Reliability-based Design Optimization of Steel-Concrete Composite Beams Using Genetic Algorithm and Monte Carlo Simulation

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Received: 23 September 2022 | Revised: 13 October 2022 | Accepted: 15 October 2022

Abstract-Steel-Concrete Composite (SCC) beams have been commonly used in civil and industrial buildings. It is the main bearing structure and accounts for 30-40% of the structural cost. Therefore, the optimal design with minimum weight and safety structure of the SCC beams is very important. Reliability is an important part of structural safety. Design according to reliability has been included in standards such as ISO 2394:2012, JB50153-92, and BS 5760-0:2014. This article aims to propose and apply a design optimization algorithm for the reliability-based design of SCC beams. The reliability-based design optimization of the SCC beams combines the safety conditions of EC-4, Genetic Algorithm, and Monte Carlo simulation. The numerical results show that with safety probability constraint conditions P_s=98%, the cross-section of the SCC beams can be reduced from IPE 400 to IPE 300.

Keywords-reliability; design optimization; Genetic Algorithm (GA); Monte Carlo simulation; steel-concrete composite beams

I. INTRODUCTION

SCC beams are designed according to the American Institute of Steel Construction (AISC360-10) [1], the European Committee for Standardization 2004a (EC-4) [2], and the Japan Society of Civil Engineers (JSCE-2009). The calculation methods for design strengths of steel–concrete composite members can be divided into the Load and Resistance Factor Design (LRFD) method and the Partial Factor Method (PFM) [3]. Reliability assessment of steel and SCC beams is an open research topic. Fatigue-reliability evaluation of steel bridges according to AASHTO was proposed in [4]. Reliability assessment of SCC beams considering metal corrosion effects was published in [5]. A reliability assessment of SCC beams according to EC-4 using FORM was proposed in [6]. Seismic reliability assessment of a two-story steel-concrete composite frame designed according to Eurocode 8 was conducted in [7].

Some recently published studies on the reliability of steel and reinforced concrete beams and design optimization can be seen in [7-17]. However, previous studies mostly focused on the structural reliability and optimization of steel and SCC structures. To the best of our knowledge, no studies have been conducted yet on the reliability-based design optimization of SCC beams combined with safety conditions according to European Committee for Standardization 2004a (EC-4), Genetic Algorithm (GA), and Monte Carlo simulations.

This study proposes an optimization algorithm for reliability-based design of SCC beams. The developed algorithm combines Monte Carlo simulation and GA. Random values of the input parameters are considered in the proposed procedure and various safety conditions according to the EC-4 are investigated. Finally, numerical validation has been performed with 5 case studies.

II. MATERIALS AND METHODS

A. *Safety Conditions of Steel-Reinforced Concrete Composite Beams*

The steel-reinforced concrete composite beams in this study were designed according to EC-4 [2]. The safe conditions of composites steel-reinforced concrete that must be satisfied are: (i) Ultimate limit state and (ii) serviceability limit state. The destructive structure of composite steel-reinforced concrete beams has three cases, as shown in Figure 1. The safe conditions can be rewritten as in (1):

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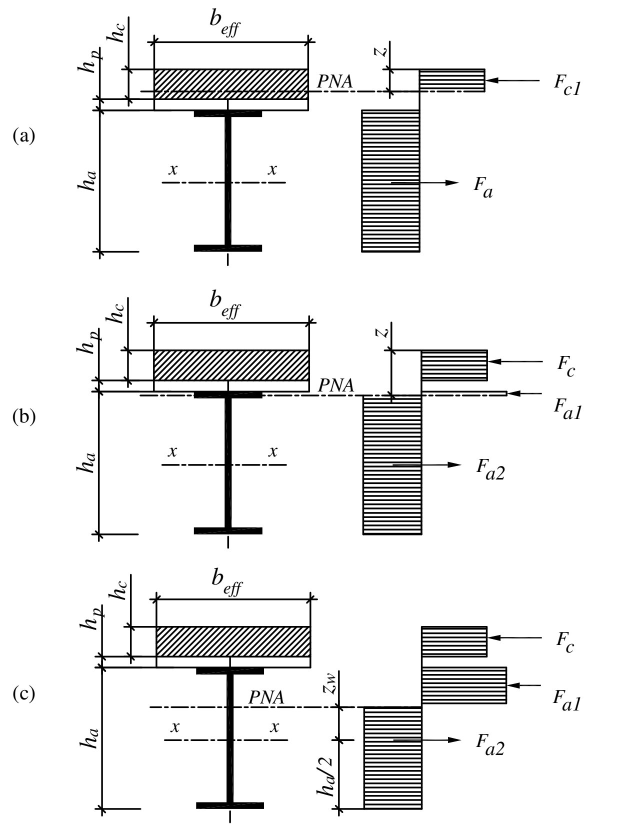

