IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: J Aloysius *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **907** 012010

Optimization of concentrically braced steel frame structures based on SNI 1726:2019, SNI 1727:2020, SNI 1729:2020, and AISC 341-16

J Aloysius[1,2], J A Sumito[1], D Prayogo[1] and H Santoso[1]

[1] Department of Civil Engineering, Faculty of Civil Engineering and Planning, Petra Christian University, Surabaya, Indonesia

[2] Corresponding author: b11170103@john.petra.ac.id

Abstract. Damages resulted from earthquakes are a loss in the economic sector. The structure of multi-story buildings needs an earthquake-proof design with higher performance to reduce such losses. By utilizing the metaheuristic algorithm, this study aims to identify the most compatible brace configuration and profile used in a concentrically braced steel frame structures with minimal total weight and that will meet the safety requirements. This algorithm is suitable owing to the fact that it is able to find solutions to any known optimization problem either through Particle Swarm Optimization (PSO), Symbiotic Organisms Search (SOS), or Differential Evolution (DE). The performance of these algorithms will demonstrated in a form of comparison through a case study of optimizing a 5-span, 6-story steel frame structure. These systems will determine the lightest frame weight, which also correlates to a lower construction cost, without compromising the constraints of SNI 1726:2019, SNI 1727:2020, SNI 1729:2020, and AISC 341-16. Based on the results of data processing, SOS is shown to achieve the highest algorithm performance compared to PSO and DE.

1. Introduction

The concentrically braced steel frame structure is one of the most effective and economic lateral load-bearing structures [1]. The concentrical brace placement is the main factor that affects the structure's performance during an earthquake. Therefore, finding the correct settings of the brace member is one of the main challenges in designing a steel frame structure [2]. Although the trial-and-error method is still possible to be used in the field, this does not always lead to the best result due to the sheer number of possibilities of the brace placement. Therefore, the structure incorporates the methodology of optimizing the angles of diagonal members along the height of multi-story buildings in the context of brace-placement optimization [3].

Based on Oteiza, Rodriguez, and Brignole, metaheuristics are able to solve multiple-objective multiple-solution and nonlinear formulations, so they are utilized to settle high-quality solutions to increasingly complex real-world problems, namely the combinatorial ones [4]. Furthemore, these algorithms are calculated for optimization problems that are elaborate where the traditional heuristics and optimization algorithms show the ineffectiveness and inefficience. Officially, a metaheuristic can be elucidated as the generation process that is continual, so it can lead a subordinate heuristic with intelligent combinations of various concepts for exploring and exploiting the search space. Moreover, the learning strategies can be applied to structure information to find the efficient near-optimal results

[5]. Structural optimization can be done through several metaheuristic algorithms, e.g., Genetic Algorithm (GA) [6], Ant Colony Optimization (ACO) [7], Differential Evolution (DE) [8], Particle Swarm Optimization (PSO) [9], and Symbiotic Organisms Search (SOS) [10].

The main benefit of the PSO algorithm lies in its simple concept, easy implementation procedures, and efficiency in its calculation [11], whereas the main benefit of SOS requires no specific parameter for its operation unlike the other algorithms [10]. DE is the evolution of GA, with a shorter calculation time and fewer iterations in its optimization process [12].

There has been a study on the optimization of concentrically braced steel frame structures on 3-story and 5-story buildings using various metaheuristic algorithms [13]. That study succeeded in showing the better standard deviation of DE compared to GA, ACO, Big Bang–Big Crunch (BB-BC), and PSO. This study investigates the behavior of a mid-rise building because in order to examine a new approach, the study of a building with simpler behavior needs to be conducted first. A 6-story building is considered as a representative of a mid-rise building. If this study is successful, it can be applied to a higher level of building.

This study aims to discover which metaheuristic algorithm has the best performance in finding the most compatible brace configuration and profile to design a structure with minimal total weight, and satisfies the safety standard. This paper discusses the optimization based on PSO, SOS, and DE algorithms, and summarizes optimization results of the multi-story steel structure based on SNI 1726:2019, SNI 1727:2020, SNI 1729:2020, and AISC 341-16.

