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CO_2 emissions optimization of reinforced concrete ribbed slab by hybrid metaheuristic optimization algorithm (IDEACO)

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Abstract. This paper presents an optimization of the reinforced concrete ribbed slab in terms of minimum CO_2 emissions and an economic justification of the final optimal design. The design variables are six geometry variables including the slab thickness, the ribs spacing, the rib width at the lower and toper end, the depth of the rib and the bar diameter of the reinforcement, and the seventh variable defines the concrete strength. The objective function is considered to be the minimum amount of carbon dioxide gas (CO_2) emission and at the same time, the optimal design is economical. Seven significant design constraints of American Concrete Institute's Standard were considered. A robust metaheuristic optimization method called improved dolphin echolocation and ant colony optimization (IDEACO) has been used to obtain the best possible answer. At optimal design, the three most important sources of CO_2 emissions include concrete, steel reinforcement, and formwork that the contribution of them are 63.72, 32.17, and 4.11 percent respectively. Formwork, concrete, steel reinforcement, and CO_2 are the four most important sources of cost with contributions of 67.56, 19.49, 12.44, and 0.51 percent respectively. Results obtained by IDEACO show that cost and CO_2 emissions are closely related, so the presented method is a practical solution that was able to reduce the cost and CO_2 emissions simultaneously.

Keywords: CO_2 emissions; economic justification; hybrid metaheuristic optimization algorithm; optimal design; reinforced concrete ribbed slab

1. Introduction

The greatest challenge of the present century is reducing the emissions of CO_2, (Pachauari and Reisinger 2007). According to the United Nations Intergovernmental Panel on Climate Change (UNIPCC) (Pachauari and Reisinger 2007), there has been significant growth in the production of global greenhouse gases (GHG) in the atmosphere, which is caused by human activities. The annual values of CO_2 emissions, the most important anthropogenic GHG, have grown by about 80% since 1970. In the construction sector, the cement industry accounted for 5% of the total global CO_2 emissions (Worrell *et al*. 2001). Since demand for concrete products and structures has increased, the carbon footprint of the cement industry has almost doubled between 1990 and 2005 (Mehta and Meryman 2009), and the need for new construction in both developed and developing

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countries (Singh 2004, Lowe 2002) is a major concern which insists on the effective use of construction materials regarding their environmental footprint. These concerns have caused research and development to move towards more sustainable materials, designs, and construction methods (Gartner 2004, Payá *et al.* 2001, Yang *et al.* 2008, González *et al.* 2006). One of the ways to reduce carbon dioxide emissions is through the efficient use and optimization of structural designs. With the variety and number of concrete structures in the world, considering the effects of environmental factors and CO_2 emissions in designs has been studied in recent research. Paya-Zaforteza *et al.* (2009) presented a methodology to design reinforced concrete (RC) building frames based on minimum embedded CO_2 emissions. The optimal design was done by a simulated annealing (SA) algorithm applied to two objective functions, namely the embedded CO_2 emissions and the economic cost of RC framed structures. Camp and Huq (2013) applied a hybrid Big Bang-Big Crunch (BB-BC) optimization algorithm to the design of reinforced concrete frames. Designs were obtained for several reinforced concrete frames that minimize the cost and the CO_2 emissions associated with construction. Eleftheriadis *et al*. (2018) used an integrated design approach for the cost and embodied carbon optimization of reinforced concrete structures to inform early design decisions. A BIM-based optimization approach that uses Finite Element Modelling (FEM) and a multi-objective genetic algorithm with constructability constraints was developed. The research of Kaveh *et al.* (2020) studied the relationship between optimal cost and optimal carbon dioxide emissions in design for RC frames of different heights by using an automatic computational procedure. Cakiroglu *et al*. (2021) expressed the comparison between social spider optimization and harmony search algorithm applications for CO_2 emissions optimization in concrete-filled steel tubular (CFST) columns. The research of Yepes-Bellver *et al*. (2022) deals with optimizing embedded carbon dioxide (CO_2) emissions using surrogate modeling, whether it is the deck of a post-tensioned cast-in-place concrete slab bridge or any other design structure. Kaveh *et al*. (2022) proposed a methodology for the optimal seismic design of reinforced concrete 3D columns and bent caps (beams) of bridges. Design variables comprised compressive strength of concrete, geometry, as well as longitudinal and shear reinforcement of columns and beams. The optimization was achieved by using the enhanced colliding bodies optimization algorithm to minimize the cost and CO_2 emissions.

