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Research Article

Optimization of axial load carrying capacity of CFST stub columns

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ABSTRACT

Concrete filled steel tubular (CFST) columns are widely used due to their enhanced mechanical properties. The interaction between the concrete core and the steel casing increases structural stability and magnifies the compressive strength of concrete. Besides the structural performance, in alignment with the commitment of the concrete industry to reduce its environmental impact, lowering the carbon emissions caused by the production of concrete structures is gaining importance in recent years. The current paper gives an overview of the equations available in the literature that predict the axial load carrying capacity of rectangular CFST columns. A modified version of the Jaya metaheuristic algorithm is being proposed and the outcome of this algorithm is being presented. The algorithm is used in order to maximize the axial load-carrying capacity of a stub column. As an optimization constraint the CO_2 emission associated with the production of the CFST column is being kept below a predefined level throughout the optimization process. The optimization process as well as the cross-sectional dimensions associated with the optimum solution are presented.

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1. Introduction

Concrete-filled steel tubular (CFST) columns are an extensively investigated field of structural engineering. A major reason for this is the ease of construction, high ductility, and strength of these composite members. Some of the application areas of these structures are piles, columns and bridge piers (Wang et al. 2017). Although a large number of experimental studies have been conducted in this field, these studies are mostly related to the displacement and compressive strength properties of CFST columns. Some of the notable works done in this field include the experimental studies of Lai and Varma (2015), Johansson and Gylltoft (2002), Wei et al. (2020) about circular CFST columns. In the area of CFST columns with rectangular cross-sections the works of Xiong et al. (2017), Zhu et al. (2017) and Chen et al. (2018) can be mentioned.

While the experimental and numerical study of CFST columns is an extensively investigated area, the research in the field of optimization of CFST columns is relatively neglected. In recent years particularly metaheuristic optimization algorithms found application in a broad range of engineering problems. Cakiroglu et al. (2021) used metaheuristic methods to minimize the CO_2 emission associated with the production of CFST columns with circular cross-section. Besides CFST columns, laminated composite plates (Cakiroglu et al. 2020), cylindrical walls (Kayabekir 2021), water networks (Geem 2009), reinforced concrete cantilever soldier piles (Arama et al. 2020), active tuned mass dampers (Kayabekir et al. 2020a) and plane stress systems (Kayabekir et al. 2020b) are some of the engineering systems to which metaheuristic methods were applied. In the current study a modified Jaya optimization is applied to the problem of axial load-carrying capacity maximization. The variables of this optimization problem are the cross-sectional dimensions shown in Figure 1. The constraints of optimization are the upper and lower bounds of the design variables for which Eqs. (1-5) are applicable and the amount of CO_2 emission related to the production process of concrete. These ranges are given in Table 1. During the production of 1 kg of concrete approximately 0.12 kg of CO_2 is emitted into the atmosphere, and during

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the production of 1 kg of steel approximately 1.38 kg of CO_2 is being emitted (Fantilli et al. 2019). Besides the ranges of applicability also, the amount of CO_2 associated with the production of a stub column is introduced as an additional optimization constraint.

Nomenclature

N_u	Ultimate axial load-carrying capacity
N_s	Contribution of the steel casing to N_u
N_c	Contribution of the concrete core to N_u
A_s	Cross-sectional area of the steel casing
A_c	Cross-sectional area of the concrete core
η_s	Reduction factor that introduces the effect of confinement on the steel casing
η_c	Amplification factor that introduces the effect of confinement on the concrete core
k_s	Equivalent confining coefficient incorporating the lack of concrete confinement
H	Longer side length of a rectangular cross-section
B	Shorter side length of a rectangular cross-section
t	Wall thickness of the steel casing
D'	Equivalent diameter of the rectangular cross-section
$f_c{}'$	Compressive strength of concrete
f_y	Yield strength of the steel casing

1.1. Equations for the prediction of N_u

The literature about CFST columns includes various equations for the prediction of N_u of stub columns. Furthermore, there are separate equations for CFST columns with circular and rectangular cross-sections. The current study focuses on rectangular cross-sections. The equations developed by Wang et al. (2017) are used since these equations are shown to deliver the most satisfactory results in terms of the prediction of N_u (Vu et al. 2021).

$$N_u = N_s + N_c \quad (1)$$

$$N_s = \eta_s f_y A_s \ \ , \ \ N_c = \eta_c f_c' A_c \quad (2)$$

$$\eta_s = 0.91 + 7.31 \cdot 10^{-5} f_y - (1.28 \cdot 10^{-6} + 2.26 \cdot 10^{-8} f_y)\left(\frac{D'}{t}\right)^2 \quad (3)$$

$$\eta_c = 0.98 + 29.5(f_y)^{-0.48} k_s^{0.2}\left(\frac{t f_y}{D' f_c'}\right)^{1.3} \quad (4)$$

$$k_s = \frac{1}{3}\left(\frac{B-2t}{H-2t}\right)^2 \quad (5)$$

The equivalent diameter in Eq. (3) is calculated as $D' = \sqrt{(B^2 + H^2)}$. The equivalent confining coefficient k_s is needed due to lack of concrete confinement caused by the rectangular shape of the cross-section. Eqs. (1) to (5) are applicable only for certain ranges of the design variables B, H and t shown in Fig. 1. These ranges are listed in Table 1.

