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Comparative Pushover Analysis of Multistory Buildings with Concrete-Filled and Non-Filled Double Channel Section with Battening Columns

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Abstract

Background: The seismic performance of steel columns is critical in earthquake-prone regions, where conventional non-filled battened double channel sections often exhibit limited lateral stiffness and ductility. Recent earthquakes, such as the 2015 Gorkha earthquake, have highlighted vulnerabilities in steel structures due to insufficient energy dissipation. Concrete-filled battened double channel columns (CFC) offer a promising solution by combining the strength of steel and the stiffness of concrete, enhancing seismic resilience. **Objective:** This study conducts a comparative pushover analysis of multistory buildings with concrete-filled (CFC) and non-filled battened double channel columns to evaluate their seismic performance. Key parameters include base shear capacity, roof displacement, ductility ratio, energy dissipation, and post-peak softening behavior. **Methods:** A G+7 residential building was modeled in SAP2000 with identical geometry and loading conditions for both column types. Nonlinear static pushover analysis was performed under displacement-controlled loading, with plastic hinges assigned per FEMA-356 guidelines. The models were compared based on seismic performance indicators, including capacity curves, hinge formation, and performance points. **Findings:** The CFC model achieved 24% higher base shear (19,230 kN vs. 15,560 kN) and greater roof displacement (446 mm vs. 402 mm). Ductility ratio improved by 12.7% (3.38 vs. 3.0) in the CFC model. Energy dissipation increased by 31.8%, with a more gradual post-peak softening response. Plastic hinge distribution showed that the CFC model exhibited better inelastic deformation capacity before collapse. **Conclusion:** Concrete-filled battened double channel columns significantly enhance lateral strength, ductility, and energy dissipation compared to non-filled sections. However, higher displacement demands must be considered in design. Future work should incorporate nonlinear dynamic time-history analysis for a more comprehensive assessment. The findings support revising seismic design codes (e.g., NBC 105:2020, AISC 360) to include provisions for composite open-section columns.

Keywords: Concrete-filled steel columns, battened double channel, pushover analysis, seismic performance, ductility, energy dissipation, SAP2000, NBC 105:2020

1. Introduction and Background

The seismic performance of structural systems is a critical concern in earthquake-prone regions, where improved resilience and energy dissipation capacity are essential for minimizing structural damage and preventing loss of life. Among structural components, steel columns are widely used due to their favorable strength-to-weight ratio and ease of construction. However, conventional steel columns—particularly non-filled battened double channel sections—often exhibit limited lateral stiffness and ductility. These deficiencies can lead to brittle failure modes under strong ground motions, compromising the integrity of the entire structural system.

This vulnerability was evident in recent earthquakes, such as the 2015 Gorkha earthquake in Nepal (Mw 7.8), where several steel and composite structures suffered damage due to insufficient ductility and poor energy dissipation mechanisms. In regions with high seismic

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hazard levels—like the Himalayan belt, classified as seismic Zone V in Nepal's National Building Code—such performance limitations pose a serious risk to structural safety and public welfare.

In response, concrete-filled battened double channel columns have emerged as a promising solution to improve seismic resilience. These composite columns leverage the compressive strength and stiffness of concrete alongside the tensile strength and ductility of steel. This synergy enhances lateral load resistance, delays local and global buckling, and significantly improves energy dissipation compared to their non-filled counterparts. This study presents a comparative pushover analysis of multistory buildings using both concrete-filled and non-filled battened double channel steel columns. Key performance indicators—including maximum base shear, roof displacement, ductility ratio, energy dissipation, and post-peak softening behavior—are evaluated under lateral loading. The goal is to quantify the seismic benefits of concrete infill and to provide performance-based design insights for more resilient buildings in high-risk seismic zones.

2. Literature Review

Concrete-filled steel sections have gained increasing attention due to their superior seismic performance, arising from the composite interaction between steel and concrete. Vafaei and Maheri (2016) investigated the cyclic behavior of concrete-filled steel batten built-up columns and reported significant improvements in strength and energy dissipation capacity compared to non-filled steel columns. Their findings highlight the potential of concrete infill to enhance ductility and delay local buckling under cyclic loads.