In the current study, the optimal design of one-way reinforced concrete ribbed slab to minimize the emissions of CO_2 is investigated. A ribbed or waffle slab is a slab system. They feature a series of parallel reinforced concrete T beams framing into reinforced concrete girders. The slab is the flange of the beam and the extended part is the web. The extended part is known as the ribs. The main benefit of ribbed floors is the lowering in weight achieved by removing part of the concrete below the neutral axis. This creates this type of floor economical for buildings with a long span with light or moderate loads. In the field of optimization in concrete structures, various researches have been done see (Günay *et al.* 2023, Bekdaş *et al.* 2023) and in this article minimizing the CO_2 emissions in the design of concrete ribbed slab is performed with the hybrid robust metaheuristic optimization algorithm that called Hybrid Improved Dolphin Echolocation Ant Colony Optimization (IDEACO) algorithm. The efficiency of this algorithm is studied for emissions optimization in concrete slabs.

The paper is structured as follows: Section 2 recalls the design of the concrete ribbed slab and the objective function of the optimization problem described. In Section 3, the IDEACO method used in this research is explained. Optimization results for the optimal design of concrete ribbed slab with minimum CO_2 emissions are presented and discussed in Section 4. Section 5 summarizes the main findings of this study.

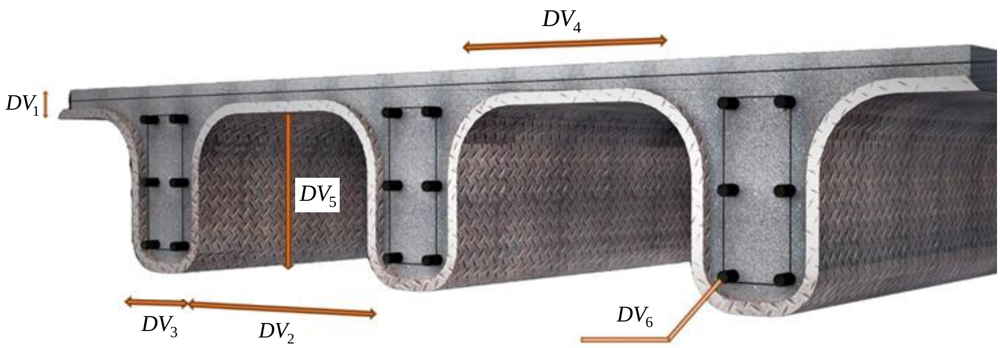

Fig. 1 The schematic of a one way concrete ribbed slab and the design variables

2. Definition of the optimization problem

The IDEACO algorithm was used to optimize geometrical design, concrete strength, and reinforcement of concrete ribbed slab. The vector DV contains the design variables, which are discrete to guarantee a real ribbed slab design. The objective function considered is CO_2 emissions (E) and the aim is to minimize the emissions of the CO_2 from the concrete ribbed slab (Eq. 1). The constraints (Eq. 2) denote the ultimate limit states and all the serviceability limit states, as well as the geometric and deflection constraints that the concrete ribbed slab must satisfy.

$$Min\ E(DV) \tag{1}$$

$$C(DV) < 0 \tag{2}$$

Seven design variables are needed to design the reinforced concrete ribbed slab with minimum CO_2 emissions. The cross-section geometry is defined by five variables: the slab thickness (DV_1), the ribs spacing (DV_2), the rib width at the lower end (DV_3), the rib width at the toper end (DV_4), and the depth of rib (DV_5). One variable determines the bar diameter of the reinforcement (DV_6), shown in Fig. 1, and the seventh variable defines the concrete strength (DV_7).

