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DAMAGE PREDICTION OF 2D/3D TRUSS STRUCTURES USING THE BLACK WIDOW OPTIMIZATION ALGORITHM

Abstract. Because of their simplicity and adaptability, nature-inspired optimization algorithms can handle a variety of technical and scientific challenges. Metaheuristic algorithms have recently emerged as effective techniques for resolving structural issues. The Black Widow Optimization Algorithm (BWOA), a metaheuristic algorithm, is used in this research to predict damage of 2D/3D truss structures. Cannibalism was one of the exclusive stages of this approach. Due to this stage, species with inappropriate fitness were omitted from the circle, thus leading to early convergence. Moreover, by using natural frequencies from finite element analysis for truss structure to set up the objective function, the final outcomes prove the effectiveness of this algorithm in solving real-world issues with unknown and challenging spaces.

Keywords: damage prediction, 2D/3D truss structure, finite element analysis, natural frequency, black widow optimization.

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Introduction. Physical-based, swarm-based, and evolutionary-based approaches are the three categories into which metaheuristic techniques fall. Physics principles like electromagnetic force, inertia force, gravitational force, and so on are the fundamental source of inspiration for physics-based algorithms. The algorithms' search agents interact and navigate the search space while taking these rules into account. The collective behavior of social beings, that is, how individuals of a swarm interact with their surroundings, inspires the algorithms in the second group, which are swarm-based. The algorithms in the final group, such as selection, reproduction, combination, and mutation, are primarily influenced by biological evolution and nature. Figure 1 shows how the metaheuristic algorithm branches out. Another optimization algorithm in group two, entitled BWOA, which imitates the strange mating behavior of the black widow spiders, was introduced by [1-8]. A poisonous spider species, the western black widow spider is distributed from southern Mexico to western Canada. A strong neurotoxin that is effective against a variety of animals is found in the venom of female black widows. Furthermore, because a single bite might result in death, the aforementioned venom is among the most deadly to humans. These spiders live in forests and marshes, construct their webs in trees, and eat insects, including cockroaches, beetles, and butterflies. Because females may engage in cannibalistic behavior, males, who utilize sex pheromones to determine a female's mating status, are known to have little interest in mating with malnourished and famished females. Additional information regarding the behavior of black widow spiders can be found in [9].

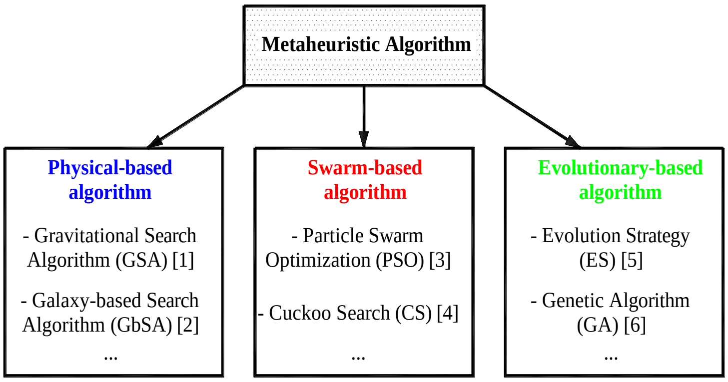

Fig. 1. Branches of the metaheuristic algorithm

When it comes to the exploration and exploitation stages of the searching process, which are two essential components of an algorithm, the majority of population-based algorithms, independent of the algorithm's structure, generally exhibit a similar trait. Metaheuristic algorithms should maintain equilibrium between the exploration and exploitation phases of the search space to achieve high efficiency.

