

Investigation of notch effect in the optimum weight design of steel truss towers via Particle Swarm Optimization and Firefly Algorithm

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ABSTRACT In this study, the optimal weight designs of steel truss towers are determined, considering the notch effect. Thus, the impact of discontinuities in the cross-sections of steel elements on the total weight of the structure is revealed. For this purpose, the optimal weight designs of different truss towers analyzed by other researchers in previous years are reexamined using Particle Swarm Optimization and Firefly Algorithm. The main program where finite element analyses and optimization algorithms are encoded has been developed in MATLAB. Displacement, stress, geometric, and section height constraints are used in optimization methods. The effectiveness of these methods has been demonstrated by comparing both the results in the literature and with each other under un-notched conditions. Subsequently, considering the notch effect on the tension bar with the highest stress capacity in each structure, the impact of stress concentration on the minimum weight sizing of the structure is investigated using these proven methods. When the analysis results of both cases are examined, it is observed that the optimum weights of all structures under the notch effect have slightly increased. The stress concentration around the notch severely raises the nominal stress in the cross-section. In this case, the cross-section becomes insufficient due to the overcapacity, requiring larger profiles. The structure's weight shows an increasing trend depending on the number of notched elements and the severity of stress concentration. Additionally, SAP2000 software is utilized for numerical simulations of the structures under identical conditions, enhancing the research content and providing further support for the comprehensive design optimization analyses. Consequently, minimizing the adverse effects of notches through careful material selection, proper manufacturing and assembly techniques, and regular maintenance is essential. The effects of notches should be considered in structural analysis and design, with measures taken to mitigate these effects when necessary.

KEYWORDS steel truss towers, optimum weight design, notch effect, particle swarm optimization, firefly algorithm

1 Introduction

The increasing world population has brought about the need for functional building design. Engineers attach importance to the design of such structures to be resistant to environmental effects and loads, to be aesthetically pleasing for the purpose to be used, and to be economically designed. Features such as ease of replacement and renewal, high quality, environmentally friendly, flexibility, earthquake resistance, high safety factor, and minimal longdate preservation and renovation

make steel a suitable construction material that can be used for this purpose. Therefore, the demand for steel structures is increasing day by day. Steel structures are more expensive than reinforced concrete structures. Efforts to produce steel structures at a lower cost have gained momentum to overcome this disadvantage in recent years. Utilizing optimization methods rooted in artificial intelligence, the structure can be designed to achieve minimal weight while maintaining the load-bearing capacities of its elements, thus enabling cost reduction to desired levels. For this purpose, size optimization studies have been carried out for mass reduction on different steel structures [1–38].

When performing an optimum weight design for steel structures, some undesired situations they may experience over their lifespan should be anticipated. One of the most crucial issues steel structures might face throughout their operational lifespan is the potential section losses in elements for various reasons. In the ideal condition, the stress state that occurs in the elements under the influence of force is $\sigma = F/A$, and the stress distribution is uniform. However, material continuity may deteriorate in the bars after manufacturing due to fatigue, corrosion, material defects, etc. In such cases, the stress distribution is not uniform, and $\sigma = F/A$ cannot describe the stress state of the element. In addition, stresses in discontinuous sections deviate from nominal values and reach maximum levels. This situation is called stress concentration. In elements where stress concentration occurs, the stress state can be complex. Solving this complexity may not be possible using classical methods alone. In such cases, the stress concentration factor K needs to be included in the calculations.

Imagine designing a steel structure without accounting for potential section losses in its members, essentially neglecting to prepare for adverse scenarios. In that case, it may experience severe damage or collapse before reaching its service life. Because notches can be the starting points of fatigue cracks under repeated loads, these cracks can grow over time, leading to the failure of the structure. Additionally, notches reduce the strength of steel structures, decreasing their load-carrying capacity and compromising the overall safety of the design. They shorten the durability and service life of the material, which may result in a reduced expected lifespan of the structure and more frequent maintenance or repairs. Notches, especially those located in critical areas, can weaken the structure's overall stability, increasing the risk of sudden collapse. Notches are also more susceptible to corrosion; accumulated moisture and dirt around them can accelerate corrosion, endangering the structure's integrity. Stress concentration is the most significant effect among these, which is considered in this study. Notches cause local stress concentration, subjecting the material to higher stress levels than the rest of the structure, leading to structural weaknesses. For these reasons, in optimal weight design, it is essential to minimize the adverse effects of notches through careful material selection, proper manufacturing and assembly techniques, and regular maintenance and inspections. The effects of notches should be considered in structural analysis and design processes, and measures should be taken to mitigate these effects when necessary. However, weight optimization studies considering this adverse scenario are quite limited in the literature. To eliminate this critical lack in the literature, this study's aim and novelty are to determine the optimum profile cross-sections and obtain the lowest structural weight value

accordingly by optimizing steel truss towers under the notch effect. Thus, it has been demonstrated how section losses in the elements can alter the structure's optimal weight. For this aim, in this study, the optimum weight designs of various truss tower systems analyzed by other researchers in the past years are repeated with two heuristic algorithm methods: Particle Swarm Optimization (PSO), a more traditional optimization technique [39], and Firefly Algorithm (FA), a more contemporary algorithmic method [40]. These two approaches are chosen to compare traditional and modern optimization algorithms and assess how they impact the results.

PSO and FA are nature-inspired optimization algorithms for solving optimization problems, but differ in their fundamental principles and mechanisms. PSO tends to balance exploration and exploitation well due to its swarm behavior and adjustment based on personal and social knowledge. FA emphasizes exploration initially, as fireflies move toward brighter ones, but it may suffer from premature convergence in specific scenarios. PSO typically involves fewer parameters to be set compared to FA, making it easier to implement and tune. FA might require more parameter adjustments, such as attractiveness, randomness, and light absorption coefficients, which can affect its performance and convergence behavior. Both algorithms are robust and can handle various optimization problems, including multimodal, noisy, and constrained optimization problems. However, FA might require more fine-tuning of parameters to achieve optimal performance in different scenarios compared to PSO. PSO is generally more straightforward in its implementation and understanding than FA, which involves more complex interaction mechanisms based on the brightness and distances between fireflies. Performance comparisons between PSO and FA can vary based on the problem being solved, parameter settings, and the nature of the optimization landscape. Each algorithm might perform better in different scenarios. Experimentation and empirical testing on specific problem domains are typically necessary to determine which algorithm performs better for a particular application. Therefore, the effectiveness of these algorithms has been confirmed through testing on four separate models that were formerly analyzed and proven for accuracy. These structures are a 25-bar steel space truss tower [41–44], a 72-bar steel space truss tower [43,45–49], a 52-bar steel plane truss tower [50–52], and a 582-bar steel space truss tower [53–55]. Then, considering the notch effect in each structure's tensile bar with the highest stress capacity, the impact of stress concentration on the minimum weight design of the structure is investigated using these proven methods. Finally, to reinforce the design optimization results detailed earlier and improve the study ingredient, analyses of all systems under identical situations are conducted using the SAP2000 program [56].

The finite element analysis of the selected structures is conducted using a program coded in MATLAB [57]. Subsequently, the algorithms of both optimization methods are embedded in this program. Stress and displacement constraints are used as constraints in optimization methods. Additionally, geometric and section height constraints are preferred in the example of a 582-bar steel space truss tower. While the output data, including minimum weight, maximum displacement, maximum stress capacity, and analysis count, are given in tables, the relation between weight and iteration count is illustrated in charts.

2 Optimum design of steel trusses

To perform optimal weight design, it is necessary to determine the design variables, constraints, and objective function.

In determining the design variables, the geometry and characteristics of the structure are initially taken into account. The number of spans, span dimensions, number of nodes, node coordinates, element groups, element dimensions, number of elements, number of supports, and stiffness conditions can be listed as geometric features. In addition, properties such as specific gravity, safety stress, and modulus of elasticity of the material should also be determined. A cross-section pool is created using the area and moment of inertia characteristics of different sections. Section assignments are made from this section pool to each element group specified in the design. As a result of the analysis, the optimum structural solution consisting of the most suitable sections is found.

In the optimization process performed in this study, the aim is to find the lightest structure weight. If there is no constraint in the system, the smallest cross-sectional area in the section pool will be the solution. In the optimization process, the structure must meet certain specifications. Therefore, the regulations should limit the solution set of objective functions. When these constraints are used, the solution will be the smallest cross-section that satisfies the boundary conditions. Constraints can be divided into manufacturing constraints and system behavior constraints. Since the manufacturing constraints are the constraints for the construction, they are considered when determining the structure geometry. The constraints related to the system behavior are displacement and stress constraints. As stated below, stress constraints are applied based on AISC-ASD (1989) [58] criteria.

If the stress in the bar is positive, that is, in a tensile situation;

$$F_a = 0.6F_y, \quad (1)$$

where F_y is the yield stress.

In the case of negative stress in the bar, that is, in the case of compression;

$$\lambda = \frac{KL}{r}, \quad (2)$$

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}}, \quad (3)$$

where λ , K , L , r , C_c , and E represent the slenderness of the element, the effective length factor ($K = 1.00$ for truss structures), the element length, the radius of inertia, the plastic slenderness value, and the elastic modulus.

The slenderness of the elements experiencing axial pressure is calculated and compared with the plastic slenderness.

For $\lambda < C_c$, the buckling is in the plastic region, and the compression safety value is calculated as follows:

$$F_a = \frac{\left[1 - \frac{\lambda^2}{2C_c^2}\right] F_y}{\frac{5}{3} + \frac{3\lambda}{8C_c} - \frac{(\lambda^3)}{8C_c^3}}. \quad (4)$$

For $\lambda \geq C_c$, the buckling is in the elastic region, and the compression safety value is calculated as:

$$F_a = \frac{12\pi^2 E}{23\lambda^2}. \quad (5)$$

In this case, the equation for calculating the stress constraint is given below:

$$g_i(x) = \left[\frac{f_a}{F_a} \right]_i - 1 \leq 0, \quad i = 1, \dots, nm, \quad (6)$$

where f_a and nm denote the calculated stress and the number of elements, respectively.

