Cover Plate Integration In Reduced Beam Section Connections: Stress

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This study presents a comparative evaluation of four steel beam-to-column connection configurations: Conventional (CONV), Cover Plate (CP), Reduced Beam Section (RBS), and a hybrid Reduced Beam Section with Cover Plate (RBSCP), under cyclic loading conditions, with particular emphasis on hysteresis behavior and energy dissipation capacity. Finite element simulations were performed up to 6% story drift to evaluate each model's performance against the seismic demand limits prescribed in ASCE/SEI 41-17. All configurations demonstrated adequate ductility for moderate to severe seismic events. The CONV connection underperformed in both energy dissipation and stiffness retention, producing narrower hysteresis loops and exhibiting earlier stiffness degradation. In contrast, the CP connection achieved the highest energy dissipation and moment strength at all drift levels, attributed to the increased flange stiffness from the cover plates. The RBS connection exhibited stable, wellbalanced hysteresis loops with slightly lower strength but effective energy dissipation, benefiting from the intentional relocation of the plastic hinge away from the column face. The RBSCP connection combined the advantages of strength and ductility, sustaining broad and stable hysteresis loops with minor asymmetry between the positive and negative directions. Although it did not surpass the CP connection in peak strength, the RBSCP connection offered a well-balanced seismic performance. Analysis of the cyclic hysteresis loops revealed distinct differences in stiffness characteristics and degradation behavior. These findings highlight the potential of hybrid configurations such as the RBSCP connection, with further geometric optimization recommended to enhance consistency and reliability.

Keywords: Cover Plate; Cyclic Loading; RBSCP Connection; Reduced Beam Section; Seismic Performance; Seismic Enhancement

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1. Introduction

The seismic performance of steel beam-column connections under cyclic loading is a critical issue in earthquake-resistant design, as it governs ductility, strength, and energy dissipation capacity. Beam-column connections play a dominant role in maintaining structural integrity during seismic events. Post-earthquake investigations following the 1994 Northridge event identified extensive brittle damage in welded moment connections, emphasizing the necessity for connection designs that can sustain significant inelastic deformation.

Among the post-Northridge innovations, the Reduced Beam Section (RBS) connection was developed to relocate plastic hinging away from the column face by locally reducing the beam flange, thereby protecting the welded joint [1, 2]. Numerous studies have confirmed the effectiveness of RBS connections in enhancing ductile behavior under cyclic loading [3–6]. However, previous studies have reported that RBS connections still exhibit several limitations, including susceptibility to premature web local buckling [7] and limited plastic rotation capacity that may not fully satisfy the Collapse Prevention (CP) criteria specified in ASCE 4117 [8]. To further improve performance, several modified RBS configurations have been proposed, including double RBS [9], curved cell web RBS [10] , and kinked-bar reinforced RBS [11], aiming to delay local buckling and enhance rotation capacity. Despite these improvements, challenges remain in balancing stiffness, strength, and deformation capacity.

To address these challenges, hybrid solutions such as Cover Plate (CP) connections and reinforced Reduced Beam Section (RBS) configurations have been investigated. CP connections increase stiffness and strength but often exhibit limited energy dissipation and suboptimal panel zone performance [12]. RBS connections enhance stress redistribution yet provide insufficient rotational capacity and energy dissipation [13].

This study presents and evaluates a Reduced Beam Section with Cover Plates (RBSCP) connection, incorporating cover plates on the top and bottom beam flanges near the RBS cut, away from the column face. The design aims to relocate the plastic hinge from critical weld zones, maintaining an optimal balance between strength and ductility, and increase energy dissipation under seismic loading. Finite element analysis under cyclic loading is employed to evaluate and compare the effectiveness of the RBSCP connection with CONV, CP, and RBS connection configurations.

