Enhancing Seismic Performance of Structural Connections in Civil Engineering Applications

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Abstract

This study evaluates the seismic performance of steel moment-resisting frames through the integration of reduced beam sections (RBS) with externally reinforced cover plates. Three-dimensional finite element analyses under cyclic loading were conducted to assess the influence of cover plates on different RBS geometries, including radius cut (RBSCP-RC), straight cut (RBSCP-SC), tapered cut (RBSCP-TC), and drilled flange (RBSCP-DF). The objective of this study is to investigate the effects of geometric variation on seismic response, moment capacity, and ductility of hybrid RBS–cover plate (RBSCP) connections. The novelty of this research lies in the systematic development and evaluation of a hybrid RBS–cover plate connection that combines the energy dissipation capability of RBS with the strengthening function of cover plates. This configuration is intended to shift plastic hinge formation away from the column face, reduce the risk of premature weld failure, and improve connection strength and energy dissipation. The numerical results indicate that the incorporation of cover plates significantly enhances the seismic performance of RBS connections, with the radius-cut configuration demonstrating the most stable hysteretic behavior and the highest energy dissipation capacity. These findings emphasize the importance of geometric optimization in hybrid RBS–cover plate designs and provide valuable guidance for improving the seismic resilience of steel moment-resisting frames.

Keywords: *Cover plate, hysteretic response, moment capacity, reduce beam section, seismic performance*

Abstrak

Penelitian ini menginvestigasi kinerja seismik rangka baja tahan momen melalui integrasi inovatif antara reduced beam section (RBS) dan pelat penutup eksternal (cover plate). Analisis elemen hingga tiga dimensi yang canggih dilakukan di bawah pembebanan siklik untuk mengkaji pengaruh pelat penutup terhadap berbagai bentuk geometri RBS, meliputi tipe potongan radius (RBSCP-RC), potongan lurus (RBSCP-SC), potongan meruncing (RBSCP-TC), dan pelat dengan lubang bor pada flens (RBSCP-DF). Tujuan penelitian ini adalah untuk menjelaskan pengaruh variasi geometri terhadap respons seismik keseluruhan, kapasitas momen, dan daktilitas pada sistem hibrid RBS–cover plate (RBSCP). Kebaruan penelitian ini terletak pada pengembangan dan evaluasi sistematis dari konsep sambungan hibrid RBS–cover plate (RBSCP), yang mengintegrasikan keunggulan kemampuan disipasi energi dari RBS dengan efek penguatan dari cover plate. Konfigurasi terintegrasi ini dirancang untuk mengontrol pembentukan sendi plastis agar terjadi menjauh dari muka kolom, sekaligus mengurangi potensi kegagalan las prematur serta meningkatkan kekuatan dan kapasitas disipasi energi sambungan. Hasil penelitian menunjukkan bahwa penyertaan cover plates secara signifikan meningkatkan kinerja seismik sambungan RBS, dengan geometri radius-cut yang paling efektif dalam disipasi energi dengan menunjukkan perilaku histeresis yang stabil. Hasil studi ini menggarisbawahi pentingnya desain geometri RBS dalam mengoptimalkan ketahanan struktur baja di daerah rawan gempa, serta memberikan wawasan untuk aplikasi rekayasa struktur diwaktu mendatang.

Introduction

Structural connections are fundamental to a structure's ability to withstand seismic and other extreme loading conditions. Appropriate connection detailing is required to ensure that plastic hinges form within the beam region, thereby preventing brittle failure at the column face (Indupriya & Anupriya, 2022). Following the Kobe and Northridge earthquakes, extensive experimental and analytical research was conducted to identify the causes of structural damage and to develop improved connection systems capable of enhancing seismic performance (Chen et al., 1997; Engelhardt & Sabol, 1997; Plumier, 1994). According to AISC 341-22, special moment frames (SMFs) must satisfy specific seismic performance requirements, including the condition that the bending moment at the column face reaches at least 80% of the beam plastic moment capacity (Mp) when subjected to a story drift angle of 4%.

