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Hybrid systems to enhance the seismic performance of steel soft-story structures

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Abstract:

Recent global seismic events have shown that most destroyed structures were irregularly designed, especially those with a soft story. A “soft story” refers to a building floor significantly weaker or more flexible than the others, often because of large openings such as windows or parking spaces. This reduction in stiffness creates a vulnerable point where excessive deformation can occur during an earthquake, leading to potential structural failure. This study proposes a practical hybrid connection strategy that combines fully rigid and semi-rigid joints to address this case and mitigate the failure mechanism affecting the overall seismic response of steel structures. The objective is to smooth stiffness discontinuities and improve earthquake performance in a 12-story steel moment-resisting frame with a mid-height soft story. Semi-rigid joints are modeled as zero-length rotational springs with a fixity factor (α), applied above the soft story in two layout configurations. Compared to the fully rigid frame, introducing semi-rigid joints increases the fundamental period (by ≈10% for $\alpha = 0.5$ and up to ≈60% for $\alpha = 0.1$ in Case 1; more moderate increases of ≈5% and ≈12% in Case 2), thereby shifting seismic demand toward lower spectral accelerations. Intermediate fixity ($\alpha \approx 0.5$–0.75) offers a balanced performance: roof displacements and inter-story drifts remain controlled while the soft-story stiffness criterion is satisfied. Overall, strategically placing semi-rigid connections above the soft story reduces drift concentration, smooths the stiffness profiles, and enhances seismic resilience without compromising global stability. These findings support hybrid connection detailing as a cost-effective and practical strategy for improving the seismic behavior of steel structures.

Keywords:
steel structures; soft story; hybrid connections; semi-rigid connections; seismic performance; resilience

1. Introduction

The seismic performance of steel structures remains a major concern in earthquake-prone regions, where structural integrity and resilience are essential. Past earthquakes have exposed significant weaknesses, particularly in buildings with irregular vertical configurations. Among these, the soft-story mechanism, a condition in which a floor exhibits significantly lower stiffness and strength than adjacent stories, has been a common cause of collapse [1].

Soft stories typically result from architectural features such as large openings or a reduced number of load-bearing elements, which amplify story drift and increase the risk of failure [2]. Notable cases, such as the 1994 Northridge and 2011 Tohoku earthquakes, showed that buildings with soft stories sustained significantly more damage than those with uniform stiffness profiles [3,4]. These cases illustrate the importance of appropriate seismic design in steel structures, which, because of their lightweight and high deformability, are particularly sensitive to stiffness irregularities [5].

This raises a key design challenge: how to optimize the connections between structural elements to minimize the effects of stiffness discontinuities while preserving global stability. Traditional modeling assumes that steel frame connections are either fully rigid or completely pinned [2,6]. Rigid joints fully transmit moments and prevent relative rotations, while pinned joints allow free rotation with no moment transfer [7]. However, this binary classification oversimplifies reality, as most actual connections exhibit behavior between these two extremes.

In practice, even the most flexible joints transmit some moment, and the most rigid allow slight rotation [8]. This phenomenon has led to the development of the semi-rigid connection concept, which reflects a more realistic intermediate stiffness [9]. These joints partially transmit moments and influence the dynamic response of the structure. Numerical studies have shown that semi-rigid connections can increase the fundamental period and reduce base shear, though they may lead to larger lateral displacements, potentially affecting serviceability [10].

Recent research has explored hybrid systems that combine rigid and semi-rigid connections within a single frame to address these limitations. For instance, Razavi and Abolmaali [11] proposed a hybrid steel moment-resisting system by strategically replacing some rigid joints with semi-rigid ones, resulting in improved seismic behavior. Other studies have investigated the configuration and efficiency of such systems, examining how the location and proportion of semi-rigid joints influence energy dissipation and residual deformation [12,13].

For instance, Daryan et al. [14] demonstrated that joint placement significantly affects lateral deformation under seismic loading, while Sharma et al. [15] showed that hybrid frames exposed to far-field earthquakes dissipate more energy and experience less damage than conventional frames.

More advanced simulation approaches, such as nonlinear finite element analysis and performance-based design, have further confirmed the benefits of hybrid systems. Sharma et al. [16] showed that hybrid frames perform better than rigid ones under near-field conditions, with improved energy dissipation and reduced long-term damage. Despite these advancements, practical limitations exist, including material variability, construction constraints, and the lack of standardized design codes for semi-rigid joints [17]. Moreover, established design standards and code provisions are necessary to promote the implementation of hybrid systems in practical applications.

This study aims to address these gaps by evaluating the seismic performance of a 12-story steel moment-resisting frame with a mid-height soft story. By integrating both rigid and semi-rigid connections, the aim is to achieve a more uniform distribution of lateral stiffness and enhance seismic performance. Using response spectrum analysis, the study assesses story displacements, inter-story drifts, and stiffness profiles to determine the optimal configurations that reduce soft story effects.

