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Cost optimization of composite beams using genetic algorithms

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ABSTRACT

This paper presents a genetic algorithm model for the cost optimization of composite beams based on the load and resistance factor design (LRFD) specifications of the AISC. The model formulation includes the cost of concrete, steel beam, and shear studs. Two design examples taken from the literature were analyzed in order to validate the proposed model, to illustrate its use, and to demonstrate its capabilities in optimizing composite beam designs. The results obtained show that the model is capable of achieving substantial cost savings. Hence, it can be of practical value to structural designers. A parametric study was also conducted to investigate the effects of beam spans and loadings on the cost optimization of composite beams.

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1. Introduction

Because of its economy, composite floor construction is widely used in commercial multistory buildings. To create a composite floor, a concrete slab is often mechanically connected to a hot-rolled steel section through shear connectors.

In practice, a composite beam is designed in a trial-and-error process to select the following parameters: (1) the concrete type expressed by its compressive strength and its unit weight, (2) the slab thickness, (3) the steel section size expressed by its cross-sectional area, and its steel grade expressed by its yield strength, and (4) the strength of the shear connectors expressed by its shear resistance, and the number of shear connectors provided.

The design of composite beams is complicated and highly iterative. Depending on the design parameters, a beam may be fully or partially composite. In the case of the LRFD design code [3], the plastic deformation has to be considered. A source of complexity is due to the fact that the location of the plastic neutral axis (PNA) may lie within the concrete slab, the flange of the steel beam, or the web of the steel beam. Since the value of a design parameter affects other values, all design parameters cannot be found simultaneously.

Mathematical optimizations provide methodologies to automate the complicated design process [1]. Moreover, one can achieve an optimum solution out of numerous solutions on the basis of a selected criterion such as the minimum weight or the minimum cost. The majority of the articles that have been published on the optimization of structural systems focused on the minimum weight design. Only a small fraction of these articles has dealt with the minimum total cost. Sarma and Adeli [17,18] published a review of the articles dealing with the cost optimization of concrete and steel structures, respectively. Jármai and Farkas [6] discussed the cost calculation and the optimization of welded steel structures.

Few journal articles on the optimization of composite beams have also been published. Zahn [19] discussed the economies of the LRFD design code versus the AISC allowable stress design code in the design of composite beams through the weight comparison of some 2500 composite designs using A36 steel. The results indicated that the LRFD design code yielded a saving of 6–15% for span lengths ranging from 3 m to 13.7 m. Lorenz [15] discussed the minimum cost design of composite beams based on the AISC–LRFD design code and argued that the real advantage of the AISC–LRFD concept could be realized in the minimum cost design. Bhatti [4] attempted to build upon the idea by casting the problem into a standard optimization formulation and solving the problem approximately using the symbolic algebra *Mathematica* [16]. His cost function, however, only includes the cost of the steel beams and the field-installed shear studs, neglecting the cost of concrete. Long et al. [14] presented a non-linear programming based optimization of cable-stayed bridges with composite superstructures and proposed a cost objective function which contained the costs of concrete, structural steel, reinforcement, cables and formwork. Kravanja and Šilih [10] introduced a non-linear programming optimization models for composite I beams. Kravanja and Šilih [11] also introduced a mixed-integer non-linear programming approach for cost optimization of composite I beams.

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Adeli and Kim [2] proposed a formulation for the cost optimization of composite beams based on the AISC LRFD specifications by including the costs of (a) concrete, (b) steel beam, and (c) shear studs. The problem is formulated as a mixed integer-discrete nonlinear programming problem and solved by the recently patented neural dynamics model of Adeli and Park. In addition, Kravanja and Šilih [12] performed an optimization based comparison between composite welded I beams and composite hollow-section trusses for a defined steel price of €/0.4 kg and for fixed economical parameters. In their work, the cost objective function includes the costs of concrete, steel sections, reinforcement, shear studs, anti-corrosion paint, fire protection paint, sheet-steel cutting costs, and welding costs as well as the formwork costs. This objective function was also used by Klanšek and Kravanja [7] for the comparison of different composite systems for a pre-defined imposed load and a fixed steel price. Kravanja et al. [13] presented a mixed-integer non-linear programming (MINLP) optimization approach to mechanical superstructures. Klanšek and Kravanja [8,9] presented the cost optimization, comparison, and competitiveness between three different composite floor systems: composite beams produced from duo-symmetrical welded I sections, composite trusses formed from rolled channel sections and composite trusses made from cold formed hollow sections. The optimization was performed by the non-linear programming approach, NLP. The aim of the comparison was to define the spans and the loads, at which each of the presented composite structures showed its advantages. Comparative diagrams, displayed at the end of the paper, can be usefully applied for choosing the optimal type of a structure.