Numerous studies have confirmed that reduced beam section (RBS) configurations provide enhanced energy dissipation capacity when subjected to cyclic loading. This behavior is largely attributed to the intentional development of plastic hinges within the reduced beam region, which limits damage to the beam–column connection and adjacent structural components (Casita et al., 2024a; Ghafouri et al., 2022; Paul & Deb, 2022; Salmasi et al., 2021; Sofias et al., 2014; Tahamouli Roudsari et al., 2019). Because of its proven ability to relocate plastic hinge formation away from the column face, the RBS connection has been widely implemented in seismic-resistant design over recent decades In comparison with conventional steel beams, RBS beams generally exhibit superior ductility, more stable strength response, and improved post-yield behavior (Akbari et al., 2022; Amalia et al., 2018; Casita et al., 2022; Oh et al., 2015; Suswanto et al., 2018; Wahyuni et al., 2018; Zhang & Ricles, 2006).

Despite these benefits, the reduction of the beam flange in RBS configurations may lead to a decrease in flexural and tensile capacities, which can reduce the overall strength relative to conventional steel beams. Under certain conditions, brittle fracture may still develop near the column face as a result of stress concentration or inadequate load redistribution, potentially initiating progressive collapse. As a result, existing studies addressing the enhancement of flexural strength and structural robustness of RBS beams remain relatively limited. A wide range of studies has investigated various modification strategies to improve the seismic performance of reduced beam section (RBS)

connections. Research on circular web openings indicates that the use of multiple openings can enhance ductility while preserving strength more effectively than configurations with one or two openings (Tsavdaridis & Papadopoulos, 2016). The double reduced beam section (DRBS) concept has also been reported to delay the onset of local web buckling, although it may lead to a reduction in overall strength (Morshedi et al., 2017). Accordion-type double-cell web RBS configurations have been shown to localize plastic deformation within corrugated regions, thereby reducing demand on beam-to-column welds (Imanpour et al., 2019).

Studies on V-cut RBS connections combined with concrete-filled tube (CFT) columns have demonstrated the ability to sustain rotation demands of up to 0.04 rad without panel zone failure, while the inclusion of kinked bar reinforcement has been shown to delay crack initiation; however, excessive reinforcement may adversely affect load-carrying capacity (Paul & Deb, 2022b; Qiao et al., 2022). Taken together, previous research has proposed several strategies to enhance the seismic performance of RBS connections. Nevertheless, challenges related to strength degradation and fabrication complexity remain unresolved. The geometric design and detailing requirements of RBS connections, defined by parameters *a, b,* and *c,* are specified in FEMA-350 and FEMA-351 and have been incorporated into EC8, Part 3 (Eurocode 8, 2011). A summary of these design provisions is presented in Table 1.

Table 1. Tensile test specimen details

FEMA 350 / FEMA 351	EC8, part 3
$a = (0.50 – 0.75)\, b_f$	$a = 0.60\, b_f$
$b = (0.65 – 0.85)\, d_b$	$b = 0.75\, d_b$
$c \leq 0.25\, b_f$	$c \leq 0.25\, b_f$

The study aims to evaluate the seismic performance of reduced beam section (RBS) connections incorporating cover plates, referred to as RBSCP (Reduced Beam Section with Cover Plate) connections, with various flange-cut geometries, including radius-cut, tapered-cut, straight-cut, and drilled-cut configurations. Comprehensive three-dimensional finite element analyses were performed to compare the hysteretic response, energy dissipation capacity, and stress–strain distribution of the different RBSCP configurations.

This investigation provides a significant scientific contribution through the systematic evaluation of hybrid Reduced Beam Section connections reinforced with cover plates (RBSCP) under cyclic loading conditions. From a theoretical perspective,

the research enhances the understanding of stress distribution, plastic hinge development, and energy dissipation mechanisms associated with different flange-cut geometries, thereby addressing key limitations of conventional RBS systems related to strength degradation and fabrication challenges. From a methodological standpoint, the study proposes a reproducible three-dimensional finite element modeling framework that incorporates detailed geometric representation and cyclic loading protocols consistent with AISC and FEMA provisions. This framework enables a rigorous assessment of seismic performance, local buckling behavior, and post-yield response. From a practical perspective, the results provide valuable design guidance for improving ductility, energy dissipation capacity, and overall seismic resilience of RBSCP connections. By integrating theoretical insight, numerical methodology, and engineering application, this research establishes a comprehensive basis for the optimization of steel moment-resisting frames subjected to earthquake loading.

