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Comparison of Flower Pollination Algorithm and Particle Swarm Optimization for Structural Weight Minimization of RC Beams with Carbon Fiber Reinforced Polymer (CFRP)

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Karbon Fiber Polimer Takviyeli Betonarme Kirişlerin Yapısal Ağırlık Minimizasyonu İçin Çiçek Tozlaşma Algoritması ve Parçacık Sürüsü Optimizasyonunun Karşılaştırılması

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Öz

En iyi diğer bir deyişle en uygun tasarımı oluşturmak için farklı metodolojiler tercih edilebilmektedir. Günümüzde ise özellikle genetik, canlıların yetenekleri veya bitkilerin doğal yaşamdaki davranışları gibi çeşitli metaforlardan ilham alınarak geliştirilmiş olan metasezgisel algoritmalar herhangi bir optimizasyon problem için hedef sonuçları sağlamak açısından kullanışlı, uygun ve etkili olabilmektedir. Bu nedenle mevcut çalışmada karbon fiber polimer takviye ile desteklenen betonarme kiriş yapıları için en uygun yapısal modelin tasarlanmasında çiçek tozlaşma algoritması ve klasik bir metot olan parçacık sürüsü optimizasyonu olarak iki farklı popülasyon tabanlı metasezgisel algoritma kullanılmıştır. Bu bağlamda CCFRP plakaların genişliği ve sayısı olarak tanımlanan tasarım parametrelerinin optimizasyonunun yanı sıra algoritmaların başarısı ve etkinliğini toplam ağırlığın minimize edilmesi açısından kıyaslamak için çeşitli bağımsız optimizasyon senaryoları uygulanmıştır. Sonuçlara göre ağırlık değerlerinin düşüklüğü ve amaç fonksiyonu için hata metrikleri dikkate alınarak minimum ağırlığın sağlanması doğrultusunda yapısal modellerin en iyi parametrelerini belirlemek için FPA' nın en güçlü algoritma olduğu söylenebilir.

Anahtar Kelimeler: *Optimizasyon; Metasezgisel algoritmalar; Yapı mühendisliği; Fiber takviyeli polimerler; Maliyet minimizasyonu.*

Abstract

In order to generate the best namely most appropriate design, different methodologies can be preferred. Nowadays, especially, metaheuristic algorithms, which have been proposed by inspiring various metaphors such as genetic, abilities of animals or natural behaviors of plants etc., can be useful, suitable and effective to provide the target results for any optimization problem. For this reason, in the current study, to design the most appropriate structural model intended for reinforced concrete (RC) beam structures supported with carbon fiber reinforced polymer (CFRP), two different population-based metaheuristic methodologies as flower pollination algorithm (FPA), and a classical one as particle swarm optimization (PSO) were operated. In this respect, several independent optimization cases were applied to compare the success and efficiency of algorithms in terms of minimization of total weight besides optimization of design parameters as number and width of CFRP plates. According to results, it can be said that FPA is the most powerful algorithm for determining the best parameters of structural models with the aim of providing minimum weight by considering the error metrics of objective function, and the lowness of weight values.

Keywords: *Optimization; Metaheuristic algorithms; Structural engineering; Fiber reinforced polymers; Weight minimization.*

1. Giriş

As in many engineering disciplines, also in structural engineering, properly realized of some operations such as designing of structures, solution of structural problems, reinforcement of buildings to some effects like seismic damages is very required and vital to can maintain of alives' life in safety. However, in the design process, economic conditions, namely providing cost efficiency, besides sustainability and aesthetics of structures are also a necessity, together with consumption less time and However, it must be considered that real-life engineering problems are not based on linearity and so, we cannot solve them with classical methods with suitable, and easy way with the aim of supplying the desired conditions. To overcome like these problems, in recent years, various methodologies such as metaheuristic algorithms are frequently preferred with the aim of providing the best namely the most economic, sustainable, profitable, eco-friendly etc. options.

If the structural engineering is investigated for these aims, it can be seen that quiet different applications are

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exist conducted by utilizing various types of metaheuristic algorithms. For example, Manahiloh et al. 2015 created an optimum reinforced earth wall design added with geosynthetic. In this respect, harmony search (HS) was employed to minimize the structural cost of wall designs, which have different heights and are subjected to static and dynamic loads. Additionally, viscous fluid dampers were added to a rubber seismic base-isolation system constructed in a five-story superstructure, which's optimal mechanical properties were obtained via genetic algorithm (GA) (Barakat et al. 2015).