Several studies have compared the seismic response of buildings using composite columns with traditional reinforced concrete or steel-only columns. Patil and Jangid (2016) conducted a comparative study on multistory buildings with RCC and concrete-filled steel tube columns, revealing improved lateral load resistance and ductility in composite systems. Similarly, Patil and Desai (2021) demonstrated through numerical analyses that composite columns contribute to increased seismic resilience in multistory buildings.

While much research has focused on closed tubular sections, battened double channel columns offer practical advantages in fabrication and cost, especially in regions with limited access to advanced manufacturing. Sharma and Patel (2024) studied seismic strengthening of low-rise steel structures using concrete infill in battened columns and confirmed enhanced lateral strength and energy dissipation capabilities.

Recent comprehensive analyses by Katsimpini et al. (2025) emphasize the importance of understanding steel–concrete composite behavior for seismic design, underscoring that geometry, material properties, and connection detailing critically influence performance.

From a methodological perspective, nonlinear static pushover analysis, as implemented in software such as SAP2000 (Computers and Structures, Inc., 2023), provides an effective tool to evaluate seismic capacity and ductility of structural models, allowing for performance-based design assessments.

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Building on this foundation, the present study aims to comparatively assess multistory buildings with concrete-filled versus non-filled battened double channel columns through pushover analysis, focusing on base shear, roof displacement, ductility, and energy dissipation under seismic loading conditions. This approach addresses the gap in applying composite open-section columns in practical seismic analysis.

3. Methodology

3.1 Building Model Description

A G+7 residential building was modeled in SAP2000, maintaining identical geometry, material properties, and loading conditions for both variants. The building features a typical floor height of 3 m and bay dimensions of 5 m × 5 m. The slab thickness was set at 75 mm, while beams comprised ISMB 550 and ISMB 200 sections with ISMB 100 stringer beams.

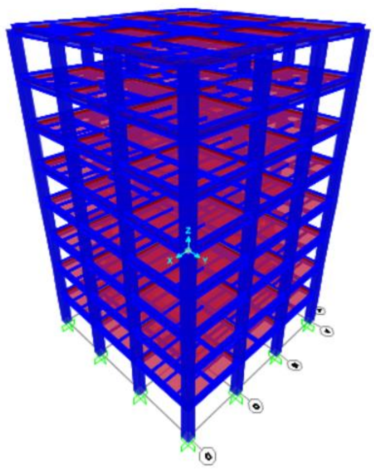

Fig 1: Extrude View of analysed model

3.2 Column Types

Two models were developed:

- **Model 1:** Utilized hollow square steel columns with dimensions 600 mm × 600 mm with flange and web thickness of 15.3 mm and 8.6 mm respectively of double channel section and battening of length 600 mm and 10 mm thick.

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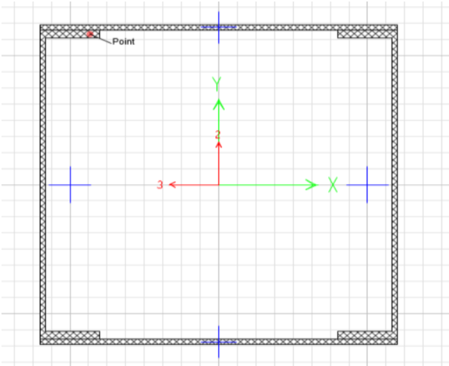

Fig 2: Column section of unfilled section

- **Model 2:** Used identical steel columns filled with M20 grade concrete, maintaining the same cross-sectional dimensions as Model 1.

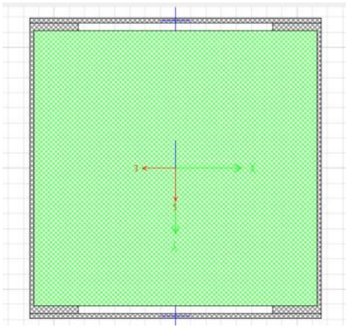

Fig 2: Column section of M20 concrete filled section

3.3 Loadings

Gravity loads accounted for dead loads (self-weight plus finishes) and a live load of 2 kN/m² with floor finish 1 kN/m². Wall load of 9.54 kN/m is applied. Seismic loading followed the NBC 105 :2020 provisions for seismic Zoning Factor 0.35, with an importance factor of 1.0, response reduction factor (R) of 4 (applicable for Steel + RC Composite Moment Resisting Frame), and soil classification type D.

