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Size, Topology, and Shape Optimization using Symbiotic Organisms Search

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***Abstract*— Truss structure is one type of structure that often used. With rapidly construction growth, the most efficient structure design are needed to minimize construction cost. One way that can be used is structure optimization. However, truss structure has a lot of constraints and variables that make optimizing this structure complex and difficult. Metaheuristic method can be applied to solve this problem, because metaheuristic has efficiency and effectiveness to solve massive and complex problem. This paper tested three metaheuristic algorithm namely, Particle Swarm Optimization (PSO), symbiotic organisms search (SOS) and differential evolution (DE). Every algorithm used to optimize ten bar planar truss structure and fifteen bar planar truss structure. The result found that SOS has best optimum result, convergence behavior and consistency.**

***Keywords*— metaheuristic algorithms, truss structure, optimization**

I. Introduction

Optimization of the truss structure has become one of the hot issues in structural engineering for the past decades. A truss structure usually involved construction of interconnected structural members that behaves as one single object where each member is subjected to tension or compression forces only [AAA]. The most widely studied truss structure optimization are size and topology optimization [1]. Size optimization is used to minimize the cross-sectional area of each member of the truss structure. Topology optimization is used to optimize the number of element while paying attention to stability of structure. Usually, a trial-and-error approach is commonly used by engineers to design an optimal truss structure, which are proven to be time consuming and cost inefficient [BBB].

Truss structure optimization problem involves many variables and constraints, making the optimization more complex and difficult. Additionally, many studies have focused only on sizing and topology optimization, but the coordinates of the nodes and the shape of the structure remain constant. Therefore, many studies are now focusing on finding the best optimization method for solving the truss structure design problems. By optimizing size, topology, and shape of the truss structure simultaneously can provide more efficient results [2].

The field of metaheuristic algorithms have gained increased attentions in optimization field study due to the use of natural phenomena and randomization concepts in finding optimal results [3]. Particle swarm optimization (PSO) [CC] and differential evolution (DE) [DD] are examples of widely used metaheuristic algorithms in solving many optimization problems. Recently, symbiotic organisms search (SOS) has been proposed by Cheng and Prayogo and has been proven to deliver outstanding performance in structural optimization [4]. Thus, this research has single objective and three optimization variables, that is topology, shape, and sizing. Total mass of steel truss structure became the objective that will be optimized. This research use three metaheuristic algorithm namely, PSO, DE and SOS.

II. Symbiotic Organisms Search (SOS)

The SOS algorithm was discovered by Cheng and Prayogo in 2014 [4]. SOS is a simple and very powerful metaheuristic algorithm. SOS algorithm is inspired by the interaction between living things to survive nature. This interaction is called symbiosis. SOS algorithm uses three forms of symbiosis that are most often found in nature, namely mutualism symbiosis, commensalism symbiosis, parasitism symbiosis.

Symbiosis mutualism describes the relationship between two organisms that are mutually beneficial to one another. For example, the relationship between bees and flowers. In the SOS algorithm, if the results of a newer organism are better than the previous organism, then the organism will be replaced by a new organism. Based on Cheng & Prayogo (2014), a mathematical model of the SOS symbiotic mutualism algorithm is found in Equations (7) – (9) as follows:

$$X_{inew} = X_i + rand(0,1) * (X_{best} - Mutual_{Vect} * BF_1) \quad (1)$$

$$X_{jnew} = X_j + rand(0,1) * (X_{best} - Mutual_{vect} * BF_2) \quad (2)$$

$$Mutual_{Vect} = \frac{X_i + X_j}{2} \quad (3)$$

where: X_i is organisms that correspond to i-members in the ecosystem; X_j is randomly selected organism from the ecosystem; X_{inew} is new candidate for X_i; X_{jnew} is new candidate for X_j; BF_1 and BF_2 is random number between one and two; X_{best} is global best solution

Commensalism symbiosis describes the relationship between two organisms that only benefit one organism, while the other organism does not get any advantage or disadvantage. The relationship between remora fish with sharks is one example of commensalism symbiosis. In the SOS algorithm, organism i (X_i) will interact with organism k

