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Design Optimization of Truss Structures by Crystal Structure Algorithm

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ABSTRACT: Optimization is an act of decision-making to reach a point in which the overall behavior of the considered system is acceptable by the field's experts. In recent decades, construction companies have been willing to provide housing services with lower construction costs that people of different kinds can afford. Although academics have introduced form-dominant methods, using artificial intelligence (AI) in structural design has been one of the most critical challenges in recent years. In the current study, the applicability of the Crystal Structure Algorithm (CryStAl) as one of the recently developed metaheuristic algorithms is investigated in the optimum design of truss structures, in which the basic concepts of crystals, including the lattice and basis, are in perspective. For numerical purposes, the 10-bar, 72-bar, and 200-bar truss structures are considered as design examples. Furthermore, for constraint-handling purposes, a simple penalty approach is implemented in CryStAl. A complete statistical analysis is conducted through multiple optimization runs for comparative purposes; at the same time, other metaheuristic approaches have been derived from the literature. Based on the results of the CryStAl and other methods in dealing with truss optimization problems, the utilized method can provide better and more competitive results in most cases.

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1- Introduction

Optimizing a system means minimizing or maximizing a function, a performance measure of the considered system. In the past, designers needed to build many knowledge-based models to reach a model with better characteristics. At the same time, these procedures can be done faster and more precisely by utilizing intelligent methods such as optimization algorithms. Over the past few decades, the development of these algorithms has made it possible for designers to perform designs more quickly through numerical simulation. However, these methods also involve a process of trial and error in the mathematical definition of the system problems and tuning internal parameters of the algorithms, so in many cases, these algorithms do not lead to an optimal solution, and the precise determination of these aspects alongside the delicate selection of the utilized algorithms are of great importance. Metaheuristic algorithms are some searching algorithms in which upper-level methodologies are utilized to reduce the complexity of the considered systems and the algorithms. Fire Hawk Optimizer [1], Genetic Algorithm (GA) [2], Grey Wolf Optimizer (GWO) [3], Material Generation Algorithm (MGA) [4], Chaos Game Optimization (CGO) [5, 6], Particle Swarm Optimizer (PSO) [7], Ant Colony Optimization (ACO) [8], Atomic Orbital Search (AOS) [9], and Crystal Structure Algorithm (CSA) [10] are some of the recently developed metaheuristic algorithms.

Reducing the overall weight of the structures is one of the most critical factors considered in construction projects. Regarding population growth and the economic requirements of society, optimizing structures and reducing their weight has been of great importance in recent decades. Structural optimization should be conducted to achieve the best design, which meets the weight, cost, and other criteria selected for the structure in a loading condition, including strength, stiffness, stability, functionality, and even aesthetics. This issue has attracted the attention of many construction companies globally, and artificial intelligence experts have proposed many metaheuristic algorithms for structural optimization purposes. Sonmez [11] utilized an artificial bee colony algorithm to optimize truss structures. Jalili and Hosseinzadeh [12] proposed a hybrid algorithm for optimum truss structures by combining the migration strategy and the differential evolution algorithm. Kaveh and Zakian [13] investigated the optimal design of truss structures by developing an improved version of the grey wolf optimizer. Gebrail Bekdas, Sinan Melih Nigdeli, and Yang [14] utilized a flower pollination algorithm for the size optimization of truss structures. Javidi, Salajegheh, and Salajegheh [15] discussed the optimum design of structures utilizing the enhanced version of the crow search algorithm. Degertekin, Lamberti, and Ugur [16] investigated the truss structure's topology, layout, and size optimization with the

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Jaya algorithm. Dizangian [17] proposed a new methodology, border-search and jump reduction, for the optimum design of spatial truss structures. Le, Bui, Ngo, Nguyen, and Nguyen-Xuan [18] investigated the optimization of truss structures by proposing a new hybrid algorithm combining the firefly algorithm and the electromagnetism-like mechanism. El Bouzouiki, Sedaghati, and Stiharu [19] discussed truss structures' size and topology optimization by proposing a non-uniform cellular automata framework.

The main contribution and reason for developing and proposing a novel metaheuristic algorithm are to evaluate its performance in dealing with different optimization problems. For this purpose, the experts in the field of optimization should solve different problems with the standard algorithms at the first stage to provide a stable base for future attempts in which the improved version of the algorithms can be proposed and tested in dealing with the same problems. In this research work, the applicability of the Crystal Structure Algorithm (CryStAl) is investigated in the optimum design of truss structures. CryStAl is one of the recently developed metaheuristic algorithms by Talatahari, Azizi, Tolouei, Talatahari, and Sareh [10]; the basic concepts of crystals, including the lattice and basis, are utilized as inspirational concepts for developing a searching algorithm. For numerical purposes, the 10-bar, 72-bar, and 200-bar truss structures are considered as design examples. For constraint-handling purposes, a simple penalty approach is implemented in CryStAl. A complete statistical analysis is conducted through multiple optimization runs for comparative purposes, while other metaheuristic approaches have been derived from the literature. Based on the results of the CryStAl and other methods in dealing with truss optimization problems, the utilized method can provide better and more competitive results in most cases.

2- Crystal Structure Algorithm

The regular and unlimited repetition makes a crystal of building blocks of atoms or molecules in space. This building unit has one atom in very simple crystals, and in complex crystals, it consists of several atoms or molecules. The word "crystal" comes from the ancient Greek word "*krustallos*," which means "rock crystal" and "ice," and the scientific study of crystals is called crystallography. Examples of everyday materials encountered as crystals are salt (sodium chloride or halite crystals), sugar (sucrose), and snowflakes. Many gemstones are crystals, including quartz and diamonds. Since a crystal is a network of material expanded in three dimensions with frequent units, it has a recognizable structure. Large crystals display tight areas (faces) and well-defined angles. Crystals with flat faces are called divine crystals, while those without are called rock crystals. A schematic presentation of different types of crystals is provided in Fig. 1.

The crystals' fundamental and most critical component is the "lattice." This aspect refers to the periodic array of points in space. The "basis" as another component is for potion determination of the atoms inside the crystals. These two aspects are combined to generally present the configuration of crystals (Fig. 1-b).

To mathematically represent the configuration of the crystals in the space, an infinite lattice shape is presumed by utilization of a vector for precise determination of the lattice points as follows (Fig. 1-c):

$$r = \sum n_i a_i , \tag{1}$$

where a_i denotes the shortest vector along with the principal crystallographic directions; n_i represents an integer number, and i determines the total number of crystal corners.

The mentioned aspects of the crystals are utilized as the inspirational concept of the Crystal Structure Algorithm (CryStAl) as a recently developed metaheuristic algorithm. In the first step, the initialization process is conducted as follows in which each of the solution candidates is determined to be a crystal in the space:

$$Cr = \begin{bmatrix} Cr_1 \\ Cr_2 \\ \vdots \\ Cr_i \\ \vdots \\ Cr_n \end{bmatrix} = \begin{bmatrix} x_1^1 & x_1^2 & \dots & x_1^j & \dots & x_1^d \\ x_2^1 & x_2^2 & \dots & x_2^j & \dots & x_2^d \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_i^1 & x_i^2 & \dots & x_i^j & \dots & x_i^d \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_n^1 & x_n^2 & \dots & x_n^j & \dots & x_n^d \end{bmatrix}, \quad \begin{cases} i = 1,2,\dots,n \\ j = 1,2,\dots,d \end{cases} \tag{2}$$

$$x_i^j(0) = x_{i,\min}^j + \xi (x_{i,\max}^j - x_{i,\min}^j), \quad \begin{cases} i = 1,2,\dots,n \\ j = 1,2,\dots,d \end{cases} \tag{3}$$

where d is the optimization problem's dimension; n represents the initial number of candidates; $x_i^j(0)$ is the initial values of the decision variables, and $x_{i,\max}^j$ are the lower and upper bounds of the variables in the search space, and ξ determines a randomly generated number in the range of [0,1].

