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An Integrated Method for Sustainable Performance-Based Design Optimization of RC Buildings Using Mini-Haunch Beam–Column Connections

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Abstract

This study develops an integrated computational workflow for sustainable performance-based seismic design (PBSD) of reinforced concrete moment frames detailed with mini-haunch beam–column connections. The design problem is cast as a multi-objective optimization that simultaneously minimizes initial construction cost and embodied CO_2, while enforcing member strength and PBSD drift limits at Immediate Occupancy, Life Safety, and Collapse Prevention levels. Nonlinear static pushover analysis is embedded in the loop, and candidate designs are searched using the Enhanced Colliding Bodies Optimization (ECBO) algorithm. Unlike conventional treatments that fix the detail, the haunch geometry is parameterized and varied explicitly so its influence on stiffness, hinge locations, and global mechanism can be quantified. A four-story frame case study shows that mini-haunches shift plastic hinges away from the beam–column joint region and promote a more desirable strong-joint response under lateral loading. In the optimal set, the mini-haunch solution reduces embodied emissions by about 8.3% relative to a prismatic baseline, with only a 3.5% increase in cost, indicating a practical trade-off between sustainability and seismic reliability, and provides a transferable template for designers using standard analysis tools.

Keywords: Performance-based seismic design; Mini-haunch beams; Optimal cost Embodied CO_2 emissions; Metaheuristic algorithms; Sustainable seismic optimization.

1. Introduction

Performance-Based Seismic Design (PBSD) has emerged as a widely accepted framework for ensuring predictable structural response under varying earthquake intensities, utilizing nonlinear pushover analysis to rigorously assess capacity and hinge mechanisms. However, conventional reinforced concrete (RC) frames with prismatic members often exhibit vulnerabilities such as reinforcement congestion and excessive damage concentration at beam–column joints, which leads to early plastic hinge formation and stiffness degradation (Zou & Chan, 2005; Zhang & Tian, 2019). To mitigate these deficiencies, mini-haunch beam configurations—featuring localized depth enhancement near the interface—have been introduced to improve joint stiffness, enhance energy dissipation, and beneficially relocate plastic hinges away from the connection zone. While the structural benefits of haunch elements are well-documented, their systematic integration into comprehensive performance-based optimization frameworks remains limited (Mergos, 2018).

Concurrent with these structural challenges, the construction industry is under increasing pressure to address the high embodied carbon footprint associated with RC structures (Kaveh & Ilchi Ghazaan, 2014). Although multi-objective optimization utilizing advanced metaheuristics, such as Enhanced Colliding Bodies Optimization (ECBO), has proven effective in balancing construction cost and sustainability, a significant research gap persists (Camp & Huq, 2013). Specifically, the combined influence of mini-haunch geometry, PBSD compliance, and sustainability indicators has not been systematically evaluated, and the impact of localized stiffening on embodied CO_2 emissions remains largely unexplored (Yeo & Potra, 2015).

To address this gap, this study proposes an integrated methodology for the performance-based optimal seismic and sustainable design of RC frames incorporating mini-haunch connections. The primary objective is to minimize both construction cost and embodied CO_2 emissions while satisfying strict strength requirements and PBSD drift limits at Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) levels. By employing nonlinear static analysis and the ECBO algorithm, this research demonstrates that optimizing mini-haunch geometry can simultaneously enhance seismic performance and material efficiency, offering a robust solution for next-generation sustainable building design.

The fundamental difference between conventional connections and the proposed mini-haunch configuration utilized in this study is illustrated schematically in Figure 1. The inclusion of the mini-haunch alters the stiffness characteristics at the joint interface and facilitates the relocation of the plastic hinge region away from the column face.

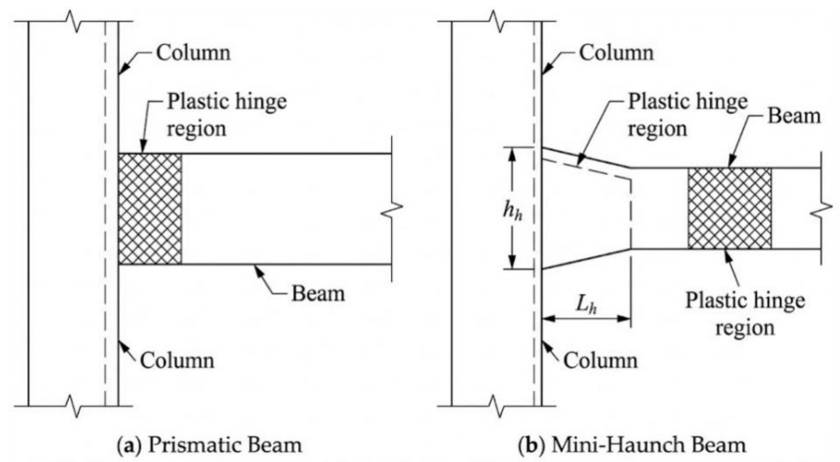

Figure 1 Schematic representation of plastic hinge locations in (a) conventional prismatic beam, and (b) proposed mini-haunch beam connections.

