Optimum Design of Reinforced Concrete T-Beam Considering Environmental Factors via Flower Pollination Algorithm

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Abstract

The minimum cost designs may be costly for the environment. In that case, the cost is not only a single objective in the design of structures. In that situation, CO_2 emission minimization can be considered in the optimum design. In this study, reinforced concrete (RC) T-beams were optimized via flower pollination algorithm for the environmental factor minimizing the CO_2 emission of the materials. The investigation was done for 4 cases of CO_2 emission values and these cases were compared with 5 cases of the cost ratios of concrete and steel. Due to this investigation, it was found that CO_2 emission optimization is effective in the reduction of the CO_2 emission value by 4.5% compared to cost optimization. If the ratios of CO_2 emission and the cost of steel per concrete are different, the optimum design variables and objectives are different. Also, the use of recycled steel is %.30.24 more effective on the reduction of CO_2 emission and saving the planet.

Keywords: Metaheuristic; Carbon Minimization; Cost Optimization; Eco-friendly design; Minimum carbon emission.

1. Introduction

Due to a shortage of resources and sustainability, engineering design must be eco-friendly. In structural engineering, choosing eco-friendly or recycled material can play an important role. For the design of steel structures, the eco-friendliest material can be chosen, and it is optimum in minimization of CO_2 emission if it has the same strength as the one with a higher emission value. Also, optimization can be done if the strengths are different for the steel types to find a design that has low CO_2 emissions.

The optimization is more challenging for RC structures. For RC structures, two materials such as concrete and steel are used to provide a design in required ductility. These materials have different costs and different CO_2 emissions. Also, the design is constrained by the factors given in design regulations. These problems can be only optimized via numerical iterations and the best way to apply numerical iteration systematically, effectively, and rapidly is through the usage of metaheuristic methods.

To reach the optimum solution of RC members, various metaheuristic algorithms have been employed. The genetic algorithm that uses the factors such as mutation, crossover, reproduction [1-2] was used in the optimum design of RC beams with rectangular cross-section [3], RC continuous beams [4], RC biaxial columns [5-6], RC frames [6] and RC T-beams [7]. Also, hybrid methods that combines GA with sequential quadratic programming [8], simulating annealing [9-10] and Hook and Jeeves method [11-12] were used to optimize RC members.

Harmony Search (HS) that imitates the musical performances and uses the harmony memory of musicians was also employed in many cost optimization methods for T-beams [13], slender columns [14-15], shear walls [16], frames [17-19] and retaining walls [20-21].

The number of metaheuristic-based cost optimization studies for RC members shows a great increase in the last decade and several examples are as follows.

An artificial bee colony algorithm was employed to optimize RC continuous beams by modifying the algorithm by Jahjouh et al. [22]. Nigdeli et al. [23] proposed a HS-based methodology for bi-axial loading of RC columns. Bat algorithm [24] and teaching-learning-based optimization (TLBO) [25] were employed for the optimum design of RC columns. Swarm intelligence was also used in the optimum design of RC members by Esfandiary et al. [26] and Chutani and Singh [27]. Kayabekir et al. employed the single-phase and parameter-free Jaya algorithm (JA) to optimize T-beams [28]. Also, Kayabekir et al. [29] evaluated four metaheuristics including HS, TLBO, JA, and Flower pollination algorithm (FPA) for the optimum design of RC T-beams, and Kayabekir and Nigdeli [30] statistically compared these algorithms according to methods such as one-way ANOVA, independent samples t-test, Friedman ranking, post-hoc Bonferroni test. By employing FPA, RC footings [31], RC cantilever retaining walls [32], and 3D RC frames [33] were optimized.

Generally, the objective function is the cost minimization, but optimization studies related with CO_2 emission minimization have been conducted. These studies include optimization of RC frames via simulated annealing [34], RC columns via GA [35], RC frames via big-bang big crunch algorithm (BB-BC) [36], precast-prestressed concrete U beam road bridges via hybrid glowworm swarm algorithm [37], post-tensioned concrete box-girders via HS [38], RC footings via BB-BC [39], RC cantilever solider piles via HS [40], RC retaining walls via HS [41], and concrete-filled steel tubular columns via spider and HS algorithms [43-43].

