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Study on structural performance and sustainability of RC buildings through design optimizations and mini-haunch connections

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Abstract
The demand for optimized RC frame designs with column-free spaces has led to the increased use of haunched beams in reinforced concrete (RC) structures. Haunched beams, characterized by a thicker cross-section at the supports compared to the mid-section, are typically placed at the bottom of beams, minimizing the need to alter the top flange or remove the floor slab. These beams create rigid moment connections between beams and clumns, enhancing the structural stability of RC frames. This research focuses on the performance and sustainability of RC frame structures by investigating the application of the Mini-Haunch connection, a novel beam-column joint design, to optimize structural behavior. The study evaluates the effects of various design optimizations, such as concrete grade, column size, and beam configuration, on the structural performance of low-to-medium-rise RC buildings. A non-linear static analysis using pushover analysis is performed on RC building frames under seismic loading (Zone IV), considering IS 1893 (Part 1): 2002 for design parameters. The study compares base shear, natural period, and hinge formation patterns of the buildings with and without the Mini-Haunch connection. The findings show the potential of the Mini-Haunch connection to enhance the sustainability and performance of RC moment-resisting frames, promoting more efficient designs with reduced material usage.

Keywords: Rc frame structures, mini-haunch connection, design optimization, pushover analysis, seismic performance, base shear, natural period, hinge formation

1. Introduction

The demand for more efficient and sustainable RC building designs has grown significantly, particularly in the context of low-to-medium-rise buildings in India, where rapid urbanization is on the rise. One of the major challenges faced by structural engineers is the need to optimize design while ensuring structural integrity and cost-effectiveness. In a reinforced concrete (RC) frame building, loads are primarily carried and transferred by beams. However, when the span increases, such as in the case of soft storey structures, bending moments and shear forces significantly increase, especially at the center of the span and over the supports. Prismatic beams often prove uneconomical in such situations, as they do not provide an optimal solution for managing the increased forces.

In such cases, non-prismatic beams, such as haunched beams, offer a more efficient and economical alternative. Haunched beams are most commonly used in bridge structures, portal frames, and cantilever retaining walls, where the span is large and needs to accommodate varying load distributions. These beams can be made non-prismatic by modifying their cross-sectional dimensions, such as varying the width, haunch depth, and haunch length along their length. By adopting haunched beams, it is possible to optimize the use of concrete and steel, reduce the overall weight of the building, and even increase headroom.

This study investigates the performance of RC moment-resisting frames optimized with Mini-Haunch connections as a solution to the challenges posed by traditional shear walls and prismatic beams. Moment-resisting frames are widely used for lateral stability, but they often come with limitations related to second-order effects (P-Δ effects), column failure, and serviceability issues in taller buildings. The Mini-Haunch connection provides an innovative way to improve the stiffness and energy dissipation of RC frames, addressing these limitations while maintaining sustainability and cost-efficiency.

The proposed model explores the use of Mini-Haunch connections as a non-prismatic solution to enhance structural performance in RC frames. To evaluate the seismic performance, nonlinear static pushover analysis will be performed. In this method, the structure is subjected to monotonically increasing lateral forces until a target displacement is reached, allowing for the evaluation of base shear, displacement curves, and the hinge pattern under seismic loading. The performance point and the base shear displacement curve will be used to assess the structural behavior and sustainability of RC buildings designed with Mini-Haunch connections.

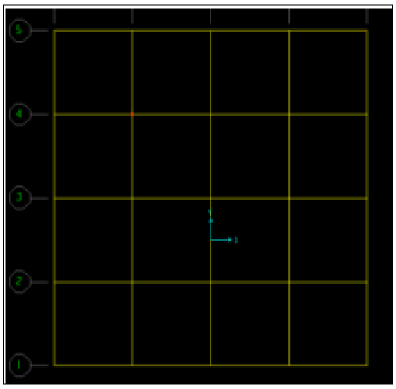


Fig 1: Plan of building frame

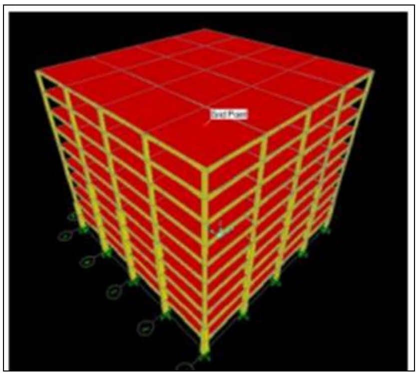


Fig 2: 3D model of haunched beam frame

By integrating innovative design solutions like the Mini-Haunch connection, this research aims to contribute to the development of RC frame buildings that are structurally efficient, economically viable, and environmentally sustainable.

