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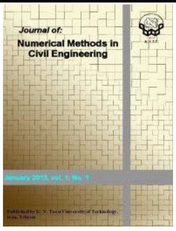

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Reliability-based multi-objective optimal design of spatial trusses using NSGA-II

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Abstract:

This paper addresses a reliability-based multi-objective design method for spatial truss structures. The uncertainties of the applied load and the resistance of the truss members have been taken into account by generating a set of 50 random numbers. The failure probability of each truss member has been evaluated and consequently, the failure probability of the entire truss system has been calculated considering a series system. A multi-objective optimization problem has been defined with objective functions of truss weight and failure probability of the entire truss structure. The cross-sectional area of the truss members has been considered as the design variable. Also ,The limitations of nodal displacements and allowable stress of the members have been defined as constraints. A 25-bar benchmark spatial truss has been considered as the case study structure and has been optimally designed using the non-dominated sorting genetic algorithm II (NSGA-II). The results show thr effectiveness and simplicity of the proposed method which can provide a wide range of optimal solutions through Pareto fronts. These optimal solutions can provide both safety and reliability for the truss structure. Also, the results indicate that the failure probability of the truss structure reduces by increasing the uncertainty level of load and resistance.

1. Introduction

Truss structures are one of the most important structures in civil engineering and have been widely used in different applications such as bridges, transmission towers, outriggers, roofs, etc. Over the decades, designing truss structures to satisfy both safety and economic requirements has received much attention and several studies have addressed this issue [1-10]. These studies have imposed limitations on nodal displacements and axial stress of the members as a safety criterion as well as limitation on truss weight as an economic criterion. The optimization techniques have been taken to design truss structures considering these limitations as objective functions or constraints in a deterministic framework. However, different sources of uncertainties within, design variables, material properties, and applied load exist and may reduce the probabilistic performance of the truss structure.

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Indeed, the main shortcoming of the previous studies is the lack of direct relevance between design criterion and the reliability of the truss structure. An accurate and reliable design of truss structures entails a probabilistic framework which explicitly involves the failure probability of the entire truss structure in the design process.

Several attempts have been made to limit the failure probability of the truss structure majorly as constraints in optimization-based procedures. Papadrakakis *et al.* [11] have considered the objective function of minimization of the structure weight while satisfying the probabilistic constraints. Yadav and Ganguli [12] optimized truss structures and laminated composite plates considering failure probability as a constraint. They have used Monte Carlo simulation to obtain the probability of failure.

Considering the uncertainties in design process of structures, the robust design optimization has been proposed. The aim of this method is to minimizing the probabilistic properties of the objective function, such as expectation value or standard deviation. Doltsinis and Kang [13] converted a multi-objective optimization problem to a single-objective optimization problem by introducing weighting coefficients for expectation value and standard deviation of the objective function. Lee and Park [14] designed truss and frame buildings using weighting coefficients. They linearized the constraint function using Taylor's series first-order approximation. Therefore, the robust optimization problem was converted to a deterministic optimization problem. Sandgren and Cameron [15] have used Monte Carlo simulation to determine the expectation value and standard deviation of the constraint function. They have used this method for topology optimization of a truss structure and an automotive inner body panel. Recently, the minimization of both weight and failure probability of the truss structure has been considered multiple-objective functions and a game theory procedure has been used to design an optimal truss by the authors [16]. However, in this case, only one solution (i.e., optimal truss) has been designed. This study has been performed to determine several optimal solutions for truss design through Pareto fronts using (non-dominated sorting genetic algorithm-II) NSGA-II method. Therefore, the aim is to shed light on the multi-objective optimization problem of truss design.

2. Reliability of truss structures

2.1 Failure definition

Failure definition is an essential task in determining the failure probability of each component and the entire structure as well. According to the reliability theory, the failure could be defined by performance function or limit state function as follows [17]:

$$g = R - Q \tag{1}$$

in which, R denotes the resistance and Q represents the load effect. Both R and Q are random variables.

When g<0, the load effect exceeds the resistance, then the performance is undesirable and the component is failed. Conversely, when g≥0, the performance is desirable and the component is safe. Consequently, the probability of failure, P_f, is the probability that the undesired performance occurs and could be expressed as:

$$P_f = P(R - Q < 0) = P(g < 0) \tag{2}$$

In this paper, the uncertainties have been accounted for both the applied load and the resistance of the truss members by generating random numbers. The uncertain applied loads cause the random stress demand in each element of the truss structure. On the contrary, randomness has also been considered for yielding and buckling stress capacity of truss elements.

