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SYMBIOTIC ORGANISMS SEARCH FOR OPTIMUM DESIGN OF FRAME AND GRILLAGE SYSTEMS

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ABSTRACT

This paper presents most recent meta-heuristic algorithm, symbiotic organisms search (SOS), for optimum design of structures. The SOS simulates the symbiotic interaction strategies adopted by organisms to survive and propagate in the ecosystem. Due to some difficulties on finding optimum design of frame structures and grillage systems, this problem is known as one of benchmark examples in the field of structural optimization. Therefore, the new algorithm is adapted to find optimum design of structures. The performance of the algorithm is then evaluated by comparing with some other methods. The results confirm the validity of the new algorithm.

Keywords: Optimum design; symbiotic organisms search; frame structures; grillage systems; meta-heuristic algorithms.

1. INTRODUCTION

Until now, a large number of meta-heuristic algorithms were developed and applied to different engineering problems [1,2]. The charged system search [3], firefly algorithm [4], cuckoo search [5], colliding bodies optimization [6] and ray optimization [7] are some recent well-known examples of these algorithms. Almost all of them are specified for continuous search space; while for discrete ones, we need some modifications. Optimum design of frame structures and grillage systems are one of these discrete problems. The aim of this problem is to determine a suitable set of sections for elements that fulfill all design requirements while have the lowest possible cost. This problem is classified as a very difficult ones, optimization point of view. Since, in line with the ‘no free-lunch’ theorem, it is impossible for one meta-heuristic algorithm to optimally solve all optimizing problems [8], thus developing new high-performance meta-heuristic algorithms are continuously needed to handle this problem [9].

This paper applies a recent developed optimization algorithm, called symbiotic organisms search (SOS), [9], for optimum design of structures. This algorithm simulates symbiotic

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interaction strategies that organisms use to survive in the ecosystem. A main advantage of the SOS algorithm over most other meta-heuristic algorithms is that algorithm operations require no specific algorithm parameters.

The rest of the paper is organized as follows: Section 2 presents the statement of optimum design of structures. The framework of the SOS algorithm as its original format and discrete variant is presented in Sections 3 and 4, respectively; Section 5 presents the numerical investigation on the performance of the SOS against some well-known algorithms. Finally, Section 6 concludes the paper.

2. STATEMENT OF STRUCTURAL OPTIMIZATION PROBLEM

Optimum design of structures includes finding optimum sections for members, that minimizes the structural weight *W*. This minimum design should also satisfy inequality constraints that limit design variables and structural responses. Thus, the optimal design of a structure is formulated as [10]:

$$\text{Minimize } W(\{x\}) = \sum_{i=1}^{n} \gamma_i . A_i . l_i \tag{1}$$

$$\text{Subject to: } g_{\min} \leq g_i(\{x\}) \leq g_{\max} \qquad i = 1, 2, 3, ..., m \tag{2}$$

where $W(\{x\})$ is the weight of the structure; *n* and *m* are the number of members making up the structure and the number of total constraints, respectively; *max* and *min* denote upper and lower bounds, respectively; $g(\{x\})$ denotes the constraints considered for the structure containing interaction constraints as well as lateral and inter-story displacements, as the following subsections.

2.1 Design constraints for frame structures

For frame structures, the following constraints should be considered:

The maximum lateral displacement:

$$g^{\Delta} = \frac{\Delta_T}{H} - R \geq 0, \tag{3}$$

The inter-story displacements:

$$g_j^d = \frac{d_j}{h_j} - R_I \geq 0, \quad j = 1, 2, ..., ns \tag{4}$$

where Δ_T is the maximum lateral displacement; *H* is the height of the frame structure; *R* is the maximum drift index; d_j is the inter-story drift; h_j is the story height of the *j*th floor; *ns* is the total number of stories; R_I is the inter-story drift index permitted by the code of the practice.

*LRFD interaction formula constraints (*AISC 2001 [11], Equation H1-1a,b):

$$g_i^I = \frac{P_u}{2\phi_c P_n} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) - 1 \geq 0 \quad \text{For} \quad \frac{P_u}{\phi_c P_n} < 0.2 \tag{5}$$

$$g_i^I = \frac{P_u}{\phi_c P_n} + \frac{8}{9}\left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) - 1 \geq 0 \quad \text{For} \quad \frac{P_u}{\phi_c P_n} \geq 0.2 \tag{6}$$

where P_u is the required strength (tension or compression); P_n is the nominal axial strength; ϕ_c is the resistance factor (ϕ_c =0.9 for tension, ϕ_c =0.85 for compression); M_{ux} and M_{uy} are the required flexural strength in the *x* and *y* directions; respectively; M_{nx} and M_{ny} are the nominal flexural strengths in the *x* and *y* directions (for two-dimensional structures, $M_{ny} = 0$); and ϕ_b is the flexural resistance reduction factor ($\phi_b = 0.90$).