(X_k), where X_k is taken randomly and $k \neq i$. This interaction will only renew i organism. The formula for X_{inew} in this symbiosis is:

$$X_{inew} = X_i + rand(-1,1) * (X_{best} - X_k) \quad (4)$$

Parasitism symbiosis describes the relationship between two organisms that only benefit one organism, while the other organism is harmed. The relationship between anopheles mosquitoes and humans is an example of symbiotic parasitism. Anopheles mosquitoes carry plasmodium parasite into the human body which can cause malaria. The organism X_i is given a similar role as the anopheles mosquito through an artificial parasite called "Parasite Vector ". Furthermore, the fitness value of the "Parasite Vector" will be compared with the fitness value of the X_j organism. If the fitness value of "Parasite Vector" is better, then the position of organism X_j will be replaced by the "Parasite Vector".

III. METHODOLOGY

Combination of direct stiffness method (DSM) and metaheuristic are used for this truss optimization. Metaheuristics is used to find the optimal cross-sectional area, while DSM is used to analyse the structure. DSM outputs are displacement, axial force, and stress of each element. This output are used as constraint for this optimization. When solution violates the constraint, then penalty are given to the solution.

Before conducting the research, researchers prepared a DSM program for planar and space truss, and prepared three metaheuristic algorithms, that is particle swarm optimization (PSO), differential evolution (DE) and symbiotic organisms search (SOS). DSM as well as metaheuristic algorithms written using MATLAB 2017a. The results of the three algorithms are compared to find out the best algorithms performance. In general, this program randomize the cross-section area and nodes coordinate , then iterate using trial and error until it reach its maximum iteration. Flow chart for truss optimization shown in Fig. 1.

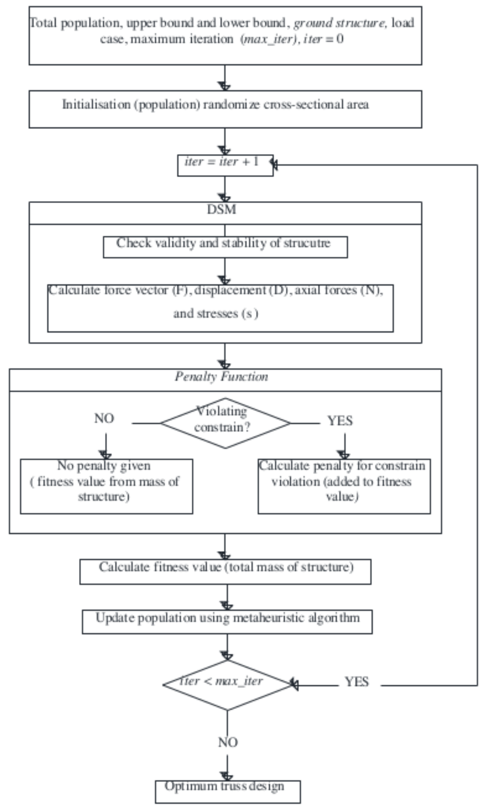

Fig. 1. Flow chart for truss optimization

IV. PROBLEM FORMULATION

The objective of this study is to get minimum weight of the structure without violating any constraint. The constraints used in this study are static constraints. The constraints are nodal displacement, element stress, validity and kinematic stability of structure. The mathematical formulation of this optimization problem can be performed as follows;

$$\text{Find,} \quad X = \{A_1, A_2, \dots, A_m, \xi_1, \xi_2, \dots, \xi_n\} \quad (5)$$

$$\text{To minimize, } f(x) = \sum_{i=1}^{m} B_i A_i \rho_i L_i$$

$$\text{where, } B_i = \begin{cases} 0, if\ A_i < Critical\ Area \\ 1, if\ A_i \geq Critical\ Area \end{cases}$$

