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Evaluation of Remaining Bending Resistance of Steel Column Base Plates Considering Effects of Metal Corrosion

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Abstract
Steel structures exposed to marine environments are vulnerable to corrosion, significantly deteriorating the structural capacity. Specifically, column base plates are crucial components in many steel structures, which are susceptible to corrosion-induced reduction in bending resistance. This study aims to evaluate the remaining bending resistance of steel column base plates considering the effects of metal corrosion. Three environmental conditions, which are rural, urban, and marine areas, were considered in the evaluation. Two proposed procedures were employed, in which the deterministic and random approaches were considered. The deterministic approach used the component method in EN 1993-1-8 to design the bending resistance of corroded steel column base plates. Meanwhile, the corroded steel structure's reliability was evaluated using the hybrid Artificial Neural Network-Monte Carlo Simulation (ANN-MCS) method. The reliability of the steel column base plate up to 100-year life-service was evaluated. Moreover, Sobol's indices were employed to calculate the sensitivity of the input variables. The results revealed that the structural capacity of the steel base plate was reduced by approximately 50% after 100 years in a strongly corrosive environment. The probability of safety of the steel base plate decreased significantly from the rural and urban areas to marine environments.

Keywords Remaining bending resistance · Steel column base plate · Metal corrosion · Marine environment · EN 1993-1-8

1 Introduction

Steel column base plates in marine environments face unique challenges due to exposure to corrosive medium like salt water, moisture, and atmospheric pollutants. Marine environments are highly corrosive due to saltwater and salt-laden air. Corrosion can weaken steel column base plates over time, compromising their structural integrity.

Steel column bases include components: (1) stiffened/unstiffened steel column, (2) steel base plates welded to the column, (3) grout layer, (4) anchor bolts, and (5) concrete foundation. Normally, the steel columns are made by HEA, HEP or IPE profiles. It should be be noted that HEA is the H-shaped cross-sectional European wide flange A profiles, which are lightweight, and have a wide flange and a relatively short height. HEB is the H-shaped cross-sectional European wide flange B profiles, which have a wider flange and taller height than HEA beams. Meanwhile, IPE is the I-shaped Profile European beams, which have the same thickness and width at both flanges. The design of steel column base plates has been specified in design standards such as EN 1993-1-8 and AISC (CEN 2005; Fisher & Kloiber, 2006). However, the design of steel column base plates is also a topic that many scientists are interested in, especially modeling and testing to evaluate the reliability and reducibility. The synthesis of design, testing, and analysis on steel column base plate connections in high-seismic zones was conducted by

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Grauvilardell et al. (2005). The reliability analysis of steel column base plates designed following BS 5950 was carried out using the First Order Reliability Method (FORM) (Idris & Umar, 2007). Column demands in steel plate shear walls with regular perforations using performance-based design methods were proposed by Moghimi and Driver (2014). The influence of base-plate connection stiffness on the design of low-rise metal buildings was investigated (Kavoura et al., 2015). However, the effects of metal corrosion on the load-bearing capacity of the base plates have not been investigated so far. Therefore, the time-dependent capacity of the column base plates should be evaluated.

Corrosion is a complicated phenomenon that has been conventionally studied through experiments and simulations. Numerous studies were implemented to understand the effects of corrosion on the responses of steel structures. Saad-Eldeen et al. (2013) conducted a series of experiments and numerical simulations to investigate the ultimate strength of steel box girders, considering the effects of severe corrosion. The influences of corrosion on the structural behavior of painted steel members were extensively conducted (Dao et al., 2018; Kim et al., 2017, 2018, 2021). Zhang et al. (2020) also carried out experimental and numerical studies to quantify the structural behaviors of corroded steel columns under compression and bending. Recently, the impact of corrosion on seismic performances H-shaped steel columns (Xu et al., 2019) and steel beam-column connections (Zhang et al., 2024) were explored. Since experimental studies require a long-term measurement and expensive cost, numerical approach is a preferred method.

A corrosion model, which is normally expressed in terms of mathematical formulations, is selected to perform numerical simulations. Komp (1987) proposed a typical corrosion model that considers different types of environments, including marine, urban, and rural areas. This proposed model has been applied in numerous studies (Landolfo et al., 2010; Nguyen & Nguyen, 2022; Nguyen et al., 2022, 2023; Secer & Uzun, 2017; Tran & Nguyen, 2020; Tran et al., 2021, 2022). However, applying a corrosion model for evaluating corroded steel column base plates has not been performed yet.

This study aims to evaluate the remaining bending resistance of steel column base plates considering the effects of metal corrosion. Three environmental conditions, which are rural, urban, and marine areas, were considered in the evaluation. Two methods were used, the deterministic and random approaches were evaluated. The deterministic approach used the component method in EN 1993-1-8 (2005) to design the bending resistance of steel column bases. Meanwhile, the reliability evaluation of the corroded steel structure was conducted using the hybrid artificial neural network- Monte Carlo simulation (ANN-MCS) method. Specifically, the reliability of the steel column base plate up to 100-year life-service was evaluated. Sobol's indices were employed to calculate the sensitivity of the input variables.

2 Theoretical Background

2.1 Bending Resistance of Steel Column Base Plates

Steel column bases serve as the interface between the column and the foundation, distributing the load from the column to the foundation structure. Steel column bases include components: (1) stiffened/unstiffened steel column (HEA, HEB, IPE steel profiles), (2) steel base plate welded to the column, (3) grout layer, (4) anchor bolts, (5) concrete foundation. Fig. 1 shows the details of steel column bases.

According to EN 1993-1-8 (2005), the design of bending resistance of steel column bases using the component method, the component method can be summarized in the following steps.