2.2 Design constraints for grillage systems

For a grillage system, we have:

The maximum displacement:

$$g_i^d = \delta_i - \delta_{all} \geq 0, \quad i = 1,2,...,m \tag{7}$$

The maximum stress:

$$\mathrm{g_j^M} = M_{u,i} - \phi_b M_{n,i} \geq 1 \quad j = 1,2,....,n \tag{8}$$

$$\mathrm{g_j^M} = V_{u,i} - \phi_v V_{n,i} \geq 1 \quad j = 1,2,....,n \tag{9}$$

where *m* is the number of nodes; *n* represent the number of elements; δ_i is the displacement of joint *i* and δ_i^u is its upper bound; $M_{u,i}$ is the required flexural strengths in member i; $M_{n,i}$ denotes the nominal flexural strengths; ϕ_b is flexural resistance reduction factor ($\phi_b = 0.90$); $V_{u,i}$ is the factored service load shear for member *i*; $V_{n,i}$ is the nominal strength in shear; and ϕ_v represents the resistance factor for shear given as 0.9.

2.3 Constraint handling method

For the proposed method, it is essential to transform the constrained optimization problem to an unconstraint one. In this study a modified penalty function method is utilized for handling the design constraints which is calculated using following formulas [12]:

$$\begin{cases} g_i \le o & \Rightarrow \Phi_g^{(i)} = 0 \\ g_i > o & \Rightarrow \Phi_g^{(i)} = g_i \end{cases} \tag{10}$$

The objective function that determines the fitness of each particle is defined as

$$Mer^k = \varepsilon_1 \cdot W^k + \varepsilon_2 \cdot (\sum \Phi_g^{(i)})^{\varepsilon_3} \tag{11}$$

where *Mer* is the merit function to be minimized; $\varepsilon_1, \varepsilon_2$ and ε_3 are the coefficients of merit function; $\Phi_g^{(i)}$ denotes the summation of penalties. In this study ε_1 and ε_2 are set to 1 and *W* (the weight of structure) respectively, while the value of ε_3 is taken as 0.85 in order to achieve a feasible solution, [12]. Before calculating $\Phi_g^{(i)}$, we first determine the weight of the structures generated by the particles and if it becomes smaller than the so far best solution, then $\Phi_g^{(i)}$ will be calculated otherwise the structural analysis does not performed. This methodology will decrease the required computational costs, considerably.

3. SYMBIOSIS ORGANISMS SEARCH ALGORITHM

The SOS algorithm simulates the interactive behavior seen among organisms in the nature. Organisms rarely live in isolation due to reliance on other species for sustenance and even survival. This reliance-based relationship is known as symbiosis [9]. In the other words, symbiosis describes a relationship between any two distinct species. Symbiotic relationships may be either obligate where the two organisms depend on each other for survival, or facultative that the two organisms choose to cohabitate in a mutually beneficial but nonessential relationship. The mutualism, commensalism, and parasitism are three types of the symbiotic relationships in the nature. The mutualism denotes a symbiotic relationship between two different species in which both benefit; the commensalism is a symbiotic relationship between two different species in which one benefits and the other is unaffected or neutral and the parasitism is a symbiotic relationship between two different species in which one benefits and the other is actively harmed, [9]. Considering these points, The SOS algorithm is developed based on three steps:

– Mutualism phase
– Commensalism phase
– Parasitism phase

This means that in the SOS, new solution generation is governed by imitating the biological interaction between two organisms in the ecosystem in these three phases. The character of the interaction defines the main principle of each phase. Interactions benefit both sides in the mutualism phase; benefit one side and do not impact the other in the commensalism phase; benefit one side and actively harm the other in the parasitism phase. Each organism interacts with the other organism randomly through all phases. The process is repeated until termination criteria are met.

3.1 Mutualism phase

X_i and X_j are two organisms selected randomly from the ecosystem to interact with each other. In this phase, new candidate solutions for these organisms are calculated based on the mutualistic, as:

$$X_{i,new} = X_i + r_1 \times (X_{best} - MV \times BF_1) \tag{12}$$

$$X_{j,new} = X_j + r_2 \times (X_{best} - MV \times BF_2) \tag{13}$$

$$MV = \frac{X_i + X_2}{2} \tag{14}$$

where r_1 and r_2 are two random vectors that its compounds are between zero to one. BF_1 and BF_2 are two benefit factors determined randomly as either 1 or 2. These factors represent the level of benefit to each organisms, i.e., whether an organism partially or fully benefits from the interaction. MV represents the relationship characteristic between organism i and j. After finding the new vectors, organisms are updated only if their new fitness is better than their pre-interaction fitness

