# COST OPTIMIZATION OF COMPOSITE BEAMS ACCORDING TO EUROCODE4-EC4

# OPTIMISATION DES COÛTS DES POUTRES MIXTES SELON EUROCODE4-EC4

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**Abstract-**This paper presents the optimum cost design of composite beams according to Eurocode4. The objective function comprises the costs of concrete flanges, formwork and steel profiles. The constraint functions are set to meet design requirements of Eurocode4 (EC4). They consist on plastic bending resistance constraints, plastic vertical shear resistance, deflection due to both dead and live loads, design constraints derived from Eurocode3 (EC3) and current practices rules. The cost optimization process is developed by the use of the Generalized Reduced Gradient (GRG) algorithm. Atypical example is included to illustrate the applicability of the proposed cost optimization model. The optimized results are compared with traditional design solutions from conventional design office methods to evaluate the performance of the developed cost model. Substantial savings have been achieved through this approach. In addition, the proposed approach is practical, reliable and computationally effective compared to classical designs procedures used by designers and engineers.

**Keywords:** cost optimization; composite beams design; limit states; Eurocode4 (EC4); nonlinear programming (NLP); generalized reduced gradient (GRG) algorithm.

**Résumé -** Cet article présente la conception à coût minimal des poutres mixtes selon Eurocode4. La fonction objective comprend le coût de béton et le coût de coffrage de la table de compression et le coût des profilés métalliques. Les fonctions de contrainte sont définies pour répondre aux exigences de conception de l'Eurocode4 (EC4). Elles sont constituées des contraintes de résistance à la flexion plastique, de la résistance au cisaillement vertical plastique, de la flexion due aux charges permanentes et de service, aux contraintes de conception issues de l'Eurocode3 (EC3) et des règles de pratique actuelles. Le processus d'optimisation des coûts est développé par l'utilisation de l'algorithme GRG (Gradient Réduit Généralisé). Typiquement, un exemple est inclus pour illustrer l'applicabilité du modèle proposé d'optimisation des coûts. Les résultats optimisés sont comparés aux solutions de conception traditionnelles issues des méthodes de bureau d'études conventionnelles pour évaluer les performances du modèle de coût développé. Des économies substantielles ont été réalisées grâce à cette approche. De plus, l'approche proposée est pratique, fiable et efficace sur le plan des calculs par rapport aux procédures de conception classiques utilisées par les concepteurs et les ingénieurs.

**Mots-clés:** Optimisation des coûts; conception de poutres mixtes; états limites; Eurocode4 (EC4); programmation non linéaire (PNL); algorithme de gradient réduit généralisé (GRG).

## 1. Introduction

Current practice often uses more beams composed of structural steel and concrete. Steel profiles connected with concrete flanges represent a modern technical solution frequently used in engineering practice and is typically applied in bridges, buildings and industrial constructions. In recent years, composite elements consisting of steel and concrete have become popular for various reasons. First, while concrete is excellent to deal with compressive forces, steel can also carry large tensile stresses. Second, weight and depth of the steel section can be reduced in relation to non-composite applications, leading to savings in both steel cost and building height. Because of the above mentioned advantages and the difficulty of the design, numerous journal articles have been published by researchers in recent years on the optimal cost design of composite beams. Sarma and Adeli [1] published a paper dealing with the cost optimization of steel structures, Adeli and Kim [2] proposed the use of neural dynamics model for cost optimization of composite beams; however, Kravanja and Silih [3] studied the economical comparison between composite I beams and composites trusses. As for Klansek and Kravanja [4, 5] they presented the cost optimization, comparison, and competitiveness between three different composite floor systems: composite beams produced from duo-symmetrical welded I sections and composite trusses made from cold formed hollow sections. Neto et al. [6] presented the generalized Timoshenko modeling of composite beam structures: sensibility analysis and optimal design; also, Senouci and Ansari [7] developed a Genetic Algorithm model for the cost optimization of composite beams, Amadio et al., [8] discussed the evaluation of the deflection of the steel-concrete composite beams at serviceability limit state. Finally, Kaveh and Ahangaran [9] presented the discrete cost optimization of composite floor system using social harmony search model.

