Numerical Investigation to Assess the Cyclic Performance of RBS Connection using Cover Plates

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Abstract. This paper presents the result of four welded connections under cyclic loading using finite element analysis, those are: Conventional Connection (C-Con), Cover Plates Connection (CP-Con), Reduced Beam Section Connection (RBS-Con), and RBS Connection using Cover Plates (RBSCP-Con) using the same material properties, including dimension of the profile and its span. Previous research indicates that, even though the fact that the initial seismic yield must be located far from the column's face, it still occurs on the majority of RBS connections on occasion. By adding a cover plate to the top and bottom flanges of the beam, the research can provide a seismic design improvement for RBS connections. The analysis results observed that cyclic performance of RBSCP-Con was much superior to the other connections in terms of plastic hinges location, panel zone's performance, and failure modes. However, CP-con has the maximum value of energy dissipation, which correlates with its hysteresis curves. Furthermore, all of the four types of connections already satisfy SMF category requirements in accordance with AISC 341-16.

1. Introduction

Since the 1994 Northridge earthquake, the brittle failure of connections between beams and columns has been identified in over 150 steel building structures. Beam-column connections are an essential structural component, particularly in structures designed to withstand earthquakes. In addition to holding components together, connections facilitate the transfer of load from one component to another. The structural strength of the connections determines whether the structure would survive an earthquake or collapse. To ensure the occurrence of plastic hinges in the beam area, it is essential to design optimal connections [1]. Due to its ductility, configuration adaptability, and construction speed, steel is one of the most commonly ways as building materials to prevents delays in construction [2].

The reduced beam section, also known as RBS, is a good method to implement the "strong column-weak beam" mechanism, according to post-Northridge research [3], [4]. A small part of the beam's flange area was cut off in order to reduce the beam's section and encourage the weakest zone to facilitate yielding. In order to effectively dissipate energy and accommodate extensive rotations under cyclic stresses, RBSs were developed in the 1990s [5].

The special moment frame must conform to AISC 341-16 [6], category requirements for SMFs. AISC 341-16 requires a minimum moment value at the column face of 80% of the nominal plastic moment capacity (Mp) at 4% rad of story drift angle for the SMF category. As shown by the data, the conventional RBS moment connections produced a minimal plastic rotation of 0.03 rad to 0.04 rad, which is still below the requirements for LS (Life Safety) leveled structures. However, they were unable to perform to CP (Collapse Prevention) standards in the context of higher seismic hazard levels required by ASCE 41-17 [7] for RBS connections under the LS and CP level, however, are 0.0525-0.00001*db* and 0.07-0.000012*db*, which *db* is the beam depth in mm. These minimum rotations are about equal to 4.5% and 6.0% rad, respectively. This problem is due to the web's premature local buckling [8].

The connection of RBS has been conducted by previous research over the past decades. As the example: In 2013, Ludovico et al. [9] determined that a plastic hinge should not occur close to the connection. Their analysis revealed that connection with RBS reduces stress concentration at the connection more effectively. Under monotonic load,

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Casita and Kamandang [10] analysed the behaviour of three varieties of RBS, namely RBS with radius cut, RBS with straight cut, and RBS with tapered cut in 2018. Afterwards in 2020, Casita et al. [11] investigated the axial load behaviour of Rectangular Concrete Filled Tubes (RCFT) and Circular Concrete Filled Tubes (CCFT) column composite, which later then combined with the RBS beam as beam-column-connection and analyzed by applying monotonic [12] and cyclic loading [13] in 2022.

Despite the application of the RBS method to the beam flanges, the fracture still occurs in close proximity of the connection in some instances [14]. In 2018, Yilmaz and Bekiroglu [15] conducted research regarding improved connections, consisting of steel connections with Cover Plates and RBS. The panel zone performance and damping performance of connections with Cover Plates are inadequate. The RBS connection, meanwhile, has comparatively low values for moment capacity, energy dissipation, and initial rotational stiffness. In addition, the location of the formation of plastic hinge is closer to the column side joint area compared to the Cover Plates Connection. In 2022, Qiao et al. [16] installed reinforcement in the RBS area to generate a good anti-progressive collapse response by way of strengthening. However, due to the relatively complex installation procedure, it is advised to utilize an alternative option.

This research incorporates the RBS connection design with the Cover Plates connection. Obviously, it presents a number of obstacles, including the requirement for design-related special considerations in connection and installation-related specialization.