3.2 Commensalism phase

Similar to the mutualism phase, an organism, X_j, is selected randomly from the ecosystem to interact with X_i. In this circumstance, organism, X_i attempts to benefit from the interaction. However, organism X_j itself neither benefits nor suffers from the relationship. This concept is modeled as the following equation:

$$X_{i,new} = X_i + (2r_1 - 1) \times (X_{best} - X_j) \tag{15}$$

3.3 Parasitism phase

In the SOS, organism X_i is given a role similar to the anopheles mosquito through the creation of an artificial parasite. For this aim, an organism is selected randomly then randomly selected dimensions of this vector is modified. If the new vector has a better fitness value, it will kill organism X_i and assume its position in the ecosystem.

4. DISCREET SYMBIOSIS ORGANISMS SEARCH

This paper presents a discrete SOS-based algorithm, DSOS, for solving structures. In the DSOS, the three main steps of the standard SOS are redefined as follows:

Mutualism phase

$$X_{i,new} = Fix\{X_i + r_1 \times (X_{best} - MV \times BF_1)\} \tag{16}$$

$$X_{j,new} = Fix\{X_j + r_2 \times (X_{best} - MV \times BF_2)\} \tag{17}$$

Commensalism phase

$$X_{i,new} = Fix\{X_i + (2r_1 - 1) \times (X_{best} - X_j)\} \tag{18}$$

Parasitism phase

$$x_{i,j,new} = Fix\{x_{j,\min} + r_1(x_{j,\max} - x_{j,\min})\} \tag{19}$$

where $Fix(X)$ is a function which rounds each elements of *X* to the nearest permissible discrete value. Using this position updating formula, the agents will be permitted to select discrete values.

5. NUMERICAL EXAMPLES

This section presents the numerical example to evaluate the capability of the new algorithm in finding optimal design of steel structures. The final results are compared to the solutions of other methods to show the efficiency of the present approach. The proposed algorithm is coded in Matlab and structures are analyzed using the direct stiffness method. The steel members used for the design consist of W-shaped sections from the AISC database.

5.1 Design of a 3-bay, 15-story frame

The configuration and applied loads of a 3-bay, 15-story frame structure is shown in Fig. 1. The sway of the top story is limited to 23.5 cm (9.25 in.). The material has a modulus of elasticity equal to E=200 GPa and a yield stress of F_y=248.2 MPa.

The effective length factors of the members are calculated as $K_x \geq 0$ for a sway-permitted frame and the out-of-plane effective length factor is specified as K_y=1.0. Each column is considered as non-braced along its length, and the non-braced length for each beam member is specified as one-fifth of the span length.

The optimum design of the frame obtained by using DSOS has the minimum weight of 406.00 kN. The optimum designs for the ICA [13] and APSO [14] had the weight of 417.46 and 411.50 kN, respectively. Table 1 summarizes the optimal results for these different algorithms. Clearly, it can be seen that the present algorithm can find the better design. Fig. 2 provides the convergence history for this example obtained by the DSOS and the ICA [14]. The figure show that in initial iterations, the ICA can find some good results very soon, however by increasing the number of iterations, the performance of the DSOS becomes better and finally overcomes to the ICA.