Material and Methods

Material properties

The finite element model employed in this research comprises WF 300×300 columns and WF 250×125 beams, which are retrofitted using a strategically designed cover plate. All steel components, including the cover plate, doubler plate, and continuity plate, were assumed to be made of SS400 steel, which is widely recognized for its reliable mechanical performance in structural applications (Casita et al., 2024b).

The nonlinear material behavior under cyclic loading was represented using a combined hardening constitutive model, following the approach proposed by Jia and Kuwamura (2014), to accurately capture inelastic response (Jia & Kuwamura, 2014). The resulting stress–strain relationship is presented in Figure 1, illustrating the material response across different loading stages. The elastic properties were defined by an elastic modulus *(E)* of 200 GPa and a Poisson's ratio *(v)* of 0.3.

Details of the model

A comprehensive overview of the model parameters and component configurations is provided in Figure 2. The figure also presents the four RBSCP connection models examined in this study, which were developed to investigate the influence of different flange-cut geometries on seismic response. The analyzed configurations include a radius-cut

model (RBSCP-RC), a straight-cut model (RBSCP-SC), a tapered-cut model (RBSCP-TC), and a drilled-flange model (RBSCP-DF) applied to the beam flanges. The geometric dimensions of the flange cuts were defined in accordance with the numerical recommendations and dimensional provisions specified in FEMA-350, 2000b.
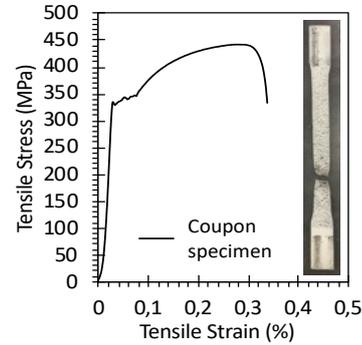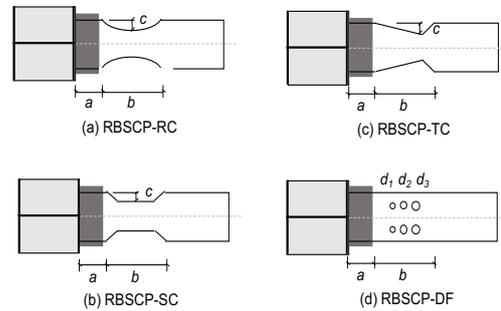

Figure 1. Stress vs strain response of coupon specimen (Casita et al., 2024b)

Note:
RBSCP = RBS connection using cover plates;
RC = radius-cut geometry; TC = tapered-cut geometry;
SC = straight-cut geometry; DF = drilled-flanges geometry

Figure 2. The details of RBS cutting geometry

As shown in Figure 2, parameter a denotes the distance from the column face to the initiation of the RBS cut, b represents the length of the reduced beam section, c defines the depth of the flange reduction, and d corresponds to the diameter of the drilled holes in the beam flanges. The column and beam members were modeled using WF 300×300×11×17 and WF 250×125×6×9 sections, respectively. The dimensions of the doubler plate and continuity plates, along with the welding details, were specified in accordance with the relevant connection detailing requirements.

Loading conditions

Cyclic displacement–controlled loading was applied at the beam ends through a pair of vertical forces, F, acting in opposite directions, in accordance with the AISC Seismic Provisions, as summarized in Table 2. The column bases were

modeled as pinned supports to restrain lateral translation, while the column tops were fully restrained in the lateral direction, as illustrated in Figure 3.
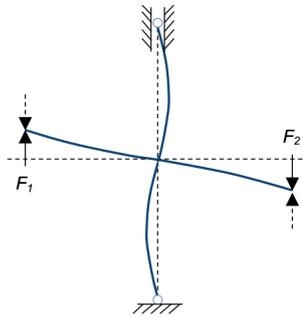

Figure 3. Modelling concept

Table 2. Applied loading protocol (AISC 341-22)

Interstory drift angle (rad)	Loading cycle
0.00375	6 cycle
0.005	6 cycle
0.0075	6 cycle
0.01	4 cycle
0.015	2 cycle
0.02	2 cycle
0.03	2 cycle
0.04	2 cycle
0.05	2 cycle
0.06	2 cycle
0.07	2 cycle
0.08	2 cycle

Four RBSCP connection configurations with different flange-cut geometries—radius cut (RBSCP-RC), straight cut (RBSCP-SC), tapered cut (RBSCP-TC), and drilled flange (RBSCP-DF)—were subjected to identical cyclic loading protocols. A comparative finite element analysis was performed to evaluate their hysteretic response, energy dissipation capacity, stress–strain behavior, and overall seismic performance, thereby elucidating the influence of flange-cut geometry on the ductility and resilience of RBSCP connections.