2. State of the art - verification phase

The experimental results reported by Lee et al. (2005) [14] were employed to verify the numerical model developed in this study. The detailed geometry of the specimens is illustrated in Fig. 1. As shown, the Reduced Beam Section (RBS) configuration was designed to concentrate plastic deformation within the beam, thereby preventing premature fracture at the beam-column interface. The column steel had a yield strength of 324 MPa , while the beam steel exhibited a yield strength of 235 MPa. Although the numerical simulation produced

slightly different response values compared with the experimental results, the overall loaddeformation behavior and failure patterns are in good agreement. This consistency confirms that the numerical model can reliably reproduce the experimental response, as further demonstrated by the comparisons presented in Fig. 2.

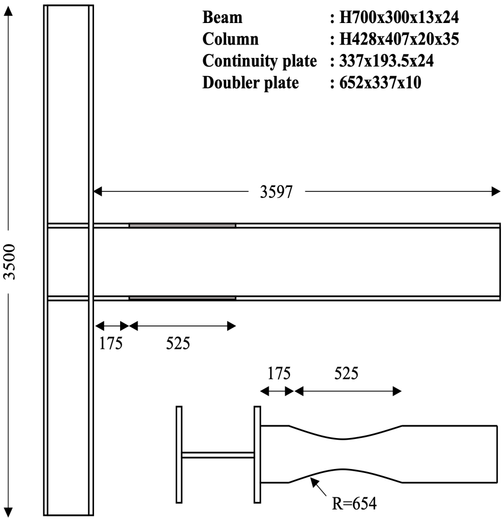


Fig. 1. Detail parameter of specimen

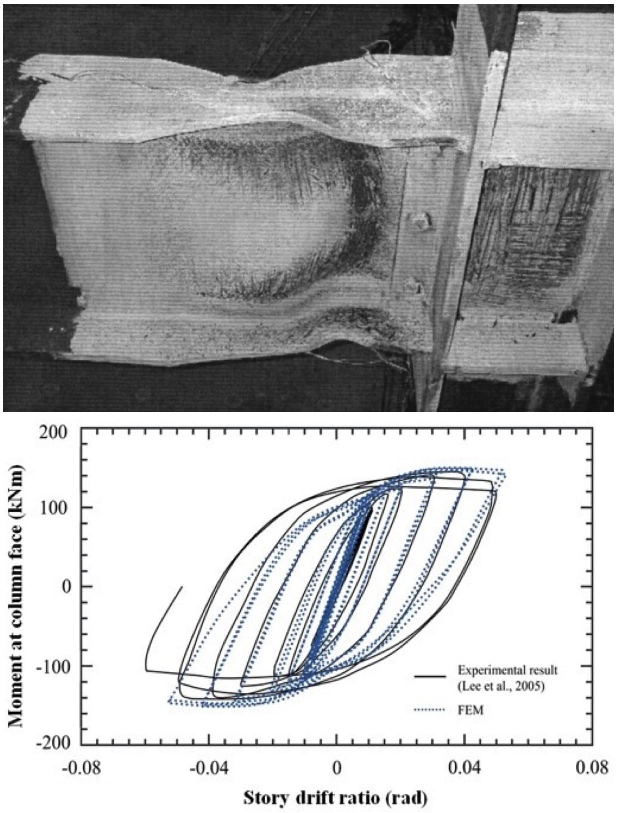


Fig. 2. Experimental vs. numerical results

3. Material and methods

This study examines the cyclic response of steel beam-column connections through finite element modeling. The beam and column lengths are 1750 mm and 2800 mm , respectively. As summarized in Table 1, the RBS cutting region is characterized by parameters $a = 75$ mm, $b = 175$ mm , and $c = 25$ mm, where a represents the distance from the column face to the start of the reduced section, b denotes the length of the reduced region, and c corresponds to the depth of the flange reduction. The material behavior is defined using SS400 steel with a combined isotropic-kinematic hardening model [15]. A displacement-controlled cyclic loading protocol is applied, with rotation amplitudes incrementally increased from ± 0.00375 rad to ± 0.08 rad in accordance with the seismic loading provisions of AISC 341-22 [16], with the geometrical profiles of the column, beam, and cover plate detailed in Table 2,. The finite element models employed three-dimensional reduced-integration solid elements (C3D8R). Local mesh refinement (approximately $10 - 15$ mm) was applied to cover plates and welded interfaces, while beam and column members were discretized using a uniform mesh. In all four sub-assembly models, the welds were not modeled explicitly, and the connection between components was represented using tie constraint definitions.