This paper presents the development of a genetic algorithm model for the cost optimization of composite beams. Genetic algorithm-based models are efficient techniques for the cost optimization of composite beams because they can generate practical and minimum cost design solutions. The formulation includes the cost of concrete, steel beam, and shear studs. The model is capable of generating optimal/near-optimal design solutions that satisfy the constraints of the AISC–LRFD specifications [3]. Two examples taken from the literature are used to illustrate the use of the proposed method, to demonstrate its capabilities in cost optimization of composite beams, and to validate its results. A parametric study was also conducted to investigate the effects of beam spans and loadings on the cost optimization of composite beams.

2. Model formulation

The primary purpose of this development stage is to formulate a robust optimization model that supports the cost minimization of composite beams. To this end, the present model is formulated in two major steps: (1) To determine the major decision variables affecting the design of composite beams; and (2) to formulate the objective of cost optimization of composite beams in a robust optimization model.

2.1. Decision variables

The present model is designed to consider all relevant decision variables that may have an impact on the cost optimization of composite beams. These include for the concrete slab: (1) the compressive strength (f'_c), (2) the unit weight (Y_c), and (3) the thickness (t_c); for the steel section: (1) the yield strength (F_y), (2) the cross-sectional area (A_s), (3) the depth (d), (4) the web thickness (t_w), (5) the flange thickness (t_f), (6) the flange width (b_f), (7) the moment of inertia (I_s), and (8) the plastic modulus (Z_s); and for the shear connectors: (1) the diameter (A_{SC}) and (2) the number (N_s) of shear connectors.

In order to reduce the complexity of the optimization model, the present model combines the decision variables related to the steel section into a single variable called a steel section decision variable.

The yield strength, F_y, of the steel section is given and fixed at the onset of each design, and hence, the fourth decision variable is not considered in the present model.

A design alternative option, which defines a complete design of a composite beam, includes the following decision variables:

x_1 = concrete compressive strength,
x_2 = concrete slab thickness,
x_3 = steel section shape,
x_4 = shear connector diameter, and
x_5 = number of shear connectors.

Table 1 lists a number of possible values for the five decision variables.

2.2. Optimization objectives

The present optimization model is formulated in order to provide the capability of cost optimization of composite beams. The model is also designed to quantify and measure the impact of various decision variables that affect the cost optimization of composite beams. It incorporates the following objective equation:

$$\text{Minimize composite beam cost} = C_t = C_c + C_s + C_{sd} \quad (1)$$

where C_c, C_s, and C_{sd} are the cost of concrete, steel beam, and shear connectors, respectively. The terms used in the objective equation are defined as follows:

$$C_c = \gamma_c L b t_c C'_c \quad (2)$$

$$C_s = \rho A_s L C'_s \quad (3)$$

$$C_s d = N_s C'_{sd} \quad (4)$$

where L is the beam span, ρ is the unit weight of steel section, C'_c is the cost of concrete per unit weight, C'_s is the cost of the steel section per unit weight, and C'_{sd} is the cost of one shear connector including installation and material costs.

The minimization of the objective function is subjected to the constraints prescribed by the AISC–LRFD specifications [3]. These constraints are described briefly in the following section.

2.3. Design constraints

2.3.1. Flexural strength constraints

The ultimate bending moment must be less than or equal to the nominal flexural strength multiplied by the resistance factor (ϕ = 0.9). Two cases must be considered. First, the moment capacity of the non-composite steel section (excluding the concrete strength) must be checked to make sure that the steel section can support its own weight, the weight of the wet concrete, and the temporary loads such as construction loads. This constraint is expressed as

$$M_{u\text{-}noncomposite} \leqslant 0.90 M_{n\text{-}noncomposite} \quad (5)$$

where $M_{u\text{-}noncomposite}$ is the ultimate factored moment due to the wet concrete weight, the temporary loads, and the own weight of the steel section, and $M_{n\text{-}noncomposite}$ is the nominal moment capacity of the steel section.