In the present study, the T-beam optimization is presented via FPA for CO_2 minimization. The results were compared with cost optimization results ad multiple cases of cost ad CO_2 ratios steel and concrete is investigated.

2. Flower Pollination Algorithm Optimization Procedure

The principles of the flower pollination algorithm optimization process were first introduced by Xin-She Yang in 2012 [44]. In this algorithm, Yang expressed his observations of the pollination characteristics of flowering plants with mathematical equations and then developed an algorithm including these equations to perform the optimum search process.

According to this; similar to the pollination process inspired by the algorithm, two different processes called global and local pollination are applied probabilistically in the optimization process. Global pollination is the pollination process of flowers through a carrier (such as wind, and various living things), and it is expressed in the algorithm as follows.

$$x_i^{t+1} = x_i^t + r1 \cdot (x_b^t - x_i^t) \tag{1}$$

Local pollination, on the other hand, refers to the pollination process carried out by the flower itself and was expressed by Yang as follows.

$$x_i^{t+1} = x_i^t + r2 \cdot \left(x_j^t - x_k^t\right) \tag{2}$$

In the equations, x_i^{t+1} is the new solution generated from the x_i^t solution, x_b^t is the best existing solution, x_j^t and x_j^t are two randomly selected solutions from the exiting solutions, r1 is the levy flight and r2 is a randomly generated decimal number between 0 and 1.

The application of the equations for optimum design of the reinforced concrete T-beam (Fig. 1) and processes of FPA can be summarized in five steps. The flowchart of the optimization is given as Fig. 2.
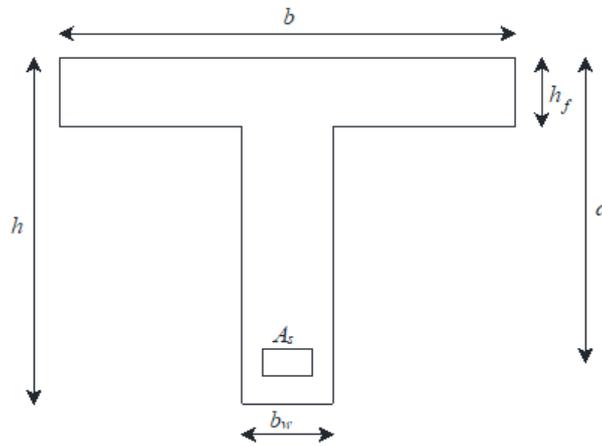

Fig. 1. Cross-section of T-shaped beam [29]

The first step is the stage where the problem is defined. At this stage, the data defined for the problem are the design constants, the lower and upper limits of the design variables, the FPA algorithm parameters, the number of solution vectors (pn), the switch probability (sp), and the maximum number of iterations as the stopping criterion. The definitions of design constants and variables and their values used in the numerical example are taken from Fedghouche and Tiliouine [7] and presented in Tables 1 and 2, respectively. The Eurocode 2 [45] regulation and the technical constraints that the section must provide are defined in Table 3.

Table 1. The design constants

Symbol	Definition	Value
f_{ck}	Characteristic compressive strength for concrete	20 MPa
f_{cd}	Allowable compressive strength for concrete	11.33 MPa
f_{yd}	Characteristic yield strength of reinforcement	348 MPa
ρ_{max}	The maximum reinforcement ratio	0.04
ρ_{min}	The minimum reinforcement ratio	0.0013
L	The length of the beam	20 m
E_s	Young's elastic modules for steel	200000 MPa
M_{Ed}	The ultimate bending moment capacity	4.991 N.m

V_{Ed}	The ultimate bending moment capacity	1.039 N
C_s/C_c	The ratio for unit steel and concrete costs	5, 10, 20, 30, 36
$C_{s,co2}/C_{c,co2}$	The ratio for unit steel and concrete costs	0.95, 10, 15, 20