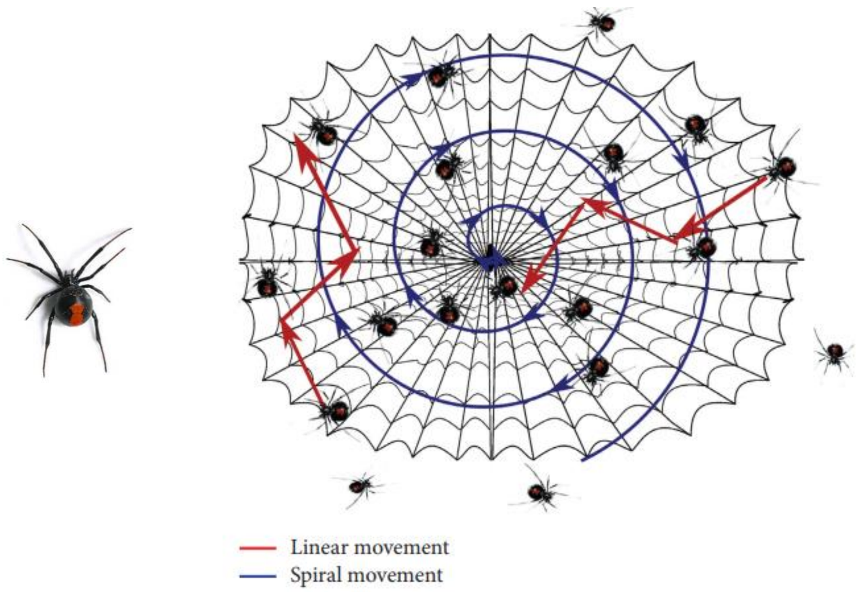

Fig. 2. Black widow spider [8]

The algorithm has the chance to examine several possible regions of the search space during the exploration phase and provide fresh solutions to get out of the local optima dilemma. The capacity of an algorithm to converge close to the obtained expected solutions during the exploration stage is referred to as exploitation. Therefore, avoiding local optima and achieving good convergence are guaranteed by effective exploration and exploitation, respectively. Nature-inspired algorithms have seen tremendous advancements in the industrial sector in recent years, where it has been demonstrated that they are highly beneficial in resolving practical optimization issues. In this study, damage to truss structures is predicted using the Black Widow Optimization Algorithm (BWOA), which was inspired by the life cycle of black widow spiders and their peculiar mating behavior (Fig. 2). It would be remiss not to mention some information about finding the natural frequencies of a structural system based on finite element analysis, as in the documents [10-12].

Materials and methods. The BWOA began with an initial population of spiders so that each spider represented a possible solution, just like other evolutionary algorithms. These first spiders attempt to procreate in pairs. During or after mating, the black widow female consumed the male. She then discharged the sperm that had been held in her sperm thecae into egg sacs. Spiderlings emerged from the egg sacs as early as 11 days after they were placed. Sibling cannibalism occurred while the spiderlings lived together on the maternal web for a few days to a week. Then the wind took them away. A Black Widow spider was thought to be a potential solution to each problem in the BWOA. The values of the problem variables were displayed by each Black Widow spider. An initial population of spiders was used to create a candidate widow matrix of size $N_{pop} \times N_{var}$ in order to initiate the optimization method. Noted that N_{var} was dimensional optimization problem and

$$\text{widow} = \left[x_1, x_2, \ldots, x_{N_{var}} \right] \quad \text{and} \quad \text{fitness} = f\left(x_1, x_2, \ldots, x_{N_{var}} \right) \tag{1}$$

Next, pairs of parents were chosen at random to carry out the procreating stage by mating, where the female black widow ate the male either during or after the mating process. Now, in order to reproduce, an array named α must also be generated, provided that it was present in the widow array with random numbers. Offspring were then made using α and Equation (2), where x_1 and x_2 were parents and y_1 and y_2 were offspring.

$$\begin{cases} y_1 = \alpha \times x_1 + (1-\alpha) \times x_2 \\ y_2 = \alpha \times x_2 + (1-\alpha) \times x_1 \end{cases} \tag{2}$$

There were three types of cannibalism. The first was sexual cannibalism, where a black widow ate her spouse either during or after mating. Sibling cannibalism, in which the stronger spiderlings devoured their weaker siblings, was another type. The third type of cannibalism, in which the young spiders devoured their mother, was occasionally seen. They are coded algorithmically through their fitness values. The Mutepop number in the mutation was chosen at random from the population. Two elements in the array were switched at random by each of the selected solutions. The mutation rate was used to compute Mutepop. Lastly, three stop conditions could be taken into consideration, similar to previous evolutionary algorithms: *(a)* a predetermined iteration count; *(b)* the best widow's fitness value remained constant throughout multiple iterations; *(c)* achieving the required degree of precision. Last but not least, the qualitative analysis results of the BWOA approach in tackling several common optimization functions are shown in Figure 3. In [4-7], these functions are explained in detail.

