An Innovative Tool for Weight Reduction in Architecturally Constrained Steel Buildings using Enhanced Genetic Algorithm

Mohamed Mahmoud Fathi
Civil Engineering Department, Faculty of Engineering, Fayoum University, Egypt
mmf11@fayoum.edu.eg (corresponding author)

Tarek Fouad Hamdy
Civil Engineering Department, Faculty of Engineering, Fayoum University, Egypt
tfh00@fayoum.edu.eg

Mohamed Sayed Gomaa
Civil Engineering Department, Faculty of Engineering, Fayoum University, Egypt
msg00@fayoum.edu.eg

Received: 13 January 2025 | Revised: 23 February 2025 and 12 March 2025 | Accepted: 29 March 2025

ABSTRACT

This study integrates theoretical optimization with practical structural design by introducing an innovative tool that combines SAP2000 and Genetic Algorithm (GA) to optimize bracing configurations while ensuring compliance with safety standards and architectural constraints. The proposed tool provides a fast, automated, and cost-efficient alternative to conventional design approaches by incorporating an enhanced GA procedure that significantly reduces computation time. A two-step validation confirms its accuracy by comparing the results with existing research and benchmarking against the trial-and-error method. Through four case studies, including symmetrical and asymmetrical layouts with regular and irregular column spacing, the introduced tool achieved up to 65.16% weight reduction while analyzing only up to 2.1% of the total solution space compared to trial-and-error procedures. The findings demonstrate the tool's effectiveness in minimizing structural weight while meeting seismic design requirements, offering valuable insights for implementing optimized and cost-efficient design solutions in modern architecture.

Keywords-steel structures; optimization; genetic algorithm; architectural constraints

I. INTRODUCTION

Among construction materials, steel stands out as a rare and valuable resource, commanding attention not only for its scarcity, but also for its exceptional strength and variety of uses. Regarding its scarcity, it elevates its value in the construction and manufacturing industries. That is why it is mainly used in high-revenue construction projects that require a swift construction process, such as factories, hotels, advertising panels, stadiums, and high-rise buildings. Nowadays in crowded cities worldwide, most construction projects tend to expand vertically rather than horizontally. Moreover, the integration of tall buildings in urban areas promotes environmental health by expanding green spaces, balancing urban development and nature conservation [1] due to rising land prices. As buildings grow taller, lateral loads increase. So, designers must select a lateral load-resisting system that balances safety, serviceability, and cost. Therefore, bracing systems are used in a vast number of medium to high-rise steel buildings because of their advantages in drift control. However, architectural openings often conflict with bracing locations. As a result, engineers may be forced to place bracing in suboptimal structural and economic locations. Locating the bracing in an uneven scheme may generate greater forces on the structure due to the additional eccentricities [2]. Consequently, under the constraints of architectural parameters, meeting design requirements can be a challenge.

Recent studies have focused on identifying the best bracing system structurally, often ignoring architectural constraints, weight, and cost [3-6]. Research indicates that X-shaped bracing enhances structural integrity and effectively reduces lateral drift and deformation under seismic loads [7]. Other studies have attempted to obtain the optimum weight of the building when providing a bracing system that satisfies the code limits for deformations and drifts [8]. However, it is noticeable that the majority of these researches have many deficiencies that may affect their conclusions. The deficiencies can be summarized as follows:

1. Conducting 2D analysis which results in ignoring the 3D effects of the resulting eccentricities, if found, especially the torsional effects due to the uneven configuration of the bracing system [9, 10].
2. Ignoring the structural constraints which can be found in the columns' orientations and/or the available locations for bracing in the building's plan [11].
3. The tedious trial-and-error procedure that some researchers have followed in their studies, in order to optimize the design [3-6].

Additionally, some studies proposed linkage systems with rotational friction dampers to dissipate seismic energy and reduce reliance on the main frame [12]. However, these studies mainly used numerical simulations to minimize inter-story drift, without considering 3D effects, architectural constraints, or cost, limiting their practical application.

In order to overcome these deficiencies, an evolutionary procedure, which can be easily followed by designers, is employed. This procedure has to take advantage of SAP2000, with its 3D modeling and analyzing capabilities, while dealing with the building. Furthermore, the former takes into consideration the architectural constraints which include not only the column orientations, but also the available bracing panels. Additionally, 3D modeling with linear analysis is used to decrease the time of analysis and take torsional effect into account. Finally, dynamic response spectrum is utilized in the seismic analysis of the building.

Optimization is a key concept across various fields, focused on finding the best solution among alternatives. It involves refining a system or process to maximize efficiency and performance. Optimization techniques include mathematical algorithms, like linear programming and genetic algorithms, which systematically explore solutions, and heuristic methods that rely on intuitive rules and trial-and-error. In engineering, finance, and artificial intelligence, optimization is essential for improving resource utilization and decision-making, rendering heuristic approaches valuable.

