Design Optimization to Minimize Material Usage in Steel Buildings Subjected to Lateral Loads

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1 Introduction

As the global construction industry steers toward sustainable practices, optimizing structural designs becomes paramount in achieving net-zero buildings while aligning with sustainable development goals. With the increasing complexity of modern structures and the necessity to meet stringent performance criteria, optimization tools play a pivotal role in assisting engineers to make informed design decisions efficiently. This chapter presents a comprehensive approach to optimize steel usage, leading to a lightweight structural system that minimizes carbon footprints in the built environment. This optimization design works with the integration of a nonlinear programming solver with ETABS, a structural analysis and design software [1]. This integration streamlines the optimization process, enabling engineers to systematically identify optimal design solutions while considering structural capacities and serviceability constraints.

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This study focuses on identifying optimum cross-sectional dimensions of structural sections to withstand lateral wind loads. The optimization objective function defined as the volume/weight of structural steel to ensure sustainability, drives the search for configurations that minimize material usage, while two constraints of the demand to capacity index (DCI) of structural members as a strength condition and inter-story drift ratio as a serviceability constraint are taken into account to meet performance criteria, safety, and cost-effectiveness designing process. The results show that this optimized design can effectively reduce the volume/weight of the structural steel usage to achieve sustainable buildings. Section 2 of this chapter outlines the optimization problem and its components, while Sect. 3 provides a case study on design iterations for a 15-story building. Section 4 explains the results obtained from the case study, and Sect. 5 summarizes the main conclusions.

2 Optimization Formulation

In this study, a nonlinear programming solver in MATLAB was utilized to optimize the thickness of structural members. This solver offers a powerful tool designed to find the minimum of a constrained nonlinear multivariable function. Specifically, a nonlinear sequential quadratic programming (SQP) method was used. This method has proven to be more efficient, accurate, and successful than other existing methods. This was confirmed through numerous test problems [2, 3]. Previous studies showed that this method closely resembles Newton's method of constrained optimization, which is similar to unconstrained optimization. This is an iterative process that involves approximating the Hessian of the Lagrangian function using the quasi-Newton updating method. Consequently, a quadratic programming subproblem was generated [4]. The optimization problem can be defined as follows:

$$\begin{aligned}&\text{Minimize steel volume/weight}\\&\text{Subjected to}: \quad \text{DCI} \le 1.0 \ (\text{strength condition})\\&\qquad\qquad\qquad \text{Inter-story drift ratio} \le 1/400 \ (\text{serviceability condition})\end{aligned}$$

Critical factors such as structural strength, represented by the DCI, and serviceability constraints like inter-story drift ratio were defined in the first step. The DCIs were calculated using Eqs. (1) and (2) from AISC 360-22 [5]:

$$\text{DCI} = \frac{P_r}{\varnothing_p P_n} + \frac{8}{9}\left(\frac{M_{rx}}{\varnothing_m M_{nx}} + \frac{M_{ry}}{\varnothing_m M_{ny}}\right) \quad \frac{P_r}{\varnothing_p P_n} \ge 0.2 \tag{1}$$

$$\text{DCI} = \frac{P_r}{2 \times \varnothing_p P_n} + \left(\frac{M_{rx}}{\varnothing_m M_{nx}} + \frac{M_{ry}}{\varnothing_m M_{ny}}\right) \quad \frac{P_r}{\varnothing_p P_n} < 0.2 \tag{2}$$

where P_r and P_n are the demand and nominal axial strength; M_{rx} and M_{nx} are the demand and nominal flexural strength about the major axis; M_{ry} and M_{ry} are the

Table 1 Acceptance criteria for various performance levels [7]

Performance levels	Story drift response	Residual story drift
Occupant comfort	–	–
Operational	*H*/400	–
Continuous occupancy	*H*/200	*H*/1000

demand and nominal flexural strength about the minor axis; and $\varnothing_p$ and $\varnothing_m$ are the resistance factors.