In the second step, the initial solution matrix is constructed. The design variables are generated randomly within the minimum ($x_{i,min}$) and maximum ($x_{i,max}$) ranges defined in the first step and recorded in this matrix (Eq. (3)).
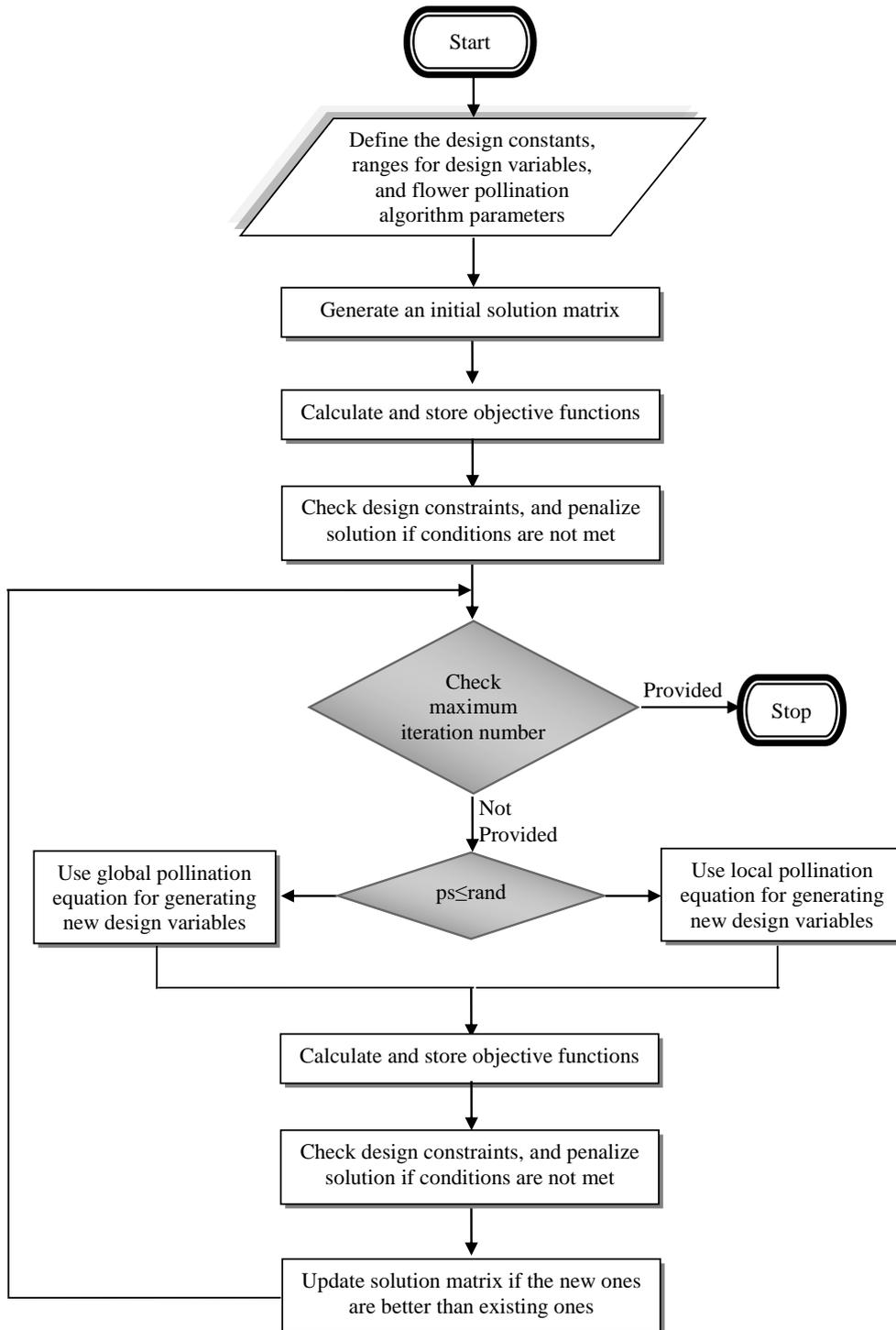
Fig. 2. Flowchart of the optimization process

$$x_i = x_{i,min} + r3 \cdot \left(x_{i,max} - x_{i,min} \right) \tag{3}$$

Table 2. Ranges of design variables

Symbol	Definition	Minimum	Maximum
b	Effective with of compressive flange [mm]	b_w	min $[0.2L + b_w, 8h_f]$
b_w	Web width [mm]	0.2d	0.4d
h	Height [mm]	L/16	2.0
h_f	Flange depth [mm]	0.15	d
d	Effective depth [mm]	0.9h	
d_s	Cover of reinforcements [mm]	0.1h	
A_s	Area of reinforcing steel [mm^2]	0	0.1

