Optimization of Fixed Supported Castellated Steel Beams

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Received:18.02.2025 Accepted: 09.04.2025

Abstract- Castellated beams have garnered increasing attention in various fields due to their aesthetically appealing design, diverse geometric shapes, environmental friendliness, and economic advantages in terms of time, cost, and performance. These beams particularly excel in resisting bending without increasing their weight. The novelty of this paper, is to optimize the performance of castellated beams by maximum vertical deflection, represented as the objective function. This is achieved by determining the optimal dimensions of the cross-section using three optimization algorithms: Gray Wolf Optimization (GWO), Particle Swarm Optimization (PSO), and Differential Evolution (DE). This study focuses on three different types of material for castellated beams: S235, S255, and S355. The results revealed that the PSO and DE algorithms produce very similar outcomes, while the GWO algorithm shows slightly different results. Overall, all three algorithms demonstrate good capability in engineering applications, with a slight preference for the PSO and DE algorithms.

Keywords Castellated Beam, Maximum Vertical Displacement, Gray Wolf Optimization (GWO), Particle Swarm Optimization (PSO), Differential Evolution (DE).

Ankastre Mesnetli Petek Kirişlerin Optimizasyonu

Öz- Petek kirişler, estetik açıdan çekici tasarımları, farklı geometrik şekilleri, çevre dostu olmaları ve zaman, maliyet ve performans açısından ekonomik avantajları nedeniyle çeşitli alanlarda giderek artan ilgi görmektedir. Bu kirişler özellikle ağırlıklarını arttırmadan eğilmeye karşı direnç gösterme konusunda mükemmeldir. Bu çalışmada, petek kirişlerin performansı, amaç fonksiyonu olarak temsil edilen maksimum düşey sapma ile optimize edilmiştir. Bu, üç optimizasyon algoritması kullanılarak kesitin optimal boyutlarının belirlenmesiyle elde edilir: Gri Kurt Optimizasyonu (GWO), Parçacık Sürü Optimizasyonu (PSO) ve Diferansiyel Evrim (DE). Bu çalışma petek kirişler için üç farklı malzeme türüne odaklanmaktadır: S235, S255 ve S355. Sonuçlar, PSO ve DE algoritmalarının çok benzer sonuçlar ürettiğini, GWO algoritmasının ise biraz farklı sonuçlar verdiğini ortaya çıkardı. Genel olarak, üç algoritmanın tümü, PSO ve DE algoritmalarını çok az fark bir şekilde tercih ederek, mühendislik uygulamalarında iyi bir yetenek sergilemektedir.

Anahtar Kelimeler: Petek Kiriş, Maksimum Düşey Yer Değiştirme, Gri Kurt Optimizasyonu (GWO), Parçacık Sürüsü Optimizasyonu, Diferansiyel Evrim (DE)

1. Introduction

Recent Metaheuristic algorithms demonstrate high performance in solving optimization problems due to the increasing demands of optimization and the engineering requirements and complexities that have emerged due to previous excessive exploitation of natural resources. Additionally, they align with the principle of sustainability. Traditional methods previously used for solving such problems were conventional and failed to keep pace with the rapid advancements and growing demands of the present time, often yielding suboptimal results. Consequently, metaheuristic algorithms have become effective and reliable approaches for optimization [1].

Sorkhabi et al. [2] addressed the beam optimization for castellated beams using the PSO algorithm, where the total cost was considered as the objective function. The study adhered to the regulations of ACD and AISC, evaluating the impact of welding and cutting parameters. Kaveh and Shokohi [3] employed the GWO with the objective function defined as the minimum cost. Several examples from the literature were analyzed, demonstrating the algorithm's capability to solve optimization problems effectively and suggesting it as a viable alternative. Kaveh et al. [4] utilized four different algorithms to optimize castellated beams with hexagonal openings, focusing on cost as the objective function. A comparison of results indicated that the algorithms performed well and effectively addressed optimization challenges. In another study, Mashayekhi and Mosayyebi [5] optimized castellated beams with hexagonal openings by considering the total cost, including construction, materials, and cutting, as the objective function. A hybrid algorithm, combining Particle PSO and Harris Hawks Optimization (HHO), was employed. Three examples were used for comparison, demonstrating that the developed algorithm produced highly satisfactory results with superior convergence speed compared to other algorithms.