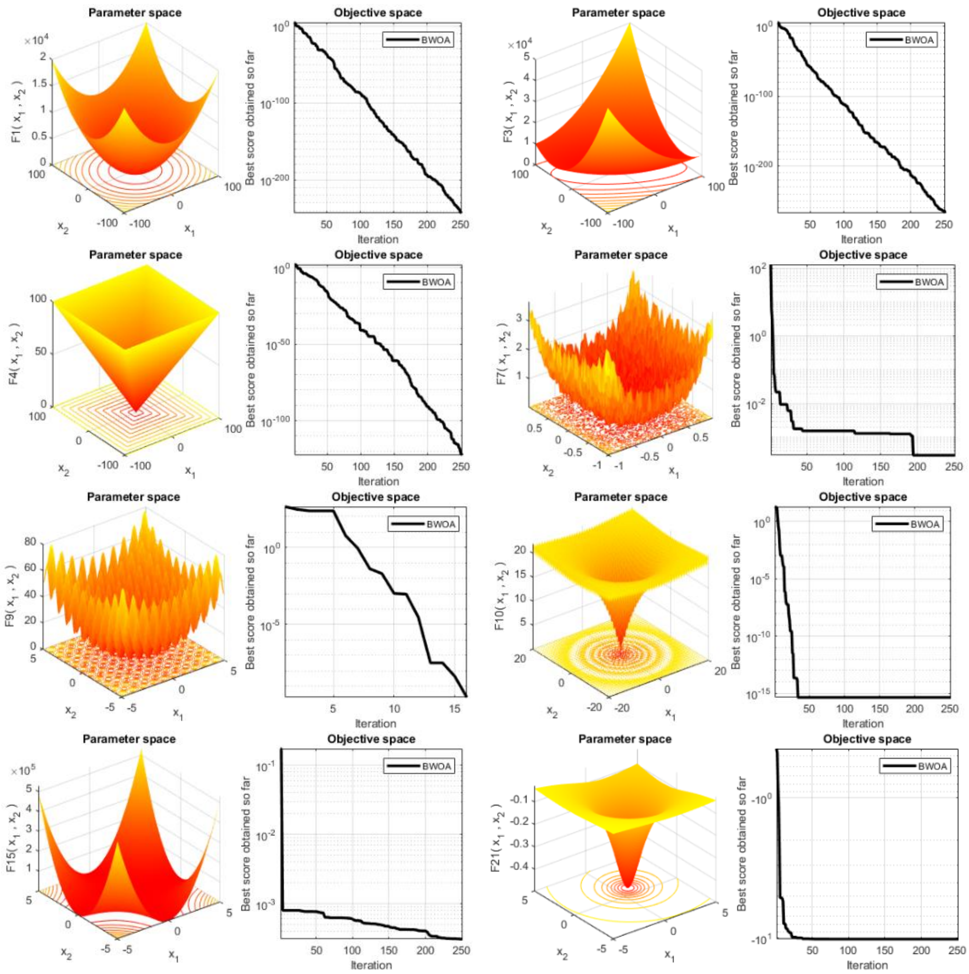

Fig. 3. Qualitative results for BWOA

Research results and discussion. In this section two truss structures with 16 bars and 21 bars are considered as in Figures 4 and Tables 1 and 2.