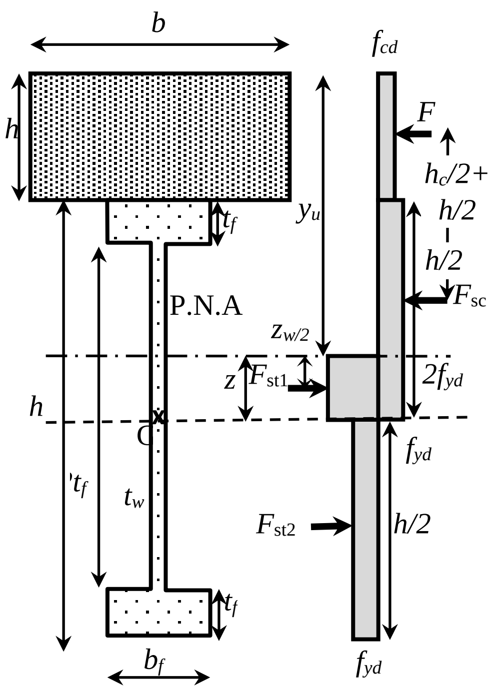
The design of composite beams is complex. The optimization of the composite structures was performed by the non-linear programming (NLP) approach. Advances in numerical optimization methods, computer based numerical tools for analysis and design of structures and availability of powerful computing hardware have significantly helped the design process to ascertain the optimum design. In this research paper the generalized reduced gradient (GRG) method is used to solve nonlinear programming in order to obtain the minimum cost design of composite beams. The GRG algorithm transforms inequality constraints into equality constraints through the introduction of slack variables, which this algorithm is very reliable and robust Fedghouche and Tiliouine [10], Lovasy and Scarf [11], Yeniay [12], Jiang et al. [13], Nocedaland Wright [14].

In this work, we have also used the latest version of Eurocode3 (EC3) and Eurocode4 (EC4). This study is based on material cost's ratios using cost sensitivity analysis in order to compare the relative gains determined for the various values unit cost ratios. The values of the cost ratios can vary from one country to another and eventually from one region to another within the same country.

This paper exposes the optimum cost design of composite according to Eurocode4. The objective function comprises the costs of concrete flanges, formwork and steel profiles, and the constraint functions are set to satisfy design requirements of Eurocode4 [15]. They consist of plastic bending resistance constraints, plastic vertical shear resistance, deflection due to both dead and live loads, design constraints derived from Eurocode3 [16] and current practices rules. The cost optimization process is developed by the use of the Generalized Reduced Gradient (GRG) algorithm; a typical example is included to illustrate the applicability of the proposed cost optimization model and the optimized results are compared with traditional design solutions from conventional design office methods to evaluate the performance of the developed cost model. Substantial savings were achieved through this approach. In addition, the proposed approach is practical, reliable and computationally effective compared to classical designs procedures used by designers and engineers.

## 2. Model formulation of composite beams

Limit states for the optimization of composite beams are set in this study in accordance with the current European design code EC3 and EC4. We consider the total cost minimization of composite beams having the cross section shown in Fig. 1 (a) and Fig. 2




(a) (b)

**Figure 1:** (a) Notations for composite beams; (b) Plastic stresses distribution and internal forces at ultimate limit states (ULS)

**Figure 1:** (a) Notations pour les poutres mixtes; b) Distribution des contraintes plastiques et forces internes aux états limites ultimes (ELU)

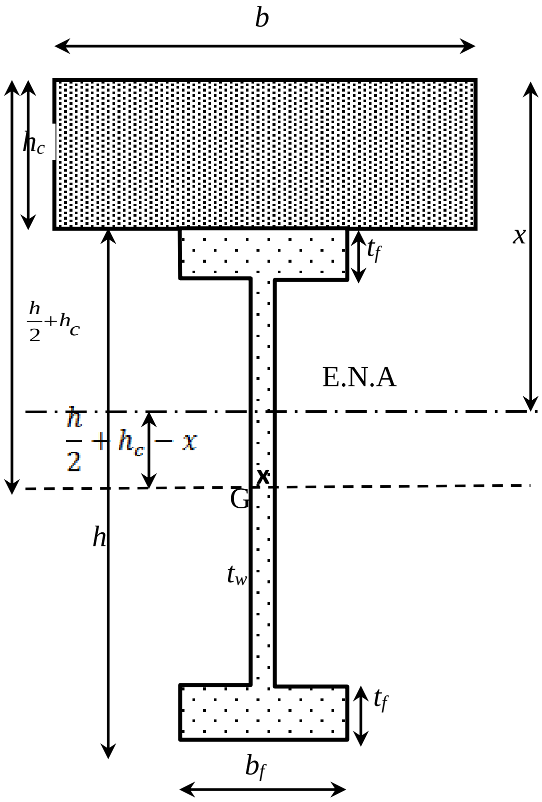



**Figure 2:** Elastic design of cross section of composite beam (serviceability limit states (SLS))

**Figure 2:** Conception élastique de la section transversale d'une poutre mixte (états limites de service (ELS))

### 2.1. Design variables

The design variables selected for the optimization are listed in Table 1 below.