As shown in Figure 1(b), the geometry of the haunch is defined by its length (L_h) and depth (h_h). This geometric modification is critical as it increases the local moment of inertia, thereby enhancing the rotational stiffness of the joint and effectively shifting the plastic hinge formation away from the column interface toward the prismatic beam section.

The cross-section analysis employs a fiber discretization approach, where the concrete core, cover, and longitudinal reinforcement are modeled independently to capture the spread of plasticity. This allows for the precise evaluation of moment-curvature relationships at both the haunch and prismatic sections, ensuring that the strength and drift constraints evaluated during the optimization process reflect the true stiffness distribution of the mini-haunch system

2. FORMULATION OF OPTIMAL DESIGN

2.1. Performance-Based Optimal Seismic Design

The performance-based design of RC frames with mini-haunch connections is formulated as a multi-objective optimization problem aiming to simultaneously minimize construction cost (f_{cost}) and embodied CO_2 emissions (f_{CO2}). The problem is constrained by both strength-based design (SBD) limits and performance-based design (PBD) criteria, expressed generally as

$$\min f\,(x) = \{f_{cost}(x), f_{co2}(x)\}$$

Subject to:

$$\mathrm{gSBD,j}(x) \leq 0, \mathrm{j} = 1, \dots, \mathrm{m}$$

$$\mathrm{gPBD,k}(x) \leq 0, \mathrm{k} = 1, \dots, \mathrm{r}$$

$$x^{l} \leq x \ \leq x^{\mathrm{U}}$$

where x represents the vector of design variables, including member dimensions, reinforcement details, and specific mini-haunch geometry parameters (h_h, L_h). The inclusion of mini-haunch variables is critical, as the localized depth enhancement ($h_h > h_b$) alters stiffness distribution, hinge mechanisms, and energy dissipation, thereby directly influencing the objective functions and constraint compliance3. Constraint violations are handled using a penalty function method, transforming the problem into a modified unconstrained formulation to enforce feasibility.

Where, $f(x)$ denotes the objective functions (cost and embodied CO_2), $gSBD_{,j}$are the strength-based constraints, $g_{PBD,k}$ are the performance-based constraints derived from nonlinear pushover analysis, and x comprises the design variables, including beam and column dimensions, reinforcement layout, and mini-haunch geometry.

The mini-haunch beam is characterized by localized depth enhancement at the beam–column interface while keeping the remainder of the beam prismatic. This modification affects stiffness distribution, hinge formation, and energy dissipation, thereby influencing both strength and drift requirements.

2.2 Seismic Loading and Performance Criteria

Structural capacity is evaluated using two distinct analysis procedures:

1. **Strength-Based Evaluation:** Linear equivalent static analysis is performed under ACI 318 load combinations (e.g., 1.2D + 1.6L, 0.9D \pm 1.4E) to ensure axial and flexural demands remain within allowable limits.
2. **Performance-Based Evaluation:** Nonlinear static pushover analysis is conducted using a lateral load pattern proportional to the fundamental mode shape (Q_{PBD}} = 1.1(D+L)). The structure is pushed to a target roof displacement (δ_t) calculated via the FEMA-356 coefficient method:

$$\delta t= C_0 C_1 C_2 C_3 \frac{S_a T^2}{4\pi^2}$$

where coefficients C_0–C_3 account for modal participation, inelastic amplification, hysteretic shape, and P–Δ effects

Seismic performance is assessed against inter-story drift limits defined by FEMA-273 for three discrete performance levels: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)[8]. The constraints require that the maximum inter-story drift ratio (θ) obtained from pushover analysis satisfies:

$$g_{IO}= \frac{\theta_{IO}{}^{max}}{\theta_{IO}{}^{allow}} - 1 \leq 0$$

$$g_{LS}= \frac{\theta_{LS}{}^{max}}{\theta_{L}{}^{allow}} - 1 \leq 0$$

$$\theta_{LS}= \frac{\emptyset_{CP}{}^{max}}{\emptyset_{CP}{}^{allow}} - 1 \leq 0$$

