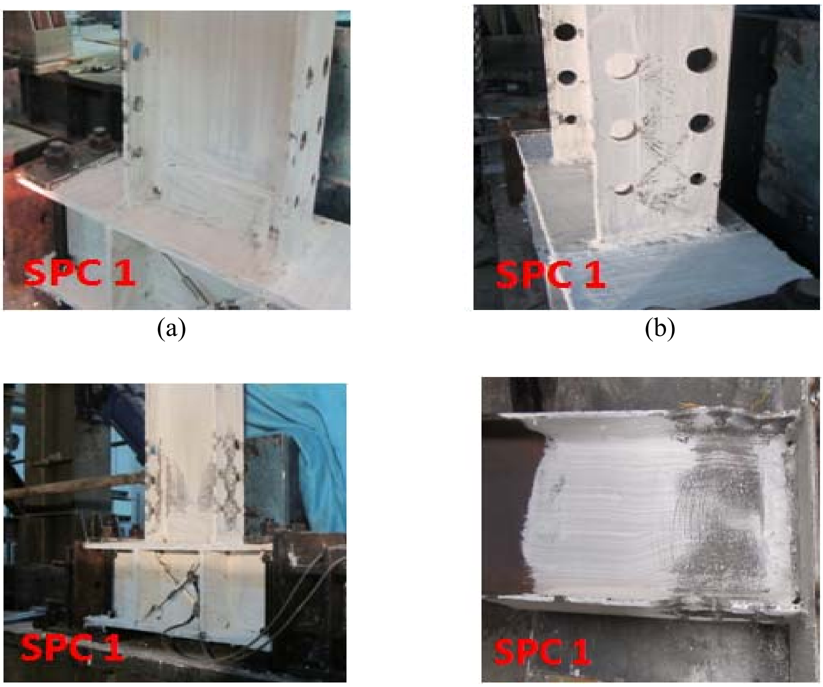
Table 3.2. Connection loading record

Loading stages	Rotation (rad)	Number cycle
1	0.005	3
2	0.0075	3
3	0.01	3
4	0.0125	3
5	0.015	3
6	0.0175	3
7	0.02	2
8	0.025	2
9	0.03	2
10	0.035	2
11	0.04	2
12	0.045	2
13	0.05	2

The loading record was selected according to the standard pattern recommended by ATC24 regulations and was applied to both laboratory samples according to Table 3.2.

4. EXPERIMENTAL RESULTS

At the end of the 10mm and start of the 12.5mm displacements, in the load location applied by the hydraulic jack (Actuator) within one meter of the column face, the lime started to shed around the holes and in front of the first row of holes near the column face on the beam flange, which tentatively indicates start of plastic hinge formation in the beam flange (Fig. 4.1-a). In the 15mm displacement, shedding of lime along the whole path specified for plastic hinge creation, indicates the near simultaneous section reduction entrance in the inelastic phase (Fig. 4.1-b).



(a) (b)

(c) (d)

Figure 4.1. Formation of plastic hinge during loading period in the first sample

In the 17.5mm displacement, in addition to the completion of plastic hinge creation in the beam flange, the hinge has been transferred to the beam's web, and in 30mm and 35mm displacements, the beam's web has predominantly become plastic hinge, and in 40mm displacement, it has turned into a shape, and gradually enters the whole beam's web into inelastic phase within the reduced section (Fig. 4.1-c). At the end of the second 40mm cycle and start of the 45mm cycle, which is equivalent to 0.045 radian rotation, Plastic hinge in web expands (Fig. 4.1-d).We stop the test at 0.045 radian rotation.

In the second experimental sample, at the end of the 35mm displacement's second cycle, some of the panel zone's lime starts to shed, which indicates that the panel zone in entering the nonlinear phase (Fig. 4.2). In the second stage of 45mm displacement, the edge of the flange ruptures adjacent to a number of holes. Finally, after withstanding the first cycle of 50mm displacement, in the second cycle, which is equivalent with 0.05 rad rotation in the beam, the flange rupture expands around the holes and progresses towards the beam's web (Fig. 4.3). It is worth noting that the web has fully transferred to plastic phase in the specified range for creating plastic hinge in the RBS-DHA connection in the first 0.05 rad rotation stage. Considering the two experimental samples, plastic hinge occurs between the holes along the length of the reduced section (Fig. 4.1-c).In addition, the beam's web along the reduced section has fully entered inelastic phase (Fig. 4.1-d). Expansion of plastic hinge in the reduced section range of the beam flange leads to reduced lateral torsional buckling, and almost until the first cycle of 0.045 rotations, lateral torsional buckling is inconsiderable. However, local buckling was observed on the reduced section in the beam flange.