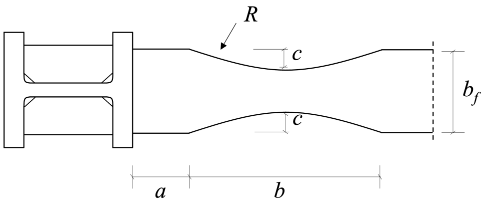


Fig. 3. Geometry of radius cut RBS

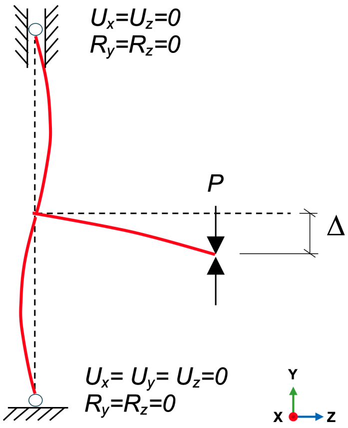


Fig. 4. Loading conditions

The boundary and loading conditions are shown in Fig. 4. The column base is fully restrained to represent a rigid support, while cyclic lateral displacement is imposed at the beam tip to simulate seismic action. To accurately capture nonlinear structural behavior, the finite element model incorporates large deformation effects and geometric nonlinearity, allowing for realistic simulation of yielding, local buckling, and post-buckling responses under cyclic loading. As shown in Fig. 5, four distinct types of beam-column connections were analyzed: (a) the CONV connection, (b) the CP connection, (c) the RBS connection, and (d) the RBSCP connection.

4. Results and discussion

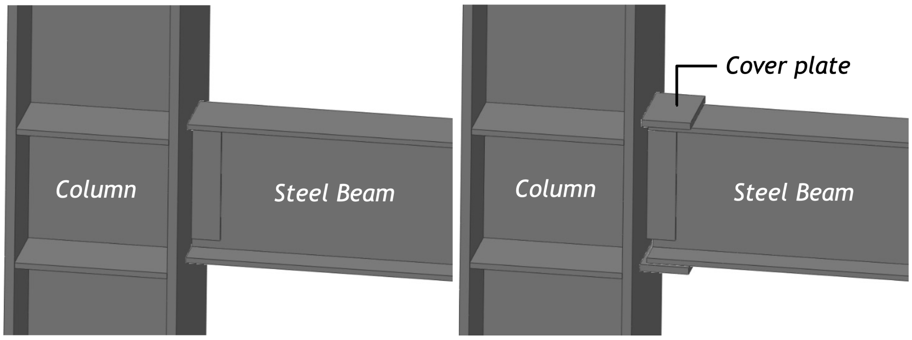
4.1. Plastic Equivalent Strain (PEEQ) Distribution

The PEEQ distribution effectively illustrates the inelastic behavior and plastic hinge formation of each connection type. In the CONV connection, plastic strain initiates and accumulates near the beam-to-column weld zone (Fig. 6a), indicating a high concentration of local plastic strain demand under cyclic loading. In the CP connection, the plastic zone shifts slightly away from the column face owing to the stiffening effect of the cover plates (Fig. 6b). Although minor strain remains near the weld, most deformation occurs at the plate ends, suggesting improved strain relocation. The RBS connection shows pronounced strain concentration within the notch region (Fig. 6c), confirming its effectiveness in shifting the plastic hinge, though excessive localization may limit energy dissipation.