2.1 The CO_2 emissions objective function

The objective function consists of three parts, which include CO_2 emissions caused by concrete, rebar, and formwork. The function is considered as follows:

$$\begin{array}{ll} \text{Find} & \{DV\} = [DV_1, DV_2, ..., DV_7] \\ \text{to minimize} & E = \left(ConcV.CO_{2c} + SteelW.CO_{2st} + formA.CO_{2f}\right) / (DV_2 + DV_3) \\ \text{subjected to} & C_j\left(DV\right) \le 0, \quad j = 1\ to\ ng \\ \text{where} & DV_{\min} \le DV \le DV_{\max} \end{array} \tag{3}$$

where *conV*, *steelW* and *formA* are the volume of the concrete, the weight of the steel reinforcement and the area of the formwork in the unit length (m^3/m, kg/m and m^2/m), respectively. DV_i (i= 1, 2, …, 7) and C_j are design variables and design constraints of the CO_2 emissions

Table 1 The values of $\rho_{\min}$ (ACI 318-08 (2008))

The grade of bars used in the slab	$\rho_{\min}$
40 or 50	0.0020
60	0.0018
> 60	$\frac{0.0018 \times 60000}{f_y}$

function (E, kg/m^2), respectively; *ng* is the number of constraints. CO_{2c}, CO_{2st} and CO_{2f} are the values CO_2 emissions from concrete, steel and formwork (kg/m^3, kg/kg and kg/m^2), respectively. DV_{min} and DV_{max} are the lower band and the upper band of the design variables, respectively.

According to the ACI 318-08 (2008), the following constraints for designing the ribbed concrete slabs, are considered.

2.2 Flexural and Shear constraint

The flexural and the shear constraints can be determined in the following forms:

$$M_u / (\varphi_b M_n) \le 1 \tag{4}$$

$$V_u / (\varphi_v V_n) \le 1 \tag{5}$$

where M_u, M_n, V_u and V_c are the ultimate design bending moment, the nominal bending moment, the ultimate factored shear force, and the nominal shear strength of the concrete, respectively.

2.3 Serviceability constraints

The serviceability constraints are expressed in terms of the limits on the steel reinforcement ratio and the bar spacing. The steel reinforcement ratio should satisfy the following constraints:

$$\rho \le \rho_{\max} = 0.75\rho_b \tag{6}$$

$$\rho \ge \rho_{\min} \tag{7}$$

where $\rho_{\min}$ is the minimum shrinkage and temperature steel ratio, which is defined according to Table 1 and should not be less than 0.0014, and the bar spacing should satisfy the following two constraints:

1. The minimum clear spacing between parallel bars in one layer should not be less than 25 *mm*.

2. The maximum spacing between the bars should not be more than five times the thickness of the rib and 450 *mm* (18 inches) (Bijari and Sheikhi Azqandi 2022).

2.4 Deflection constraints

Deflection constraints are expressed in terms of the thickness of the top slab. The thickness of the top slab should be not less than one-twelfth of the clear spacing between the ribs and 50 *mm* (2

Table 2 Minimum slab thickness (ACI 318-08 (2008))

Member	Simply supported	One end continuous	Both ends continuous	Cantilever
Beams or ribbed one way slabs	L/16	L/18.5	L/21	L/8

inches). Also, the overall height of the slab should be greater than the minimum slab thickness. The minimum slab thickness depends on the support conditions, which defines based on Table 2, where L is the effective span length of the concrete slab.

2.5 Geometry constraints

The dimensions of the ribs should be in accordance with the regulations of ACI 318-08 (2008). The width of the ribs should not be less than 100 *mm* (4 inches) and their depth should not be more than 3.5 times the width of the ribs. The clear spacing between the ribs should not exceed 750 *mm* (30 inches).

3. Hybrid metaheuristic optimization method (IDEACO)

3.1 Dolphin echolocation optimization

A brand-new, reliable, and effective metaheuristic algorithm for engineering optimization problems is called the Dolphin Echolocation Algorithm. DE is a straightforward formulation that doesn’t require complex mathematical calculations or parameter tuning. It is frequently used to solve optimization issues in a variety of fields (Kaveh and Farhoudi 2013).