By Ulusoy et al. (2018), an optimization methodology was applied with the usage of HS in order to create the cost-efficiency case for two-story two-span reinforced concrete (RC) frames. As concerned the study carried out by Lu et al. (2018), is based on proper adjusting of properties of tuned impact dampers as a vibration control system. Within this scope, a benchmark model as steel frame structure was handled, and mechanical parameters of located damper system to it were best configured with the usage of differential evolution (DE) algorithm in the direction that different structural responses together with injuries were tried to decrease. Also, for minimizing the structural weight for cantilever beam model, different metaheuristic methods (artificial bee colony (ABC), bat (BA), and a modified bat algorithms (MBA), which is combined with Lévy flight) have been preferred (Yucel et al., 2020). Nguyen-Van et al. 2020 created a metaheuristic algorithm combination, which is comprised of differential evolution (DE) and Jaya algorithm (JA), to make possible sizing, besides shape optimization for truss structures subjected to frequency limitations. Also, by using a metaheuristic algorithm as biogeography-based optimization (BBO), both the cost minimization and sustainability objects were handled together in terms of providing the best model for RC frame structures (Negrin and Chagoyén 2022). To generate the most appropriate structural model in terms of two targets as economy and eco-friendly conditions, three different metaheuristics as flower pollination algorithm (FPA), Jaya algorithm (JA), and HS were operated for RC beams (Yucel et al. 2022). Moreover, GA was applied to detect the optimal cost value for creation of the RC strap combined footings under biaxial bending moment (Luévanos-Rojas et al. 2024). On the other side, an improved version of artificial rabbits optimization algorithm (ARO) has been utilized by SeyedOskouei et al. 2024 to generate the best design for truss structures under natural frequency constraints with the aim of ensuring optimum both shape and size.

In order to make possible to lighten the structural weight for reinforced concrete (RC) beam model combined with carbon fiber reinforced polymer (CFRP), a classical and effective, and novel population-based and widely-used metaheuristic algorithm were preferred including particle swarm optimization (PSO) and flower pollination algorithm (FPA). For this respect, in the current study, different optimization cases were applied to make a decision about which algorithm is more useful, more effective, and more sensitive to minimize the weight. In this scope, the 1st application case is related to the usage of constant population (10) and iteration numbers (3000) utilized during multiple independent cycles to investigate the statistical efficiency. Also, the 2nd one is based on the evaluation of different ranges of both population (10-20 by increasing 5), and iterations (from 100 to 1000 by increasing 50) to understand the best algorithm option to realize the objectives by optimizing design parameters. In the direction of these applications, it can be accepted that FPA is more effective, and sensitive in terms of minimizing the weight (comprised of concrete, steel reinforcement and FRP) by providing the smallest error values for objective function as minimum structural weight.

2. Materials and Methods

2.1. Flower Pollination Algorithm (FPA)

FPA was developed by Xin-She Yang 2012 that is a population-based metaheuristic methodology proposed with the consideration of pollination process belonging flowering plants, which ensures to maintain of continuities with the help of some factors like insects, wind, water etc. According to this natural behavior of plants, two different options may be realized to optimize real-life problems: 1st. global search (cross-pollination), and 2nd. Local search (self-pollination). These processes can be expressed via Eq. (1) and (2), respectively.

$$X_i^{new} = X_i^{old} + Levy\left(X_i^{best} - X_i^{old}\right) \quad (1)$$

$$X_i^{new} = X_i^{old} + r\left(X_i^{m} - X_i^{k}\right) \quad (2)$$

Also, to realize the flight for global search, a random distribution function as $Levy$ has been utilized (Eq. (3)):

$$Levy = \frac{1}{\sqrt{2\pi}}(r)^{-1.5}\, e^{\left(-\frac{1}{2r}\right)} \quad (3)$$

X_i^{new} and X_i^{old} are new/updated and old/current values for i^{th} design parameter, respectively. X_i^{best}, X_i^{m}, and X_i^{k}

express the best value in terms of objective function, and m^{th} with k^{th} random-selected solution values for this parameter. Additionally, r defines a function that utilized for producing a random number between [0,1].