Table 3. The design constraints

$$\omega(1 - 0.5\omega) \leq 0.392$$
$$0.0035(0.8 - \omega)/\omega \geq f_{yd}/E_s$$
$$\rho_{min} \leq \rho \leq \rho_{max}$$
$$M_{Ed} \leq M_{Ed1}$$
$$V_{Ed} \leq V_{Rd\,max}$$

After the design variables are determined, beam reinforced concrete designs are performed for each solution (from first to pn number of solutions) in the initial solution matrix. The reinforced concrete design must satisfy the Eurocode 2 [45] regulation constraints presented in Table 3 calculated based on Eqs. (4)-(9) for the situation without shear reinforcement optimization as presented in Fedghouche and Tiliouine [7].

$$\omega = (f_{yd}/f_{cd})(A_s/b_w d) - (b - b_w)h_f/(b_w d) \tag{4}$$

$$\rho = A_s/(b_w d) \tag{5}$$

$$M_{Ed1} = f_{cd}(b - b_w)h_f\left(d - 0.50h_f\right) + f_{cd}b_w d^2 \omega(1 - 0.5\omega) \tag{6}$$

$$V_{Rd\,max} = \nu_1 f_{cd} b_w z/(tan(45) + cot\,(45)) \tag{7}$$

$$\nu_1 = 0.6(1 - f_{ck}/250) \tag{8}$$

$$z = 0.9d \tag{9}$$

Finally, in this step, the total CO_2 emission value for each beam design is calculated and stored as the corresponding solution. This expression is the objective function of the optimization problem. If constraints are provided in the design, the solution is evaluated by subjecting the objective function of the design to a process called penalty. In the literature, various penalty

methods are depending on the problem. In this study, equating the objective function to a high value (10^6) was applied.

$$f_{co2}(x) = C_{c,co2}b_w d + C_{c,co2}(b - b_w)h_f + (C_{s,co2}/C_{c,co2})A_s \tag{10}$$

For the compared cases for cost optimization, the objective function as the total beam cost is shown in Eq. (11).

$$f_{cost}(x) = C_c b_w d + C_c(b - b_w)h_f + (C_s/C_c)A_s \tag{11}$$

In the third step, the new solutions are derived. According to the algorithm rules, one of the global (Eq. (1)) or local (Eq. (2)) pollination equations is used to generate a new solution. The value of switch probability (sp) is used for the global and local pollination probabilistic selection. According to this; if the randomly generated number between 0 and 1 is less than the sp value, new solutions are generated according to global pollination, otherwise, local pollination rules are applied.

In the fourth step, old and new solutions are compared. The objective functions of each solution are compared, in case the new solution is better (the objective function is lower), the existing solution is deleted and the values of the new solution are saved instead. Otherwise, the existing solution is preserved.

In the last step, the stopping criterion is checked. New solution generation and comparison processes (steps 3 and 4) are repeated until the criterion is determined in the first step as the maximum number of iterations are met.

3. Numerical Examples

For the T-beam given in Figure 1, the analysis was carried out by the numerical values of the design constants, design constraints, and design variable limits given in Section 2. Analysis with the objective function of the total beam cost was also performed simultaneously to compare with the optimization results for CO_2 emission.

As it is known, unit costs of concrete and steel vary in different parts of the world. To take this situation into account, 5 different steel and concrete unit cost ratios were taken into account in the analysis. Information on these cases is presented in Table 4.