3.2 Ant colony optimization

Dorigo developed the metaheuristic optimization technique known as ant colony optimization (ACO). The behavior of actual ant colonies serves as the algorithm’s motivating source (Ghoddosian and Sheikhi Azqandi 2013). Ants initially wander aimlessly around their nest’s surroundings. Ants left pheromone trails on the ground as they moved. An ant evaluates the quantity and quality of the food as soon as it locates a food source and transports some of it to the nest. The amount and quality of the food can affect how much pheromone an ant spits on the ground as it makes its way to the nest. Other ants are taught where their food comes from by the pheromone. It has been demonstrated that ants can find the shortest routes between their nest and food sources thanks to pheromone’s indirect communication with them. Artificial ant colonies use the skills of natural ants to solve engineering issues (Socha and Dorigo 2008). For more information on ACO, see (Ghoddosian and Sheikhi Azqandi 2013, Socha and Dorigo 2008, Kaveh and Farhoudi 2016).

3.3 Hybrid improved dolphin echolocation ant colony optimization

A hybrid optimization algorithm using improved dolphin echolocation and ant colony optimization was presented in this section. In order to achieve the best convergence and more dependable optimal designs, especially in the final iterations, and explore the best results than previous studies, IDE optimization was introduced. An improved dolphin echolocation and ant colony optimization algorithm is called IDEACO. This algorithm uses ant colony optimization to take advantage of the best design while improving dolphin echolocation for the exploration phase of usable space (Arjmand *et al.* 2018). The following is a summary of IDEACO's main discrete optimization steps:

Step 1. Produce the alternative matrix (AM)

The matrix *AM* is first taken into account when calculating the entire search space. The value of allowable that can be assigned to design variables is one of the matrix's elements.

$$AM = \begin{bmatrix} am_{1,1} & am_{1,2} & \cdots & am_{1,nDV} \\ am_{2,1} & am_{2,2} & \cdots & am_{2,nDV} \\ \vdots & \cdots & \ddots & \vdots \\ am_{k,1} & am_{k,2} & \cdots & am_{k,nDV} \end{bmatrix} \tag{8}$$

where the number of design and alternative variables, respectively, is k and nDV. Each column's matrix elements are arranged in a less-to-more order.

Step 2. Produce the initial population

Matrix *LM* is a candidate for the optimization algorithm because it represents the initial population's size $(N_P \times nDV)$ matrix, which was generated at random from matrix *AM*.

$$LM = \begin{bmatrix} lm_{1,1} & lm_{1,2} & \cdots & lm_{1,nDV} \\ lm_{2,1} & lm_{2,2} & \cdots & lm_{2,nDV} \\ \vdots & \cdots & \ddots & \vdots \\ lm_{np,1} & lm_{np,2} & \cdots & lm_{np,nDV} \end{bmatrix} \tag{9}$$

where the number of population is np.

Step 3. Calculate the augmented objective function

The better solutions must receive higher values when fitness is defined. In contrast, the fitness (*AOF*) must be increased by reducing the objective function (f). *AOF* is defined as Eq. 10.

$$AOF = \frac{C}{f} \tag{10}$$

C is a constant coefficient that depends on the kind of problem in cases where f is the primal objective function.

Step 4. Sort the matrix LM

The rows of matrix *LM* based upon the augmented objective function, was sorted descending that is called *SLM*. The fitness array of *SML* is *SAOF*.

Step 5. Compute the effective radius

The *AOF* of each member's matrix *SLM* is distributed by radius (R_j). The main loop's radius (R_{ML}), the number of iterations (It), the maximum of iterations (It_{max}), and the location of each member on the matrix *SLM* all affect the value of R_j as Eq. 11.

$$R_j = (R_{ML} - (\frac{R_{ML} - 1}{np}) j), \; j = 1, 2, \ldots, np \tag{11}$$

$$R_{ML} = (R_M - (\frac{R_M - R_m}{It_{\max}})(It)) \tag{12}$$

where j represents each member of the matrix *SLM*. R_M, R_m are the minimum and maximum of radius of main loop that chosen according to the dimensions of search domain.

Step 6. Compute the accumulative augmented objective function (AAOF)

The matrix *SLM* members discovered from matrix *AM* and accumulative augmented objective function (*AAOF*) is determined by Eq. 13.

$$AAOF(a+k,i) = \frac{1}{j^2}\left(\frac{R_j - |k|}{R_j}\right) SAOF(j) + AAOF(a+k,i), \quad \begin{array}{l} i = 1,2,\ldots,nDV \\ j = 1,2,\ldots,np \end{array} \tag{13}$$

By growing the value of the parameter j, the *AOF* of each member of the matrix *SLM* is decreased. Coefficient $\frac{1}{j^2}$ was exacerbated this effect.