The novelty of this work lies in the strategic integration of semi-rigid connections to control lateral deformation while preserving the structural benefits of rigid frames. Preliminary results indicate that this hybrid system can significantly reduce the negative impact of the soft story without compromising global stability. These results contribute new insights into the design of seismically resilient steel structures and support the implementation of hybrid systems as practical solutions in earthquake engineering.

2. Methods

2.1. Semi-rigid connection

In structural modeling, semi-rigid connections play a crucial role in accurately representing the interaction between structural elements such as beams and columns. Unlike perfectly hinged connections, which allow free rotation, or fully fixed connections, which prevent any rotation, semi-rigid connections provide intermediate flexibility. They allow limited rotation while transmitting part of the bending moment [18].

Two main approaches are commonly used to model semi-rigid connections in structural analysis. The first approach, proposed by Chen [19], involves defining a new finite element representing the beam-column connection itself. This method captures complex deformation mechanisms, including nonlinear and asymmetric behaviors between members. Its main advantage is its accuracy and flexibility in capturing local connection phenomena in integrating various types of nonlinear and asymmetric behaviors [20]. However, it requires extensive parameter calibration, sophisticated modeling, and significant computational effort, which may limit its applicability in large-scale analyses (Fig. 1).

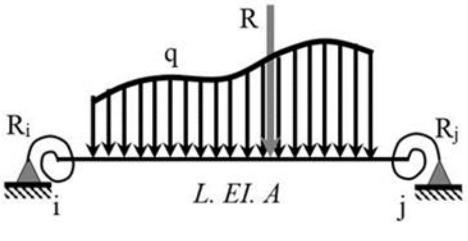


Fig. 1. Element with semi-rigid nodes [19]

The second approach, developed by Abidelah [18], models the connection as a zero-length rotational spring placed between adjoining members. This spring resists relative rotation according to its assigned stiffness, enabling a simplified yet realistic representation of joint flexibility.

The benefits of this method include easy adoption of this process to conventional analysis software and low computational cost compared to defining a new element. However, this approach remains an approximation that may not fully capture highly nonlinear or asymmetric joint behavior. It is therefore most effective when the connection response is predominantly linear or mildly nonlinear.

The fixity factor (α) represents the actual proportionality of the springs added to the model in terms of stiffness. This factor reflects the stiffness of the connection relative to the adjacent members, from which the overall behavior of the structure is affected. This dimensionless parameter is mathematically defined as the ratio between the rotational stiffness of the joint (R_k) and the flexural stiffness of the connected member (EI):

$$\alpha = \frac{R_k}{EI} \tag{1}$$

where E is the Young modulus and I is the moment of inertia of the connected element.

A high fixity factor ($\alpha > 1$) indicates a stiff connection that concentrates bending moments at the joint, while a low fixity factor ($\alpha < 1$) corresponds to a more flexible joint that allows greater rotation and promotes a more uniform redistribution of moments along the frame. It is crucial for modelers to be able to correctly apply the fixity factor to achieve better and more accurate results in the structural analysis of semi-rigid systems.

In summary, while the first method of Chen [19] captures joint mechanics in detail and provides higher accuracy, we adopt Abidelah’s zero-length rotational spring model [18] for its simplicity, direct compatibility with ETABS software, and direct control of the fixity factor α required in the present study.

2.2. Soft story

A soft story is defined as a building floor whose lateral stiffness is significantly lower than that of the stories above. It is typically characterized by significantly reduced lateral stiffness due to fewer structural elements or large openings such as parking spaces, shopfronts, or glazing panels, that reduce its capacity to resist lateral loads. As a result, the soft story becomes the weakest link in the load path, exhibiting excessive deformation during seismic events and increasing the likelihood of local or global collapse.

According to Eurocode 8 (EN 1998) [21] and the Algerian Earthquake Regulation (RPA) [22], a story is classified as "soft" if its lateral stiffness is less than 70% of the stiffness of the story directly above it or less than 80% of the average lateral stiffness of the three stories directly above. Such a discontinuity in stiffness disrupts the uniform transfer of lateral forces, severely compromising the stability of the building and safety during an earthquake.

Consistently, ASCE 7 (American Society of Civil Engineers 7) [23] provides similar definitions, identifying soft stories as vertical stiffness irregularities based on equivalent thresholds (story stiffness less than 70% of the story above or 80% of the three-story average). The alignment of EN 1998 [21], RPA [22], and ASCE 7 [23] confirms the validity of the stiffness criteria adopted in this study.