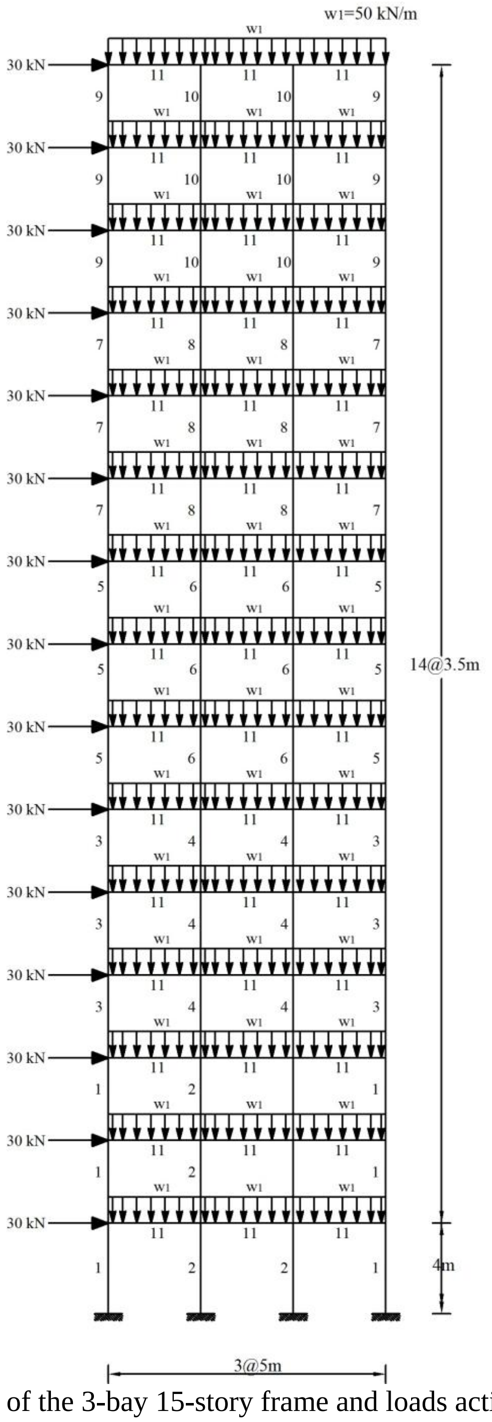


Figure 1. Schematic of the 3-bay 15-story frame and loads acting on the structure

The maximum inter-story drift and stress ratio are respectively equal to 1.05 cm and 0.9936 which are very close to their corresponding allowable values of 1.216 cm and 1.0. The total sway is 11.95 cm while its allowable value is 17.67 cm. Fig. 3 presents the inter-story drifts and the stress ratio of elements for the DSOS design against its maximum values.

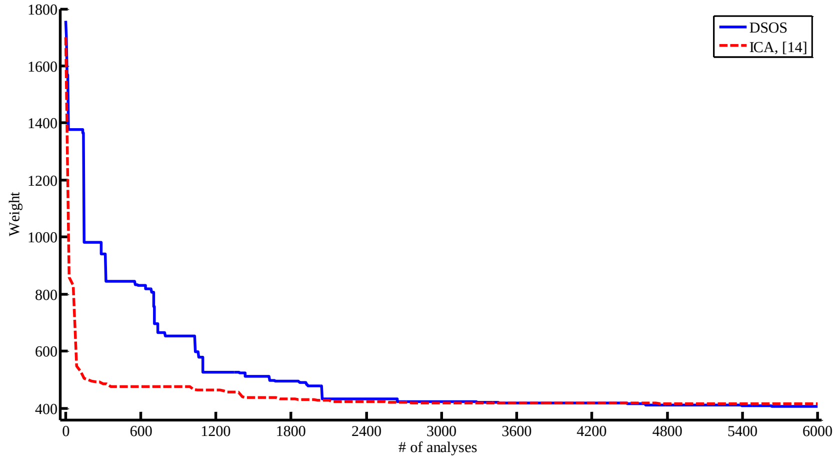
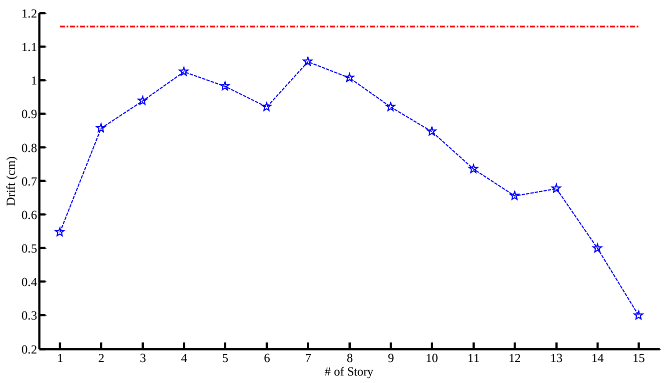


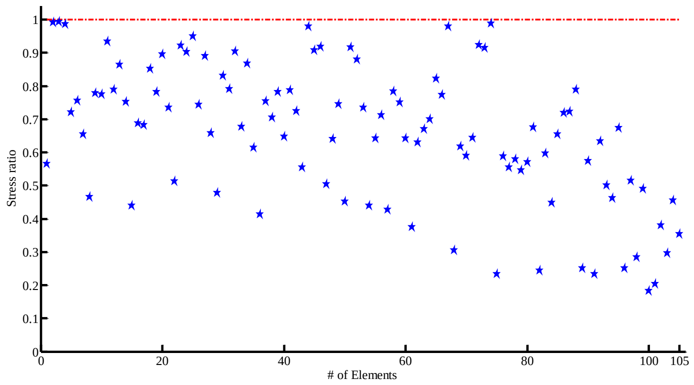
Figure 2. The best convergence curves of DSOS and ICA obtained in the 3-bay 15-story frame problem

Table 1: Optimization results obtained for the 3-bay 15-story frame problem

Element group	Optimal W-shaped sections		
	ICA [14]	APSO [15]	DSOS
1	W24X117	W27X129	W16X100
2	W21X147	W21X147	W32X152
3	W27X84	W16X77	W12X79
4	W27X114	W27X114	W27X114
5	W14X74	W14X74	W21X93
6	W18X86	W30X99	W12X79
7	W12X96	W12X72	W21X55
8	W24X68	W12X79	W14X61
9	W10X39	W8X24	W14X22
10	W12X40	W14X43	W14X43
11	W21X44	W21X44	W21X48
Weight (kN)	417.46	411.50	406.00



(a)



(b)

Figure 3. Comparison of the allowable and existing constraints for the 3-bay 15-story frame using the DSOS (a) inter-story drift and (b) stress ratio.