Table 4. Cases for Cost optimization

Case No	1	2	3	4	5
C_s/C_c	36	30	20	10	5

A similar situation is seen in unit carbon emission rates. In addition to many factors such as the materials and additive rates in the concrete content and the production method, the recycled material content of the steel, even the region where the materials are produced affects the unit carbon emission rates of these materials. To take these variations into account, studies in the literature were examined and carbon emission ratios were determined for four different steel and concrete units [34, 46]. The carbon emission rates in question are shown in Table 5. Case 6 shows the value for the use of recycled steel.

Table 5. Cases for CO_2 optimization

Case No	6	7	8	9
$C_{s,co2}/C_{c,co2}$	0.95	10	15	20

The optimum results for these cases are given in Tables 6 and 7. In addition to the optimum results of the design variables, the carbon emission and total cost values for the relevant cases are presented in the tables to examine the cost-carbon emission relationship.

Table 6. Optimum results for cost optimization

Design variables	Case 1	Case 2	Case 3	Case 4	Case 5
b (m)	1.137640	1.155663	1.229911	1.330057	1.378292
b_w (m)	0.304351	0.298164	0.291116	0.278516	0.272245
h (m)	1.690838	1.656469	1.617309	1.547309	1.512473
d (m)	1.521755	1.490822	1.455578	1.392578	1.361225
h_f (m)	0.150000	0.150000	0.153739	0.166323	0.172287
A_s (m^2)	0.011414	0.011870	0.012071	0.012442	0.012651
ω	0.487053	0.530813	0.534350	0.534348	0.534351
$f_{cost}(x)$	0.999034	0.929226	0.809488	0.687166	0.624400
$C_{s,co2}/C_{c,co2}$=0.95	0.598984	0.584411	0.579538	0.574569	0.573162
$C_{s,co2}/C_{c,co2}$=10	0.702278	0.691832	0.688780	0.687166	0.687656
$C_{s,co2}/C_{c,co2}$=15	0.759346	0.751180	0.749134	0.749375	0.750912
$C_{s,co2}/C_{c,co2}$=20	0.827828	0.822398	0.821559	0.824025	0.826819

Table7. Optimum results for CO_2 optimization

Design variables	Case 6	Case 7	Case 8	Case 9
b (m)	1.382218	1.327519	1.278476	1.217860
b_w (m)	0.271727	0.278872	0.285113	0.292575
h (m)	1.509592	1.549286	1.583961	1.625415
d (m)	1.358633	1.394358	1.425565	1.462873
h_f (m)	0.172777	0.165940	0.159810	0.152232
A_s (m^2)	0.012669	0.012430	0.012239	0.012032
ω	0.534351	0.534351	0.534345	0.534351
$f_{co2}(x)$	0.573080	0.687161	0.748787	0.821529
C_s/C_c=5	0.624391	0.625010	0.626393	0.629018
C_s/C_c=10	0.687737	0.687161	0.687590	0.689178
C_s/C_c=20	0.814431	0.811463	0.809984	0.809497

optimization may have very different optimum results if $C_{s,co2}/C_{c,co2}$, and C_s/C_c are different. The use of recycled steel is 30.24% more eco-friendly comparing to Case 9.