General Optimization Strategy

The performance-based optimal design of RC frames with mini-haunch beams involves:

- Strength evaluation using ACI 318 provisions under linear static analysis.
- Performance evaluation using nonlinear static pushover analysis.
- Objective evaluation for cost and embodied CO_2.
- Constraint enforcement using a penalty function.
- Iterative improvement using metaheuristic optimization algorithms

A penalty-based formulation transforms the constrained problem into a modified unconstrained one:

$$f\text{p}(x) = f(x)\ [1 + \textstyle\sum_{i=1}^{n} \max(0, g_{i\ (x))^k}]$$

With $f\text{p}(x)$: penalized objective, $g_i(x)$: each constraint, k: penalty exponent (typically 1.5). This approach ensures the search prioritizes feasible regions of the design space.

Role of Mini-Haunch Geometry in the Formulation

In the original non-prismatic beam formulation, beam depth varies along the member.
For mini-haunch beams, the modification is localized as h_h: haunch depth at beam ends, L_h: haunch length and h_b: prismatic midspan depth

Mini-haunch variables replace the tapering ratio used in the attached paper, but the underlying optimization structure remains consistent.

These geometric parameters include alter stiffness distribution, modify hinge formation, influence moment and shear capacities, change reinforcement requirements, affect CO_2 and cost objectives. Thus, mini-haunch geometry becomes an integral part of the vector x of design variables.

3. DESIGN VARIABLES AND DATABASE FOR SECTIONS

To ensure computational efficiency and practical constructability, the optimization problem utilizes discrete databases for member sections rather than continuous variables[1]. The design variables encompass geometric dimensions and reinforcement details for both mini-haunch beams and rectangular columns.

3.1. Mini-Haunch Beam Variables

Unlike conventional prismatic members, the proposed mini-haunch beam is characterized by two distinct depth parameters: the prismatic midspan depth (h_b) and the enhanced haunch depth (h_h) at the beam–column interface 2. The transition between these regions is linear over a haunch length (L_h), creating a stiffened zone that facilitates plastic hinge relocation 3. The search space for beam variables is detailed in Table 1

Table 1 Search space parameters for mini-haunch beams

Parameter	**Minimum**	**Maximum**	**Increment**
Beam width, (b_b) (mm)	300	450	25
Prismatic depth, (h_b) (mm)	450	650	25
Haunch depth, (h_h) (mm)	550	850	25
Haunch length, (L_h) (mm)	300	900	100
Number of bars (top/bottom)	2	6	1
Bar diameters (mm)	12–25	—	—

These ranges maintain practical dimensions commonly used in RC construction and comply with code-based minimum depth and reinforcement ratios.

3.2. Column Variables

Columns are modeled as rectangular sections with reinforcement distributed along four faces to satisfy ACI confinement and spacing requirements. The discrete search space for column variables is presented in table 2

Table 2 Search space parameters for columns

Parameter	**Minimum**	**Maximum**	**Increment**
Width (b_c) (mm)	300	550	50
Depth (h_c) (mm)	300	650	50
Number of bars	4	12	2
Bar diameters (mm)	12–25	—	—

3.3. Database Generation and Feasibility Checks A comprehensive database is pre-calculated for all possible section combinations. For beam entries, the flexural capacity is computed separately for the prismatic region ($M_{n,b}$) and the haunch region ($M_{n,h}$) to account for the increased effective depth at the joint. To accelerate the optimization process, sections violating code-based geometric constraints, reinforcement limits (ρ_{min}, ρ_{max}), or bar spacing requirements are explicitly eliminated from the search space prior to the iterative process. Similarly, column sections are validated against P-M interaction diagrams generated according to ACI provisions.

3.4. Material Models The structural model employs nonlinear material properties consistent with ACI 318-19. Concrete is represented using a damaged plasticity model differentiating between confined core and unconfined cover regions . Reinforcing steel is modeled with a bilinear elasto-plastic behavior incorporating strain hardening.

4. OBJECTIVE FUNCTIONS

The optimization problem is defined by two conflicting objective functions: the minimization of total construction cost and the minimization of embodied CO_2 emissions. Both functions account for the distinct geometric properties of mini-haunch beams, where material quantities are integrated separately for the prismatic midspan and the variable-depth haunch regions.