**Table 1:** Definition of design variables

**Tableau 1:** Définition des variables de conception

| Design variables | Defined variables |
|---|---|
| $b$ | Effective width of the concrete flange |
| $h_c$ | Depth of concrete |
| $b_f$ | Width of the tension and compression flange of steel |
| $t_f$ | Bottom and top flange thickness of steel |
| $t_w$ | Thickness of web |
| $h$ | Total dépit of steel |
| $y_u$ | Depth of plastic neutral axis (PNA) |

### 2.2. Cost function

The objective function to be minimized in this optimization problem is the total cost of construction material per unit length of the beam. This function can be defined as:

$$C_0 = C_c bh_c + C_f \left(2h_c + b - b_f\right) + C_s\left[2t_f b_f + \left(h - 2t_f\right)t_w\right] \quad (1,a)$$

Where:

$C_0$ : Total cost per unit length of composite beam
$C_c$ : Unit cost of concrete
$C_f$ : Unit cost of formwork
$C_s$ : Unit cost of structural steel

It should be noted that in a cost optimization problem, the optimal values of the design variables are affected only by the relative cost values of the objective function and not by the absolute cost values. In other words, the absolute cost values affect only the final value of the objective function not the optimal values of the design variables.
The absolute cost $C_0$ can then be recovered by the optimized relative cost $C$ by using the relation:

$$C_0 = C_c LC \quad (1, b)$$

Thus, the objective function to be minimized can be written as follows:

$$C = bh_c + C_f/C_c(2h_c + b - b_f) + C_s/C_c[2t_f b_f + (h - 2t_f)t_w]$$
(1, c)

The values of the cost ratios $C_f / C_c$ and $C_s / C_c$ varyfrom a country to another and may eventually vary from one region to another for certain countries.

The values of these cost ratios can be estimated on the basis of data given in applicable unit price books of construction materials Davis [17] and Pratt [18].

### 2.3. Formulation of design constraints

The following constraints for the composite beams are definedin accordance with the design code specifications of EC4:

Given the (1, a) characteristics of material, loading data and constant parameters.

Find the design variables $b, h_c, b_f t_f, t_w, h$ and $y_u$ that minimize total cost of construction material per unit length of composite beam such that:

$$C = bh_c + C_f/C_c(2h_c + b - b_f) + C_s/C_c[2t_f b_f + (h - 2t_f)t_w] \quad (1)$$

Subjected to the design constraints:

a-The plastic neutral axis lies within the steel web:

$$\left(h_c + t_f\right) < y_u \quad (2)$$

b- Positive moment capacity of section with full shear connection:

$$M_{Ed} \le f_{yd}\left[(b_f - t_w)(h - t_f)t_f + \frac{t_w h^2}{4}\right] +$$

$$bh_c f_{cd}((h_c + h)/2) - b^2 h_c^2 f_{cd}^2 / (4 f_{yd} t_w) \quad (3)$$

(External moment $M_{Ed}$ $\le$plastic resistance moment of the composite section with Full shear connection $M_{pl,Rd}$ )

c- Internal force equilibrium:

$$h/2 + h_c - y_u = bh_c f_{cd} / \left(2 f_{yd} t_w\right) \quad (4)$$

d- Resistance of the composite beam to vertical shear:

$$V_{Ed} \le \left[\left(h - t_f\right) t_w / (3)^{0.5}\right] f_{yd} \quad (5)$$

(External shear $V_{Ed} \le$ plastic resistance of the structural steel section to vertical shear $V_{pl,a,Rd}$ )

As there is no shear force at the point of maximum bending moment at mid-span, no reduction due to shear in resistance moment is required.