Subjected to:

g_1= check on validity of structure

g_2 = Check on Stability of structure

$g_3(X)$ = Stress Constraints $|B_i\sigma_i| - |\sigma_i^{max}| \leq 0$

g_4 = Displacement Constraints $|\delta_i| - |\delta_j^{max}| \leq 0$

g_5 = Size Constraint $A_i^{Critical} \leq A_i \leq A_i^{Upper}$

g_6 = Shape Constraint $\xi_j^{Lower} \leq \xi_j \leq \xi_j^{Upper}$

where, A_i, ρ_i, L_i and σ_i are cross-sectional area, density, modules of elasticity, length, and stress of element 'i' respectively. σ_i and ξ_j are real values of nodal displacement and coordinates of node 'j' respectively. B_i is a topological bit, which is 0 for absence and 1 for presence of element 'i', respectively. The superscript, 'max' and 'min' signify maximum and minimum allowable values respectively. Truss structure is called invalid (g_1) if during optimization process there are loaded node and support node being deleted.

In this study, kinematic stability is reviewed in 2 ways. That is rank of stiffness matrix is same as the size of global stiffness matrix and the global stiffness matrix is positive definiteness. When g_1 and g_2 is violated, fitness value will be given dead penalty (infinite as total mass of the structure). While for the other constraint violation, penalty will be added to the total mass of the structure using the formula from Tejani, Savsani, Bureerat, & Patel (2018):

$$F_{penalty} = (1 + \varepsilon_1 \times C)^{\varepsilon_2} \tag{6}$$

$$C = \sum_{i=1}^{q} C_i \tag{7}$$

$$C_i = \left|1 - \frac{p_i}{p_i^*}\right| \tag{8}$$

p_i is a level of violation that is violated against the p_i * limit; q is the number of constraints used; ε1 and ε2 are parameters set by the researcher, this study takes a reference based [1] Where the values of ε_1 and ε_2 are 3. Then the results of the $F_{penalty}$ will be multiplied by the total mass of the structure to get the fitness value.

V. Test Problem and Results

This paper compares three metaheuristic algorithms performances using planar and spatial bar structure problem. Each structure has their load cases and discrete variable which will be mention next. The goal is to minimize the weight of the structure while not violating the constraint. All algorithm were run 30 times and with 50 populations. Structures are analysed using direct stiffness method. Algorithms and structural analyses are coded in MATLAB 2017a. Cognitive (C1) and social (C2) parameters for PSO were set to 2 and inertia weight (W) was set to 0.8.

A. Planar 10-bar truss structure

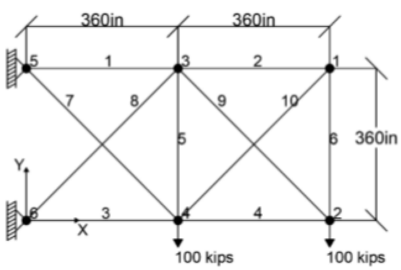

Fig. 2. Ground structure of 10-bar truss

This 10-bar structure has six nodes and twelve degree of freedom due to X and Y direction. Structure are shown in Fig. 2. The material density is 0.1 lb/in3 and elastic modulus 107 psi. The stress limits for compression/tension is 25,000 psi and displacement should not more than ± 2 in. There are 13 design variables in this problem, which is ten cross-section area variables and three geometry variables. For geometry variables, node 1, 3, and 5 could move between 180 and 1000 inch in Y direction. The cross-sectional areas that available are;

D=[0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, 10.5, 11.0, 11.5, 12.0, 12.5, 13.0, 13.5, 14.0, 14.5, 15.0, 15.5, 16.0, 16.5, 17.0, 17.5, 18.0, 18.5, 19.0, 19.5, 20.0, 20.5, 21.0, 21.5, 22.0, 22.5, 23.0, 23.5, 24.0, 24.5, 25.0, 25.5, 26.0, 26.5, 27.0, 27.5, 28.0, 28.5, 29.0, 29.5, 30.0, 30.5, 31.0, 31.5] (in2).

Table I shows that SOS had the best result with smallest standard deviation. All algorithm runs 15,000 structural analyses. PSO, SOS and DE obtain the minimum weight of 2749.171 lb, 2705.169 lb, 2940.873 lb respectively. Fig. 3. Shows the iteration process of 10-bar truss structure optimization. In terms of consistency, SOS had the best convergence behaviour as shown in Fig. 4.