Second, the moment capacity of the composite section must be checked to make sure that the composite section can support all dead and live loads, as defined by the following constraint:

Table 1
Design variable range values.

Gene values	Concrete strength f'_c (MPa)	Concrete slab thickness t_c (mm)	Steel section shape	Shear stud diameter STD (mm)	Number of shear studs NS
0	20	100	W200 × 15	13	10
1	25	110	W200 × 19.3	16	12
2	30	120	W200 × 22.5	19	14
3	35	130	W200 × 26.6	22	16
4	40	140	W200 × 31.3		20
5		150	W200 × 35.9		22
6		160	W200 × 41.7		24
7		170	W250 × 17.9		26
8		180	W250 × 22.3		28
9		190	W250 × 25.3		30
10		200	W250 × 28.4		32
11			W250 × 32.7		34
12			W250 × 38.5		36
13			W310 × 21		38
14			W310 × 23.8		40
15			W310 × 28.3		42
16			W310 × 32.7		44
17			W310 × 38.7		46
18			W310 × 44.5		48

$$M_{u\_composite} \leqslant 0.85 M_{n\_composite} \tag{6}$$

where $M_{u\_composite}$ is the factored moment due to dead and live loads, and $M_{n\_composite}$ is the moment capacity of the composite beam.

Using the notation of Fig. 1, the moment capacity of the composite beam when the plastic neutral axis (PNA) lies within the beam flange is given by:

$$M_{n-composite} = C_{con}\left(x_1 + x_2 + t_c - \frac{a}{2}\right) + C_{flange}\left(x_2 + \frac{x_1}{2}\right) \tag{7}$$

where a is the depth of the concrete equivalent rectangular stress block, which is given by

$$a = \frac{C_{con}}{0.85 f'_c b_{eff}} \tag{8}$$

Since the concrete compression capacity of a partially composite beam is governed by the resistance of the shear connectors, the concrete compression resistance, C_{con}, is substituted by the resistance of the shear connectors between the points of the maximum and the zero moments. Thus, Eq. (8) may be re-written as

$$a = \frac{\sum Q_n}{0.85 f'_c b_{eff}} = \frac{Q_n(\frac{N_s}{2})}{0.85 f'_c b_{eff}} \tag{9}$$

The distance between the bottom of the concrete slab and the PNA, d_1, is found by equating the tension force to the compression forces as follows:

$$d_1 = \frac{A_s F_y - \sum Q_n}{2 b_f F_y} \tag{10}$$

From geometry,

$$d_2 = \frac{A_s(\frac{d}{2} - d_1) + b_f \frac{d_1^2}{2}}{A_s - b_f d_1} \tag{11}$$

When the PNA lies within the beam web as shown in Fig. 2, the moment capacity of the composite beam is given by

$$M_{n\_composite} = C_{con}\left(d_1 + d_2 + t_c - \frac{a}{2}\right) + C_{flange}\left(d_1 + d_2 - \frac{t_f}{2}\right) + C_{web}\left(\frac{d_1 - t_f}{2} + d_2\right) \tag{12}$$

Similarly, d_1 and d_2 are determined as follows:

$$d_1 = t_f + \frac{A_s F_y - \sum Q_n - 2C_{flange}}{2 F_y t_w} \tag{13}$$

$$d_2 = \frac{A_s(\frac{d}{2} - d_1) + b_f t_f (d_1 - \frac{t_f}{2}) + (d_1 - t_f)^2 (\frac{t_w}{2})}{A_s - b_f t_f - t_w d_1 + t_f t_w} \tag{14}$$

2.3.2. Deflection constraint

The deflection of a composite beam depends on whether it is shored or not during the construction phase. The unshored construction is less labor-intensive and faster than the shored construction, and hence, it is often the preferred method of

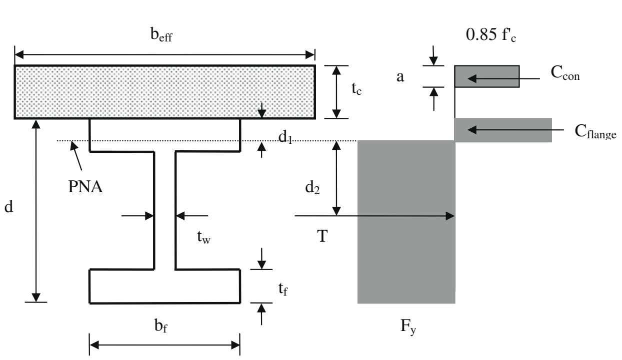

Fig. 1. Plastic design of composite beam when PNA lies in steel flange.