3.4 Pushover Analysis

Nonlinear static pushover analysis was performed using a displacement-controlled incremental lateral load pattern. The analysis was displacement-controlled at the roof level by applying incremental lateral displacements at a control node located at the roof, up to a maximum displacement of 0.6 meters. This method allowed for detailed monitoring of the structural response as the displacement increased.

Plastic hinges were assigned following FEMA-356 guidelines to capture the nonlinear behavior of structural members under lateral loading:

- **Columns:** PMM (P-M-M) hinges were manually assigned to model combined axial force and biaxial bending effects.

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- **Beams:** M3 (moment-curvature) hinges were assigned predominantly at beam ends to capture plastic hinge formation due to bending.

Plastic hinge performance levels were defined as:

- **Immediate Occupancy (IO):** Minimal deformation, no significant damage, maintaining full structural functionality.

- **Life Safety (LS) & Collapse Prevention (CP):** Presence of plastic deformation, with members retaining load-carrying capacity to ensure safety and stability.

- **Collapse (C) & Exceeding Collapse (E):** Failure of members with loss of load capacity, contributing to structural collapse.

3.5 Comparative Parameters Evaluated

The pushover analysis results were compared between the concrete-filled (CFC) and non-filled column models based on key seismic performance indicators:

• **Base Shear Capacity:**
The CFC model attained a maximum base shear of 19,230 kN, approximately 24% higher than the non-filled model's 15,560 kN, indicating superior lateral strength.

• **Roof Displacement:**
Despite the higher strength, the CFC model showed larger roof displacement (446 mm vs. 402 mm), suggesting reduced lateral stiffness and increased deformation demands.

• **Ductility and Energy Dissipation:**
The ductility ratio was higher in the CFC model (3.38 compared to 3.0), indicating better deformability. Energy dissipation improved significantly by about 31.8%, reflecting enhanced seismic energy absorption. The gradual post-peak softening behavior indicates a more stable and ductile response after peak loading.

• **Plastic Hinge Formation:**
More Collapse Prevention (CP) and Collapse (C) hinges were observed in the CFC model, indicating extensive plastic deformation and ductile failure mechanisms, which may require careful detailing to maintain seismic robustness.

• **Seismic Resilience:**
The concrete-filled column (CFC) system demonstrated superior strength, ductility, and energy dissipation, indicating enhanced seismic performance. While the gradual post-peak softening indicates stable strength degradation, the increased roof displacement signals higher deformation demands, which could pose challenges for displacement-sensitive components

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and overall structural stability under severe seismic events. Therefore, despite its improved strength and energy absorption, the CFC system requires careful design consideration for displacement capacity.

3.6 Element Perimeter and Reinforcement Details

The steel double-channel sections used in this study have a total perimeter of approximately 2400 mm, including flanges and webs. The concrete infill in Model 2 is assumed to be unreinforced M20 grade concrete confined by the steel channels and batten plates. No additional longitudinal or transverse reinforcement was modeled within the concrete core. This assumption reflects typical practice for concrete-filled steel composite columns where steel provides confinement and load resistance.

4.0 Results and Discussion

The pushover analysis results demonstrate a marked difference in seismic performance between the two structural models. The concrete-filled column (CFC) model (Model 2) achieved a maximum base shear of 19,230 kN at a roof displacement of 446 mm, outperforming the non-filled column model (Model 1), which reached a peak base shear of 15,560 kN at 402 mm displacement.

The pushover curves clearly show that the CFC model possesses higher lateral strength and greater displacement capacity compared to its non-filled counterpart. This improved performance indicates an enhanced ability of the CFC system to resist seismic forces, largely due to the composite action between the steel tube and the concrete infill. The concrete core increases axial load capacity and delays local buckling of the steel section, thereby improving the overall ductility and energy absorption characteristics.

Moreover, the higher base shear and larger roof displacement observed in the CFC model suggest superior energy dissipation capabilities. This implies that the CFC columns can undergo larger inelastic deformations while maintaining structural integrity, an important trait for seismic resilience. The gradual post-peak softening behavior observed in the CFC model further confirms its improved stability after peak strength is reached.