- Step 1. Determination of the basic components.
- Step 2. Characterization of resistance and stiffness.
- Step 3. Assembly of the individual component properties to obtain the overall properties of the connection.
- Step 4. Classification of the connection in terms of resistance and stiffness.

Modeling typical individual components of steel column bases has been proposed by Wald (2008), which is divided into load-bearing components. Detailed components include: (1) anchor bolt, key in shear, (2) column web and flange in shear and compression, (3) base plates in bending and anchor bolts in tension, and (4) base plate and concrete block in compression.

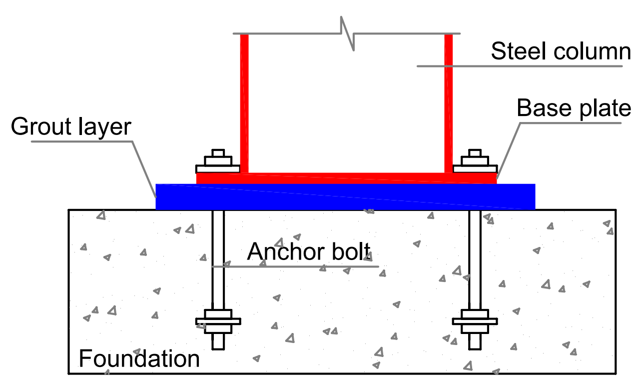


Fig. 1 Details of steel column bases

2.2 Modelling of Bending Resistance

The steel column bases are subjected to a bending moment, a part base plates are under tension; thus, the anchor bolts are the only elements capable of working in tension. Therefore, the failure modes for the tensile part are the yielding of the base plates, the rupture of the anchor bolts, or both failure modes simultaneously. According to EN 1993-1-8 (2005), an alternative computational model called T-stub with a width equal to the effective length $\left(l_{eff}\right)$ has been proposed to calculate the bending resistance of the base plates and rupture of the anchor bolts. T-stub nomenclature is shown in Fig. 2.

According to EN 1993-1-8 (CEN 2005), the bending resistance value depends on the failure modes of the T-stub. Three modes of failure mechanisms are considered as follows.

- *Mode 1*. The base plate is flexible, and the anchor bolts show high resistance.

$$F_{T,1,Rd} = \frac{4M_{pl,1,Rd}}{m} \text{ for prying forces Q } \left(L_b \le L_b^*\right) \tag{1}$$

or

$$F_{T,1,Rd} = \frac{\left(8n - e_w\right)M_{pl,1,Rd}}{2mn - e_w(m+n)} \text{ for prying forces Q } \left(L_b \le L_b^*\right) \tag{2}$$

$$F_{T,1-2,Rd} = \frac{2M_{pl,1,Rd}}{m} \text{for no prying forces Q} \tag{3}$$

- *Mode 2*. A combination of anchor bolt failure and base plate yielding in the presence of prying forces.

$$F_{T,1,Rd} = \frac{2M_{pl,2,Rd} + n\sum F_{t,Rd}}{(m+n)} \text{for prying forces Q } \left(L_b \le L_b^*\right) \tag{4}$$

$$F_{T,1-2,Rd} = \frac{2M_{pl,1,Rd}}{m} \text{for no prying forces Q} \tag{5}$$

- *Mode 3*. Thick base plates and low anchor bolt resistances.

$$F_{T,3,Rd} = \sum F_{t,Rd} \tag{6}$$

A calculation procedure of the design resistances according to failure modes has been provided by EN 1993-1-8 (2005). From EN 1993-1-8, Table 1 summarizes the calculation of bending resistances for the available cases in Fig. 3. The design process of the moment resistance of steel column base plates according to EN 1993-1-8 is developed using MATLAB.

2.3 Metal Corrosion Model

Metal atmospheric corrosion is a process where metal surfaces deteriorate due to exposure to the environmental condition. In this study, we adopt the atmospheric corrosion model suggested by Komp (1987). This proposed model has been used in many previous studies on metal corrosion with reliable results (Landolfo et al., 2010; Nguyen & Nguyen, 2022; Nguyen et al., 2022; Secer & Uzun, 2017; Tran & Nguyen, 2020). Corrosion models usually describe the corrosion depth as a function of time in the form of a power model. The mathematical expression and diagram of time-dependent corrosion depth are shown in Eq. (7) and Fig. (4), respectively.

$$d(t) = a \cdot t^b \tag{7}$$

where $d(t)$ is the time-dependent corrosion depth (μm); t is the metal corrosion time; a and b are the corrosion coefficients which depend on the environments.