In practice, soft stories result from architectural configurations that interrupt stiffness continuity, such as large open areas, wide façades, or a reduced number of columns [24]. Under lateral loading, these discontinuities amplify horizontal displacements, leading to cracking in load-bearing walls, column buckling, or even partial or total collapse (Fig. 2).

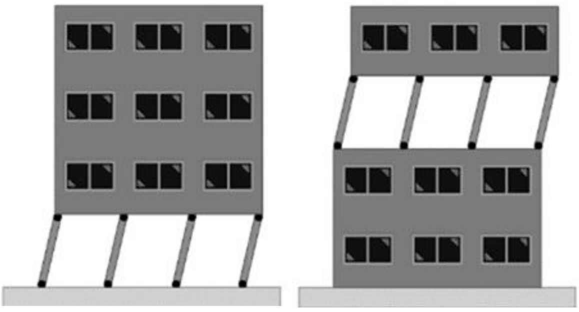


Fig 2. Soft story [25]

The causes of soft stories include architectural requirements for large spaces, subsequent modifications inconsistent with the original structural design, or aesthetic choices by designers without adequate consideration of the structural implications [26]. During earthquakes, these stories experience excessive oscillations, causing permanent deformations and uneven redistribution of internal forces. To mitigate these risks, it is essential to perform a thorough structural analysis and strengthen the inter-story connections with bracing, rigid frames, or energy dissipation systems [27].

Seismic codes such as Eurocode 8 [21] provide clear recommendations for identifying, assessing, and retrofitting soft stories. Many national standards complement these guidelines with specific requirements for reinforcement [28]. The RPA [22], for example, mandates the inclusion of bracing systems or shear walls arranged in two orthogonal directions to improve torsional and lateral stiffness.

Other available techniques for mitigating the effects of soft stories include:

- Increasing the dimensions and number of columns;
- Adding steel bracing to match the stiffness of the upper story [29];
- Limiting seismic demands through methods like seismic isolation of foundations, energy dissipation systems, and mass reduction.

Although effective, these solutions often involve substantial cost and design complexity, which points to the importance of innovative, economically viable alternatives such as hybrid connection systems explored in the present study.

2.3. Numerical application

2.3.1. Description of the analyzed structure

To evaluate the effectiveness of the proposed hybrid system, a 12-story steel moment-resisting frame was selected from the literature [30, 31], as depicted in Figs 3(a) and 3(b). The structure is subjected to a uniform distributed gravity load of 27.5 kN/ml. Comprehensive details regarding the cross-sectional dimensions and mechanical properties of the frame members are summarized in Tables 1 and 2, respectively.

Fixed supports are assigned at the base to simulate a rigid foundation, and this implies that the base level cannot be displaced. A damping ratio of 5% is adopted, consistent with common practice for representing energy dissipation in steel structures subjected to dynamic loading.

Table 1. The sections of columns and beams for each story

Story number	Columns: (HEB) - Beams: (IPE)
1	400-360
2-3	400-400
4-5	400-450
6-7	360-400
8-9	340-400
10	340-360
11-12	340-330

Table 2. Material properties

Grade	fy (N/mm²)	fu (N/mm²)	E (N/mm²)
S235	235	360	210000

Numerical analyses are performed using ETABS software [32], a widely validated structural analysis and design program capable of simulating both the static and dynamic behavior of complex frame systems. ETABS offers advanced modeling capabilities for moment-resisting frames, making it well suited for evaluating the seismic performance of the hybrid system proposed in this study.

In this analysis, two distinct connection configurations are analyzed to assess their impact on the structural performance:

Fully rigid connections: All beam-to-column joints are modeled as perfectly rigid, with no relative rotation between members.

Semi-rigid connections (hybrid system): Selected joints are modeled as semi-rigid, allowing limited rotational deformation according to an assigned stiffness.

To identify the optimal configuration of the hybrid system, two specific cases are considered, as illustrated in Figs 3(b) and 3(c):

Case 1: Semi-rigid connections are implemented on all floors above the soft story. This configuration targets the enhancement of higher-story performance while maintaining rigidity in the lower sections.

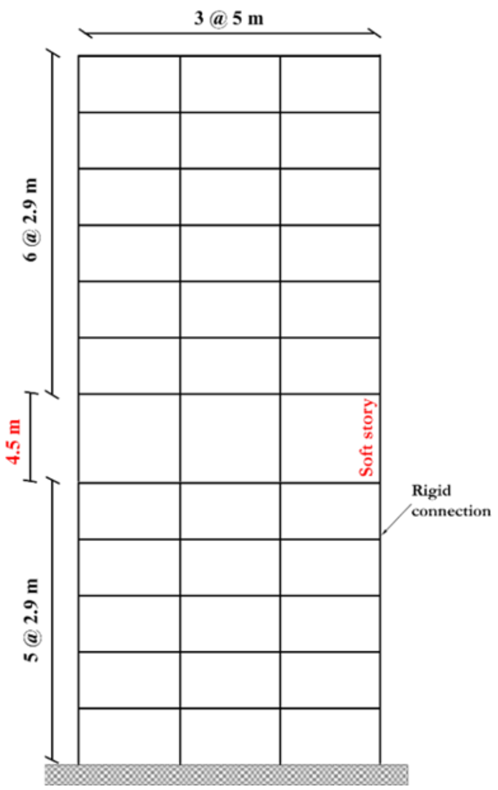
Case 2: Semi-rigid connections are applied only to selected upper floors. This selective approach aims to balance structural performance and material efficiency by targeting specific stories for enhanced flexibility.