The position updating process for the crystals (candidates) in the search space is conducted in the main loop of the CryStAl, in which the basic and advanced aspects of the crystallography are utilized for this purpose. The paramount crystals are determined as the corner pints in the crystal (Cr_b), selected randomly, while the crystal with the best configuration is also defined accordingly. The mean of the main crystals, which have been determined randomly, is also calculated F_c. For position updating, the common varieties of the cubic crystal system (Fig. 1-d) are utilized as an inspirational concept in which the following equations are being used:

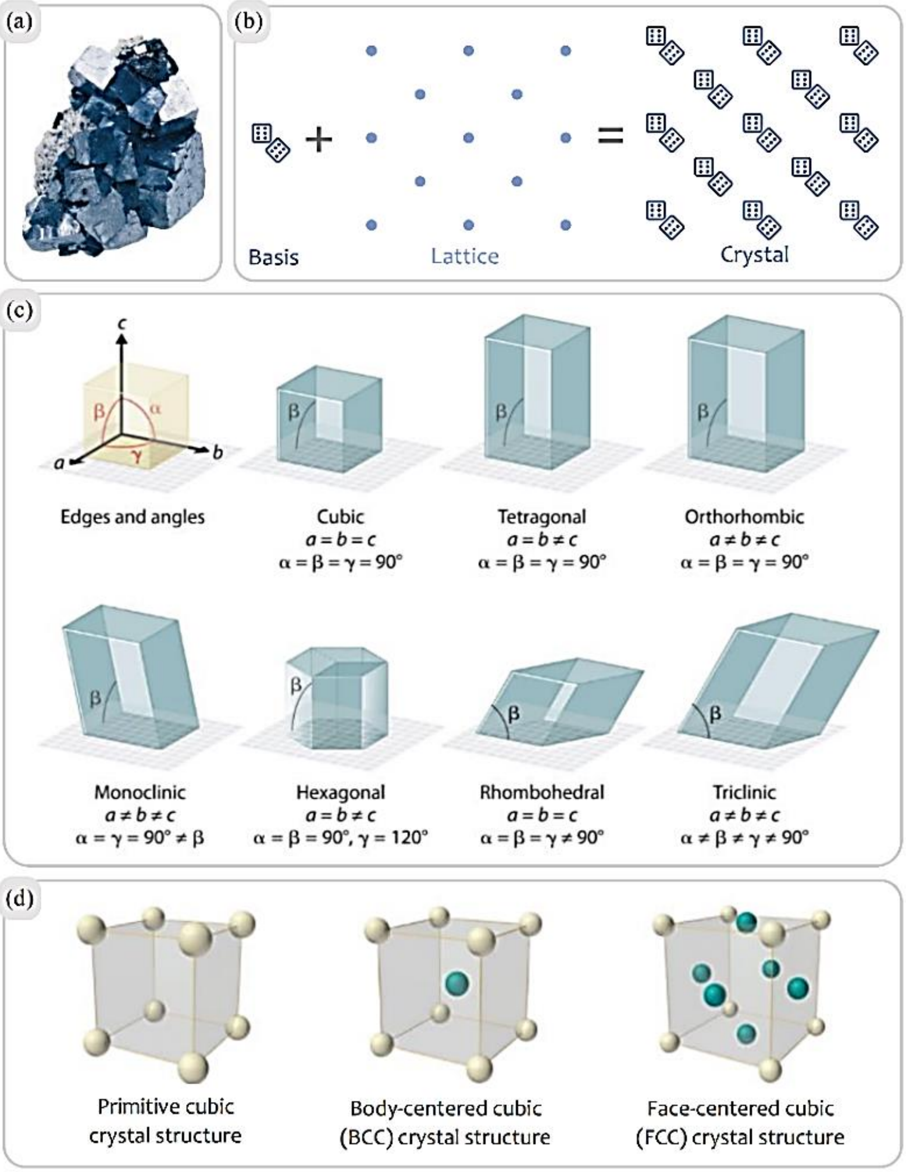

Fig. 1. (a) Schematic presentation of Galena as a natural crystal, (b) Crystal configuration by adding lattice to a basis, (c) Different configurations of a lattice, and (d) Three common varieties of the cubic crystal system.