2. Metaheuristic Algorithms

A metaheuristic is a advanced-level mechanism that guides the searching process in a certain space efficiently to produce the best and optimal solution to be applied to various problems [14]. Metaheuristic can be viewed as a general framework that can be applied to various optimization problems with relatively few modifications to adapt to a certain condition. Metaheuristic plays a huge role in solving various optimization problems, especially in the civil engineering world where an optimal result is always demanded, both in terms of the design and its implementation.

The aim of this study is to minimize the total weight of the structure. The objective function of this study is as follows:

$$f(X) = \gamma \sum_{i=1} A_i L_i \quad (1)$$

where $f(X)$ is objective function, γ is the density, A_i is the cross sectional area of ith member, and L_i is the length of ith member.

In order to optimize the brace configuration and profile used in steel frame structures, constraints are used to ensure the design result will not fail. The inter-story drift and stability requirements are taken from SNI 1726:2020 in which design story drift should not exceed 2% of the story height below level x, and the value of θ should not be higher than 0.01 to make sure the P-Delta effect is not included. The profile capacity should satisfy the requirements of both AISC 341-16 and SNI 1729:2020 specification. The structures need to be checked using the interaction formula taken from SNI 1729:2020 to make sure the combination of axial and bending forces does not cause the structures to fail. Members also need to satisfy the profile capacity requirements and the interaction formula when the structures are applied with capacity design concept as a structure is loaded with the yielding forces of the braces in exchange for the earthquake loads. Table 1 shows the constraints used in the optimization process are based on SNI 1726:2019, SNI 1729:2020, and AISC 341-16.

Table 1. Constraints used in optimization process.

Constraint		Design Requirements	Designation Code
$g_1(X)$	Inter-story drift	$\leq 0.02h_{sx}$	SNI 1726:2019
$g_2(X)$	Stability	≤ 0.01	SNI 1726:2019
$g_3(X)$	Profile capacity	$\leq R_u$	AISC 341-16 and SNI 1729:2020
$g_4(X)$	Interaction formula	≤ 1	SNI 1729:2020
$g_5(X)$	Capacity design	$\leq g_3(X), g_4(X)$	AISC 341-16 and SNI 1729:2020

3. Methodology

There are three main phases of this optimization: the analysis of the structure using the Finite Element Method – Direct Stiffness Method (DSM) phase; the search for the structure element profile and optimized brace configuration using the metaheuristic algorithm phase; and the comparison of the optimized result from the PSO, SOS, and DE algorithm phase. The process of structure analysis calculation and optimization with the algorithm is carried out using MATLAB R2017b software. There are 4 different design codes used in this study, which are SNI 1727:2020 [15] for the dead load and live load calculation, SNI 1726:2019 [16] for earthquake load calculation, SNI 1729:2020 [17] for structural steel building's specification, and AISC 341-16 [18] for structural steel building's seismic provisions.

The structure is subjected to a load according to SNI 1727:2020 [15] and then analyzed in order to acquire data in the form of bending moment and axial tension as well as the necessary displacement to be checked against the limits/constraints listed in the requirements for SNI 1726:2019 [16], SNI 1729:2020 [17], and AISC 341-16 [18]. After the first phase, the optimization phase is done using PSO, SOS, and DE algorithms in order to find the structure element profile, the optimal brace configuration, and the lightest total structure weight for the concentrically braced steel frame. The total weight of the frame structure is an objective function with the aim of finding the lightest weight. Total weight of the structure, deviation standard, mean value, and success rate from PSO, SOS, and DE will be compared to determine which algorithm produces the lightest weight efficiently and consistently. The research flowchart is shown in Figure 1.

