Reliability-based design size and shape optimization of truss structure using symbiotic organisms search

By Doddy Prayogo

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Abstract. Studies on truss design optimization have been conducted extensively over the past decades. One of the significant current discussions is the reliability aspect of the truss design in addition to optimal design. This problem becomes more important, especially in sizing and shaping the optimization of truss structures. Reliability-based design optimization is defined as finding the optimum structure while satisfying the given uncertainty and reliability criteria. This study aims to investigate the performance of metaheuristic algorithm in optimizing the truss structure design and satisfying the reliability constraints. Latin hypercube sampling method was used to model the presence of uncertainty. Symbiotic organisms search was also utilized as a metaheuristic algorithm to solve a modified 15-bar planar truss. The results indicated that reliability design gives a significant result in the shape and size of truss.

Keywords: metaheuristic algorithms, reliability-based design optimization, truss structure

1. Introduction

Structure optimization has become an important and challenging topic in civil engineering because it can increase the efficiency of structure. Structure optimization is the act of designing and developing structures to achieve the maximum profit of available resources [1]. Many researchers are, therefore, interested in structure optimization to minimize cost and structure's weight with optimizing the diameter size of steel pipe, the thickness of plate, or steel's cross-section area [4]. Element's number and constraint in the structure's design has caused complexity in structure optimization. Hence, metaheuristic has become more popular in solving structure optimization cases than gradient method [3]. In metaheuristic, the concept of randomness is useful to find global solution of a case. Nowadays, Symbiotic Organisms Search (SOS) has been used by numerous researchers in optimization cases because its operations require no specific algorithm parameters [2].

Furthermore, uncertainty has also become an inevitable problem in structure optimization. In practice, truss structure is sensitive to uncertain design variables, such as cross-section, or uncertain parameter, such as force and material's modulus elasticity [5]. Structure's strength and safety are also affected by the changing of those variables and parameters; hence, uncertainty must be calculated in the design [5]. As a result, Reliability-Based Design Optimization (RBDO) optimization has become an important matter in the structure design. Some methods are needed to analyze the probability and reliability of structure in order to solve RBDO problems. There are three methods to analyzed RBDO problem, such as moment method, simulation method, and heuristic method [6].

This research aims to optimize a single variable which is the structure's weight. In order to model the uncertainty of variables, random variable with certain mean and standard deviation were defined. The model was simulated using Latin Hypercube Sampling (LHS) method. Reliability of structure was analyzed by LHS method because it can achieve reliable results compared with response surface method-based optimization [8].To achieve the reliable smallest weight, we employed SOS as a metaheuristic algorithm and then provided some constraints in the process with a probability of success not less than 99%.

2. Symbiotic Organisms Search

Symbiotic organisms search algorithm simulates the interactive behavior seen among organisms in nature [2]. This method is compatible with the nature of living organisms which cannot live alone and need interaction with others. Three kinds of interaction exist in SOS: mutualism phase, commensalism phase, and parasitism phase.

Mutualism phase occurs between two organisms that gain advantages from the interaction. If the new organism's fitness is improved after the interaction, this organism is updated with a new one. Mathematic model of mutualism phase is defined by Cheng and Prayogo, as shown in equation 1, 2, and 3 [2].

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

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

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

where X_i is an organism matched to the i-th member of the ecosystem, X_j is an organism that is selected randomly from the ecosystem, X_{inew} is a new candidate from X_i, X_{jnew} is the new candidate from X_j, BF_1 and BF_2 are random numbers between one or two, and X_{best} is the global solution.

Commensalism phase is an interaction between two organisms where one of them gain an advantage while the other is not affected. If the new fitness value of the organism is better than the pre-interaction one, this organism is updated. Formula for X_{inew} in this phase is:

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

Parasitism phase is an interaction where one organism benefits, and the other is harmed. $\boldsymbol{X_i}$ is given a role as the parasite named "Parasite_Vector". Then, the fitness value of "Parasite_Vector" is compared with the fitness value of $\boldsymbol{X_j}$. If the fitness value of "Parasite_Vector" is better, position of $\boldsymbol{X_j}$ is replaced with "Parasite_Vector". After going through this phase, this algorithm is repeated until satisfying the criteria.