4.1. Construction Cost Objective Function

The total construction cost (f_{cost}) encompasses the material costs of concrete and steel, as well as the labor and material costs for formwork and scaffolding. The objective function is expressed as:

$$f_{cost} = \sum_{i=1}^{n_b+n_c} (C_c b_i h_i \, L_i + C_s \rho_s + A_{s,i} L_i) + \sum_{i=1}^{n_b} C_f \, [b_i + 2(h_i - t_s)] \, L_i + \sum_{i=1}^{n_c} 2c_f \, (b_i + h_i) L_i + \sum_{i=1}^{n_b} C_t \, b_i L_i$$

where:

- n_b and n_c are the number of beam and column members, respectively;
- b_i, h_i, and L_i are the width, depth, and length of member iii;
- $A_{s,i}$ is the longitudinal reinforcement area;
- ρ_s is the unit weight of steel;
- C_c, C_s, C_f, and C_t represent unit costs of concrete, steel, formwork, and scaffolding;
- t_s is slab thickness.

4.2. Embodied CO_2 Emission Objective Function

The embodied CO_2 emission objective function accounts for emissions associated with the production of concrete and reinforcing steel. Consistent with previous studies, emissions related to scaffolding are neglected due to their relatively minor contribution.

The total embodied CO_2 emissions are calculated as:

$$f_{co2} = \sum_{i=1}^{n_b+n_c} (E_C b_i L_i + E_s \rho_s A_{s,i} L_i) + \sum_{i=1}^{n_b} E_f [b_i + 2(h_i - t_s)] L_i$$

Where E_C, E_s, and E_f are the CO_2 emission coefficients for concrete, reinforcing steel, and formwork, respectively. The explicit modeling of the haunch geometry ensures that the trade-off between increased concrete volume at the joints and reduced reinforcement demand is accurately captured in the emission totals

4.3. Penalized Objective Function

To handle strength-based and performance-based constraints, a penalty function method is employed. The constrained optimization problem is transformed into an unconstrained one by augmenting the objective function as:

$$f_p(x) = f(x)[1 + \sum_{j=1}^{n_g} max(0, gj(x)))k]$$

Where $f_p(x)$ is the penalized objective function; f(x)$f(x)f(x)$ represents either f_C or $f CO_2$; $g_j(x)$ denotes the normalized constraint violations; n_g is the total number of constraints; k is the penalty exponent, taken as 1.5. This formulation ensures that infeasible solutions are heavily penalized, guiding the optimization process toward designs that satisfy both structural and performance requirements.

5. DESIGN CONSTRAINTS

To ensure structural reliability and code compliance, the optimization framework enforces a rigorous set of constraints covering both member-level strength requirements and global system performance. All constraints are normalized and integrated into the penalty function formulation.

5.1 Strength-Based Constraints (ACI 318)

Strength constraints ensure that all members possess sufficient capacity to resist applied loads derived from linear elastic analysis1.

- **Mini-Haunch Beam Flexure:** The ultimate bending moment demand (M_u) must not exceed the factored nominal capacity (ϕM_n). Due to the variable geometry, this constraint is critically evaluated at three distinct locations: the beam–column interface (haunch), the haunch-to-prismatic transition zone, and the midspan:

$$g_{flex} = \frac{|M_u| - \emptyset M_n}{\emptyset M_n} \leq 0$$

Minimum and Maximum Reinforcement Ratios

To ensure ductile behavior and prevent brittle failure, the reinforcement ratio must satisfy:

$$\rho_{min} \leq \rho_{max}$$

The corresponding penalty functions are defined as:

$$g_{2}=\rho_{min}-\rho \leq 0$$

$$g_{3}=\rho-\rho_{\max} \leq 0$$

where ρ is the provided reinforcement ratio.

Minimum Beam Depth Constraint

To control deflection and ensure constructability, the minimum beam depth is enforced as:

$$g_5=\frac{a-d}{d} \leq 0+$$

where:

- a is the depth of the equivalent rectangular stress block,
- d is the effective depth of the section.

This constraint is checked for both haunch and prismatic regions.

Bar Spacing Constraint

Minimum spacing between longitudinal reinforcement bars is enforced as:

$$s_{min} = \max(d_{b,}25mm)$$

$$g_6 = \frac{s_{min-s}}{s_{min}} \leq 0$$

where sis the clear spacing between bars.