The present paper is focused on three different algorithms. The first one is GWO. In this algorithm, the behavior of gray wolves during the hunting process is considered as the basis of its work. It gives good results because its working mechanism depends on finding the three best candidate solutions [6], and the second algorithm is PSO, which simulates the social behavior of a group of living organisms and simplifies the movement of this group using mathematical equations. This algorithm requires fewer function evaluations to achieve results of the same quality compared to other methods [7]. The third type of optimization algorithm is the DE algorithm, where population evolution forms the basis of its operation. It is a stochastic search algorithm that uses specific processes like mutation, crossover, and selection to enhance optimization performance. DE encodes real numbers to reduce the complexity caused by genetic operations. It is characterized by using a small number of control parameters while maintaining robustness and good search capability [8].

Heuristic algorithms can provide effective and efficient solutions to numerous engineering problems related to design requirements, analysis, cost reduction, and time savings. These algorithms have gained significant attention across all engineering fields. One prominent application is in castellated beams, which have become essential structural elements.

Castellated beams have a unique castle-like appearance, so they were named this way, featuring regular patterns of various openings such as hexagonal, circular, pentagonal, rectangular, and square [9-10]. Castellated beams are highly efficient, allowing for time and natural resource savings, as their production requires minimal natural resources. Additionally, they reduce building height [11], which positively impacts the spacing between floors [12]. Despite using fewer resources, castellated beams maintain their performance against deflection, when applying loads [13-16]. They exhibit excellent resistance to vertical bending and are particularly effective over long spans [17-19].

The manufacturing process of castellated beams consists of two main parts: cutting and welding. A series of beams are cut into a semi-hexagonal shape, using one of two methods, either by oxy or plasma cutting. The beam pieces are then placed side by side and arranged to form the final shape, with a slight gap among them of up to half a unit. The welding process then begins, marking the end of the manufacturing process This manufacturing method enhances the flexural resistance of the castellated beam, resulting from an increase in its moment of inertia due to the added thickness [20]. However, this increase in depth simultaneously causes stability issues during construction [21].

The presence of openings in castellated beams offers numerous benefits, including architectural advantages, as they enhance the aesthetic appeal of the structural design. Additionally, they provide practical benefits in terms of facilitating ductwork, communications, and other services. From a financial perspective , as previously mentioned, the openings reduce the material cost and quantity of steel required for fabricating castellated beams [22]. However, there are also drawbacks associated with the presence of openings. These openings alter the structural performance of the castellated beam [23] by weakening its ability to bear applied loads [24]. As noted earlier, the openings come in various shapes, which in turn affect the failure modes of the beam. The openings induce changes in the local internal shear force transfer, leading to variations in the stress distribution and a decrease in the beam's shear resistance. Consequently, this results in a reduced load-bearing capacity for both flexural and axial stresses in the castellated beam [25].

The failure modes of castellated beams are numerous and have been explained in many studies. The causes of their occurrence, as well as methods for addressing and preventing them, have also been identified. The first type of failure occurs when the main axis of the castellated beam is subjected to transverse loads, known as lateral-torsional buckling, which is considered one of the most dangerous failure modes for castellated beams. This type of failure reduces the beam's resistance to torsion due to the deformation of the web post, which in turn causes lateral bending and twisting of the top flange (i.e., the flange above the opening). To prevent this failure, lateral bracing is used in this area [26-27]. Another failure mode in castellated beams is a flexural failure. This occurs when the beam reaches full plasticity in the upper and lower T - sections, i.e. above and below the openings, as a result of exposure to high bending moments and low shear forces, which can be neglected. This is referred to as pure bending moment, which causes yielding in the upper and lower sections of the openings. Another failure mode in castellated beams is the Vierendeel mechanism. This failure occurs in the transverse section of the upper T, which is naturally above the opening. Physically, this failure is caused by the yielding of the steel due to the simultaneous presence of vertical and shear stresses. Factors that influence the occurrence of this failure include the thickness of the web post and the diameter of the opening. The four corners of the opening may tear due to the forming of plastic hinges at these corner joints [28-30].

There is another type of failure pattern in castellated beams caused by horizontal shear stresses. If these stresses exceed the yield strength of the joint, they cause tearing, which is known as weld failure. This type of failure has design criteria that must be taken into account [31-32]. Buckling failure in the web post of castellated beams is one of the failure patterns that occur. This failure can either be due to the horizontal shear force combined with the moment present at the mid-height of the web post. Due to its slenderness, the web post is subjected to lateral displacement and twisting, which is known as buckling of the web due to shear. Alternatively, it can occur due to concentrated compressive forces, in which case twisting does not occur. This is known as compressive buckling in the web post [34-37].