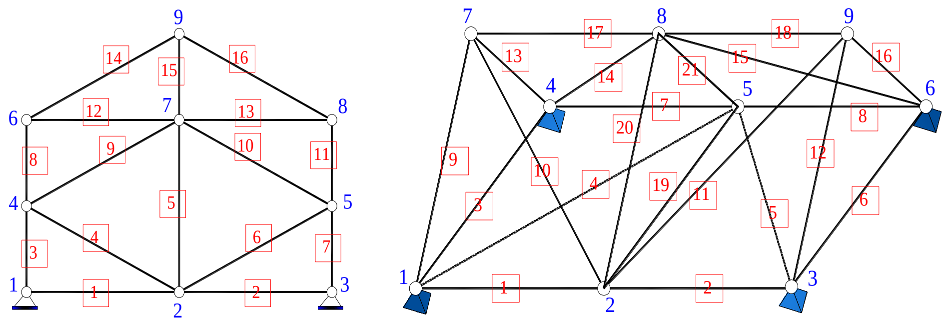

Fig. 4. 16-bar truss and 21-bar truss

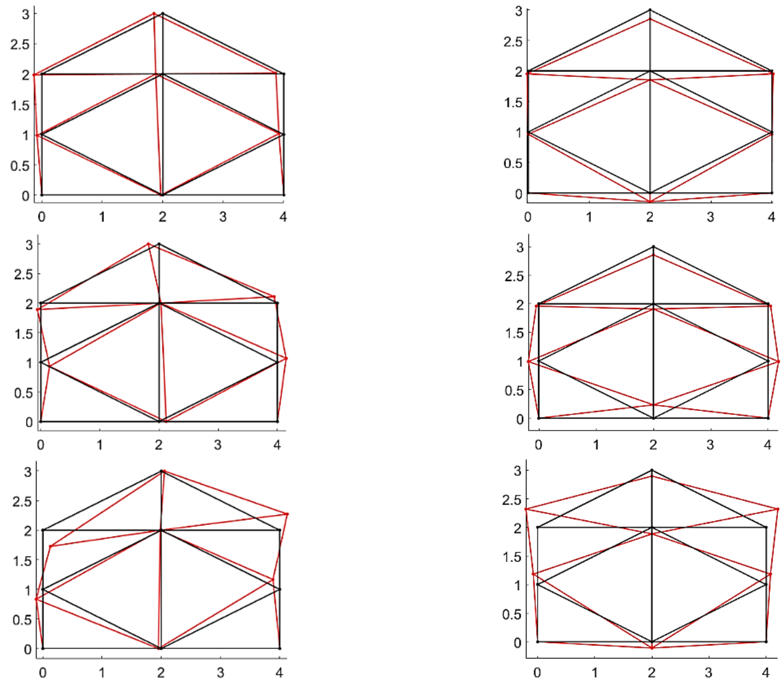

Fig. 5. The first six mode shapes of 16-bar truss structure

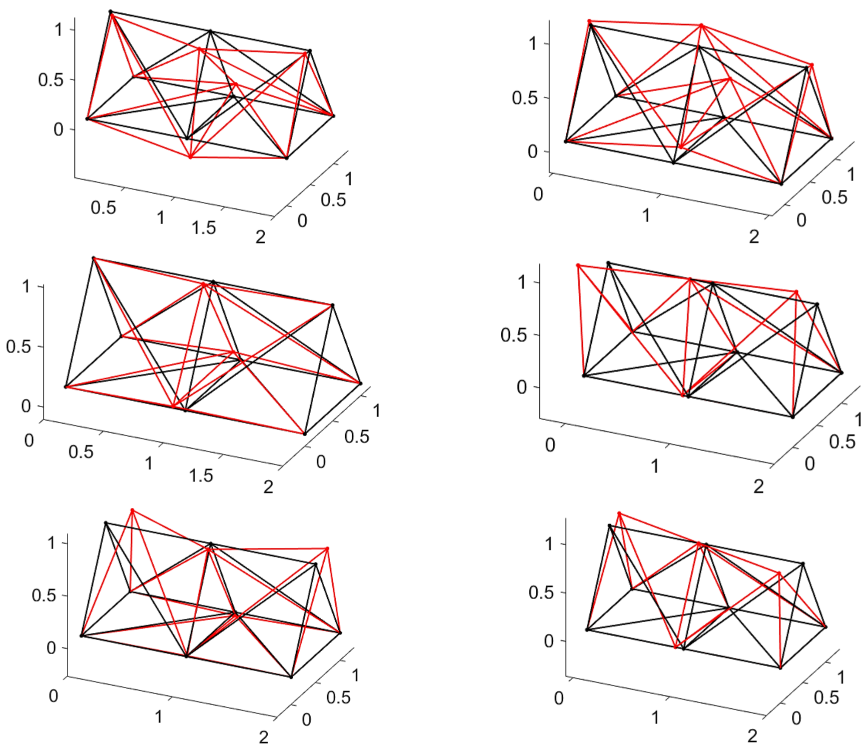

Fig. 6. The first six mode shapes of 21-bar truss structure

Table 1

Properties of bar

A	E	ρ
0,000707 m^2	205e9 N/m^2	7833 kg/m^3

Table 2

Coordinates of nodes

16-bar truss			21-bar truss			
Node	x(m)	y(m)	Node	x(m)	y(m)	z(m)
1	0	0	1	0	0	0
2	2	0	2	1	0	0
3	4	0	3	2	0	0
4	0	1	4	0	1	0
5	4	1	5	1	1	0
6	0	2	6	2	1	0
7	2	2	7	0	0,5	√3/2
8	4	2	8	1	0,5	√3/2
9	2	3	9	2	0,5	√3/2