Fig. 1. Plastic design of steel-reinforced concrete beams: (a) when the PNA lies in concrete slab, (b) when the PNA lies in steel flange, (c) when the PNA lies in steel web.

$$M_{saf} = \begin{cases} \dfrac{\tau_{Ed} \cdot \gamma_{M0}}{f_y / \sqrt{3}} \le 1.0; & (\text{Ultimate limit state}) \\ \dfrac{M_{pl,Rd}}{M_{Ed}} \le 1.0 & (\text{Ultimate limit state}) \\ \dfrac{w}{w_{\lim}} \le 1.0 & (\text{Serviceability limit state}) \end{cases} \quad (1)$$

where M_{saf} represents the safe conditions based on EC-4.

B. Structural Reliability

The probability of failure of a structure for random strength (R) and random load (Q) is calculated according to [18]:

$$P_f = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(r,q) f_R(r) f_Q(q) \, dr dq \quad (2)$$

where f_R represents the load probability density functions, f_Q the strength probability density functions, and $I(r,q)$ is a function indicator and defined by:

$$I(r,q) = \begin{cases} 0 & \text{failure condition} \\ 1 & \text{safety condition} \end{cases} \quad (3)$$

Equation (3) cannot be solved in a closed form but is instead estimated using analytical or numerical techniques. Determining the reliability of the structure has been covered in detail in [18], where the reliability structure has been proposed through the first-order reliability index with the assumption that R and Q have independent normal distributions.

$$\beta_1 = \ln \frac{\left(R_m / Q \right)}{\sqrt{COV_R^2 - COV_Q^2}} \quad (4)$$

where R_m is the mean of "true" resistance and R_n the nominal resistance as determined by a specification procedure.

Monte Carlo simulation [18] has been proposed to estimate the probability of failure and avoid the limitations of the first-order reliability index method. The general expression (1) can be rewritten as follows:

$$P_f = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{I(x,y) f_R(x) f_Q(y)}{k_{XY}(x,y)} k_{XY}(x,y) \, dx dy \quad (5)$$

where $k_{XY}(x,y)$ is importance sampling density. This integral can be estimated by the sum of the discrete values as follows:

$$\widehat{P}_f = \frac{1}{N} \sum_{i=1}^{N} \frac{I(x_i, y_i) f_Q(y_i)}{f_{Q*}(y_i)} \quad (6)$$

The variance of the sampled estimated significance is given by:

$$Var\left(\widehat{P}_f\right) = \frac{1}{N-1} \left\{ \frac{1}{N} \sum_{i=1}^{N} \left[\frac{I(x_i, y_i) f_Q(y_i)}{f_{Q*}(y_i)} \right]^2 - \widehat{P}_f^2 \right\} \quad (7)$$

C. Genetic Algorithm

GA is based on Darwinian evolution theory. The aim of GAs is to search for an optimized solution to a technical problem. GA basics can be found in [19-21]. The main structure of GA is a 5-step process:

Step 1. Randomize the first generation.

Step 2. Evaluate the fitness of each individual.

Step 3. Compute the probability distribution.

Step 4. Create the next generation via crossover and mutation.

Step 5. Repeat steps 2 to 5 for the desired number of generations.