The literature survey shows that there is no previous study investigating the optimization of vertical displacement of fixed-ended castellated beams with GWO, PSO, and DE algorithms. The algorithms employed in this research are among the most effective for optimizing beams, as supported by previously published studies on the subject. In this paper, the failure modes are ignored and it mainly focuses on the maximum deflection values for the maximum distributed loads; computed for the allowable stress values. To present this research paper in a better way, it is organized as follows: Section 2 shows the design variables, constraints, materials, geometry of the beam, and short information about the GWO, PSO, and DE. Section 3 gives the optimum values for the objective functions and designed parameters, and Section 4 presents the most important outcomes of this research.

2. Materials and Method

In this study, optimization processes are carried out using three algorithms: GWO, PSO, and DE. The vertical displacement is considered to be the objective for performing the optimization for the castellated beams with hexagonal web openings. It is assumed that three types of materials are used for manufacturing the toothed beams, as shown in Table 1.

The beam geometry is illustrated in Figure 1. The optimization sought by this study is the deflection of the castellated beam based on not considering some failure mechanisms such as shear failure, welding failure, lateral torsional buckling, and the Vierendeel mechanism. The optimization processes are carried out using three different algorithms with inputs related to the length of the beam. 10 different lengths are used. The distance between the beam's support and the nearest opening is set at 30 cm, which is a distance that allows for the analysis of all forces near the support, including tensile forces. This analysis is conducted for all ten different lengths used in this study. The beam lengths and the number of openings are presented in Table 2.

Table 1. Mechanical properties of steel materials

Steel grade	f_y (yield stress)	Modulus of elasticity
S235	235 MPa	200 GPa
S255	255 MPa	200 GPa
S355	355 MPa	200 GPa

Table 2. Beam lengths and number of spaces.

Length of beam (L) cm	Number of openings (ng)
200	5
300	9
400	11
500	15
600	17
700	21
750	22
800	23
900	27
1000	29

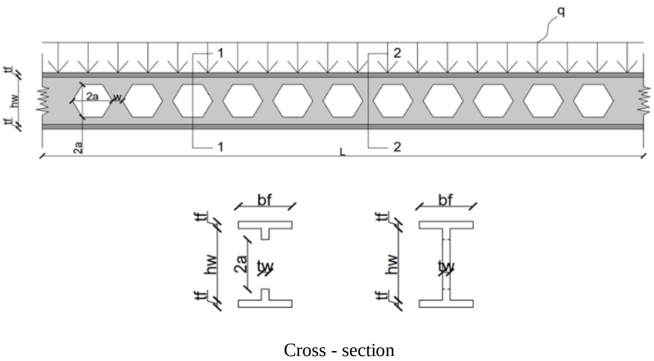

Fig. 1: Section and geometry of the castellated beam

Minimum and maximum values for the design variables used in this study: beam height (h_w), flange width (b_f), web thickness (t_w), flange thickness (t_f), opening height (2a), and weld length (w) are summarized in Table 3.

Table 3. Design variables

Design variable	Definition	Minimum value (cm)	Maximum value (cm)
h_w	web height	10	72
b_f	flange width	8	25
t_w	web thickness	0.7	1.5
t_f	flange thickness	0.4	1.5
a	opening height/2	0.3 h_w	0.4 h_w
w	weld length	0.5 a	a

Three design constraints are used according to Eqs. (1 -3). The first of these constraints (g_1) involves calculating the T cross-sectional area above and below the opening, which bears the applied loads, with a value of 40 cm^2. The cross-section area can be taken from the intial beam. The second constraint (g_2) represents the load bearing capacity of the castellated beam based on the allowable yield stress values for each material type, according to Table 1. The third and final constraint in this study (g_3) is the imposed distance between the beam's support and the edge of the opening, set at 60cm for both ends of the beam.