In both layouts, semi-rigid beam-column joints are represented as zero-length rotational springs following the Abidelah [18] model. Each joint is assigned a rotational stiffness R_k proportional to the flexural stiffness EI of the connected member, characterized by a fixity factor $\alpha \in \{0.75, 0.50, 0.20, 0.10\}$. Fully rigid joints correspond to $R_k \rightarrow \infty$.

The seismic analysis is evaluated through linear elastic response-spectrum analysis with 5% damping. This procedure allows direct comparison across different connection configurations while eliminating variability due to ground-motion selection. The response spectrum used in this study, shown in Fig. 4, provides a comprehensive representation of the expected seismic demand based on the structural properties and the defined loading conditions. This analysis facilitates the assessment of the dynamic behavior of the structure and its capacity to withstand seismic forces, thereby informing the optimization of the hybrid connection system.

The present analysis focuses on global structural behavior under linear elastic conditions. Nonlinear phenomena like cyclic strength and stiffness degradation, panel-zone yielding, connection hysteresis (moment–rotation M–θ laws), and geometric nonlinearity (*P*–Δ effects) are not shown. As a result, the stated reactions should be seen as comparison measures within a linear framework instead of as predictions of absolute seismic requirements or damage states.

This modeling choice allows for a clear assessment of how connection rigidity and distribution influence global response parameters, such as natural periods, lateral displacements, inter-story drifts, and story stiffness, while maintaining computational efficiency and methodological consistency.



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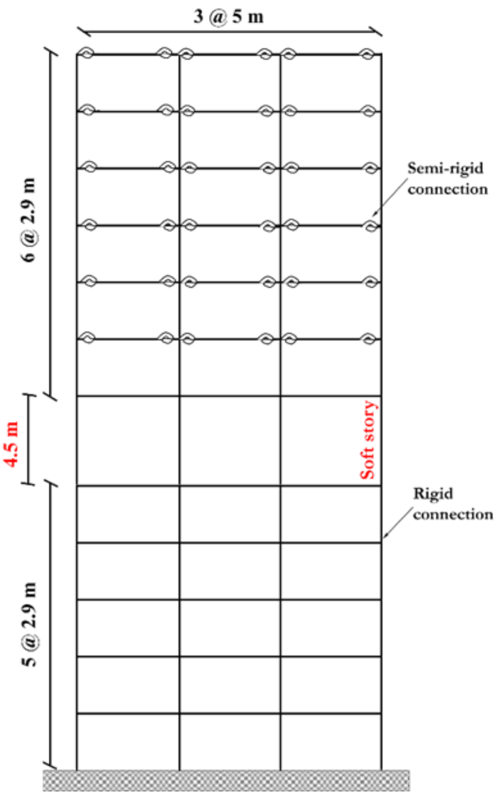

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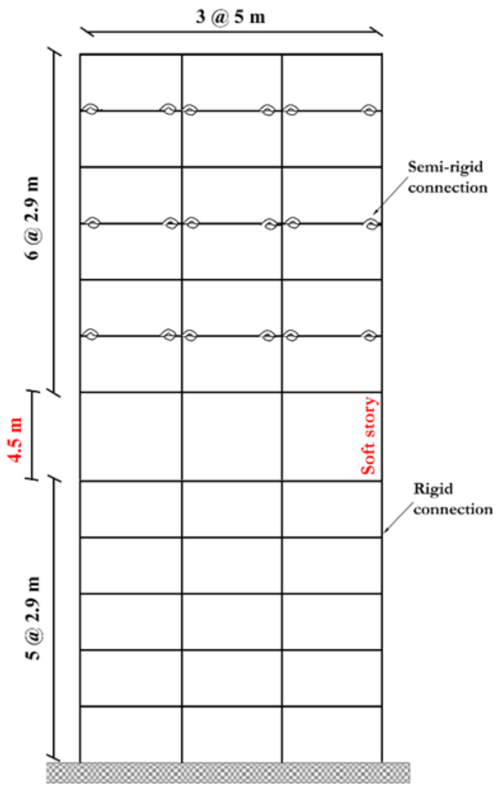