GA is a powerful optimization technique that finds near-optimal solutions within the design space [13]. GA technique is based on Darwin's theory of evolution by natural selection. This procedure has been proven to be reliable and accurate compared to other optimization techniques. As GA starts a population of possible solutions and each of them is evaluated with a fitness function which determines the probability of this solution to be right and so on, the solutions with powerful genes remain, while those with weak genes vanish. Subsequently, populations evolve in their own way to the optimum solution. It is also argued that GA could be useful in solving structural problems [14].

This paper aims to construct an advanced tool by combining the advantages of a well-known structural analysis software, SAP 2000, and a powerful optimization tool, GA, which entailing python and VBA codes, deals with the weight optimization of high-rise buildings. The developed tool achieves the building's safety according to the limitations of the AISC [15] considering all the constraints related to column orientation and permitted bracing locations. After having developed the tool, a two-step verification procedure was followed to calculate its accuracy and reliability. Then, the tool would be applied in certain cases, to illustrate its simplicity and the advantages it offers to researchers, as well as designer engineers.

This tool bridges the gap between theoretical optimization and real-world steel building design. It provides powerful help for the engineers, regardless of their level of experience, to optimize the building's weight while maintaining the safety and architectural features as well.

II. GENETIC ALGORITHM

GA is a heuristic search technique under evolutionary algorithms, inspired by natural selection and survival of the fittest. While traditional optimization methods work well for small-scale problems, they struggle with large, complex, and nonlinear search spaces [16]. GA overcomes these challenges by iteratively evolving solutions through selection, crossover, and mutation. For implementation, the Py-GAD library [17] in Python, based on Holland's technique [18], is used. This open-source toolkit supports various genetic operators, making it flexible for both single and multi-objective optimization tasks.

The optimization process is structured to minimize the total weight while ensuring compliance with serviceability, safety, and design constraints using:

$$\min f\left(x\right)=\sum_{i=1}^{N}A_iL_i\rho \tag{1}$$

where A_i, L_i, and ρ are the cross-sectional area, length, and material density of the bracing member, respectively.

The constraints are:

- Inter-story drift: $\delta_{\mathrm{max}} \le \delta_{\mathrm{limit}}$
- Safety: $S_{design} \ge S_{required}$
- Bracing placement: $L_{\mathrm{used}} \in [0, L_{\mathrm{max}}]$
- Bracing type: $T_{\mathrm{selected}} \in \{T_{\mathrm{allowed}}\}$

The optimization process follows a structured approach for allocating the best bracing configuration employing GA, as shown in Figure 1. It begins with population initialization, where the VBA generates diverse bracing configurations, each represented as a chromosome, and then proceeds to a fitness evaluation deploying SAP 2000, assessing weight, stability, and compliance with design standards. During selection, the fittest designs are chosen as parents, while the filtering of invalid chromosomes eliminates infeasible solutions to ensure structural integrity. Next, Crossover and Mutation combine strong traits and introduce variations to enhance exploration. Moreover, Precomputed Solution Storage reuses previously evaluated configurations, reducing redundant computations and improving efficiency. Subsequently, a stopping criterion determines whether the optimization should continue or stop. Finally, optimized output generation extracts the best-performing bracing configuration for real-world implementation, ensuring optimal balance between efficiency and structural performance.

Despite its efficiency, GA has inherent limitations, particularly in parameter selection. The number of genes directly impacts search complexity; more genes increase the solution space, requiring longer convergence time and higher computational cost. Similarly, the number of generations influences solution refinement; too many iterations may waste resources with minimal improvement, while too few risks premature convergence to suboptimal results. The filtering mechanism, intended to discard infeasible solutions, may unintentionally eliminate promising candidates, reducing genetic diversity and limiting exploration. Additionally, GA's sensitivity to parameter tuning, such as mutation and crossover rates, can either slow progress or introduce excessive randomness, affecting convergence stability.

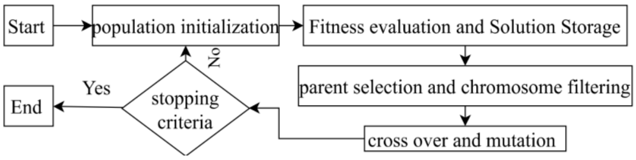


Fig. 1. GA flow chart for optimization process.

III. OPTIMIZATION TOOL

Based on Py-Gad's library, a new optimization tool has been developed with two enhancements. This tool facilitates the design of steel buildings with bracing systems to resist lateral and seismic loads while optimizing building weight and considering architectural constraints, helping engineers select the best bracing system to meet function, safety, serviceability, and cost requirements. The developed tool comprises three primary components: VBA script, Python script, and SAP2000. Its operation follows three key steps:

1. Data entry through the user interface.
2. Data transmission between VBA, Python, and SAP2000.
3. Generating results using VBA in Excel.

