Numerical and Experimental Assessment of Seismic Behavior of Rigid I-Beam to Circular Steel-Box Column Connections

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ABSTRACT

In this study, the seismic behavior of an I-beam to hollow circular column connection with a steel box was investigated. In the first phase, three experimental samples with different stiffener configurations were subjected to quasi-static cyclic loading. The first sample, designed with four internal stiffeners to transfer forces from the box to the column (baseline model), was analyzed. The second sample added two internal stiffeners aligned with the beam flanges, while the third sample incorporated external stiffeners at the beam-to-box connection along with an internal arrangement similar to the first sample. After cyclic loading, stiffness, ultimate moment, ductility, and cumulative energy absorption were extracted from the moment-rotation curves. Additionally, the connection's rotation and maximum strain in the main members of each sample were measured. Based on the experimental results, a calibrated finite element model for the second sample (due to better performance) was developed, and the effect of steel box thickness in the range of 4 to 14 mm on these responses and connection stiffness was assessed. The main objective of the numerical studies was to determine the minimum thickness beyond which responses became insensitive to further increases in thickness. Experimental results showed that the use of internal stiffeners aligned with the beam flanges improved the connection's performance, increasing the ultimate moment, elastic stiffness, and ductility. Numerical results indicated that with a steel box thickness at least 2 mm greater than the beam flange thickness, the responses became independent of further thickness increases, and the connection was classified as rigid.

KEYWORDS

Rigid connection, Circular column, Steel box, Stiffener, Seismic performance

1. Introduction

In seismic design, the proper detailing of beam-to-column connections is paramount for ensuring the integrity and energy dissipation capacity of steel moment frames [1]. Moment frames dissipate seismic energy primarily through the formation of plastic hinges in the beam or connection zone. However, historical earthquakes, such as Northridge, highlighted the vulnerability of poorly designed connections, leading to brittle failures. Consequently, the development of robust, ductile, and easily constructible rigid connections, especially for structures incorporating hollow circular steel columns (HCSCs), remains a key research priority [2].

Existing rigid connection details for HCSCs often suffer from geometrical complexity, high manufacturing costs, or requirements for local column cutting (e.g., through-plate or external diaphragm solutions) [3, 4]. This study introduces a novel, practical, and reinforced steel box connection detail that eliminates the need for complex internal plates or column interruption. The box, reinforced with internal and external stiffeners, effectively transfers flexural and shear forces from the I-beam to the HCSC across four distinct directions, simplifying fabrication and reducing construction time. The research combines experimental testing and numerical analysis to thoroughly evaluate this proposed detail, focusing on the impact of various stiffener configurations and steel box thickness on seismic performance indicators. The configuration of the proposed model in this study is illustrated in Fig. 1.

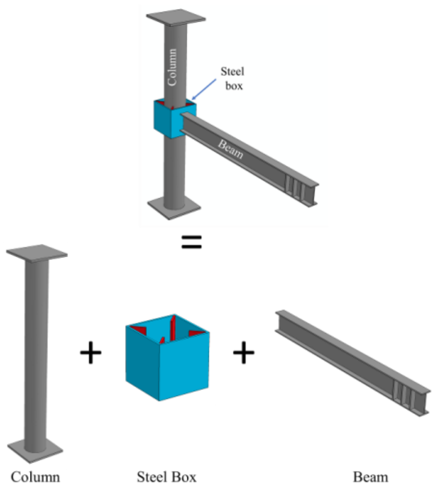

Fig. 1 Configuration of the proposed connection model.

2. Experimental Program and Specimen Details

Three full-scale beam-to-column connection specimens were fabricated to evaluate the effect of different stiffener configurations on the seismic performance of the proposed I-beam to hollow circular column (HCSC) steel box connection. All specimens shared identical components: an IPE180 beam (L=1500 mm), an HCSC (Ø220 mm, t=8 mm, L=2000 mm), and an 8 mm thick steel box (300×300 mm). The design rigorously followed the strong-column/weak-beam criterion, ensuring that plastic action was concentrated in the connection zone or the beam. The column ends were fixed to the rigid laboratory floor to simulate fixed boundary conditions. The key variable was the arrangement of stiffeners within the steel box:

Specimen ES1 (Baseline): Contained four internal stiffeners connecting the steel box to the column wall, serving as the reference configuration.

Specimen ES2 (Best Performance): Included the four ES1 stiffeners plus two additional internal stiffeners aligned with the beam flanges, functioning similarly to continuity plates and providing a direct force-transfer path.

Specimen ES3 (External Stiffeners): Maintained ES1’s internal layout and added two external stiffener plates at the beam-to-box interface to locally strengthen the box plate.

All samples were subjected to quasi-static cyclic loading based on the ATC-24 protocol [5]. and testing continued until a noticeable drop in load capacity or clear failure signs such as buckling or fracture appeared. Key performance indicators—including ultimate moment (Mu), elastic stiffness (Ke), ductility (μ), and cumulative energy dissipation (CED)—were obtained from the hysteretic moment-rotation curves. The three specimens exhibited distinctly different behaviors, emphasizing the importance of stiffener configuration.