Loading protocol

The numerical loading protocols applied to the connection models were defined in accordance with the provisions of ANSI/AISC 341-22, 2022. The cyclic loading history adopted in the finite element analysis is summarized in Table 2, including the prescribed drift ratios and corresponding number of loading cycles. Specifically, each connection model was subjected to six cycles at drift ratios of 0.00375,

0.005, and 0.0075; four cycles at a drift ratio of 0.01; and two cycles at each subsequent drift ratio of 0.015, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, and 0.08.

Result and Discussion

Stress and Strain Distribution

As illustrated in Figures 4 and 5, the incorporation of cover plates in the RBSCP connection effectively redistributes stresses away from the column face, thereby reducing the likelihood of brittle fracture in the connection region. The numerical results indicate that the panel zone remains predominantly elastic, allowing inelastic deformation to concentrate within the beam away from the column face. This mechanism contributes to improved ductility and enhanced energy dissipation capacity, underscoring the important role of cover plates in increasing both the strength and flexibility of the connection.

Under cyclic loading, local buckling was observed in the reduced regions of the RBSCP-TC and RBSCP-DF models. The initiation of local buckling led to asymmetric stress distributions within the plastic hinge zones, which in turn diminished the moment-resisting capacity of the connections. Stress evaluation revealed that the RBSCP-DF configuration experienced the highest stress demand, followed sequentially by the RBSCP-TC, RBSCP-SC, and RBSCP-RC models. This trend reflects the comparative performance of the investigated geometries, with the RBSCP-RC configuration demonstrating the greatest moment-resisting capacity. Furthermore, in the straight-cut (RBSCP-SC) and tapered-cut (RBSCP-TC) models, stress concentration at re-entrant corners may promote beam flange fracture, indicating the susceptibility of these geometries to damage under cyclic loading conditions.

Hysteretic Behavior

The hysteretic moment–rotation (M–θ) responses of the analyzed connection models, obtained from the finite element simulations, are shown in Figure 6. The inter-story drift angle was calculated as the ratio of the total lateral displacement at the free end of the beam to the distance between the beam end and the column centerline. All models demonstrated stable hysteretic behavior with high strength and considerable ductility. Each configuration attained an inter-story drift angle of 4% radians while maintaining a flexural resistance greater than 0.8 Mp, thereby meeting the acceptance criteria for Special Moment Frames (SMFs) as specified in the AISC Seismic Provisions.
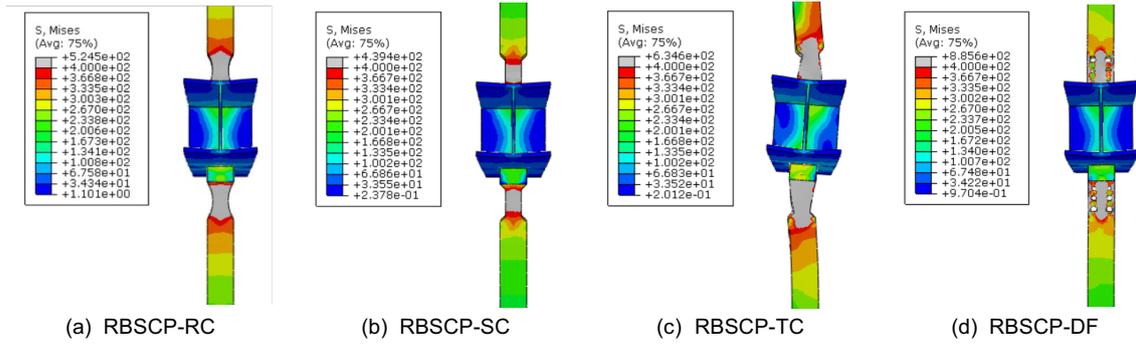
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(a) RBSCP-RC   (b) RBSCP-SC   (c) RBSCP-TC   (d) RBSCP-DF