An objective function is defined as the difference in natural frequencies between the finite element model and true measurements. Thereby, the severity and location of damage will be predicted. The definition of damages in which a decrease in the member's modulus of elasticity is crucial is demonstrated by Equation (3):

$$E_b = (1-\xi)E, \quad 0 \le \xi \le 1 \tag{3}$$

where, in which ξ is the variable showing the damage severity of each bar. The location and severity of the damage(s) can then be easily ascertained by minimizing the following objective function:

$$O = \sqrt{\sum_{i=1}^{6} \left(f_i^a - f_i^{fe}\right)^2 / \left(f_i^a\right)^2} \tag{4}$$

where 6 is the number of considered frequencies, and (a) and (fe) indicate the "actual" and "finite element" cases, respectively. Figures 5 and 6 depict the first six mode shapes of the 16-bar and 21-bar truss structures.

Table 3

The damage situations of 16-bar truss

Situations	Damage bar(s)	Severity of damage
The first situation	Bar 9	35%
The second situation	Bar 7 Bar 11	40% 30%
The third situation	Bar 1 Bar 11 Bar 13	30% 25% 20%

Table 4

The damage situations of 21-bar truss

Situations	Damage bar(s)	Severity of damage
The first situation	Bar 13	35%
The second situation	Bar 6 Bar 16	40% 30%