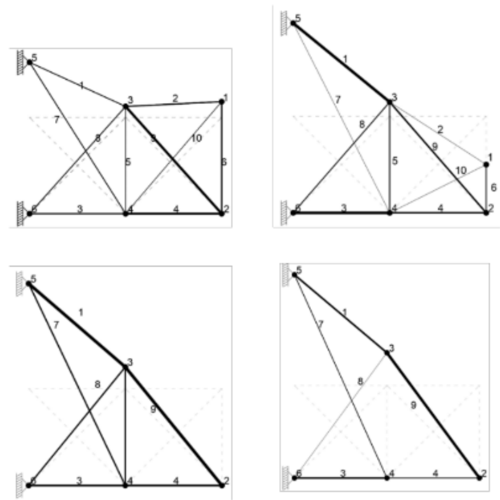
Fig. 3. Iteration of 10-bar truss structure

TABLE I. FINAL DESIGNS OF SIZING, SHAPE AND TOPOLOGY FOR THE 10-BAR TRUSS

Variables	(GA)[x]	PSO	DE	SOS
A1	11.5	11.5	11.5	11.5
A2	0	0	0	0
A3	11.5	11.5	11.5	11.5
A4	5.74	7.22	11.5	7.22
A5	0	0	0	0
A6	0	0	0	0
A7	5.74	5.74	5.74	5.74
A8	3.84	3.13	4.18	2.88
A9	13.5	13.5	11.5	13.5
A10	0	0	0	0
Y3	-	-	-	-
Y2	485.5	486.7639	505.3918	486.6614
Y1	789.7306	780.6457	760.5712	789.9996
Best (lb)	2723.05	2749.171	2940.873	2705.169
Average (lb)	-	3118.027	3084.237	2848.516
Stdev (lb)	-	260.0294	100.1667	85.03397
Max Stress(ksi)	19.1463	19.1849	19.2746	19.1452
Max Displacement(inch)	1.999996	2	1.995376	2
No. of analyses	-	15000	15000	15000
Constrain violation	None	2.44E-11	None	None

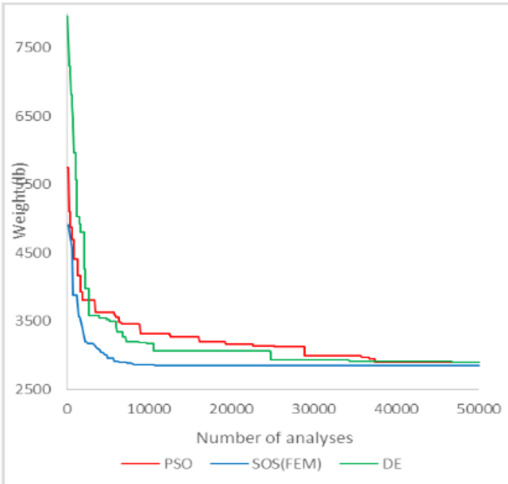

Fig. 4. Convergence history for the size, shape and topology for 10-bar truss optimisation

B. Planar 15-bar truss structure

The ground structure is illustrated in Fig. 5, showing a vertical tip load of 10 kips applied on node 8. The allowable strength is 25 ksi and the material properties (modulus of elasticity and weight density) are the same as in the previous examples. The x- and y- coordinates of nodes 2, 3, 6 and 7 and the y-coordinate of nodes 4 and 8 are taken as design variables. However, nodes 6 and 7 are constrained to have the same x-coordinates of the nodes 2 and 3, respectively. Thus, the problem includes 15 size and eight shape variables (x2 = x6, x3 = x7, y2, y3, y4, y6, y7, y8). The cross-sectional areas are chosen from;

D =[0.111, 0.141, 0.174, 0.220, 0.270, 0.287, 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] (in2).

The side constraints for the configuration variables are 100 in. ≤ x2 ≤ 140 in., 220 in. ≤ x3 ≤ 260 in., 100 in. ≤ y2 ≤ 140 in., 100 in. ≤ y3 ≤ 140 in., 50 in. ≤ y4 ≤ 90 in., -20 in. ≤ y6 ≤ 20 in., -20 in. ≤ y7 ≤ 20 in., 20 in. ≤ y8 ≤ 60 in.