e- Maximum width to thickness ratios for compression elements: outstand flanges: (flange in compression, section in class 1):

$$\left(b_f - t_w\right) / 2t_f \le 9\varepsilon \quad (6)$$

f- Maximum width to thickness ratios for the unstiffened web subject to bending (section in class1). The shear buckling resistance of the unstiffened web need not be verified when:

$$\left(h - 2t_f\right) / t_w \le 69\varepsilon \quad (7)$$

g- Deflection constraint: the mid-span deflection of simply supported beam under distribution load w (dead load + live load) for the composite beam:

$$\frac{5wL^4}{384 E_s I} \le \delta_{lim} \quad (8)$$

$$I = I_s + A_s\left(\frac{h}{2} + h_c - x\right)^2$$

$$+ \frac{bh_c}{n}\left[\frac{h_c^2}{12} + \left(x - \frac{h_c}{2}\right)^2\right]$$

$$A_s = 2t_f b_f + \left(h - 2t_f\right) t_w$$

$$x = \left(A_s\left(\frac{h}{2} + h_c\right) + \frac{bh_c^2}{2n}\right) /$$

$$\left(A_s + \frac{bh_c}{n}\right)$$

h- Design variables constraints including rules of current practice:

$$b_{min} \le b \quad (9)$$

$$h_{min} \le h \le h_{max} \quad (10)$$

$$h_{c\ min} \le h_c \quad (11)$$

$$t_{f\ min} \le t_f \le t_{f\ max} \quad (12)$$

$$t_{w\ min} \le t_w \le t_{w\max} \quad (13)$$

$$b_f \le b_{f\max} \quad (14)$$

$$h / b_f \ge 1.2 \quad (15)$$

i- Non-negativity variables:

$$b, h_c, b_f t_f, t_w, h, y_u > 0 \quad (16)$$

*Construction stage deflection :*

In this study, the doubly symmetrical steel beam is fully propped at the construction stage and the deflection of the steel beam at the construction stage is considered equal to zero. In this case, there is no deflection of the steel beam.

## 2.4. Formulation of optimum cost design problem

The formulation of the optimum cost design of composite beams can be mathematically stated as follows:

Given the characteristics of material, loading data and constant parameters.

Find the 07 design variables

$b, h_c, b_f t_f, t_w, h \; and \; y_u$ that minimize total cost of construction material per unit length of composite-beams such that:

$$C = bh_c + C_f/C_c(2h_c + b - b_f) + C_s/C_c[2t_f b_f + (h - 2t_f)t_w]$$

Subjected to 15 constraints.

## 2.5. Solution methodology

The objective function Eq.(1) and the constraints equations, Eq.(2) through Eq.(16), together form a nonlinear optimization problem. The reasons for the nonlinearity of this optimization problem are essentially due to the expressions of the cross sectional area, bending moment capacity and other constraints equations. Both the objective function and the constraint functions are nonlinear in terms of the design variables. In order to solve this nonlinear optimization problem, the generalized reduced gradient (GRG) algorithm is used. The Generalized Reduced Gradient method is applied as it has the following advantages: i) The GRG method is widely recognized as an efficient method for solving a relatively wide class of nonlinear optimization problems.

ii) The program can handle up to 200 constraints which is suitable for composite beams design optimization problems.

## 3.Numerical results

A typical example problem is now considered, followed by step by step procedure of optimum cost design model then a comparison between the standard design solution and the optimal solution has been obtained. Finally, a cost sensitivity analysis has been conducted for different values of the unit cost ratios.

## 3.1. Design example

As previously mentioned, the design constraints are defined in accordance with the code design specifications of EC4. The optimal solutions are compared with the standard design solutions obtained in accordance with EC4 design code.

The study of composite beam corresponds to a beam simply supported at its ends and pre-designed in accordance with provisions of EC4 design code.

The corresponding pre-assigned parameters are defined as follows:

*Input data for loads and concrete dimensions:*

$L = 16.00m$

$h_{c\ min} = 0.10m$

$h_{min} = L/25 = 0.64m$

$h_{max} = L/20 = 0.80m$

$b_{min} = 2m$

$t_{f\ min} = 0.01m$

$t_{w\ min} = 0.01m$

$t_{w\ max} = 0.04m$

$t_{f\ max} = 0.04m$

$b_{f\ \max} = 0.30m$

$M_{Ed} = 3MNm$

$V_{Ed} = 1MN$

$w = 0.06MN/m$

$\delta_{lim} = L/500 \; (span/500) = 0.032m$

*Input data for concrete characteristics:*

Strength class of concrete C25/30.