5.2 Design of a 3-bay, 24-story frame

Fig. 4 shows the schematic of the 3-bay 24-story frame and the loads applied to the structure. This frame is comprised of 168 members, and was solved by Camp et al. utilized ACO [15], Degertekin utilized improved harmony search (HS) [16], Kaveh and Talatahari utilized improved ACO (IACO) [12] and ICA [14]. The modulus of elasticity is E=205GPa while the yield stress is Fy=230.3 MPa.

Table 2: Optimization results obtained for the 3-bay 24-story frame problem

Element group	Optimal W-shaped sections			
	ACO [16]	HS [17]	ICA[14]	DSOS
1	W30X90	W30X90	W30X90	W30X90
2	W8X18	W10X22	W21X50	W21X62
3	W24X55	W18X40	W24X55	W21X48
4	W8X21	W12X16	W8X28	W21X55
5	W14X145	W14X176	W14X109	W14X176
6	W14X132	W14X176	W14X159	W14X109
7	W14X132	W14X132	W14X120	W14X120
8	W14X132	W14X109	W14X90	W14X82
9	W14X68	W14X82	W14X74	W14X61
10	W14X53	W14X74	W14X68	W14X99
11	W14X43	W14X34	W14X30	W14X34
12	W14X43	W14X22	W14X38	W14X38
13	W14X145	W14X145	W14X159	W14X120
14	W14X145	W14X132	W14X132	W14X109
15	W14X120	W14X109	W14X99	W14X90
16	W14X90	W14X82	W14X82	W14X90
17	W14X90	W14X61	W14X68	W14X82
18	W14X61	W14X48	W14X48	W14X38
19	W14X30	W14X30	W14X34	W14X38
20	W14X26	W14X22	W14X22	W14X22
Weight (kN)	980.63	956.13	946.25	933.46

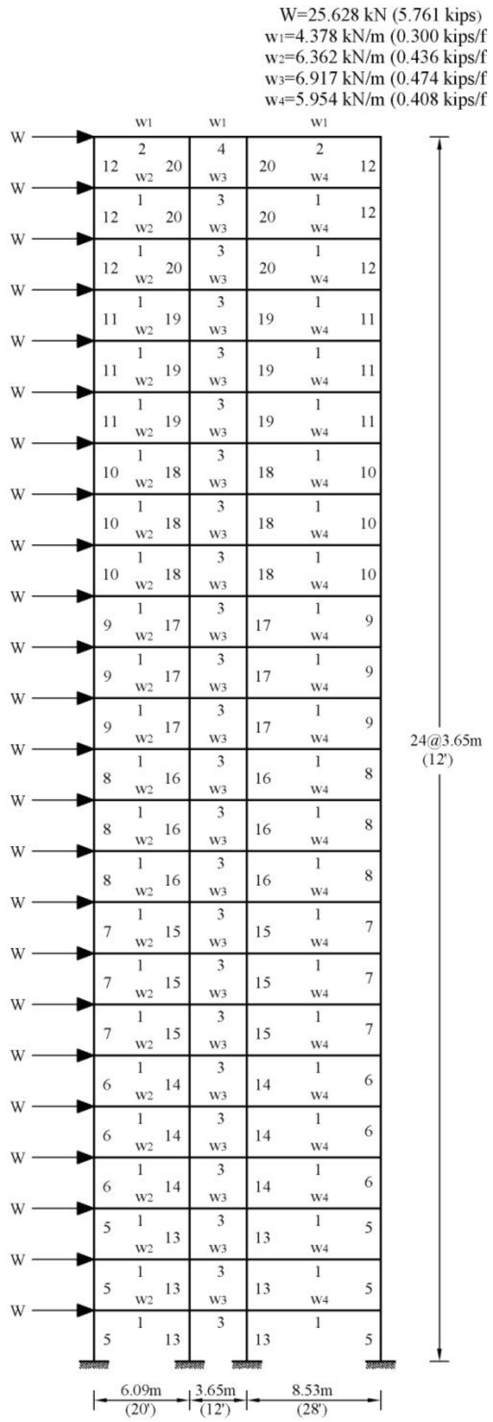


Figure 4. Schematic of the 3-bay 24-story frame and loads acting on the structure