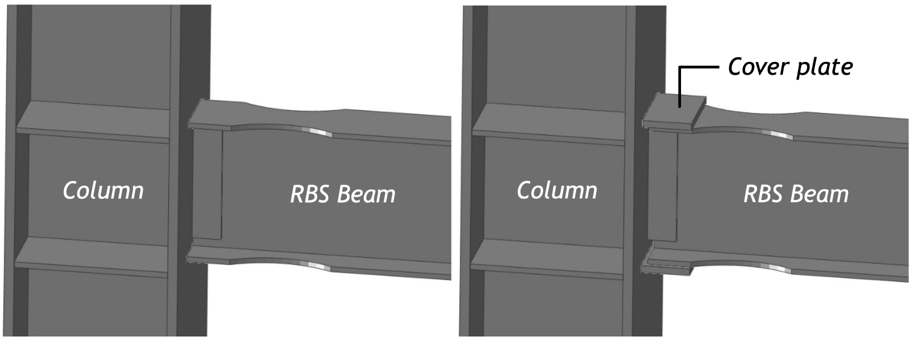
The RBSCP connection exhibits the most favorable pattern, with plastic strain distributed more uniformly along the beam and peaking near the plate end (Fig. 6d), successfully relocating the hinge away from the weld and maintaining an optimal balance between strength and ductility, and seismic resilience. However, in the RBSCP connection, the redistribution of plastic deformation toward the reduced beam section mitigated stress concentration at the plate ends, resulting in a smoother stress gradient along the beam flange. This behavior suggests a reduced plastic strain concentration near the column face compared to the CP connection, highlighting the beneficial role of combining RBS geometry with cover plates in controlling stress concentration under cyclic loading.

4.2. Plastic Strain Path

To evaluate the plastic deformation behavior in greater detail, a path analysis of Plastic Equivalent Strain (PEEQ) was performed along the $\mathrm{A} - \mathrm{B}$ line positioned on the beam



(a) CONV Connection **(b)** CP Connection



(c) RBS Connection **(d)** RBSCP Connection

Fig. 5. Details of the connection model configurations

Table 1. Details of the RBS geometry

$a(\text{ mm})$	75
$b(\text{ mm})$	175
$c(\text{ mm})$	25

Table 2. Details of connection model

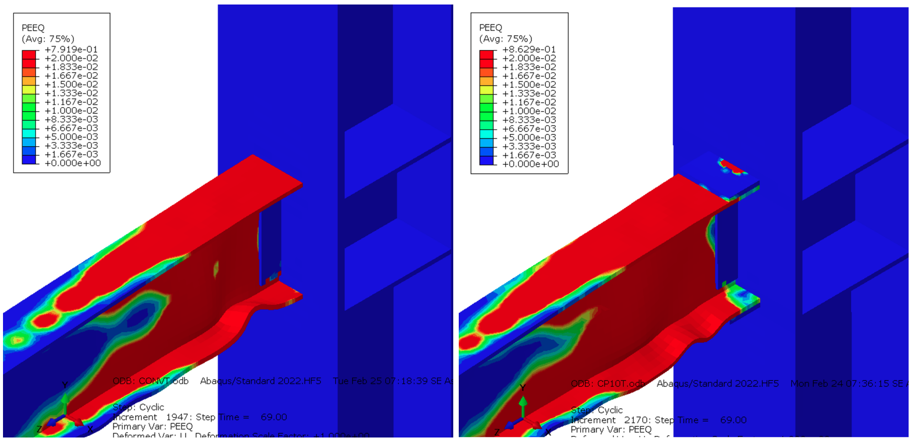
Column	WF 300 × 300 × 12 × 17
Beam	WF 250 × 12 × 6 × 9
Cover plate	125 × 75 × 10
Steel grade	SS400

Table 3. The energy dissipation results of each connection model at various story drift angles