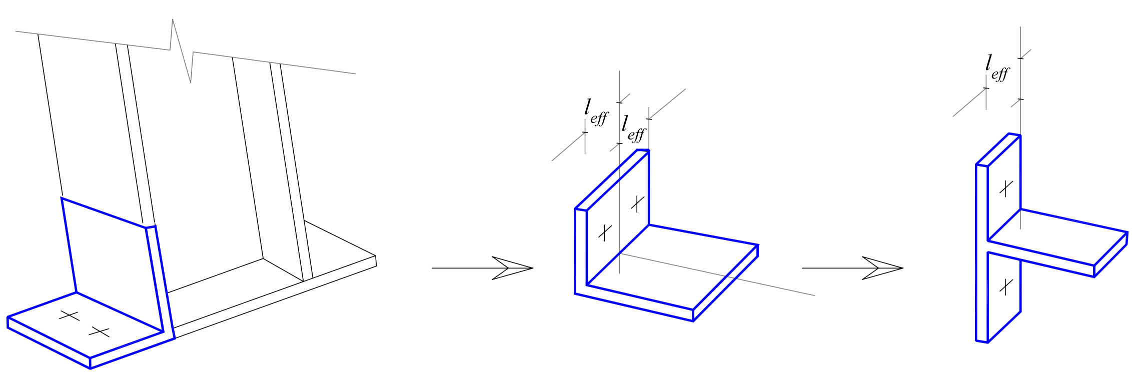


Fig. 2 T-stub nomenclature

Table 1 Design bending resistance of a column plate

Loading	Lever arm, z	Design moment resistance, $M_{j,Rd}$	
Left side in tension and right side in compression	$z = z_{T,1} + z_{C,r}$	$N_{Ed} > 0$ and $e > z_{T,1}$ $\min\begin{cases} \frac{F_{T,1,Rd} z}{\frac{z_{C,r}}{e}+1} \\ \frac{-F_{C,Rd} z}{\frac{z_{T,1}}{e}-1} \end{cases}$	$N_{Ed} \le 0$ and $e > -z_{C,r}$
Left and right side in tension	$z = z_{T,1} + z_{T,r}$	$N_{Ed} > 0$ and $0 < e < z_{T,1}$ $\min\begin{cases} \frac{F_{T,1,Rd} z}{\frac{z_{T,r}}{e}+1} \\ \frac{F_{T,r,Rd} z}{\frac{z_{T,1}}{e}-1} \end{cases}$	$N_{Ed} > 0$ and - $z_{T,1} < e \le 0$ $\min\begin{cases} \frac{F_{T,1,Rd} z}{\frac{z_{T,r}}{e}+1} \\ \frac{F_{T,r,Rd} z}{\frac{z_{T,1}}{e}-1} \end{cases}$
Left side in compression and right side in tension	$z = z_{C,1} + z_{T,r}$	$N_{Ed} > 0$ and $e < -z_{T,r}$ $\min\begin{cases} \frac{-F_{C,1,Rd} z}{\frac{z_{T,r}}{e}+1} \\ \frac{F_{T,r,Rd} z}{\frac{z_{C,1}}{e}-1} \end{cases}$	$N_{Ed} \le 0$ and $e > z_{C,1}$
Left and right side in compression	$z = z_{C,1} + z_{C,r}$	$N_{Ed} \le 0$ and $0 < e < z_{C,1}$ $\min\begin{cases} \frac{-F_{C,1,Rd} z}{\frac{z_{C,r}}{e}+1} \\ \frac{-F_{C,r,Rd} z}{\frac{z_{C,1}}{e}-1} \end{cases}$	$N_{Ed} > 0$ and - $z_{C,r} < e \le 0$ $\min\begin{cases} \frac{-F_{C,1,Rd} z}{\frac{z_{C,r}}{e}+1} \\ \frac{-F_{C,r,Rd} z}{\frac{z_{C,1}}{e}-1} \end{cases}$

$M_{Ed} > 0$ is clockwise and, $N_{Ed} > 0$ is tension

$e = \frac{M_{Ed}}{N_{Ed}} = \frac{M_{Rd}}{N_{Rd}}$

Prying forces Q: $F_{T,Rd} = \min\left(F_{T,1,Rd}; F_{T,2,Rd}; F_{T,3,Rd}\right)$

No prying forces Q: $F_{T,Rd} = \min\left(F_{T,1-2,Rd}; F_{T,3,Rd}\right)$

and $F_{C,Rd} = \min\left(F_{c,Rd}; F_{c,fc,Rd}\right)$

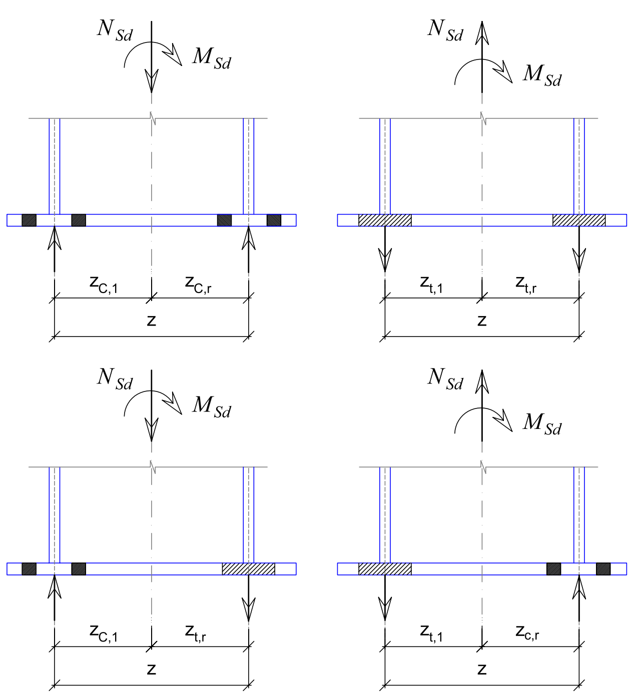


Fig. 3 Determination of the lever arm z for column base plates

3 Deterministic Evaluation

3.1 Validation of Computer Program

In this section, we develop a computer program to design the bending resistance of column base plates according to EN 1993-1-8 (EN, 1993-1-1 2005) based on MATLAB. To confirm that computer programs have been built to be reliable, the study verified the calculation results