3. Latin Hypercube Sampling

Latin Hypercube Sampling method was used to assure a good estimation of the statistical moments of response functions. In this method, sample points are well spread out when projected onto a subspace spanned by several coordinate axes. Latin Hypercube Sampling selects n different values of k variables X_1, ..., X_k where the range of each variable is divided into n nonoverlapping intervals on the basis of equal probability. It then selects a value randomly from each interval. The sampled cumulative probability can be written as:

$$Probi = \left(\frac{1}{N}\right) r_u + \frac{(i-1)}{N} \quad (5)$$

where r_u is uniformly distributed random number ranging from zero to one. Then, the probability of failure can be obtained from equation 6.

$$Pf \cong \frac{N_H}{N} \quad (6)$$

where N_H is the number of failures, and N is the number of simulations.

4. Problem Formulation

This study aims to minimize the weight of truss structure without violating any constraints. The constraints used in this study are static constraints and include element stress and reliability. The mathematical formulation of this optimization problem can be performed as follows:

Find, $X = \{A_1, A_2, \ldots, A_m, \xi_1, \xi_2, \ldots, \xi_n\}$

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

Subjected to:

g1: Check probability of success $\geq 99\%$

g2: Stress constraints, $|\sigma_i| - |\sigma_i^{max}| \leq 0$

g3: Shape constraints, $\xi_j^{lower} \leq \xi_j \leq \xi_j^{upper}$

where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. A_i, ρ_i, L_i, and σ_i are cross-sectional area, weight density, length, and stress of element (i), respectively.

5. Methodology

Reliability-Based Design Optimization was modeled by combining metaheuristic algorithm as optimization method and LHS to model the uncertainty. Metaheuristic was used to find the optimal cross-sectional area and shape of truss structure while Direct Stiffness Method (DSM) was used to analyze the structure. This paper also used DSM to obtain the displacement, axial force, and stress of each element. These outputs were utilized to detect the number of structures that failed. Structure's probability of failure was then obtained from LHS. When the structure was not reliable, a penalty was given to the calculation of weight as the fitness value. Direct Stiffness Method as well as the metaheuristic algorithms were written using MATLAB R2018b. A flow chart of the truss optimization process is presented in Figure 1.

6. Test Problem and Results

In this paper, we compare the 15-bar planar truss structure problem, as shown in Figure 2 with a deterministic and non-deterministic variable. Each structure had its load cases. The goal was to minimize cross-sectional area so that the minimum weight could be obtained for the structure while meeting the strength, serviceability, and reliability requirements. Thirty experimental runs with 1000 iterations and 30 populations resulted in the same 120000 function evaluation. These two cases were simulated 100 times with modulus elasticity (E) = 10^4 ksi, weight density (ρ) = 0.1 lb/in.^{3}, and available cross-sectional areas 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] (in^2). Stress limits in tension or compression were 25 ksi. There were 23 design variables in this problem: 15 cross-section area variables and eight configuration variables. The configuration variables were the x- and y-coordinates of nodes 2, 3, 6, and 7 and the y-coordinate of nodes 4 and 8. However, nodes 6 and 7 were constrained to have the same x-coordinates of nodes 2 and 3, respectively. The side constraints for the configuration variables were 100 in. $\leq x_2 \leq$ 140 in., 220 in. $\leq x_3 \leq$ 260 in., 100 in. $\leq y_2 \leq$ 140 in., 100 in. $\leq y_3 \leq$ 140 in., 50 in. $\leq y_4 \leq$ 90 in., -20 in. $\leq y_6 \leq$ 20 in., -20 in. $\leq y_7 \leq$ 20 in., and 20 in. $\leq y_8 \leq$ 60 in.