$$g_1 = 2 \times b_f \times t_f + t_w(h_w - a) \leq 40 \quad (1)$$

$$g_2 = (L^2 \times q \times (h_w + 2 \times t_f))/(16 \times 3 \times (\frac{1}{12} \times b_f \times (h_w + 2 \times t_f)^3 - 1/12 \times t_f{}^3 \times (b_f - t_w)) - 2 \times a^3 \times \frac{t_w}{3}) \leq \sigma_{allow} \quad (2)$$

$$g_3 = (n_b - 1) \times w + 2 \times a \times n_b \leq L - 60 \quad (3)$$

Generally in the design of castellated beams, the calculation of the vertical displacement is required in optimization problems and the objective function, which expresses the feasibility of the optimization. Therefore, in this study, the objective function represents the vertical displacement by minimizing it to the best possible level. An objective function, Fx, is used, as shown in Eq. (4), which means the vertical displacement value of the castellated beam, assuming a fixed-fixed type beam. The thin beam theory is adopted, and shear deformations are neglected.

$$Fx = L^4 \times q/(384 \times E \times I_{re}) \quad (4)$$

In this equation, (q) is a uniformly distributed load along the beam's span, (E) represents the modulus of elasticity of steel, and (I_{re}) denotes the reduced area moment of inertia for the castellated beam. The maximum vertical displacement is in the middle of a beam span and this is consistent with the objective function based on the structural analysis for fixed-fixed beam. The reduced area moment of inertia is calculated using Eq. (5), and the uniform load along the castellated beam is determined using Eq. (6) [11].

$$I_{re} = (1/12 \times b_f \times (h_w + 2 \times t_f)^3) - (\frac{1}{12} \times h_w{}^3 \times (b_f - t_w) - (2 \times a^3 \times \frac{t_w}{3}) \quad (5)$$

$$q = f_y \times I_{re}/(L^2 \times (h_w + 2 \times t_f)) \quad (6)$$

In this study, three different optimization algorithms are used for solving the problem. Below are some information about these three algorithms.

The GWO algorithm is based on the behavior exhibited by gray wolves, which follows a hierarchical structure. The hierarchy begins with the leader, known as alpha, followed by beta, the leader's assistant responsible for receiving instructions from alpha and conveying them to the delta wolves. Delta wolves have lower competence than beta but higher than the last rank, Omega. The alpha, beta, and delta wolves work collaboratively to locate prey and move randomly based on the prey's position. The movement of the wolves is influenced by factors related to exploration, search, encirclement, and hunting. In the algorithm, the distance between each wolf and the prey is represented mathematically, and these three types of wolves signify the top three solutions. These solutions drive the process of optimization and enhancement within the algorithm, which records the best solutions through iterations [38-39]. In this study, the process is executed over 30,000 iterations with 20 solution vectors.

The PSO algorithm has a significant and beneficial impact in the field of engineering design by optimizing geometric shapes and topology, requiring only a few function evaluations to achieve good results. Its mechanism is based on the principle of bird swarms, which possess intelligence enabling them to coordinate their movements according to their needs. Each bird in the swarm represents a particle within the algorithm and simultaneously serves as a solution to the problem. The algorithm starts by generating a swarm randomly, and through iterations, it can reach optimal solutions. These particles communicate with each other to identify the best among them, moving towards the optimal solution at a certain speed. Each particle in the algorithm has three vectors: speed, current position, and the best position it has reached during previous iterations [40-43]. In this study, 30,000 iterations were used with 20 solution vectors.

The DE algorithm is considered one of the effective methods and is an improved version of the genetic algorithm (GA). It leverages the evolution of populations to solve complex optimization problems through a random search based on selection, mutation, and crossover mechanisms. This robust algorithm demonstrates good results with minimal control parameters, enhancing the success rate of population evolution. Its working mechanism involves selecting a group at random, from which two individuals are randomly chosen. The difference between these two individuals forms a vector that acts as a source of variation for a third individual. This vector is weighted according to specific rules within the algorithm, which determines the crossover cases between the initial chromosome and the new solution through a probability value known as the crossover probability (CR) [44-45]. In this study, 30,000 iterations and 20 solution vectors are used.

The three algorithms will start with defining constants, constraints, variable boundaries, and set algorithm parameters (population size, mutation factor, crossover rate, max iterations) and the second step will be Initialization will randomly generate candidate solutions within the search space. The third step is defined as the mutation that creates mutant vectors by combining three random individuals to enhance diversity and the fourth step is followed by position updates. Fitness evaluation ensures improvements by updating and adjusting accordingly (for GWO) and for PSO will be as exploration & exploitation for adjusting coefficient vectors (A and C) to balance searching new areas and refining good solutions in DE the fourth step is a crossover that will be form trial vectors by mixing mutant and original vectors, guided by the crossover rate. The fifth last step is the stopping criterion it will be treated until max iterations, selecting the best-found solution as the final result.