2.2 Failure probability of truss element

Several methods could be used for estimating the failure probability of a truss element. As a common approach, a reliability index denoted by β has been introduced by Hasofer and Lind [18] as follows:

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \tag{3}$$

where μ and σ respectively denotes mean and standard deviation. By assuming a normal distribution for both random variables R and Q, the probability of failure could be derived by:

$$P_f = \Phi(-\beta) \tag{4}$$

in which Φ is the standard normal cumulative distribution function. This equation represents the failure probability of a single truss element, while the failure probability of the entire truss structure is required.

2.3 Failure probability of the entire truss system

Determining the failure probability of a truss structure is a challenging task which should be performed properly. Indeed, it is important to distinguish that the failure of a single element may or may not cause the failure of the entire structure. The truss system configuration is within series and parallel systems. In a series structural system, the failure of each element leads to immediate failure of the whole system. A definite truss and an indefinite truss with brittle elements are examples of series systems. Conversely, in a parallel system, all of the elements must fail before the system fails. An indefinite truss structure with ductile elements behaves similarly to a parallel system. In this paper, the case study truss structure is assumed to be an indefinite truss with brittle elements and thus, it is categorized as a series structural system. The failure probability of a series structural system belongs to the following range [17]:

$$\max(P_{f-i}) \leq P_{f-sys} \leq 1 - \prod_{i=1}^{N_e} \left(1 - P_{f-i}\right) \tag{5}$$

where $P_{f\text{-}sys}$ is the failure probability of the system, $P_{f\text{-}i}$ is the failure probability of the i-th element, and N_e is the number of truss elements. In a series system, the failure probability of the system depends on the statistical dependence among failures of elements. The lower bound is the failure probability of the system when all elements are fully coupled. The upper bound relates to the case that all elements are uncorrelated and statistically independent. This upper bound provides a conservative estimate of failure probability and it is commonly used for series systems in the literature [19-21]. In this paper, the case study truss structure is an indefinite truss with brittle elements and it is assumed that the failure of its elements is uncorrelated. Hence, the failure probability of this system could be evaluated by the upper bound of the Equation (5) which is as follows:

$$P_{f-sys} = 1 - \prod_{i=1}^{N_e}\left(1 - P_{f-i}\right)$$
$$= 1 - \left[\left(1 - P_{f-1}\right)\left(1 - P_{f-2}\right) * \dots * \left(1 - P_{f-N_e}\right)\right] \quad (6)$$

3. Multi-objective optimization problem of truss structure

In many realistic engineering problems, it is required to satisfy some different objectives that conflict with each other. The multi-objective optimization is a practical method to solve such problems and represents Pareto optimal solutions instead of a single solution. The Pareto optimal solutions do not dominate each other. Generally, the definition of a multi-objective optimization problem is as follows:

$$\begin{aligned}
&Find &&: \mathbf{X}^* = [X_1^*, X_2^*, \dots, X_n^*]^T \\
&Optimize &&: \mathbf{f}(\mathbf{X}) = [f_1(\mathbf{X}), f_2(\mathbf{X}), \dots, f_m(\mathbf{X})]^T \\
&Subject\ to &&: g_i(\mathbf{X}) \geq 0, \quad i = 1,2,\dots,p \\
& && \quad h_i(\mathbf{X}) = 0, \quad i = 1,2,\dots,q
\end{aligned} \quad (7)$$

where **f** is the vector of m number of objective functions. **X** denotes the vector of design variables which may have several solutions such as $\mathbf{X}^*$. Also, n is the number of design variables and m is the number of objective functions. The inequality constraints, $g_i(X)$, and the equality constraints, $h_i(X)$, with the number of p and q, respectively, should be satisfied.

The multi-objective optimization problem to design the spatial truss structure is defined as follows:

$$\begin{aligned}
&Find &&: \mathbf{X}^* = [A_1^*, A_2^*, \dots, A_{nv}^*]^T \\
&Optimize &&: f_1 = W = \sum_{i=1}^{n} \gamma_i A_i L_i \\
& && \quad f_2 = P_{f-sys} \\
&Subject\ to &&: \delta_{min} \leq \delta_i \leq \delta_{max}, \quad i = 1,2,\dots,p \\
& && \quad \sigma_{min} \leq \sigma_{T,i} \leq \sigma_{max}, \quad i = 1,2,\dots,q \\
& && \quad \sigma_i^b \leq \sigma_{C,i} \leq 0, \quad i = 1,2,\dots,ns \\
& && \quad A_{min} \leq A_i \leq A_{max}, \quad i = 1,2,\dots,nv
\end{aligned} \quad (8)$$

in which W is the weight of the truss structure. p and q are respectively the numbers of nodes and members of the truss. Also, ns is the number of compression members and nv is the number of design variables. L_i is the length of i-th element. A_i is the cross-section area of the i-th member. σ and δ are stress and nodal deflection, respectively. σ^b is allowable buckling stress when the member i-th is in compression. This constrained optimization problem is reformulated into an unconstrained optimization problem according to the penalty method [22] and the new objective functions are as follows:

$$\begin{aligned}
&F_1 = \alpha f_1 + \beta(\max[0, g_1] + \max[0, g_2] + \max[0, g_3]) \\
&F_2 = \alpha f_2 + \beta(\max[0, g_1] + \max[0, g_2] + \max[0, g_3]) \\
&g_1 = \frac{|\delta_i|}{\delta_{max}} - 1, g_2 = \frac{\sigma_{T,i}}{\sigma_{max}} - 1, g_3 = \frac{\sigma_{C,i}}{\sigma_i^b} - 1
\end{aligned} \quad (9)$$

α and β are penalty parameters that can be determined either through parametric study or by trial and error. The values of α=1 and β=200 have been considered.

4. Multi-objective optimal design using NSGA-II

Several metaheuristic algorithms have been proposed for solving optimization problems [23-27]. The genetic algorithm, GA, is one of the most practical algorithms which is inspired by the evolution process in nature. The GA was been developed first by Holland [28] and it is widely used in engineering applications [29] due to its simplicity and effectiveness for solving nonlinear optimization problems. The GA has three main operations, including selection, crossover, and mutation [30].

A common technic for solving multi-objective problems in the literature is converting them to a single objective optimization problem [31]. Nevertheless, the main drawback of these methods is the requirement of several runs using various adjustments and even a considerable portion of Pareto front may not be discovered. Therefore, other algorithms have been proposed to solve the multi-objective optimization problem directly and detect the Pareto answers in a single run.

Srinivas and Deb [32] have developed the non-dominated sorting genetic algorithm, NSGA, which was efficient to solve multi-objective optimization problems. Further, this algorithm has been improved to version II [33] and version III [34] to overcome some disadvantages including high processing cost and lack of elitism. For optimization problems with a few objective functions such as this study, the NSGA-II seems efficient and has been used in solving the multi-objective optimization problem.

Figure 1 illustrates the flowchart of the NSGA-II method to solve the multi-objective optimization problem of designing truss structure. The NSGA-II is comprised of nine operations including, Initialization, fitness, evaluation, non-dominated sorting, crowding distance evaluation, selection, crossover, mutation, combination, and truncate. Initially, a random population P with the size of N_{ind} is generated. Then, the fitness of each individual is calculated via each objective function. Following, these individuals are sorted based on the non-domination concept and placed into successive Pareto fronts. The crowding distance calculates how close an individual is to its neighbors. Then, the GA operators, including selection, crossover, and mutation are conducted to generate a new_born population Q with size N_{new}. The population R=P+Q contains the current and the new_born populations to ensure the elitism of the best individuals. Finally, the population is truncated to the size N_{ind} based on the rank values. This process of optimization is repeated until reaching the maximum number of generations.

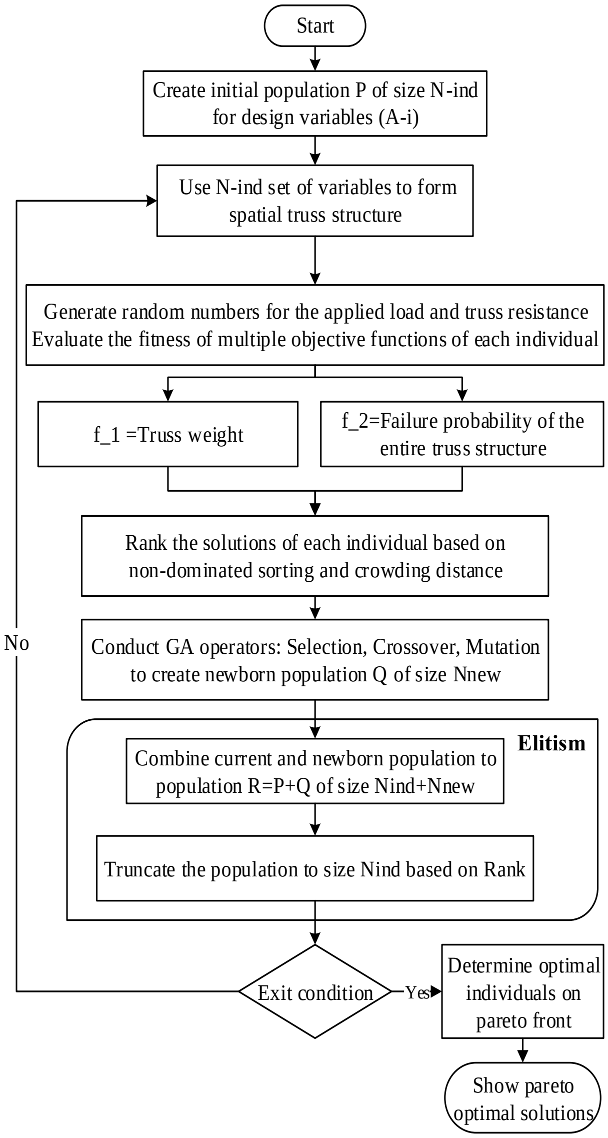

Fig. 1: Flowchart of multi-objective optimal design of spatial truss structure based on NSGA-II method