D. Deterministic Model and Stochastic Model

The deterministic model is a composite steel-reinforced concrete beam design problem according to EC-4. The input parameters used include geometrical properties (L, b, IPE), material properties (f_{kc}, f_u), and total active load (g). The input parameters can be written as $\boldsymbol{X} = [L, b, IPE, f_{kc}, f_u, g]$. The deterministic model has the following form:

$$M_{saf} = \Im(\boldsymbol{X}) \quad (8)$$

The stochastic model was built based on the deterministic model, in which some input parameters are randomized. In this study, two input vectors have been used. The first vector consists of a deterministic inputs group $\boldsymbol{X_1} = [L, b, IPE]$ and the second vector consists of a stochastic inputs group $\boldsymbol{X_2}(\omega) = [f_{kc}(\omega), f_u(\omega), g(\omega)]$, where ω characterizes the random value. The stochastic model has the form of:

$$M_{saf} = \Im(\boldsymbol{X_1}, \boldsymbol{X_2}(\omega)) \quad (9)$$

III. RELIABILITY-BASED DESIGN OPTIMIZATION OF THE STEEL-CONCRETE COMPOSITE BEAMS

A. Schematic Diagram Algorithm

In this study, reliability-based design optimization of SCC beams has been built based on the stochastic model, Monte Carlo simulation, and GA. The algorithm consists of the following steps:

Step 1. Prepare the input data (geometrical properties, material properties, and total active load)

Step 2. Design and safety testing for cross-section of SCC according to EC-4 with deterministic input parameters.

Step 3. Randomize input parameters and build the stochastic model based on the deterministic model.

Step 4. Reliability assessment based on the stochastic model and Monte Carlo simulation.

Step 5. Reliability-based design optimization of steel-concrete composite beams.

- Constraint conditions: The safety probability structure.
- Objective function: Minimum weight of steel beam.

Step 6. Reliability-based design optimization using GA.

The process diagram of the reliability-based design optimization of the SCC beams using GA and Monte Carlo simulation is shown in Figure 2. From the process diagram, a program has been built on MATLAB.

B. Optimization Analysis of Steel-Concrete Composite Beams

In this section, we apply reliability-based design optimization of SCC beams using GA and Monte Carlo simulation, considering the SCC beam example in [22] as shown in Figure 3. The deterministic and random input parameters are shown in Table I. The distribution of material properties are based on [23] and the cross-section and loading are adopted from [24]. The upper and lower bounds of the cross-section of the steel beam are shown in Table II. The safety probability constraint conditions of steel-concrete composite beams are P_s = 98% and the objective function of steel beams is minimum weight. Optimization analysis results of the steel beams through 5 case studies are shown in Table III, which shows that with deterministic input parameters and safety conditions according to EC-4 [22], the obtained cross-section design of the steel beams is IPE 400. Meanwhile, when the reliability-based design optimization was applied to the SCC beams using GA and Monte Carlo simulations with safety probability constraint conditions P_s = 98%, the obtained optimal design of the cross-section of the steel beams is IPE 300. This proves that reliability-based design optimization of the SCC beams using GA and Monte Carlo simulation has great economic and technical advantages.

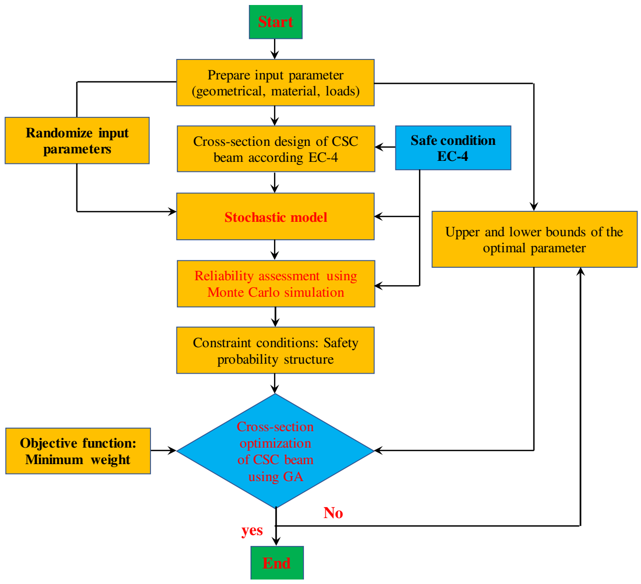

Fig. 2. The schematic diagram of reliability-based design optimization of SCC beams.