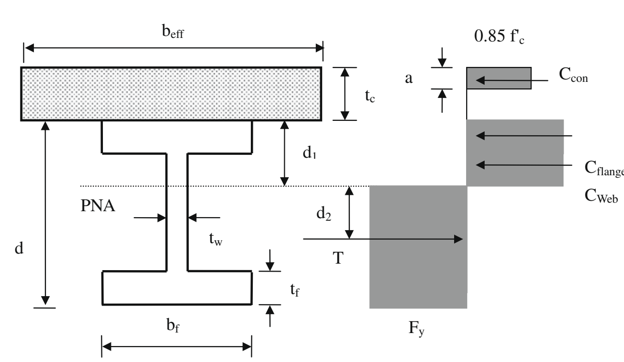

Fig. 2. Plastic design of composite beams when PNA lies in steel web.

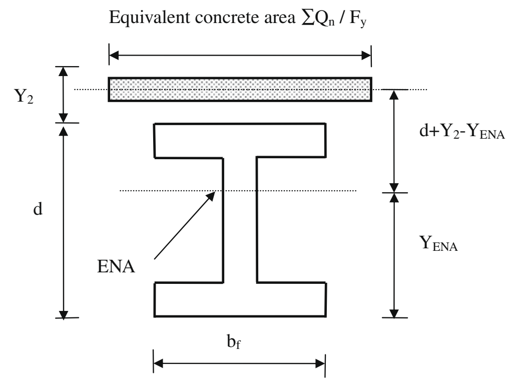

Fig. 3. Composite beam elastic design.

construction. For unshored composite beams, the deflection of the composite beam due to live loads, Δ_{LL}, is given by [3]:

$$\Delta_{LL} = \frac{5w_{LL}L^4}{384E_sI_{LB}} \leqslant C_1L \tag{15}$$

where w_{LL} is the service live load per unit length of the beam, E_s is the modulus of elasticity of the steel section, I_{LB} is the lower bound moment of inertia, and C_1 is a coefficient ranging from $\frac{1}{300}$ to $\frac{1}{360}$ for building structures or $\frac{1}{500}$ to $\frac{1}{900}$ for highway bridges.

The lower bound moment of inertia I_{LB}, which is based on the area of the beam and an equivalent concrete area of Q_n/F_y (Fig. 3), is given by the following equation [3]:

$$I_{LB} = I_s + A_s\left(Y_{ENA} - \frac{d}{2}\right) - \left(\frac{\sum Q_n}{F_y}\right)(d + Y_2 - Y_{ENA}) \tag{16}$$

Y_{ENA} represents the distance from the bottom of the steel beam to the elastic neutral axis (ENA) and it is given by the following equation:

$$Y_{ENA} = \frac{\frac{A_sd}{2} + \left(\frac{\sum Q_n}{F_y}\right)(d + Y_2)}{A_s + \left(\frac{\sum Q_n}{F_y}\right)} \tag{17}$$

Y_2 is given by:

$$Y_2 = Y_{con} - \frac{a}{2} \tag{18}$$

where Y_{con} is the distance from the top of the steel beam to the top of the concrete.

2.3.3. Shear stud spacing constraint

AISC–LRFD defines the minimum center-to-center spacing of shear connectors, p, not to be less than six times the diameter, ϕ, of the shear connector, and the maximum center-to-center spacing not to be greater than eight times the total slab thickness, t_c, i.e.