5. Numerical analysis and discussion

In this section, the methodology of reliability-based multi-objective optimal design of truss structures has been explained through numerical analysis. A bi-objective optimization problem including the objectives of minimization of the truss weight as well as the probability of failure of the entire truss structure, has been defined. The NSGA-II method has been used for solving the bi-objective optimization problem and determine the Pareto optimal solutions. The cross-section areas of the truss elements have been considered as design variables. Also, the nodal displacements and stress of elements have been constrained.

5.1 Twenty five-bar spatial truss

In this paper, a 25-bar benchmark spatial truss structure has been considered as the case study structure. This benchmark truss structure has been previously studied in several researches [1-7]. The topology and nodal and element numbers of this truss structure have been illustrated in Figure 2. This truss structure has been subjected to two different load cases as represented in Table 1. The density and elasticity modulus of the material are considered the values of 0.1 lb/in^3 (2767.99 kg/m^3) and 10000 ksi (68950 Mpa), respectively. The elements of the truss have been categorized into eight groups in terms of cross-section area, including: (1) A_1, (2) A_2-A_5, (3) A_6-A_9, (4) A_{10}-A_{11}, (5) A_{12}-A_{13}, (6) A_{14}-A_{17}, (7) A_{18}-A_{21}, (8) A_{22}-A_{25}. The maximum displacement of all nodes is imposed to be within ± 0.35 in (8.89 mm) in every direction. The tensile stress is constrained to be below the value of 40 ksi (275.8 Mpa) and the limitations of the compressive stress are considered according to Table 2. The cross-section area varies in the range of 0.01 to 3.4 in^2 (0.6452-21.94 cm^2).

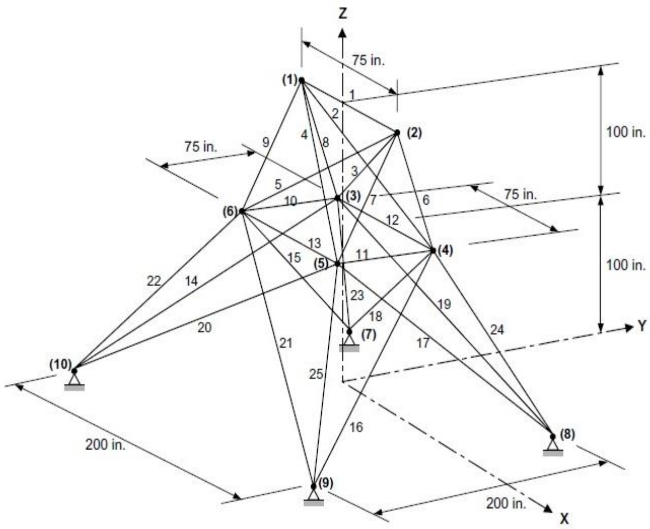

Fig. 2: The 25-bar spatial truss [7]

Table 1: The load case for the spatial truss

Load case	Nod e	P_X kips (kN)	P_Y kips (kN)	P_Z kips (kN)
Case 1	1	0	20 (89)	-5 (22.25)
	2	0	-20 (89)	-5 (22.25)
Case 2	1	1 (4.45)	10 (44.5)	-5 (22.25)
	2	0	10 (44.5)	-5 (22.25)
	3	0.5 (2.22)	0	0
	6	0.5 (2.22)	0	0

Table 2: The limitations of compressive stress for the spatial truss members

	Element group	Compressive Stress ksi (Mpa)
1	A_1	35.092 (241.96)
2	A_2~A_5	11.590 (79.913)
3	A_6~A_9	17.305 (119.31)
4	A_{10}~A_{11}	35.092 (241.96)
5	A_{12}~A_{13}	35.092 (241.96)
6	A_{14}~A_{17}	6.759 (46.603)
7	A_{18}~A_{21}	6.959 (47.982)
8	A_{22}~A_{25}	11.082 (76.410)

5.2 Uncertainties of load and resistance

Properly accounting on the effects of uncertainties is a crucial task in the reliability assessment of truss structures. The significant uncertainties involved in this problem are uncertainties of the applied load and the resistance of the truss members. The effects of load uncertainties are taken into account by modeling them as random variables. Therefore, random variables with normal distribution have been generated for all loads applied to the truss structure. According to Table 1, two load cases including 11 separate loads, have been applied to the truss structure. It has been assumed that these loads are statistically independent. For each of these loads, 50 normal random numbers with the mean values according to Table 1 and different coefficient of variations (CoVs), including 0.1, 0.2, 0.3, and 0.4, have been generated.