The displacement constraint is applied as follows:

$$g_j(x) = \frac{\delta_j}{\delta_{ju}} - 1 \leq 0, \quad j = 1, \dots, m, \quad (7)$$

where δ_j , δ_{ju} , and m symbolize the displacement value of the j th node, the displacement limit value of the j th node, and the number of nodes in the truss system, respectively.

In the example of a steel space truss tower with 582 bars, the following geometric constraints are also used among the vertical elements.

$$g_m(x) = \frac{A_{u,m}}{A_{l,m}} - 1 \leq 0, \quad (8)$$

$$g_m(x) = \frac{D_{u,m}}{D_{l,m}} - 1 \leq 0, \quad (9)$$

where $A_{u,m}$, $A_{l,m}$, $D_{u,m}$, and $D_{l,m}$ denote the cross-section

area of the upper vertical element, the cross-section area of the lower vertical element, the cross-section height of the upper vertical element, and the cross-section height of the lower vertical element, respectively.

In engineering problems, the structure weight and the cost of the structure are generally considered objective functions. The objective function created for the minimum weight design of the space truss systems discussed in this study is as follows;

$$\min W(x) = \sum_{k=1}^{ng} A_k \sum_{i=1}^{nm} \rho_i L_i, \quad (10)$$

where $W(x)$, k , A_k , ng , nm , ρ_i , L_i represent the truss system's weight, the groups' element number, the areas of the cross-sections of elements within group k , the overall amount of groups within the system, the overall count of elements in the system, the density of the i^{th} element, and the height of the i^{th} element, respectively.

Below is the equation incorporating the weight-constraining functions of the truss system.

$$WT_C(x) = W_i(1 + PC), \quad (11)$$

$$\text{for } g_i(x) \leq 0, \quad gc_i = 0, \text{ for } g_i(x) > 0, \quad gc_i = g_i(x), \quad (12)$$

$$\text{for } g_j(x) \leq 0, \quad gc_j = 0, \text{ for } g_j(x) > 0, \quad gc_j = g_j(x), \quad (13)$$

$$C = \sum_{i=1}^{nm} gc_i + \sum_{j=1}^{nm} gc_j, \quad (14)$$

where WT_C , P , and C represent the total system weight (penalty weight), a fixed coefficient determined according to the problem, and the penalty function, respectively.

The stress constraint is given in Eq. (12), and the displacement constraint is shown in Eq. (13). If constraints are provided, Eq. (14) will be zero, and the total system weight will be equal to the weight of the truss system. The system weight will reach its minimum value by providing the objective function. If the constraints are not provided, Eq. (14) will have a value, and the total system weight will increase. Thus, the objective function will not be provided. For this reason, the objective function value of a solution set that does not satisfy the boundary conditions will be higher than the other solution sets that meet the boundary conditions.

3 Particle Swarm Optimization

The PSO, an evolutionary optimization algorithm, was discovered by Eberhart and Kennedy [39]. It was inspired by the behaviors of animals moving in herds, such as foraging for food and avoiding danger. When birds search

for food, they move based on each other's positions through social information sharing. Thus, a bird that finds food guides others and shares the location information of the food with all the birds in the flock.

This algorithm is based on swarm intelligence. Each individual describes a particle. Particles form the swarm. Each particle represents a possible solution. Initially, parameters are established, and particles assume random positions. Subsequently, the fitness value of these positions is computed, with each initial fitness value serving as the local best value for its respective particle. This is because there is no past fitness value to compare with the fitness values of the particles. This value is denoted as "pbest". The optimum fitness value within the swarm is called "gbest", representing the global best value. Both these values are retained in memory. In each iteration of a PSO involving n particles, only one global best value exists, while each particle retains its own "pbest." Velocities are calculated using the initial solution. Subsequently, the new positions of the particles are determined by using the previous velocity values and social and conceptual coefficients. The fitness values of these new positions are calculated, and velocities are updated. Then, while making the next position update, the particles move toward the particle with the best fitness value in the swarm and take new positions, taking advantage of the previous velocity values and social and conceptual coefficients. Fitness values are recalculated based on these positions. The most optimal local and global solutions obtained thus far are stored in memory. Consequently, in every iteration, particles endeavor to move closer to the particle with the best position within the swarm. With each iteration's conclusion, particles advance to positions superior to their preceding ones. This convergence process toward the optimal position continues until the particle achieves its target.

After the best two values are found, the new velocities and positions of the particles are updated according to the following equations:

$$V_{i+1} = W \times V_i + c_1 \times rand_1 \times (pbest_i - x_i) + c_2 \times rand_2 \times (gbest_i - x_i). \quad (15)$$

In this equation, c_1 and c_2 are scaling factors. These values are stochastic acceleration terms enabling each particle to move toward its local and global best positions. c_1 drives the particle based on its own experience, while c_2 drives the particle based on the experience of the swarm. Choosing small values for these factors allows the particle to explore regions far from the target before reaching it, thus extending the time to get it. Conversely, selecting higher values shortens the time to reach the target but may result in unexpected movements. The W in the equation represents the inertia weight. $rand_1$ and $rand_2$ are uniformly distributed random numbers between $[0,1]$.

The position update is performed using the following equation.

$$X_{i+1} = x_i + V_{i+1}. \quad (16)$$

In this equation, the new position of the particle is determined using the velocity value obtained from Eq. (15).

The flowchart of the PSO algorithm is given in Fig. 1.

The PSO described in detail above and whose operating process is depicted in the flowchart in Fig. 1 is utilized for the minimum weight designs of the structures addressed in this study as follows. The solution models are established once the initial population is determined. Different cross-sections are assigned to each system, as many as the population, and subsequent analyses are conducted to calculate stress and displacement values. The appropriateness of solution vectors to the problem constraints is determined based on these values and ranked according to their fitness levels. The pbest, which is equal to the number of individuals in the population and represents the local best value for each element, is determined. Updating the positions and velocities in the algorithm refers to the updates occurring in the solution vectors of the population during the transition to successive iteration. The solution vectors in the

population are subjected to analysis for the initially determined iteration count until the most optimal solution that satisfies the problem constraints is reached.

4 Firefly Algorithm

The FA, developed by Yang [40], is a metaheuristic optimization algorithm based on the social behavior of fireflies that can glow in dark environments. Fireflies emit light, serving as a signaling system that attracts other fireflies. Many researchers interpret the behaviors of fireflies as finding their mates, attracting prey, and protecting themselves from predators. This algorithm takes its name from the fireflies that inspired its creation. The fact that fireflies are accepted as a single species and attract each other with their brightness is an element that forms the basis of the algorithm.

In this algorithm, fireflies are considered a single genus. Because of this assumption, all fireflies are attracted to other fireflies. The temptation of fireflies increases as the brightness increases, and the fireflies move toward the brightest firefly. The greater the distance between fireflies, the lower the attractiveness, as the light intensity decreases with distance. If there is no brighter firefly in the environment where fireflies are present, the fireflies will move in random directions. To obtain effective optimal solutions using the FA in an optimization problem, the objective function of the problem is achieved by guiding the firefly swarm to brighter and more attractive locations. This tendency is related to flashing lights or light intensity [59].

The change in light intensity and attractiveness are two essential elements of the FA. In fireflies, attractiveness varies depending on distance and brightness. Each firefly has different values of attractiveness.

The attractiveness value for any firefly is denoted β and is calculated by the following equation.

$$\beta(r) = \beta_0 e^{-\gamma r^2}. \quad (17)$$

In this equation, $\beta(r)$ is the distance between two fireflies, β_0 is the attractiveness value for $r = 0$, and γ is an absorption coefficient that controls the decrease in light intensity.

The distance r_{ij} between the i th and j th fireflies, represented by design variables X_i and X_j , is calculated using the following equation.

$$r_{ij} = \|X_i - X_j\| = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}. \quad (18)$$

The movement of the i th firefly toward the j th firefly, which is more attractive than itself, is determined by the following equation:

$$X^{i+1} = X^i + \beta_0 e^{-\gamma r_{ij}^2} (X_i - X_j) + \mu(rand - 0.5). \quad (19)$$

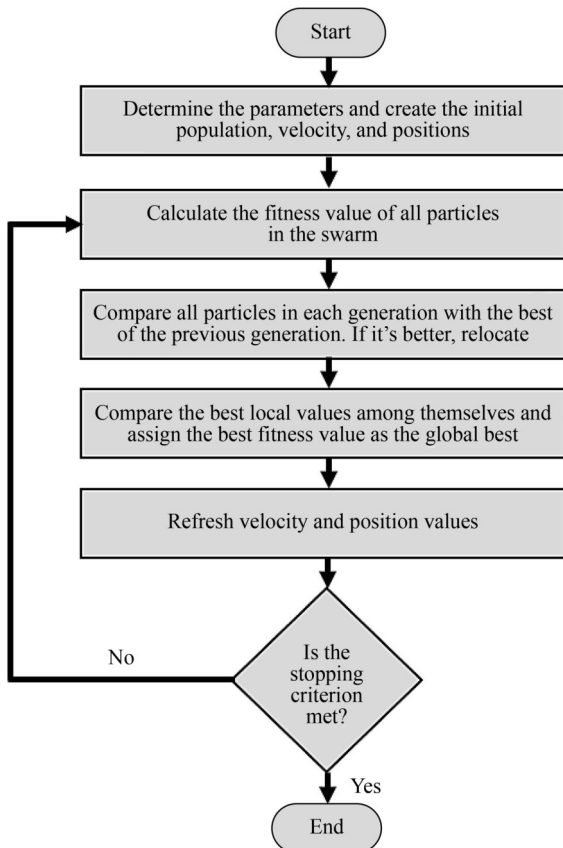


Fig. 1 The flow chart of the PSO algorithm.

The term μ represents a random selection parameter, while rand denotes a randomly generated real number within the range [0,1].

The first part in Eq. (19) represents the current position of the firefly. The second part relates to the relationship between the light intensity perceived by neighboring fireflies and the attractiveness of the current firefly. The last part enables the firefly to make a random movement when there is no more attractive firefly around it. The flowchart of the FA is given in Fig. 2.