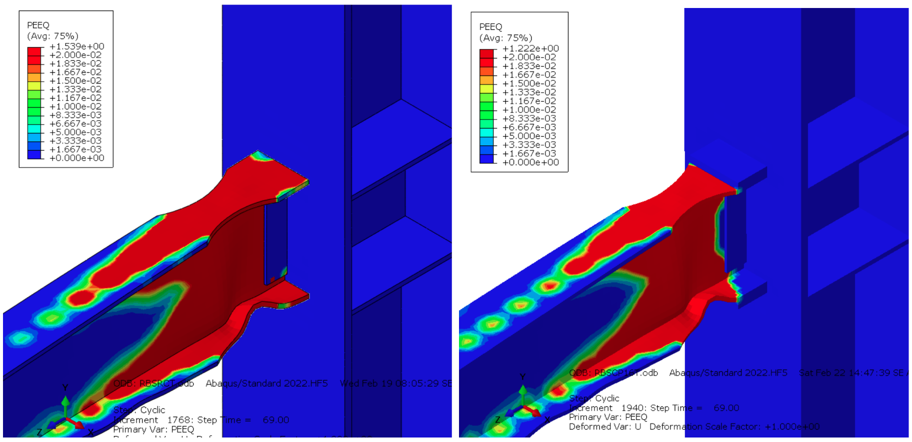
Drift Angle (% rad)	CONV (kNm)	CP (kNm)	RBS (kNm)	RBSCP (kNm)
1	0.14	0.22	1.01	1.35
2	5.39	5.69	7.17	8.29
3	14.78	15.35	17.24	18.61
4	31.49	32.23	33.67	35.74
5	54.03	56.34	55.45	58.19
6	81.26	86.10	81.00	83.87

flange surface (Fig. 7). For the CP and RBSCP connection, this path lies beneath the top cover plate

yet remains on the flange surface, enabling clear observation of strain development despite plate coverage. The CONV connection exhibits a steep and early PEEQ increase along the AB path, reflecting severe strain concentration near the beam-to-column weld. In contrast, the CP connection shows a more gradual PEEQ rise and broader strain spread, with the peak shifted away from the column face, indicating improved inelastic demand redistribution. The RBS connection displays a sharply peaked PEEQ profile centered within the reduced section, confirming effective



(a) CONV Connection **(b)** CP Connection



(c) RBS Connection **(d)** RBSCP Connection

Fig. 6. PEEQ distribution of proposed connection models

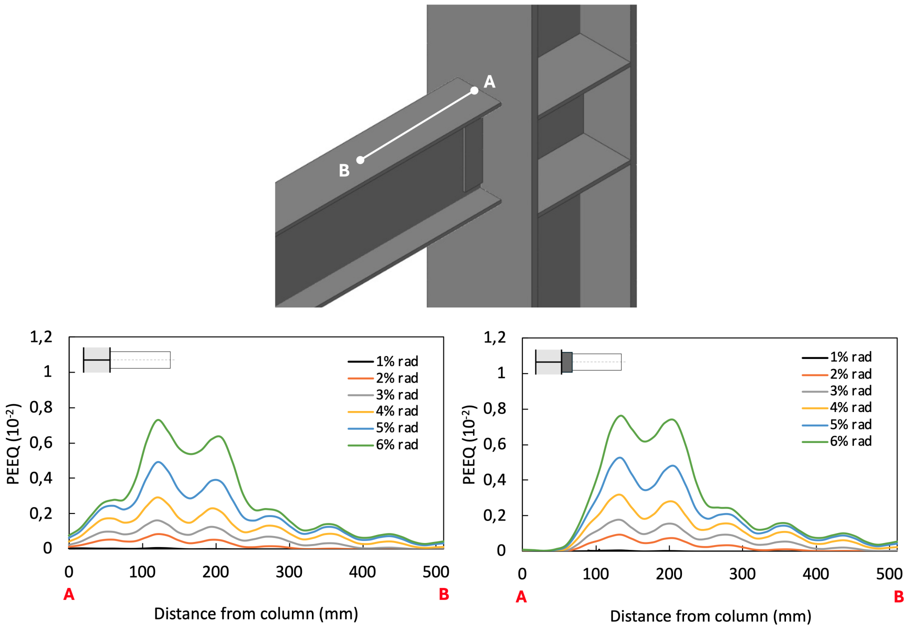
hinge relocation but with high strain localization. Similarly, the RBSCP connection exhibits a localized peak near the plate end, corresponding to the RBS notch termination. This behavior relocates rather than broadens the plastic zone while reducing weld vulnerability.