(c)

Fig. 3. Steel frame: (a) Rigid, (b) Hybrid - Case 1, (c) Hybrid – Case 2

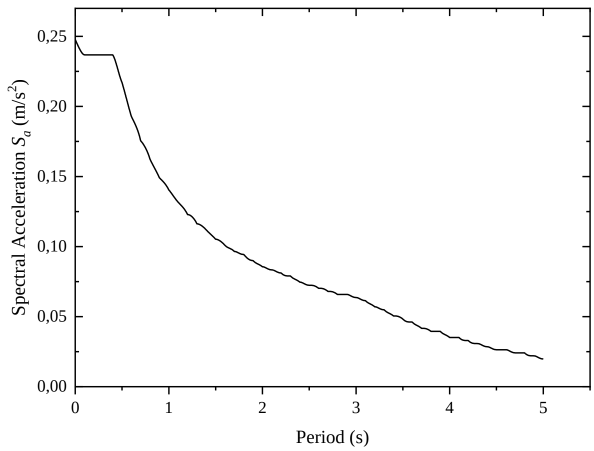


Fig. 4. The response spectrum of the studied structure

3. Results and discussion

3.1. Preliminary results

The natural vibration periods of the analyzed steel frames are detailed in Tables 3 and 4.

Table 3. Eigenmodes of the structure in the rigid connection model

Modes	Model	Periods (s)	UX (%)
Mode 1		1.962	77.23
Mode 2	Rigid	0.645	12.10
Mode 3		0.402	3.96

Table 4. The eigenmodes of the structure in the two models of hybrid connections studied

Modes	Model	Case 1 Periods (s)	Case 1 UX (%)	Case 2 Periods (s)	Case 2 UX (%)
Mode 1	Semi-rigid (α = 0.75)	2.016	75.61	1.992	76.38
	Semi-rigid (α = 0.50)	2.160	71.37	2.053	74.71
	Semi-rigid (α = 0.20)	2.640	59.78	2.153	72.12
	Semi-rigid (α = 0.10)	3.137	52.13	2.196	71.07
Mode 2	Semi-rigid (α = 0.75)	0.691	12.82	0.667	12.55
	Semi-rigid (α = 0.50)	0.794	15.38	0.706	13.57
	Semi-rigid (α = 0.20)	1.002	24.02	0.758	15.34
	Semi-rigid (α = 0.10)	1.113	30.10	0.778	16.09
Mode 3	Semi-rigid (α = 0.75)	0.423	4.60	0.413	4.23
	Semi-rigid (α = 0.50)	0.465	5.69	0.431	4.64
	Semi-rigid (α = 0.20)	0.542	7.54	0.455	5.15
	Semi-rigid (α = 0.10)	0.579	8.65	0.464	5.34

As determined by the analyses, the addition of semi-rigid joints within the hybrid frames lengthens the natural periods relative to rigid frames, indicating greater global flexibility. Lengthening this period shifts the structural response toward lower spectral accelerations, resulting in the ability to decrease force and acceleration demands and provide more favorable conditions for energy dissipation under seismic loading. As a result, hybrid frames with semi-rigid connections show improved energy dissipation potential and enhanced dynamic performance under seismic loading.

Modal results confirm this trend. In Case 1, the lowest fixity level (α = 0.10) leads to significantly higher periods for all vibration modes, reflecting greater flexibility. For example, Mode 2 and Mode 3 periods increase by approximately +72% and +44%, respectively, compared with the rigid frame. Consistent with this, the modal mass participation in the X-direction decreases as α is reduced by 2.1%, 7.6%, 22.6%, and 32.5% for α = 0.75, 0.50, 0.20, and 0.10, respectively (rigid baseline UX = 77.23%). Case 2 shows the same tendency, but the reductions are milder (around 1 to 8% over the same α range), indicating a more balanced modal contribution.

These variations confirm that decreasing connection rigidity enhances the higher vibration of the participation modes, which can mitigate seismic forces through energy redistribution. However, increased flexibility also leads to higher lateral drifts, highlighting the need to carefully control "α" during design.