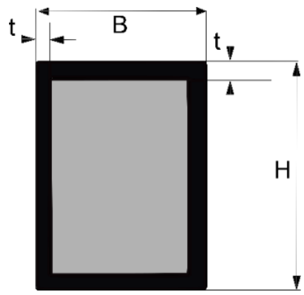

Fig. 1. Dimensions of a rectangular CFST column.

Table 1. Ranges of design variables.

Width to thickness ratio	$12 \leqslant B/t \leqslant 100$
Height to width ratio	$1 \leqslant H/B \leqslant 2$
Yield strength of the steel tube	175 MPa $\leqslant f_y \leqslant$ 960 MPa
Compressive strength of the concrete	20 MPa $\leqslant f_c' \leqslant$ 120 MPa
Steel wall thickness [mm]	$3 \leqslant t \leqslant 30$

2. Methods

The goal of the optimization is to maximize N_u while keeping the CO_2 emission associated with the production of the stub column below a certain threshold level at all times. Furthermore, throughout the iterations the design variables are kept within their corresponding upper and lower bounds of applicability as given in Table 1. The class of concrete has been varied between C25, C40, C60 and the yield stress of steel is fixed at 500 MPa.

2.1. Optimization process

A modified version of a metaheuristic optimization algorithm called Jaya optimization has been utilized in this study. The algorithm starts with the random generation of a population of solution candidates. Each solution candidate consists of a list of design variable values. In the current study these lists contain the cross-section side lengths, steel casing wall thickness and the corresponding axial load-carrying capacity and CO_2 emission. Once the initial population has been created all vectors in the population go through a Jaya iteration given in Eq. (6) (Venkata Rao 2016).

$$x_i^{k+1} = x_i^k + r1 \cdot \left(x_b^k - \left|x_i^k\right|\right) - r1 \cdot (x_w^k - |x_i^k|) \quad (6)$$

In Eq. (6) x_i^k is the $i-th$ vector in the population after k Jaya iterations and x_i^{k+1} is the updated version of this vector. x_b^k and x_w^k are the best- and worst-performing members of the population respectively in the $k-th$ Jaya iteration step. r_1 and r_2 are three dimensional vectors of random numbers between zero and one. In the proposed modified Jaya algorithm r_1 and r_2 are assigned according to the Lévy distribution given in Eq. (7) (Nolan 2020). The Lévy distributions for different values of γ and $\delta = 0$ are shown in Fig. 2. For each design variable the parameters of the Lévy distribution are tuned separately. A flowchart of the modified Jaya algorithm can be seen in Fig. 3.

$$f(x) = \sqrt{\frac{\gamma}{2\pi}\frac{1}{(x-\delta)^{1.5}}} e^{\frac{-\gamma}{2(x-\delta)}}, \quad \delta < x < \infty \tag{7}$$

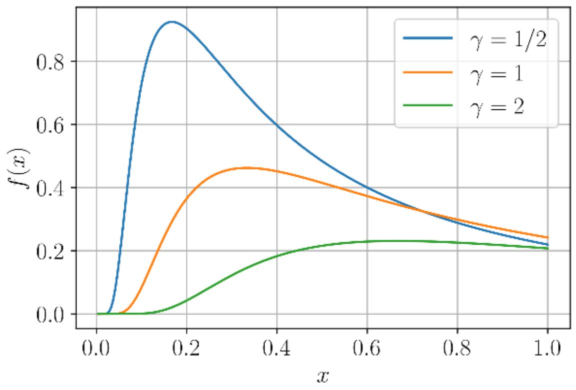

Fig. 2. Lévy distributions.