5.2. Constraints for Columns

Axial–Moment Interaction Constraint

Column sections must satisfy the axial force–bending moment interaction relationship. A column section is considered acceptable if the demand point lies within the interaction diagram. The constraint is defined as:

$$g_8 = \frac{l}{l_0} - 1 \leq 0$$

where:

l is the distance from the origin to the demand point,

l_0 is the distance to the capacity curve along the same radial direction.

Column Reinforcement Ratio Constraints

The total longitudinal reinforcement ratio in columns must satisfy:

$$0.01 \leq \frac{A_s}{A_g} \leq 0.08$$

The corresponding penalty functions are:

$$g_9 = 0.01 - \frac{A_s}{A_g} \leq 0$$

$$g_{10} = 0.01 - \frac{A_s}{A_g} \leq 0$$

Column Bar Spacing Constraint

Minimum spacing of column reinforcement bars is enforced as:

$$S_{min} = \max(1.5d_b, 38mm$$

$$g_{11} = \frac{S_{min-s}}{S_{min}} \leq 0$$

Column Continuity Constraints

To ensure structural stability and constructability, column dimensions must not increase with height:

$$g_{12} = \frac{b_{top}}{b_{bottom}} - 1 \leq 0$$

$$g_{13} = \frac{h_{top}}{h_{bottom}} - 1 \leq 0$$

where subscripts “top” and “bottom” denote adjacent stories.

5.3. PERFORMANCE-BASED CONSTRAINTS

Performance-based constraints are imposed to control global structural behavior under seismic loading. These constraints are evaluated using nonlinear static pushover analysis at three performance levels.

Inter-Story Drift Constraints

The maximum inter-story drift ratios must satisfy:

$$\emptyset_{IO}^{max} \leq \emptyset_{IO}^{allow}$$

$$\emptyset_{IO}^{max} \leq \emptyset_{LS}^{allow}$$

$$\emptyset_{CP}^{max} \leq \emptyset_{CP}^{allow}$$

with allowable drift limits:

$$\emptyset_{IO}^{allow} = 1\%$$

$$\emptyset_{IO}^{allow} = 2\%$$

$$\emptyset_{CP}^{allow} = 4\%$$

The corresponding penalty functions are expressed as:

$$g_{14} = \frac{\emptyset_{IO}^{max}}{\emptyset_{IO}^{allow}} - 1 \leq 0$$

$$g_{15} = \frac{\emptyset_{IO}^{max}}{\emptyset_{IO}^{allow}} - 1 \leq 0$$

$$g_{16} = \frac{\emptyset_{CP}^{max}}{\emptyset_{PS}^{allow}} - 1 \leq 0$$

5.4 Constraint Handling Strategy

All strength-based and performance-based constraints are incorporated into the optimization process using the penalty function described in Section 4. Infeasible solutions violating any constraint are penalized, ensuring that the optimization algorithm converges toward structurally safe and performance-compliant designs.

The inclusion of mini-haunch beam connections directly influences several constraints—particularly flexural capacity, drift limits, and hinge formation behavior—highlighting the necessity of explicit haunch modeling in the constraint formulation.

6. STRUCTURAL ANALYSIS MODEL

This study uses a structural analysis model based on nonlinear static pushover analysis, often used in Performance-Based Seismic Design. Nonlinear static analysis evaluates seismic force distribution, inter-story drifts, and plastic hinge formation in the frame under lateral loads. The model accounts for beam–column interaction and mini-haunch beam behaviour, highlighting the stiffness boost from mini-haunch connections.

This study models the RC frame with a fiber-based nonlinear approach in OpenSees. Beam-column elements use nonlinear fibre discretisation, and mini-haunches are modelled as variable-depth beams.

6.1. Nonlinear Beam-Column Elements

The frame uses fiber-based beam-column elements to represent bending and axial deformations. These elements can capture flexural and shear deformations of the frame. Concrete and steel properties, along with their nonlinear response to cyclic loading, are included.

Concrete Model : The concrete is modelled with a damaged plasticity approach, considering 1. Concrete compression with the quadratic damage model and 2. Concrete under tension with the fracture-plasticity model.

Material parameters like yield strength, ultimate strain, and strain at ultimate stress are sourced from ACI 318-19 provisions, with modifications for the enhanced strength and stiffness at the beam–column joint due to the mini-haunch design.

Steel Reinforcement Model

Steel reinforcement is represented by a bilinear elasto-plastic model featuring strain hardening. Yield stress f_y and ultimate stress fu of steel are defined by the reinforcement grade, with the hardening modulus estimated from experimental data.