The uncertainty in the resistance of the truss members has been considered by taking into account the allowable stress of truss members as random variables. The mean value of tensile stress has been taken 40 ksi (275.8 Mpa) and the mean values of compressive stresses have been considered according to Table 2. Different CoVs, including 0.01, 0.05, and 0.1, have also been considered for them.

5.3 Reliability assessment of the truss structure

In this section, the reliability of the 25-bar spatial truss with the previously designed cross-sectional area of the members has been assessed. Several studies have been addressed the optimal design of this truss structure in a deterministic framework [1-7]. In these studies, the optimization problem of equation (8) without consideration of the second objective function, the failure probability of the truss, has been evaluated. Thus, only the objective function of minimization of the truss weight under the assumption of deterministic load and resistance has been intended. As sample, the results of works performed by Kaveh and Talatahari [7] have been assessed. The optimal cross-section areas of the eight groups of truss members and the corresponding truss weight of these works have been reported in Table 3.

Table 3: Optimal cross-sectional area of truss members and truss weight

	Element group	Kaveh and Talatahari [7]	
		in^2	cm^2
1	A_1	0.010	0.065
2	A_2~A_5	1.993	12.856
3	A_6~A_9	3.056	19.717
4	A_{10}~A_{11}	0.010	0.065
5	A_{12}~A_{13}	0.010	0.065
6	A_{14}~A_{17}	0.665	4.293
7	A_{18}~A_{21}	1.642	10.594
8	A_{22}~A_{25}	2.679	17.281
weight		545.16 lb	2425 N

The uncertainties of the applied load and members' allowable stress have been considered by generating normal random numbers. The failure probability of each member has been calculated by equation (4) and the failure probability of the entire truss has been evaluated by equation (6). Table 4 represents the failure probability of each member and the entire truss system by considering the CoV of 0.2 and 0.05 for load and resistance, respectively.

The failure probabilities of the entire truss structure with different CoVs for load and resistance have also been reported in Table 5. It seems that generally, the failure probability of the truss is amplified by increasing the level of uncertainties in resistance.

Table 4: The failure probability of each member under two load cases

Element number	P_f under load case 1	P_f under load case 2	Maximum P_f
1	3.22657e-60	1.58599e-59	1.58599e-59
2	0.00037	6.38464e-22	0.00037
3	6.02146e-46	8.34645e-27	8.34645e-27
4	1.16521e-45	9.76495e-73	1.16521e-45
5	0.00041	5.85352e-72	0.00041
6	1.01730e-51	8.42004e-35	8.42004e-35
7	9.38051e-14	3.99225e-70	9.38051e-14
8	3.99817e-14	4.77697e-34	3.99817e-14
9	1.28088e-50	3.42804e-68	1.28088e-50
10	1.47452e-76	6.70770e-77	1.47452e-76
11	1.44007e-77	1.25741e-76	1.25741e-76
12	6.93282e-71	6.92197e-65	6.92197e-65
13	4.16909e-69	1.50471e-80	4.16909e-69
14	0.00053	0.02703	0.02703
15	2.21834e-60	2.952317e-61	2.21834e-60
16	7.38021e-61	0.07453	0.07453
17	0.00109	1.01778e-63	0.00109
18	8.09802e-50	1.75182e-06	1.75182e-06
19	0.58134	2.02725e-05	0.58134
20	0.62966	1.36176e-71	0.62966
21	9.95950e-49	4.74842e-71	9.95950e-49
22	2.82709e-13	1.43733e-61	2.82709e-13
23	2.37910e-17	3.11733e-11	3.11733e-11
24	4.13807e-14	4.57208e-09	4.57208e-09
25	2.69044e-16	2.03856e-64	2.69044e-16
Failure probability of the entire truss (%)			86.07

Table 5: The failure probability of the entire truss (%)

		CoV of allowable stress		
		0.01	0.05	0.1
CoV of the load	0.1	81.58	81.26	81.87
	0.2	86.03	86.07	86.42
	0.3	83.69	84.05	85.23
	0.4	81.49	82.02	83.52

5.4 Reliability-based multi-objective optimal design of truss structure

In this section, the reliability-based multi-objective method has been used to design an optimal cross-sectional area of the 25-bar spatial truss. According to Equation (8), the two objective functions of minimization of the truss weight and minimization of the failure probability of the entire truss system have been considered in the multi-objective optimization problem. The cross-sectional areas of the truss members are the design variables. The optimal values of the design variable are searched within the pre-defined domains in the optimization process. The upper and lower bounds of these domains affect the convergence speed. However, if they include the optimal answer, they have no significant effect on the final answer. In order to provide an acceptable convergence speed, the search domain of design variables has been selected 0.01 to 3.4 in^2 (0.6452-21.94 cm^2) according to [7]. The multi-objective optimization has been solved frequently, where the parameters of the GA have been selected as presented in Table 6.