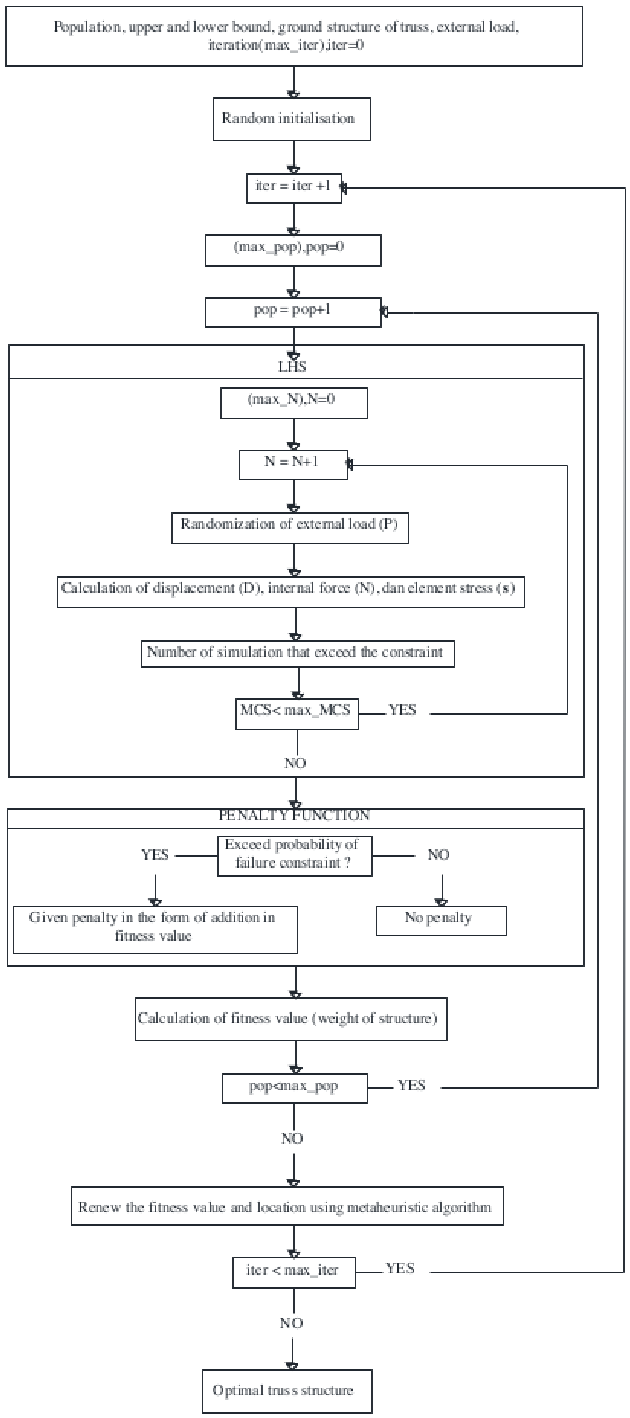

Figure 1. Flow chart for truss optimization.

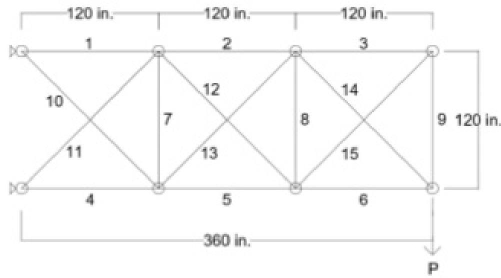

Figure 2. 15-bar problem.

6.1. 15-bar planar truss structure with deterministic load

The structure model shown in Figure 2 [7] gave deterministic load P = 10000 lb on node 8. Table 1 shows that SOS has a better result than the reference. Figure 3 shows the iteration process of 15-bar truss structure optimization. In terms of consistency, the convergence behavior of SOS is depicted in Figure 4.