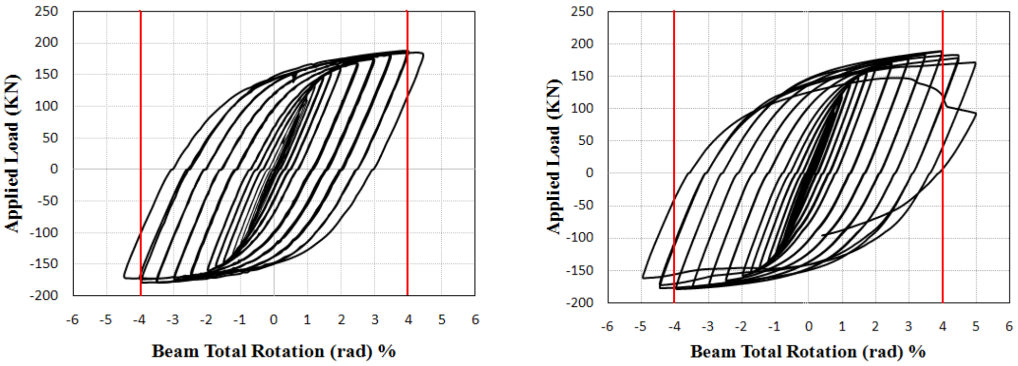
Figure 4.2. Formation of plastic hinge in the beam and panel zone of the second sample

Figure 4.3. Method of rupture in the second sample

4.1. Examining the Cyclic Behavior of Experimental Samples in the Proposed Connection

The first sample of the RBS-DHA proposed connection was capable of withstanding two 0.04 rad cycles, and one cycle of the 0.045 rad rotation without force loss. Thus considering laboratory setup conditions, the test was stopped. In terms of seismic behavior, the RBS-DHA connection in the first sample was capable of withstanding minimum 0.04 rad rotation mentioned in AISC regulations without decline in resistance. Therefore, the proposed RBS-DHA connection can be employed in special moment frames in steel structures. The second experimental sample in addition to withstanding two 0.04 rad cycles and two 0.045 rad cycles with low force decline, also withstood one 0.05 rad rotation, which is considered suitable terms of ductility.

Considering the suitable behavior of both experimental samples, the RBH-DHA connection with its suitable ductility can be used for special moment frame applications. The hysteresis curve of both experimental samples is demonstrated in Fig. 4.4.



(a) (b)

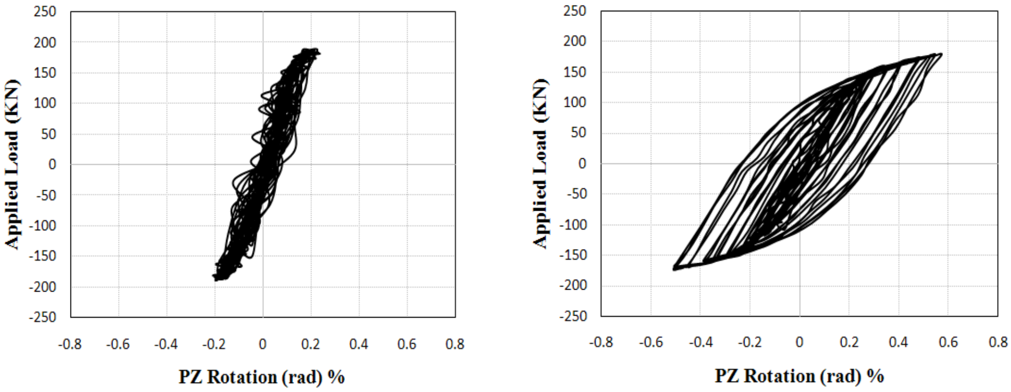
Figure 4.4. Hysteresis curve a) First sample (test stopped in 0.045 rad rotation) b) Second sample (test continued until rupture, 0.05 rad rotation)