3.2. Story displacement profiles

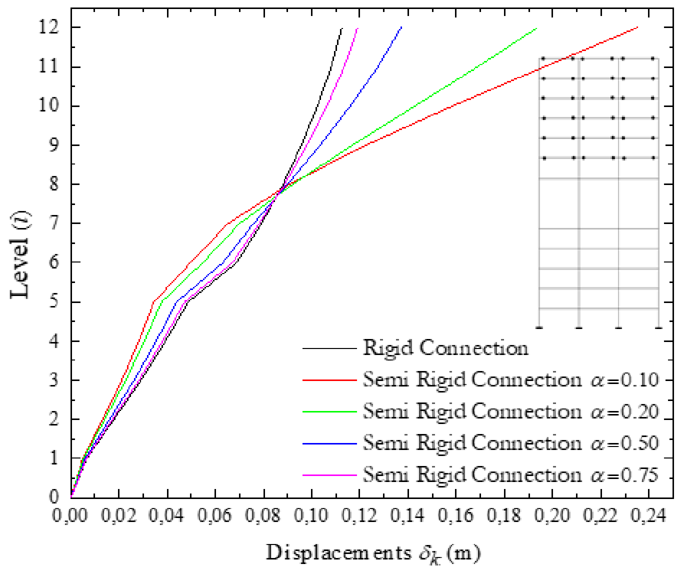
As seen in Fig. 5, the horizontal displacements (δ_k) increase as the fixity factor (α) decreases from 1.0 (fully rigid) to 0.10 (highly flexible). This effect is most pronounced on the upper stories and at roof level.

Case 1 shows that the α = 0.10 configuration gives the largest global displacement because of the strong softening influence of low-stiffness joints.

By contrast, intermediate fixity levels (α = 0.50–0.75) lead to moderate increases in drift. This range appears to introduce enough rotational flexibility to enhance energy dissipation while avoiding the very soft response observed at α = 0.10, thereby maintaining more acceptable displacement control.

Case 2, which includes fewer semi-rigid joints, displays consistently lower displacement sensitivity to α than Case 1. The variations among different fixity levels are less pronounced, demonstrating that selective use of semi-rigid connections can help distribute flexibility more uniformly and control drifts more effectively.

Overall, these results confirm that both the magnitude of α and the layout of semi-rigid connections are critical design parameters for achieving optimal seismic performance in hybrid frames.



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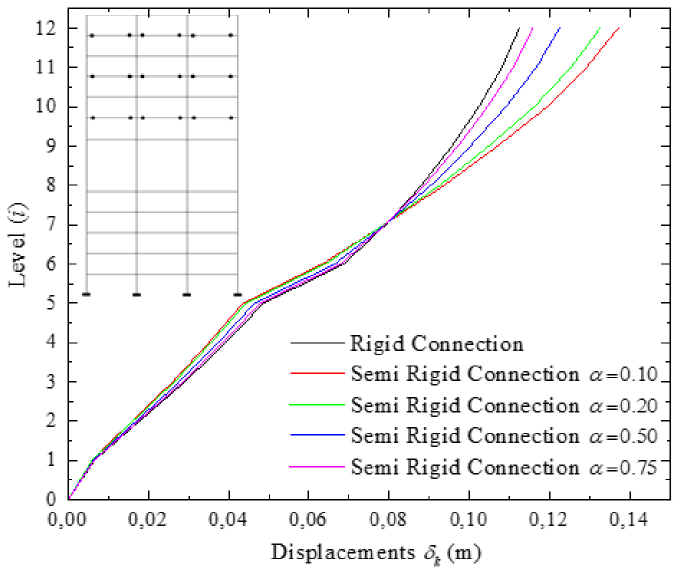


(b)

Fig. 5. The story displacements of the structure for the two hybrid layouts: (a) Case 1, (b) Case 2

3.3. Inter-story drift

Figure 6 shows the inter-story drift ratio (Δ_k/h) for each level of the studied frames. The inter-story drift is defined as $\Delta_k = \delta_k - \delta_{k-1}$, where δ_k is the horizontal displacement at level "k" and "h" is the story height. These results align with the displacement profiles, showing that joint flexibility strongly affects lateral deformation. In Case 1, where a larger number of joints are semi-rigid, inter-story drifts are significantly higher than in the fully rigid system, especially when the fixity factor α is reduced to 0.10.

A marked soft story effect appears on the 6th floor in Case 1, characterized by a sudden drift concentration due to local stiffness loss. Increasing α to 0.50 reduces this irregularity, resulting in a smoother drift distribution along the structure height.

In contrast, Case 2, which applies semi-rigid connections more selectively, achieves superior drift control. Even for lower fixity values (α = 0.20–0.10), the drift profile stays relatively smooth and more uniform than in Case 1, indicating improved deformation compatibility. This finding suggests that strategic placement of semi-rigid joints can minimize stiffness irregularities and enhance seismic resilience.