2. Case Study Details

To evaluate the performance of RC moment-resisting frames in low-to-medium-rise buildings without shear walls, a 10-storey RC structure is considered in this case study. This structure is designed to optimize the structural performance and sustainability by integrating the Mini-Haunch connection into the moment-resisting frame. The building consists of four bays in both the X and Y directions, with each bay spaced 8 meters apart. The story height is 3 meters, and the building is located in seismic zone IV, which represents an area with moderate seismic activity in India.

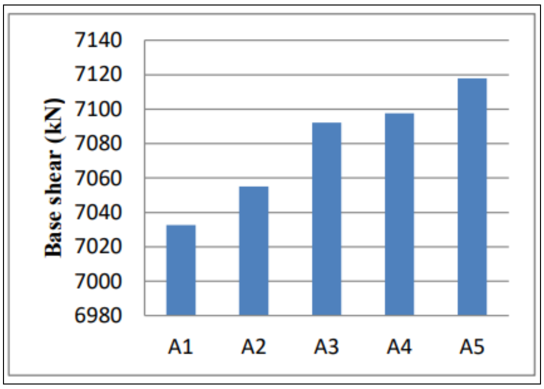


Fig 3: Base shear variation for different haunch depth frames

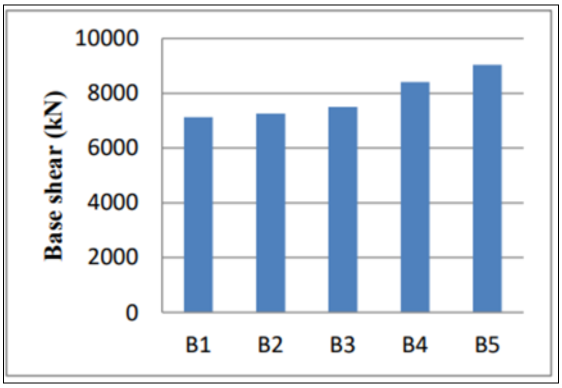


Fig 4: Base shear variation for different haunch length frames

A. Design Data

Live Load

- 3.0 kN/m² at each floor
- 1.5 kN/m² on the terrace
- **Earthquake Load:** As per IS 1893 (Part 1) 2002 for seismic design considerations.
- **Type of Soil:** Type II (Medium soil) as per IS 1893, affecting the foundation design.
- **Storey Height:** 3 meters per floor.
- **Floors:** Ground Floor + 9 upper floors, resulting in a 10-storey building.
- **Walls:** 230 mm thick brick masonry walls.
- **Seismic Zone:** Zone IV (Moderate seismic zone) as per the Indian seismic classification.

B. Building Frame Details

Number of Bays

- Along the X direction: 4 bays
- Along the Y direction: 4 bays

Spacing:

- Along the X-axis: 8 meters
- Along the Y-axis: 8 meters
- **Story Height:** 3 meters per storey, consistent with typical low-to-medium-rise buildings in urban India.
- **Number of Floors:** Ground Floor (G.F) + 9 upper floors, creating a 10-storey building.

Column Sizes

- 300 mm x 450 mm for typical columns.
- 400 mm x 900 mm for major structural columns, particularly at intersections or where additional load is anticipated.