Figure 4. Stress distribution of proposed connection models

(a) RBSCP-RC   (b) RBSCP-SC   (c) RBSCP-TC   (d) RBSCP-DF
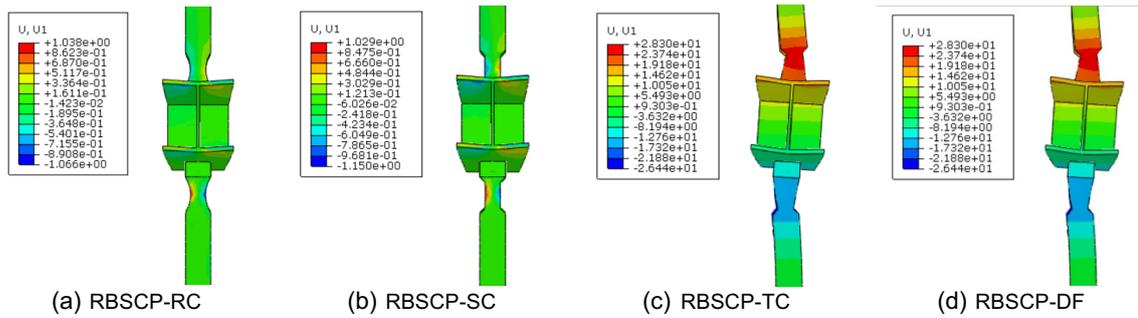
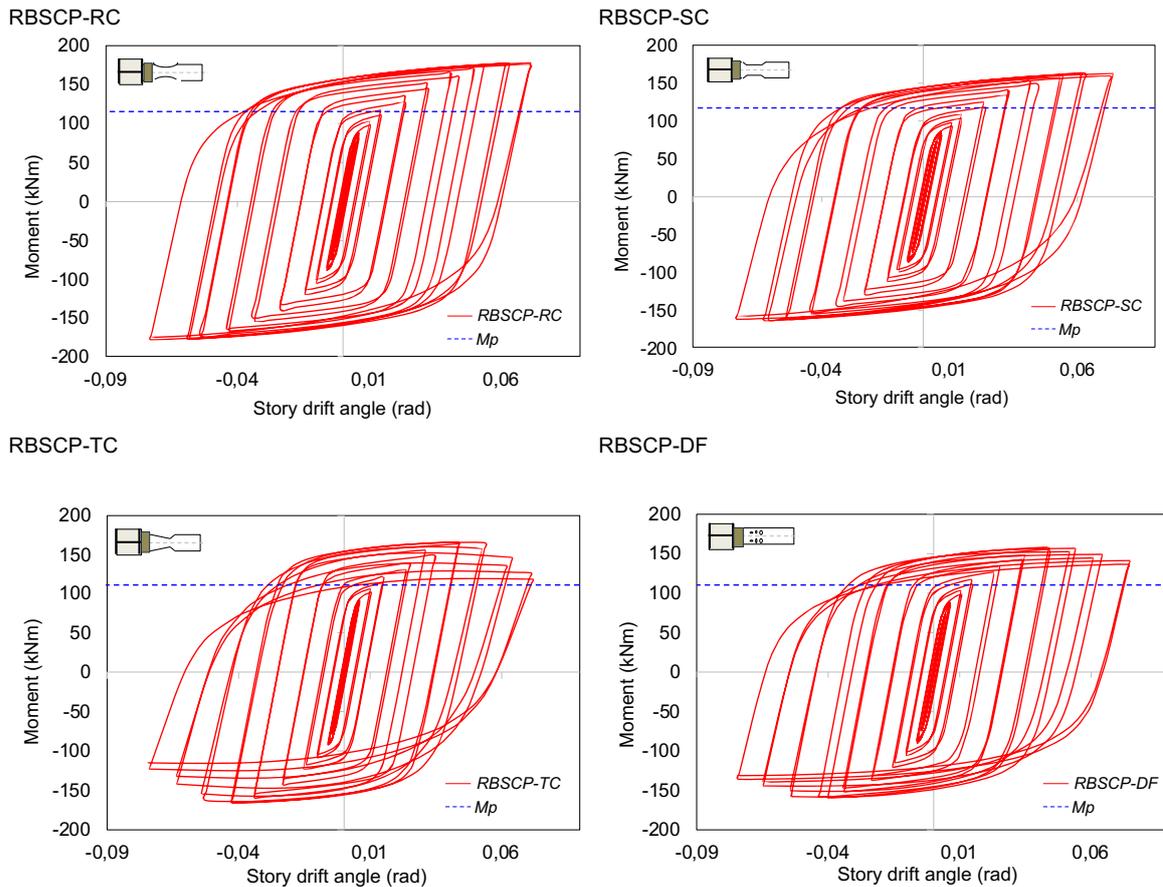**Figure 5. Occurred local buckling of proposed connection models**