In contrast, the non-filled model exhibited a lower peak base shear and smaller displacement, with a more abrupt post-peak strength degradation. This behavior signals earlier stiffness loss and a comparatively brittle failure mechanism, limiting the structure's ability to dissipate seismic energy effectively

. Overall, the results highlight that the integration of concrete-filled steel columns in multistory buildings enhances seismic performance by increasing lateral load capacity, ductility, and energy dissipation. However, the increased displacement demands in the CFC model must be considered carefully during design to ensure serviceability and prevent excessive deformation during strong seismic events.

4.1 Capacity Curves:

The capacity curves presented in Figures 1 and 2 clearly illustrate the superior performance

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of the concrete-filled column (CFC) model in terms of both lateral strength and displacement capacity when compared to the non-filled column model. The CFC model achieves a higher peak base shear—approximately 19.23×10³ kN—at a larger displacement, indicating enhanced ductility and energy dissipation capacity. In contrast, the non-filled model reaches its maximum base shear of around 15.56×10³ kN at a smaller displacement, followed by a sharp decline, which signals early stiffness degradation and a more brittle behavior. Moreover, the CFC model maintains a relatively stable post-peak response, with a gradual reduction in base shear, while the non-filled model experiences a more abrupt loss of strength. This improved performance of the CFC system can be attributed to the composite action between the concrete infill and the steel section, which together delay local buckling and increase the energy absorption under lateral loading. The concrete core not only enhances axial load capacity but also contributes significantly to lateral stability, resulting in a more resilient seismic response. These results highlight the effectiveness of concrete-filled columns in improving structural robustness during seismic events.