$$p \geqslant 6(\phi) \tag{19}$$

$$p \leqslant 8(t_c) \tag{20}$$

3. Model implementation

Genetic algorithms, which are used for the implementation of the proposed model, are search and optimization tools that assist decision makers in identifying optimal or near-optimal solutions for problems with a large search space. They are inspired by the mechanics of evolution. They adopt the survival of the fittest and the structured exchange of the genetic materials among populations of chromosomes (bit-strings) over successive generations as a basic mechanism for the search process [5]. The size of the initial population should be between 30 and 500 chromosomes [5] and could be manually prepared or randomly generated. Consecutive generations evolve by applying the operators of reproduction, crossover, and mutation on a population of chromosomes whose patterns depend upon the problem under consideration. The chromosome format could either be binary (or true-valued) and ordering coding. The chromosome size is determined by the model, considering the total number of decision variables included in the design problem. The number of generations (G) and the population size (S) are identified based on the selected chromosome size in order to improve the quality of the solution. The forms of reproduction, crossover, and mutation operators depend on the way the problem is coded. A brief description of each of these operators is given as follows:

Reproduction measures the fitness of individuals in a generation and then reproduces some of the individuals in proportion to their fitness values. The reproduction aim is to give good (individuals) solutions a higher chance than the bad ones of passing their "genes" to the next generation.

Crossover is an operation that allows chromosomes to swap parts of bit-strings at randomly selected crossing point(s). The crossover is done with a crossover rate, P_c, that represents the probability that two strings will swap their bits. The crossover operation creates variations in the solution population by producing new solution strings that consist of parts taken from selected parent solution strings. Its value varies between 0.7 and 0.9. A value of 0.8 is commonly used.

Mutation is a random change of bits in a chromosome to reintroduce lost bit values into a population. Without this mechanism, a genetic algorithm system might unintentionally exclude promising areas of searching space due to premature convergence of certain genes in the whole population to a common bit value. In a uniform mutation operation, a gene (real number) is replaced with a randomly selected number within a specified range. The mutation rate represents the probability that a bit within a string will be flipped (0 becomes 1, 1 becomes 0). The mutation operation introduces random changes in the solution population. In genetic algorithms, the mutation operation can be beneficial in reinforcing diversity in a population. The mutation rate has usually a very low value for binary encoded genes, say 0.005.

The computation procedure of the composite beam design is shown in Fig. 4 as a flowchart while the steps are described as follows:

(1) Read project and genetic algorithm parameters needed to initialize the search process. The project parameters include: (1) steel section modulus of elasticity, (2) steel section yield strength, (3) concrete unit weight, (5) steel section unit cost, (6) concrete unit cost, (7) shear connector unit cost, (8) beam span, (9) beam spacing, and (10) section properties for 77 commonly-used W-shape sections. The required genetic algorithm parameters for this initialization phase include: (1) a string size; (2) the number of generations; (3) a population size; (4) a mutation rate; and (5) a crossover rate.

(2) Generate random solutions (s = 1 to S) for the initial population P_1 in the first generation (g = 1). These solutions represent an initial set of feasible design solutions that satisfy all the constraints listed in the preceding section. This set of solutions is then evolved in order to generate a set of optimum/near optimum feasible design alternatives.