The main idea is to add a new capability to Holland's optimization procedure to comply with the target of this study. Holland's procedure does not filter the chromosomes. So, any chromosome which does not meet the specific boundary conditions of the main problem, should be excluded from the solution space. However, in some problems, in the real world, there are several boundary conditions which need to be met; otherwise, the obtained solution is useless. This can be clearly found in the current study, with the presence of invalid chromosomes, particularly those representing structural configurations which do not meet the serviceability conditions. These chromosomes often correspond to structures optimized for minimal weight. However, failure to address these invalid chromosomes can lead to misleading outcomes, undermining the reliability of the optimization tool. To tackle this issue, a strategic solution has been implemented through integrating an array into the code structure, systematically storing the values of all valid chromosomes alongside their corresponding fitness scores. During optimization, if an invalid chromosome is detected, it is promptly replaced with a randomly selected one from the top 20% stored in the array. This random selection mechanism helps prevent the optimization process from biasing towards specific solution regions, ensuring the integrity of the genetic algorithm's core principles. A supplementary array stores previously solved chromosome data, enabling a pre-check before executing the GA script. If a match exists, the fitness value is retrieved directly, bypassing VBA processing. This capability minimizes runtime and improves efficiency.

The developed tool follows the procedure outlined in the flowchart presented in Figure 3, which can be summarized as follows: The process begins by defining building parameters through the tool's interface (Step A), including dimensions, bracing type, loads, available sections, and permitted bracing locations, as shown in Figure 4. Accordingly, the initial structural model is set up. Chromosomes representing potential solutions are then generated according to the defined parameters, forming the initial population for optimization (Step B). The VBA script initiates the creation of an initial population of potential solutions, which are sent to GA for optimization. GA processes the chromosomes, with each of them representing bracing locations, as depicted in Figure 2, facilitating communication between GA and VBA. First, the model is designed under vertical loads and then the initial weight is obtained. The design is iteratively optimized until consistency is achieved (Step C). The drift values are checked according to code limits before transmitting results to GA. Crossover and mutation operations are applied to maintain diversity and ensure convergence. Each generated structural model is evaluated for safety and serviceability (Step D), taking into account compliance with design codes. Solutions that fail to meet these conditions are discarded using the newly added enhancements. The iterations continue until convergence criteria are met or a maximum generation limit is reached (Step E), resulting in an optimized, efficient structural design.

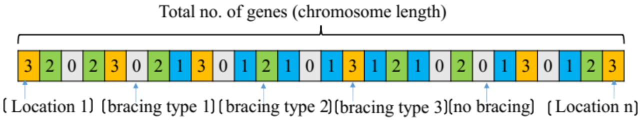


Fig. 2. Chromosome structure.

Linear analysis is adopted to simplify computations and reduce solving time, aligning with conventional design approaches. However, it results in lower displacement compared to non-linear analysis. While the proposed tool can handle large data sets, its performance is limited by hardware resources. Additionally, it is constrained in dealing with irregular or circular building shapes, variations in elevation even for rectangular structures, and complex problems requiring simultaneous chromosome processing. Addressing these limitations in future developments could further enhance its applicability in structural optimization.

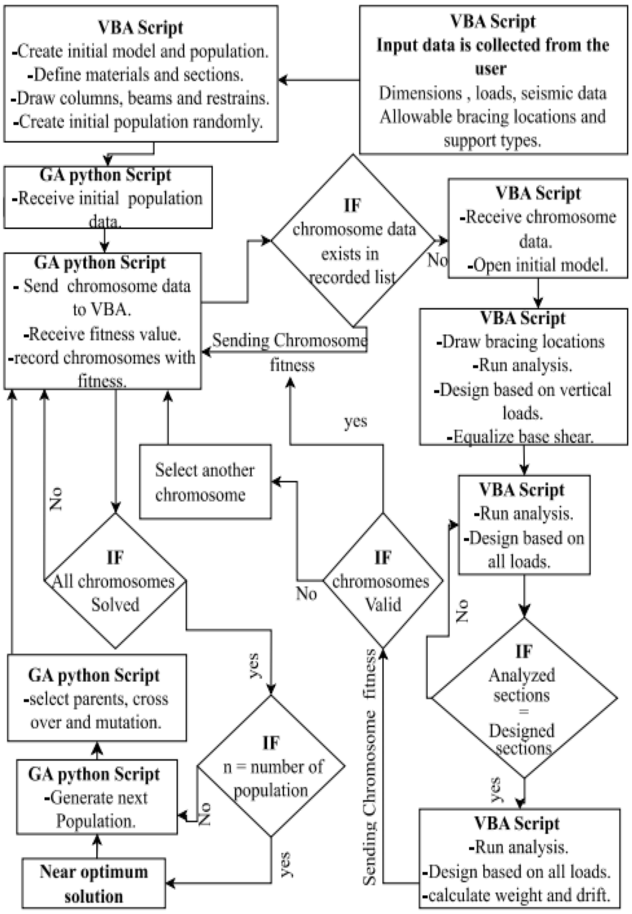
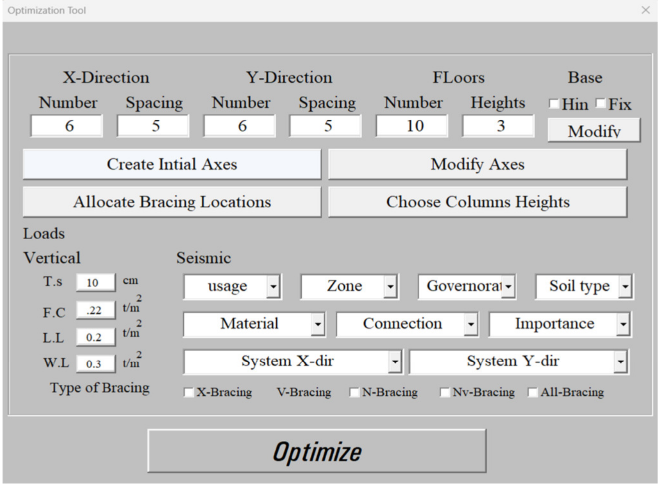


Fig. 3. Simplified flow chart for optimization tool.