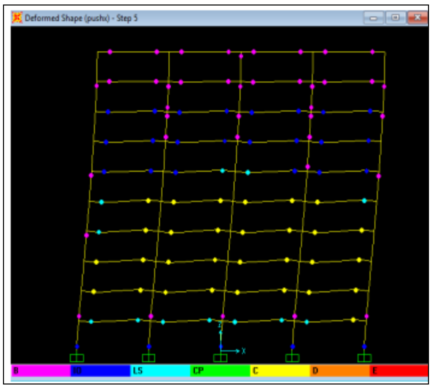


Fig 5: Hinge pattern in X direction for frame with haunch depth of 500mm

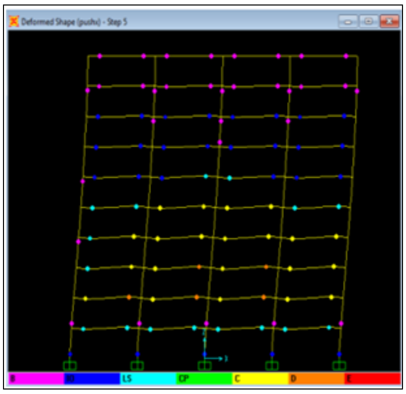


Fig 6: Hinge pattern in X direction for frame with haunch depth of 600mm

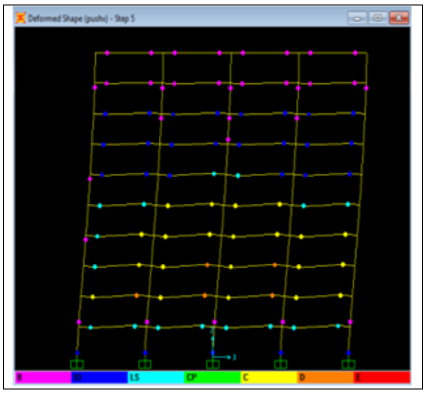


Fig 7: Hinge pattern in X direction for frame with haunch depth of 700mm

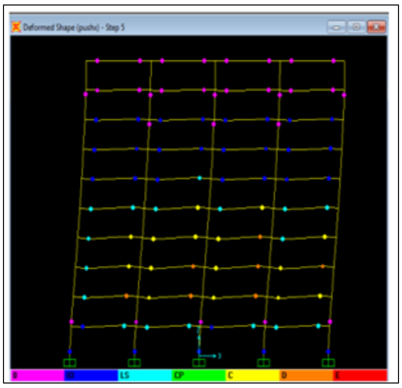


Fig 8: Hinge pattern in X direction for frame with haunch depth of 800mm

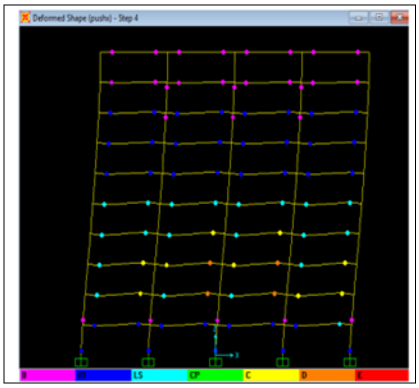


Fig 9: Hinge pattern in X direction for frame with haunch depth of 900mm

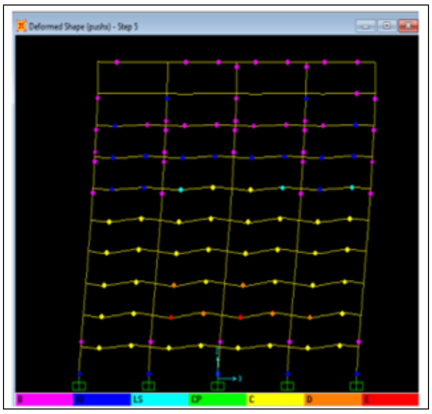


Fig 10: Hinge pattern in X direction for frame with haunch length of 150mm

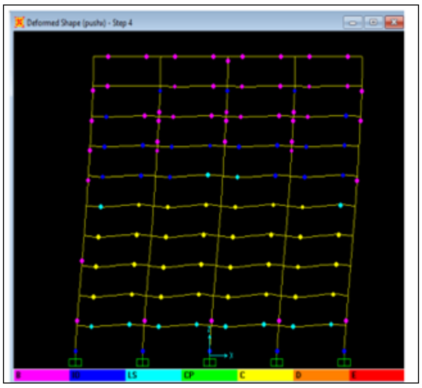


Fig 11: Hinge pattern in X direction for frame with haunch length of 200mm

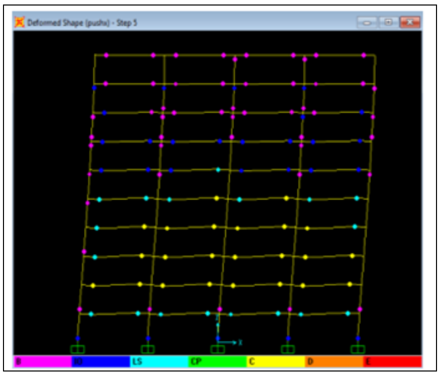


Fig 12: Hinge pattern in X direction for frame with haunch length of 250mm

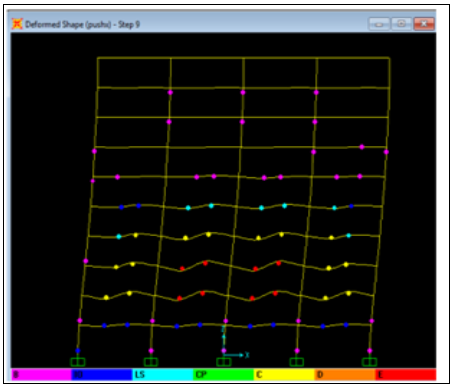


Fig 13: Hinge pattern in X direction for frame with haunch length of 350m

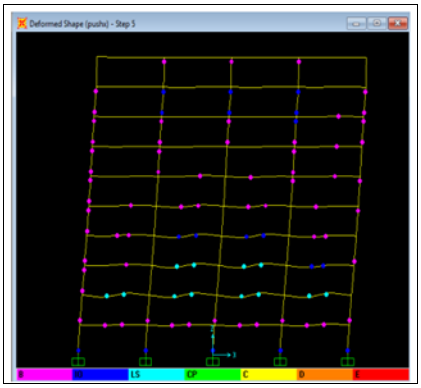


Fig 14: Hinge pattern in X direction for frame with haunch length of 300mm

Beam Size
Width: 300 mm.

- **Haunch Length and Depth:** Varies according to the specific structural requirements to optimize load transfer and moment resistance in moment-resisting frames.
- **The Mini-Haunch connection** is designed with a focus on improving energy dissipation and structural stiffness, helping to enhance the lateral stability of the frame while minimizing material consumption.
- **Slab:** The floor slab thickness is 150 mm, providing the necessary strength and rigidity while maintaining overall cost-efficiency and sustainability in design.

Table1: Haunch Length and Beam Dimensions

S. No.	Model	Haunch Length (mm)	1/5th Clear Span (mm)	Beam Depth at Support (mm)	Beam Depth at Midsection (mm)	Beam Width (mm)
1	A1	160	500	300	300	300
2	A2	160	600	300	300	300