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procedure Crystal Structure Algorithm (CryStAl)
        Create random values for initial positions (x_i^j) of initial
crystals (Cr_i)
        Evaluate fitness values for each crystal
        while (t < maximum number of iterations)
            for i=1: number of initial crystals
                Create Cr_main
                Create new crystals by Eq. 4
                Create Cr_b
                Create new crystals by Eq. 5
                Create F_c
                Create new crystals by Eq. 6
                Create new crystals by Eq. 7
                    if new crystals violate boundary conditions
                        Control the position constraints for new crystals and
amend them
                    end if
                Evaluate the fitness values for new crystals
                Update Global Best (GB) if a better solution is found
            end for
            t = t+1
        end while
        Return GB
end procedure
```

Fig. 2. Pseudo-code of the CryStAl.

Simple cubicle:

$$Cr_{new} = Cr_{old} + rCr_{main}, \tag{4}$$

Cubicle with the best crystals:

$$Cr_{new} = Cr_{old} + r_1 Cr_{main} + r_2 Cr_b, \tag{5}$$

Cubicle with the mean crystals:

$$Cr_{new} = Cr_{old} + r_1 Cr_{main} + r_2 F_c, \tag{6}$$

Cubicle with the best and mean crystals:

$$Cr_{new} = Cr_{old} + r_1 Cr_{main} + r_2 Cr_b + r_3 F_c, \tag{7}$$

where Cr_{new} represents the new position vector for the crystals, Cr_{old} is the previous position vector of the crystals r_1, r_2 and r_3 are three randomly created numbers in the range of [0, 1].

For termination purposes, a predefined maximum number of iterations or the maximum number of function evaluations are utilized, while a boundary control flag is also determined for the variables outside the predefined bounds. The pseudo-code of the algorithm is presented in Fig. 2.

The utilized Crystal Structure Algorithm (CryStAl) is a parameter-free algorithm in which there are not any internal parameters to be tuned.

3- Problem Statement

In this section, a structural design optimization problem is formulated in which a weight minimization procedure is conducted by considering the required design constraints of the related codes and standards. The objective function is regarded as the structure's overall weight, while discrete design variables are considered for assigning predefined design sections to the structural elements during the optimization process. The mathematical presentation of these aspects is as follows:

$$Weight\ (A) = \sum_{i=1}^{e} \rho_i I_i A_i, \quad i = 1, 2, ..., e. \tag{8}$$

$$\delta_{\min} \le \delta_i \le \delta_{\max}, \qquad i = 1, 2, ..., n \tag{9}$$

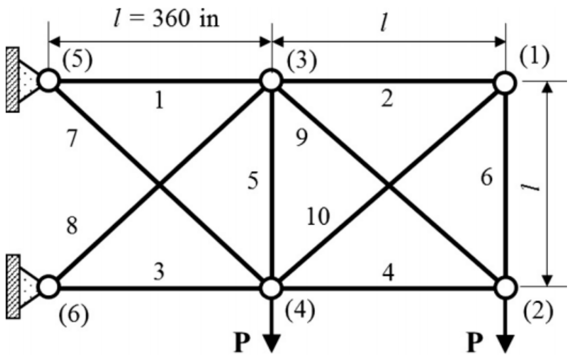


Fig. 3. 10-bar truss structure.

$$\sigma_{\min} \le \sigma_i \le \sigma_{\max}, \qquad i = 1, 2, ..., e. \tag{10}$$

$$\sigma_i^b \le \sigma_i \le 0, \qquad i = 1, 2, ..., nc \tag{11}$$

$$A \in S = \{A_1, A_2, ..., A_i\} \tag{12}$$

where A represents a vector including the cross-sectional area of the design sections (A_i); ρ_i is the density of the utilized material; l_i is the length of the structural elements; n and e are the total numbers of nodes and elements in the structure; nc represents the total number of structural elements subjected to compressive loading; σ_i and δ_i are the nodal stress and displacement in the structure; σ_i^b is the allowable buckling stress, and S is the predefined set of discrete cross-sectional areas.

Since structural design optimization is a constraint optimization problem, a constraint handling approach should be utilized for conducting the optimization procedure. For this purpose, a penalty function is determined as follows, which is part of the penalty constraints handling method used in this paper:

$$f_{penalty}(A) = (1 + \varepsilon_1 . \upsilon)^{\varepsilon_2} \times Weight(A) \tag{13}$$

$$\upsilon = \sum_{i=1}^{q} \max\{0, g_i(A)\} \tag{14}$$

where q represents the total number of design constraints; v is the summation of the violated design constraints; $g_i(A)$ represents the *ith* design constraints; ε_1 and ε_2 denotes the control values for determining the penalty during the optimization process.