X-Direction Number: 6
X-Direction Spacing: 5
Y-Direction Number: 6
Y-Direction Spacing: 5
FLoors Number: 10
FLoors Heights: 3
T.s 10 cm
F.C .22 t/m^2
L.L 0.2 t/m^2
W.L 0.3 t/m^2

Fig. 4. Proposed user interface for the optimization tool.

IV. VERIFICATION PROBLEM

Due to the tool's complexity, verification involves two steps: first, validating the tool's ability to build the model and retrieve data, such as weight and displacement; second, verifying its optimization process, including the design process.

A. First Step (Modeling process verification)

A building studied in previous research [4] has been used. The building consists of ground and 14 typical stories with ground beams 2.00 m from the foundations. The building has a 9 x 3 span configuration, each of 5.00 m length. The steel grade is S275 and the Young's modulus is 2.05 × 105 N/mm². Columns and beams are box sections with dimensions of 180 × 260 × 6 mm and 250 × 250 × 12 mm, respectively. The applied loads comprise a dead load of 5.0 kN/m² and live load of 3.0 kN/m², while seismic parameters follow IS-1893:2002 for seismic zone IV, with an importance factor of 1 and a response reduction factor of 5. The tool's modeling capabilities have been validated through a modeling process and results extraction. The obtained results closely align with those of [4], confirming the tool's accuracy and reliability, as shown in Figure 5.

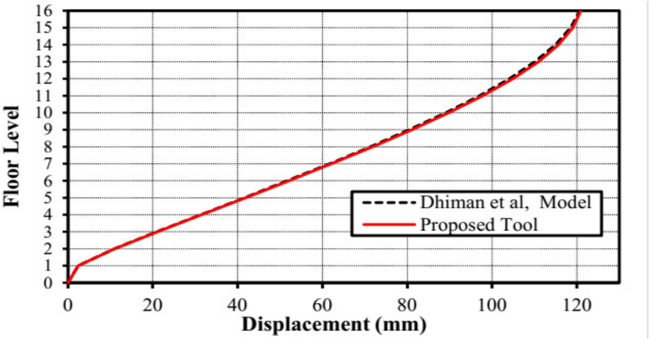


Fig. 5. Comparison between the tool results and results in [4].

B. Second Step (optimization process verification)

The second step validates the optimization process itself by comparing the developed tool with a trial-and-error method to assess accuracy and computational efficiency. A square, six-story, two-bay residential building with 4.00 m span, and a typical floor height of 3.00 m has been analyzed. It comprises nine columns, with six of them aligned in X-direction and three in Y-direction, and follows [19], soil type C, seismic zone (coastal), and ground acceleration of 0.125 g. The Young's modulus is 2.05 × 105 N/mm². A comprehensive steel section library was used, including HEA, HEB, and IPE profiles for columns and beams, and angles and UPN profiles for bracing.

With 4096 potential X-bracing configurations and no architectural constraints, the tool's results closely align with the reference solution, confirming its reliability. To evaluate these configurations, a comprehensive trial-and-error analysis has been conducted to generate all the possible arrangements. This exhaustive process identifies the optimal solution with a structural weight of 124.7702 tons. In contrast, the developed tool has analyzed only 350 configurations (8.5% of the total probabilities) across 16 generations. Despite fewer evaluations, the tool achieved the same optimal weight (124.7702 tons) and bracing arrangement in just 4:29:35 hours, compared to 52:20:16 hours for the trial-and-error analysis, as detailed in table I. This comparison underscores the developed tool's efficiency in reducing computational effort while maintaining accuracy. Although identical results have been achieved in this case, minor differences may arise for larger buildings due to increased bracing options and solution space.

A statistical analysis of five independent runs further confirms the tool's reliability and consistency. The mean structural weight across these runs is 125.60 tons, with a standard deviation of 0.82 tons and a margin of error of ±1.02 tons, indicating minimal variation in the results. The best solution found is 124.577 tons, while the worst is 126.658 tons, showing that the optimization process remains stable and produces reliable outputs within a narrow range.