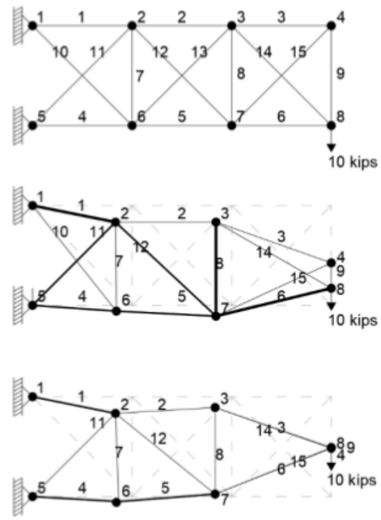

Fig. 5. Ground structure of 15-bar truss and iteration

TABLE II. FINAL DESIGNS OF SIZING, SHAPE AND TOPOLOGY FOR THE 15-BAR TRUSS

Variables	PSO	DE	SOS
A1	1.174	0.954	1.333
A2	0.44	0.954	0.539
A3	0	0	0.27
A4	1.174	1.333	0.954
A5	0.954	0.539	0.954
A6	0.44	0.539	0.347
A7	0	0.141	0.141
A8	0.347	0.22	0.22
A9	0	0	8.525
A10	0.141	0.347	0
A11	0.347	0	0.347
A12	0.954	0	0.539
A13	0	0.539	0
A14	0.44	0.539	0.347
A15	0	0	0.27
X2	100	139.5696	104.5112
X3	220	260	220.342
Y2	100	107.224	101.0084
Y3	140	100	107.2495
Y4	50	63.36982	58.91903
Y6	-14.7454	12.88183	-6.51056
Y7	-19.9961	20	3.457589
Y8	60	60	58.91903
Best (lb)	84.06829	78.88377	76.97567
Average (lb)	99.99107	84.05521	80.8648
Stdev (lb)	15.10979	3.2419	2.404869
Max Stress(ksi)	24.3588	24.9776	24.9998
No. of analyses	50000	50000	50000
Constrain violation	2.44E-11	None	None

In this case SOS also shown the best performance out of three algorithms. As seen on TABLE II. The iteration process of 15-bar truss displayed on Fig. 5. SOS has most optimum result and smallest standard deviation, while on Fig. 6. SOS also beat other algorithm in convergence behavior.

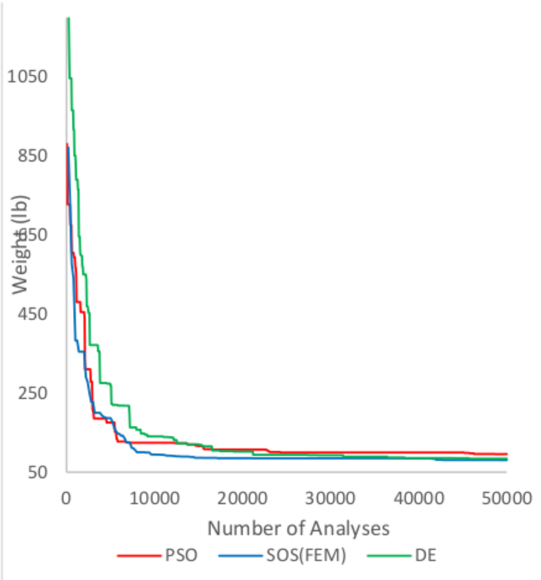

Fig. 6. Convergence history for the size, shape and topology for 15-bar truss optimisation

VI. CONCLUSION

This paper has compared the optimization performance of three metaheuristic algorithms namely PSO, SOS, and DE by reviewing two case studies. All algorithms run planar and spatial truss problem that coded using direct stiffness method. With same number of analyses from both, the result shown that SOS are the best algorithm in terms of optimum result, convergence behavior and consistency from three algorithms that was tested. SOS also has no violation in both 10-bar and 15-bar problem. In term of optimum result, DE perform worst on10-bar problem, while PSO perform worst in 15-bar problem. In terms of consistency, DE has better performance than PSO on both problem.

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