Table 6: Parameters of GA

N_{ind}	Number of individuals in each generation	50
N_{new}	Number of newborns	18
m_r	Mutation rate	0.02
N_{max}	Maximum number of generations	300

In order to ensure an accurate design, at least ten discrete simulation runs of NSGA-II with different initial individuals have been performed. The optimization process has been conducted for different levels of uncertainties for both the applied load and allowable stress. Figure 3 shows the Pareto optimal answers of four different runs correspond to CoV of applied load equal to 0.2 and CoV of allowable stress equal to 0.1. It is observed that all 50 individuals have stood on Pareto front. Also, it seems that different Pareto fronts are almost coincident with each other, which confirms the convergence of the algorithm. It is also evident that the lower values of failure probability of the truss structure could be obtained. As an example, the failure probability of 25% is obtained with the truss weight near 575 lb and the failure probability of 10% is provided with the truss weight about 600 lb.

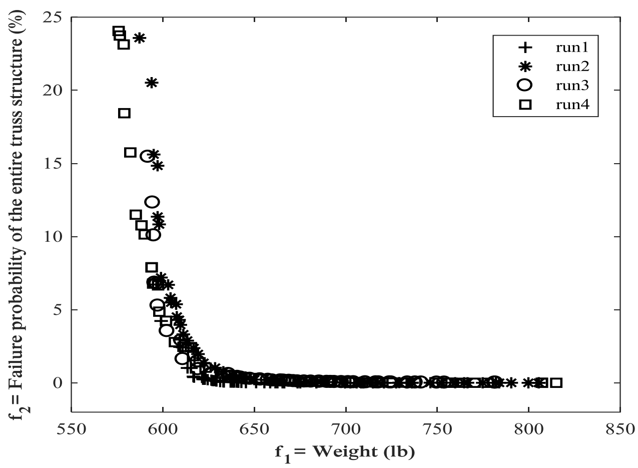

Fig. 3: The Pareto optimal answers of the multi-objective optimization problem for CoV load=0.2 and CoV allowable stress=0.1

In comparison with the previously designed truss, by considering only the minimization of the truss weight, it could be stated that assessing only the truss weight as a cost criterion will devote the safety of the truss. As an example, the failure probability of the truss structure with this level of uncertainty in load and resistance has been evaluated about 86% according to Table 5. Note that the weight of truss structure was achieved about 545 lb. For instance, by comparing this solution with the optimal truss with the weight of 575 lb and the failure probability of 25% it could be concluded that the optimal solution determined by the proposed method can reduce the failure probability about 61% while the truss weight has increased only 5%. Accordingly, the reliability-based multi-objective optimal design of truss structure can provide several design scenarios via the Pareto fronts, which can consider the safety criterion along with the cost criterion. The multi-objective optimization problem of designing the spatial truss has been solved frequently, considering different levels of uncertainties within the applied loads and allowable stress of truss members. Figures 4 to 7 show the Pareto fronts of the optimal truss structures with different levels of uncertainties for the applied load, including the CoVs of 0.1, 0.2, 0.3, and 0.4, respectively. Each of these figures contains the Pareto fronts with the uncertainties of allowable stress, including the CoVs of 0.01, 0.05, and 0.1. Also, the Pareto fronts of the optimal truss structures with different level of uncertainties for the allowable stress including the CoVs of 0.01, 0.05, and 0.1, respectively, are compared in Figures. 8 to 10. As a main result, it could be concluded that increasing the level of uncertainty of the resistance leads to an increment in the failure probability of the entire truss system which is more evident in Figures 7 and 10. It is noteworthy to mention that, for the reliability-based design of truss structures, it is more appropriate that the reliability index is greater than 2.5, which corresponds to the failure probability of 0.00621. As a sample, according to the results, the designed trusses with the failure probability of 0.6% have the weight of 601 lb, 603 lb, 721 lb and 683 lb, respectively, for load CoVs of 0.1, 0.2, 0.3, and 0.4 with allowable stress CoVs of 0.05.