Optimization problems are non-linear problems and require many iterations to obtain the optimal solution and design using different formulas. Therefore, the use of algorithms is very important in improving the control system to reduce the displacement of structures [46-48].

3. Numerical results and discussion

This paper aims to determine the optimal dimensions of castellated beams using the three algorithms mentioned earlier. The study is based on the principle of deflection, which has not been a primary focus in recent optimization studies. To address this gap, optimizations were performed based solely on maximum vertical displacement values. This approach differs from other studies that base the design of castellated beams on criteria such as weld failure, lateral-torsional buckling, Vierendeel mechanism, and shear failure. While these are essential factors, this study focuses specifically on deflection as its main criterion.

The material properties are illustrated in Table 1. The different lengths used in this study and the number of web openings for each length are shown in Table 2. The obtained results for S235, S255, and S355 are listed in Tables (4 -5), Tables (6 - 7) and Tables (8 - 9), respectively.

Table 4: Optimum design values for S235 (*L*=200,300,400,500,600 cm)

	Algorithm	L = 200	L = 300	L = 400	L = 500	L = 600
h_w	GWO	34.477	30.8853	35.6545	34.5878	39.1147
	PSO	38.877	36.3636	41.7636	39.6396	42.8539
	DE	38.8889	36.3636	41.9753	39.6396	42.8571
b_f	GWO	10.916	11.7637	10.3572	9.1438	17.6904
	PSO	8	8	8	8	8
	DE	8.6093	8.7381	8	8	8
t_w	GWO	1.2229	1.1537	1.3524	1.1343	0.8488
	PSO	0.7	0.7	0.7	0.7	0.7
	DE	0.7	0.7892	0.7824	1.0091	0.9248
t_f	GWO	1.0173	1.1217	0.5145	0.772	0.685
	PSO	1.5	1.5	1.5	1.5	1.5
	DE	1.5	1.5	1.5	1.5	1.5
a	GWO	10.4335	10.2758	12.1588	10.9784	12.1146
	PSO	11.6631	10.9091	12.5815	11.8919	12.1146
	DE	11.6667	10.9091	12.5926	11.8919	12.8571
w	GWO	6.8059	6.052	6.3848	6.4495	7.6143
	PSO	5.8316	5.4545	6.2907	5.9459	6.4300
	DE	5.8333	5.4545	6.2963	5.9459	6.4286
Fx	GWO	0.0035	0.0083	0.0134	0.0211	0.0272
	PSO	0.0029	0.007	0.011	0.018	0.0241
	DE	0.0029	0.007	0.0109	0.018	0.0241

Table 5: Optimum design values for S235 (*L*=700,750, 800, 900, 1000 cm)

	Algorithm	L = 700	L = 750	L = 800	L = 900	L = 1000
h_w	GWO	36.6919	35.6649	36.6526	35.7593	39.144
	PSO	41.0143	42.1885	43.2749	41.791	43.5185
	DE	41.0256	42.2018	43.2749	41.791	43.5185
b_f	GWO	13.3893	10.5359	10.9378	10.8977	11.5945
	PSO	8	8	8	8	8
	DE	8	8	9.0291	8	8
t_w	GWO	1.2232	1.0516	1.0084	1.0771	0.8951
	PSO	0.8322	0.7	0.7	0.7571	0.7
	DE	0.8694	0.8639	0.7221	0.8835	0.7619
t_f	GWO	0.6672	1.0191	0.9409	1.1206	1.0232
	PSO	1.5	1.5	1.5	1.5	0.4
	DE	1.5	1.5	1.5	1.5	1.5
a	GWO	11.0506	11.0313	12.0769	11.5994	12.4459
	PSO	12.3052	12.6597	12.9825	12.5373	13.0556
	DE	12.3077	12.6606	12.9825	12.5373	13.0556
w	GWO	7.9132	8.4271	7.1725	7.7452	7.2712
	PSO	6.1546	6.3318	6.4912	6.2687	6.5278
	DE	6.1538	6.3303	6.4912	6.2687	6.5278
Fx	GWO	0.0395	0.0457	0.0509	0.0653	0.0744
	PSO	0.0341	0.0381	0.0424	0.0554	0.0691
	DE	0.0341	0.0381	0.0424	0.0554	0.0659

Based on the results obtained from Tables (4 - 9), it is observed that as the length of the castellated beam increases, the value of vertical displacement also increases, but only slightly and in an incremental manner, depending on the length of the beam. Regarding the type of material used, there are very minimal differences in the results, with a slight increase in dimensions that correlates with the type of material. This provides an economic impression and evaluation for using these types under the structural operating conditions.