Specimen ES1 performed weakly, failing early due to substantial plastic deformation in the box plate and mobilizing only 7.24 kN·m (17%) of the beam’s plastic moment (Mp = 43.8 kN·m). This showed that four internal stiffeners were insufficient to transfer the full moment. Specimen ES2 showed the best seismic response, forming the desired plastic hinge in the beam and reaching 43.22 kN·m (99% of Mp), fully utilizing beam capacity. Specimen ES3 improved over ES1, achieving 32.56 kN·m (74% of Mp), but failure was still controlled by box plate yielding and weld fracture at 0.05 rad.

Performance comparisons clearly highlight the superiority of ES2: its ultimate moment was about six times that of ES1 and 1.3 times that of ES3; its elastic stiffness (Ke = 3450 kN·m/rad) was roughly twelve times ES1; and its ductility (μ=6.0) and energy dissipation (CED = 38.22 kN·m) were far greater, with CED about 9.5 times higher than ES1.

Overall, the results confirm that internal stiffeners aligned with the beam flanges (ES2) provide the most effective force transfer, ensuring full beam capacity mobilization and the intended plastic hinge mechanism, making ES2 the optimal rigid connection configuration.

3. Numerical Analysis and Discussion

Following the identification of Specimen ES2 as the best-performing configuration, a finite element (FE) model was developed and validated in Abaqus using the same geometry and material properties as the test. The four-node shell model accurately reproduced the experimental hysteretic response and captured the intended plastic hinge, as confirmed by the Von Mises stress concentration in the beam flange and web.

The validated model was then used to study the effect of steel box plate thickness, varied from 4 to 14 mm, to identify the minimum required for stable performance and rigid behavior.

Results showed a strong dependence of ultimate moment, stiffness, and energy dissipation on plate thickness, with all performance gains leveling off at 10 mm, where indicators exceeded 95% of their maximum values. Stress patterns also revealed that thin plates localized stresses in the box, preventing hinge formation, while plates of 10 mm or more shifted stresses into the beam, enabling the desired energy-dissipation mechanism.

4. Connection Rigidity Classification

The influence of t_{box} on the connection's rigidity was evaluated according to the AISC 360-16 specification, which classifies connections based on the ratio of their initial stiffness (K) to the beam stiffness (EI/L). The analysis showed that connections with t_{box}=4 mm, 6 mm, and 8 mm were classified as semi-rigid, falling within the specified 2EI/L to 20EI/L range. Importantly, the connection achieved full rigid classification (exceeding 20EI/L) when the thickness reached 10 mm (t_{box}/t_f =1.25). This transition point is critical for design, confirming that t_{box} acts structurally similar to increasing the depth of a cantilever beam supported by column stiffeners; increasing its thickness substantially enhances flexural resistance and rotational stiffness, shifting the connection behavior from semi-rigid to rigid. This finding establishes a key design requirement directly linked to the thickness ratio, highlighting that the minimum effective box thickness must be carefully considered during the design process.

5. CONCLUSIONS

The combined numerical and experimental investigations into the seismic performance of the I-beam to circular column connection with a stiffened steel box lead to the following key conclusions:

The use of internal stiffeners aligned with the beam flanges (ES2) proved to be the most effective configuration. This detail enabled the connection to mobilize 99% of the beam's flexural capacity and enforce the desired plastic hinge formation in the beam. This superior configuration resulted in an ultimate moment approximately six times greater and an elastic stiffness nearly twelve times greater than the baseline model (ES1). Ductility and energy absorption: The best-performing model (ES2) demonstrated high resilience and energy dissipation capacity, achieving a ductility index of 6.0 and a cumulative energy dissipation capacity approximately 9.5 times greater than the reference model (ES1).

The connection performance is highly sensitive to the steel box thickness. Performance saturation and the transition to rigid classification occur when the steel box thickness (t_{box}) is at least 2 mm greater than the beam flange thickness (t_f), that is, $t_{box} / t_f \geq 1.25$. For the tested IPE180 beam (t_f = 8 mm), the minimum effective thickness is 10 mm.

[1] a. Solhmirzaei, m. TahamouliRoudsari, B. Hosseini Hashemi, Proposing a New Detailing Scheme for Rigid Connection with Endplate without the Need for Welding in Column, Journal of Structural and Construction Engineering, 8(Special Issue 4) (2022) 411-438.
[2] M. Gerami, A. Zarei, M. Ghaderi, Effect of low cycle fatigue on steel moment frames with prequalified rigid connections (bolted unstiffened and stiffened extended end-plate moment connections), Journal of Structural and Construction Engineering, 6(Special Issue 3) (2019) 149-162.
[3] M.M. Ahmadi, S.R. Mirghaderi, N. Bakhshayesh Eghbali, Cyclic testing of through-plate moment connection for beam to concrete filled and unfilled circular column, Engineering Structures, 267 (2022) 114695.
[4] M. Tahamouli Roudsari, S. Sohaei, M. Torkaman, S.A. Safaee, S. Tahmasebi, S. Mohammadi, M.M. Ghiasvand, Presenting a New Detail for the Rigid Connection Between I-Shaped Beam and Concrete-Filled Steel Tube Column with Stiffened Channel Link, International Journal of Steel Structures, 20(2) (2020) 655-667.

[5] H. Krawinkler, Guidelines for cyclic seismic testing of components of steel structures, Applied Technology Council, 1992.