The FA explained in detail above, whose solution steps are shown in the flowchart in Fig. 2, is utilized in the minimum weight designs of the structures addressed in this study as follows. First, solution models are generated upon determining the initial population. Subsequently,

different sections equal to the number of populations are assigned to each system. Analyses are conducted to calculate displacement and stress values. The compliance of solution vectors with problem constraints is determined and verified based on these values. The population's solution vectors are arranged based on the fitness levels computed for each firefly. Updating the positions and velocities in the algorithm refers to the updates occurring in the solution vectors of the population during the transition to the next iteration. The solution vectors in the population are subjected to analysis for the initially anticipated iteration count until the most suitable solution satisfying the problem constraints is reached.

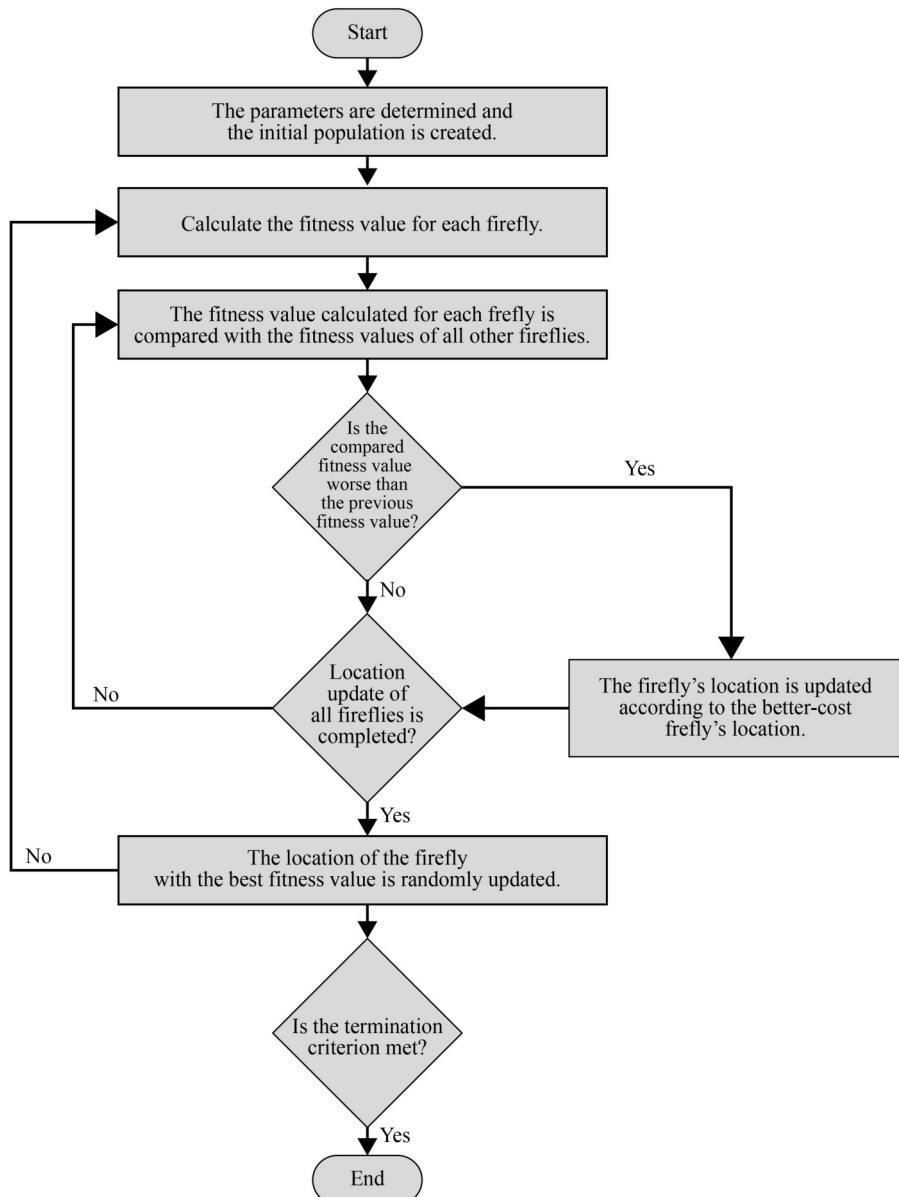


Fig. 2 The flow chart of the FA.

5 Notch effect on steel members

Stress in the elements under the influence of force can be complex in some cases. Solving this complexity may not be possible using only simple compression, simple torsion, and simple bending methods. In the ideal case, the stress distribution is uniform, and the mean stress relation is expressed as $\sigma = F/A$. However, fatigue (In this study, the change in the mechanical properties of the material due to fatigue is not taken into account) or material defects (cavities in parts, sudden cross-section changes on the element, notches, or holes) that may occur in the tension bars may cause deterioration of material continuity after manufacturing. In this case, the stress distribution in the cross-section may not be uniform, and the mean stress equation differs from $\sigma = F/A$. At points where the continuity of the material is disturbed, stresses move away from their normal value and reach the maximum level. This situation is called stress concentration.

Discontinuities causing stress concentration arise due to factors that cause changes in the cross-sectional area, such as notches, holes, protrusions, and keyways. Since the cross-sectional area is reduced, the greatest normal stress ($\sigma_{\max}$) occurs in the regions where these discontinuities exist.

$$\sigma_{\max} = K \frac{F}{A'}, \quad (20)$$

where A' , F , and K denote the cross-section area, applied force, and stress concentration coefficient, respectively.

It is always $K \geq 1$. The stress concentration coefficient can be expressed as the ratio of the maximum local stress to the nominal stress as follows:

$$K = \frac{\sigma_{\max}}{\sigma_N}, \quad (21)$$

where σ_N is the nominal stress, that is, the stress in the material away from the discontinuity and is calculated as follows:

$$\sigma_N = \frac{F}{A'}. \quad (22)$$

The stress intensity factor, also known as K , is a dimensionless factor that measures the increase in stress around geometric discontinuities in materials. These discontinuities may be features such as notches, holes, sharp corners, or other irregularities. These properties result in increased local stress compared to the nominal stress in the rest of the material. Stress intensity factors are critical in engineering and materials science because they help predict where and how materials under load may fail. It is typically determined through experimental data, analytical calculations, and finite element analysis.

To calculate the stress intensity factor, knowing the maximum stress and the nominal stress values caused by specific geometric discontinuities is necessary. These values are usually obtained through experimental data, analytical solutions, or finite element analysis. In experimental methods, maximum and nominal stress values are measured using strain gauges, and K is calculated from these measurements. In analytical methods, relevant formulas and tables found in engineering literature can be used to calculate K . Additionally, finite element analysis can be employed to model structures and determine maximum and nominal stress values. Moreover, standardized formulas and tables for some standard geometries are available in Ref. [60]. The K value for this study is taken from the graph about the theoretical stress concentration coefficients of a rectangular cross-section part with notches on both sides (a rectangular perforated part). $g/b = 0.14$, which is the ratio of the notch radius (g) to the plate length after the notch (b); $B/b = 1.02$, which is the ratio of the plate length (B) to the plate length after the notch (b), is accepted. According to these assumptions, K takes the value of 1.5 [60].

6 Design examples and optimization results

In this part of the study, the optimum weight designs of different truss towers studied in the previous years are re-examined using two heuristic algorithm methods (PSO and FA). Thus, the effectiveness of these methods has been demonstrated by comparing both the results in the literature and with each other. Subsequently, considering the notch effect on the tension bar with the highest stress capacity in each structure, the influence of stress concentration on the sizing of the structure to minimize its weight is investigated with these proven methods.

Exhaustive numerical and empirical research proposals published in the literature are used to select algorithm control parameters. For example, for the PSO, values of $c_1 = c_2 = 0.8$, $w = 0.9$, and number of individuals = 20 are taken into account, while for the FA, values of $\mu = 0.2$, $\beta_0 = 0.5$, $\gamma = 1$ and the number of individuals is taken as 20. The iteration count fluctuates based on structural complexity factors, such as the number of elements. The main program in which Finite Element Analysis (FEA) and optimization algorithms are written has been developed in MATLAB [57]. It is also desirable to validate the precision of the optimal design results derived from methodologies proposed in this study using the same material parameters and load values as those used in relevant literature studies. The analyses for all structures considered in this study are repeated five times. Average and best convergence curves are obtained. Only the best results extracted from evaluating these curves are

presented with tables and graphs. Other results are not provided to avoid confusion due to the abundance of tables and graphs. The minimum weight, maximum displacement, maximum stress capacity, and analysis count are illustrated in the tables, and the correlation between the weight and the iteration is presented on the graphs.

The efficiency of the algorithms used in this study has been tested on four distinct models formerly examined and verified. These systems are 1) a 25-bar steel space truss tower, 2) a 72-bar steel space truss tower, 3) a 52-bar steel plane truss tower, and 4) a 582-bar steel space truss tower.

6.1 A 25-bar steel space truss tower

The geometric characteristics of the structure, formed by connecting 25 steel bars grouped in eight different ways

at ten nodal points, are presented in Fig. 3. The system is loaded through four different nodes (1), (2), (3), and (6). Single loads of 4.448 kN in the x direction and -44.48 kN in the y and z directions are applied to node 1. Forces of -44.48 kN are loaded to the system from node 2 in the y and z directions. In addition, concentrated loads of 2.224 and 2.669 kN are applied only in the x direction from nodes 3 and 6, respectively. The modulus of elasticity and density of the material used in the structure are 68950 MPa and 2767.991 kg/m^3 , respectively. In this example, stress and displacement constraints are used according to the AISC-ASD 1989 [58] criteria. The limit values for tensile and compressive stresses are 275.8 MPa and -275.8 MPa, respectively. The maximum displacement limit value is ± 8.899 mm in the x and y directions at nodes 1 and 2.