4- Numerical Investigations

In this section, the structural details of the truss structures are presented, and the results of the optimization procedures are reported in detail. A total of 30 independent optimization runs are conducted in each case for statistical purposes, while the results of the CryStAl are compared to the result of other metaheuristic approaches in the literature.

4- 1- 10-bar truss structure

This truss structure has 10 members and 6 nodes with stress and displacement limitations of ±25 ksi and ±2 in., respectively. The modulus of elasticity is 104 ksi, and the density of the utilized steel material is 0.1 lb/in3. The discrete design variables for this problem are as S = {1.62,1.80,1.99 ,2.13,2.38,2.62,2.63,2.88,2.93,3.09,3.13,3.38,3.47,3.55,3.63 ,3.84,3.87,3.88,4.18,4.22,4.49,4.59,4.80,4.97,5.12,5.74,7.22 ,7.97,11.50,13.50,13.90,14.20,15.50,16.00,16.90,18.80,19.9 0,22.00,22.90,26.50,30.00,33.50} (in.2) while the complete description of loading scenario and other characteristics of this problem is provided by Ho-Huu, Nguyen-Thoi, Vo-Duy, and Nguyen-Trang [20]. The schematic presentation of this structure is illustrated in Fig. 3.

For the CryStAl as the utilized optimization algorithm, the convergence history for the best and all of the 30 independent runs are presented in Fig. 4, considering the 10-bar truss design example.

Table 1 presents the best result of the multiple optimization runs by the CryStAl in dealing with the 10-bar truss problem. The discrete design variables are also provided for comparative purposes. The lowest possible weight for the structure is calculated for the CryStAl. The results of other alternative metaheuristics are also derived from the literature to have a better perspective on the capability of the CryStAl. Based on the results, the CryStAl can reach 5490.7379 lb, which is way better than the previously reported results in the literature, so the CryStAl has outranked these alternative approaches; the utilized algorithm in this paper has better performance in

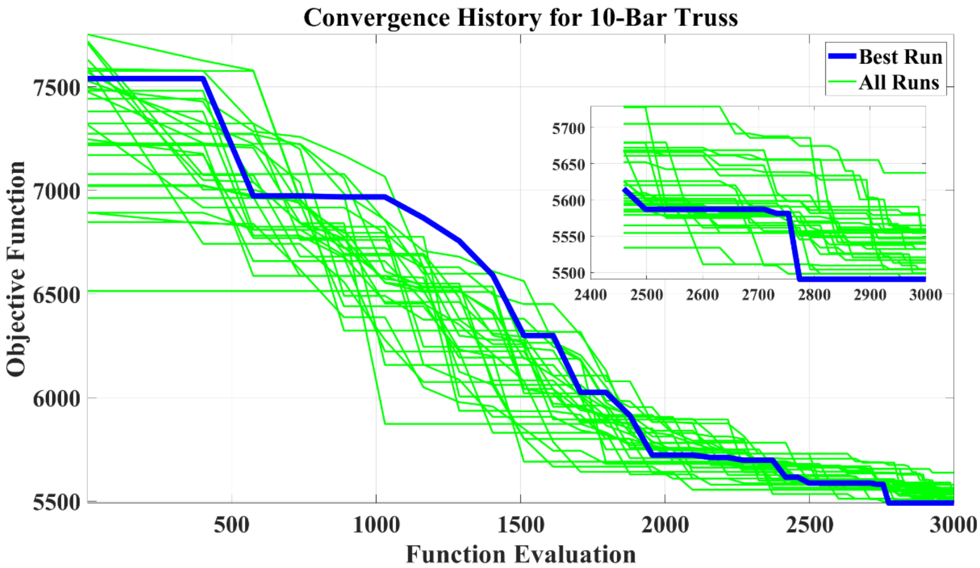


Fig. 4. Convergence history of CryStAl for 10-bar truss structure.

Table 1. Comparative results of CryStAl and other approaches in dealing with the 10-bar truss problem.

Design Variables (in.^{2})	GA [21]	HPSO [22]	MBA [23]	CryStAl
A_1	33.5	30	30	33.5
A_2	1.62	1.62	1.62	1.62
A_3	22	22.9	22.9	22.9
A_4	15.5	13.5	16.9	14.2
A_5	1.62	1.62	1.62	1.62
A_6	1.62	1.62	1.62	1.62
A_7	14.2	7.97	7.97	7.97
A_8	19.9	26.5	22.9	22.9
A_9	19.9	22	22.9	22
A_{10}	2.62	1.8	1.62	1.62
Weight (lb)	**5613.84**	**5531.98**	**5507.75**	**5490.7379**
Worst weight (lb)	–	–	**5536.965**	**5637.5228**
Mean weight (lb)	–	–	**5527.296**	**5536.2248**
Standard deviation (lb)	–	**3.8402**	**11.38**	**31.8862**

HPSO: Heuristic Particle Swarm Optimization
MBA: Mine Blast Algorithm
DE: Differential Evolution

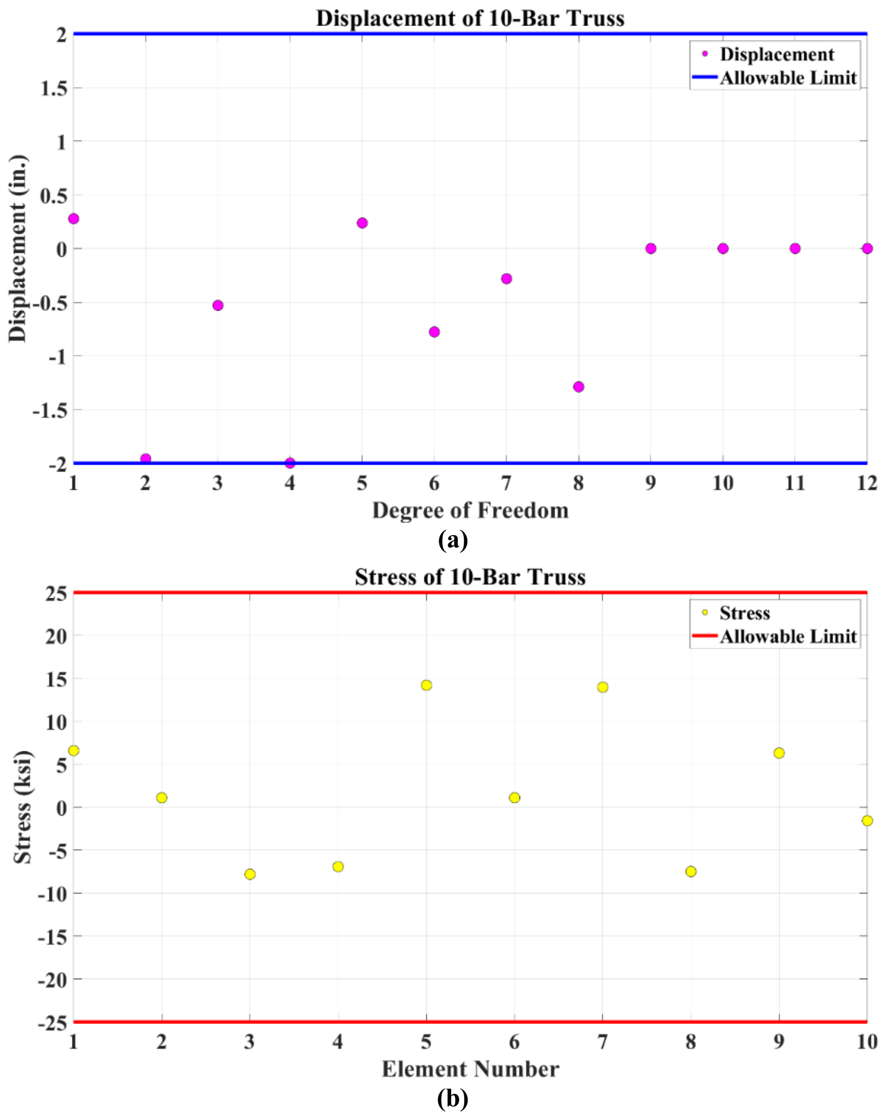


Fig. 5. (a) Displacement and (b) stress design constraints for 10-bar truss problem.

dealing with this problem. Regarding the statistical analysis, the results of the CryStAl are competitive by considering the means of worst results of multiple optimization nuns.

The design constraints, including the displacement and stress limitations for the best optimization run by CryStAl, are presented in Fig. 5, in which the capability of the constraint handling approach is in perspective.

4- 2- 72-bar truss structure

This truss structure has 72 members and 20 nodes with stress limitations of ±25 ksi. The modulus of elasticity is 10^4 ksi, and the density of the utilized steel material is 0.1 lb/in^3. The discrete design variables for this problem are as $\boldsymbol{S}$ = {0.111, 0.141, 0.196, 0.25, 0.307, 0.391,0.442, 0.563, 0.602, 0.766, 0.785, 0.994, 1, 1.228, 1.266, 1.457, 1.563 1.62, 1.8 1.99, 2.13, 2.38, 2.62, 2.63, 2.88, 2.93 3.09, 1.13 3.38, 3.47, 3.55 3.63, 3.84, 3.87, 3.88, 4.1 4.22 4.49, 4.59, 4.8, 4.97 5.12, 5.74, 7.22, 7.97 8.53 9.3 10.85, 11.5, 13.5, 13.9, 14.2, 15.5, 16 16.9 18.8 19.9 22, 22.9, 24.5, 26.5, 28,30, 33.5} (in.2) while the complete description of loading scenario and other characteristics of this problem is provided by Ho-Huu, Nguyen-Thoi, Vo-Duy, and Nguyen-Trang [20]. The schematic presentation of this structure is illustrated in Fig. 6.