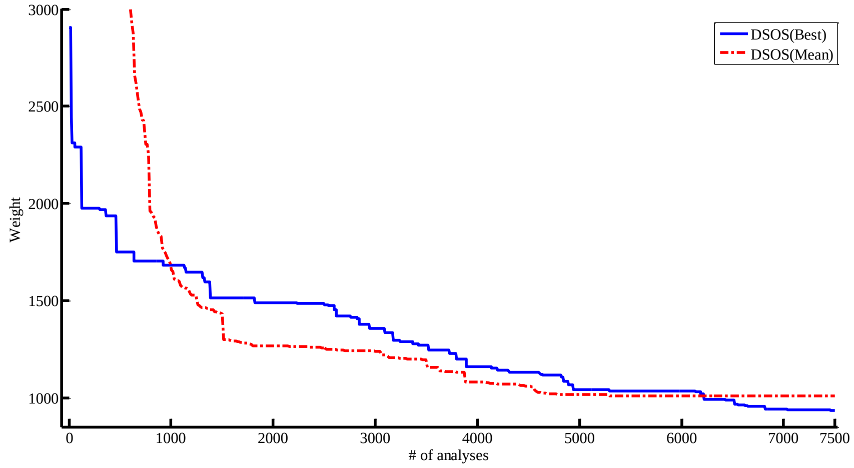
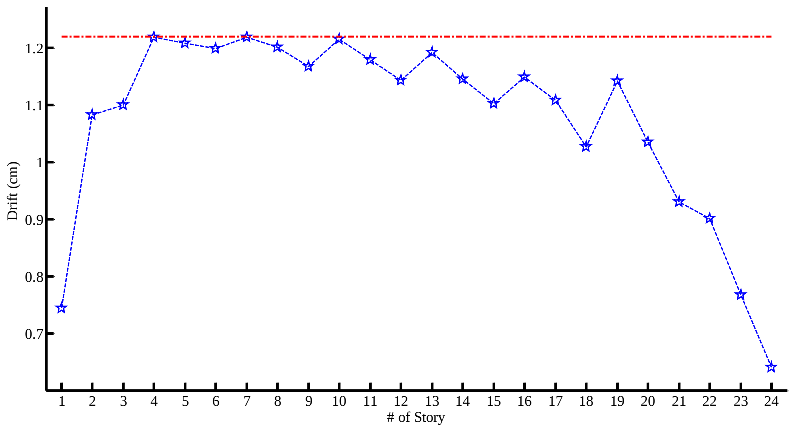
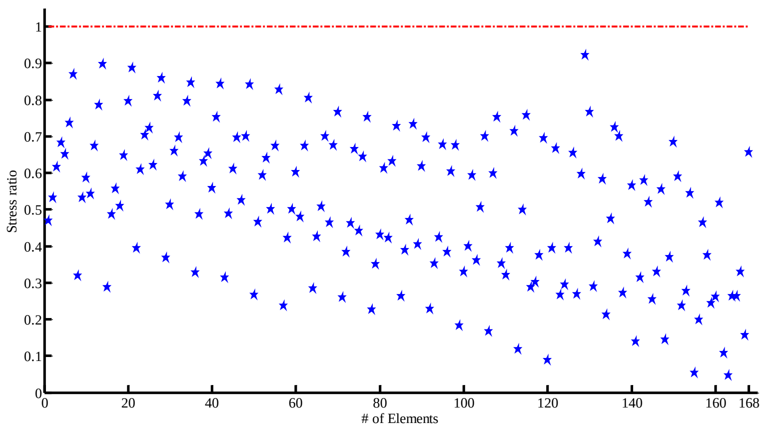


Figure 5. The best and mean convergence curves of DSOS obtained in the 3-bay 24-story frame problem



(a)



(b)

Figure 6. Comparison of the allowable and existing constraints for the 3-bay 24-story frame using the DSOS (a) inter-story drift and (b) stress ratio

The effective length factors of the members are again calculated as $K_x \geq 0$ for a sway-permitted frame and the out-of-plane effective length factor is specified as K_y = 1.0. Optimization results are compared with literature in Table 2. The DSOS found the best design overall corresponding to a structural weight of 933.46 kN. Optimized weights reported in literature are heavier than that found by this algorithm.

The DSOS required 7,500 structural analyses to complete the optimization process and were faster than the ACO [15] and improved HS [16] which required 15,500 and 13,924 analyses, respectively. Fig. 5 shows the best and mean convergence curves obtained for the DSOS algorithms. The mean convergence history shows that the algorithm could not find optimum domain in the initial iterations however after almost 3000 analyses, it convergences toward the optimum design.

The maximum value for the inter-story drift is its maximum value (1.216 cm). The total sway is 25.82 cm which is less than its maximum value (29.20 cm). The maximum value for the stress ratio is 92.08%. Fig. 6 compares the allowable and existing values of the inter-story drifts and the stress ratio of elements for the DSOS design.