4.2. Examining the Behavior of Panel Zone in Experimental Samples

Considering that two displacement gauges were installed on experimental samples, these devices were installed on the panel zone in diametrical form according to Fig. 4.2, so that panel zone rotation could be calculated. Eqn. 4.1 can be used to obtain panel zone rotation.

$$\gamma_{pz} = \frac{a^2 + b^2}{2ab}(\delta_1 - \delta_2) \tag{4.1}$$

Were a and b, are length and width of the panel zone, and δ_1 and δ_2 are changes in panel zone diameter length. The panel zone rotation in both experimental samples is demonstrated in Fig. 4.5. Considering obtained experimental results of the panel zone in Fig 4.5, and the analytical coefficients of the panel zone (V_{pz}/R_v), panel zone contributions can be compared.



(a) (b)

Figure 4.5. Panel zone rotation curve a) First sample, b) Second sample

4.3. Examining the Formation of Plastic Hinges Using Strain Gauges

In the first sample, strain gauges number 1 to 4 have been used according to Fig 4.6. Strain gauge results in the first sample are compared in Fig.4.7. The values of strain gauges 3 and 4, which were closer to the column face are more than those of 1 and 2; and in the second sample, rupture occurs from the location of holes near the column face.

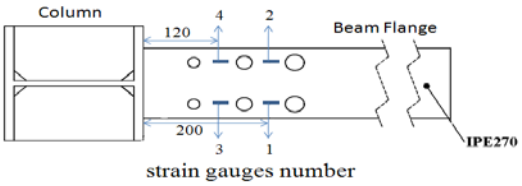


Figure 4.6. Location of strain gauge installations in the first sample

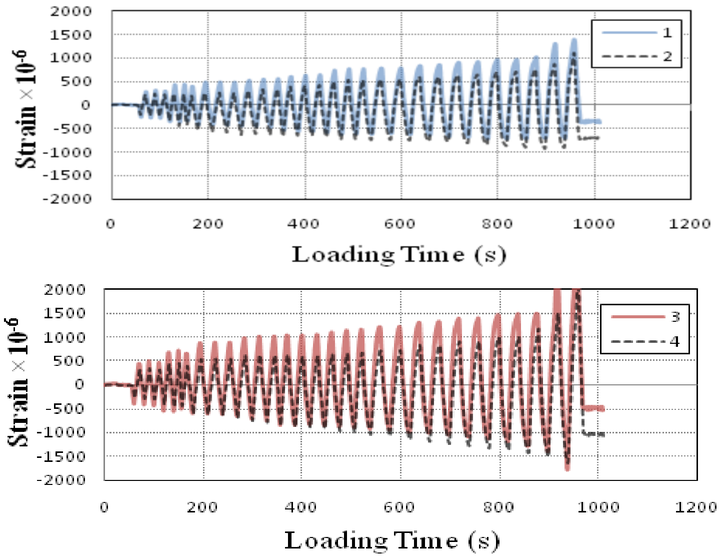


Figure 4.7. Strain gauge value curve based on tome of loading in the first sample

5. CONCLUSIONS

Moment connection with reduced section in the beam flange via drilled holes with variable diameter and orderly layout (RBS-DHA) is capable of reaching 0.05 rad rotation. Therefore, this connection can be employed in special steel moment frames.

In moment connection with reduced section in the beam flange via drilled holes with variable diameter and orderly layout (RBS-DHA), compared to the RBS connection with radius cut, the effective length of the plastic hinge has increased, and this issue leads to reduction in lateral torsional buckling in the beam, and consequently delays instability in the beam during cyclic behavior. Thus, it can cause energy absorption within a further range of the beam’s web and flange compared to the RBS connection with radius cut.

In the proposed connection, the panel zone rotation in the experimental sample continued rotation until 0.0057 rad, and no fracture has occurred on the face of the column. Therefore, the contribution of higher rotations in the panel zone can be examined for further improvement of seismic behavior.

Considering strain gauges have recorded higher strain values around holes near the column face, and the fact that fracture has occurred in the second cycle of 0.05 rad rotation in the nearest distance of holes to the column face, therefore calculating a optimized and suitable distance for creating more steady strains in the reduced section region for further improved seismic behavior of the proposed connection can be examined.

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