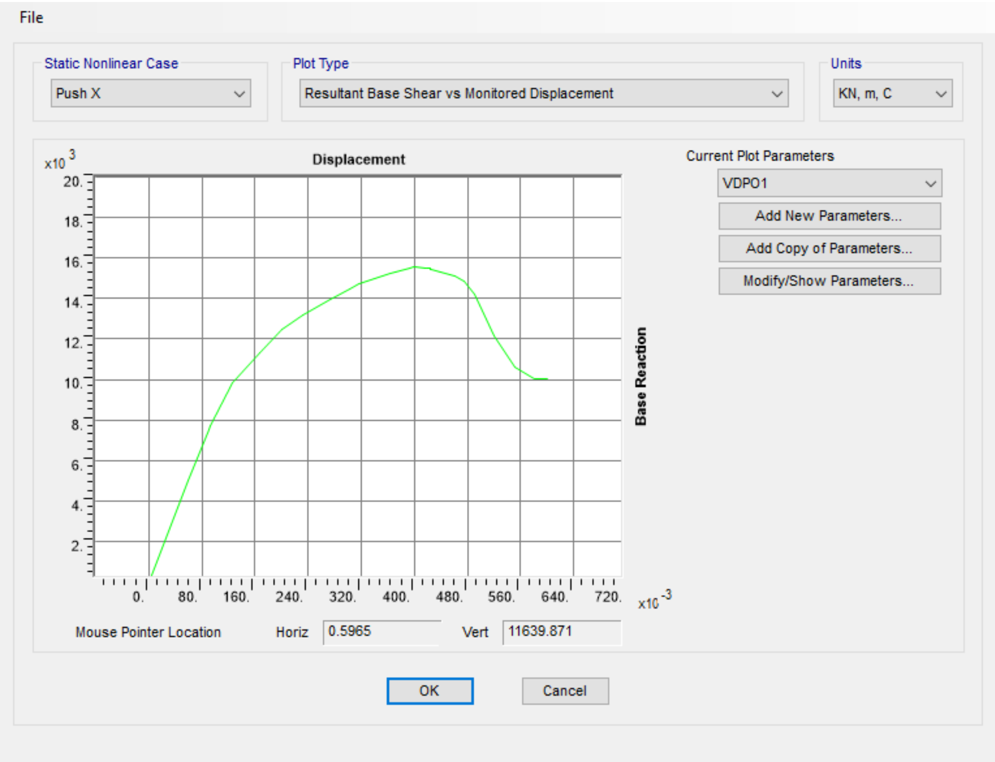

Fig3. Base shear vs displacement curve for unfilled section

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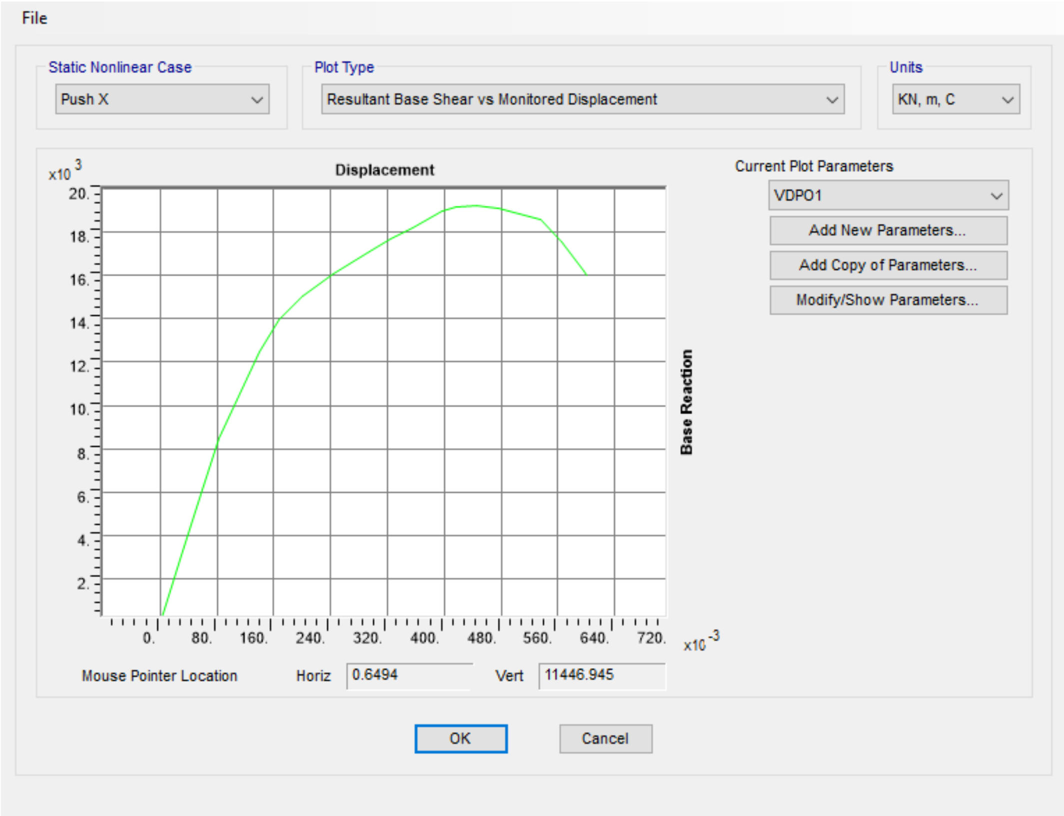

Fig 4. Base shear vs displacement curve for Concrete filled column section

4.2 Hinge Formation:

Figure 3 presents a bar graph comparing plastic hinge distributions across performance levels for concrete-filled and non-filled battened double channel frame systems. In the A to IO (Immediate Occupancy) range, both models exhibit a high number of hinges, with the non-filled frame showing slightly more (1,188) than the filled frame (1,180). This suggests that the non-filled system may have marginally higher initial stiffness and better elastic performance under service-level seismic loads.

In the IO to LS (Life Safety) range, both frames show an equal and minimal number of hinges (12), indicating similar structural responses under moderate inelastic demands.

A significant difference appears in the LS to CP (Collapse Prevention) range, where the concrete-filled frame forms 12 hinges, while the non-filled frame has none. This highlights the filled frame's ability to undergo further inelastic deformation and maintain stability before reaching collapse, demonstrating better ductility in this range.

In the >CP (beyond Collapse Prevention) category, the non-filled frame exhibits more hinge formation (80) compared to the filled frame (76). Although the difference is slight, it implies that the non-filled frame may experience more widespread failure at extreme deformations, while the filled frame exhibits slightly better containment of damage, likely due to the confining effect of the concrete infill.

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Overall, the results suggest that while the non-filled frame shows slightly better elastic behavior, the concrete-filled frame offers superior inelastic performance, particularly by extending its deformation capacity before collapse.