The inter-story drift ratio is a crucial metric in structural engineering that measures the relative translational displacement observed between two consecutive floors in a building, divided by the height of each story. This parameter significantly evaluates structural performance, especially when exposed to seismic or wind forces [6]. Saini et al. [7] conducted a study on the performance of a steel building based on three criteria: occupant comfort, operational efficiency, and continuous occupancy. The referenced study [8–12] calculated different performance measures, such as inter-story drift ratio, as one of the most critical criteria. The calculated inter-story drift ratio was compared to the acceptance criteria of the desired performance objectives, as listed in Table 1. The performance assessment revealed that the building met the requirements for strength design, as well as performance limitations for continuous occupancy and limited interruption in Risk Category II. However, the building failed to meet the serviceability requirement for the performance level of operation, which has a limited story drift of *H*/400, where *H* is the story height. As a result, the building needed to be redesigned to meet this performance level. In the current study, to optimize the building design for serviceability requirements, a limit for the story drift equal to *H*/400 was considered.

Initially, within the ETABS software environment, frame elements and floor decks were created, along with their respective constraints and boundary conditions. Subsequently, preliminary design parameters were defined. The numbers of property types for beams, columns, and braces were chosen, and initial section dimensions were assigned to members. Then, all the crucial data such as node and frame coordinates, frame labels, and section properties were extracted from ETABS and stored within MATLAB for further analysis.

Load patterns and combinations were then defined, and lateral loads were applied to model joints. The maximum values of DCIs and inter-story drift ratios were determined by considering the wind loads acting laterally and the gravity loads, such as dead and live loads. The load combination specified in ASCE 7-22 [13] was used (Eq. 3), involving the consideration of dead load (DL), live load (LL), and wind load (WL).

$$\text{Load combination} = 1.2\ \text{DL} + 1.0\ \text{LL} + 1.0\ \text{WL} \tag{3}$$

At the next step, the optimization phase commenced to determine the optimal thickness for each section property. Using the solver in MATLAB, member thickness was optimized to minimize steel volume/weight while limiting the predefined criteria, such as the DCI or DCI and drift ratio within specified thresholds. Finally, after finding the thicknesses, the volume/weight of steel and DCI for the optimized frame members were recalculated and presented, signifying the conclusion of the optimization process, and providing insights into an enhanced structural design.

3 Steel Building Structure

In this section, the optimization process is studied for a 15-story moment resisting frame building. This building had a floor height of 4.0 m and bay width of 7.62 m. All the beams of the building were assumed to have one HSS section with outer dimensions of 300 mm × 300 mm, while the column sections were assumed to be HSS section with outer dimensions of 400 mm × 400 mm for the first five stories (stories 1–5), 300 mm × 3000 mm for the next five stories (stories 6–10), and 200 mm × 200 mm for the last five stories (stories 11–15), respectively. Floor diaphragms were modeled. In addition to the dead loads, a live load of 2.4 kN/m^2 is applied on floor slabs of each floor, which are typical live load expected for the office building. On one face of the building, a constant point load of 50 kN was applied on all nodes in the horizontal direction.

Before optimization, the first step was to create a model of the beam and column elements using ETABS software. This model includes specific section properties and the geometry of the model, which can be seen in Fig. 1. Once the model was complete, the optimization code was initiated. It began by extracting all section

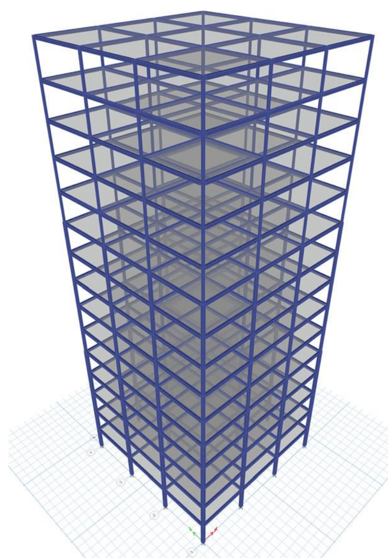

Fig. 1 A 15-story building model developed in ETABS with necessary beam, column, and connection details

properties from the ETABS model and then iterated through each beam and column type, retrieving important parameters such as area, torsional properties, moments of inertia, and other relevant data.