	Case 1	Case 2	Case 3	Case 4	Case 5
fcost(x)	0.999034	0.929226	0.809488	0.687166	0.624400
Cs,co2 /Cc,co2=0.95	0.598984	0.584411	0.579538	0.574569	0.573162
Cs,co2 /Cc,co2=10	0.702278	0.691832	0.688780	0.687166	0.687656
Cs,co2 /Cc,co2=15	0.759346	0.751180	0.749134	0.749375	0.750912
Cs,co2 /Cc,co2=20	0.827828	0.822398	0.821559	0.824025	0.826819
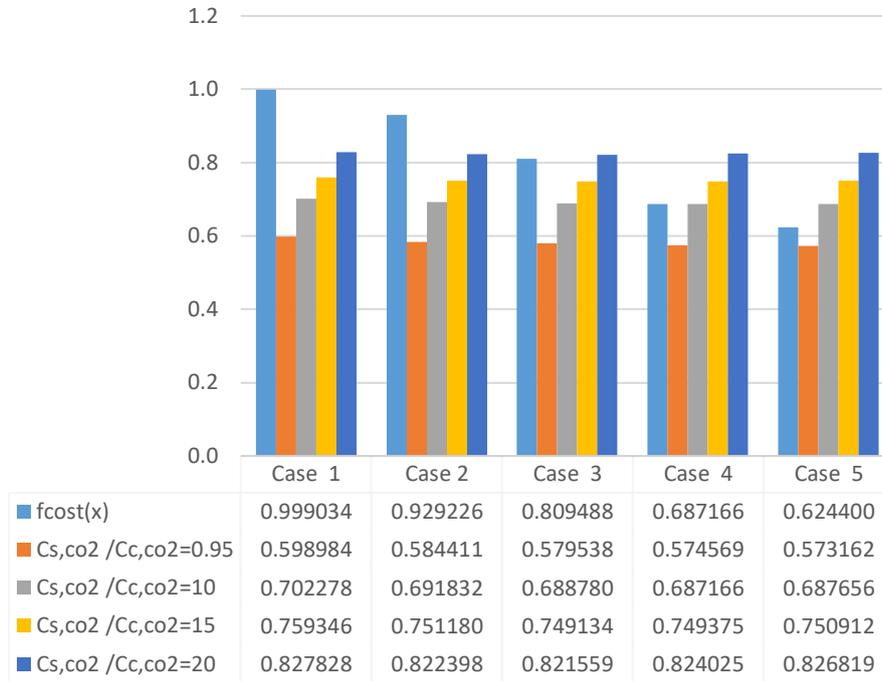
Fig. 4. Objective functions for cost optimization

	b (m)	bw (m)	h (m)	d (m)	hf (m)	As (m2)	ω
Case 6	1.382218	0.271727	1.509592	1.358633	0.172777	0.012669	0.534351
Case 7	1.327519	0.278872	1.549286	1.394358	0.165940	0.012430	0.534351
Case 8	1.278476	0.285113	1.583961	1.425565	0.159810	0.012239	0.534345
Case 9	1.217860	0.292575	1.625415	1.462873	0.152232	0.012032	0.534351
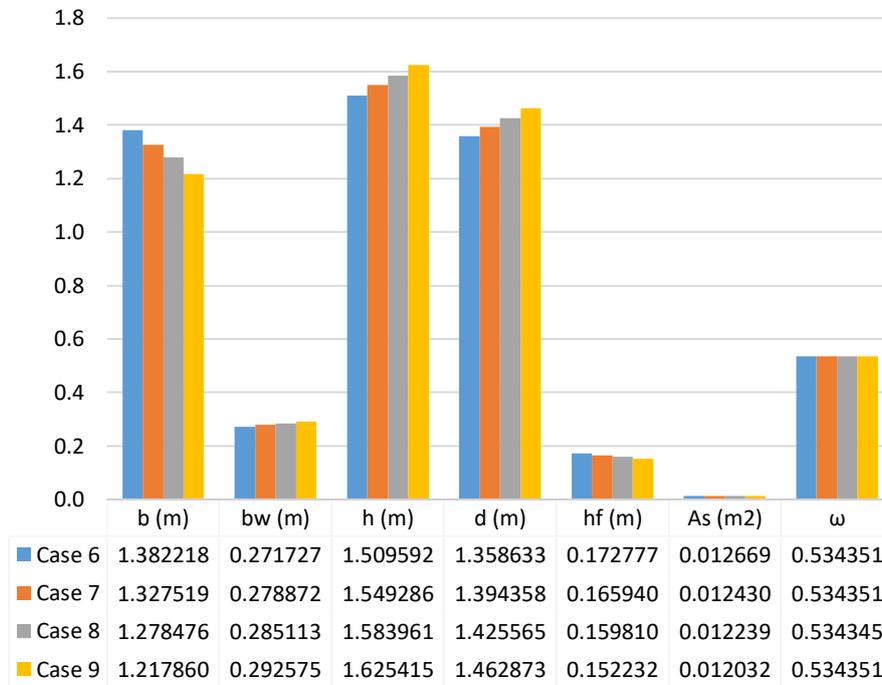
Fig. 5. Design variables for the CO_2 optimization