TABLE I. COMPARISON BETWEEN OPTIMIZATION TOOL RESULTS VS TRIAL-AND-ERROR ANALYSIS

	Optimization tool	**Trial-and-error analysis**
Solution space	4096	4096
Explored space	350	4096
Explored space (%)	0.085	100
Optimum weight (Ton)	124.7702	124.7702
Time (h:m:s)	4:29:35	52:20:16

V. APPLICATION OF THE DEVELOPED TOOL

After verifying the accuracy of the developed tool, it has been applied to four case studies representing varying levels of structural complexity commonly encountered by design engineers. These cases featured different types of buildings, each presenting a distinctive scenario to evaluate the influence of bracing configurations. This diverse range of structural challenges provides a comprehensive assessment of the optimization tool's effectiveness in real-world applications. All cases share fundamental design parameters, featuring ten stories with a consistent floor height of 3.00 m and with all columns fixed at the base. The chosen bracing system across these structures is the X-bracing configuration, offering binary options for bracing placement: either no bracing or X-bracing. The applied loads include employing a 100 mm metal deck slab with floor, live, and a uniform wall load of 2.20 kN/m^2, 2.00 kN/m^2, and 3.00 kN/m^2, respectively. The seismic load has been applied according to ECP-201 [19], with a soil type C, an importance factor 1, and ground acceleration of 0.125 g. Furthermore, the materials and sections used are consistent with those in the second step of verification. GA parameters have been systematically defined to maintain consistency and facilitate comparison across the cases. The crossover operation employs a two-point method, while mutation operations utilize the random technique. Elitism is maintained by preserving the best solution throughout the optimization process. Parent selection follows a steady-state approach, ensuring the efficiency of the optimization process. These standardized parameters enable rigorous analysis and comparison of optimization outcomes, providing valuable insights into the efficiency of the optimization tool across the different structural configurations. Then the optimization ratio is referenced against the total weight of the full bracing system.

A. *Case-1: Unsymmetrical Bracing Pattern*

Case-1 addresses optimizing an unsymmetrical bracing pattern due to real-life architectural constraints. The building is square with uniform spans of 3.00 m in both directions, as displayed in Figure 6. Using 23 genes per chromosome and exploring 5,200 of 8,388,608 permutations. The tool has identified an optimal bracing layout that minimized the weight to 732.93 tons, achieving 58.53% optimization rate. Figure 9 presents the optimization curve of the studied case. The resulting configuration, portrayed in Figure 6, has one braced bay in the x-direction and two in the y-direction, attributed to torsional deformations caused by asymmetrical bracing locations. This asymmetry shifts the center of rigidity, resulting in additional drift. Despite this, the tool mitigated excessive drift, maintaining the maximum inter-story drift ratio at 0.9975, within code limits. The use of 23 genes allowed detailed exploration of possible configurations, while 104 generations ensured convergence. Though this required more computation time, it was essential for optimizing the complex unsymmetrical pattern. This case highlights the tool's ability to address real-life constraints and optimize complex structural configurations.

B. *Case-2: Unsymmetrical Pattern with Varying Spacing*

Case-2 explores an unsymmetrical bracing pattern with irregular column spacing, as shown in Figure 7, simulating real-world scenarios. The algorithm has explored 1,000 of 65,536 permutations, converged after 20 generations, achieving a minimum structural weight of 815.85 tons with a 56.29% optimization ratio, as depicted in Figure 10. The optimal configuration includes one braced bay in the x-direction and two in the y-direction, forming a C-shaped layout in plan. This design effectively resists torsional effects due to uneven lateral stiffness. The maximum inter-story drift ratio is 0.4867, well within code limits, ensuring seismic stability. The use of 16 genes reduced the solution space compared to Case-1, requiring fewer generations to converge. This allowed for efficient optimization without significantly increasing computational time, as fewer generations were sufficient for finding the optimal solution. This case highlights the proposed tool's ability to address architectural constraints and irregular geometries.

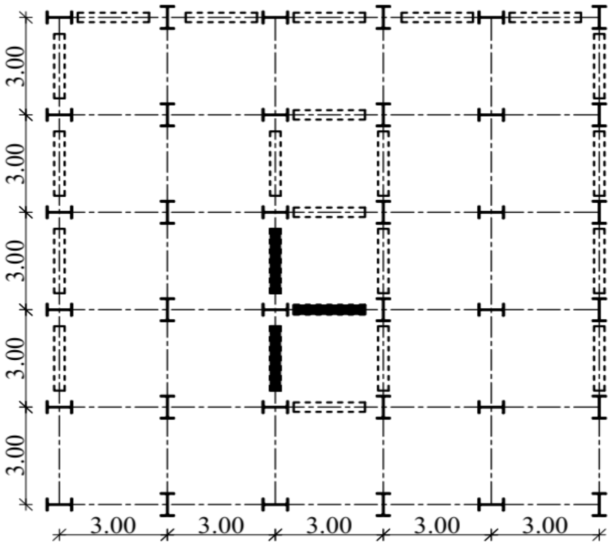


Fig. 6. Configuration of case study 1.