Step 7. Generate the best solutions and obtain BL matrix

The *BL* matrix contains the best solutions that have been found up to this point. Based on their *AOF*, *BL* matrix rows are sorted. The first row of this matrix has the best optimal designs among the other rows because the top rows have larger *AOF*s. The matrix *BL*'s *AOF* array is called *BF*. The memory known as *BL* can enhance algorithm performance, such as higher rate convergence, without raising computational costs (Sheikhi Azqandi 2021).

Step 8. Determine the effective parameters for increasing AAF on BL

The *AAF* of *BL* members is increased in this step by applying the ant colony optimization properties to continuous variables (Socha and Dorigo 2008). Parameter η is defined as Eq. 14 for this purpose.

$$\eta_j = \frac{1}{Q^2\sqrt{2\pi}} e^{\left(-\frac{(j-1)^2}{2Q^2}\right)}, \; j = 1,2,\ldots,np \tag{14}$$

where Q is defined as Eq. 15.

$$Q = U\left(1 - \left(\frac{It}{It_{\max}}\right)^P\right) + E \tag{15}$$

where U is defined as the result of dividing the *AOF* of the best solutions in all iterations by the *AOF* of the best solution in the current iteration. The coefficients P and E are dependent on the problem which have the value 0.4 and 1e-6 here.

Step 9. Compute the enhance probability of BL in AAOF matrix

The values of members in the *AAOF* matrix are enhanced based on *BL* as Eq. 16.

$$AAOF(X,i) = \left(AAOF(X,i) + \frac{BF(rs)}{rs}\right)(1+\eta), i = 1,2,\ldots,np \tag{16}$$

where rs and X are r and selection in ith column of *BL* and the row of rs in *AM*. In Eq. 16, $\frac{BF(rs)}{rs}$ prevents the members of the matrix *AAOF* is zero. Additionally, it led to the algorithm can escape from the local optimal solutions.

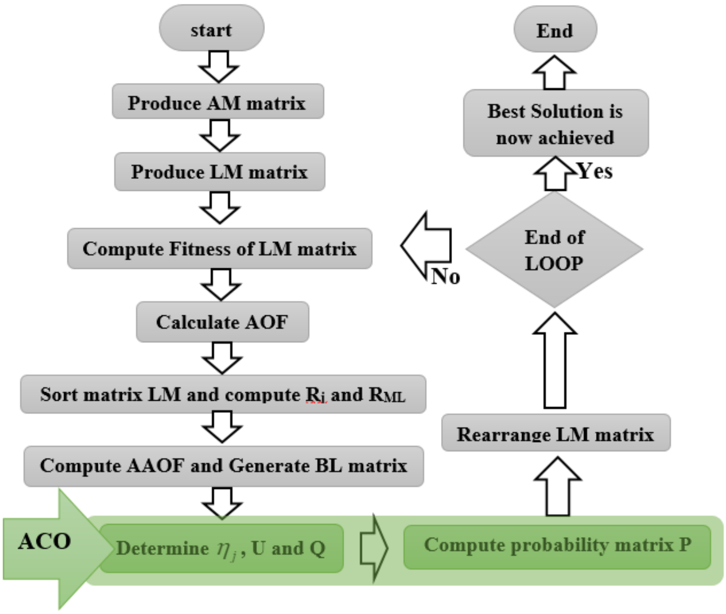

Fig. 2 The flowchart of IDEACO algorithm

Step 10. Compute the probability of each member of AM

Each member matrix *AM*'s probability is calculated using *AAOF* by Eq. 17.

$$Pi,j = \frac{AAOF_{i,j}}{\sum_{i=1}^{n_m} AAOF_{i,j}}, i = 1,2,\ldots,m \;\&\; j = 1,2,\ldots,nDV \tag{17}$$

Step 11. Reorganize the LM

The new matrix *LM* is determined by roulette wheel according to matrix *P*.

As many times as the stop criteria are satisfied, steps 3 through 11 are repeated. Fig. 2 depicts the IDEACO flowchart. The green steps are obtained from ant colony optimization in this flowchart.