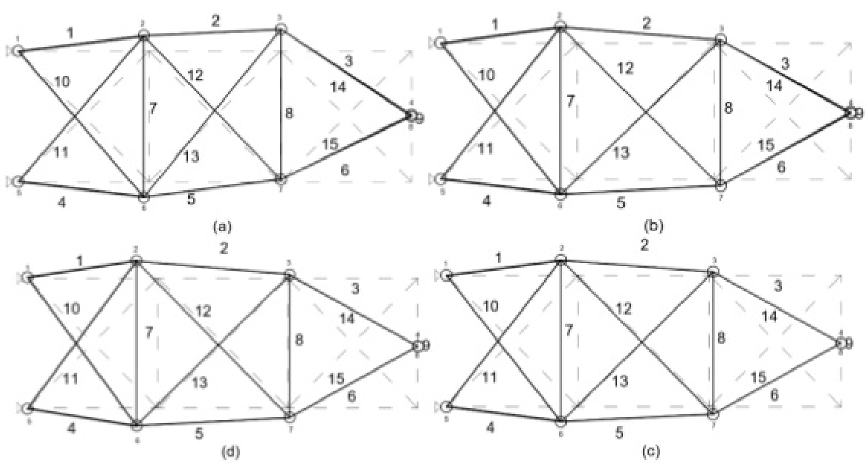

Figure 3. Iteration of 15-bar truss structure with deterministic load: (a) iteration number 100; (b) iteration number 500; (c) iteration number 700; (d) iteration number 1000.

Table 1. Final design of size and shape for the 15-bar truss with the deterministic load.

Variable	Miguel et al. [7] FA	SOS	Variable	Miguel et al. [7] FA	SOS
A1 (in^2)	0.954	0.954	A14 (in^2)	0.270	0.270
A2 (in^2)	0.539	0.539	A15 (in^2)	0.220	0.141
A3 (in^2)	0.220	0.141	X2 (in^2)	114.967	100.018
A4 (in^2)	0.954	0.954	X3 (in^2)	247.040	241.51
A5 (in^2)	0.539	0.539	Y2 (in^2)	125.919	135.727
A6 (in^2)	0.220	0.27	Y3 (in^2)	111.067	123.187
A7 (in^2)	0.111	0.111	Y4 (in^2)	58.298	57.189
A8 (in^2)	0.111	0.111	Y6 (in^2)	-17.564	-16.331
A9 (in^2)	0.287	0.141	Y7 (in^2)	-5.821	-8.822
A10 (in^2)	0.440	0.440	Y8 (in^2)	31.465	57.184
A11 (in^2)	0.440	0.440	Best Weight (lb)	75.55	73.596
A12 (in^2)	0.220	0.220	Average (lb)	82.64	79.9
A13 (in^2)	0.220	0.270	Stdev	2.96	2.881

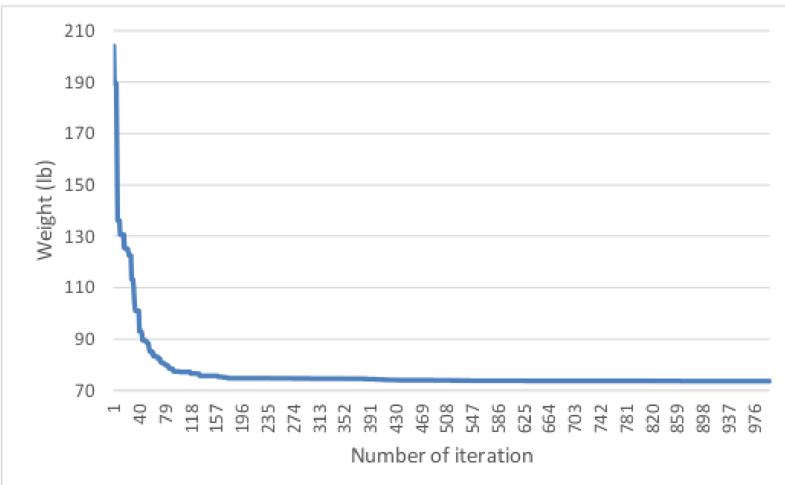

Figure 4. Convergence behavior for the size and shape for 15-bar truss with the deterministic load.