2.2. Particle Swarm Optimization (PSO)

PSO method is a population-based metaheuristics algorithm proposed by Kennedy and Eberhart 1995. In PSO algorithm, three different algorithm parameters, which are specific to method, are utilized as inertia coefficient (w), and acceleration constants (c_1 and c_2).

On the other side, in each iteration, besides the current solutions, the velocity vectors, which shows the movement simulation of particle/solution within swarm, are also generated. New solutions are provided in the direction that the mentioned velocity vectors are produced according to PSO rules, and used together with the current solutions, which are defined as X_i^{old}. Velocity vector, which is utilized when the new solutions are ensured in PSO algorithm, is expresses with Eq. (4), and ultimate new solution value is also calculated with Eq. (5).

$$V_i^{new} = w\,V_i^{old} + c_1 r\left(X_i^{gbest} - X_i^{old}\right) + c_2 r\left(X_i^{lbest} - X_i^{old}\right) \quad (4)$$

$$X_i^{new} = X_i^{old} + V_i^{new} \quad (5)$$

where X_i^{new} and X_i^{old} demonstrate the new and old solutions in terms of i^{th} particle; X_i^{gbest} and X_i^{lbest} are meant to the best particle within all population for iterations and for the current iteration, respectively. Here, V_i^{new} and V_i^{old} express the updated and current velocity values in terms of i^{th} design parameter, too. In Table 1, all of the settings, and parameters of FPA and PSI algorithms are presented, too:

Table 1. Settings of algorithms.

Algorithm	Specific Parameter	Parameter Name	Value
FPA	sp	Key possibility	0.5
PSO	w	Inertia coefficient	0.1
	c_1	Acceleration constant	1
	c_2		2

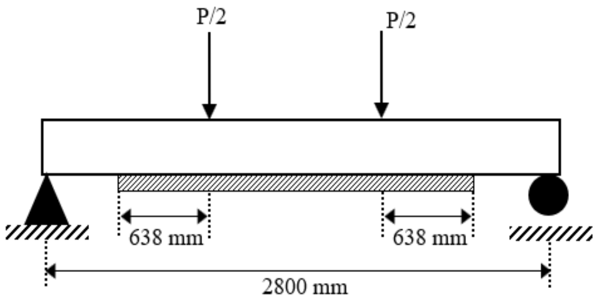
2.4. Optimization Details of Beam Structure Added CFRP

The structural model is comprised of a reinforced concrete (RC) beam utilized with CFRP plate illustrated in Figure 1. All of the design parameters, constant and material with structural properties can be investigated as indicated in Figure 1.

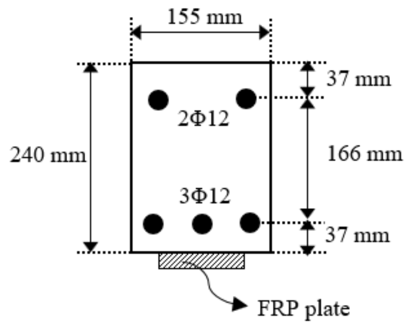
For optimum design of RC beam added CFRP plate, several design constants are handled as variable, and design parameter, which will be optimized, is handled as the width (w_f) of CFRP to minimize the total weight (Eq. (6)). Additionally, several structural parameter properties for concrete, steel reinforcement, and FRP plate are summarized within Table 2:

$$Min_{Tw} = Min_{CFRPw} + Min_{Cw} + Min_{Sw} \quad (6)$$

Here, Min_{Tw} expresses the total structural weight. Also, Min_{CFRPw}, Min_{Cw}, and Min_{Sw} are meant to the weight of CFRP plate, concrete, and steel reinforcement, respectively.



(a) Longitudinal section



(b) Cross-section

Figure 1. The structural model of RC beam added CFRP.

Moreover, some rules as structural limitations for design must be satisfied according to a regulation of ACI-440.2R-17 Guide for the Design and Construction of Externally Bonded FRP systems for Strengthening Concrete Structures (ACI Committee 440). The constraints are investigated to prevent to rupture of CFRP, to limit the tension of CFRP, and to save the moment capacity of beam, too (Table 3).