The 25-bar steel space truss tower given in Fig. 3 was first researched by Zhu [41]. Then, it has become one of

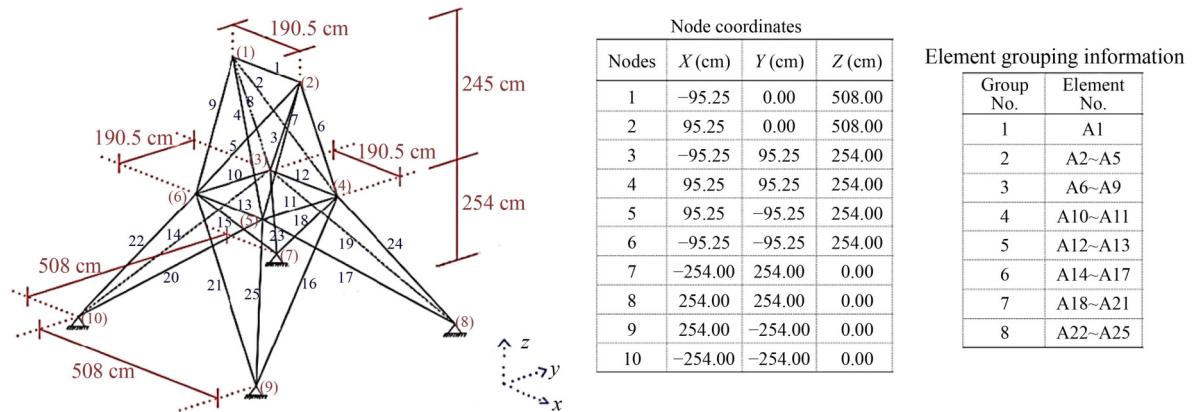


Fig. 3 Configuration of 25-bar steel space truss tower.

Table 1 Optimization values for the 25-bar steel space truss tower

Element group	Rajeev and Krishnamoorthy GA [42]	Erbatur et al. IGA [43]	Zhang et al. GSFP [44]	Optimum cross-sectional areas (cm ²)			
				This paper (un-notched cond.)		This paper (notched cond.)	
				PSO	FA	PSO	FA
1	0.65	0.65	0.65	0.65	0.65	0.65	0.65
2	11.61	7.74	2.58	1.94	4.52	1.94	8.39
3	14.84	20.64	21.94	21.94	21.94	21.94	21.94
4	1.29	0.65	0.65	0.65	0.65	0.65	0.65
5	0.65	7.10	14.19	14.19	14.84	10.32	10.32
6	5.16	5.81	6.45	7.10	5.81	5.81	5.81
7	11.61	2.58	2.58	2.58	1.94	6.45	0.65
8	19.36	21.94	21.94	21.94	21.94	20.65	21.94
Weight (kN)	2.43	2.20	2.50	2.18	2.17	2.22	2.21
Max. displacement (mm)				8.874	8.877	8.873	8.892
Max. stress capacity (%)				72.61	74.57	92.58	99.22
Analysis count				10000	10000	10000	10000

the basic structure types on which many researchers study optimization. For example, Rajeev and Krishnamoorthy [42] used the Genetic Algorithm (GA), Erbatur et al. [43] used the Improved Genetic Algorithm (IGA), Zhang et al. [44] used the Generalized Shape Functions with Penalization (GSFP). The results of these studies are shown in Table 1. The results obtained from un-notched and notched conditions using the methods discussed in this study (PSO and FA) are also presented in the same table. In addition to this information, the values, such as the maximum displacement and maximum stress capacity acquired with PSO and FA for the structure, are provided in the table, and the results are interpreted.

When the notch effect is disregarded, it can be observed from the data presented in Table 1 that the structure weight is 2.18 kN for PSO and 2.17 kN for FA. These values are lighter than the literature results, at 10.3–10.7% [42], 0.9–1.4% [43], and 12.8%–13.2% [44], respectively. Upon comparison, it is evident that FA yields a more optimal solution. This value is also the lightest structure weight in the table. The results are consistent with each other and with other literature findings. This situation demonstrates that these optimization methods can provide realistic results and can be readily preferred in the optimum weight designs of such structures. A comprehensive comparison of the weight outcomes yielded by all optimization techniques listed in the table is elaborated upon in Fig. 4.

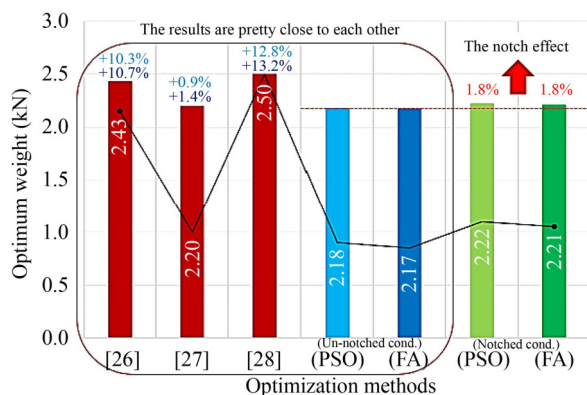


Fig. 4 Comparison of optimum weight results for the 25-bar steel space truss tower.

The element with the highest tensile capacity for both optimization methods is the tension bar, number 11. For this bar, the maximum tensile stress values are obtained as 162.48 MPa (58.91% capacity ratio) for PSO and 174.53 MPa (63.28% capacity ratio) for FA, respectively. To observe the effect of the notch on the optimum structure weight, stress values are multiplied by the stress concentration coefficient ($K = 1.5$), and optimization processes are repeated. As a result of these processes, the structure weight is obtained as 2.22 kN for PSO and 2.21 kN for FA, with an increase of 1.8% for both methods (Table 1).

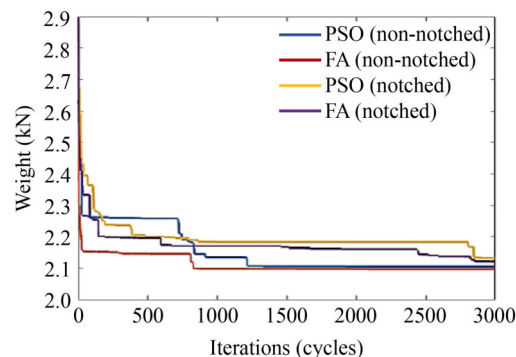


Fig. 5 The variation of the total weight of the 25-bar steel space truss tower based on the iteration count.

It can be observed that the calculated maximum displacement values for both un-notched and notched conditions are quite close to each other, and these values are just below the allowable displacement limit. Therefore, displacement values are effective in the optimal design of the structure. When the notch effect comes into play, a significant increase occurs in the stress-carrying capacities of the members, reaching from 72.61% to 92.58% for PSO and from 74.57% to 99.22% for FA (Table 1).

The graphs recorded in the process of reducing the 25-bar steel space truss tower to its lightest weight with PSO and FA and expressing the change of the total weight of the structure with the number of algorithm cycles are presented in Fig. 5.

To support the design optimization analysis results described in detail above and to introduce a distinction to study compared to similar ones, the 25-bar steel space truss tower has been subjected to numerical simulations using the SAP2000 program under the same boundary conditions and material properties. The maximum displacement values obtained as structural responses from the analyses are presented over the deformed shape of the structure given in Fig. 6. It can be observed that the results obtained for both cases where the notch effect is considered and not considered are almost the same as the values given in Table 1. This result demonstrates that PSO and FA are suitable optimization methods for conducting optimal design processes to achieve the lightest weights for such structures.

6.2 A 72-bar steel space truss tower

Figure 7 illustrates the geometric properties of the structure formed by arranging 72 steel bars into 16 distinct groupings at 20 nodal points. L length is 152.4 cm, and the tower height is 609.6 cm. The system is loaded from four nodes (1), (2), (3), and (4). It is loaded from node 1 in two different ways. First, singular loads of 22.2685 in the x and y directions and -22.2685 kN in the z direction are applied. Second, a concentrated load of

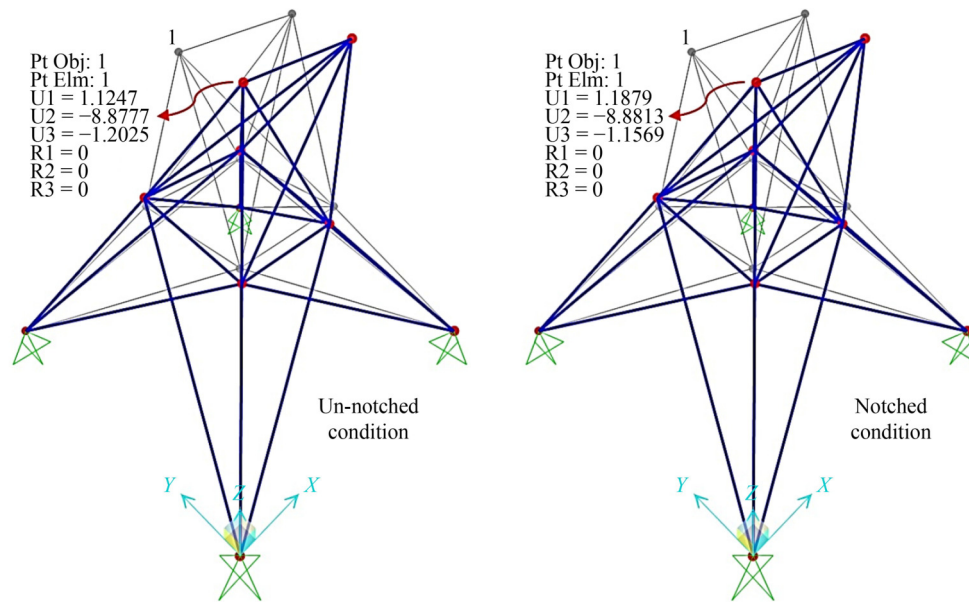


Fig. 6 Maximum displacement values obtained by numerical simulations for un-notched and notched cases.