5.3 A 40-member grillage system

The grillage system shown in Fig. 7 has 40 members which are collected in four groups, [17]. The outer and inner longitudinal beams are considered to be group 1 and 2, respectively, while the outer and inner transverse beams are taken as group 3 and 4. The external loading is equal to 200kN in each unsupported node. The vertical displacements of four middle joints are restricted to 25 mm.

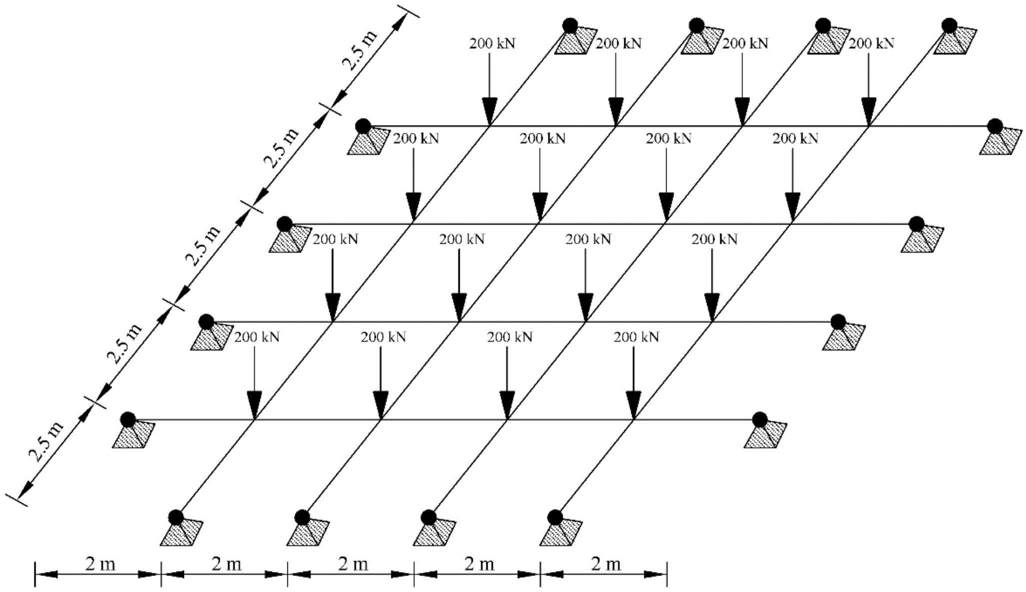


Figure 7. Schematic of the 40-elements grillage system and loads acting on the structure

The minimum weight of the design by the DSOS for this example is 6,956.6 kg while it is 7,168.04 for the standard CSS [17], and 7,198.2 kg and 8,087.91 kg for the harmony search and genetic algorithm, respectively [18]. The optimum designs obtained by the DSOS and CSS are given in Table 3. The DSOS similar to the CSS finds the result after 3,000 analyses [17] and the harmony search obtains the optimum design after 4,558 grillage analyses and the genetic algorithm requires 27,200 grillage analyses to reach the final solution [18]. The design history curve for the DSOS algorithm is plotted in Fig. 8.

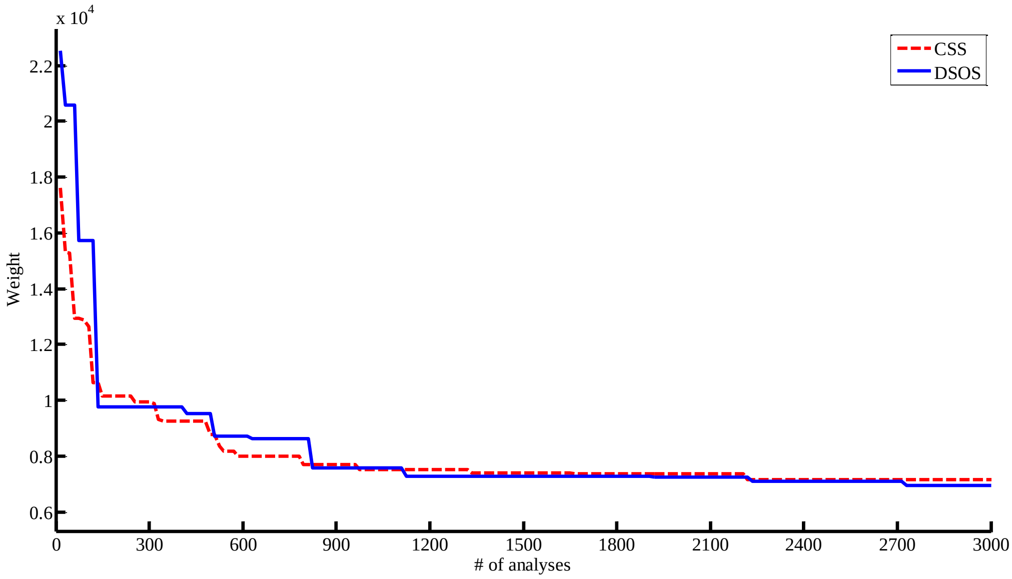


Figure 8. The best convergence curves of DSOS and CSS obtained in 40-member grillage system