The optimization code then sets out to determine the optimal thickness for both beam and column sections including T_{C1}, T_{C2}, and T_{C3}, which refer to the thickness of columns at first five stories (story 1 to story 5), second five stories (story 6 to story 10), and third five stories (story 11 to story 15), respectively, and the beam thickness which refers to as T_b. Determining the optimal thickness was achieved by formulating an objective function based on the volume/weight of the steel sections, while also applying constraints on the DCI indices and story drift ratios. This constraint framework is necessary to ensure the performance of the building design. Specifically, the constraints of this study ensured that the DCI indices for structural members did not exceed one and that the story drift remained within acceptable limits (H/400).

4 Results and Findings

In this section the results of design optimization are discussed. Section 4.1 evaluates the optimization results for strength constraint, and Sect. 4.2 examines the results for both strength and serviceability constraints.

4.1 Optimization Results with Strength Constraint

The design of the building was investigated for achieving optimal section properties while adhering to strength constraints, ensuring that the DCI indices for all the structural members do not surpass one. The lower and upper bounds for the flange/web thickness of beam and column sections were set at 12.7 mm and 100 mm, respectively. These bounds allowed the optimization algorithm to explore a range of thickness options while maintaining structural integrity within specified limits. Initially, the beam and column sections are configured with flange and web thicknesses set to 12.7 mm. After the optimization code was executed, the results indicated a shift in the thickness values of both column and beam sections from their initial starting points to the end points. The results of the optimization are summarized in Table 2. In the referenced table, the *Feasibility* column indicates the maximum constraint violation, with lower values reflecting closer adherence to

Table 2 Optimization results for member thicknesses with strength constraint

Iter.	Feasibility	T_b (mm)	T_{C1} (mm)	T_{C2} (mm)	T_{C3} (mm)	Weight (ton)
0	6.60E-01	12.70	12.70	12.70	12.70	424.21
7	1.92E-13	15.60	23.21	19.63	21.14	563.40

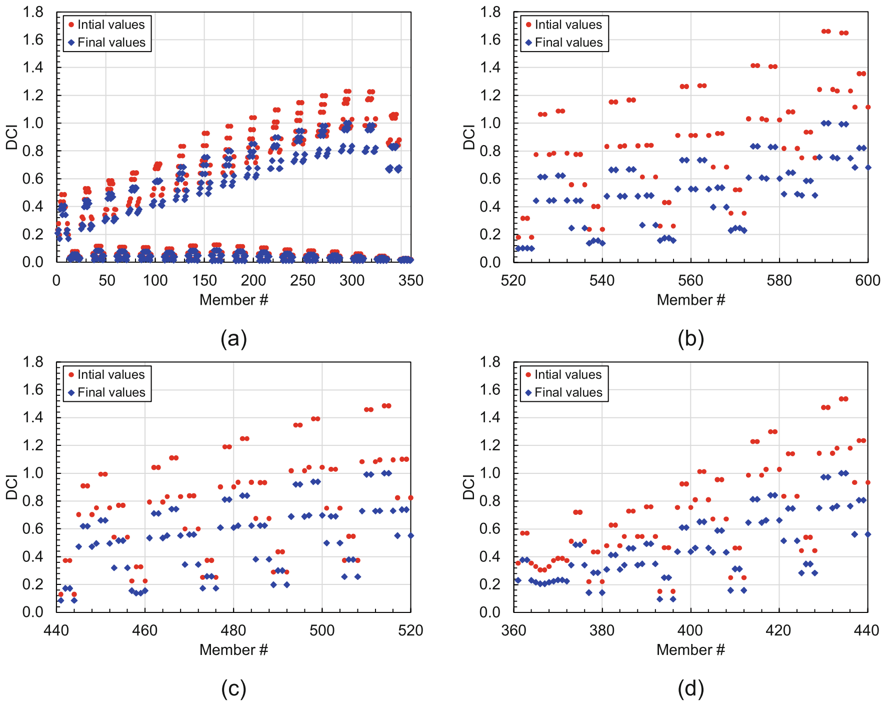

Fig. 2 Optimization results of DCI indices for building with strength constraint: (**a**) beams, (**b**) columns at stories 1–5, (**c**) columns at stories 6–10, and (**d**) columns at stories 11–15