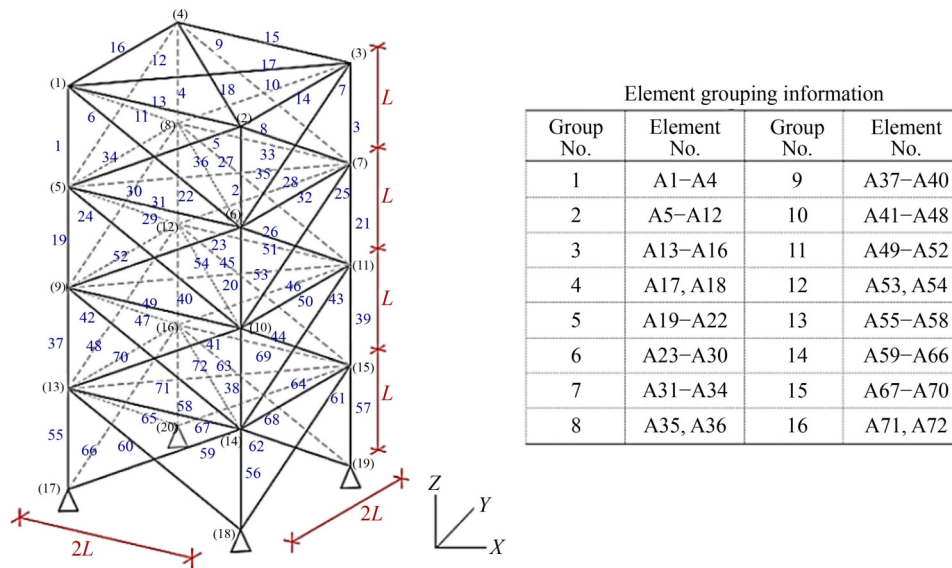


Fig. 7 Configuration of 72-bar steel space truss tower.

–22.2685 kN acts only in the z -direction. Forces of –22.2685 kN are loaded to the system from nodes 2, 3, and 4 in the z -direction. The profile cross-sections used in the optimum solution vary between 0.65 and 20 cm². A total of 194 profile cross-sections are used. The modulus of elasticity and density of the material used in the structure are 68950 MPa and 0.0272 N/cm³, respectively. The limit values of tensile and compressive stresses are 172.375 and –172.375 MPa. The maximum displacement limit value is 0.635 cm.

The 72-bar steel space truss tower shown in Fig. 7 was first examined by Venkayya [45]. Then, it has become one of the primary structure types on which many researchers practice optimization [43,46–49]. The results

of these studies are shown in Table 2. In the same table, results obtained from the methods (PSO and FA) discussed in this study according to both un-notched and notched conditions are also included. In addition to this information, the values of the structure, such as maximum displacement and maximum stress capacity obtained by PSO and FA, are also presented in the table, and the results acquired are analyzed.

When examining Table 2 for the case where the notch effect is not considered, it is observed that the structure's weight is 1.72 kN for PSO and 1.70 kN for FA. These optimal weight outcomes are heavier than the best result obtained by Kaveh et al. [48], 1.74% and 0.59%, respectively. Upon comparison, it is evident that FA yields a

Table 2 Optimization values for the 72-bar steel space truss tower

Element group	Venkayya [45]	Xicheng and Guixu [46]	Erbatur et al. GA [43]	Gellatly and Berke [47]	Kaveh et al. GA-NN [48]	Artar and Daloglu TLBO [49]	Optimum cross-sectional areas (cm ²)		This paper (un-notched cond.)		This paper (notched cond.)	
							PSO	FA	PSO	FA	PSO	FA
1	1.04	1.01	1.00	0.96	1.01	0.65	0.65	0.65	0.65	0.65	0.65	0.65
2	3.59	3.46	3.45	4.99	3.53	3.12	4.75	4.55	3.45	5.05		
3	2.43	2.65	3.10	2.93	2.63	3.12	2.45	2.75	1.05	3.15		
4	3.26	3.68	3.35	2.20	3.70	5.22	2.55	3.05	3.45	3.15		
5	3.94	3.28	2.97	3.56	3.35	3.12	3.25	4.15	2.55	3.05		
6	3.43	3.37	3.42	3.93	3.34	3.12	3.25	3.65	3.75	3.25		
7	0.65	0.65	0.77	0.65	0.65	0.65	0.65	0.65	0.75	0.65		
8	0.65	0.65	1.06	0.65	0.65	3.12	0.65	1.15	0.75	1.45		
9	8.04	8.30	7.45	6.60	8.21	7.68	9.25	8.35	6.55	6.35		
10	3.38	3.33	3.77	3.50	3.27	4.61	2.35	2.95	4.05	2.85		
11	0.65	0.65	0.65	0.65	0.65	1.00	0.65	0.65	0.85	0.65		
12	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65		
13	11.73	12.29	11.32	9.44	12.17	10.07	13.95	10.05	11.85	9.75		
14	3.38	3.34	3.26	3.36	3.32	3.12	3.35	2.75	4.15	3.55		
15	0.65	0.65	0.68	0.65	0.65	0.65	0.65	0.65	0.65	0.65		
16	0.65	0.65	1.00	0.65	0.65	0.65	0.65	0.65	0.75	0.65		
Weight (kN)	1.70	1.70	1.72	1.76	1.69	1.76	1.72	1.70	1.74	1.73		
Max. displacement (mm)							6.349	6.348	6.348	6.349		
Max. stress capacity (%)							88.15	86.62	85.15	85.17		
Analysis count							60000	60000	60000	60000		

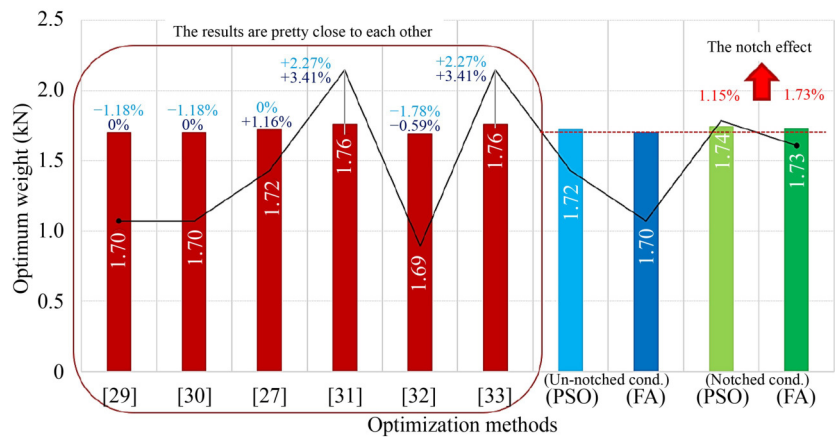


Fig. 8 Comparison of optimum weight results for the 72-bar steel space truss tower.

more optimal solution. The results are consistent with each other and with other literature findings. This indicates that these optimization methods can provide accurate results in the optimum weight designs of such structures and can be readily preferred. Figure 8 provides a detailed comparison of the weight outcomes derived

from all optimization techniques listed in the table. The element with the highest tensile capacity for both optimization methods is tension bar number 36. The maximum tensile strength values for this bar are obtained as 42.84 MPa (24.85% capacity ratio) for PSO and 33.47 MPa (19.42% capacity ratio) for FA, respectively.

To observe the effect of the notch on the optimum structure weight, stress values are multiplied by the stress concentration factor ($K = 1.5$), and optimization processes are repeated. As a result of these processes, the structure weight is obtained as 1.74 kN with a 1.15% increase for PSO and 1.73 kN with a 1.73% increase for FA (Table 2).

It can be observed that there is no meaningful gap between the calculated maximum displacement values for both un-notched and notched conditions, and these values are close to the allowable displacement limit. Therefore, displacement values are efficient in the optimal design of the structure. When the notch effect is considered, a slight reduction occurs in the stress-carrying capacities of the members, decreasing from 88.15% to 86.62% for PSO and from 86.62% to 85.17% for FA (Table 2).

The curves recorded in the iterative reduction of the 72-bar steel space truss tower to its lightest weight using PSO and FA and expressing the variation of the total weight of the structure over the number of algorithm cycles are illustrated in Fig. 9.

To corroborate the design optimization analysis results described in detail above and to distinguish this study

from similar ones, numerical simulations have been conducted on the 72-bar steel space truss tower using the SAP2000 program under the same boundary conditions and material properties. The maximum displacement values obtained as structural responses from the analyses are depicted on the deformed shape of the structure given in Fig. 10. It is evident that the results obtained for both cases where the notch effect is considered and not considered are closely aligned with the values provided in Table 2. This result underscores the suitability of PSO and FA as optimization methods for facilitating optimal design processes aimed at achieving the lightest weights of such structures.

6.3 A 52-bar steel plane truss tower

The geometric characteristics of the structure built by joining 52 steel bars categorized in 12 different ways at 20 nodal points are shown in Fig. 11. It is designed with three spans and four floors. The width of the tower is 6 m (3×2 m), and the height is 12 m (4×3 m). The system is loaded through four nodes (17, 18, 19, and 20). Forces of 100 kN in the x -direction and 200 kN in the y -direction are loaded into the system from these nodes. The profile cross-sections used in the optimum solution vary between 1 and 50 cm². A total of 491 profile cross-sections are used. The modulus of elasticity and density of the material used in the structure are 2.07×10^5 MPa and 7860 kg/m³, respectively. The limit values of tensile and compressive stresses are 180 MPa.

The 52-bar steel plane truss tower given in Fig. 11 was first researched by Wu and Chow [50]. Then, it has become one of the basic structure types on which many researchers study optimization. For example, Li and Lian [51] used the Fruit Fly Optimization Algorithm (FOA), and Li et al. [52] used the Improved Chicken Swarm

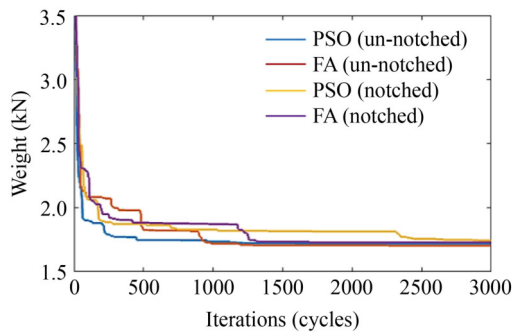


Fig. 9 The variation of the total weight of the 72-bar steel space truss tower based on the iteration count.