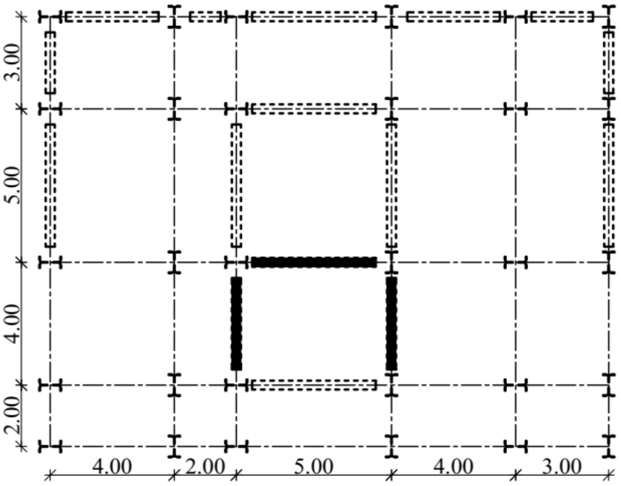


Fig. 7. Configuration of case study 2.

C. *Case-3: Symmetrical Pattern (Ideal Equal Spacing)*

Case-3 revisits the geometric setup of Case-1 but with a symmetrical bracing configuration and equal column spacing, as shown in Figure 8. Exploring 2,950 of 4,194,304 permutations, the tool has achieved a minimum weight of 732.33 tons with a 56.48% optimization ratio after 59 generations, as exhibited in Figure 9. The resulting bracing layout is strategically located near the building's center of mass in the y-direction, while the x-direction uses two bays farther from the center, forming a balanced configuration. The maximum inter-story drift ratio is 0.7812, within the allowable limits, ensuring stability under seismic loads. Symmetry in the bracing layout and column spacing allowed for multiple optimal configurations, enabling faster convergence than in Case-1, despite a similar number of genes. With only 59 generations, the tool efficiently achieved the optimal design, highlighting the reduced computational effort required for symmetrical patterns. This case demonstrates the tool's efficiency in idealized scenarios.

D. *Case-4: Symmetrical Pattern with Varying Spacing*

Case-4 investigates a symmetrical bracing configuration with irregular column spacing, as evidenced in Figure 11. Employing 17 genes and exploring 2,750 of 131,072 permutations, the algorithm converged after 55 generations, minimizing the structural weight to 815.25 tons with an impressive 65.16% optimization ratio, as can be seen in Figure 10. The optimal layout features bracing close to the center of the mass in the y-direction and two braced bays farther from it in the x-direction, effectively mitigating torsional deformations. The maximum inter-story drift ratio is 0.832, within code limits. The use of fewer genes helped reduce the solution space, although the optimization process still required a considerable number of generations due to the irregular spacing of the column and the initial conditions. This case highlights the tool's ability to address complex scenarios.

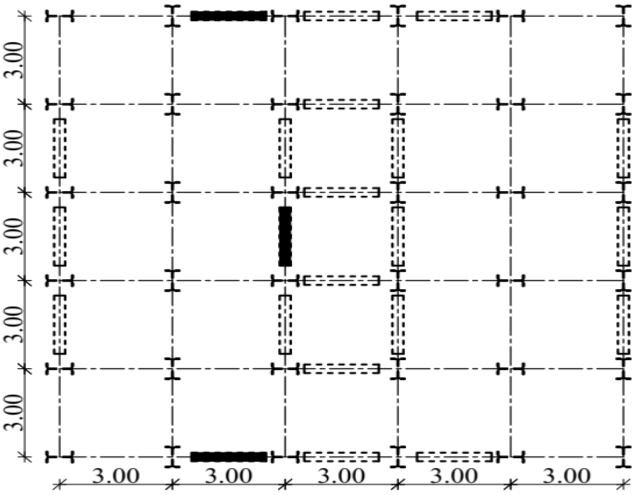


Fig. 8. Configuration of case study 3.

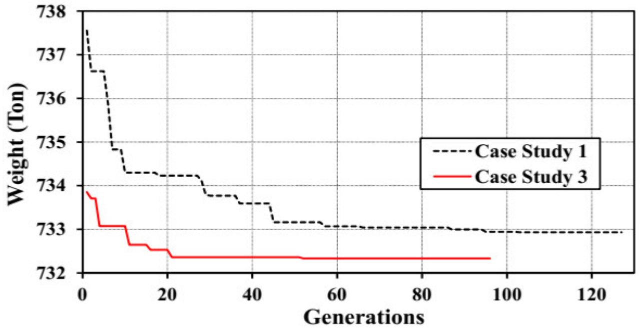


Fig. 9. Optimization curves of all the studied cases.

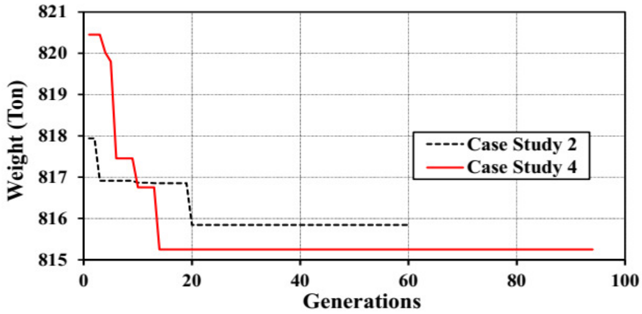


Fig. 10. Optimization curves of case studies 2 and 4.