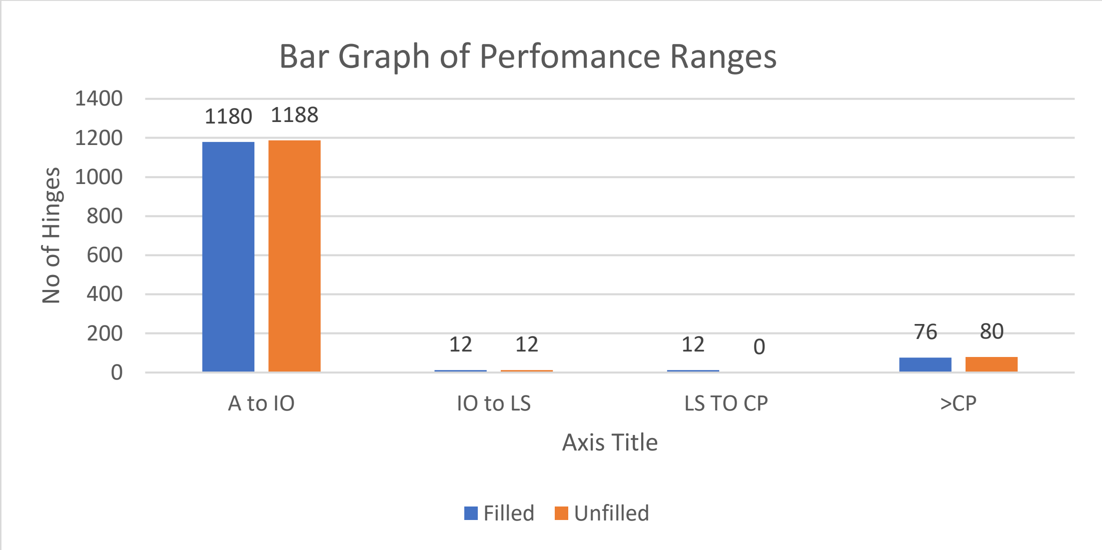

Figure 5: Comparison of plastic hinge distribution for CFT and unfilled sections based on SAP2000 output at final pushover step

4.3 Performance Point:

The performance points of both models were determined by analyzing the relationship between base shear and monitored roof displacement, with the results summarized in Table 1. The concrete-filled column (CFC) model (Model 2) achieved a performance point at a roof displacement of 446 mm, compared to 402 mm for the non-filled column model (Model 1). This indicates that the CFC model can sustain larger displacements before reaching its performance limit, reflecting enhanced ductility and better overall seismic performance.

Supporting this, the pushover analysis shows that the CFC model reached a higher maximum base shear of 19,230 kN—approximately 24% greater than the 15,560 kN recorded for the non-filled column model—demonstrating increased lateral load capacity. The ductility ratio of the CFC model was also higher, at 3.38 versus 3.0, alongside greater roof displacement (446 mm compared to 402 mm). Furthermore, energy dissipation in the CFC model was significantly improved, with 8910 kN·m—31.8% more than the 6761 kN·m for the non-filled column. The CFC model exhibited a more gradual post-peak softening, indicating improved stability and resilience after peak strength.

These improvements are attributed to the presence of concrete infill, which enhances the structural stiffness, strength, and energy dissipation capacity of the columns, ultimately leading to better seismic performance under lateral loading.

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Table 1: Comparison of performance parameters between CFC and non-filled models.

Parameter	Non-Filled Column	Concrete-Filled Column
Max Base Shear (kN)	15560	19230
Roof Displacement (mm)	402	446
Ductility Ratio	3	3.38
Energy Dissipation (%)	6761(reference)	8910(+31.8% over reference)
post peak softening	steeper	gradual

4.4 Discussion

The analysis clearly demonstrates that concrete-filled battened double channel columns significantly enhance the seismic performance of multistory buildings. Compared to the non-filled column model, the concrete-filled configuration achieved higher lateral strength, greater displacement capacity, and improved energy dissipation, confirming the positive impact of concrete infill on structural behavior under seismic loading.