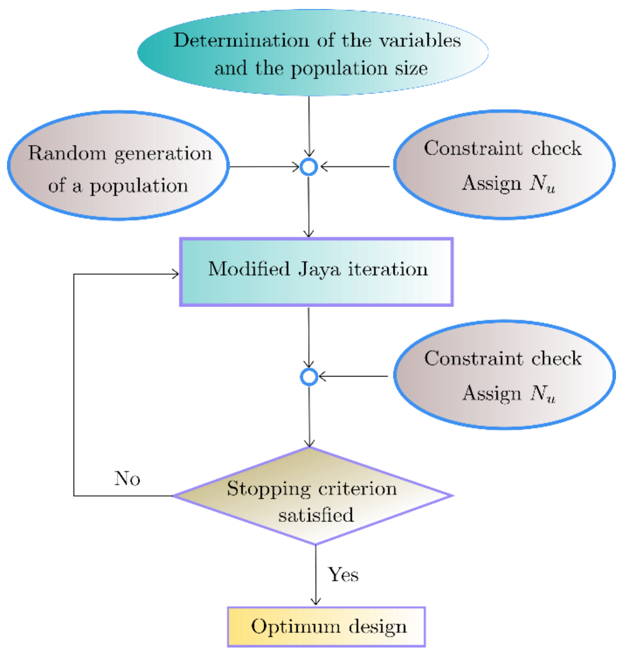

Fig. 3. Flow chart of the modified Jaya algorithm.

3. Results

Fig. 4 shows the optimization process where the best- and worst-performing solution vectors and the average value of the entire population are shown in different colors. It is observed that after the first ten iterations no more major update happened in the best solution vector. On the other hand, the convergence of the worst and average solution vectors to the optimum solution is observed after twenty-five iterations. The maximum axial load that could be achieved through the optimization was around 10759 kN in case of C25 concrete class. Similarly, Figs. 5 and 6 show the development of the best, worst and average solutions throughout the Jaya iteration steps for C40 and C60 concrete classes respectively. For all three concrete classes the corresponding cross-sectional dimensions and the maximum axial load-carrying capacities are listed in Table 2.

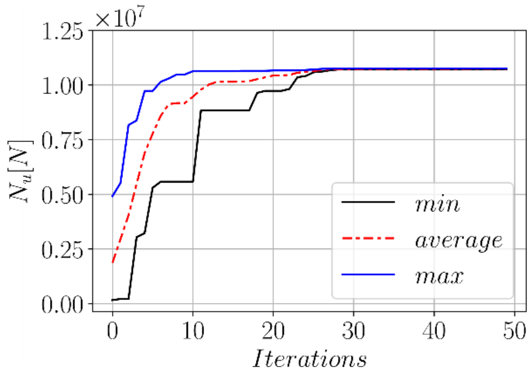

Fig. 4. Modified Jaya optimization for C25 concrete.

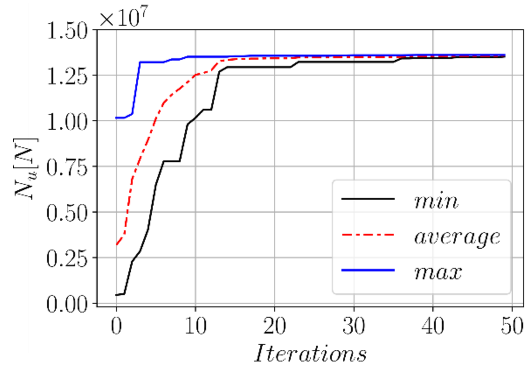

Fig. 5. Modified Jaya optimization for C40 concrete.

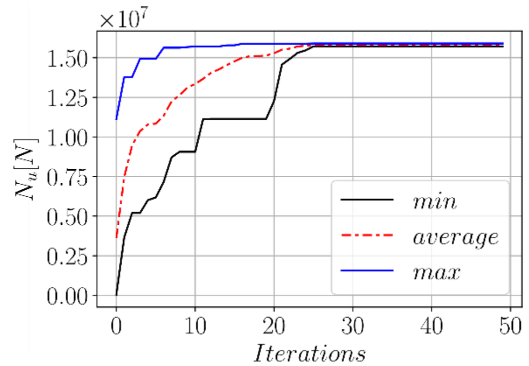

Fig. 6. Modified Jaya optimization for C60 concrete.

Table 2. Optimized cross-sections.

	B	H	t	$N_{u,\max}$ (kN)
C25	300	537	3	10759
C40	300	433	3	13618
C60	230	443	3	15905

4. Conclusions

Concrete-filled steel tubular (CFST) columns are widely used due to their favorable properties such as increased ductility and stability. Although structural performance is the primary concern of design engineers, the construction industry in general is aiming to reduce its carbon footprint in the recent years. The current study is considering both of these aspects of structural design. The cross-sectional dimensions of a stub column are optimized to increase the ultimate load-carrying capacity of the CFST structure while keeping the carbon emission below a predetermined level. To this end the modified version of a metaheuristic technique called Jaya algorithm has been used. The optimization process has been done for C25, C40 and C60 concrete classes. The results showed that through optimization the performance of a CFST column can be significantly increased without causing excessive carbon emissions.

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Conflict of Interest

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