A summary of the results of all studied cases is listed in Table II. It can be noticed that despite the tremendous number of probabilities in the solution space, the tool has obtained its near-optimum solution by exploring no more than 2.1% of the solution space. This ratio tends to be less when the building has a symmetric configuration; no more than 0.07%.

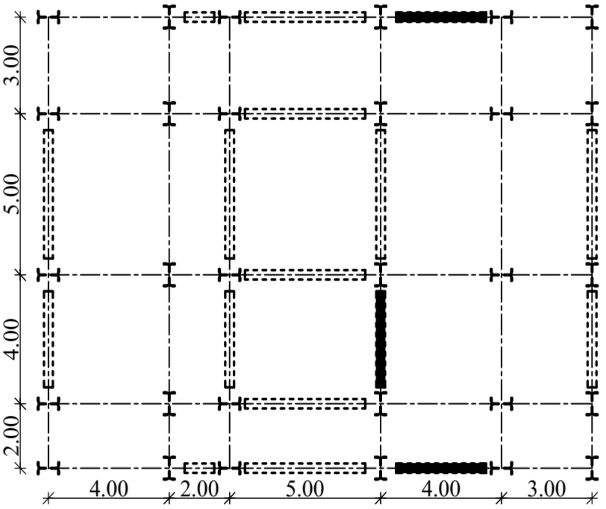


Fig. 11. Configuration of case study 4.

TABLE II. SUMMARY OF THE INVESTIGATED CASE STUDIES

	Case 1	**Case 2**	**Case 3**	**Case 4**
No. of genes	23	16	22	17
No. of generations	104	20	59	55
Solution space	8,388,608	65,536	4,194,304	131,072
Explored space	5,200	1,000	2,950	2,750
Explored space (%)	0.06	1.53	0.07	2.10
Optimum weight (Ton)	732.93	815.84	732.33	815.25
Optimization ratio (%)	58.53	56.29	56.48	65.16
Parent selection: steady-state selection Crossover: two-point (0.70) - mutation: random mutation (0.03)				

VI. CONCLUSIONS

This study introduces an innovative design tool for braced steel buildings, accessible to engineers of all experience levels. The tool combines the capabilities of the SAP2000 software with the GA optimization technique in such an innovative way that makes the complex design process much easier. Unlike the other studies conducted to optimize the building's weight, which were limited to a 2D analysis of the buildings, the current tool supports 3D analysis. Even in the minority of the other studies/prior research in which 3D analysis was deployed, only the trial-and-error technique - with its extraordinary solving time - was used to compare the different types of bracing, but without taking into consideration any architectural constraints. All these reasons make the available studies and techniques unsuitable for studying large scale problems. The proposed tool is based on the Holland's GA optimization technique and its available open-source script is provided by Py-Gad. Two new enhancements have been added to the adopted GA technique: a) filtering the invalid chromosomes and, b) adding a supplementary array to store all the solved cases and avoid resolving them again in any further generation, cutting down on solving time. A two-step verification process has been adopted including validating the tool's ability in modeling and then in obtaining the near-optimum weight. The results have shown good agreement with previous research findings and with the trial-and-error technique. The developed tool has been used to conduct four case studies considering buildings with different geometries and architectural constraints. Across varying scenarios, from asymmetrical patterns with irregular spacing to symmetrical layouts with equal column spacing, the developed tool consistently demonstrated its capability of navigating diverse architectural constraints while achieving optimal solutions. Throughout the exploration of vast solution spaces, the tool successfully minimized structural weight without compromising stability, thereby enhancing the efficiency and cost-effectiveness of the design process. These findings not only highlight the practicality of the tool in real-world architectural contexts, but also provide valuable insights for the development of structurally sound buildings. According to the case studies' results, the following conclusions can be drawn:

1. The analysis reveals a consistent trend across all cases: the utilization of only three bracings, albeit positioned differently in each scenario. This observation underscores a crucial inference: in asymmetrical structures, prioritizing bracing placement within the core proves more effective than dispersing them unevenly along the outer perimeter. Such an arrangement often incurs additional forces, resulting in heightened straining actions and potentially increased weights. Conversely, symmetrical structures benefit from outer perimeter bracing, which maximizes the torque arm between outer bracings, thereby bolstering resistance against torsional effects induced by seismic forces.
2. Furthermore, it is noteworthy that in cases where the two outer bracings align in the x-direction, the third bracing typically assumes the y-direction, strategically positioned within the core to withstand seismic forces. Additionally, in a varying spacing configuration, the bracing direction within the core often aligns with the bay of shorter length, leveraging its inherent stiffness to effectively counteract seismic forces.

Accordingly, for rectangular steel buildings, this study proposes the following:

1. Optimal structural configuration: the analysis highlights the significance of employing three bracing locations in two orthogonal directions as the minimum requirement for achieving structural optimization, ensuring balance between stability and simplicity.
2. Outer perimeter bracing strategy: until symmetry is attained, it is advisable to position bracings along the outer perimeter of the building. This strategic placement maximizes the structure's resistance against torsional effects induced by seismic forces, enhancing overall stability.
3. Strategic core bracing placement: in asymmetrical configurations, directing bracing towards the core, appears as a strategic approach. This utilization capitalizes on the inherent stiffness of shorter bays, effectively mitigating seismic forces and reinforcing structural integrity.