Table 3. ACI-440.2R-17 Limitations for structural beam model added CFRP.

Design constraint	Limitation	Unit
Flexural moment capacity (M_n) Design moment for beam (M_u)	$M_n > M_u$	kNm
Design strain value for CFRP (ε_{fd}) Effective strain of FRP under load (ε_{fe})	$\varepsilon_{fe} \leq \varepsilon_{fd}$	-
Design rupture strain for (ε_{fu})	$\varepsilon_{fd} < 0.9\,\varepsilon_{fu}$	

Where, RC beam was designed according to flexural strength. As Table 2 was evaluated with the consideration of ACI-440.2R-17, design moment value (M_u) should be smaller than capacity of flexural strength (M_n). Also, effective strain FRP (ε_{fd}) must be bigger or equal to design strain (ε_{fd}). Additionally, ε_{fd} value should not exceed the 0.9 times of design rupture strain for FRP (ε_{fu}). Here, $\boldsymbol{\varepsilon_{fe}}$, $\boldsymbol{\varepsilon_{fd}}$, and $\boldsymbol{\varepsilon_{fu}}$ can be formulized via Eqs. (7)-(9).

$$\varepsilon_{\mathrm{fe}} = 0.003\left(\frac{d_f - c}{c}\right) - \varepsilon_{\mathrm{bi}} \tag{7}$$

$$\varepsilon_{\mathrm{fd}} = 0.41\sqrt{\left(\frac{f_c}{n_f\, E_f\, t_f}\right)} \tag{8}$$

$$\varepsilon_{\mathrm{fu}} = \frac{f_{fu}}{E_f} \tag{9}$$

Here, $\varepsilon_{\mathrm{bi}}$ is the deformation happened in the bottom fiber of beam before reinforcement (Eq. (10)).

$$\varepsilon_{\mathrm{bi}} = \frac{M_{DL}(d_f - kd)}{I_{cr}\, E_c} \tag{10}$$

Where, M_{DL} is the moment value, which was calculated according to the dead load assumption by considering ACI-440.2R-17. Also, I_{cr} is the inertia moment of cracked section (Eq. (11)).

$$\mathrm{I}_{\mathrm{cr}} = \frac{bc^3}{3} + n_s A_s (d - c)^2 \tag{11}$$

$\boldsymbol{n_s}$ means to elasticity modular ratio between steel and concrete and calculated via $\frac{\boldsymbol{E_s}}{\boldsymbol{E_c}}$.

Table 2. Design parameters and constants for materials of beam structure combined with CFRP.

	Parameter expression	Symbol	Values	Unit
Design constants	Thickness of CFRP	t_f	1.2 (for 1st case) 1.2, and 1.5-2.5 by increasing 0.5 (for 2nd case)	mm
	Height of beam	h	240	
	Breadth of beam	b	155	
	Beam length	L	2800	
	Effective depth for tension bar	d	203	
	Effective depth for compression bar	d'	37	
	Effective depth for FRP	d_f	240	
	Distance between extreme compression fiber and neutral axis	c	58	
	Strength reduction factor for moment	ϕ	0.726	-
	Number of tension reinforcement bar	n_t	3	
	Number of compressive reinforcement bar	n_c	2	
	Strength reduction factor for FRP	ψ	0.85	
	Environment reduction coefficient	CE	0.95	
	Diameter of tension reinforcement bar	ϕ_t	12	mm
	Diameter of compressive reinforcement bar	ϕ_c		
	Tensile strength of steel after yielding	f_y	532	MPa
	Compressive strength for concrete	f_c	80	
	Tensile strength of steel before yielding	f_s	204	
	Elasticity modulus for steel	E_s	204000	
	Elasticity modulus for concrete	E_c	39200	
	Elasticity modulus for CFRP	E_f	155000	
	Rupture strength	f_{fu}^*	2400	
	Ultimate rupture strength	f_{fu}	$f_{fu}^* CE$	
Design parameters	Layer width of FRP	w_f	100-150	mm
	Number of layers	n_f	1-2	-

Table 4. Optimum design parameters and statistical values of minimum weight according to 25 cycles