The seismic capacities of RBS connections can be enhanced, providing the opportunity to strengthen the performance of the frame. A cover plate placed on the top and bottom of the beam flange is one method for preventing the first yield from occurring near to the connection. Therefore, this could lead to the development of an RBS connection design that is effective and efficient in terms of installation and earthquake resilience.

2. Materials and Methods

In this paper, the connection performance is assessed under cyclic loading using Indonesian profiles, those are: Conventional Connection (C-Con), Cover Plates Connection (CP-Con), Reduced Beam Section Connection (RBS-Con), and RBS Connection using Cover Plates (RBSCP-Con). The radius cut geometrical characteristics of RBS connection are determined according to FEMA-350 [17] design procedures. The material characteristics were defined by using SS400 with a combined hardening parameter [18] with elastic modulus E = 200 GPa, Poisson's ratio ν = 0.3. The analysis was carried out on the wide flange using 300x300x11x17 as a column, while 250x125x6x9 as a beam for Indonesian profile with the attached welded shear plate PL 200.50.6 mm. The length of the column is 2800 mm and the length of each beam is 1600 mm. The details of the connections are provided in Figure 1.

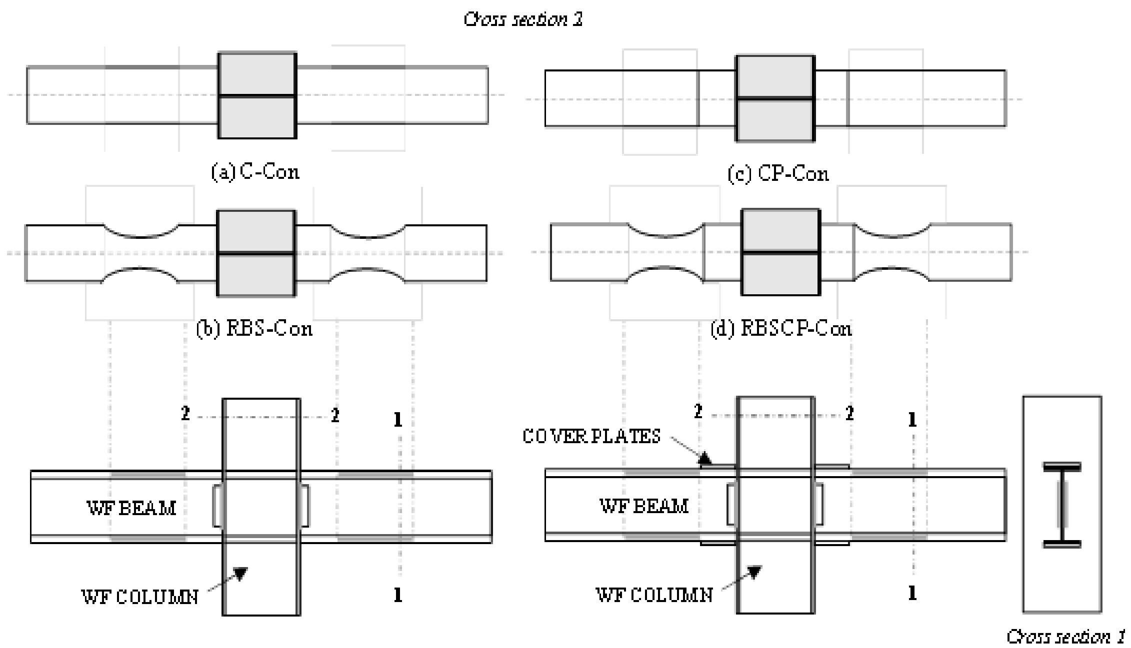

Fig. 1. Connection variation for proposed model

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Table 1. Details of the connection model

Specimens	Column	Beam	Continuity plate thickness (mm)	Doubler plate thickness (mm)	Cover plate thickness (mm)
C-Con	WF 300x300x11x17	WF 250x125x6x9	10	10	-
RBS-Con	WF 300x300x11x17	WF 250x125x6x9	10	10	-
CP-Con	WF 300x300x11x17	WF 250x125x6x9	10	10	10
RBSCP-Con	WF 300x300x11x17	WF 250x125x6x9	10	10	10

Figure 2 shows a schematic view of the idealized boundary condition of the model and the loading conditions. Pin support is in the bottom end of the column, while the displacement forces, F, is placed on the top end of the column which constrained in the lateral direction by imposing cyclic displacement, based on AISC Seismic Provisions loading protocol to 8% rad drift angle as in Table 2 and Figure 3. A pair of roller supports are applied to the two beam ends. The welds were not modeled in the subassemblies for these four models, instead using tie constraint definition for combining the connection instances.