	Case 6	Case 7	Case 8	Case 9
■ Fx	0.573080	0.687161	0.748787	0.821529
■ Cs /Cc=5	0.624391	0.625010	0.626393	0.629018
■ Cs /Cc=10	0.687737	0.687161	0.687590	0.689178
■ Cs /Cc=20	0.814431	0.811463	0.809984	0.809497
■ Cs /Cc=30	0.941124	0.935765	0.932378	0.929817
■ Cs /Cc=36	1.01713989	1.010346646	1.005814598	1.002008735

Fig. 6. Objective functions for the CO_2 optimization

5. Conclusion

In the present paper, an optimization methodology for the CO_2 emission minimization of T-beams is presented. To find out the differences between CO_2 and cost optimization, both objectives are calculated for multiple cases of cost and CO_2 emission ratios of steel and concrete. According to the results, the cross-section dimensions ad steel reinforcement area shows great differences for these ratios. For both increases of cost and CO_2 emission of steel, the optimum design tends to be minimum in reinforcement area and maximum in the moment arm value by increasing the height and directly increasing the depth of T-beam.

Since the cost and CO_2 objectives are similar in form with the only difference in cost and CO_2 values of the materials, the behavior is the same in CO_2 and cost optimization. Due to that, the difference in CO_2 values for cost and CO_2 optimization are close if cost and CO_2 ratios of steel per concrete are similar as seen from the results of Case 3 and Case 9 or Case 4 and Case 7. This is not acceptable for Case 6 where recycled steel bars are used. This case has 4.5% reduced CO_2 emission concerning cost optimization and 30.24% reduced CO_2 emission compared to Case 9.

As the final remarks, CO_2 optimization may have different optimum results if C_s/C_c and $C_{s,co2}/C_{c,co2}$ are different. Also, recycled steel is very useful in the protection of the earth by conducting an optimum design.
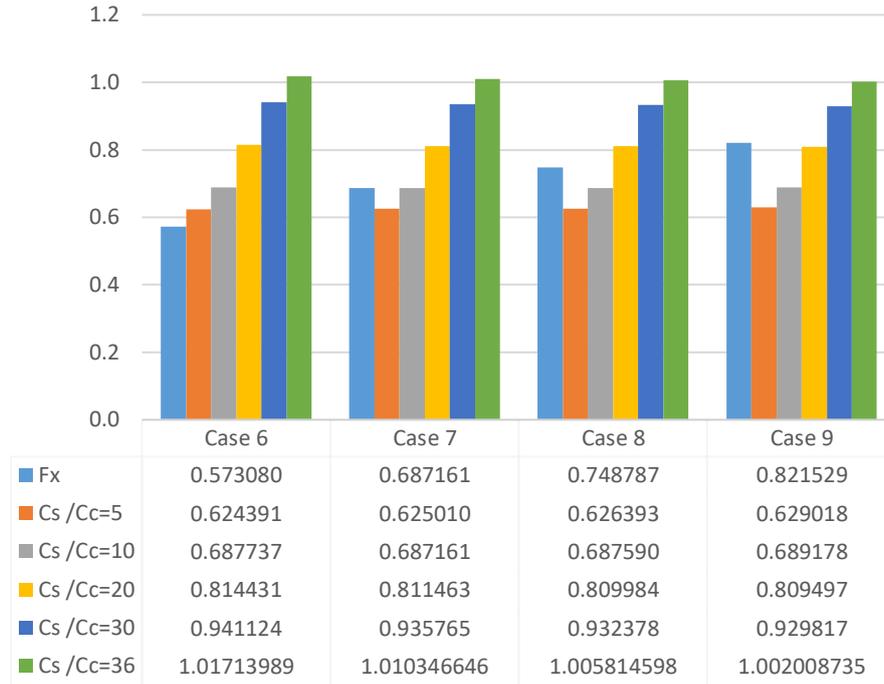
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