3	A3	160	700	300	300	300
4	A4	160	800	300	300	300
5	A5	160	900	300	300	300

Table 2: Symmetric Variation in Haunch Length for RC Moment-Resisting Frames

S. No.	Model	Haunch Length (mm)	Beam Depth at Support (mm)	Beam Depth at Midsection (mm)	Beam Width (mm)
1	B1	150	500	300	300
2	B2	200	500	300	300
3	B3	250	500	300	300
4	B4	300	500	300	300
5	B5	350	500	300	300

In this case study, the 10-storey RC structure is designed with a focus on eliminating shear walls and integrating moment-resisting frames enhanced by the Mini-Haunch connection to achieve superior structural performance and sustainability. The structural elements are optimized through careful consideration of load distribution, material savings, and enhanced energy dissipation, in line with the research goals of improving the sustainability of RC buildings in India.

3. Results Obtained

C. Fundamental Time Period (sec.)

The natural period of a structure is defined as the time it takes for the building to complete one cycle of undamped free vibration. This period is crucial in understanding the building's response to seismic forces and its ability to resist lateral forces. The first modal time period corresponds to the dominant mode of vibration, which plays a significant role in the structure’s performance during an earthquake.

For the RC moment-resisting frames optimized in this research, variations in the fundamental time period were observed as different design parameters (e.g., column size, slab thickness, and concrete grade) were modified. The Mini-Haunch connection introduced in the beam-column joints also contributed to a noticeable change in the natural time period, as the connection improved the stiffness and damping characteristics of the structure. The time period for various frame configurations with and without the Mini-Haunch connection is summarized in the tables below, illustrating how structural performance is affected by these modifications.