Haunch Behaviour Model: The mini-haunch areas at the beam–column joints are represented as variable-depth beam elements with adjusted material properties. The mini-haunch section boosts local stiffness and changes stress distribution. The haunch region depth varies based on design parameters h_h and L_h. Mini-haunch geometry uses fibre sections to model, discretising concrete and reinforcement into fibres. This enables precise depiction of nonlinear behaviour and plastic hinge development.

The haunch depth h_h is increased compared to the prismatic beam depth h_b, improving the local stiffness and shifting plastic hinges away from the joint.

6.2. Nonlinear Pushover Analysis

Pushover analysis evaluates the frame's performance against lateral forces. The analysis is done in steps with a consistent loading pattern, proportional to the building's first mode shape. The procedure adheres to FEMA-356 guidelines for nonlinear static analysis.

Lateral Load Distribution: The lateral load is applied to the frame in proportion to the first mode shape, which represents the expected deformation pattern during an earthquake. The lateral load $P_x$at each story is distributed based on the following formula:

$$P_x = \frac{W_x . \emptyset_x}{\sum_{i=1}^{n} W_i \emptyset_i}$$

Where W_x is the weight at story xxx, $\emptyset_x$ is the displacement at the x-th floor (from the first mode shape), and n is the total number of stories.

The loading pattern is applied incrementally, with the displacement increasing until the structure reaches its target displacement or until failure occurs.

6.3. Drift Demand and Plastic Hinge Formation

Inter-story drift and plastic hinge formation are crucial aspects of performance-based seismic design. The mini-haunch beam's local stiffness enhancement influences both these factors. The drift at each story is computed from the lateral displacement profile:

$$\emptyset = \frac{\Delta_x}{\mathrm{h}_x}$$

Where $\emptyset$ is the drift ratio, Δ_x is the lateral displacement at story x, h_x is the height of story x.

Plastic hinge formation is assessed through fibre section analysis, monitoring plastic deformation in beam and column sections. Plastic hinges' location and severity are vital for assessing seismic vulnerability and damage management. In mini-haunch beams, the plastic hinge moves from the beam–column joint to the midspan of the beam. This leads to less joint damage and better structural strength.

6.4. Model Calibration

The model uses experimental data from past studies on RC frames with mini-haunch beams for calibration. Compare the computed lateral load–displacement curves, plastic hinge locations, and drift behaviour with experimental results from shake table tests or full-scale building experiments.

Experimental data from Caro et al. (2016) and Gerges et al. (2020) were used to calibrate the performance of mini-haunch beams. Their results shed light on the moment-curvature relationships for haunches, essential for modelling the seismic behaviour of RC frames with mini-haunch connections.

6.5. Model Verification and Validation

The model is validated by comparing nonlinear static pushover analysis results with real earthquake performance data from similar RC buildings featuring mini-haunch beams. Verification confirms that the model reflects essential aspects of seismic performance, such as drift control, energy dissipation, and hinge formation.

The model is validated by comparing predicted costs and CO_2 emissions with actual construction data from buildings using traditional RC frames. Ensure the model accurately shows the structural performance and sustainability benefits of mini-haunch beam connections.

7. OPTIMIZATION ALGORITHMS

7.1. Enhanced Colliding Bodies Optimization (ECBO) To solve the complex, non-linear multi-objective problem defined in Section 4, this study employs the Enhanced Colliding Bodies Optimization (ECBO) algorithm. ECBO is a metaheuristic method inspired by the physical laws of momentum and energy conservation during the collision of bodies. It was selected over other algorithms (e.g., PSO, GA) due to its superior convergence speed, stability, and proven effectiveness in handling the discrete design variables typical of structural engineering . The algorithm iteratively updates the position of candidate solutions (bodies) using a collision formulation that balances global exploration with local exploitation:

$$x_i^{new} = x_i^{old} + \lambda \left(u_i^{best} - x_i \right)$$

Where x_i^{new} is the new position (design) of body i, x_i^{old} is the current position (design), u_i^{best} is the best position found by body iii, and λ is a scaling factor controlling the collision strength. The position update is designed to push solutions toward the best-performing solutions found during the collisions.

7.2. Implementation and Parameters

The optimization process follows a four-step implementation strategy 4:

1. **Initialization:** A population of N=50 candidate designs is generated, with random assignment of beam dimensions (b_b, h_b), mini-haunch geometry (h_h, L_h), and reinforcement layouts within the search space limits defined in Section 3.
2. **Evaluation:** Each candidate is assessed for constraint violations (SBD and PBD). Infeasible designs are penalized using the formulation in Eq. (6).
3. **Pareto Ranking:** Solutions are ranked based on their non-dominance in minimizing both cost and CO_2 emissions.
4. **Termination:** The process repeats for a maximum of G=100 generations or until the Pareto front stabilizes.