The larger area under the pushover capacity curve for the filled model reflects its superior energy absorption capability, allowing it to dissipate more seismic energy and thereby reduce potential damage during earthquake events. Moreover, the delayed formation of collapse-level hinges (hinge states C and E) in the concrete-filled frame indicates a higher tolerance for inelastic deformation prior to failure, contributing to enhanced structural resilience. The elevated performance point of the filled system further confirms its improved behavior under lateral seismic demands.

These findings are consistent with previous research highlighting the benefits of concrete infill in steel sections—typically explored in the context of closed tubular geometries—but here extended to battened double channel sections, which offer practical fabrication and construction advantages. This study reinforces the case for incorporating concrete-filled open-section columns in the seismic design of multistory buildings, particularly in regions of high seismic risk.

However, it is important to acknowledge the limitations of the static pushover analysis used in this study. While effective for comparative performance evaluation, pushover analysis does not capture dynamic effects, such as time-dependent seismic loading and higher-mode contributions. Future research should incorporate nonlinear dynamic time-history analysis to assess real-time performance and validate the observed improvements under actual earthquake scenarios. Such investigations will be essential to refining design guidelines and enhancing the reliability of composite battened column systems in seismic applications.

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4.5. Practical Implications and Code Considerations:

The increased roof displacement observed in the concrete-filled column (CFC) model, while indicative of improved ductility, also has important implications for foundation design and the overall structural system. Larger lateral displacements can impose greater demands on foundation elements, potentially requiring more robust footing design or deeper foundations to prevent excessive settlement or overturning. Additionally, increased deformation may affect non-structural components such as partitions, cladding, and service systems, necessitating careful coordination in architectural and MEP design to accommodate anticipated drifts. Therefore, seismic design using CFC systems must carefully balance strength and ductility benefits against serviceability limits and foundation capacity.

The observed improvements in strength, ductility, and energy dissipation in concrete-filled battened double channel columns suggest that current design codes, such as NBC 105:2020 and international standards like AISC 360, could consider specific provisions for composite open-section columns to optimize seismic resilience. Incorporating factors that account for enhanced post-yield behavior and gradual softening could lead to more efficient use of materials and improved safety margins. Moreover, performance-based design approaches could leverage these findings by defining acceptance criteria for displacement and energy dissipation tailored to composite battened sections, providing engineers with clear guidelines for seismic detailing and capacity design.

4.6. Limitation and Future Work

The authors acknowledge that the static pushover analysis, while effective for comparative assessment, does not account for important dynamic seismic effects such as higher-mode responses, time-dependent loading, and varying seismic intensities. Higher-mode effects, in particular, can significantly influence the behavior of mid- and high-rise buildings during strong earthquakes, potentially affecting displacement demands and internal force distributions. To address these limitations, nonlinear dynamic time-history analyses are suggested for future work. Such analyses will provide a more holistic understanding of the structures' real-time behavior under varying seismic excitations and will help validate the current static results. Incorporating these advanced analyses will enable a more accurate assessment of seismic performance and enhance the reliability of design recommendations for concrete-filled and non-filled battened double channel columns.

5. Conclusion

This study confirms that concrete-filled steel tube (CFC) columns significantly improve the lateral strength and energy dissipation capacity of multistory buildings compared to traditional non-filled columns. The CFC model exhibited a higher maximum base shear of 19,250 kN, greater roof displacement of 446 mm, and a higher ductility ratio of 3.38, indicating enhanced seismic performance in terms of both strength and deformability. The more gradual post-peak softening observed in the CFC model further suggests improved stability after peak loading.

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However, the increased displacement demands and earlier onset of collapse-level hinges highlight potential challenges in seismic resilience, demonstrating that higher strength does not always equate to better overall seismic behavior. These results suggest a trade-off between strength gains and deformation capacity in CFC systems, which should be carefully considered in design.

Given the limitations of the nonlinear static pushover analysis employed in this study, future research should incorporate nonlinear dynamic time-history analyses to fully capture the seismic response of buildings with concrete-filled columns under realistic earthquake loading conditions. Such analyses will provide a more comprehensive understanding of their performance and enable refinement of design recommendations.

The findings of this study recommend that seismic design codes and guidelines, such as NBC 105:2020 and AISC 360, consider incorporating specific provisions for concrete-filled open-section composite columns. Integrating these insights into codes can help engineers design safer and more resilient structures by balancing strength, ductility, and displacement demands unique to these composite systems.

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