6.2. 15-bar planar truss structure with non-deterministic load

This case was given a non-deterministic load (P) using lognormal distribution with mean 10 kips and dispersion ± 5% on node 8. This random variable was modeled by LHS method. Figure 5 shows the iteration process of 15-bar truss structure optimization. In terms of consistency, the convergence behavior of SOS is shown in Figure 6.

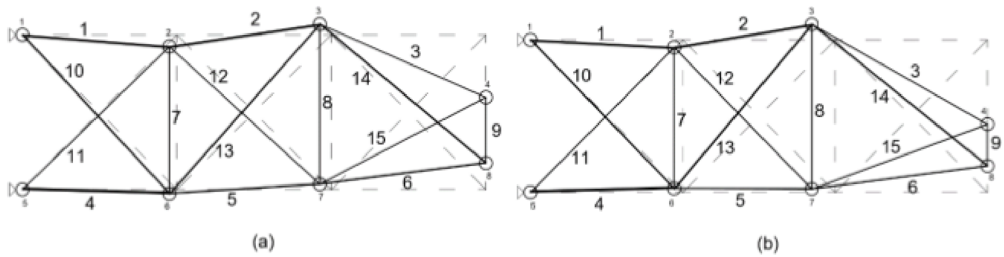

Figure 5. Iteration of 15-bar truss structure with non-deterministic load: (a) iteration number 100; (b) iteration number 1000.

Table 2. Final design of size and shape for the 15-bar truss with the non-deterministic load.

Variable	SOS	Variable	SOS
A1 (in^2)	0.954	A14 (in^2)	0.539
A2 (in^2)	0.954	A15 (in^2)	0.111
A3 (in^2)	0.111	X2 (in)	113.151
A4 (in^2)	1.333	X3 (in)	221.644
A5 (in^2)	0.539	Y2 (in)	114.121
A6 (in^2)	0.44	Y3 (in)	132.255
A7 (in^2)	0.111	Y4 (in)	53.554
A8 (in^2)	0.111	Y6 (in)	2.923
A9 (in^2)	0.111	Y7 (in)	2.582
A10 (in^2)	0.539	Y8 (in)	20.558
A11 (in^2)	0.111	Best Weight (lb)	87.314
A12 (in^2)	0.111	Average (lb)	92.2
A13 (in^2)	0.539	Stdev	4.018

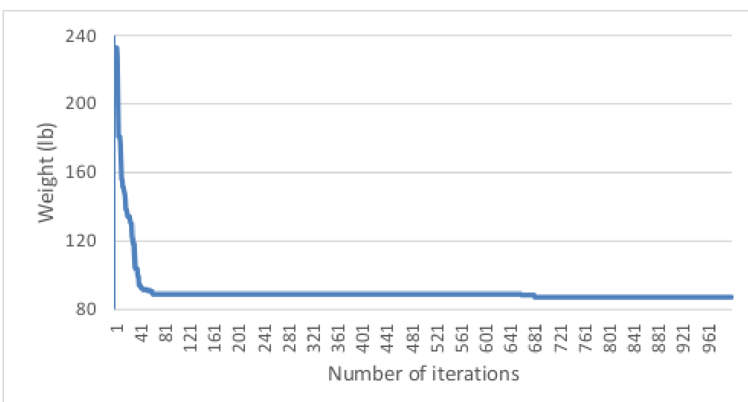

Figure 6. Convergence behavior for the size and shape for 15-bar truss with the non-deterministic load.

Conclusion

This paper compared the size and shape optimization result in 15-bar planar truss structure with deterministic and non-deterministic load using SOS by reviewing two case studies. With the same number of function evaluation for each case, the result showed that uncertainty of load makes significant changes in size and shape optimization. Case with the non-deterministic problem needs to be designed with a larger size of steel which leads to increase weight. This paper shows that RBDO is important in structure design and cannot be neglected.

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