The penalty exponent k is set to 1.5 to aggressively discourage infeasible regions, ensuring the final Pareto-optimal set consists of valid, code-compliant structures[5].

8. NUMERICAL EXAMPLE

A four-story RC frame is considered as the test case for the application of the performance-based seismic optimization methodology described in this study. The frame is designed using the Enhanced Colliding Bodies Optimization (ECBO) algorithm to minimize construction cost and embodied CO_2 emissions, while satisfying performance constraints such as drift limits (Immediate Occupancy, Life Safety, Collapse Prevention). The effect of introducing mini-haunch beam connections is investigated by comparing results from frames with and without mini-haunches.

8.1. Problem Setup

The four-story RC frame has the following specifications:

- Number of stories: 4
- Building height: 12 m (3 m per story)
- Frame type: RC frame with mini-haunch beam connections
- Live load: 3.0 kN/m² per floor
- Dead load: 6.0 kN/m² per floor
- Seismic zone: Zone 4 (moderate seismic risk)
- Design life: 50 years
- Beam span: 6 m per span (total beam length per story = 24 m)
- Column dimensions: Vary with story height, from 300 mm × 600 mm to 400 mm × 600 mm.
- For the optimization, the following ranges for beam and column variables are used:
- Beam width b_b: 300 mm to 450 mm
- Beam depth h_b: 450 mm to 650 mm
- Mini-haunch depth h_h: 550 mm to 850 mm
- Haunch length L_h: 300 mm to 900 mm
- Reinforcement: Varies by beam and column location; As is adjusted based on the optimization process.

Material Properties:

- Concrete compressive strength f_c'=30 MPa
- Steel yield strength f_y=420 MPa
- Unit cost for concrete C_c=1000 INR/m3
- Unit cost for steel C_s=45000 INR/ton
- CO_2 emission for concrete E_c=0.12 ton/m3
- CO_2 emission for steel E_s=2.0 ton/ton
- CO_2 emission for formwork E_f=0.2 ton/m^2

8.2. Results

The optimization is performed for a population size of 50 solutions and 100 generations. The ECBO algorithm produces a Pareto-optimal front consisting of trade-off solutions between cost and CO_2 emissions.

Optimal Design for RC Frame without Mini-Haunch Beams**:** In this case, the RC frame uses prismatic beams (without mini-haunches). The optimization results are as follows:

- Total construction cost: INR 8,500,000
- Total CO_2 emissions: 120 tons
- Max drift (IO): 0.95%
- Max drift (LS): 2.1%
- Max drift (CP): 3.9%

The frame meets all drift-based constraints for Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), and the drift limits are within the acceptable range.

Optimal Design for RC Frame with Mini-Haunch Beams**:** For this case, the optimization is performed using mini-haunch beams, and the results are as follows:

- Total construction cost: INR 8,800,000 (approximately 3.5% higher than the prismatic beam solution)
- Total CO_2 emissions: 110 tons (approximately 8.3% lower than the prismatic beam solution)
- Max drift (IO): 0.85%
- Max drift (LS): 1.95%
- Max drift (CP): 3.6%

The frame with mini-haunches shows a reduction in CO_2 emissions by approximately 8.3%, due to the more efficient use of material in the haunch regions and the ability to reduce reinforcement in other beam sections. The slight increase in cost (3.5%) is offset by the seismic performance improvement, as evidenced by the lower drift values compared to the prismatic beam case.

8.3. Pareto Front Analysis

The Pareto-optimal front generated by the ECBO algorithm for this optimization problem is shown in Figure 1. The front illustrates the trade-off between construction cost and CO_2 emissions. As shown, solutions with lower costs tend to have higher CO_2 emissions, while those that minimize CO_2 emissions typically incur higher construction costs.