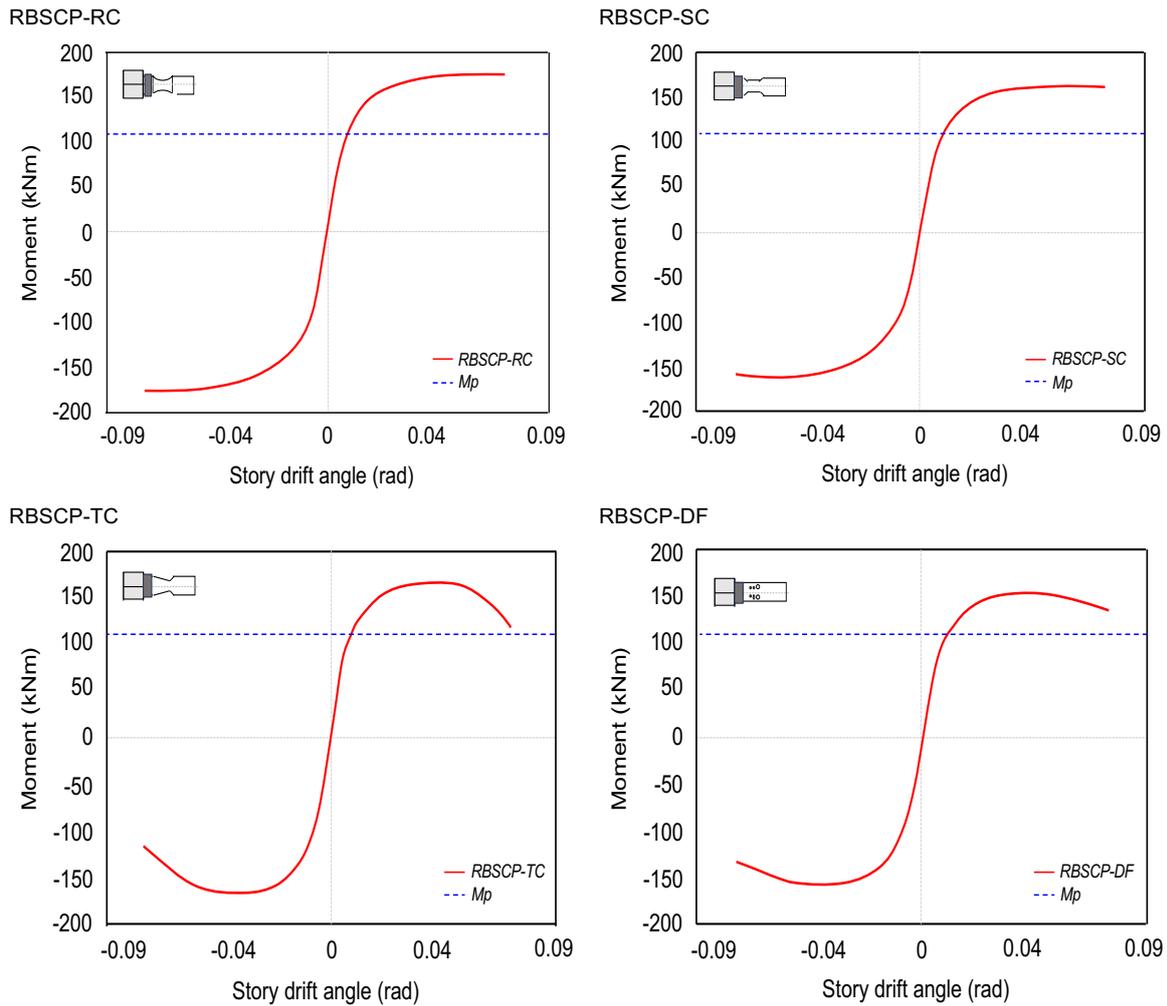**Figure 6. Hysteresis responses for proposed connection models**