Future work for the optimization tool could include expanding to handle irregular shapes, incorporating real-time feedback, moving to a cloud-based platform, and integrating with BIM systems. Additionally, the use of AI and machine learning to predict optimal designs could reduce computation time.

REFERENCES

[1] W. Wang, "The Role in Tall Building Design in Greening the City," *Academic Journal of Architecture and Geotechnical Engineering*, vol. 5, no. 4, pp. 20–27, 2023.

[2] O. Chirag and D. Tarachandani, "Comparative Study of Effect of Structural Irregularities & Different Types of Bracings in Multistoried Steel Building," *International Journal for Scientific Research & Development*, vol. 4, no. 3, pp. 547–552, 2016.

[3] J. S. Jagadish and T. D. Doshi, "A Study On Bracing Systems On High Rise Steel Structures," *International Journal of Engineering Research & Technology*, vol. 2, no. 7, pp. 1672-1676, 2013.

[4] S. Dhiman, M. Nauman, and N. Islam, "Behaviour of Multistory Steel Structure with Different Types of Bracing Systems (A Software Approach)," *International Refereed Journal of Engineering and Science*, vol. 4, no. 1, pp. 70-82, 2015.

[5] O. Alshamrani, G. G. Schierle, K. Galal, and D. Vergun, "Optimal Bracing Type and Position to Minimize Lateral Drift in High-Rise Buildings," *WIT Transactions on The Built Environment*, vol. 106, pp. 155-166, 2009.

[6] Z. Tafheem and S. Khusru, "Structural Behavior of Steel Building with Concentric and Eccentric Bracing: A Comparative Study," *International Journal of Civil and Structural Engineering*, vol. 5, no. 2, pp. 56-63, 2019.

[7] A. Yassin and K. Sadeghi, "Structure Behaviour under Seismic Loads using X-Bracing, Inverted V-Bracing Systems and without Bracing," *International Journal of Innovative Science and Research Technology*, vol. 8, no. 1, pp. 1091–1098, 2023.

[8] T. Balogh and L. G. Vigh, "Genetic Algorithm Based Optimization of Regular Steel Building Structures Subjected to Seismic Effects," in *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012.

[9] S. Qiao, X. Han, K. Zhou, and W. Li, "Conceptual Configuration and Seismic Performance of High-Rise Steel Braced Frame," *Steel and Composite Structures*, vol. 23, no. 2, pp. 173–186, 2017, https://doi.org/10.12989/scs.2017.23.2.173.

[10] A. Issa, S. Stephen, and A. Mwafy, "Unveiling the Seismic Performance of Concentrically Braced Steel Frames: A Comprehensive Review," *Sustainability*, vol. 16, no. 1, Jan. 2024, Art. no. 427, https://doi.org/10.3390/su16010427.

[11] X. Yan, G. Shu, N. Rahgozar, and M. S. Alam, "Seismic Design and Performance Evaluation of Hybrid Braced Frames Having Buckling-Restrained Braces and Self-Centering Viscous Energy-Dissipative Braces," *Journal of Constructional Steel Research*, vol. 213, Feb 2024, Art. no. 108359, https://doi.org/10.1016/j.jcsr.2023.108359.

[12] G. Xu and M. Yamanari, "Performance of Steel Frame with Linkage System under Earthquake Excitation," *Engineering, Technology & Applied Science Research*, vol. 9, no. 1, pp. 3796–3802, Feb. 2019, https://doi.org/10.48084/etasr.2519.

[13] A. E. Eiben and J. E. Smith, *Introduction to Evolutionary Computing.* 2nd ed. Berlin, Germany: Springer, 2015.

[14] P. Ghannadi, S. S. Kourehli, and S. Mirjalili, "A review of the application of the simulated annealing algorithm in structural health monitoring (1995-2021)," *Fracture and Structural Integrity*, vol. 17, no. 64, pp. 51–76, Mar. 2023, https://doi.org/10.3221/IGF-ESIS.64.04.

[15] Specification for Structural Steel Buildings, ANSI/AISC 360-16, Chicago, IL, USA: AISC, 2016.

[16] M. I. E. T. Hassaine, S. M. E. A. Bourdim, H. Varum, A. Benanane, and A. Nour, "Push-over Analysis of Optimized Steel Frames," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9720–9725, Dec. 2022, https://doi.org/10.48084/etasr.5326.

[17] "PyGAD - Python Genetic Algorithm!" PyGAD 3.4.0 Documentation. [Online]. Available: https://pygad.readthedocs.io/en/latest/.

[18] J. H. Holland, "Genetic Algorithms," *Scientific American*, vol. 267, no. 1, pp. 66–72, Jul. 1992, https://doi.org/10.1038/scientificamerican0792-66.

[19] ECP Committee 203, *The Egyptian Code for Design and Construction of Concrete Structures*, Cairo, Egypt, 2007.