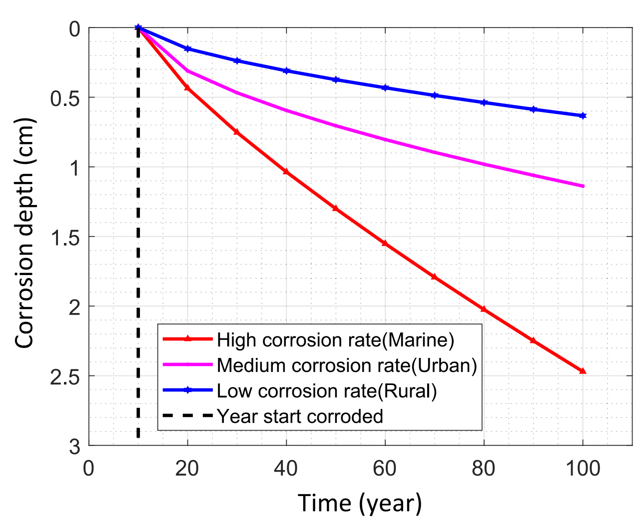


Fig. 4 The time-dependent corrosion depth in various environments

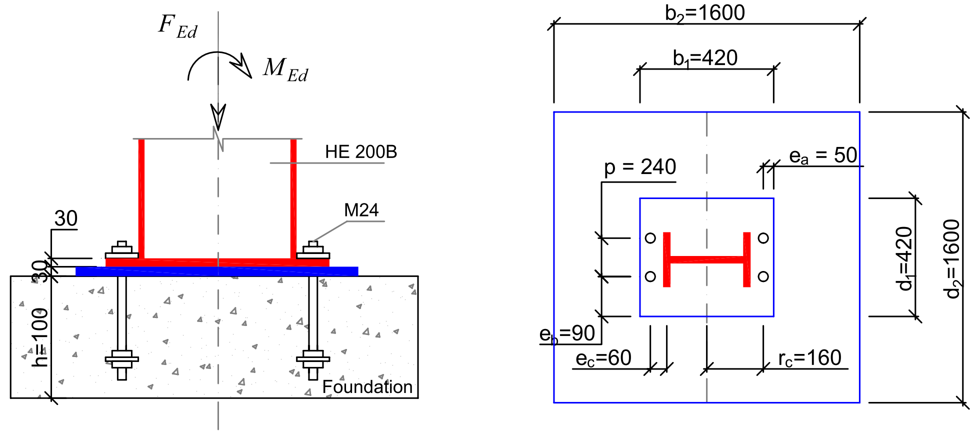


Fig. 5 The structural diagram and geometric parameters for validating example

Table 2 Input and output parameters of the validation model

Property	Symbol	Wald (2008)	This study	Error
Column	HE 200B	100.90	103.92	2.90%
Force	500 (kN)			
Concrete block	C16/20			
Steel	S235			
thickness	30 (mm)			

published by Wald (2008). The structural properties and geometric parameters of the validation study are shown in Fig. 5. Meanwhile, the materials parameters, cross-section parameters, and calculation results of the computer program are given in Table 2. It can be seen that the error of the computer program and the results of Wald (2008) is 2.90%. This error is small; thus, it can be concluded that the computer program ensures reliability in calculations of bending resistance of the base plate.

3.2 Procedure for Bending Resistance of Corroded Steel Column Base Plates

To assess the remaining bending resistance of corroded steel column base plates, this study uses the component method in EN 1993-1-8 to design the bending resistance of steel column base plates. Meanwhile, the metal corrosion model was adopted from the suggestion of Komp (1987). The assessment process of the remaining bending resistance of steel column base plates is performed according to the following steps. The calculated flowchart is shown in Fig. 6.

- Step 1. Prepare computational data and metal corrosion model.
- Step 2. Calculate the remaining thickness of the column base plate.
- Step 3. Calculate the resistance of the component base plate in bending and anchor bolts in tension.
- Step 4. Evaluate the compressed part resistance.
- Step 5. Calculate the width of the strip c around the column cross-section and the active effective width.
- Step 6. Calculate bending resistance under normal force and check the resistance of the column.

3.3 Numerical Application

The steel column base with the structural diagram and geometric parameters shown in Fig. 5 is employed for numerical investigations. The materials properties and cross-section parameters are given in Table 2. The study is done with the scenario that steel buildings have a lifespan of 100 years, and the column base starts to corrode from the 10th year. The reduction rate of bending resistance of the steel column base plates is shown in Fig. 7. It can be found that after 100 years, the remaining bending resistance of steel column base plates in rural areas is reduced to 90% compared to the design's original. Meanwhile, the steel structure located in the marine environment shows a significant reduction of the structural capacity, approximately 50%. This finding implies that the effects of metal corrosion should be considered in the design process for steel structures.

4 Reliability and Sensitivity Evaluation

In this study, we employ a hybrid model, which combines artificial neural network (ANN) and Monte Carlo simulations (MCS) to calculate the Sobol's sensitivity indices. A brief background of the model is presented as follows.

4.1 Artificial Neural Network (ANN)

An Artificial Neural Network (ANN) is a computational model inspired by biological neural networks in the human brain process information. It is composed of layers of interconnected neurons (i.e., nodes) that work together to solve