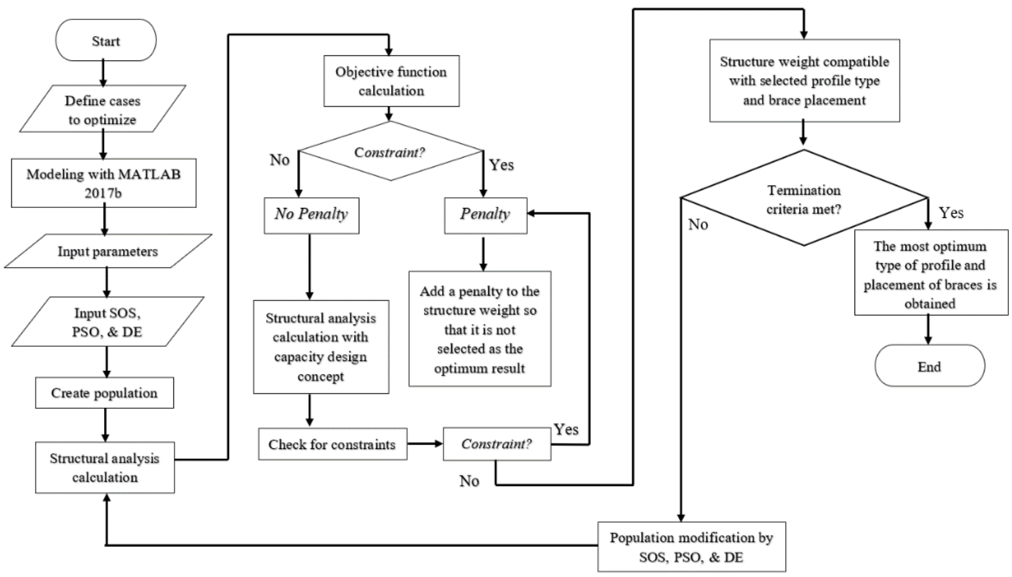

Figure 1. Research Flowchart.

4. Result and discussion

Figure 2 shows a 5-span, 6-story frame structure with element numbering. This structure bears a distributed vertical load on each beam, with a dead load of 6.3 kN/m^2 and a live load of 1.96 kN/m^2. The elements' grouping is as follows:

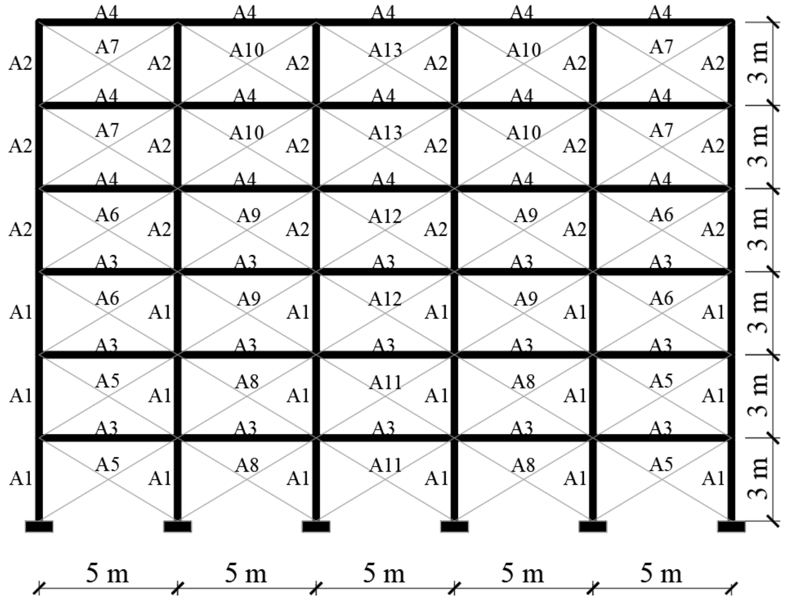

Figure 2. Front view of a 5-span, 6-story frame structure.

The material properties, geometry, and earthquake load of the frame structure are as follow:

Material properties
ρ = 78.5 (kN/m^3), E = 2e8 (kN/m^2), μ = 0.3, and f_y = 248.2 (MPa)

Geometry
Height of each floor = 3.0 m
Width of the frame = 5.0 m
Three degrees of freedom for each joint (x, y-translations and z-rotation)
All connections and supports are rigid

Earthquake load
Earthquake concentrated loads are calculated according to SNI 1726-2019 [16] by considering:
R = 6, I = 1, S_S = 0.75, S_1= 0.35, and seismic design category = E

Earthquake loads acting on 5-span, 6-story frame are shown in table 2.