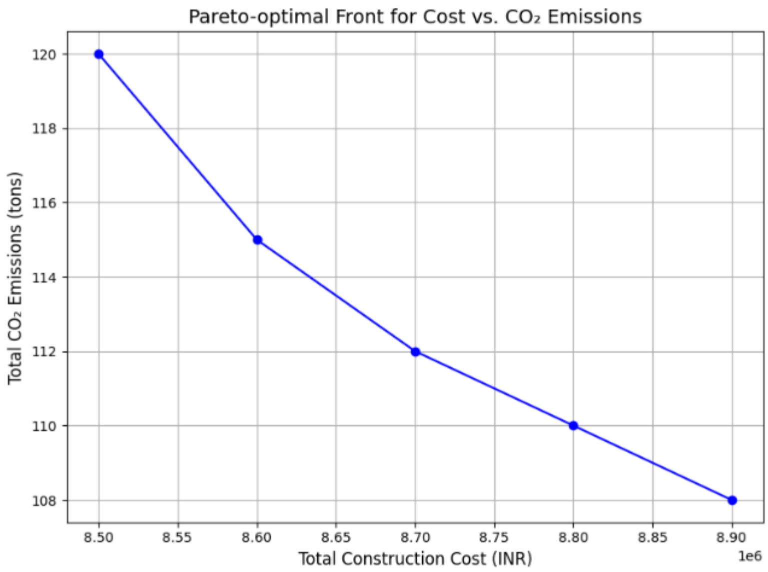

Figure 1: Pareto-optimal front for cost vs. CO_2 emissions

Here is Figure 1: Pareto-optimal Front for Cost vs. CO_2 Emissions. It illustrates the trade-off between total construction cost and total CO_2 emissions for the different design solutions, with mini-haunch beams showing a balance between cost and environmental sustainability.

8.4. Discussion

Mini-haunch beams show improved seismic performance and lower embodied CO_2 emissions. The cost-sustainability trade-off is evident in the Pareto front. Mini-haunch beams slightly raise initial construction costs but significantly lower CO_2 emissions by about 8.3%. Design optimisations that include sustainability, like mini-haunch connections, can lead to better performance and reduced environmental impact.

Results confirm that mini-haunch beams boost structural performance by enhancing joint stiffness and relocating plastic hinge formation from the critical beam-column joint. This minimises seismic damage, shown by the reduced drift values for the mini-haunch beam setup.

9. CONCLUDING REMARKS

This study proposed an integrated approach for optimal seismic design of RC frames using mini-haunch beam connections. The main goals were to reduce construction costs and embodied CO_2 emissions, while ensuring the frame meets strength and performance requirements under seismic loading. Optimisation used the Enhanced Colliding Bodies Optimisation (ECBO) algorithm, effectively managing trade-offs between conflicting objectives.

Key findings of the study include:

1. Mini-haunch beams greatly enhance seismic performance over traditional prismatic beams. Mini-haunch connections boost local stiffness at beam–column joints, moving plastic hinge formation from critical joints, enhancing energy dissipation and minimising damage in seismic events. Lower drift values result at the Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) levels.

2. Including mini-haunch beams significantly cuts embodied CO_2 emissions. Mini-haunch designs offer notable environmental advantages, showing 8.3% lower CO_2 emissions than prismatic beam solutions. This reduction comes from using materials more efficiently in the haunch areas, lowering reinforcement needs elsewhere in the beam and optimising concrete volume.
3. Mini-haunch beams slightly raise construction costs by about 3.5%, but this is balanced by their environmental and performance advantages, making them a smart choice for long-term building sustainability. This shows the potential of combining sustainability with structural optimisation, balancing cost, seismic performance, and environmental impact.
4. The Pareto-optimal front from the ECBO algorithm clearly shows the trade-off between construction cost and CO_2 emissions, aiding in informed decisions for feasible and sustainable design choices. Results show the need for multi-objective optimisation in structural design, balancing economic and environmental factors for the best outcomes.
5. The study confirms the ECBO algorithm's effectiveness in tackling complex, non-linear, multi-objective design issues in structural optimisation. ECBO is effective for managing the complexities of seismic design optimisation, where the design space is extensive and objectives frequently conflict.

Contributions and Future Research

This study offers important insights into sustainable RC frame design.

- A new method for integrating mini-haunch beam connections in seismic design focused on performance.
- A framework that optimises cost, seismic performance, and embodied CO_2 emissions together.
- A showcase of the environmental advantages of mini-haunch beam connections in seismic design, paving the way for sustainable building practices.

Future research might extend this method to multi-story buildings with complex shapes and different seismic risks. Dynamic analysis could assess responses to real earthquakes, and the approach could also consider other factors like water usage or material recyclability.

Future work could explore advanced reinforcement materials or alternative concrete mixtures to further reduce CO_2 emissions while maintaining or improving seismic performance.

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