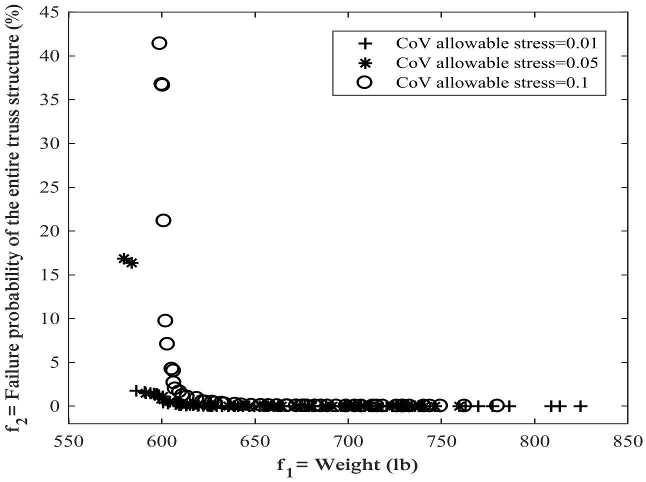

Fig. 4: The Pareto optimal answers of the multi-objective optimization problem for CoV load=0.1

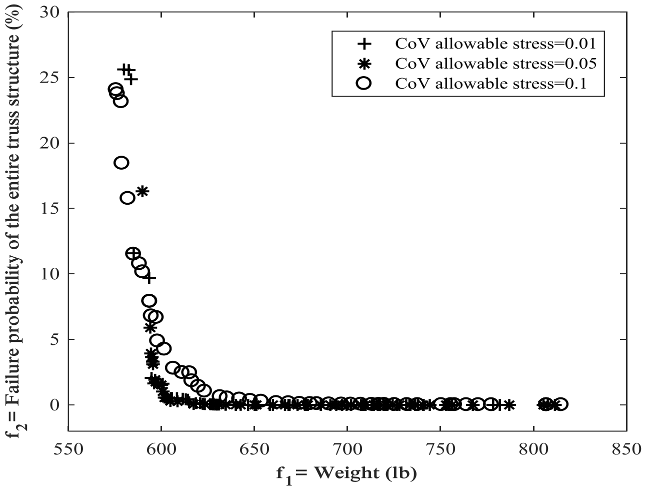

Fig. 5: The Pareto optimal answers of the multi-objective optimization problem for CoV load=0.2

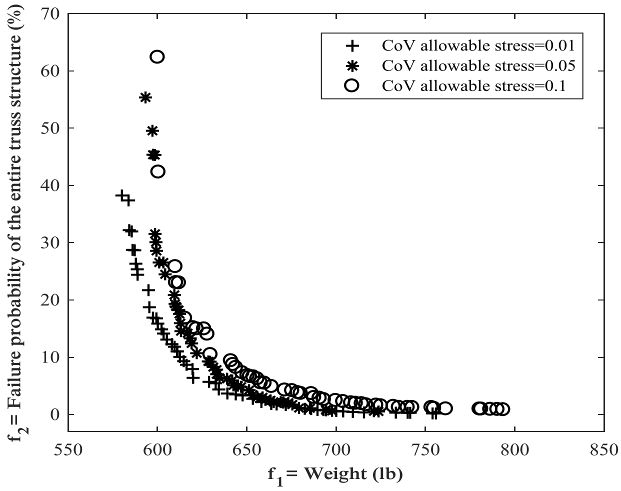

Fig. 6: The Pareto optimal answers of the multi-objective optimization problem for CoV load=0.3

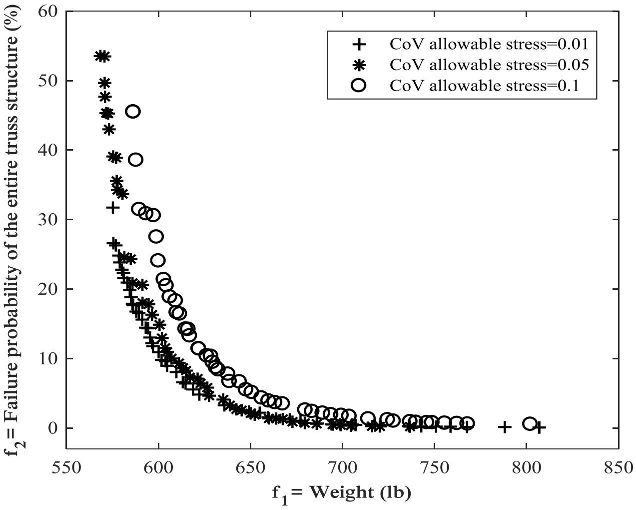

Fig. 7: The Pareto optimal answers of the multi-objective optimization problem for CoV load=0.4