4.2.1. Hysteretic Behavior and Energy Dissipation

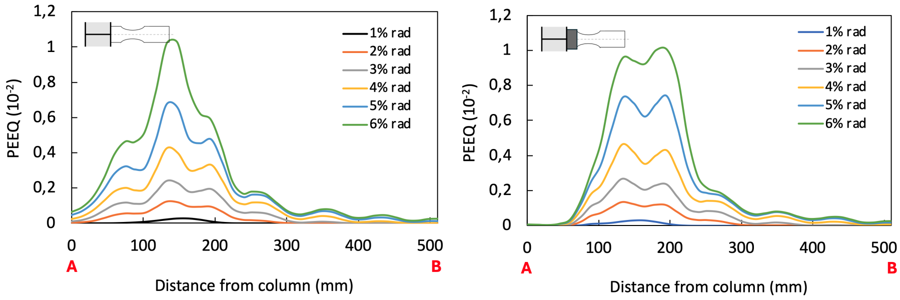
The hysteresis responses in Fig. 8, together with the cumulative energy dissipation data in Table 3, provide clear insights into the cyclic performance of the four connection types. The CONV connection exhibits narrow, pinched hysteresis loops with rapid stiffness and strength degradation beyond 4% story drift, indicating poor energy absorption, with total dissipated energy of 81.26 kNm at 6% drift, the lowest among all configurations. The CP connection displays wider loops and greater energy dissipation (86.10kNm), though stiffness degradation and limited strength gain appear at higher drifts, reflecting improved absorption without yielding relocation. The RBS connection maintains symmetrical, stable loops, representing controlled yielding and ductile deformation, with total energy dissipation of 81.00 kNm

slightly lower but more stable than the CONV connection. The RBSCP connection demonstrates a well-balanced response between strength and ductility with stable hysteresis loops and total energy dissipation of 83.87 kNm . Although drifts. Minor loop asymmetry suggests uneven plastic strain between the beam flange and cover slightly below the CP connection in cumulative energy, the RBSCP connection shows superior strength retention at large plates, indicating complex but stable deformation behavior.

Although the cumulative energy dissipation values in Table 2, show only modest differences ($81 - 86$kNm), they should be interpreted within the context of deterministic finite element analysis. As all models share identical geometry, material properties, and loading protocols, these variations reflect differences in hysteretic stability and plastic deformation distribution rather than statistical variability. In particular, the RBSCP connection exhibit more stable hysteresis loops and delayed stiffness degradation. Accord-



(a) CONV Connection **(b)** CP Connection



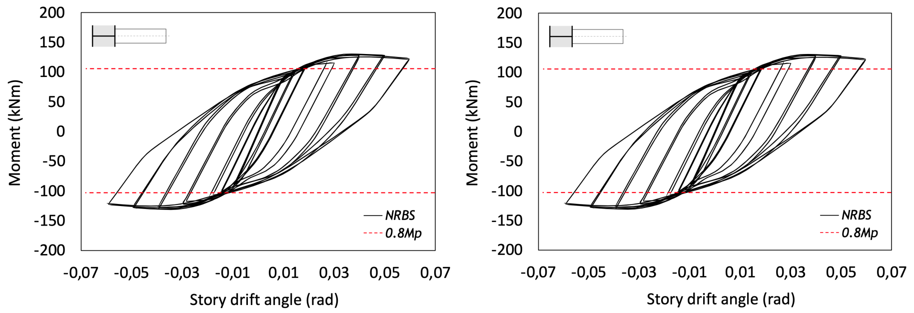
(c) RBS Connection **(d)** RBSCP Connection