Table 6: Optimum design values for S255 (*L*=200,300,400,500,600 cm)

	Algorithm	L = 200	L = 300	L = 400	L = 500	L = 600
h_w	GWO	34.4113	33.8424	38.1092	30.7984	34.7615
	PSO	38.8878	36.3432	41.9639	39.6396	42.8571
	DE	38.8889	36.3636	41.9753	39.6396	42.8571
b_f	GWO	9.3917	10.39	15.2856	12.8758	11.2633
	PSO	8	8	8	8	8
	DE	8.8201	8	8	8	8
t_w	GWO	1.0864	0.8625	1.0057	1.0741	0.968
	PSO	0.7	0.7	0.7	0.7	0.7
	DE	0.832	1.0823	0.7	0.9885	0.7347
t_f	GWO	0.9707	1.1114	0.6931	0.9341	1.1423
	PSO	1.5	1.5	1.5	1.5	1.5
	DE	1.5	1.5	1.5	1.5	1.5
a	GWO	11.0602	10.176	12.2324	11.2351	11.8218
	PSO	11.6663	10.903	12.5922	11.8919	12.8571
	DE	11.6667	10.9091	12.5926	11.8919	12.8571
w	GWO	5.867	5.8289	6.7218	6.1966	7.3906
	PSO	5.834	5.4515	6.2982	5.9459	6.4286
	DE	5.8333	5.4545	6.2963	5.9459	6.4286
Fx	GWO	0.0037	0.0083	0.0134	0.0254	0.0323
	PSO	0.0032	0.0076	0.0118	0.0195	0.0261
	DE	0.0032	0.0076	0.0118	0.0195	0.0261

Table 7: Optimum design values for S255 (*L*=700,750, 800, 900, 1000 cm)

	Algorithm	L = 700	L = 750	L = 800	L = 900	L = 1000
h_w	GWO	34.638	36.8683	36.5633	32.3704	38.1128
	PSO	41.0256	42.2018	43.2749	41.791	43.5185
	DE	41.0256	42.2018	43.2749	41.791	43.5185
b_f	GWO	10.9592	10.8683	10.7633	10.4433	11.7784
	PSO	8	8	8	8	8
	DE	8.3705	8	8	8	8
t_w	GWO	1.0896	1.2933	0.7865	0.9414	0.8856
	PSO	0.7	0.7	0.7	0.7	0.7
	DE	0.7	0.7702	0.806	0.7675	0.8134
t_f	GWO	0.7855	0.8958	0.9182	1.0329	0.9524
	PSO	1.5	1.5	1.5	1.5	1.5
	DE	1.5	1.5	1.5	1.5	1.5
a	GWO	10.8454	12.2041	11.9582	10.3072	12.1827
	PSO	12.3077	12.6606	12.9825	12.5373	13.0556
	DE	12.3077	12.6606	12.9825	12.5373	13.0556
w	GWO	7.0688	6.5589	7.1655	6.2953	6.8251
	PSO	6.1538	6.3303	6.4912	6.2687	6.5278
	DE	6.1538	6.3303	6.4912	6.2687	6.5278
Fx	GWO	0.0449	0.0483	0.0553	0.0781	0.0829
	PSO	0.0369	0.0413	0.0459	0.06	0.0713
	DE	0.0369	0.0413	0.0459	0.06	0.0713

A comparison of the results for the three materials using the three algorithms reveals that the DE and PSO algorithms produced identical values for some cross-sectional dimensions and objective function values. However, for the web thickness and flange width, the DE algorithm yielded values up to 12% higher than PSO, with an increase not exceeding 1 cm. Regarding the GWO algorithm, the total section height is up to 15% lower than that obtained with DE and PSO. For other dimensions and objective function values, the increase compared to the other two algorithms does not exceed 15%. Morever the standart deviation values for the objective funtions is so small for all the compared alogrithms.