4. Results

For the optimal design of the one way concrete ribbed slab with minimum CO_2 emissions, 7 design variables are considered. For each variable, a discrete set of practical values is selected, which is shown in Table 3. The length of the beam span is 6 *m*, the value of dead load and live load per square meter of surface are equal to 0.78 kN/m^2 and 4 kN/m^2, respectively. The tensile strength of the steel used in the slab rebars is 420 *MPa*. The density of concrete and reinforcement of the slab is equal to 24 kN/m^2 and 78.5 kN/m^3, respectively.

Table 4 summarizes the unit prices obtained from the BEDEC database of the Institute of Construction Technology of Catalonia (2016), including transport and placing. According to Table 4, the relationship between the strength of concrete and the CO_2 emissions of the concrete is

Table 3 The values of design variables for one way ribbed slab

No.	Design variables	Symbol	DV_{min}	DV_{max}
1	thickness of slab (cm)	DV_1	2.5	10
2	spacing of ribs (cm)	DV_2	40	75
3	width of rib at the lower end (cm)	DV_3	10	25
4	width of rib at the taper end (cm)	DV_4	10	30
5	Rib depth (cm)	DV_5	15	75
6	diameter of bar (cm)	DV_6	1	2
7	strength of concrete (MPa)	DV_7	20	50

Table 4 Unit prices and CO_2 emissions considered in this analysis (Catalonia Institute of Construction Technology 2016)

Unit measurements	Cost (€)	CO_2 Emission (kg)
m^2 of formwork	33.81	2.08
kg of steel (B-500-S)	1.16	3.03
kg of prestressing steel (Y1860-S7)	3.4	5.64
m^3 of concrete HP-35	104.57	321.92
m^3 of concrete HP-40	109.33	338.9
m^3 of concrete HP-45	114.1	355.88
m^3 of concrete HP-50	118.87	372.86
t CO_2 emission	5	

obtained by fitting presented in Fig. 3(a) which is in the form $CO_{2c} = 16.98f'_c + 304.94$ where CO_{2c} is the CO_2 emissions of concrete and f'_c is the strength of the concrete. Using this formula, the value of the CO_{2c}, which is a function of concrete strength, is calculated and used in the objective function at Eq. 3.

To determine the cost of the concrete ribbed slab in each step, the following equation is used,

$$CT = \left(ConcV.\mathrm{C}_c + SteelW.\mathrm{C}_{st} + formA.\mathrm{C}_f\right) / br + E.C_E \tag{18}$$

In this equation CT is the cost function of the slab (/m^2) which consists of four parts including the cost caused by concrete, rebar, formwork, and CO_2 emissions. C_c, C_{st}, C_f and C_E are the unit prices of concrete, steel, formwork and CO_2 emissions, respectively which are derived based on Table 4. The relationship between concrete strength and concrete unit price is in the form of $C_c = 4.767f'_c + 99.8$ where shown in Fig. 3(b) and C_c is the unit price of concrete obtained for each value of concrete strength and is used in Eq. 18.

The number of population in the IDEACO metaheuristic algorithm and the number of iterations are considered equal to 30 and 150, respectively. By applying IDEACO for the optimal design of the concrete ribbed slab with minimizing CO_2 emissions, the optimal values obtained for the considered design variables are shown in Table 5. According to the values determined for the optimization problem variables in Table 5, the values of slab cost, concrete volume, steel reinforcement weight and the area required for formwork in each square meter of slab are equal to 96.52 *€*, 0.0675 m^3, 7.25 *kg* and 1.35 m^2, respectively.