$f_{ck} = 25 MPa$
$\gamma_c = 1.5$
$f_{cd} = 14.17 MPa$

*Input data for units costs ratios of construction materials:*

$C_s / C_c = 30 \ and \ C_f / C_c = 0.10$

Input data for structural steel characteristics:

S355  Grade of steel

$f_{yk} = 355 MPa$
$\gamma_s = 1.1$
$f_{yd} = f_{yk} / \gamma_s$
$f_{yd} = 322.73 MPa$
$\varepsilon = (235/355)^{0.5} = 0.8136$
$E_s = 210000 MPa$
$n = 18$

### 3.2. Step by step procedure of cost optimization model for composite beams

Find the design variables $b, h_c, b_f t_f, t_w, h \ and \ y_u$ that minimize total cost of construction material per unit length of composite beam such that:

$$C = bh_c + 0.10(2h_c + b - b_f) + 30[2t_f b_f + (h - 2t_f)t_w] \quad (1')$$

Subjected to the design constraints:

*a*-The plastic neutral axis lies within the steel web:

$$(h_c + t_f) < y_u \quad (2')$$

*b*- Positive moment capacity of section with full shear connection:

$$3 \le 322.73[(b_f - t_w)(h - t_f)t_f + t_w h^2/4] + 14.17bh_c((h_c + h)/2) - 14.17^2\ b^2 h_c^2/(1290.92 t_w) \quad (3')$$

(External moment $M_{Ed} \le$ plastic resistance moment of the composite section with Full shear connection $M_{pl,Rd}$)

*c*- Internal force equilibrium:

$$h/2 + h_c - y_u = 14.17bh_c / (645.46 t_w) \quad (4')$$

*d*- Resistance of the composite beam to vertical shear:

$$1 \le 322.73\left[(h - t_f)t_w / (3)^{0.5}\right] \quad (5')$$

(External shear $V_{Ed} \le$ plastic resistance of the structural steel section to vertical shear $V_{pl,a,Rd}$)

As there is no shear force at the point of maximum bending moment at mid-span, no reduction due to shear in resistance moment is required.

*e*- Maximum width to thickness ratios for compression elements: outstand flanges: (flange in compression, section in class 1):

$$(b_f - t_w)/2t_f \le 7.32 \quad (6')$$

*f*- Maximum width to thickness ratios for the unstiffened web subject to bending (section in class1). The shear buckling resistance of the unstiffened web need not be verified when:

$$\left(h-2t_f\right)/t_w \leq 56.14 \qquad (7')$$

*g*- Deflection constraint: the mid-span deflection of simply supported beam under distribution load w

$$\frac{0.00762}{I} \leq 1 \qquad (8')$$

$$I = I_s + A_s\left(\frac{h}{2}+h_c-x\right)^2$$
$$+\frac{bh_c}{n}\left[\frac{h_c^2}{12}+\left(x-\frac{h_c}{2}\right)^2\right]$$
$$A_s = 2t_f b_f + \left(h-2t_f\right)t_w$$
$$x = \left(A_s\left(\frac{h}{2}+h_c\right)+\frac{bh_c^2}{2n}\right)/$$
$$\left(A_s+\frac{bh_c}{n}\right)$$

*h* - Design variables constraints including rules of current practice:

$$2 \leq b \qquad (9')$$

$$0.64 \leq h \leq 0.80 \qquad (10')$$

$$0.10 \leq h_c \qquad (11')$$

$$0.01 \leq t_f \leq 0.04 \qquad (12')$$

$$0.01 \leq t_w \leq 0.04 \qquad (13')$$

$$b_f \leq 0.30 \qquad (14')$$

$$h/b_f \geq 1.2 \qquad (15')$$

*i*- Non-negativity variables:

$$b, h_c, b_f, t_f, t_w, h, y_u > 0 \qquad (16')$$

### 3.3. Comparison between the optimal cost design solutions and the standard design approach

The vector of design variables from the conventional design solution and the optimal cost design solution using the proposed approach are shown in the Table 2 below.