The convergence history of the CryStAl in dealing with the 72-bar truss design example is illustrated in Fig. 7, in which the convergence curves for best, worst, and mean of

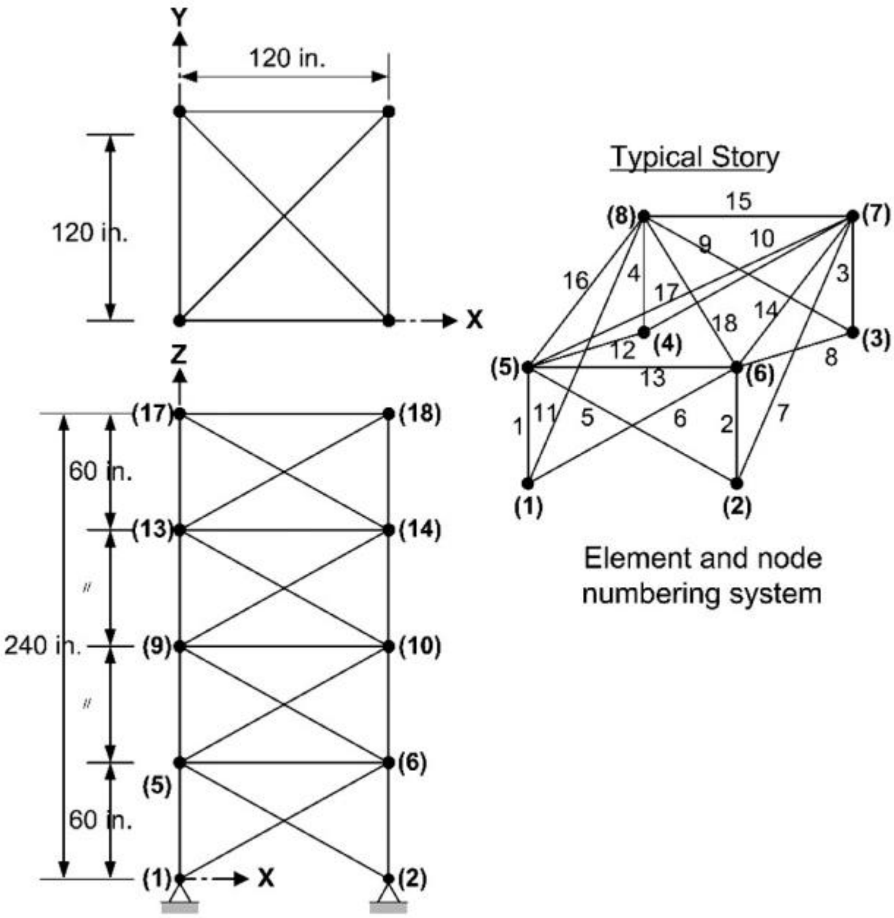


Fig. 6. 72-bar truss structure.

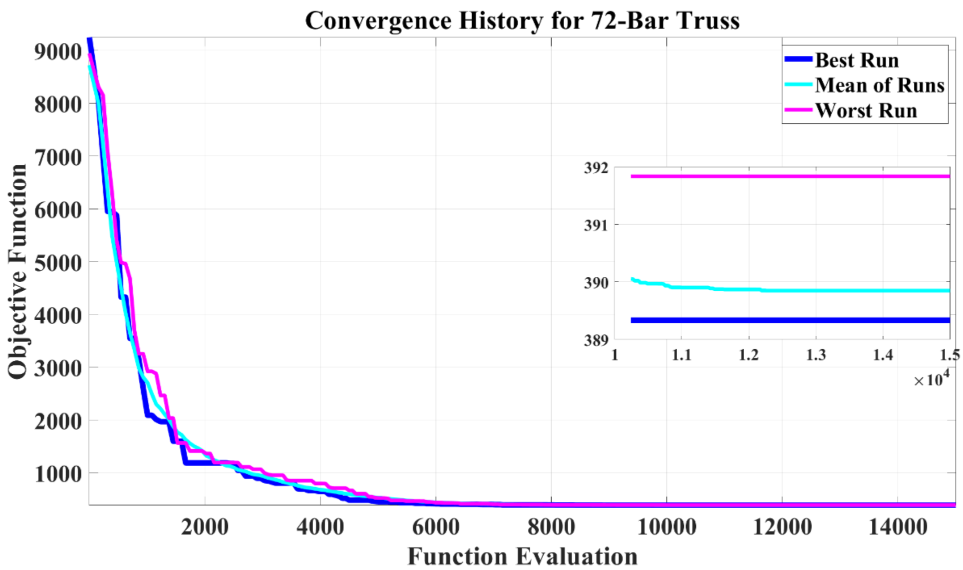


Fig. 7. Convergence history of CryStAl for 72-bar truss structure.

Table 2. Comparative results of CryStAl and other approaches in dealing with the 72-bar truss problem.

Design Variables (in.^{2})	SGA [24]	DHPSACO [25]	HPSO [22]	MBA [23]	CBO [26]	ECBO [27]	WCA [28]	IMBA [28]	DE [20]	AEDE [20]	CryStAl
A1	0.196	1.800	4.970	0.196	1.620	1.990	1.990	1.990	1.990	1.990	1.99
A2	0.602	0.442	1.228	0.563	0.563	0.563	0.442	0.442	0.563	0.563	0.563
A3	0.307	0.141	0.111	0.442	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A4	0.766	0.111	0.111	0.602	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A5	0.391	1.228	2.880	0.442	1.457	1.228	1.228	1.228	1.228	1.228	1.228
A6	0.391	0.563	1.457	0.442	0.442	0.442	0.563	0.563	0.442	0.442	0.442
A7	0.141	0.111	0.141	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A8	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A9	1.800	0.563	1.563	1.266	0.602	0.563	0.563	0.563	0.563	0.563	0.563
A10	0.602	0.563	1.228	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563
A11	0.141	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A12	0.307	0.250	0.196	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A13	1.563	0.196	0.391	1.800	0.196	0.196	0.196	0.196	0.196	0.196	0.196
A14	0.766	0.563	1.457	0.602	0.602	0.563	0.563	0.563	0.563	0.563	0.563
A15	0.141	0.442	0.766	0.111	0.391	0.391	0.391	0.391	0.391	0.391	0.391
A16	0.111	0.563	1.563	0.111	0.563	0.563	0.563	0.563	0.563	0.563	0.563
Weight (lb)	427.203	393.380	933.09	390.73	391.07	389.33	389.334	389.334	389.334	389.334	389.3341
Worst weight (lb)	–	–	–	399.49	495.97	–	393.778	389.457	394.170	393.325	391.8370
Mean weight (lb)	–	–	–	395.432	403.71	391.59	389.941	389.823	390.531	390.913	389.8477
Standard deviation (lb)	–	–	–	3.04	24.8	–	1.43	0.84	1.400	1.161	0.6157

DHPSAC: Harmony Search Algorithm
CBO: Colliding bodies optimization
WCA: Water cycle algorithm
IMBA: Improved Mine Blast Algorithm

the 30 independent optimization runs are presented.

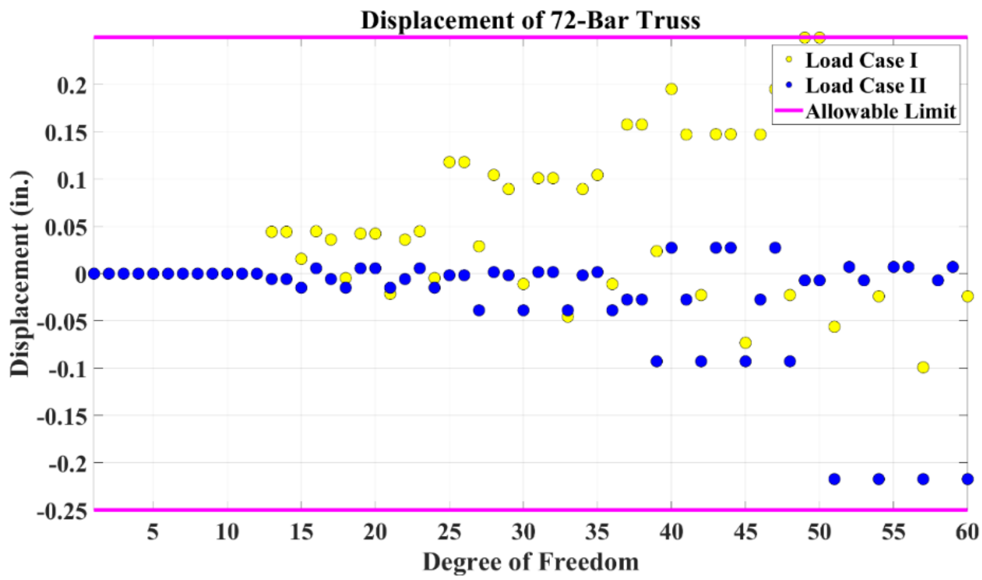
For a better perspective on the overall performance of the CryStAl optimization algorithm, the discrete design variables for the best results of the optimization procedures are presented in Table 2 for comparative purposes. Based on the results, CryStAl can provide 389.3341 lb, which is the lowest possible weight for this structure based on the reported results in the literature. Furthermore, the statistical results indicate that the utilized algorithm can calculate 389.8477 lb as the mean of multiple optimization runs, which is the best among other approaches.

The design constraints, including the displacement and stress limitations for the best optimization run by CryStAl regarding the two main load cases of the 72-bar truss problem, are presented in Fig. 8, in which the capability of the constraint handling approach is in perspective.

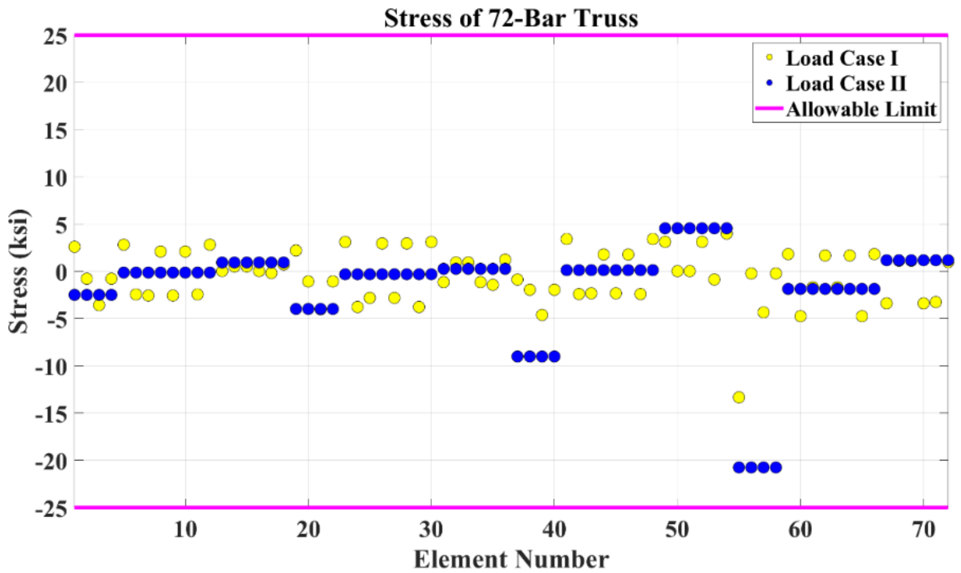
4- 3- 200-bar truss structure

This truss structure has 200 members and 6 nodes with stress limitations of ±10 ksi, 30000 ksi as modulus of elasticity, and 0.283 lb/in3 as the density of the utilized steel material. The discrete design variables for this problem are as $\boldsymbol{S}$ = {0.100, 0.347, 0.440, 0.539, 0.954, 1.081, 1.174, 1.333, 1.488, 1.764, 2.142, 2.697, 2.800, 3.131, 3.565, 3.813, 4.805, 5.952, 6.572, 7.192, 8.525, 9.300, 10.850, 13.330, 14.290, 17.170, 19.180, 23.680, 28.080, 33.700} (in.2) while the complete description of loading scenario and other characteristics of this problem is provided by Ho-Huu, Nguyen-Thoi, Vo-Duy, and Nguyen-Trang [20]. The schematic presentation of this structure is illustrated in Fig. 9.