Table 3: Time Period and Mode Shapes Obtained from Modal Analysis for Haunch Depth Variation

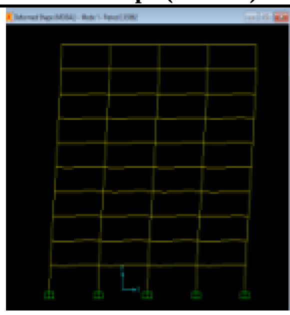
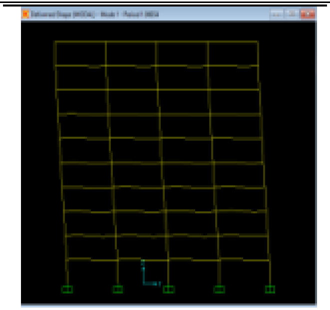
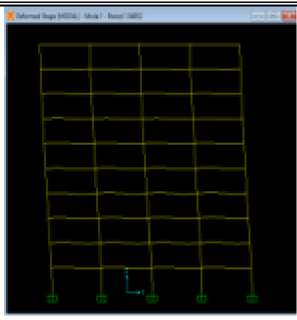
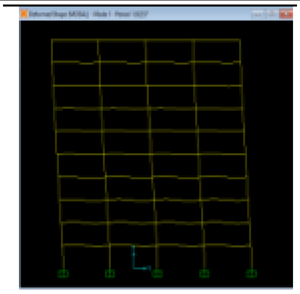
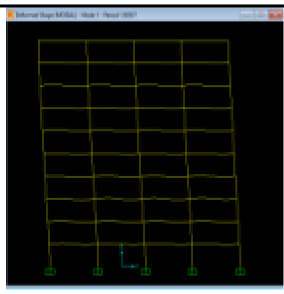
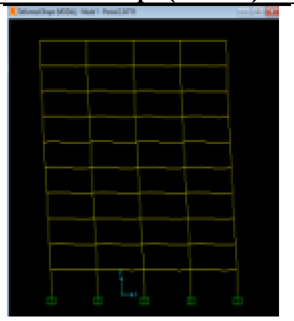
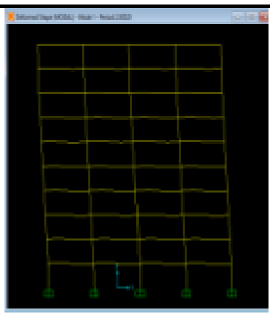
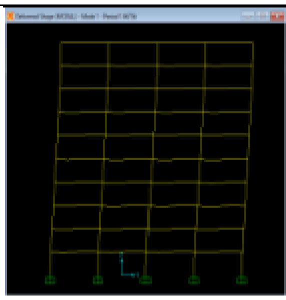
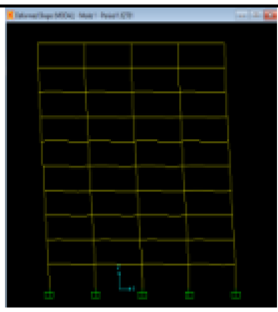
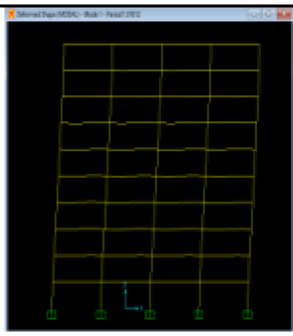
S. No.	Model	Time Period (s)	Mode Shape (Mode 1)
1	A1	2.03862	 Y Translation
2	A2	1.98654	 Y Translation
3	A3	1.94852	 Y Translation
4	A4	1.92237	 Y Translation
5	A5	1.90557	 Y Translation

Table 4: Time Period Obtained from Modal Analysis for Haunch Length Variation

S. No.	Model	Time Period (s)	Mode Shape (Mode 1)
1	B1	2.04719	 Y translation
2	B2	2.00520	 Y translation
3	B3	1.96756	 Y translation
4	B4	1.92781	 Y translation
5	B5	1.91612	 Y translation

To assess the seismic performance of the optimized RC moment-resisting frames, a non-linear static pushover analysis was conducted. This analysis involves applying a monotonically increasing lateral load to the structure until a target displacement is reached, thereby simulating the building's response to earthquake-like forces. The pushover analysis provides important insights into the structural behavior, specifically in terms of base shear and displacement.

Various pushover cases were considered in the analysis, including push-down, push-X, and push-Y load cases, which simulate different directions of lateral forces. The load combinations applied were in accordance with IS 1893 (Part 1): 2002 guidelines, ensuring that the analysis aligns with Indian seismic standards.