**Table 2:** Comparison of the classical solution and the optimal solution

**Tableau 2:** Comparaison de la solution classique par rapport à la solution optimale

| Vector solution for $C_P/C_c$=30, $C_f/C_c$=0.1 | Classical Solution | Optimal Solution |
|---|---|---|
| b[m] | 2.00 | 2.00 |
| $h_c$[m] | 0.15 | 0.10 |
| $b_f$[m] | 0.3 | 0.30 |
| $t_f$[m] | 0.02 | 0.02 |
| $t_w$[m] | 0.02 | 0.013 |
| h[m] | 0.80 | 0.80 |
| $y_u$[m] | 0.22 | 0.18 |
| C | 1.316 | 1.068 |
| Gain | | 23% |

From the above results, it is clearly observed using the values of the relative costs $C_s/C_c = 30$, $C_f/C_c = 0.10$ and comparing the classical with optimal solutions, that a significant gain equal to 23% can be obtained by using the proposed design formulation.

### 3.4. Cost sensitivity analysis

The relative gains can be determined for various values of the unit cost ratios: $C_s/C_c$=10; 20; 30; 40; 50; 60; 70; 80; 90;100

For a given unit cost ratio $C_f / C_c = 0.00$ and $C_f / C_c = 0.10$

The corresponding results are reported in Table 3 and illustrated graphically in Figure 3 for $C_f / C_c$=0.00 and $C_f/C_c$=0.10.

**Table 3 :** Variation of relative gain in percent (%) versus unit cost ratio $C_s/C_c$ for a given cost ratio $C_f/C_c$=0.00 and $C_f/C_c$=0.10

**Tableau 3 :** Variation en pourcentage (%) du gain relatif en fonction du rapport decoût $C_s/C_c$ pour un rapport de coût donné $C_f /C_c$=0.00 et $C_f /C_c$=0.10

| $C_s/C_c$ | Gain % For $C_f/C_c$=0.00 | Gain % For $C_f/C_c$=0.10 |
|---|---|---|
| 10 | 34 | 25 |
| 20 | 29 | 24 |
| 30 | 27 | 23 |
| 40 | 25.8 | 22.8 |
| 50 | 24.8 | 22 |
| 60 | 25.8 | 22 |
| 70 | 27.6 | 23 |
| 80 | 29 | 24 |
| 90 | 30 | 26 |
| 100 | 31 | 27 |

It can be observed from Table 3 and Figure 3, that the relative gain decreases for increasing values of the unit cost ratio $C_s / C_c$, stabilizes around an average value for $40 \leq C_s / C_c \leq 60$ and then increases significantly beyond this average value.

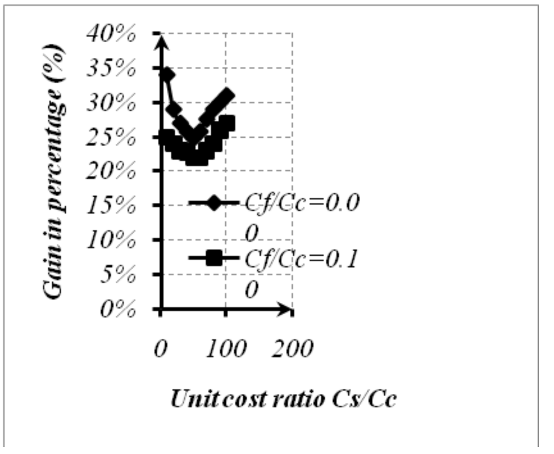



**Figure3:** Variation of relative gain in percentage versus two unit cost $C_f /C_c$ ratios, for different values of $C_s /C_c$.

**Figure 3 :** Variation en pourcentage (%) du gain relatif en fonction du rapport decoût $C_s/C_c$ pour un rapport de coût donné $C_f /C_c$=0.00 et $C_f /C_c$=0.10

The relative gains can be determined for various values of the unit cost ratios

$C_f /C_c$= 0.01, 0.02; 0.03; 0.04; 0.05; 0.06; 0.07; 0.08; 0.09; 0.10.

for a given unit cost ratio $C_s / C_c = 10$ and $C_s / C_c = 30$.

The corresponding results are reported in Table 4 and illustrated graphically in Figure 4 for $C_s /C_c=10$ and $C_s /C_c$=30.

**Table 4:** Variation of relative gain in percent (%) versus unit cost ratio $C_f/C_c$ of construction materials for $C_s/C_c$=10 and

$C_s/C_c$=30

**Tableau 4:** Variation en pourcentage (%) du gain relatif en fonction du rapport de coût $C_f/C_c$ pour les matériaux de construction pour $C_s/C_c$=10 et $C_s/C_c$=30

| $C_f/C_c$ | Gain % For $C_s/C_c$=10 | Gain % For $C_s/C_c$=30 |
|---|---|---|
| 0.01 | 33 | 26 |
| 0.02 | 31 | 26 |
| 0.03 | 30 | 25 |
| 0.04 | 30 | 25 |
| 0.05 | 29 | 24 |
| 0.06 | 28 | 24 |
| 0.07 | 27 | 24 |
| 0.08 | 26 | 23 |
| 0.09 | 25 | 23 |
| 0.10 | 25 | 23 |

From Table 4 and Figure 4 the gain decreases monotonically with the increasing of the unit cost ratio $C_f/C_c$.