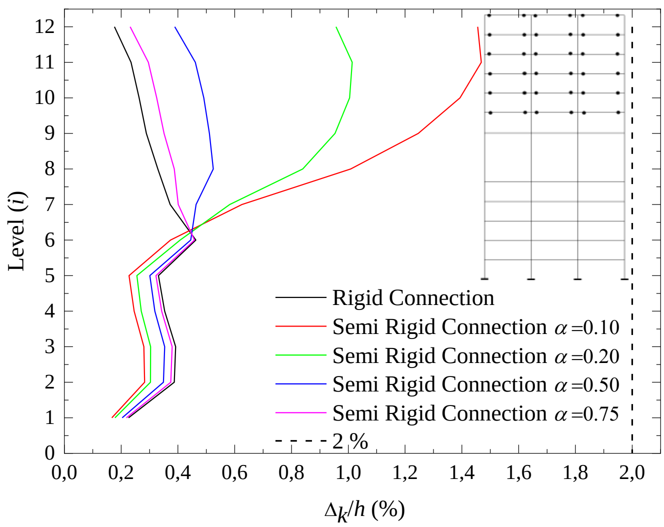
3.4. Story stiffness

Figure 7 compares the story stiffness distributions for the rigid baseline and the proposed hybrid systems. In the baseline, a pronounced drop at the 6th story confirms the presence of a typical soft-story weakness. Introducing semi-rigid connections above this level significantly improves stiffness continuity in both hybrid cases (1 and 2).

Using very low fixity levels (α = 0.20–0.10) helps to reduce the stiffness gap at the soft story and increase stiffness compared to the baseline but tends to cause larger lateral drifts elsewhere, making them less desirable for balanced performance.

Conversely, moderate fixity (α ≈ 0.50) provides the most effective compromise: it increases the 6th-story stiffness, produces a smoother profile, and satisfies international code requirements (EN 1998-1-1 [21], RPA [22], ASCE 7 [23], AISC 360 [33]), which mandate that the lateral stiffness of a soft story must not fall below 70% of that of the story immediately above.

These findings further establish the connection rigidity in regulating story stiffness and validate the hybrid system for achieving maximum code-compliant stiffness levels. It is therefore reasoned that improving the capacities of fixity factors within the hybrid system presents as one appropriate solution to improving overall seismic safety and energy dissipation.



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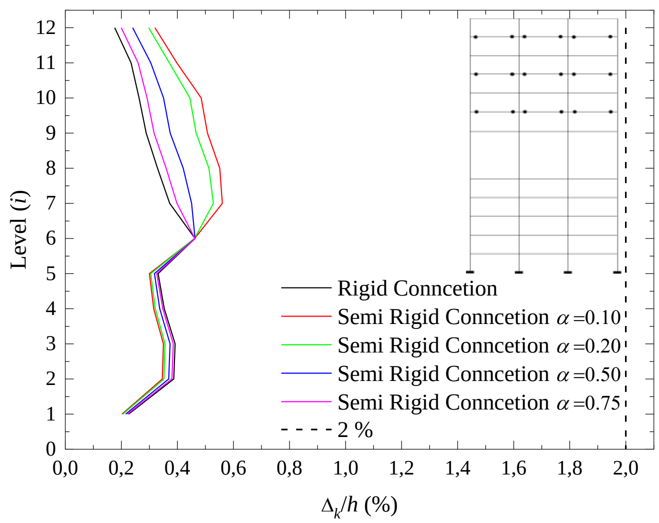
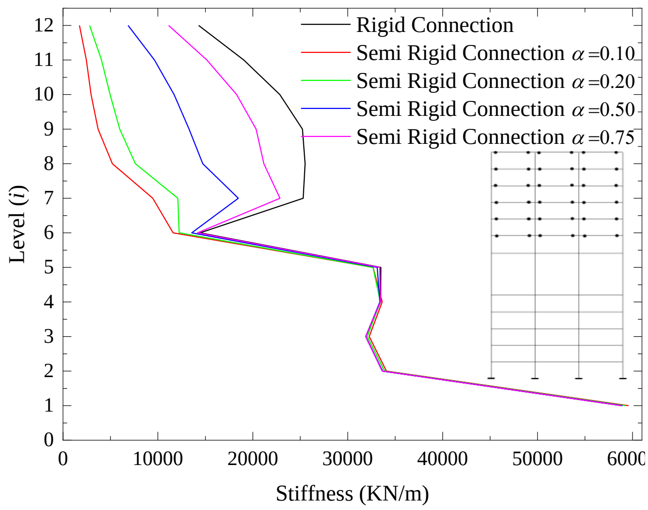


(b)

Fig. 6. The inter-story drift ratios of the structure for the two hybrid layouts: (a) Case 1, (b) Case 2