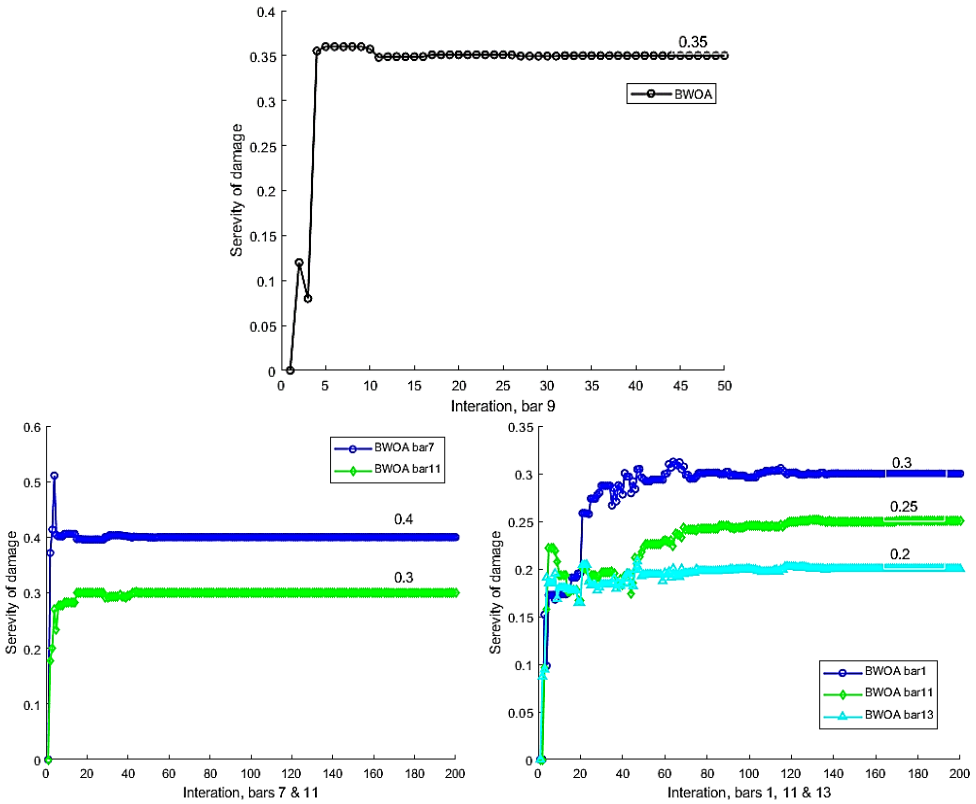

Fig. 7. The convergence for the damage situations of 16-bar truss

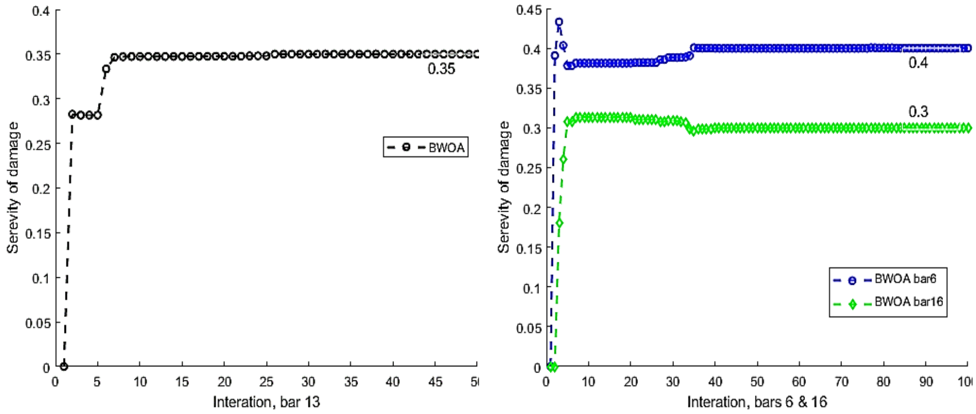

Fig. 8. The convergence for the damage situations of 21-bar truss

Tables 3 and 4 provide some damage situations to verify the accuracy. The findings show that BWOA yields the expected outcomes for damage structure prediction, which are detailed in Figures 7 to 8. Additionally, it is evident that the BWOA requires only 50–150 iterations to achieve the desired outcomes.

Conclusion. This article presents how to use the Black Widow Optimization Algorithm (BWOA) to detect damage in 2D/3D truss structures. A number of situations, from simple to complex, are given to evaluate this algorithm's performance. The outcomes demonstrate how well the BWOA predicts the location and magnitude of damage.

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BLACK WIDOW ОПТИМИЗАЦИЯ АЛГОРИТМІН ҚОЛДАНУ АРҚЫЛЫ 2D/3D ФЕРМАЛЫҚ ҚҰРЫЛЫМДАРДАҒЫ ЗАҚЫМДАЛУДЫ БОЛЖАУ

Аңдатпа. Қарапайымдылығы мен бейімделгіштігінің арқасында табиғаттан шабыт алған оңтайландыру алгоритмдері техникалық және ғылыми есептердің кең ауқымын шешуге қабілетті. Соңғы жылдары метаэвристикалық алгоритмдер құрылымдық механика мәселелерін шешудің тиімді әдістері ретінде кеңінен қолданылып келеді. Бұл зерттеуде 2D/3D фермалық құрылымдардың зақымдалуын болжау үшін метаэвристикалық Black Widow Optimization Algorithm (BWOA) қолданылады. Каннибализм осы алгоритмнің ерекше кезеңдерінің бірі болып табылады. Осы кезеңнің нәтижесінде жарамдылығы төмен дарақтар популяциядан алынып тасталады, бұл ерте жинақталуға әкеледі. Сонымен қатар, фермалық құрылымдарға арналған соңғы элементтер әдісі арқылы алынған меншікті тербеліс жиіліктерін мақсаттық функцияны қалыптастыруда қолдану бұл алгоритмнің белгісіз және күрделі іздеу кеңістігі бар нақты инженерлік есептерді шешудегі тиімділігін дәлелдейді.

Тірек сөздер: зақымдалуды болжау, 2D/3D фермалық құрылым, соңғы элементтер әдісі, меншікті жиілік, black widow оптимизациясы.

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ПРОГНОЗИРОВАНИЕ ПОВРЕЖДЕНИЙ ПЛОСКИХ И ПРОСТРАНСТВЕННЫХ ФЕРМ С ИСПОЛЬЗОВАНИЕМ АЛГОРИТМА ОПТИМИЗАЦИИ «ЧЁРНАЯ ВДОВА»

Аннотация. Благодаря своей простоте и адаптивности алгоритмы оптимизации, вдохновлённые природой, способны решать широкий круг технических и научных задач. В последние годы метаэвристические алгоритмы зарекомендовали себя как эффективные методы решения задач строительной механики. В данной работе для прогнозирования повреждений плоских и пространственных ферм используется метаэвристический алгоритм оптимизации «Чёрная вдова» (Black Widow Optimization Algorithm, BWOA). Каннибализм является одним из уникальных этапов данного алгоритма. Благодаря этому этапу особи с неудовлетворительной приспособленностью исключаются из популяции, что приводит к ускоренной сходимости. Кроме того, использование собственных частот, полученных на основе конечно-элементного анализа ферменных конструкций, при формировании целевой функции подтверждает эффективность данного алгоритма при решении практических задач с неизвестными и сложными пространствами поиска.

Ключевые слова: прогнозирование повреждений, плоская и пространственная ферма, конечно-элементный анализ, собственная частота, оптимизация «Чёрная вдова».