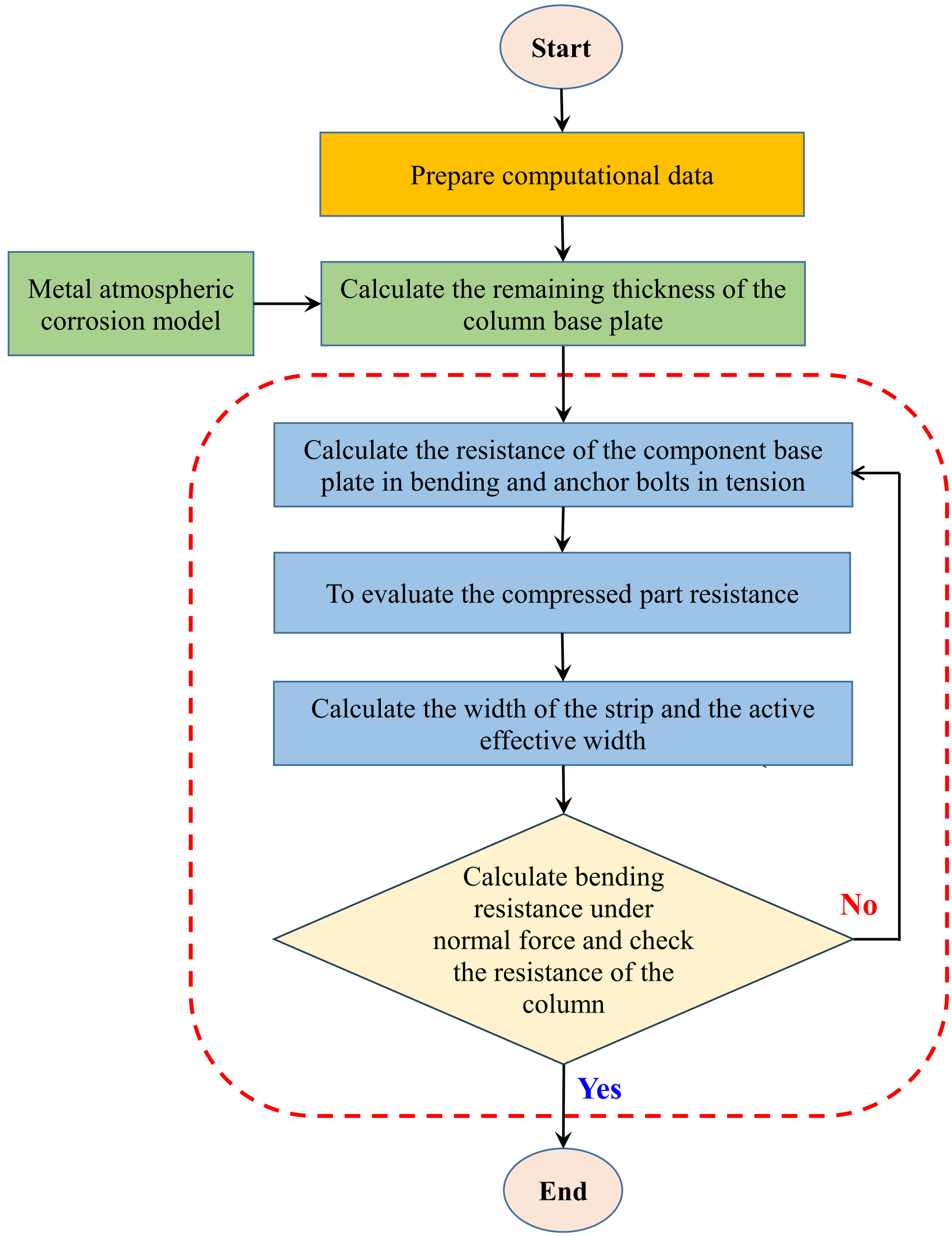


Fig. 6 Flowchart for calculating bending resistance of corroded steel column base plates

a specific task, such as classification and regression. The structure of ANN consists of an input layer, hidden layer(s), and output layer.

- The input layer is the first layer of ANN where the input data is fed into the network. Each neuron in the input layer represents one feature of the input data.
- ANN can have one or more hidden layers, which are intermediate layers between the input and output layers. Each neuron in the hidden layer is connected to neurons in the previous and next layers.
- The output layer is the final layer in the network, where the processed information is output.

Each neuron in an ANN takes input from multiple neurons in the previous layer or from the input data and applies a mathematical operation. Typically, the output of a neuron is a weighted sum of its inputs passed through an activation function. Each connection between neurons has an associated weight that determines the strength of the connection. Weights are adjusted during training using algorithms like gradient descent to minimize the error in predictions. Moreover, a bias term is added to the weighted sum of inputs before passing it through the activation function for making better predictions.

In ANN, forward propagation and backward propagation are the two primary steps for training a model. These

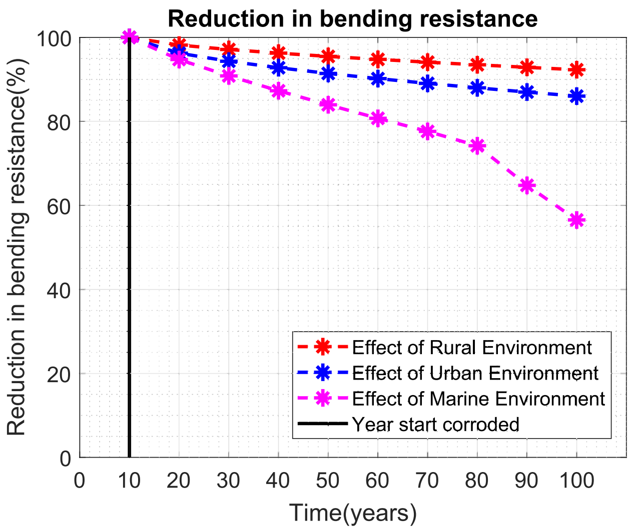


Fig. 7 Time-dependent bending resistance of column base plates in different environments

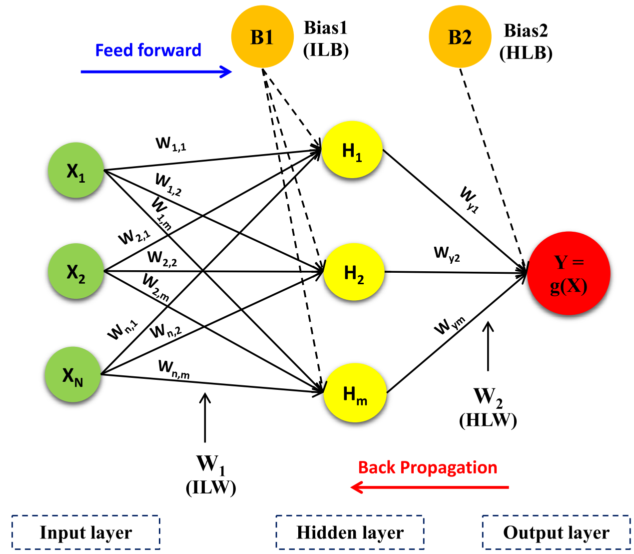


Fig. 8 ANN structure

processes involve the flow of information through the network and the adjustment of weights to minimize error. The forward propagation refers to the process of passing the input data through the network to obtain the predicted output. Meanwhile, the backward propagation is the process of adjusting the weights to minimize the error (i.e., loss). It uses the gradient descent algorithm to update the weights by calculating the gradient of the loss with respect to each weight.