In order to simplify the modeling, the flanges and web profiles are taken to have rectangular cross sections. Multiplying q by L_c produces the required displacement values at the loading point. To obtain the value of required displacement loading at the loading point, which is on the top of the column, story drift angle (q) is multiplying by the distance from column centerline to the loading point (L_c).

Table 2. RBS dimensions

Specimens	a (mm)	b (mm)	c (mm)	R (mm)
Beam WF 250x125x6x9	75	187	25	187.34

Table 3. Loading protocol

Load step	**Drift angle, rad**	**Number of cycles, *N***
1	0.00375	6
2	0.005	6
3	0.0075	6
4	0.01	4
5	0.015	2
6	0.02	2
7	0.03	2
8	0.04	2
9	0.05	2
10	0.06	2
11	0.07	2
12	0.08	2

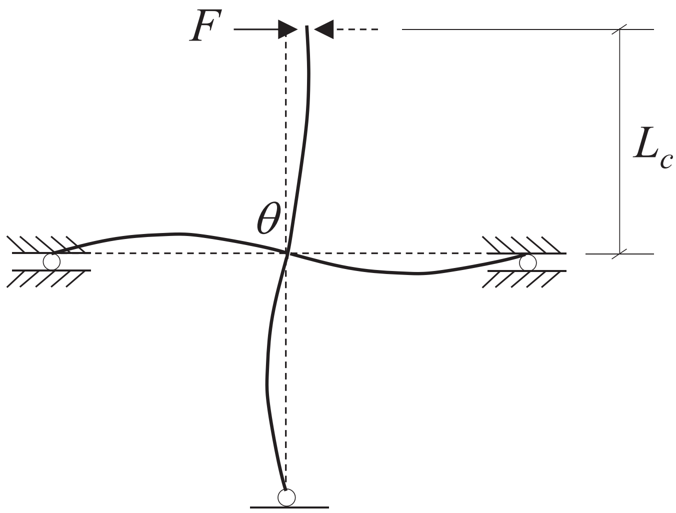


Fig. 2. Schematic view of boundary condition

In accordance with the FEMA-350 recommendations, the dimensions values of RBS are determined using Eqs. (1) - (3). The parameters *a*, *b*, and *c* represent the distance of RBS from the column face, the RBS size, and the RBS depth, respectively.

$$0.5\, b_f \leq a \leq 0.75\, b_f \tag{1}$$

$$0.65\, d \leq b \leq 0.85\, d \tag{2}$$

$$0.1\, b_f \leq c \leq 0.25\, b_f \tag{3}$$

where b_f indicates the beam width, while d indicates the depth of the beam.