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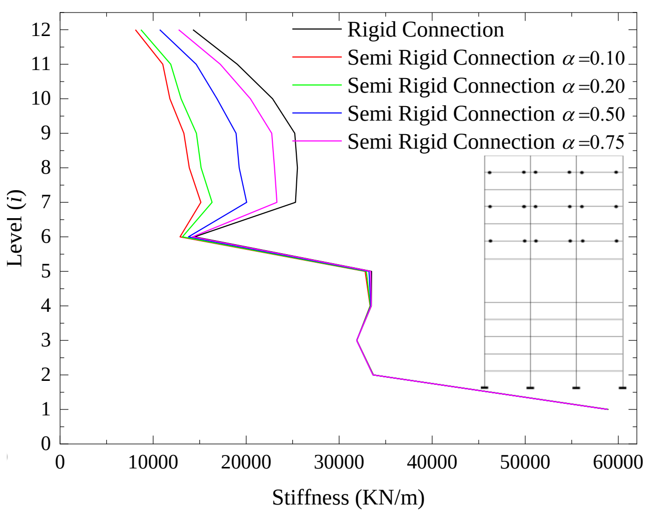

(b)

Fig. 7. The story stiffness of the structure for the two hybrid layouts: (a) Case 1, (b) Case 2

4. Conclusions

This study proposed a cost-effective hybrid system that combines rigid and semi-rigid connections to reduce lateral stiffness discontinuities in high-rise steel structures with a soft story. The numerical results showed significant improvements in seismic performance, particularly in terms of energy dissipation, drift control, and stiffness uniformity.

The results indicate that hybrid steel frame systems combining rigid and semi-rigid connections can significantly enhance seismic performance. The reduction of the connection fixity factor (from 1.0 to 0.1) increases floor displacements, especially in the upper stories. However, adopting intermediate fixity factors ($\alpha \approx 0.5$–0.75) provides an effective balance between flexibility and stiffness. These values optimize energy dissipation, maintain acceptable drift limits, and ensure global structural stability. Among all configurations, a fixity factor around 0.5 offers the best compromise between seismic safety and cost efficiency.

The key to these improvements lies in the strategic distribution of semi-rigid connections. Properly placed semi-rigid joints reduce stiffness discontinuities, alleviate soft story effects, and promote a more uniform inter-story drift profile. These findings align with previous studies (Razavi & Abolmaali [11]; Sharma et al. [16]) highlighting that intermediate stiffness levels ($\alpha \approx 0.5$) concentrate energy dissipation and limit drift irregularities. Furthermore, controlled stiffness allocation through hybrid detailing minimizes residual deformation, enhances code compliance, and reduces construction costs, findings consistent with Daryan et al. [14] and Boukhalkhal et al. [10].

Collectively, the results reinforce the adequacy of hybrid systems for addressing stiffness variation challenges in steel construction. These trends are consistent with international design requirements: AISC 360 (American Institute of Steel Construction) [33] for the classification and modeling of steel connections, and ASCE 7 [23] for drift and irregularity checks, thereby confirming the transferability of the hybrid strategy beyond the EN 1998 [21] and RPA [22] frameworks.

From a design standpoint, engineers should consider semi-rigid connections with intermediate fixity ($\alpha \approx 0.5$–0.75) to optimize both performance and economy. The number and placement of these connections are crucial design variables that can significantly improve seismic resilience in medium and high-rise steel frames.

This research is limited to linear elastic response-spectrum analysis. Nonlinear effects such as joint hysteresis, panel-zone yielding, cyclic degradation, and P–Δ phenomena were not considered. Therefore, the reported results should be interpreted as comparative performance indicators rather than absolute seismic predictions.

To validate and extend these findings, future work should incorporate experimental investigations, including

- Quasi-static cyclic tests on representative semi-rigid beam-to-column joints at selected fixity levels, using standard low-cycle protocols to extract M–θ envelopes and recalibrate zero-length rotational springs;
- Beam–column subassembly tests including realistic panel-zone details to capture interaction effects;
- System-level shake-table tests on a soft-story frame comparing all-rigid and hybrid layouts in terms of drift limits, residual deformation, and damage, complemented by parametric variations to probe robustness and constructability.

Future research should prioritize experimental validation of hybrid systems, including component and system-level tests under controlled seismic loading. Comprehensive 3D finite-element models with nonlinear time-history analyses should be developed to explore the influence of higher-mode effects and torsional responses. Finally, cost–benefit studies are needed to evaluate the economic feasibility of hybrid detailing for practical construction projects in seismic regions.

Overall, this study reinforces the potential of hybrid connection systems as practical, reliable, and economical solutions for enhancing the seismic resilience of steel structures with stiffness irregularities. By bridging the gap between theory and practice, these systems offer a promising pathway toward safer and more sustainable earthquake-resistant design.

List of abbreviations

EN 1998 – Eurocode 8.
RPA – Algerian Earthquake Regulation.
ASCE 7 – American Society of Civil Engineers 7.
AISC 360 – American Institute of Steel Construction.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

KCN, AYR, SHB and MB collecting the literature, performed the data collection, performed simulation and analysis, validation interpretation of data, KCN, AYR, SHB and MB examine the first draft of the manuscript, supervising the work, and revising the paper. All authors approved the final paper.

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