constraints. A decrease in *Feasibility* indicates a closer match and convergence in the results. The optimization process was initiated with an initial thickness of 12.7 mm for each component. Through iterative adjustments, the thickness values evolved until convergence or meeting the specified stopping criteria; and shifted to a stable solution, which was between the defined lower and upper bound, meeting all the constraints. Column thicknesses were shifted to 23.21, 19.63, and 21.14 mm, while beam thickness became 15.60 mm after seven iterations. The objective function of this case, which was the total steel volume/weight, had an initial value of 424.21 ton and a final value of 563.40 ton.

Figure 2 illustrates the comparison between the initial and final DCI indices. Initially, the DCI indices for beam and column members surpassed 1.0, implying member failure. After optimization, the maximum DCI for these members was reduced to 1.0. For instance, the maximum DCI for stories 1–5 columns decreased from 1.65 to 1.00, as depicted in Fig. 2b. This shows that the structural elements now offer adequate capacity to withstand applied loads without risking failure, while having the optimum member size with the minimum steel usage.

4.2 Optimization Results with Both Strength and Serviceability Constraints

The optimization results for the same 15-story building were further evaluated by considering both serviceability and strength constraints. To verify the serviceability constraint, larger member sizes were found to be needed to meet the requirements compared to Sect. 4.1. Therefore, for the beams, HSS sections were employed with outer dimensions of 400 mm × 400 mm. As for the column sections, HSS sections were assumed with outer dimensions of 500 mm × 500 mm for the stories at floors 1–5, 450 mm × 450 mm for the next five stories at floors 5–10, and 400 mm × 400 mm for the last five stories at floors 11–15. The lower and upper bounds for the flange/web thickness of beam and column sections were set at 12 mm and 100 mm, respectively. These bounds allowed the optimization algorithm to explore a range of thickness options while maintaining structural integrity within specified limits. Initially, the beam and column sections were configured with flange and web thicknesses set to 16 mm. After the optimization code was executed, the results indicated a shift in the thickness values of both column and beam sections from their initial starting points to the end points. The results of the optimization for iteration 0 (start point) and final iteration are summarized in Table 3.

The optimization process commenced with an initial uniform thickness setting of 16 mm for all columns and beams. The optimization algorithm continuously improved the solution by adjusting the thickness of the members to minimize the steel volume/weight, while meeting strength and serviceability criteria. In Table 3, *Feasibility* shows how much a solution violates the constraints. It quantifies the degree of constraint violation, with lower values indicating closer adherence to constraints. A decrease in *Feasibility* indicates a better convergence in results.

After 29 iterations, column thicknesses evolved to 64.59, 29.81, and 12.00 mm for T_{C1}, T_{C2}, and T_{C3}, respectively, while beam flange and web thicknesses became 39.17 mm. The initial objective function was 738.53 ton, which ultimately reached a final value of 1672.68 ton steel. Table 3 also shows the initial and final inter story drift ratios, confirming that serviceability constraints have been satisfied. The final story drift ratio matched the specified limit of 0.0025H, meeting the requirements set forth by the serviceability constraint. This outcome ensured that the structure maintains adequate performance under operational conditions, safeguarding against excessive drifts that could compromise its usability and safety.