$$R = \frac{4c^2 + b^2}{8c} \tag{4}$$

where R represents the radius of RBS cut

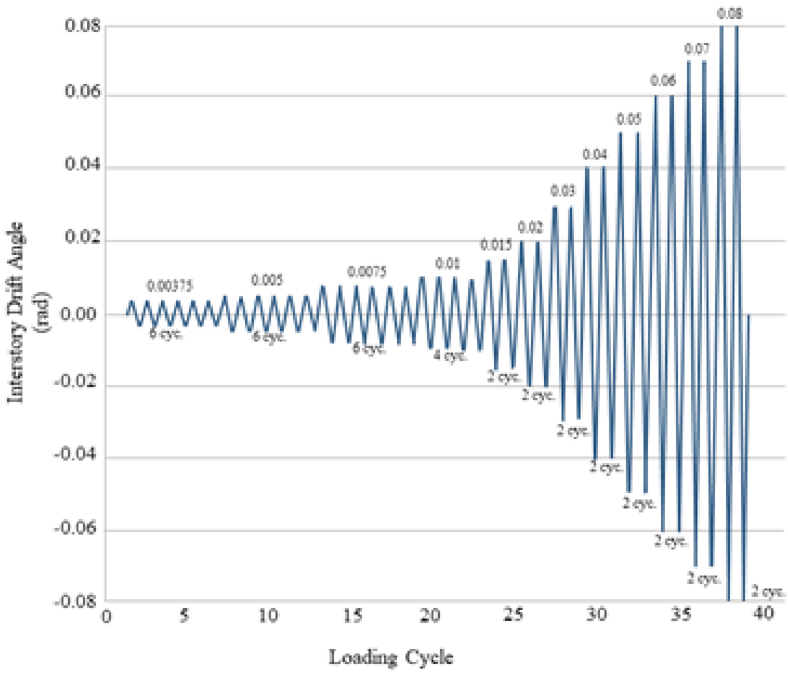


Fig. 3. Loading history based on AISC Seismic Provisions

3. Results and Discussion

A numerical analysis has been conducted in order to determine the influence of various parameters. Based on these comparisons, the RBS model's design was developed by adding cover plates (CP) on the upper and lower sides of the beam in order to reduce the occurrence of stresses in the area of the beam close to the column face which is named by RBSCP-Con. For all varieties of connection models, Figures 5 exhibits a moment-rotation curve and a backbone curve, respectively.

The results of numerical analysis on the four connection models indicate that they conform to the AISC Seismic Provisions standard, which stipulates that a structure in the SMF category must have at least 80% of the nominal beam moment capacity, or 0.8 Mp, with a deviation of 4% rad, or 0.04 radians. In the following illustration, the presence of cover plates on RBSCP-Con can reduce the stress on the beam that is adjacent to the face of the column when compared to ordinary RBS connection in RBS-Con model.

The equivalent plastic strain (PEEQ) is recognized as an index of localized failure that contributes to the restructuring of connections under seismic loading. For the C-Con model as in Figure 6, the PEEQ is observed to be greater in the very close distance to the column face, which leads to localized weld fracture. A level of moderate to high PEEQ was observed in the RBS region of the RBS-Con model, while significant PEEQ was additionally noticed in the connections. However, by placing cover plates on the top and bottom sides of the beam, it is conclusively shown that much less PEEQ occurred in the connection in both CP-Con and RBSCP-Con model. It is evident that the plastic hinge was formed in the RBS region rather than the connection area