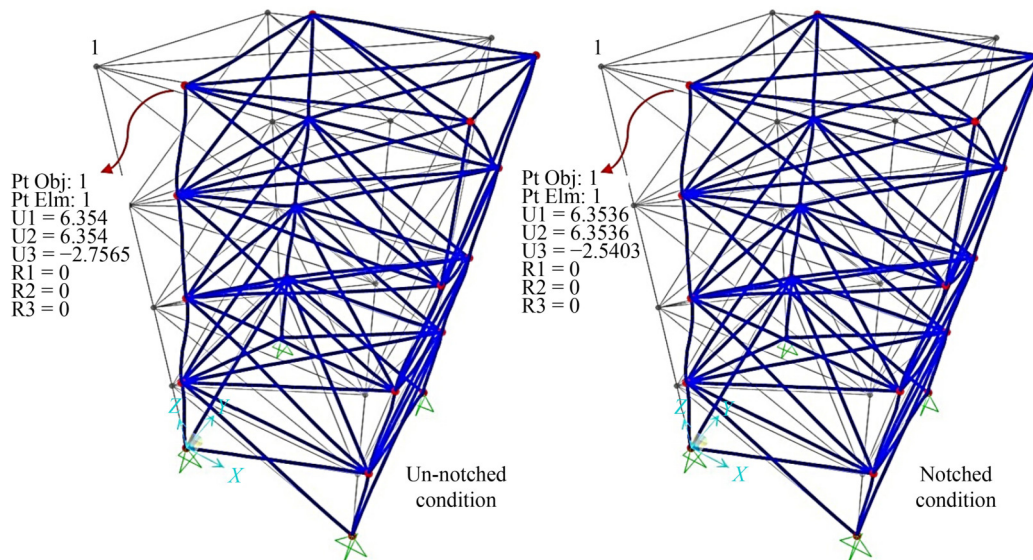


Fig. 10 Maximum displacement values obtained by numerical simulations for un-notched and notched cases.

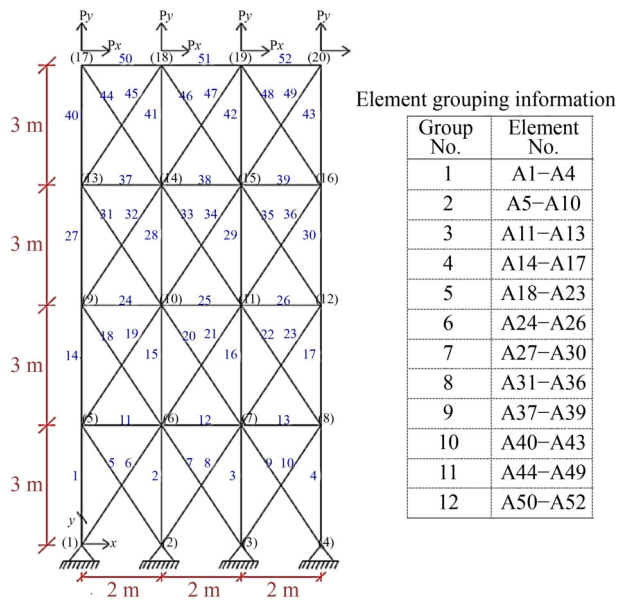


Fig. 11 Configuration of 52-bar steel plane truss tower.

Table 3 Optimization values for the 52-bar steel plane truss tower

Element group	Optimum cross-sectional areas (cm ²)					
	Li and Lian FOA [51]	Li et al. ICSOA [52]	This paper (un-notched cond.)		This paper (notched cond.)	
			PSO	FA	PSO	FA
1	46.48	46.50	42.30	43.40	43.70	41.60
2	11.41	11.60	13.40	11.40	11.70	14.80
3	4.54	3.63	7.70	3.30	11.90	7.20
4	33.33	33.03	32.60	32.90	32.10	32.40
5	9.20	9.35	10.60	9.70	11.10	9.80
6	4.90	4.94	4.00	6.60	5.10	5.40
7	22.18	22.10	22.30	22.30	35.50	35.20
8	10.28	10.05	10.80	10.20	10.00	9.50
9	4.74	3.88	4.80	6.50	5.80	7.60
10	12.54	12.80	13.10	13.30	12.70	12.20
11	11.81	11.54	11.00	10.70	10.90	11.10
12	4.90	7.92	4.40	4.40	5.30	7.10
Weight (kN)	18.64	18.59	18.80	18.32	20.07	20.03
Max. displacement (mm)			–	–	–	–
Max. stress capacity (%)			100	100	100	100
Analysis count			60000	60000	60000	60000

Optimization Algorithm (ICSOA). The results of these studies are shown in Table 3. The results obtained from un-notched and notched conditions using the methods discussed in this study (PSO and FA) are also presented in the same table. In addition to this information, the values, such as maximum displacement and maximum

stress capacity obtained with PSO and FA for the structure, are represented in the table, and the results are assessed.

When examining Table 3 for the case where the notch effect is not considered, it is observed that the structure's weight is 18.80 kN for PSO and 18.32 kN for FA. Upon comparison, it is evident that the FA yields a more optimal solution. This value is also the lightest structure weight value in the table. The results are consistent with each other and with other literature findings. This indicates that these optimization methods can provide accurate results in the optimum weight designs of such structures and can be readily preferred. Figure 12 illustrates a thorough comparison of the weight outcomes achieved through each optimization method listed in the table.

The element with the highest tensile capacity for both optimization methods is tension bar number 27. The maximum tensile strength values for this bar are obtained as 179.99 MPa (100% capacity ratio) for PSO and 179.99 MPa (100% capacity ratio) for FA, respectively. To observe the effect of the notch on the optimum structure weight, stress values are multiplied by the stress concentration factor ($K = 1.5$), and the optimization

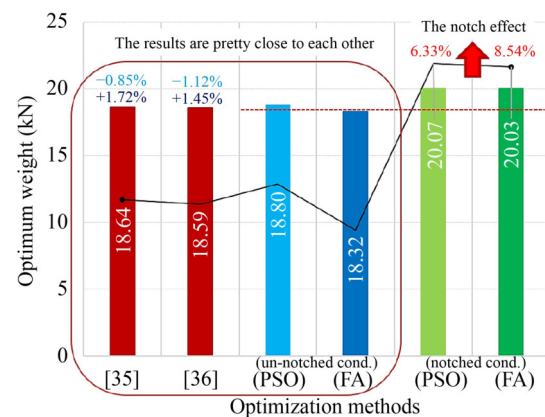


Fig. 12 Comparison of optimum weight results for the 52-bar steel plane truss tower.

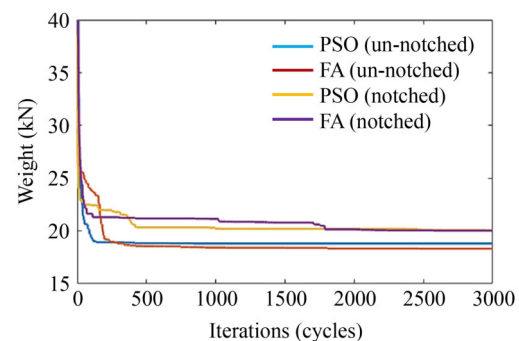


Fig. 13 The variation of the total weight of the 52-bar steel plane truss tower based on the iteration count.

processes are repeated. As a result of these processes, the structure weight is obtained as 20.07 kN with a 6.33% increase for PSO and 20.03 kN with an 8.54% increase for FA (Table 3).

The charts taken in the process of reducing the 52-bar steel plane truss tower to its lightest weight through PSO and FA and demonstrating the variation of the structure's total weight over the number of algorithm cycles are given in Fig. 13.

To contribute to design optimization analysis outcomes

discussed earlier and to distinguish this study from similar ones, numerical simulations have been conducted on the 52-bar steel plane truss tower using the SAP2000 program. The simulations are performed under identical boundary conditions and material properties. Figure 14 illustrates the joint reaction values and the structural weights calculated from their sum. It can be observed that the results obtained for both cases where the notch effect is considered and not considered are closely aligned with the values presented in Table 3. This finding underscores

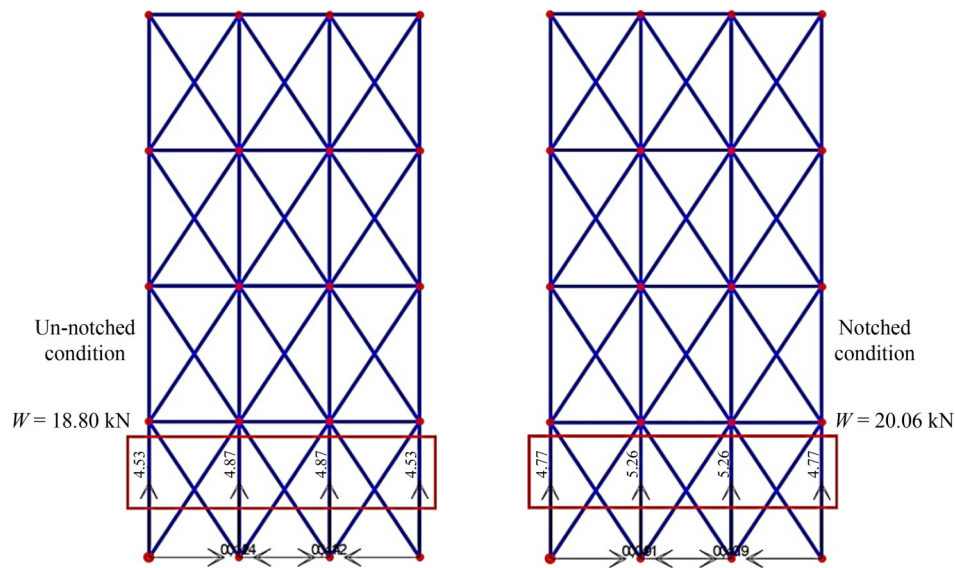


Fig. 14 Structural weight values obtained by numerical simulations for un-notched and notched cases.