Assuming that the output form is $g(X)$, where $X = \left(X_1, X_2, X_3, \ldots, X_N, \right)$ are input variables. ANN is trained to simulate the limit state function $g(X)$ based on the data sets.

$$\hat{g}(X) = ANN(X) \tag{8}$$

where $\hat{g}(X)$ is the predicted output of ANN, $\hat{g}(X)$ represents the probability of failure (or 1-$\hat{g}(X)$ is the reliability) of system based on the input $\overline{X}$. Figure 8 depicts the structure of the ANN model.

4.2 Monte Carlo Simulation (MCS)

Monte Carlo simulation (MCS) is a powerful computational technique, which is employed to understand the impact of uncertainty and variability in complex systems. It relies on repeated random sampling to obtain numerical results and make predictions. To perform MCS, typical steps are as follows:

- *Step 1. Define a model*: Start by creating a mathematical model of the system. This model includes input variables that have inherent uncertainty.
- *Step 2. Input distributions*: For each uncertain input, define a probability distribution. These distributions represent the range of values the inputs can take and their associated probabilities.
- *Step 3. Random sampling*: Use simple random sampling to generate many scenarios based on the defined probability distributions. This is typically implemented using a random number generator.
- *Step 4. Simulate*: For each trial/scenario, run the model with the sampled input values and record the output.
- *Step 5. Analyze results*: After running enough trials, analyze the collected results to determine the probability distributions of the output variables. This analysis often includes calculating means, variances, confidence intervals, and probabilities of different outcomes.

Monte Carlo simulations were performed based on the random variables X. The number of simulations N, we obtained the samples:

$$X^{(j)} = \left(X_1^{(j)}, X_2^{(j)}, X_3^{(j)}, \ldots X_N^{(j)}\right) \tag{9}$$

The output is calculated using ANN, as follows:

$$\hat{g}^{(j)} = ANN\left(X^{(j)}\right) \tag{10}$$

4.3 Sobol's Sensitivity Analysis

In this study, we employ Sobol's indices (Saltelli, 2008; Sobol, 2001) to perform the sensitivity analysis. Two indicators including the first-order and the total Sobol's indices, are calculated using MCSs, as follows.

- The first-order Sobol's index S_i: It is measured the direct effects of the variable X_i, calculated by:

$$S_i = \frac{Var\left(E\left[\hat{g}(X)|X_i\right]\right)}{Var\left(\hat{g}(X)\right)} \tag{11}$$

where $\left[\hat{g}(X)|X_i\right]$ is the expectation of the output when fixing X_i,

- The total Sobol's index S_{Ti}: It is measured the total effects of X_i including the direct effects and interactive effects between variables. S_{Ti} is expressed bywhere $X_{\sim i}$ are all parameters except X_i, and $\hat{g}(X)|X_{\sim i}$ is the expectation of output when fixing all variables except X_i.

$$S_{Ti} = 1 - \frac{Var\left(E\left[\hat{g}(X)|X_{\sim i}\right]\right)}{Var\left(\hat{g}(X)\right)} \tag{12}$$

4.4 ANN-MCS Model

To evaluate reliability of the structure and to calculate Sobol's indices, the following steps are implemented using the ANN-MCS technique. The flowchart of ANN-MCS is shown in Fig. 9.