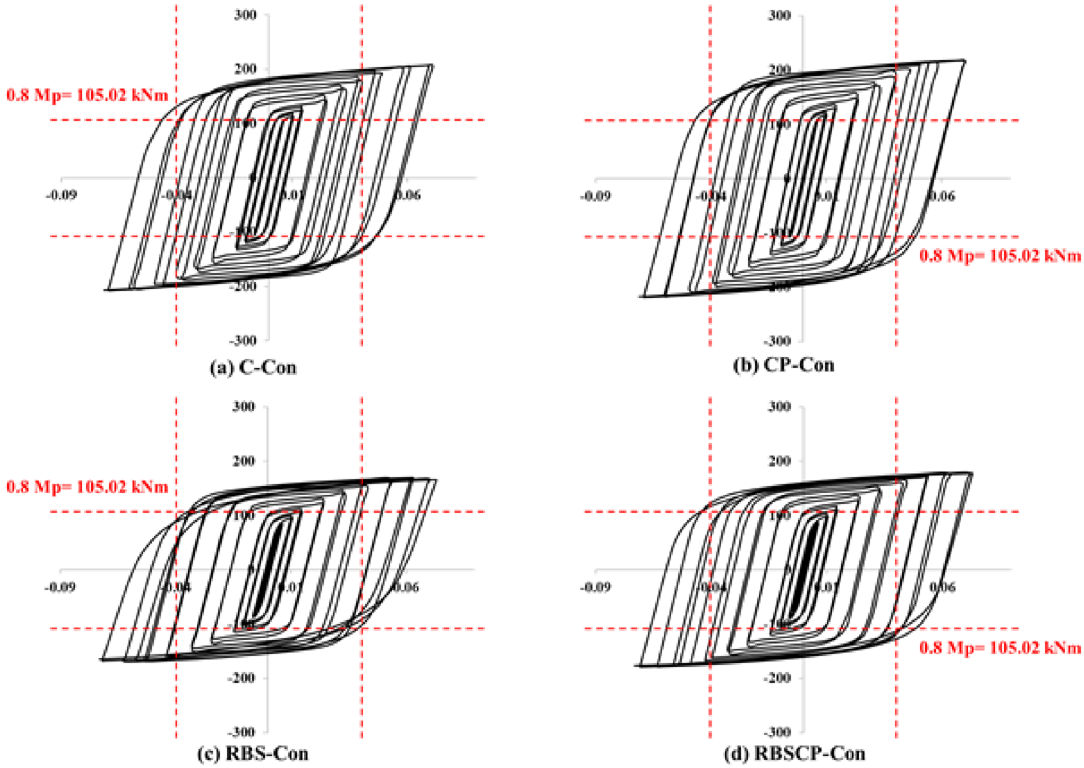


Fig. 4. Cyclic response in the hysteresis curve for each connection models

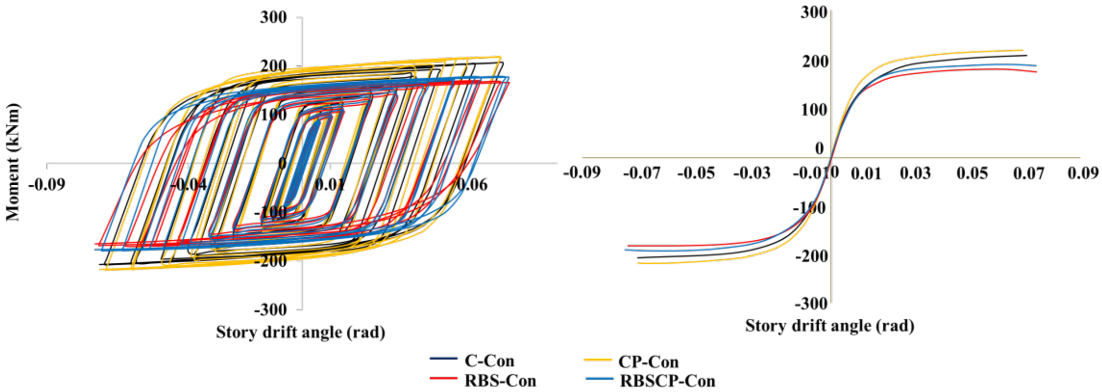
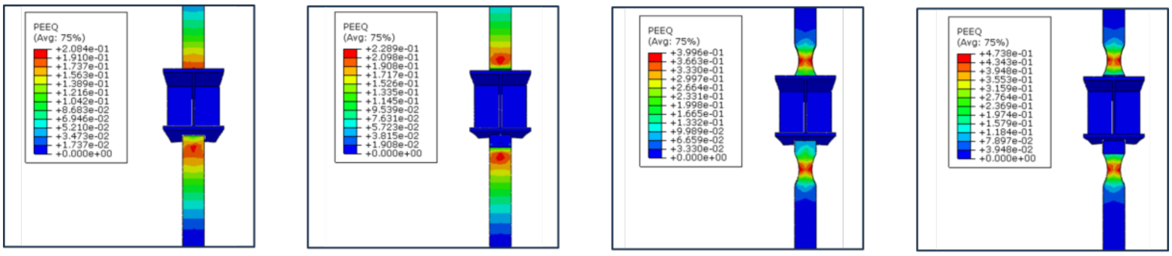


Fig. 5. Moment-rotation curve and backbone curve for all types of connection models

Figure 7 illustrates the von Mises contours for every connection model. In C-Con model, it is evident that the maximal distribution Von Misses continues to occur in the vicinity of the beam near the connection until 4% rad. However, in the CP-Con model, it is recognized that the maximal regions of stress contours are no longer in the connection. In RBS-Con, the maximal regions of stress contours are observed in the region of the reduced beam section, whereas a certain negligible stress also occurred in the connection near to the column face. As it turns out, the maximum value of stress in the RBSCP-Con model occurred only in the reduced region of the beam, because of the addition of cover plates in that connection. Before 0.04 rad of rotation, no out-of-plane buckling existed throughout the entire connection.

Calculating the area of the hysteresis curve provides energy dissipation capability. Observations reveal that the energy dissipation at 8% story drift angle of the RBSCP-Con model (555.53 kNm) is significantly greater than that of the RBS-Con model (518.96 kNm), but not as considerable as that of the CP-Con model (630.14 kNm) and the C-Con model (602.13 kNm). Notably, applying a plate to reduce the risk of local buckling in the flange and web regions of the beam can increase the moment capacity and stiffness of the connection, whereas reducing the section of the beam may reduce its strength.