Table 2. Earthquake loads acting on 6-story frame.

Floor	Earthquake Load (kN)
1	37.37
2	74.75
3	112.12
4	149.49
5	186.87
6	217.43
Base shear	778.02

Hyperparameter of algorithms
The hyperparameters of the algorithms are as follow:
PSO: w = 1, c1 = 2, and c2 = 2
DE: F_{max} = 2, F_{min} = 0, and CR = 0,5.

The optimization of this structure uses an HSS profile for braces based on ASTM A1085. The W profile for the beams and columns is taken from the steel profile table [19]. All data used from the table are calculated thoroughly to ensure the given constraints are not breached. A trial is considered a success if the algorithm is able to produce a value that has not broken any constraint at the last iteration. Based on 30 trials on each of the algorithms, it is found that SOS displays a significant margin of error as it fails to find the optimal solution 11 times compared with DE, which only failed 3 times. However, SOS manages to produce the smallest mean value and standard deviation value out of all, producing 447.74 kN and 67.48 kN while DE as the runner-up generates 464.75 kN and 171.29 kN, respectively. Even though PSO manages to complete 25 out of 30 trials and produces the second-best standard deviation value of 80.19 kN, it still demonstrates the worst performance compared to DE and SOS due to having the biggest mean value of 686.30 kN. In terms of producing the minimum (best) result, SOS and DE are on par because both produce the same number of 350.04 kN while PSO further demonstrate its under-performed capability by producing the largest minimum structure weight of 545.05 kN. Even so, PSO's maximum (worst) result is better than DE with 820.99 kN, weighing up to DE's maximum result of 1028.11 kN while SOS constructs the best result because it constructs the maximum value of 572.29 kN. SOS's failure in consistency of the trial's success is probably due to random initial solutions that were not quite compatible with the constraints and its lack of ability to explore new variables, which results in a value that does not satisfy the constraints. However, SOS excels in exploiting the values it has produced. That is why it has the consistency of producing the minimum result that can be seen from the mean and standard deviation value. Table 3 compares the optimization results of PSO, SOS and DE.

Table 3. Optimization results of 5-span, 6-story frame structure.

Variable	PSO	SOS	DE
A1	0.03607 m^2	0.02224 m^2	0.02224 m^2
A2	0.03076 m^2	0.01077 m^2	0.01077 m^2
A3	0.03098 m^2	0.02355 m^2	0.02355 m^2
A4	0.01077 m^2	0.01077 m^2	0.01077 m^2
A5	0	0	0
A6	0	0	0
A7	0	0.00155 m^2	0.00155 m^2
A8	0.00232 m^2	0.00155 m^2	0.00155 m^2
A9	0	0	0
A10	0	0	0
A11	0	0	0
A12	0.00241 m^2	0.00155 m^2	0.00155 m^2
A13	0.00167 m^2	0	0
Min (kN)	545.05	350.04	350.04
Max (kN)	820.99	572.29	1028.11
Mean (kN)	686.30	447.74	464.75
Standard Deviation	80.19	67.48	171.29
Success Rate	25/30	19/30	27/30
Running Time (hr)	50.09	203.24	47.84

Figure 3 shows the brace placement of the 5-span, 6-story concentrically braced steel frame structure using PSO, SOS, and DE (from left to right, respectively).

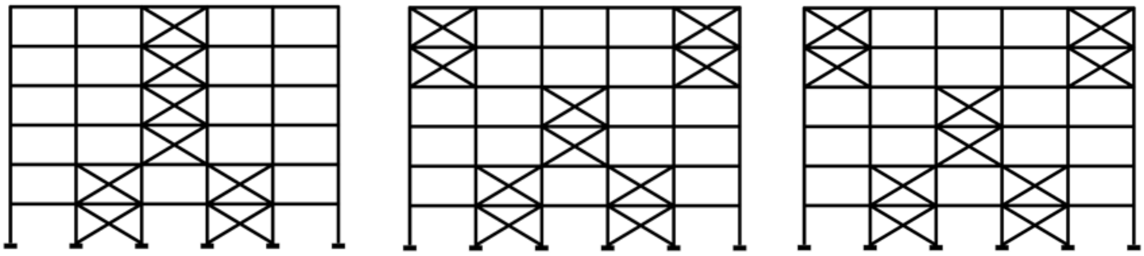

Figure 3. Brace placement of the 5-span, 6-story concentrically braced steel frame structure.