Following the pushover analysis, the demand curve and capacity curves were obtained, allowing for the determination of the performance point of the structure an indicator of the structural limits under seismic loading. The base shear and displacement values at the performance point were analyzed for various configurations of RC moment-resisting frames, both with and without the Mini-Haunch connection.

The results from the pushover analysis for different configurations are shown in the tables below. The data indicates that frames with Mini-Haunch connections exhibit higher base shear resistance and more favorable displacement characteristics, leading to improved seismic resilience.

Table 5: Performance Point Characteristics of RC Moment-Resisting Frames with Optimized Mini-Haunch Depth (X and Y Directions)

S. No.	Mini-Haunch Depth (mm)	Base Shear - X Direction (kN)	Displacement - X Direction (m)	Base Shear - Y Direction (kN)	Displacement - Y Direction (m)
1	500	7032.57	0.146	6210.610	0.168
2	600	7055.126	0.147	6210.554	0.169
3	700	7092.122	0.146	6228.486	0.169
4	800	7097.612	0.146	6246.416	0.171
5	900	7117.880	0.146	6248.580	0.171

Table 6: Performance Point Variation of RC Moment-Resisting Frames with Mini-Haunch Connection under Symmetric Haunch Length Optimization

S. No.	Mini-Haunch Length (mm)	PUSH-X Direction - Base Shear (kN)	PUSH-X Direction - Displacement (m)	PUSH-Y Direction - Base Shear (kN)	PUSH-Y Direction - Displacement (m)
1	150	7126.161	0.146	6294.716	0.171
2	200	7253.889	0.142	6354.351	0.166
3	250	7504.697	0.139	6523.756	0.162
4	300	8411.802	0.138	7374.717	0.163
5	350	9046.280	0.139	7746.390	0.165

4. Conclusion

1. RC buildings designed with optimized moment-resisting frames (without shear walls) perform efficiently under seismic loading, adhering to the IS 1893:2002 standards for earthquake design. The Mini-Haunch connection improves structural stability while eliminating the need for shear walls, providing a sustainable and cost-effective solution for low-to-medium-rise buildings.
2. Frames with optimized design parameters and Mini-Haunch connections demonstrate improved lateral resistance, resulting in reduced base shear compared to conventional designs. The Mini-Haunch connection enhances the stiffness and energy dissipation of the frame, providing better overall performance during seismic events.
3. Increasing the haunch length from 150mm to 350mm in Mini-Haunch connections shows a significant increase in base shear by approximately 26%, highlighting the role of the Mini-Haunch in improving the frame’s seismic performance.
4. The variation in haunch length has a slight effect on higher storey displacements, indicating that higher storey displacements are not as sensitive to haunch length variations. This finding suggests that Mini-Haunch connections can maintain serviceability even in taller buildings.
5. Collapse hinges were primarily located in the mid-storey beams when haunch lengths were varied. Full collapses were observed in lower haunch length frames, while higher haunch length frames demonstrated an increase in frame stiffness, concentrating hinge formation in lower storey beams. This indicates that Mini-Haunch connections improve frame stiffness and enhance seismic resistance at lower storey levels.
6. Frames with lower haunch depth members exhibited lower base shear when compared to higher haunch depth members. This is attributed to the reduced stiffness of frames with lower haunch depths, which can influence the seismic performance of the structure.
7. The variation in haunch depth did not significantly affect higher storey displacements, suggesting that the Mini-Haunch connection offers a uniform improvement in performance across the entire building, regardless of the storey height.
8. For frames with lower haunch depths, collapse hinges were found to propagate towards the upper storey beams. In contrast, higher haunch depth frames led to hinge formation concentrated at the lower storeys, further confirming that increased haunch depth improves structural stability by enhancing the overall stiffness of the frame.
9. As haunch depth and haunch length increase, the natural time period of the structure decreases, indicating a stiffer frame that responds more effectively to dynamic loads.
10. The presence of non-prismatic members (such as Mini-Haunch connections) significantly affects the seismic behavior of RC frames. The introduction of Mini-Haunch connections enhances frame stiffness, which results in improved seismic performance and reduced collapse risk during earthquake events.
11. In haunched building frames, collapse hinges were primarily concentrated at the lower storey beams, highlighting the importance of structural optimization in lower storeys for seismic safety.

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