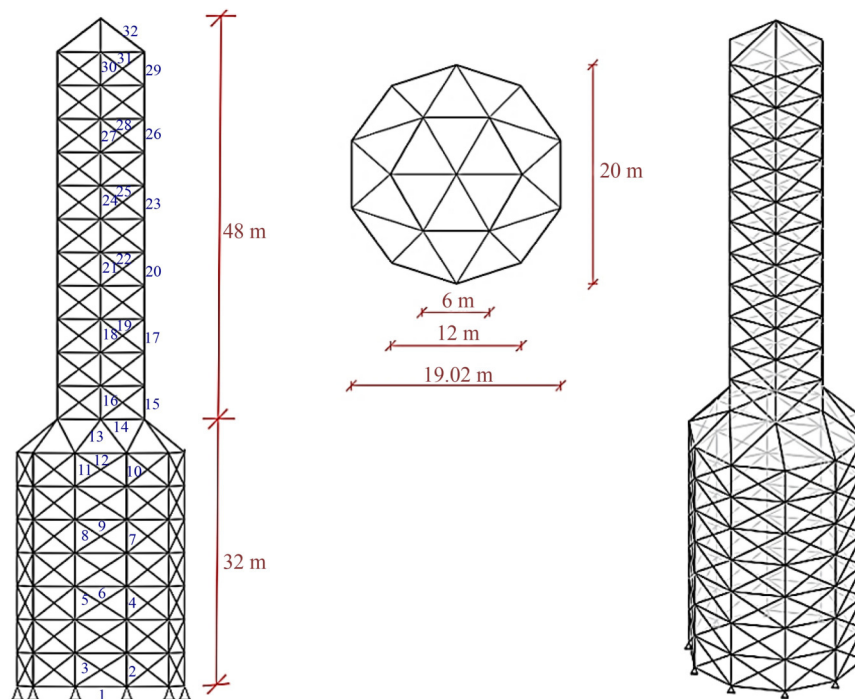


Fig. 15 The geometrical characteristics of the 582-bar steel space truss tower.

Table 4 Optimization values for the 582-bar steel space truss tower

Element group	Optimum cross-sectional areas (cm ²)								
	Hasancebi et al. [53]	Artar HSA [55]	Artar and Daloğlu JA [54]	This paper (un-notched cond.)		This paper (un-notched cond.) (virtual cross-sec.)		This paper (notched cond.) (virtual cross-sec.)	
				PSO	FA	PSO	FA	PSO	FA
1	w8×21 (39.74)	w10×12 (22.84)	w6×12 (22.9)	w6×16 (30.58)	w10×15 (28.45)	42.00	37.80	46.40	43.40
2	w12×79 (149.68)	w30×108 (204.52)	w12×152 (288.39)	w24×117 (221.94)	w33×152 (288.39)	132.00	176.80	163.20	126.00
3	w8×24 (45.68)	w8×10 (19.1)	w8×10 (19.1)	w12×26 (49.35)	w14×22 (41.87)	38.40	42.00	42.00	46.40
4	w10×60 (113.55)	w16×67 (127.1)	w12×152 (288.39)	w18×76 (143.87)	w21×93 (176.13)	126.00	130.00	126.00	126.00
5	w8×24 (45.68)	w8×15 (28.65)	w8×10 (19.1)	w8×15 (28.65)	w10×17 (32.19)	38.40	38.40	46.40	38.40
6	w8×21 (39.74)	w6×20 (37.87)	w8×10 (19.1)	w10×19 (36.26)	w10×22 (41.87)	37.80	42.00	44.40	44.40
7	w14×48 (90.97)	w16×50 (94.84)	w10×60 (113.55)	w12×45 (85.16)	w21×73 (138.71)	77.00	77.00	126.00	126.00
8	w8×24 (45.68)	w6×20 (37.87)	w8×10 (19.1)	w8×21 (39.74)	w6×12 (22.90)	37.60	49.50	44.40	37.60
9	w8×21 (39.74)	w10×15 (28.45)	w8×13 (24.77)	w6×16 (30.58)	w5×16 (30.19)	32.20	49.00	37.60	37.60
10	w10×45 (85.81)	w16×31 (58.84)	w10×39 (74.19)	w10×39 (74.19)	w21×68 (129.03)	43.20	49.00	126.00	88.80
11	w8×24 (45.68)	w5×16 (30.19)	w8×15 (28.65)	w10×12 (22.84)	w12×14 (26.84)	38.40	38.40	37.60	46.40
12	w10×68 (129.03)	w10×68 (129.03)	w16×31 (58.84)	w16×40 (76.13)	w14×43 (81.29)	210.00	114.80	77.00	126.00
13	w14×74 (140.64)	w16×67 (127.1)	w10×68 (129.03)	w10×60 (113.55)	w16×50 (94.84)	198.00	115.20	100.80	96.60
14	w14×74 (140.64)	w18×106 (200.64)	w14×48 (90.97)	w21×101 (192.26)	w14×43 (81.29)	49.50	126.00	108.00	126.00
15	w18×76 (143.87)	w16×100 (189.68)	w12×152 (288.39)	w27×217 (411.61)	w36×194 (367.74)	140.00	140.00	177.60	130.00
16	w8×31 (58.9)	w12×19 (35.94)	w8×13 (24.77)	w10×22 (41.81)	w8×24 (45.68)	81.20	49.00	61.20	66.00
17	w16×67 (127.1)	w16×89 (169.03)	w12×152 (288.39)	w24×68 (129.68)	w27×114 (216.13)	140.00	130.00	130.00	126.00
18	w8×24 (45.68)	w12×19 (35.94)	w10×12 (22.84)	w5×19 (35.74)	w12×14 (26.84)	37.80	38.40	43.40	44.40
19	w8×21 (39.74)	w12×35 (66.45)	w10×12 (22.84)	w6×20 (37.87)	w4×13 (24.71)	42.00	37.80	46.40	32.20
20	w8×40 (75.48)	w16×50 (94.84)	w12×152 (288.39)	w21×50 (94.84)	w21×83 (156.77)	126.00	126.00	126.00	126.00
21	w8×24 (45.68)	w6×15 (28.58)	w10×15 (28.45)	w6×9 (17.29)	w6×12 (22.90)	42.00	46.40	49.50	42.00
22	w8×21 (39.74)	w14×30 (57.1)	w10×15 (28.45)	w10×12 (22.84)	w5×16 (30.19)	42.00	37.80	42.00	32.20
23	w10×22 41.87	w14×30 (57.1)	w14×43 (75.48)	w18×35 (66.45)	w24×55 (104.52)	126.00	126.00	61.20	126.00
24	w8×24 (45.68)	w8×10 (19.1)	w10×15 (28.45)	w6×9 (17.29)	w10×12 (22.84)	42.00	38.40	74.20	55.00
25	w8×21 (39.74)	w18×46 (87.1)	w12×14 (26.84)	w6×12 (22.9)	w8×28 (53.23)	42.00	42.00	32.20	37.60
26	w8×21 (39.74)	w14×22 (41.87)	w12×30 (56.71)	w12×30 (56.71)	w16×36 (68.39)	126.00	46.40	61.20	126.00
27	w8×24 (45.68)	w12×26 (49.35)	w10×15 (28.45)	w6×12 (22.9)	w10×12 (22.84)	37.80	50.40	32.20	37.60
28	w8×21 (39.74)	w10×39 (74.19)	w8×10 (19.1)	w8×28 (53.23)	w10×15 (28.45)	43.40	55.80	37.60	37.60
29	w8×24 (45.68)	w10×15 (28.45)	w6×12 (22.9)	w12×19 (35.94)	w12×26 (49.35)	49.00	46.40	32.20	38.40
30	w8×21 (39.74)	w8×13 (24.77)	w12×14 (26.84)	w12×22 (41.81)	w10×12 (22.84)	43.20	49.50	43.40	46.40
31	w8×21 (39.74)	w8×31 (58.9)	w10×15 (28.45)	w18×46 (87.1)	w6×9 (17.29)	50.40	46.40	42.00	37.80
32	w8×24 (45.68)	w16×26 (49.55)	w10×15 (28.45)	w10×26 (49.1)	w8×13 (24.77)	42.00	32.20	37.60	38.40
Weight (kN)	1618.80	1579.80	1536.31	1601.30	1593.30	1676.40	1651.80	1690.80	1673.60
Max. displacement (mm)				78.34	77.05	79.60	79.99	79.97	80.00
Max. stress capacity (%)				73.30	67.61	98.41	92.79	69.69	67.07
Analysis count				20000	20000	20000	20000	20000	20000

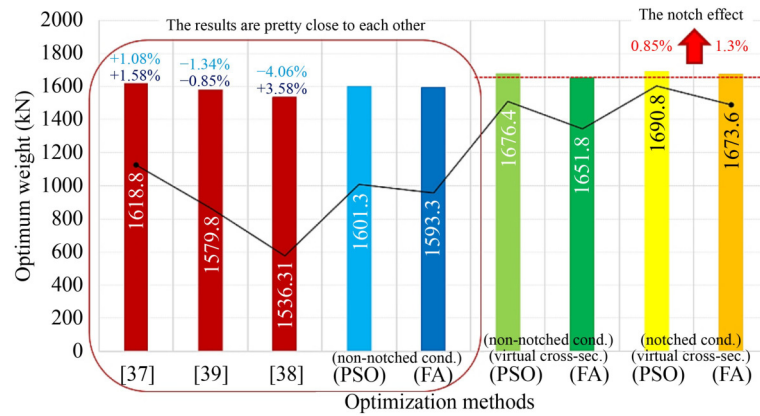


Fig. 16 Comparison of optimum weight results for the 582-bar steel space truss tower.

the efficacy of PSO and FA as optimization methods for achieving the lightest possible weights in such structural designs.

6.4 A 582-bar steel space truss tower

The tower, which has a height of 80 m, consists of 32 different groups, as given in Fig. 15. In the optimum solution of this structure, 297 W profiles from the AISC-ASD 1989 [58] are used. A single lateral load of 5 kN is applied to the system from every node in the x and y directions, and a vertical force of -30 kN is acted at every node in the z -direction. The modulus of elasticity and yield stress of the material used in the structure are 203893.6 MPa and 253.1 MPa, respectively. The maximum displacement limit value is 80 mm.