(a) C-Con (b) CP-Con (c) RBS-Con (d) RBCP-Con

Fig. 6. PEEQ distribution for each connection models at 4% story drift

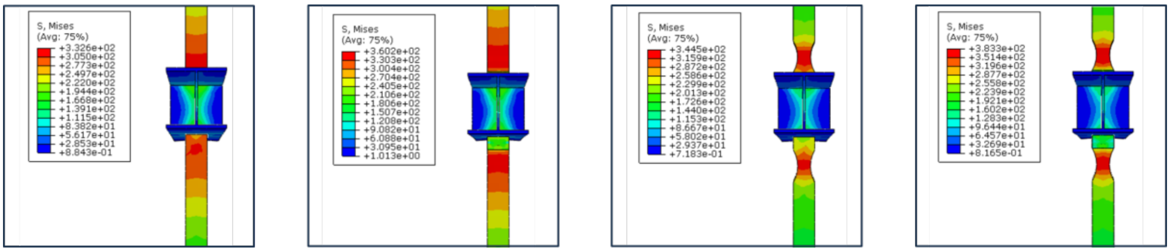


Fig. 7. Von Mises distribution for each connection models at 4% story drift

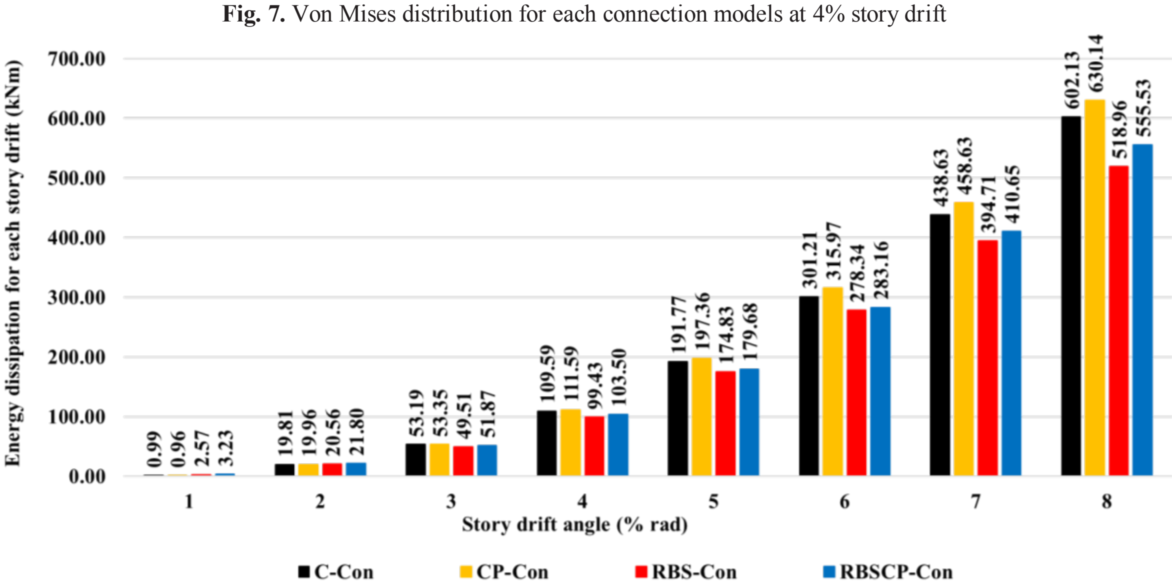


Fig. 8. Energy dissipation comparison for each story drift

4. Conclusions

1. The design development of the RBS model was carried out by adding cover plates (CP) on the upper and lower sides of the beam, named RBS-Con model. All proposed connection models, including C-Con model, CP-Con model, RBS-Con model, and RBSCP-Con model were meet the requirements for Special Moment Frames (SMF) category, according to AISC 341-16, with at least 80% of the nominal plastic moment capacity at 4% rad of story drift angle.
2. Observations indicate that the energy dissipation at 8% story drift angle of the RBSCP-Con model (555.53 kNm) is marginally higher than the RBS-Con model (518.96 kNm). Moreover, the resulting hysteresis curves of both connections were satisfactory, with no degradation observed up to a rotation of 8% radian. It is important to note that adding the cover plates in RBSCP-Con model has a slight effect on the hysteresis curve of the connection.
3. In RBS-Con model, the maximum regions of stress are observed in the reduced beam section region as well as in the vicinity of the beam, in very near proximity to the column face. Fortunately, the highest value of stress in the RBSCP-Con model occurred only in the beam's reduced region, which are no longer in the vicinity of the beam because of cover plates.

4. By selecting the proper dimension and contemplating the appropriate cutouts, local buckling in the plastic hinge zone can be prevented for rotations in 0.04 radians. In models examined, neither local buckling nor a substantial degradation in rigidity and stiffness were observed at inter-story drift angles of 0.04 radians or less.

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