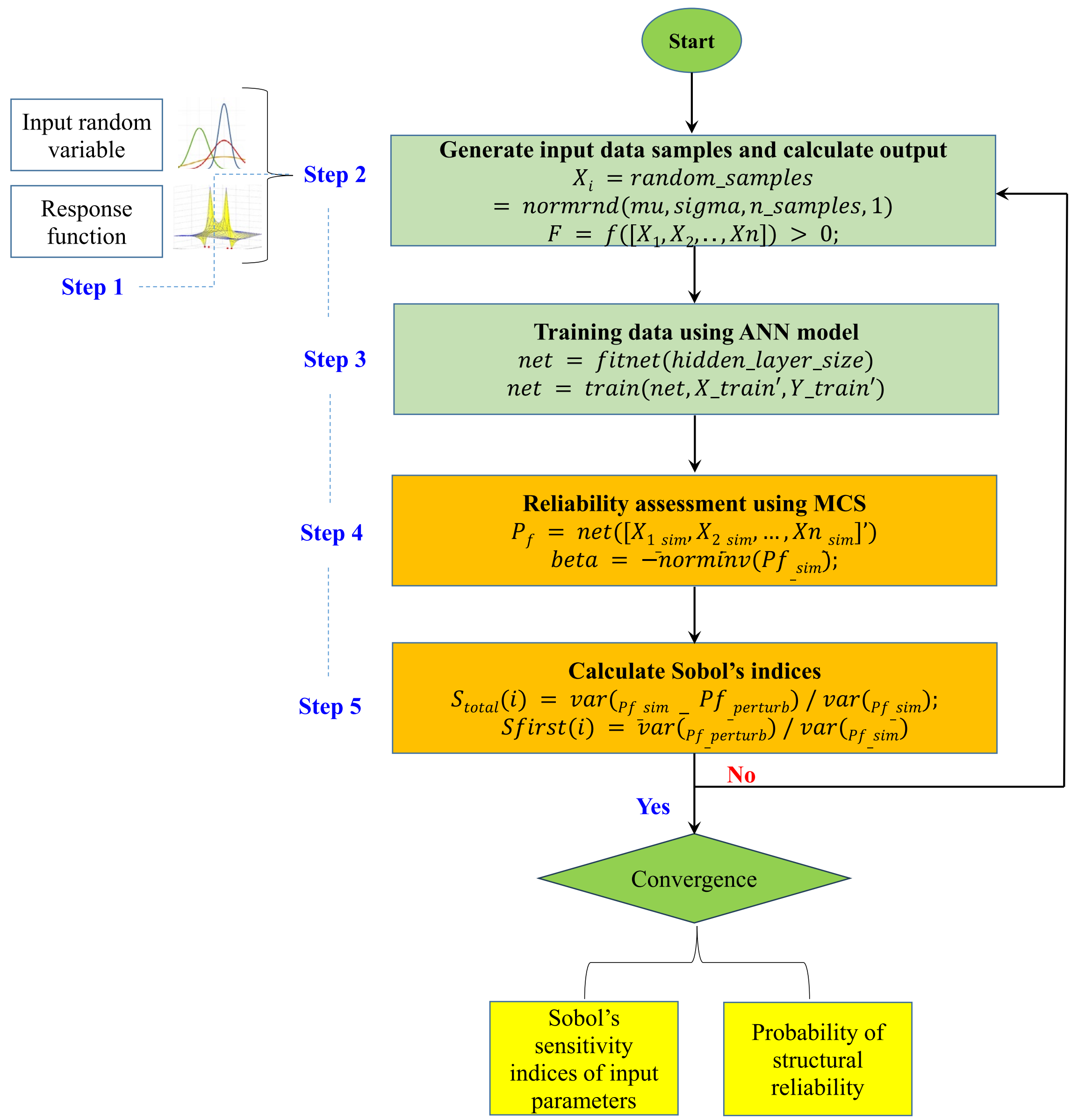


Fig. 9 Flowchart of reliability evaluation of column base plates

Table 3 Random input parameters and distributions

Properties	Variables	Nominal	Mean/Nominal	COV	Distribution	Ref
	$d(X1)$	24 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
Anchor bolt	$f_{ub}(X2)$	360.0 (MPa)	1.10	0.06	Lognormal	Ellingwood et al. (1982)
	A_s	335 $\left(mm^2\right)$	1.00	–	Deterministic	–
	γ_{mb}	1.25	1.00	–	Deterministic	–
	t_n	19.0 (mm)	1.00	–	Deterministic	–
Steel column	$h(X6)$	200 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
	$b_f(X3)$	200 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
	$t_f(X4)$	15.0 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
	$t_w(X5)$	9.0 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
Concrete foundation	$b_1(X7)$	420.0 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
	$b_2(X8)$	1600.0 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
	$d_1(X9)$	420.0 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
	$d_2(X10)$	1600.0 (mm)	1.00	0.05	Normal	Bartlett et al. (2003)
	$f_{ck}(X11)$	16.0 (MPa)	1.10	0.06	Lognormal	Ellingwood et al. (1982)
	γ_c	1.5	1.00	–	Deterministic	–
Steel base plate	$t_{bp}(X12)$	30.0 (mm)	1.00	0.06	Normal	Ellingwood et al. (1982)
	$f_y(X13)$	235 (MPa)	1.10	0.06	Lognormal	Ellingwood et al. (1982)
	$E_s(X14)$	21E4 (MPa)	1.10	0.06	Lognormal	Ellingwood et al. (1982)

- Step 1. Determine random variables and distributions.
- Step 2. Generate random samples for X using MCS.
- Step 3. Calculate output $\hat{g}(X)$ using ANN.
- Step 4. Evaluate reliability of the structure.
- Step 5. Use the output from ANN to determine Sobol's indices S_i and S_{Ti}.

4.5 Reliability and Sensitivity Results

The results of reliability and sensitivity analyses of steel column base plates are presented in this section. Three corrosion conditions, which are rural, urban, and marine environments are investigated. The structural reliability and sensitivity of input parameters on bending resistance of steel column base plates are evaluated until 100 years of life-service. Table 3 shows random input parameters, and their distributions used in this study. Based on these random variables, a set of 100,000 data samples is generated using MCS to train ANN models. The structural reliability and sensitivity analysis results are shown for different cases: without corrosion, with corrosion after 100 years in rural, urban and marine environments.

To evaluate the reliability of the steel base plates in various scenarios, the hybrid ANN-MCS model is performed with 10,000 simulations. Figure 10 shows a convergence of ANN model during the training performance. It is found that a very small mean squared error (MSE) is reached at the 9th epoch. The probability of safety $\left(P_s\right)$ and reliability index (β) of the column base plates are obtained in Table 4. The probability of safety $\left(P_s\right)$ is reduced from the case of