Table 8: Optimum design values for S355 (L=200,300,400,500,600 cm)

	Algorithm	L = 200	L = 300	L = 400	L = 500	L = 600
h_w	GWO	34.9577	30.1885	37.4998	33.9071	39.0861
	PSO	38.8889	36.3636	35.8519	39.6396	42.8571
	DE	38.8889	36.3636	41.9735	39.6396	42.8571
b_f	GWO	11.4362	11.9613	9.9068	14.1154	9.2731
	PSO	8	8	8	8	8
	DE	8.1123	8	8	8.091	8
t_w	GWO	1.1429	1.1897	1.0651	0.8328	0.9372
	PSO	0.7	0.7	1.5	0.7	0.7
	DE	0.7	0.8471	0.8155	0.7	0.7
t_f	GWO	0.8157	0.8968	0.9544	0.8576	1.0849
	PSO	1.5	1.5	1.5	1.5	1.5
	DE	1.5	1.5	1.5	1.5	1.5
a	GWO	11.009	9.8634	11.8313	10.6202	12.0261
	PSO	11.6667	10.9091	12.5926	11.8919	12.8571
	DE	11.6667	10.9091	12.5926	11.8919	12.8571
w	GWO	6.3912	7.1837	7.2153	7.1145	7.1606
	PSO	5.8333	5.4545	6.2963	5.9459	6.4286
	DE	5.8333	5.4545	6.2963	5.9459	6.4286
Fx	GWO	0.005	0.0129	0.0187	0.0323	0.0401
	PSO	0.0044	0.0105	0.0189	0.0269	0.0361
	DE	0.0044	0.0105	0.0163	0.0269	0.0361

Table 9: Optimum design values for S355 (L=700,750, 800, 900, 1000 cm)

	Algorithm	L = 700	L = 750	L = 800	L = 900	L = 1000
h_w	GWO	35.4059	37.4219	38.0747	38.1407	38.6325
	PSO	41.0256	42.2018	43.2748	41.791	43.3481
	DE	41.0256	42.2008	43.2789	41.791	43.5185
b_f	GWO	11.8576	9.54	18.1994	12.7779	16.1788
	PSO	8	8	8	8	8
	DE	8	8	8	8	8
t_w	GWO	1.1946	1.3077	1.0448	0.843	1.0848
	PSO	0.7	0.7	0.7	0.7	0.7
	DE	0.7086	0.7063	0.8123	0.7371	0.8467
t_f	GWO	0.6945	0.6478	0.6649	0.7032	0.7479
	PSO	1.5	1.5	1.5	1.5	1.5
	DE	1.5	1.5	1.5	1.5	1.5
a	GWO	10.8512	11.4764	11.811	11.8186	12.5348
	PSO	12.3077	12.6606	12.9824	12.5373	13.0044
	DE	12.3077	12.6606	12.9825	12.5373	13.0556
w	GWO	7.8739	7.6771	7.6294	6.7315	6.2807
	PSO	6.1538	6.3303	6.4913	6.2687	6.5256
	DE	6.1538	6.3303	6.4912	6.2687	6.5278
Fx	GWO	0.0612	0.0668	0.0746	0.0941	0.1145
	PSO	0.0511	0.0572	0.0636	0.0831	0.0992
	DE	0.0511	0.0572	0.0636	0.0831	0.0988

4. Conclusions

In this study, optimization is carried out using three different algorithms: GWO, PSO, and DE, for castellated beams of various lengths (10 different lengths) and three manufacturing materials (S235, S255, and S355). The objective function considered is the amount of vertical displacement, with three constraints specified. Based on this study, the following results are obtained:

- Increasing the length of the castellated beam leads to a slight increase in the vertical displacement, proportional to the increase in length.
- Increasing the yield strength causes a slight increase in vertical displacement.
- The objective function value, representing vertical displacement, is very similar for all three algorithms, with only minor differences reaching up to millimeters.
- The cross-sectional dimensions for the PSO and DE algorithms are very close to each other.
- The cross-sectional dimensions for the GWO algorithm differ slightly, either increasing or decreasing compared to those for the PSO and DE algorithms. The employed algorithms demonstrate a similar performance for the problem in the hand.
- Regarding the standard deviation indicator, it is found that there are very small differences for the objective functions which can be almost negligible.
- The results of the three algorithms differ slightly due to variations in the mechanisms and methodologies each algorithm uses to solve problems.

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