The 582-bar steel space truss tower given in Fig. 15 was first optimized by Hasancebi et al. [53]. Then, it has become one of the basic structure types on which some researchers study optimization. For example, Artar and Daloğlu [54] used the Jaya Algorithm (JA), and Artar [55] used the Harmony Search Algorithm (HSA). The results of these studies are shown in Table 4. The results obtained from un-notched and notched conditions using the methods discussed in this study (PSO and FA) are also presented in the same table. In addition to this information, the values, such as maximum displacement and maximum stress capacity obtained with PSO and FA for the structure, are shown in the table, and the results are evaluated.

Ignoring the notch effect, the data in Table 4 reveals that the structure weighs 1601.3 kN with PSO and 1593.3 kN with FA. These optimal weight outcomes are heavier than the best result obtained by Artar and Daloğlu [54] by 4.06% and 3.58%, respectively. Upon comparison, it is evident that FA yields a more optimal solution. The results agree with each other and with other results from the literature. This case shows that these optimization methods can offer exact results in optimal weight designs of such structures and can be easily

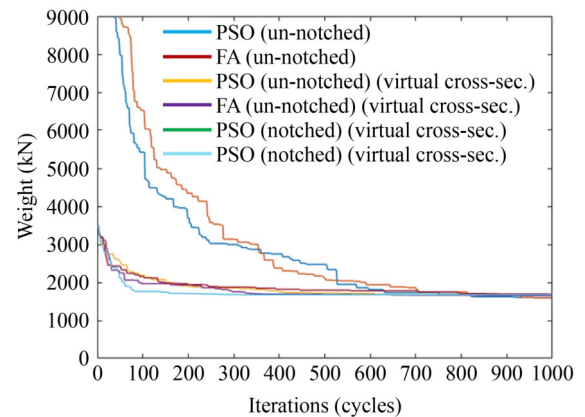


Fig. 17 The variation of the total weight of the 582-bar steel space truss tower based on the iteration count.

preferred. Figure 16 compares the weight outcomes obtained from all optimization techniques in the table.

The cross-sectional area values of the bars are needed to apply the stress concentration coefficient to the values of the tension bar elements with the maximum stress capacity. Therefore, virtual cross-sectional areas are assigned to each member. For PSO and FA, the elements with the highest tensile capacity are tension bars numbered 333 and 289, respectively. The maximum tensile strength value for bar 333 is calculated as 47.28 MPa (0.31% capacity ratio), while for bar 289, this value is obtained as 76.71 MPa (0.51% capacity ratio). To observe the effect of the notch on the optimum structure weight, stress values are multiplied by the stress concentration factor ($K = 1.5$), and optimization processes are repeated. As a result of these processes, the structure weight for PSO and FA is obtained as 1690.8 and 1673.6 kN, respectively, with an increase of 0.85% and 1.3% (Table 4).

It can be observed that the calculated maximum displacement values for both un-notched and notched conditions are quite close to each other, and these values are close to the allowable displacement threshold. For this

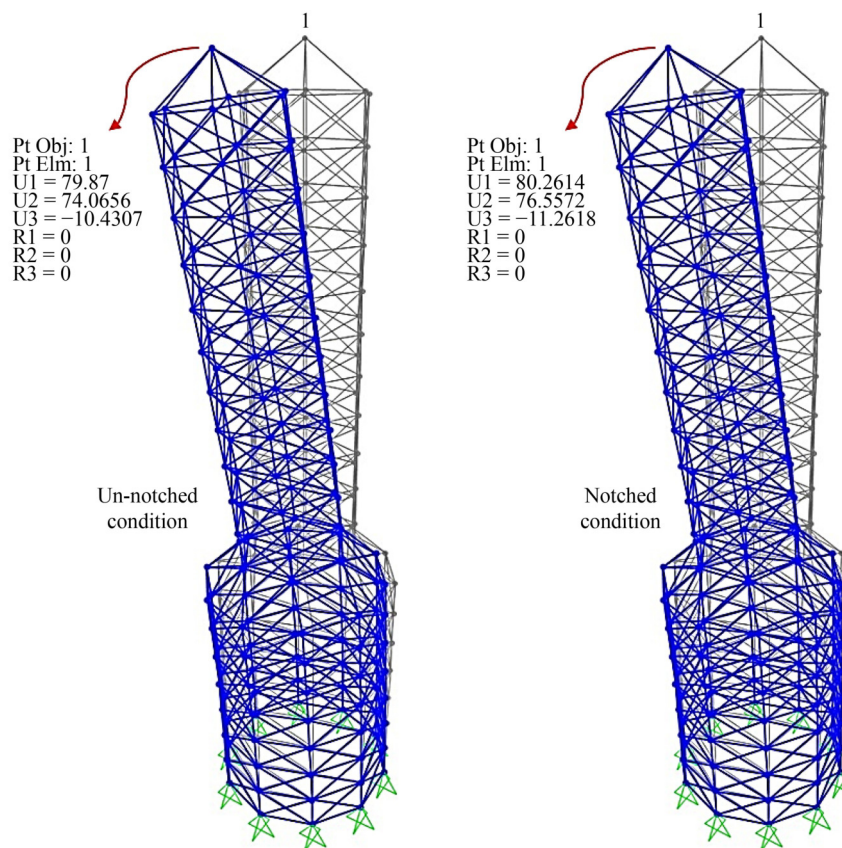


Fig. 18 Maximum displacement values obtained by numerical simulations for un-notched and notched cases.

reason, the displacement values are efficient in the optimal design of the structure. With the introduction of the notch effect, there is a slight rise in the stress-carrying capacities of the members, elevating from 79.60% to 79.97% for PSO and from 79.99% to 80.00% for FA, as indicated in Table 4.

The graphs recorded in the iterative weight reduction process of the 582-bar steel space truss tower using PSO and FA and depicting the variations in the total weight of the structure by the number of algorithm cycles are illustrated in Fig. 17.

To improve the design optimization analysis results described in detail above and to introduce a distinction to study compared to similar ones, the 582-bar steel space truss tower has been subjected to numerical simulations using the SAP2000 program under the same boundary conditions and material properties. The maximum displacement values obtained as structural responses from the analyses are presented over the deformed shape of the structure given in Fig. 18. It can be observed that the results obtained for both cases where the notch effect is considered and not considered are almost the same as the values given in Table 4. This high similarity demonstrates that PSO and FA are suitable optimization methods for conducting optimal design processes to achieve the lightest weights for such structures.

7 Conclusions

This study determines the optimal weights of tower-type steel truss systems, taking into account the notch effect and the resulting stress concentration. Consequently, significant conclusions have been drawn concerning the impact of discontinuities arising in the cross-sections of steel elements due to various factors on the structure's overall weight.

1) In the scenario where the notch effect is not considered, it can be seen that the analysis results obtained for all structures are quite similar to ones of previous studies conducted on the same structures. This finding indicates that both methods used in this study can provide good results in the optimal weight design of such systems.

2) Incorporating the notch effect into the calculations reveals a slight increment in the weights of the structures. Due to the stress concentration around the notch in the cross-section, an excessive increase in the tensile stress value occurs. In this case, the bearing capacity of the profile may be insufficient. Hence, a top cross-section is chosen from the available options and assigned to the corresponding element. If it proves inadequate, another upper cross-section is sought again. This iterative selection process persists until the most appropriate cross-section is identified. The structure's weight rises at that

rate as the number of transitions between cross-sections increases to locate the most appropriate cross-section. The notch effect mainly increases the structure's weight because the initially selected cross-sections are insufficient, and it is necessary to switch to larger cross-sections. In this case, larger profiles must be used in the design. This results in an elevation of the overall optimal weight of the structure.

3) The optimal weight values for the 25-bar steel space truss tower in the notched condition are respectively 1.8% higher for PSO (2.22–2.18) and 1.8% higher for FA (2.21–2.17) compared to the values obtained in the un-notched scenario. PSO and FA show similar increases of 1.15% (1.74–1.72) and 1.70% (1.73–1.70) for the 72-bar steel space truss tower, respectively. The increase in the 52-bar plane truss system is slightly higher than in the first two examples. These percentages are 6.33% (20.07–18.80) for PSO and 8.54% (20.03–18.32) for FA, respectively. It can be said that the lowest increase values are for the 582-bar steel space truss tower, which is the latest example. Compared to the un-notched condition, the optimum structure weight under the influence of notch increased by 0.85% (1690.8–1601.3) and 1.3% (1673.6–1651.8) for PSO and FA, respectively.

4) When comparing the two optimization methods, it is seen that FA gives lighter results for all examples for both un-notched and notched cases. Therefore, the FA option may be a better alternative when choosing between these two techniques for the optimal weight design of such systems. However, FA might require more fine-tuning of parameters to achieve optimal performance in different scenarios than PSO. Also, performance comparisons between PSO and FA can vary based on the problem being solved, parameter settings, and the nature of the optimization landscape. Each algorithm might perform better in different scenarios. Experimentation and empirical testing on specific problem domains are typically necessary to determine which algorithm performs better for a particular application.

One of the most crucial issues that steel structures may encounter throughout their service life is the potential section losses that may occur in the elements for various reasons. Even the formation of notches in only one element creates a significant rise in the weights of all the structures considered in this study. Therefore, it is possible that the occurrence of this effect in many more elements could result in a significant rise in weight. For this reason, it would be beneficial to consider such a pessimistic scenario in the first place while designing the optimum weight of such structures. Otherwise, an unsafe design can be created while trying to reduce the weight, in other words, the cost. This can lead to irreversible disasters. Weight optimization studies considering this adverse scenario are very limited in the literature. To eliminate this lack, in this study, the optimum weight

designs of different steel structures are made by considering the notch effect. Analyzing such structures, which are vulnerable to environmental effects under various external impacts such as corrosion and temperature, as well as the notch effect discussed in this study, and designing them with optimal weight will also significantly contribute to the engineering field and the literature.

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Competing interests The authors declare that they have no competing interests.

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