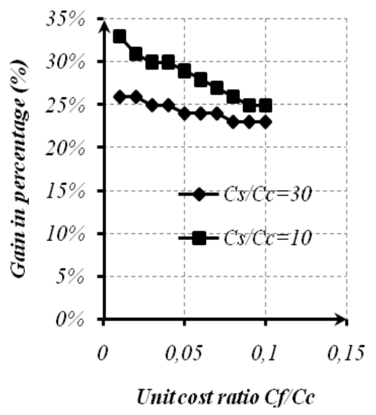



**Figure 4 :** Variation of relative gain in percentage versus two unit cost $C_s/C_c$ ratios, for different values of $C_f/C_c$.

**Figure 4 :** Variation en pourcentage (%) du gain relatif en fonction du rapport de coût $C_f/C_c$ pour les matériaux de construction pour $C_s/C_c$=10 et $C_s/C_c$=30

## 4. Conclusions

The following conclusions have been drawn from this study:

1. The problem formulation of the optimal cost design of composite beams can be cast into a nonlinear programming problem, the numerical solution has been efficiently determined through the use of the GRG (Generalized Reduced Gradient) method.
2. Optimal values of the design variables are affected only by the relative cost values of the objective function and not by the absolute cost values.
3. The observations of the optimal solutions results reveal that the use of the optimization based on the optimum cost design concept may lead to substantial savings in the amount of the construction materials to be used in comparison to classical design solutions of composite beams.
4. The objective function and the constraints considered in this paper are illustrative in nature. This approach based on nonlinear mathematical programming can be easily extended to other sections commonly used in structural design. More sophisticated objectives and considerations can be readily accommodated by suitable modifications of this optimal cost design model.
5. The proposed methodology of optimum cost design is effective and more economical comparing to the classical methods. The results of the analysis show that the optimization process presented herein is effective and its application appears feasible.

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**Symbols**

The following symbols are used in this paper:

$L$ Beam span

$M_{Ed}$ Maximum design bending moment

$M_{pl,Rd}$ Design value of the plastic resistance moment of the composite section with full shear connection

$V_{Ed}$ Maximum design shear force

$V_{pl,a,Rd}$ Design value of the plastic resistance of

the structural steel section to vertical

shear

$b_{min}$ Minimum effective width of concrete flange

$h_{c\,min}$ Minimum depth of concrete flange

$t_{fmin}$ Minimum thickness of structural steel flange

$t_{w\,min}$ Minimum thickness of structural steel web

$b_{f\,min}$ Minimum width of structural steel flange

$h_{min}$ Minimum total depth of structural steel

$h_{max}$ Maximum total depth of structural steel

C25/30 Class of concrete

$f_{ck}$ Characteristic compressive cylinder

strength of concrete at 28 days

$f_{cd}$ Design value of the cylinder compressive

strength of concrete

$\gamma_c$ Partial safety factor for concrete

x Depth of Elastic Neutral Axis (ENA)

$\delta_{lim}$ Limit deflection recommended

w Characteristic load combination (dead load + live load) for the composite beam

n Ratio of the modulus of elasticity of steel

to that of concrete

$F_c$ Compressive normal force in the concrete flange

$F_{sc}$ Compressive normal force in the

structural steel

$F_{st}$ Tensile normal force in the structural

steel

S355 Grade of structural steel

$f_y$ Nominal value of the yield strength of structural steel

$f_{yd}$ Design value of the yield strength of

structural steel

$\gamma_s$ Partial safety factor for steel.

$\varepsilon$ $(235/f_y)^{0.5}$ , where $f_y$ is in $N/mm^2$

$A_s$ Area of steel

$E_s$ Young's Modulus for structural of steel

I Gross uncracked moment of inertia of composite section

$C_0$ Total cost per unit length of composite beams

$C_f$ Unit cost of formwork

$C$ Total relative cost of composite beams

$C_s$ Unit cost of structural steel

$C_c$ Unit cost of concrete