The results of the CryStAl in dealing with the 200-bar truss problem are presented in Table 3. Besides, the results of other alternative approaches are also provided for



(a)



(b)

Fig. 8. (a) Displacement and (b) stress design constraints for 72-bar truss problem.

comparative purposes. Based on the provided results, the CryStAl can calculate 28006.2276 lb, which is a competitive result, while the results of other approaches are better than this value. Based on the fact that the different approaches have not reported statistical results, the provided results of the CryStAl can be utilized in the comparative investigations of future research works.

The design constraints, including the stress limitations for the best optimization run by CryStAl, are presented in Fig. 10 for three different load cases, in which the capability of the constraint handling approach is in perspective.

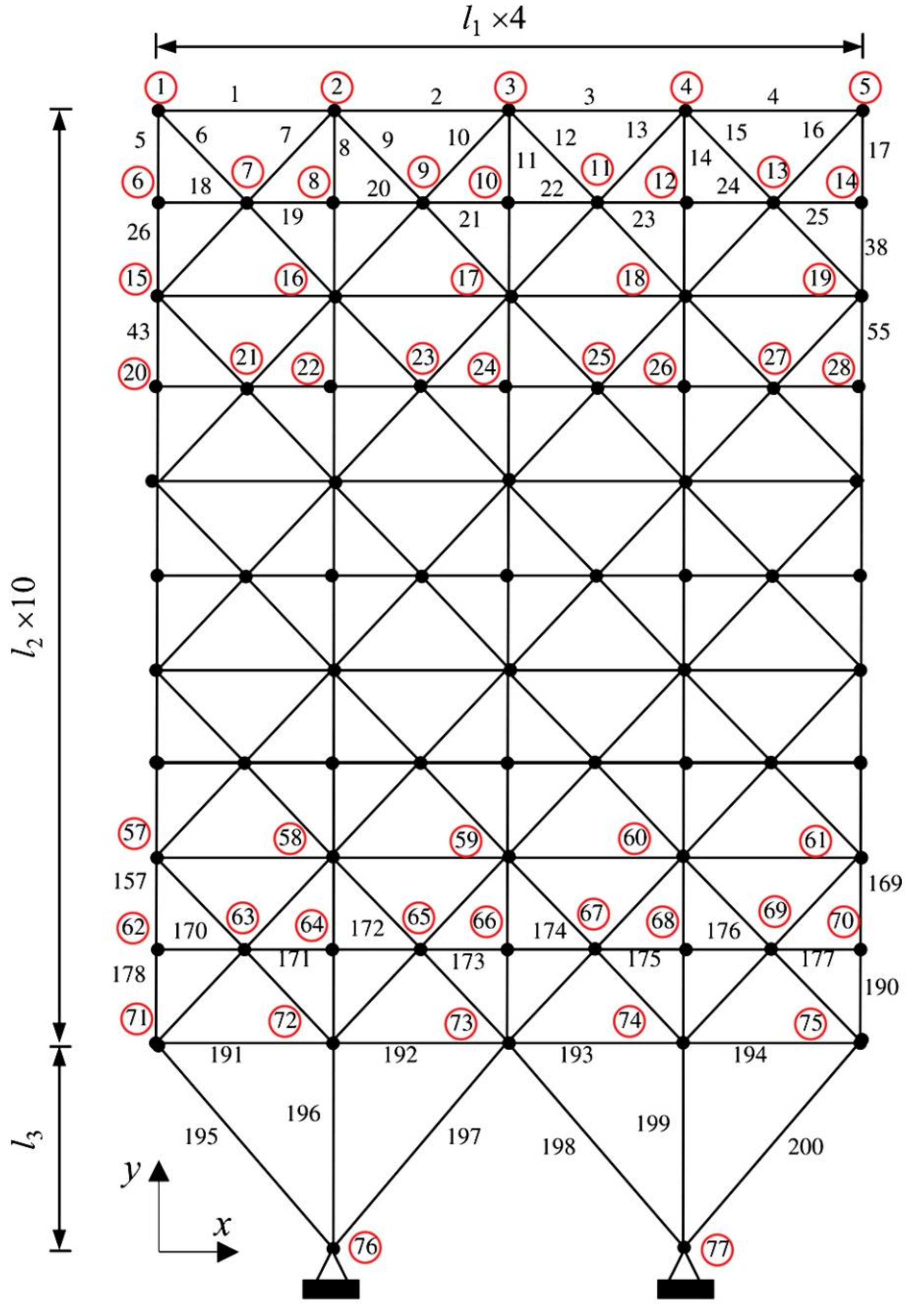


Fig. 9. 200-bar truss structure.

Table 3. Comparative results of CryStAl and other approaches in dealing with the 200-bar truss problem.(Continued)

El. No.	Members of the group	IGA [29]	HACOHS-T [30]	ARCGA [31]	MABC [31]	ESASS [31]	DE [20]	AEDE [20]	CryStAl
1	1, 2, 3, 4	0.347	0.1	0.1	0.1	0.1	0.1000	0.1000	0.347
2	5, 8, 11, 14, 17	1.081	1.081	1.081	1.333	0.954	0.9540	0.9540	0.954
3	19, 20, 21, 22, 23, 24	0.1	0.347	0.1	0.1	0.1	0.3470	0.3470	0.347
4	18, 25, 56, 63, 94, 101, 132, 139, 170, 177	0.1	0.1	0.1	0.1	0.1	0.1000	0.1000	0.347
5	26, 29, 32, 35, 38	2.142	2.142	2.142	2.697	2.142	2.1420	2.1420	2.142
6	6, 7, 9, 10, 12, 13, 15, 16, 27, 28, 30, 31, 33, 34, 36, 37	0.347	0.347	0.347	0.347	0.347	0.5390	0.3470	0.44
7	39, 40, 41, 42	0.1	0.1	0.1	0.1	0.1	0.1000	0.1000	0.1
8	43, 46, 49, 52, 55	3.565	3.131	3.131	3.131	3.131	3.5650	3.1310	3.565
9	57, 58, 59, 60, 61, 62	0.347	0.1	0.1	0.1	0.1	0.3470	0.3470	0.1
10	64, 67, 70, 73, 76	4.805	4.805	4.805	4.805	4.805	4.8050	4.8050	4.805
11	44, 45, 47, 48, 50, 51, 53, 54, 65, 66, 68, 69, 71, 72, 74, 75	0.44	0.44	0.347	0.44	0.347	0.5390	0.5390	0.44
12	77, 78, 79, 80	0.44	0.1	0.1	0.539	0.1	0.1000	0.3470	0.1
13	81, 84, 87, 90, 93	5.952	5.952	5.952	5.952	5.952	5.9520	5.9520	5.952
14	95,96, 97, 98, 99, 100	0.347	0.1	0.1	0.1	0.1	0.3470	0.1000	0.539
15	102, 105, 108, 111, 114	6.572	6.572	6.572	6.572	6.572	6.5720	6.5720	6.572
16	82, 83, 85, 86, 88, 89, 91, 92, 103, 104, 106, 107, 109, 110, 112, 113	0.954	0.539	0.539	1.081	0.44	0.9540	0.9540	0.954
17	115, 116, 117, 118	0.347	1.174	1.081	0.347	0.539	0.3470	0.4400	0.539
18	119, 122, 125, 128, 131	8.525	8.525	7.192	8.525	7.192	8.5250	8.5250	8.525

Table 3. Comparative results of CryStAl and other approaches in dealing with the 200-bar truss problem.

19	133, 134, 135, 136, 137, 138	0.1	0.1	0.539	0.1	0.44	0.1000	0.1000	0.539
20	140, 143, 146, 149, 152	9.3	9.3	8.525	9.3	8.525	9.3000	9.3000	9.3
21	120, 121, 123, 124, 126, 127, 129, 130, 141, 142, 144, 145, 147, 148, 150, 151	0.954	1.333	1.333	0.954	0.954	0.9540	0.9540	1.333
22	153, 154, 155, 156	1.764	0.539	1.081	1.764	1.174	1.3330	1.0810	0.539
23	157, 160, 163, 166, 169	13.3	13.33	10.85	13.33	10.85	13.3300	13.3300	13.33
24	171, 172, 173, 174, 175, 176	0.347	1.174	0.1	0.44	0.44	0.3470	0.5390	0.44
25	178, 181, 184, 187, 190	13.3	13.33	13.33	13.33	10.85	13.3300	14.2900	14.29
26	158, 159, 161, 162, 164, 165, 167, 168, 179, 180, 182, 183, 185, 186, 188, 189	2.142	2.697	1.488	2.142	1.764	2.1420	2.1420	1.764
27	191, 192, 193, 194	4.805	3.565	5.952	3.813	8.525	3.8130	3.8130	3.813
28	195, 197, 198, 200	9.3	8.525	13.33	8.525	13.33	8.5250	8.5250	8.525
29	196, 199	17.17	17.17	14.29	19.18	13.33	17.1700	17.1700	17.17
Weight (lb)		28544.014	28030.20	28347.594	28366.365	28075.488	27901.5830	27858.5000	28006.2276
Worst weight (lb)		–	–	–	–	–	29652.8910	29415.0000	29568.5188
Mean weight (lb)		–	–	–	–	–	28470.1140	28425.8710	28772.3089
Standard deviation (lb)		–	–	–	–	–	457.4670	481.5900	362.815636
	IGA: Improved Genetic Algorithm **HACOHS-T**: Hybridized Ant Colony–Harmony Search-Genetic Algorithm **ARCGA**: Adaptive Real-Coded Genetic Algorithm **MABC**: Modified Artificial Bee Colony Algorithm **ESASS**: Elitist Self-Adaptive Step-Size Search								