Method	n_f	w_f (mm)	t_f (mm)	Min weight	Mean weight	Std. dev. of weight
FPA	2	146.0	1.2	259.011	259.017	0.014
PSO	2	146.0		259.011	3.60E+02	1.88E+02

3. Results and Discussions

3.1. Numerical results for 1st Case

For the 1st case, 25 independent cycles are evaluated to determine the best metaheuristic algorithm in terms of minimization of structural weight. For this reason, iteration, and population numbers are defined constant as 2000 and 10, respectively. According to this, for constant CFRP thickness (1.2 mm), the best results for optimization process in terms of objective function can be analyzed via Table 4.

Table 5. Optimum design parameters and minimum weight values for the best iteration-population combination

Method	n_f	w_f (mm)	t_f (mm)	Min weight	İteration number	Population number
FPA	2	146	1.2	259.011	150	20
		117	1.5	259.014	100	10
		100	2.0	259.234	100	10
		100	2.5	259.682	100	10
PSO	2	146	1.2	259.011	100	10
		117	1.5	259.014	100	10
		100	2.0	259.234	100	20
		100	2.5	259.682	100	10

Figure 2. Distribution of min, mean and standard deviation of weight values according to iterations (FPA).

3.2. Numerical results for 2nd Case

For the 2nd case, different values of iteration and population numbers were preferred to minimize the structural weight value. independent cycles are evaluated to determine the best metaheuristic algorithm in terms of minimization of structural weight. For this reason, iteration, and population numbers are defined constant as 2000 and 10, respectively. According to this, for constant CFRP thickness (1.2 mm), the best results for optimization process in terms of objective function can be analyzed via Table 5.

Here, via Figures 2 and 3, the distribution of minimum, average/mean and standard deviation namely error values of weight function are shown for 1.2 mm thickness of FRP in terms of each population number in order to represent the sensitivity of algorithms.

Figure 3. Distribution of min, mean and standard deviation of weight values according to iterations (PSO).

4. Conclusions

Respect to the 1st optimization case, it can be said that, the lowest weight can be detected as 259.011 kg by optimizing of FRP layer number as 2, and width as 146.0 mm (Table 3). Here, it is clear that FPA is better than PSO in terms of the minimization of weight by providing smaller standard deviation/error value according to all cycles. Also, for each cycle, due to that the structural weight values cannot be reached as minimum for each cycle, it should be recognized that PSO algorithm is not reliable and talented to determine the objective function accurately in any time. For this reason, FPA method is more effective than PSO.

On the other side, it is understood that the lowest weight can be detected as 259.011, 259.014, 259.234 and 259.682 kg for each thickness value by optimizing of FRP layer number as 2, respectively (Table 3) (2nd case). Here, it is clear that PSO and FPA show a similar behavior in terms of the minimization of weight by providing almost the same iteration and population numbers (Table 4).

As in the final step, FPA is more effective, reliable, and usable to minimize the weight value due to that standard deviation, and mean values of weights for PSO are arisen extremely variable in terms of whole of candidate solutions namely all population when 10 and

15 populations are considered. For 20 populations, the behavior of optimization process can be seen similarly respect to the thickness of FRP as 1.2 mm (Figure 2 and 3). So, totally, FPA was found as more successful and reliable method to create the best namely most appropriate model for a structural design supported via CFRP material.

According to the outcomes, the optimized design parameters as layer number and width of CFRP can be evaluated for different structural combinations, and also the design process can be handled to ensure the optimized values for various structural beam models with the aim of minimization of structural weight. On the other side, by changing the type of FRP material, the best design options can be created for optimizing the design parameters, too.

For the upcoming, and novel studies, this research can be a sample application in the way of ensuring the optimized design rules for structural concrete models design with fiber reinforced polymers. Also, for the following researches, the studies can be extended with the evaluation of minimum cost, CO_2 emission, energy etc. similar to the total weight value.

Declaration of Ethical Standards
Author declares to follow all ethical rules.

Credit Authorship Contribution Statement
Author: Sources, Research, Writing – Visualization of original manuscript, Codding of design and data.

Declaration of Competing Interest
The author declare that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability
All data are available in a data repository via the link as https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/PIBWIP.

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