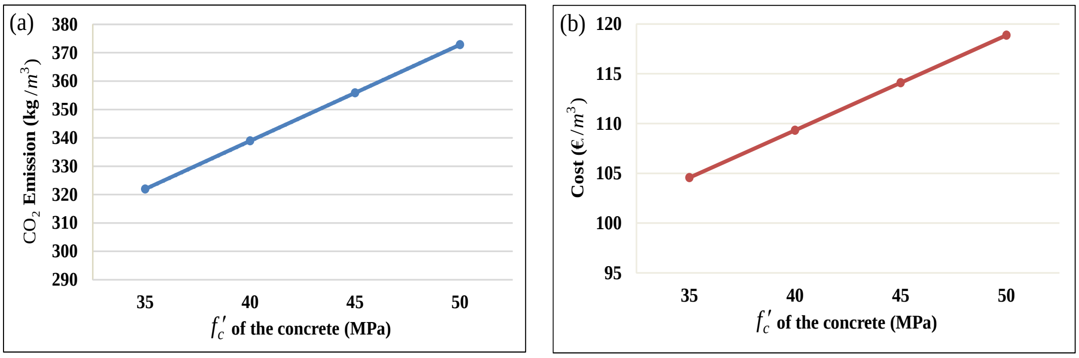

Fig. 3 (a) CO_2 emissions of the concrete, (b) Unit prices of the concrete

Table 5 The Optimal values obtained for design variables

	DV_1	DV_2	DV_3	DV_4	DV_5	DV_6	DV_7	CO_2 emissions
IDEACO	5 cm	60 cm	10 cm	10 cm	32.5 cm	1.4 cm	20 MPa	97.55 kg/m^2

Table 6 The contribution of each part

Function	Part	Value	
CO_2 (kg/m^2)	Concrete	62.15	63.72%
	Formwork	4.01	4.11%
	Steel Reinforcement	31.38	32.17%
Cost (€/m^2)	Concrete	18.82	19.49%
	Steel Reinforcement	12.01	12.44%
	Formwork	65.21	67.56%
	CO_2	0.49	0.51%

The results reveal total CO_2 emissions of 97.55 kg for one m^2 of concrete ribbed slab. The contribution of each part of the CO_2 function and the cost function is shown in Table 6. Among the three sources of CO_2 emissions, the greatest contributor to CO_2 reduction is the embodied carbon dioxide emissions of the one m^2 concrete slab, which accounts for 62.15 kg CO_2. The second highest contributor is the rebar, accounting for 31.38 kg CO_2 and the formwork is 4.11% of the total emissions reduction. As can be seen in the four sources of slab cost, the greatest contribution is for the formwork part which accounts for 65.21 €. The diagram of convergence rate in the objective function values in different iterations is shown in Fig. 4. The IDEACO algorithm was able to obtain the best design in the number of 1,200 structural analyses. After execution of 50 independent runs of the design program for the concrete ribbed slab structure with IDEACO, the average optimized CO_2 emissions, the best optimized CO_2 emissions, the worst optimized CO_2 emissions, and the standard deviation on average CO_2 emissions have been achieved as 97.9564 kg/m^2, 97.5477 kg/m^2, 102.5903 kg/m^2, and 1.3098 kg/m^2 respectively. As can be seen from Fig. 4 and the statistical results, the IDEACO algorithm has good convergence and a good performance in achieving minimal carbon dioxide emissions in the concrete ribbed slab.

The diagram of changes for slab cost, concrete volume, steel reinforcement weight, and formwork area is shown in Fig. 5 (a)-(d). As it is clear from Fig. 5, the history of the convergence