Figure 7. Envelope curves for proposed connection models

Energy dissipation

Energy dissipation, evaluated as the area enclosed by the hysteretic loops, is a key indicator of seismic performance. At a story drift angle of 8 percent, the RBSCP-RC configuration exhibited the highest energy dissipation capacity at 553.0 kNm. The RBSCP-SC model followed, reaching 514.0 kNm, while the RBSCP-DF and RBSCP-TC configurations dissipated 508.0 kNm and 488.0 kNm, respectively, as shown in Figure 8. These results demonstrate that the radius-cut RBSCP configuration provides the most effective energy absorption, thereby enhancing the overall seismic resilience of the connection.

Moment-rotation envelope curves

The hysteretic response demonstrates that the ultimate moment capacity of certain connection configurations is reduced due to the occurrence of local buckling in the beam under cyclic loading, most notably in the RBSCP-TC and RBSCP-DF models. The moment–rotation envelope curves

presented in Figure 7 indicate that the onset of moment strength degradation is directly associated with the initiation of local buckling.
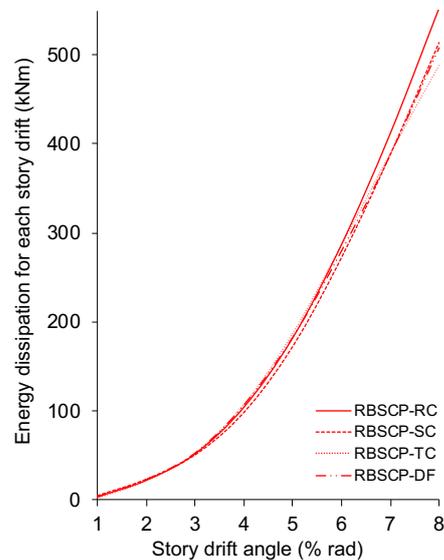

Figure 8. Energy dissipation comparison

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Although the RBSCP-TC and RBSCP-DF configurations exhibit a discernible reduction in moment capacity at a rotation level of approximately 6 percent, the residual moment capacity after buckling remains higher than the plastic moment capacity. This observation suggests that the nominal strength of these connections is only marginally affected. In contrast, the RBSCP-RC and RBSCP-SC configurations maintain stable moment resistance with negligible strength degradation throughout the loading history.

Conclusion

This research evaluated the seismic performance of Reduced Beam Section connections strengthened with cover plates, referred to as RBSCP connections, under cyclic loading, with particular emphasis on the influence of different flange-cut geometries. The primary contribution of this study lies in the systematic development and numerical assessment of a hybrid RBS–cover plate connection concept. By integrating the inherent energy dissipation capability of RBS with the strengthening effect of cover plates, the proposed configuration effectively relocates plastic hinge formation away from the column face, reduces stress concentration, and mitigates the potential for brittle fracture. In doing so, this study addresses unresolved issues in previous RBS research related to strength degradation and fabrication complexity.

A comprehensive finite element investigation was carried out for four RBSCP configurations, namely radius-cut, straight-cut, tapered-cut, and drilled-flange designs. The numerical results demonstrate that the incorporation of cover plates substantially improves stress distribution, enhances energy dissipation capacity, and increases ductility relative to conventional RBS connections. Among the examined configurations, the radius-cut RBSCP model exhibited the most favorable seismic performance in terms of moment resistance, ductility, and energy absorption, followed by the straight-cut, drilled-flange, and tapered-cut models. Although local buckling observed in the tapered-cut and drilled-flange configurations resulted in minor reductions in ultimate moment capacity, the residual strength remained above the nominal level, indicating no significant compromise in structural performance.

Overall, the findings confirm that RBSCP connections represent an effective and practical solution for enhancing the seismic resilience of steel moment-resisting frames. The outcomes of this study provide valuable design guidance for hybrid RBS–cover plate connections and offer new insights into the optimization of flange-cut geometries. By addressing critical issues associated with strength degradation and constructability, this research contributes to the advancement of more resilient, ductile, and reliable steel connection systems capable of withstanding severe seismic demands.

Acknowledgement

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