Table 3: Optimization results obtained for the 40- and 60- member grillage systems

Element group	Optimal W-shaped sections			
	40-members grillage system		60-members grillage system	
	CSS [17]	**DSOS**	**CSS [17]**	**DSOS**
1	W16X31	W6X9	W6X9	W8X10
2	W18X35	W24X55	W36X135	W14X22
3	W6X8.5	W14X34	W12X14	W10X12
4	W36X149	W36X135	W12X22	W36X135
Weight (kg)	7,168	6,956	9,251	9,211

5.4 A 60-member grillage system

The second examples is a 60-elements grillage system [17] as shown in Fig. 9. The loads is a 15kN/m^2 uniformly distributed load (total load is 2160kN). The grillage system that can be used to cover the area will have the longitudinal beams of length 12m and the transverse beams of length 12m. The total external load is distributed to the joints of the grillage system as point loads. Their values are calculated according to beam spacing. Similar to the previous example, four design groups are considered. The vertical displacements of middle joints are restricted to 25 mm.

For the 60-member grillage system, the weight obtained by the new algorithm is 9,211 kg while it has been 9,251 kg for the CSS method [17]. The number of required structural analyses for the DSOS algorithm is equal to 3,000 analyses similar to the CSS. The maximum vertical displacement is 23.4 mm, while the maximum value of the strength ratio is 99.2%. The optimum result obtained by the new algorithm is summarized in Table 3.

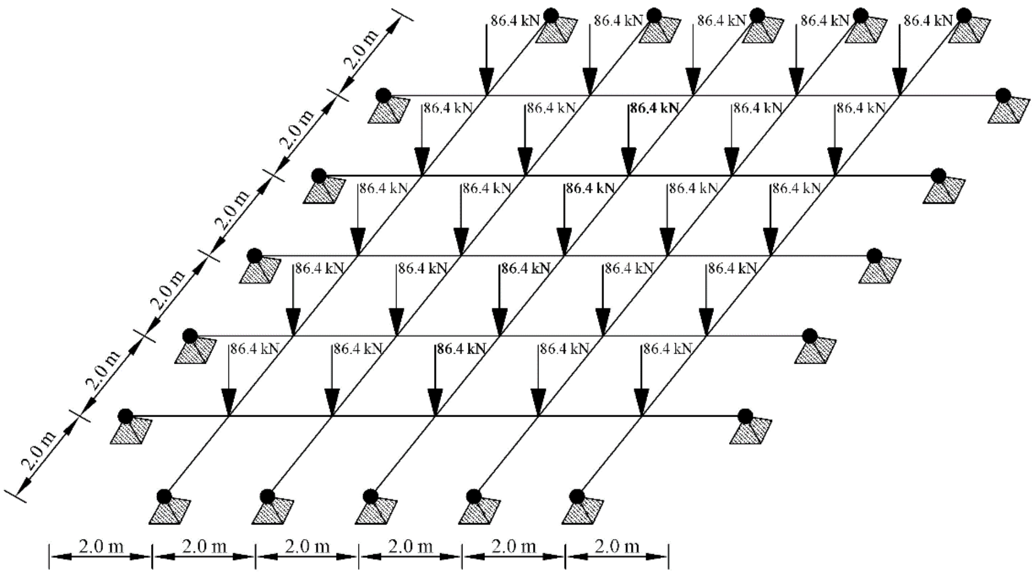


Figure 9. Schematic of the 60-elements grillage system and loads acting on the structure

6. CONCLUSIONS

Finding optimum design of structures becomes an important issue in the field of structural design. There are many optimization methods for solving this problem. However, difficulty of optimizing structures forces the researchers to examine new approaches. In this regards, this paper applied a new meta-heuristic algorithm, symbiotic organisms search. The SOS simulates the symbiotic interaction strategies adopted by organisms to survive and propagate in the ecosystem. Contrary to many other meta-heuristic, this algorithm does not need many modifications to be adaptive for solving frame structures. The change is limited on replacing continues results by the nearest discreet ones. Although this is one of simplest methods and may cause some difficulty on the search abilities of the algorithm, however the performance of the SOS shows a fact against this. In the other words, the obtained optimum design of four well-studied examples by the new method and comparing them with those of other meta-heuristics show the efficiency of the algorithm. Also, the comparison of the results show that the SOS algorithm provides results as good as or better than other algorithms and can be used effectively for solving engineering problems.

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