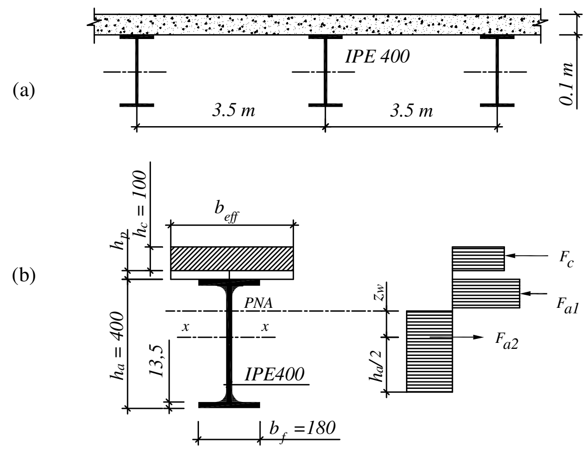

Fig. 3. (a) Cross-section of slabs and (b) stress distribution of the cross-section.

TABLE I. STATISTICAL PROPERTIES OF RANDOM VARIABLES FOR RELIABILITY ASSESSMENT OF SCC BEAMS

Properties	Variables	Nominal	Mean/ nominal	COV	Distribution	Ref.
Material (N/mm^2)	f_{ck}	25.0	1.10	0.06	Lognormal	[23]
	f_u	450	1.10	0.06	Lognormal	[23]
Loading (kN/m)	g_k	9.54	1.05	0.10	Normal	[24]
	q_k	13.69	1.05	0.10	Normal	[24]
Cross-section IPE 400 (mm)	b_f	180.00	1.00	0.05	Normal	[24]
	t_f	13.50	1.00	0.05	Normal	[24]
	h_a	400	1.00	0.05	Normal	[24]
	t_w	8.60	1.00	0.05	Normal	[24]
	r	21.0	1.00	0.05	Normal	[24]

* Load combinations of the overall dead load (g_k) and the service load on the floor (q_k))

TABLE II. UPPER AND LOWER BOUNDS OF THE CROSS-SECTION OF BEAM STEEL

No.	h_a (mm)	b_f (mm)	t_w (mm)	t_w (mm)	Weight (kg/m)	Area (cm²)
IPE 300	300	150	7.1	10.7	15	42.2
IPE 330	330	160	7.5	11.5	18	49.1
IPE 360	360	170	8.0	12.7	18	57.1
IPE 400	400	180	8.6	13.5	21	66.3
IPE 450	450	190	9.4	14.6	21	77.6
IPE 500	500	200	10.2	16.0	21	90.7
IPE 550	550	210	11.1	17.2	24	106
IPE 600	600	220	12.0	19.0	24	122

TABLE III. OPTIMIZATION ANALYSIS RESULTS THROUGH 5 CASE STUDIES

Case study	Minimum weight of SCC beams (kg/m)	Cross-section of optimization	Results in [22]
1	17.60	IPE 300	IPE 400
2	18.01	IPE 300	IPE 400
3	17.50	IPE 300	IPE 400
4	16.90	IPE 300	IPE 400
5	17.56	IPE 300	IPE 400

IV. CONCLUSIONS

This study proposes an optimization algorithm for reliability-based design of steel-concrete composite beams. The developed algorithm combined Monte Carlo simulations and Generic Algorithm. Random variables for input design parameters are considered in the proposed procedure. Additionally, the safety conditions according to EC-4 are investigated. Finally, a numerical validation has been performed with 5 case studies. The main points of the current paper are:

- A reliability-based design optimization algorithm of steel-concrete composite beams was developed.
- The proposed optimization procedure was successfully built on MATLAB platform and it can be convenient for design practices.
- A numerical validation has been performed with 5 case studies. The result shows that with safety probability constraint conditions of $P_s = 98\%$, the SCC beam can reduce the cross-section from IPE 400 to IPE 300.

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