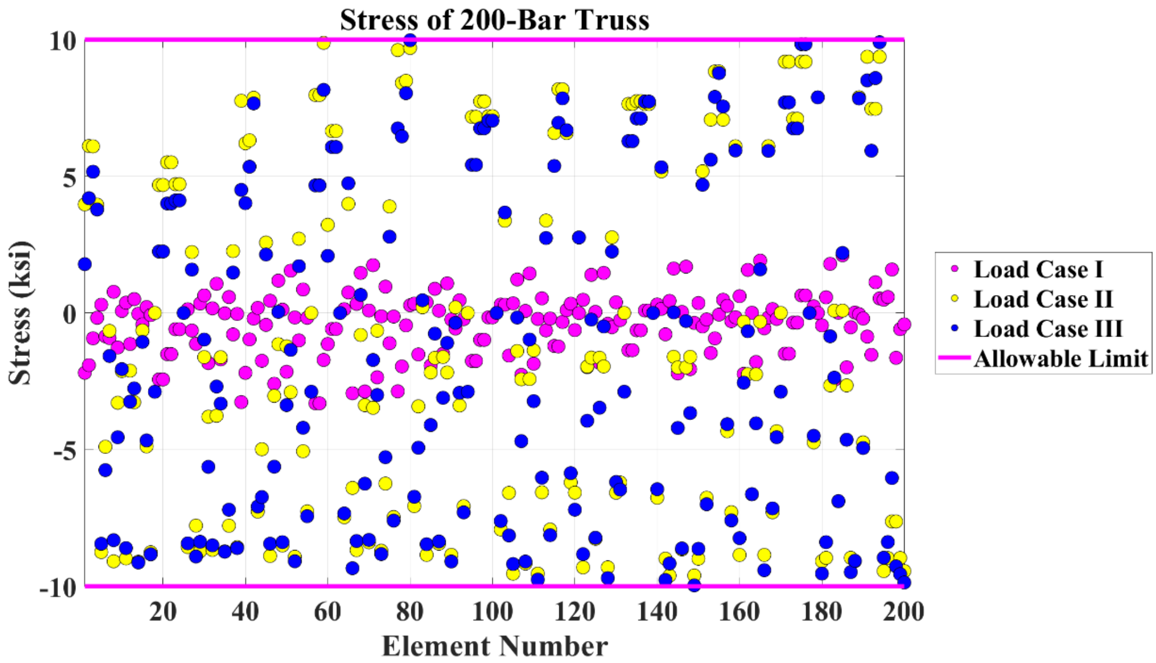


Fig. 10. Stress design constraints for 200-bar truss problem.

5- Conclusion

In this research work, the applicability of the Crystal Structure Algorithm (*CryStAl*) as one of the recently developed metaheuristic algorithms is investigated in the optimum design of truss structures in which the basic concepts of crystals, including the lattice and basis, are in perspective. For numerical purposes, the 10-bar, 72-bar, and 200-bar truss structures are considered as design examples. For constraint-handling purposes, a simple penalty approach is implemented in CryStAl. A complete statistical analysis is conducted through multiple optimization runs for comparative purposes, while other metaheuristic approaches have been derived from the literature. Based on the results of the CryStAl and other methods in dealing with truss optimization problems, the utilized method can provide better and more competitive results in most cases. Based on the results, the CryStAl is capable of reaching 5490.7379 lb in dealing with a 10-bar truss problem, which is way better than the previously reported results in the literature, so the CryStAl has outranked these alternative approaches, and the utilized algorithm in this paper has better performance in dealing with this problem.

Regarding the statistical analysis, the results of the CryStAl are competitive by considering the means of worst results of multiple optimization nuns. The CryStAl can provide 389.3341 lb, the lowest possible weight for the 72-bar truss structure based on the reported results in the literature. Besides, the statistical results denote that the utilized algorithm can calculate 389.8477 lb as the mean of multiple optimization runs, which is the best among other approaches. Besides, the CryStAl can calculate 28006.2276 lb as the best optimum weight of the 200-bar structure, while the results of other approaches are lower than this value. Based on the fact that the other approaches have not reported statistical results, the provided results of the CryStAl can be utilized in the comparative investigations of future research works.

For future challenges, the applicability of the Crystal Structure Algorithm (CryStAl) in different applications, including the optimal design of large-scale frame structures and the optimization of resource trade-offs in construction projects, can be considered, while the improved and hybridized versions of this algorithm can also be proposed for optimization purposes.

References

[1] M.B. Shishehgarkhaneh, M. Azizi, M. Basiri, R.C. Moehler, BIM-Based Resource Tradeoff in Project Scheduling Using Fire Hawk Optimizer (FHO), Buildings, 12(9) (2022) 1472.

[2] J.H. Holland, Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence, MIT Press 1992.

[3] S. Mirjalili, S.M. Mirjalili, A. Lewis, Grey Wolf Optimizer, Advances in Engineering Software, 69 (2014) 46-61.

[4] S. Talatahari, M. Azizi, A.H. Gandomi, Material Generation Algorithm: A Novel Metaheuristic Algorithm for Optimization of Engineering Problems, Processes, 9(5) (2021) 859.

[5] S. Talatahari, M. Azizi, Chaos Game Optimization: a novel metaheuristic algorithm, Artificial Intelligence Review, 54(2) (2021) 917-1004.

[6] M. Azizi, U. Aickelin, H.A. Khorshidi, M.B. Shishehgarkhaneh, Shape and size optimization of truss structures by Chaos game optimization considering frequency constraints, Journal of Advanced Research, (2022).

[7] R. Eberhart, J. Kennedy, A new optimizer using particle swarm theory, in: MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science, 1995, pp. 39-43.

[8] M. Dorigo, V. Maniezzo, A. Colorni, Ant system: optimization by a colony of cooperating agents, IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), 26(1) (1996) 29-41.

[9] M. Azizi, Atomic orbital search: A novel metaheuristic algorithm, Applied Mathematical Modelling, 93 (2021) 657-683.

[10] S. Talatahari, M. Azizi, M. Tolouei, B. Talatahari, P. Sareh, Crystal Structure Algorithm (CryStAl): A Metaheuristic Optimization Method, IEEE Access, 9 (2021) 71244-71261.