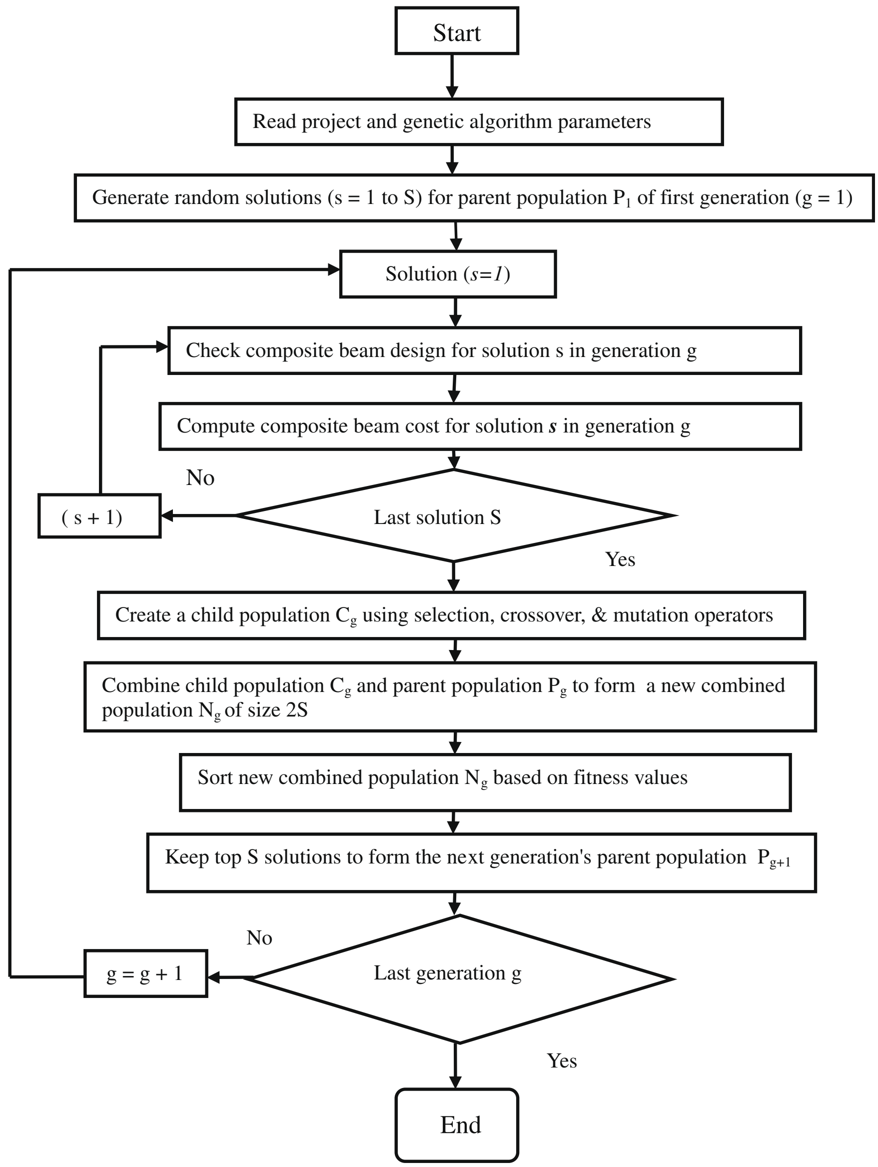

Fig. 4. Computational flowchart of the proposed model.

(3) Calculate the composite beam cost for each feasible design alternative (s) in generation g in order to determine the fitness of the solution.
(4) Create a child population C_g using selection, crossover, and mutation operators.
(5) Combine the child population C_g and the parent population P_g to form a new combined population Ng with a size of 2*S*. This combined population allows good solutions of the initial parent population to pass on to the following generation in order to avoid the loss of good solutions of the initial parent population once they are found.
(6) Sort the new combined population, N_g based on their fitness values, which are the total costs.
(7) Keep the top *S* solutions from the combined population N_g to form the parent population ($P_g + 1$) of the next generation. This parent population is then returned to Step 3 for generating a new iterative process, which continues until the specified number of generations is completed.

These computational steps were implemented using a C++ computer program (see Fig. 4).

4. Illustrative examples

Two examples taken from the literature [3] were analyzed and presented in order to illustrate the use of the proposed model, to demonstrate its capabilities, and to validate its results. The rates of crossover and mutation were set to 0.8 and 0.005, respectively. After a number of trial-and-error adjustments, a population size of 1500 individuals and 100 generations were found to meet the accuracy requirements for the two examples. Table 2 summarizes the input data needed for both examples. The cost values C'_c, C'_s, C'_{sd} were selected to be \$1.15kg^{-1}\$0.3kg^{-1}, and \$3.3stud^{-1}, respectively.

Three cases were considered. In the first case, the slab thickness and the concrete compressive strength were kept constant. In the second case, only the compressive strength was kept constant. In the third case, all decision variables were allowed to vary. Tables 3 and 4 summarize the results obtained in the examples. The results show that the proposed model was able to achieve significant cost savings in both examples as it is shown that the cost savings in Examples 1 and 2 reach the values of 25.3% and 11.4%, respectively.

Table 2
Input data for Examples 1 and 2.

Example number	Beam span (m)	Beam spacing (m)	Dead load (kN/m)	Live load (kN/m)	Concrete unit weight (kg/m3)	f'_c (MPa)	t_c (mm)	F_y (MPa)	Stud diameter (mm)	Construction type (mm)
1	9	3	13.0	19.0	1845	25	160	345	19	Shored
2	12	3	13.5	36.0	2320	25	190	345	19	Unshored

Table 3
Result summary for Example 1.