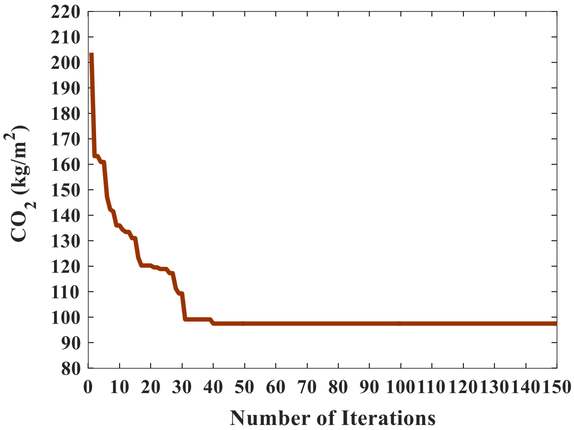

Fig. 4 The history of convergence of the objective function

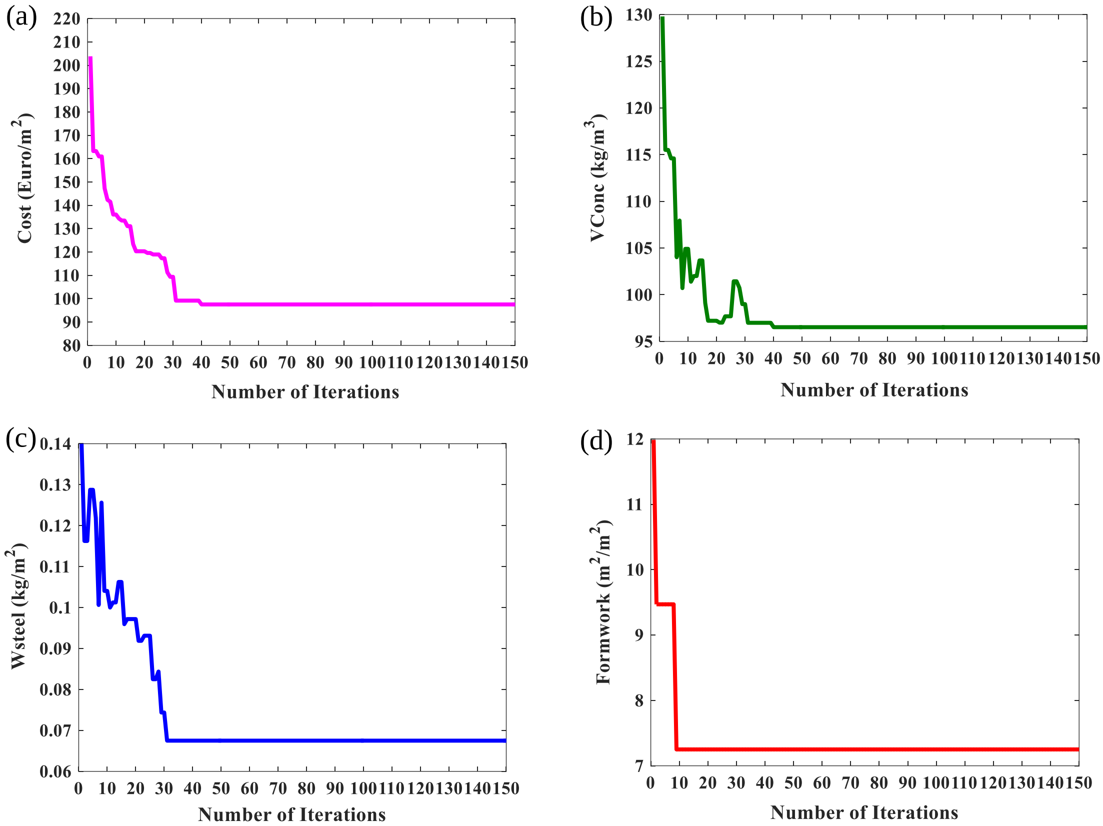

Fig. 5 Time history of (a) the cost of slab, (b) the volume of the concrete, (c) the weight of steel reinforcement, (d) the area of the formwork

of cost and CO_2 graphs is similar to each other, which is because one of the sources of the cost function is due to the value obtained from the CO_2 function.

5. Conclusions

The purpose of this study is carbon dioxide emissions optimization of one way reinforced concrete (RC) ribbed slab. Seven design variables considered for formulation of the design of structure with minimum emissions of CO_2. In this study three sources of carbon dioxide emissions for the RC ribbed slab are identified. The emission amount of CO_2 from each of the sources was investigated, which would be beneficial to lower the carbon dioxide emissions in the construction industry. These sources include embodies carbon dioxide emissions of concrete, steel reinforcement and formwork. Concrete plays the greatest contribution with 63.72% of the total emissions reduction. According to the values obtained for the design variables of the CO_2 function, the cost of the slab is calculated. In the cost function, four sources are recognized including the cost caused by concrete, rebar, formwork and CO_2, among which the formwork has the greatest impact on the finished cost of the concrete slab which accounts 67.56% of the total cost. CO_2 emissions optimization of RC ribbed slab problem are investigated to show the efficiency of the IDEACO in finding optimal solutions. According to the statistical results attained from the implementation of 50 independent runs of the concrete slab design program with the IDEACO, it can be understood that the difference between the best optimized solution and the worst optimized solution and the difference between the best optimized solution and the average optimized solution are equal to 5.17% and 0.42%, respectively. The results illustrate that the IDEACO has a good performance and it can be utilized for other optimization problems. As future research, it can be mentioned to the optimal design of the mix ratios for fiber concrete with the minimum CO_2 emissions.

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