Figure 3 shows the DCI values for structural members. All elements exhibited final DCI values within acceptable limits, confirming compliance with strength constraints and ensuring an economically efficient structural design. The final DCI

Table 3 Optimization results for member thicknesses with both strength and serviceability constraints

Iter.	Feasibility	T_b (mm)	T_{C1} (mm)	T_{C2} (mm)	T_{C3} (mm)	Weight (ton)	Max IDR
0	3.20E-03	16.00	16.00	16.00	16.00	738.53	0.0057H
29	1.65E-12	39.17	64.59	29.81	12.00	1672.68	0.0025H

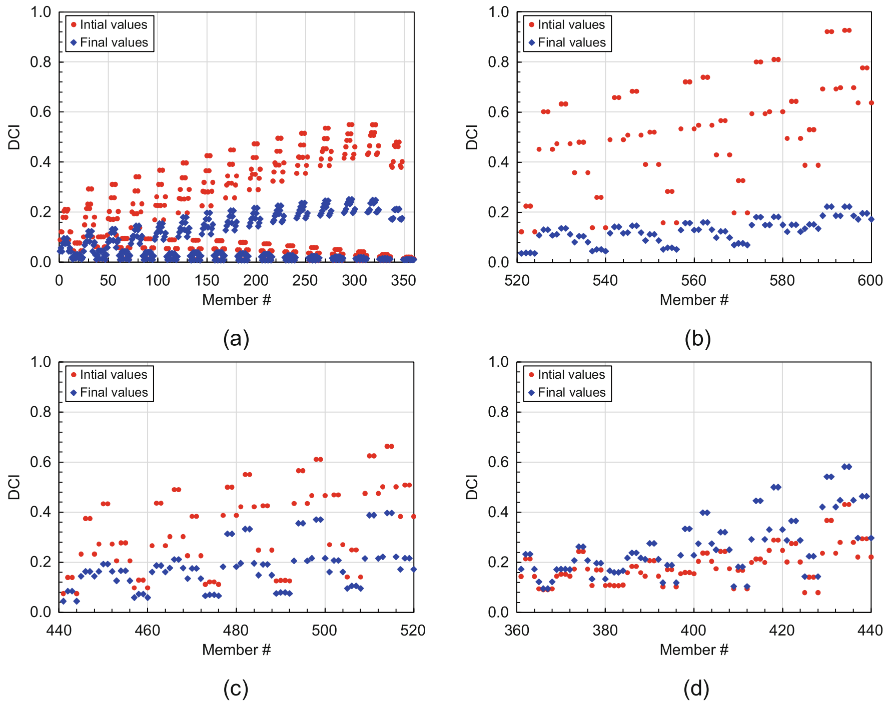

Fig. 3 Optimization results of DCI indices for building with strength and serviceability constraints: (**a**) beams, (**b**) columns at stories 1–5, (**c**) columns at stories 6–10, and (**d**) columns at stories 11–15

indices were in the range of 0–0.6, which is less than 1.0. It shows that inter story drift ratio governed the member size in a way that maximum inter story drift ratio was less than *H*/400.

In summary, the optimization method effectively generates cost-effective designs for structural members of a 15-story building under different scenarios, including both strength and serviceability constraints. These results highlight the versatility of the approach in achieving sustainable outcomes. Sustainable design practices, including minimizing material usage and optimizing energy efficiency, are essential for achieving net-zero buildings. By reducing steel usage while maintaining structural integrity, engineers contribute to environmental sustainability and align with broader goals of sustainable development.

5 Conclusions

This study evaluated the design optimization of steel buildings to optimize steel usage for achieving net-zero buildings, aligning with sustainable development goals. The outcome presented a robust framework for engineers to efficiently identify the optimal cross-sectional dimensions of structural sections through automating the iterative design refinement process, while ensuring compliance with performance criteria, and minimizing carbon footprints in the built environment. The results obtained from applying the optimization tool to a 15-story building demonstrate its effectiveness in meeting both structural yield requirements and operational performance criteria, including a maximum story drift limited to $H/400$. This indicates that the presented approach offers a viable solution for designing buildings that not only fulfill structural demands but also uphold stringent operational standards, contributing to sustainable construction practices.

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