Cases	f'_c (MPa)	t_c (mm)	Steel section	Shear connectors		Beam cost ($)	% Cost saving
				Diameter (mm)	Number		
First	25	160	W410 × 38.8	19	24	1777	2.9
Second	25	100	W410 × 46.1	19	32	1392	23.9
Third	35	100	W410 × 46.1	19	24	1366	25.3
AISC	25	160	W410 × 38.8	19	40	1830	

Table 4
Result summary for Example 2.

Cases	f'_c (MPa)	t_c (mm)	Steel section	Shear connectors		Beam cost ($)	% Cost saving
				Diameter (mm)	Number		
First	25	190	W610 × 82.0	22	44	3328	2.3
Second	25	160	W610 × 82.0	22	56	3183	6.6
Third	40	100	W610 × 82.0	22	56	3017	11.4
AISC	25	190	W610 × 82.0	19	68	3407	

5. Parametric study

A parametric study was also presented to investigate the effects of beam spans and loadings on the cost optimization of composite beams. Table 5 summarizes the beam spans and the loadings considered in the study. A concrete strength of 30 MPa and a concrete slab thickness of 100 mm were also selected.

Table 6 summarizes the design results obtained in the case study using the present model. As expected, the steel section size increases with both the beam span and the acting loads as to satisfy the strength and the deflection constraints. Similarly, the size and the number of studs increase with both the beam span and the loadings as to satisfy force and moment equilibrium. Fig. 5 shows the curves representing the variations between the total costs and the beam spans under three different loadings. The curves for the three loading combinations. The curves have the same non-linear trend that increases with the beam span. Table 7 summarizes the second-order polynomial fits between the beam costs and the spans, which can be used to get an initial estimation of the total cost under a given span length or a given loading combination.

Table 5
Parametric study.

Beam spacing (m)	Load combinations		Beam spans			
	Dead (kN/m)	Live (kN/m)	(m)	(m)	(m)	(m)
3	10	20	4	6	8	10
3	20	29	4	6	8	10
3	30	49	4	6	8	10

6. Conclusions

A robust optimization model is developed to perform the cost optimization of composite beams. The proposed model enables structural designers to generate and evaluate optimal/near-opti-

Table 6
Parametric study results.

Dead loads DD (kN/m)	Live loads LL (kN/m)	Beam spacing (m)	Beam span (m)	Concrete strength f'_c (Mpa)	Concrete slab thickness t_c (mm)	Steel section W-shape	Shear stud diameter STD (mm)	Shear stud number NS	Beam total cost ($)
10	20	3	4	30	100	W200 × 15	13	10	495
			6	30	100	W310 × 23.8	19	10	770
			8	30	100	W360 × 39.0	22	10	1152
			10	30	100	W460 × 52.0	22	12	1583
20	29	3	4	30	100	W310 × 21.0	19	10	523
			6	30	100	W360 × 39.0	19	10	875
			8	30	100	W460 × 52.0	22	16	1304
			10	30	100	W530 × 74.0	22	22	1896
30	49	3	4	30	100	W310 × 28.3	19	10	556
			6	30	100	W460 × 52.0	22	10	965
			8	30	100	W610 × 82.0	22	10	1547
			10	30	100	W610 × 113.0	22	22	2346

Table 7
Polynomial best-fit equations.

Dead load (kN/m)	Live load (kN/m)	Beam span (m)	Beam total cost ($)	Coefficient of determination (R^2)
10	20	L	$24.47L^2 - 44.92L + 346.8$	0.9999
20	29	L	$14.974L^2 + 17.835L + 216.1$	0.9996
30	49	L	$9.81L^2 + 45.10L + 154.8$	0.9998

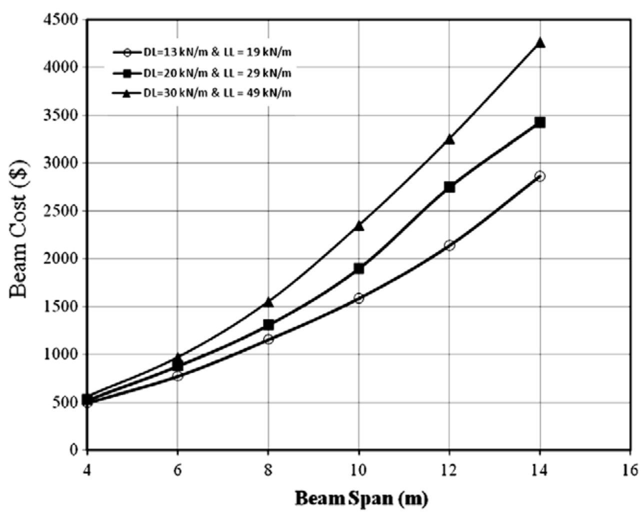

Fig. 5. Optimal composite design total costs.