According to the convergence graph shown in figure 4, the DE algorithm is able to produce the most optimal result at the end of the iteration, whereas the SOS is able to produce an optimal result albeit not as light as DE. On the other hand, PSO is shown to construct the heaviest structure weight among all three algorithms. Therefore, it can be said that the performance of DE algorithm is similar to SOS as both of their system processes and final structure share a fair amount of resemblance. Meanwhile, PSO still displays inferiority compared to the other two algorithms in terms of finding the used profile and brace placement in the 5-span, 6-story frame structure.

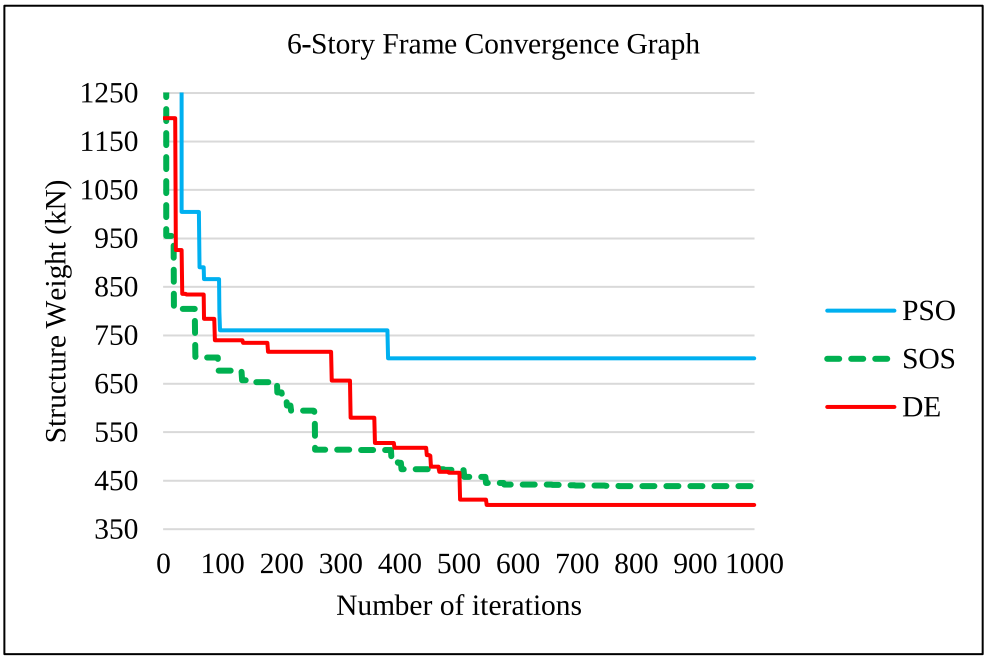

Figure 4. 6-story frame convergence graph

5. Conclusion

Based on the above results, the metaheuristic algorithm proves to be successful in finding the the most compatible brace configuration and profile for a 5-span, 6-story concentrically braced steel frame structure with minimal total weight that satisfies the safety standard. SOS and DE proved to be superior to PSO in the ability to find a lighter total weight structure. Moreover, SOS also has a lower standard deviation and mean value compared to PSO and DE, but lacks consistency in finding optimal results. This result can be seen from the lower success rate than DE. The low success rate is concluded from the initial random that does not satisfy the constraints and the lack of ability of SOS in exploration. Nonetheless, SOS also has advantages over DE, namely the average experimental results and standard deviation. These two points are less than DE because SOS has the benefit in exploitation of existing results.

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