[11] M. Sonmez, Discrete optimum design of truss structures using artificial bee colony algorithm, Structural and multidisciplinary optimization, 43(1) (2011) 85-97.

[12] S. Jalili, Y. Hosseinzadeh, Combining migration and differential evolution strategies for optimum design of truss structures with dynamic constraints, Iranian Journal of Science and Technology, Transactions of Civil Engineering, 43(1) (2019) 289-312.

[13] A. Kaveh, P. Zakian, Improved GWO algorithm for optimal design of truss structures, Engineering with Computers, 34(4) (2018) 685-707.

[14] Gebrail Bekdas, Sinan Melih Nigdeli, X.-S. Yang, Size Optimization of Truss Structures Employing Flower Pollination Algorithm without Grouping Structural Members, International Journal of Theoretical and Applied Mechanics, 1 (2016) 269-273.

[15] A. Javidi, E. Salajegheh, J. Salajegheh, Enhanced crow search algorithm for optimum design of structures, Applied Soft Computing, 77 (2019) 274-289.

[16] S. Degertekin, L. Lamberti, I. Ugur, Discrete sizing/layout/topology optimization of truss structures with an advanced Jaya algorithm, Applied Soft Computing, 79 (2019) 363-390.

[17] B. Dizangian, Border-search and jump reduction method for size optimization of spatial truss structures, Frontiers of Structural and Civil Engineering, 12 (2018).

[18] D.T. Le, D.-K. Bui, T.D. Ngo, Q.-H. Nguyen, H. Nguyen-Xuan, A novel hybrid method combining electromagnetism-like mechanism and firefly algorithms for constrained design optimization of discrete truss structures, Computers & Structures, 212 (2019) 20-42.

[19] M. El Bouzouiki, R. Sedaghati, I. Stiharu, A non-uniform cellular automata framework for topology and sizing optimization of truss structures subjected to stress and displacement constraints, Computers & Structures, 242 (2021) 106394.

[20] V. Ho-Huu, T. Nguyen-Thoi, T. Vo-Duy, T. Nguyen-Trang, An adaptive elitist differential evolution for optimization of truss structures with discrete design variables, Computers & Structures, 165 (2016) 59-75.

[21] S. Rajeev, C.S. Krishnamoorthy, Discrete Optimization of Structures Using Genetic Algorithms, Journal of Structural Engineering, 118(5) (1992) 1233-1250.

[22] L.J. Li, Z.B. Huang, F. Liu, A heuristic particle swarm optimization method for truss structures with discrete variables, Computers & Structures, 87(7) (2009) 435-443.

[23] A. Sadollah, A. Bahreininejad, H. Eskandar, M. Hamdi, Mine blast algorithm for optimization of truss structures with discrete variables, Computers & Structures, 102-103 (2012) 49-63.

[24] S.-J. Wu, P.-T. Chow, Steady-state genetic algorithms for discrete optimization of trusses, Computers & structures, 56(6) (1995) 979-991.

[25] S. Talatahari, M. Azizi, H. Veladi, Moutabi-Alavi A., S. Rahnema, Optimum Structural Design of Full-Scale Steel Buildings Using Drift-Tribe-Charged System Search, Earthquake Engineering and Engineering Vibration, (2021).

[26] A. Kaveh, V.R. Mahdavi, Colliding Bodies Optimization method for optimum discrete design of truss structures, Computers & Structures, 139 (2014) 43-53.

[27] Kaveh, M. Ilchi Ghazaan, A comparative study of CBO and ECBO for optimal design of skeletal structures, Computers & Structures, 153 (2015) 137-147.

[28] Sadollah, H. Eskandar, A. Bahreininejad, J.H. Kim, Water cycle, mine blast and improved mine blast algorithms for discrete sizing optimization of truss structures, Computers & Structures, 149 (2015) 1-16.

[29] V. Toğan, A.T. Daloğlu, An improved genetic algorithm with initial population strategy and self-adaptive member grouping, Computers & Structures, 86(11) (2008) 1204-1218.

[30] M.H. Talebpour, A. Kaveh, V. Kalatjari, Optimization of skeletal structures using a hybridized ant colony-harmony search-genetic algorithm, Iranian Journal of Science and Technology - Transactions of Civil Engineering, 38 (2014) 1-20.

[31] S.K. Azad, O. Hasançebi, An elitist self-adaptive step-size search for structural design optimization, Applied Soft Computing, 19 (2014) 226-235.

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