mal design solutions. To accomplish this, the model incorporates (1) a design module that performs the design of composite beams; (2) a cost module that computes the total cost of composite beams; and (3) an optimization module that searches for and identifies optimal/near-optimal design alternatives. Two examples and a case study were used to illustrate the capabilities of the developed model in generating all optimal design solutions that achieve minimum total costs. Substantial cost savings were achieved by using the present model. This new capability should prove useful to structural designers and is expected to advance existing design practices of composite beams.

References

[1] Adeli H, editor. Advances in design optimization. New York (London): Charpman and Hall; 1994.
[2] Adeli H, Kim H. Cost optimization of composite beams using the neural dynamics model. Commun Numer Meth Eng 2001;17(11):771–87.
[3] AISC. Structural members, specifications, and codes. Manual of steel construction – load and resistance design, vol. I. Chicago, USA: American Institute of Steel Construction; 1999.
[4] Bhatti MA. Optimum cost design of partially composite steel beam using LRFD. AISC Eng J 1996(1st Qtr):18–29.
[5] Goldberg DE. Genetic algorithms in search, optimization, and machine learning. Addison-Wesley; 1989.
[6] Jármai K, Farkas J. Cost calculation and optimization of welded steel structures. J Construct Steel Res 1999;50(2):115–35.
[7] Klanšek U, Kravanja S. Comparison between three different composite systems. In: Brebbia CA, De Wilde WP, editors. High performance structures and materials II, second international conference on high performance structures and materials. Southampton (Boston): WIT press; 2004. p. 87–97.
[8] Klanšek U, Kravanja S. Cost estimation, optimization and competitiveness of different composite floor systems—part 1: self-manufacturing cost estimation of composite and steel structures. J Construct Steel Res 2006;62(5):434–48.
[9] Klanšek U, Kravanja S. Cost estimation, optimization and competitiveness of different composite floor systems—part 2: optimization based competitiveness between the composite I beams, channel-section and hollow-section trusses. J Construct Steel Res 2006;62(5):449–62.
[10] Kravanja S, Šilih S. The competitive spans of composite beams. In: Studenička J, Wald F, Machaček J, editors. Proceedings of the conference Eurosteel 99. Prague: Czech Technical University in Prague; 1999. p. 623–6.
[11] Kravanja S, Šilih S. The MINLP optimisation of composite I-beams. In: De Wilde WP, Blain WR, Brebbia CA, editors. Computer aided optimum design of structures VII, seventh international conference on computer aided optimum design of structures. Southampton (Boston): WIT press; 2001. p. 401–7.
[12] Kravanja S, Šilih S. Optimization based comparison between composite I beams and composite trusses. J Construct Steel Res 2003;59(5):609–25.
[13] Kravanja S, Šilih S, Kravanja Z. The multilevel MINLP optimization approach to structural synthesis: the simultaneous topology, material, standard and rounded dimension optimization. Adv Eng Softw 2005;36(9):568–83.
[14] Long W, Troitsky MS, Zielinski ZA. Optimum design of cable stayed bridges. Struct Eng Mech 1999;7(3):241–57.
[15] Lorenz RF. Understanding composite beam design methods using LRFD. AISC Eng J 1988(1st Qtr):35–8.
[16] Mathematica. Mathematica 6. Champaign, (IL, USA): Wolfram Research, Inc.; 2008.
[17] Sarma KC, Adeli H. Cost optimization of concrete structures. J Struct Eng ASCE 1998;124(5):570–8.
[18] Sarma KC, Adeli H. Cost optimization of steel structures. Eng Optim 2000;32:777–802.
[19] Zahn MC. The economies of LRFD in composite floor beams. AISC Eng J 1987;24(2nd Qtr):87–92.