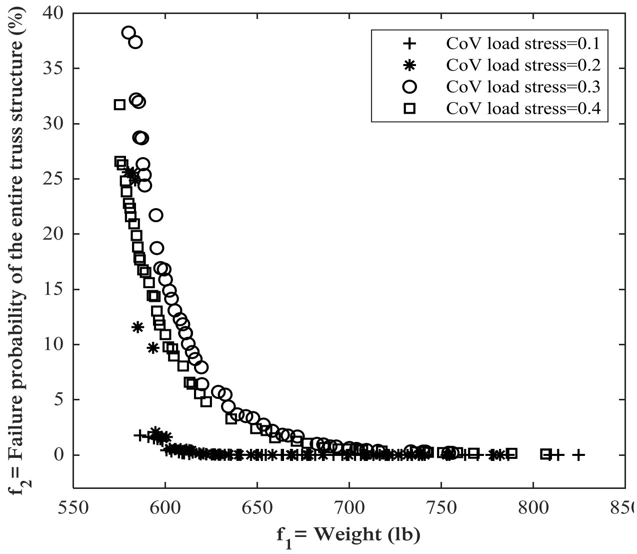

Fig. 8: The Pareto optimal answers of the multi-objective optimization problem for CoV allowable stress=0.01

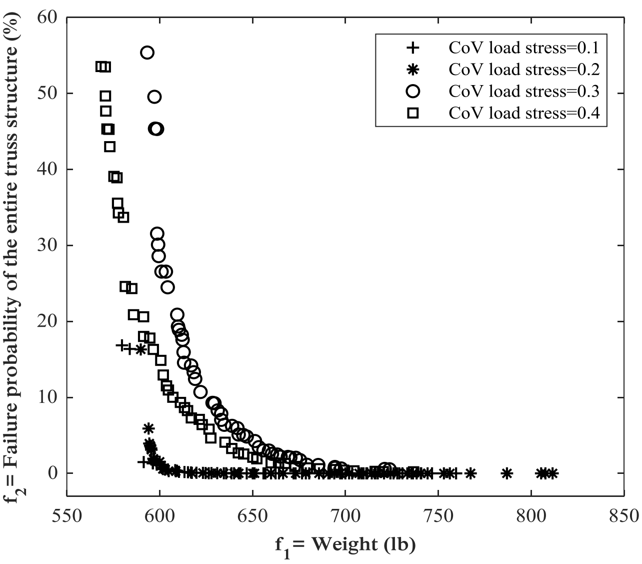

Fig. 9: The Pareto optimal answers of the multi-objective optimization problem for CoV allowable stress=0.05

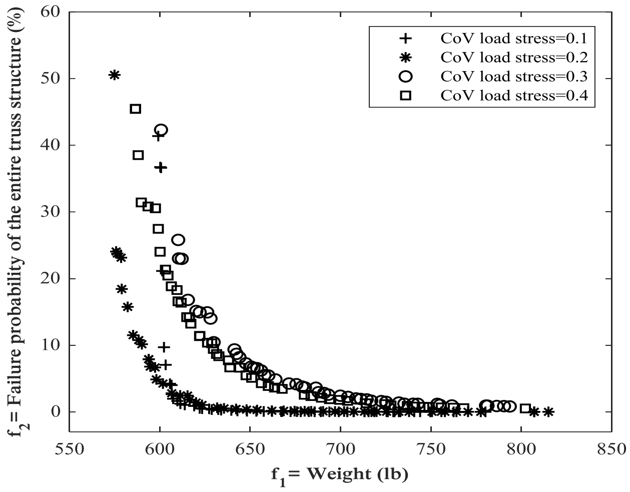

Fig. 10: The Pareto optimal answers of the multi-objective optimization problem for CoV allowable stress=0.1

6. Conclusions

This paper presents a reliability-based multi-objective optimal design method to design spatial truss structures while accounting for the uncertainties of the applied load and allowable stresses of the truss members. The methodology is based on defining a multi-objective optimization problem and solving it using an improved version of the non-dominated sorting genetic algorithm, NSGA-II. The aim is to provide both cost criterion by minimizing the truss weight as well as safety criterion by minimizing the failure probability of the entire truss structure. For illustration, the method has been applied to design optimal cross-sectional areas of the members of a 25-bar benchmark spatial truss structure. The Pareto fronts of the optimal truss have been derived for different uncertainty levels of load and resistance. Numerical studies have shown the capability and simplicity of the applied method in designing cross-sectional areas of the truss elements. This method has led to derive a wide range of optimal design solutions throughout the resulted Pareto fronts, which provide various optimal choices regarding both cost and safety criteria. The results show that the failure probability of the truss structure reduces by increasing the uncertainty level of the resistance. The failure probability of the 25-bar truss structure under the considered load cases with the previously deterministic design was about 86%, while the proposed method has introduced an optimal solution with the failure probability of 25% and only with 5% increment in truss weight.

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