Fig. 7. PEEQ distribution along the A-to-B line with a length of 500 mm

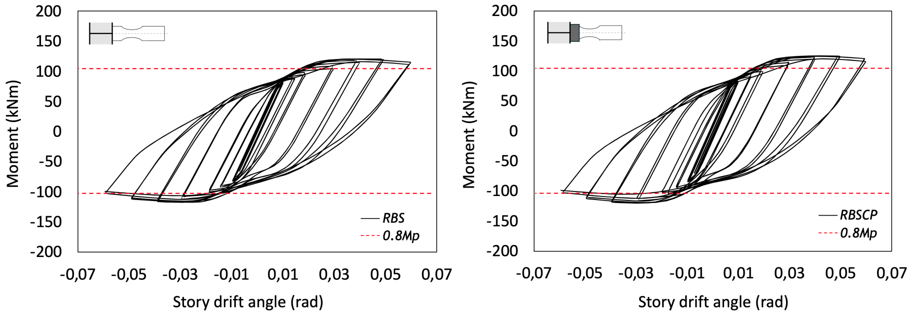
ingly, we clarify that the engineering significance lies in the stability of hysteretic response, distribution of plastic deformation, and delayed damage progression rather than differences in absolute energy magnitude.

5. Conclusions

The comparative evaluation of four steel moment connection types (CONV, CP, RBS, and RBSCP) reveals notable differences in cyclic performance. PEEQ contours indicate that the CONV connection exhibits severe plastic strain concentration near the beam-to-column weld, reflecting a high local strain demand and unfavorable plastic hinge development at the column face. In contrast, both the CP and RBSCP connections successfully relocate the plastic hinge away from the critical weld zone. The RBSCP connection displays a broader and more evenly distributed plastic zone along the beam flange near the cover plate termination, indicating an optimal balance between strength and ductility and improved energy dissipation. Analysis of plastic strain along the A − B path further emphasizes the influence of connection geometry. The RBS connection demonstrates highly localized strain within the reduced section, whereas CP presents a more gradual strain gradient. Interestingly, the RBSCP connection mirrors the sharp strain peak of the RBS connection but shifts it farther from the weld zone, confirming that cover plates effectively relocate, but do not significantly broaden, the plastic hinge region. Hysteretic behavior corroborates these observations: the RBSCP connection exhibits stable, wide loops and substantial cumulative energy dissipation (83.87 kNm), combining an optimal balance between strength and ductility with consistent cyclic stability. Minor asymmetry in the loops suggests localized inelastic effects near the plate end. Overall, the RBSCP connection demonstrates the most balanced seismic performance in terms of energy dissipation and strength retention under cyclic loading, indicating its



(a) CONV Connection **(b)** CP Connection



(c) RBS Connection **(d)** RBSCP Connection

Fig. 8. Hysteresis responses of proposed connection models

potential as a viable alternative design for enhancing ductility and promoting stable plastic hinge formation away from the column face in steel moment connections subjected to seismic loading.

In addition to the findings presented, further geometric optimization of the RBSCP connection is recommended. Key parameters include the cover plate dimensions and plate termination detailing, as these directly influence stress concentration and strain localization near the beam flange-plate interface. Optimizing the plate dimensions may improve stress redistribution while avoiding excessive stiffness that could shift plastic hinging away from the intended RBS region. Moreover, design recommendations for the RBS cut radius geometry in relation to the cover plate dimensions are suggested. Future parametric studies on these parameters would help identify balanced configurations that enhance ductility while maintaining stable cyclic performance.

6. Acknowledgements

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