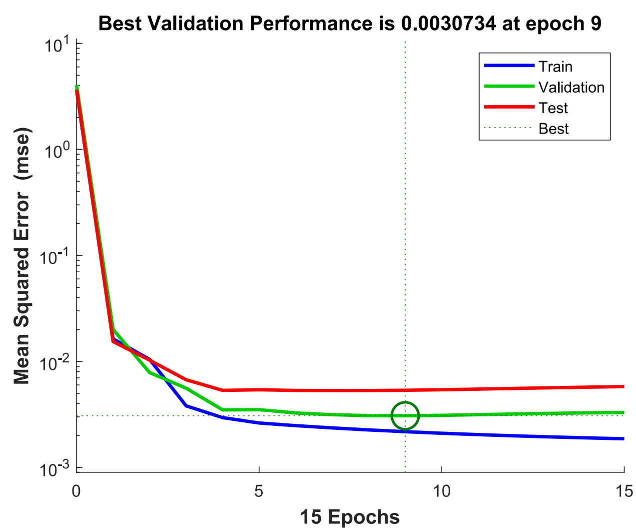


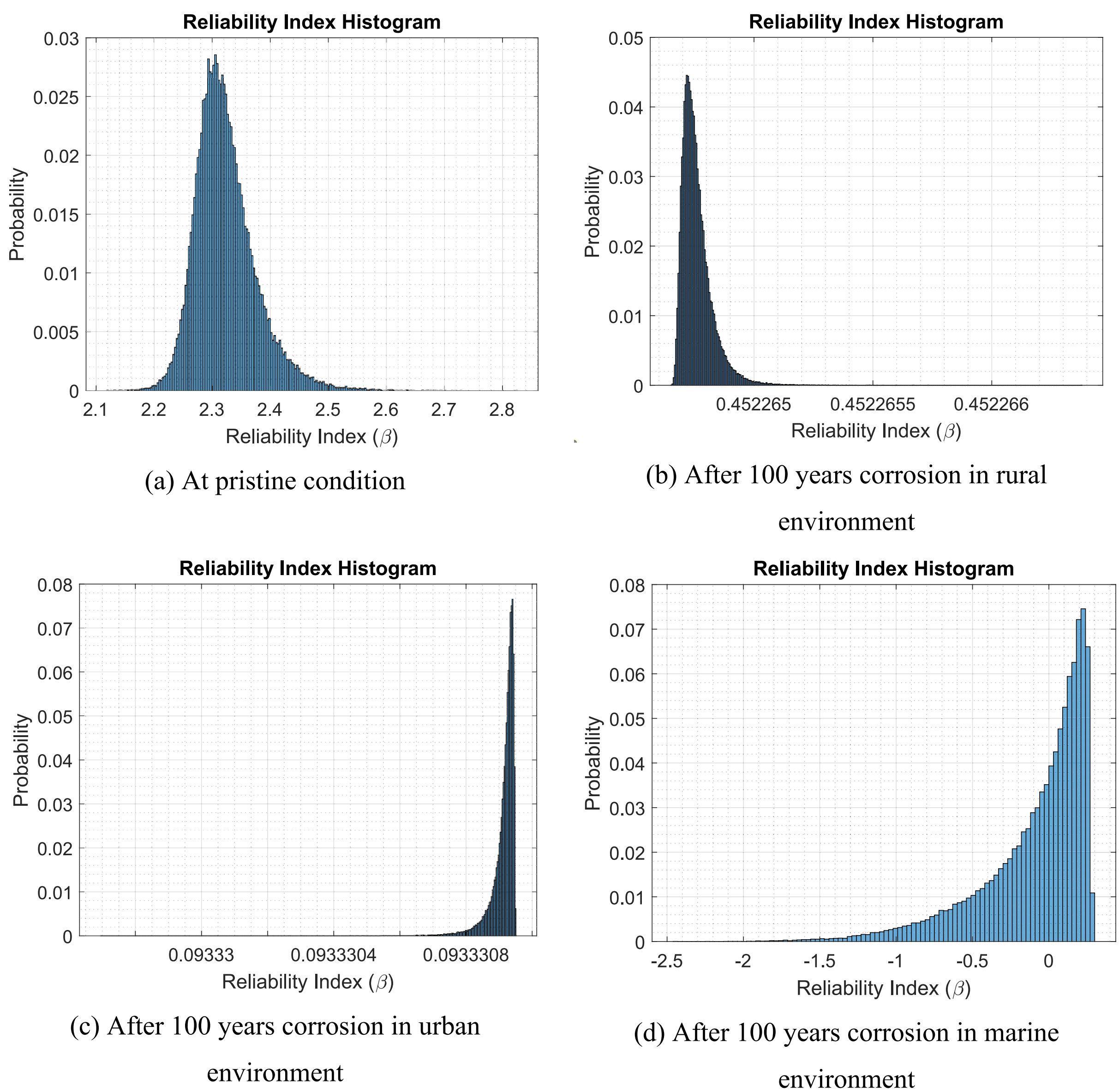
Fig. 10 Illustration of the best performance of ANN

Table 4 Probability safety and reliability index of steel column base plate in various conditions

Environment condition	Probability of safety $\left(P_s\right)$	Reliability index (β)
Without corrosion	98.99%	2.4709
After 100 years in rural area	67.45%	0.4523
After 100 years in urban area	53.80%	0.0933
After 100 years in marine area	46.90%	−0.8747

without corrosion (98.99%) to the case of after 100 years in rural environments (67.45%), and the smallest probability of safety (46.90%) is for the structure after 100 years in marine environments. Similarly, the reliability index (β), which measures the margin to the failure region, tends to significantly decrease from 2.4709 (at the pristine condition) to 0.0933 for urban and -0.8747 for marine environments, as shown in Fig. 11. It highlights that the steel structure is seriously affected by the corrosion in the marine environment.

Fig. 12 shows the sensitivity of input design parameters to the remaining bending resistance of the corroded steel column base plates. The Sobol's indices, presented in Sect. 4.3, are employed to evaluate the sensitivity. It can be observed that the effects of input parameters are mostly equal, contributing from 6 to 8%, in terms of the first-order Sobol's indices for all investigated cases. Meanwhile, the sensitivity has changed significantly in the total Sobol's indices. For the case of without corrosion (i.e., pristine condition), the base plate dimensions (b_1 and d_1) are the most influential variables to the structural reliability, followed by the foundation block dimension (d_2) and the width of the column flange (b_f). After 100 years in rural and urban environments, the steel column plate is significantly affected by the strength of anchor bolts (f_{ub}). For the steel structure in marine environments after 100 years, the structural reliability is affected by the dimensions and strength of the base plate (d_1 and f_y), the dimensions of the concrete block (d_2), and the dimensions of the steel column (t_f, t_w and b_f). It is



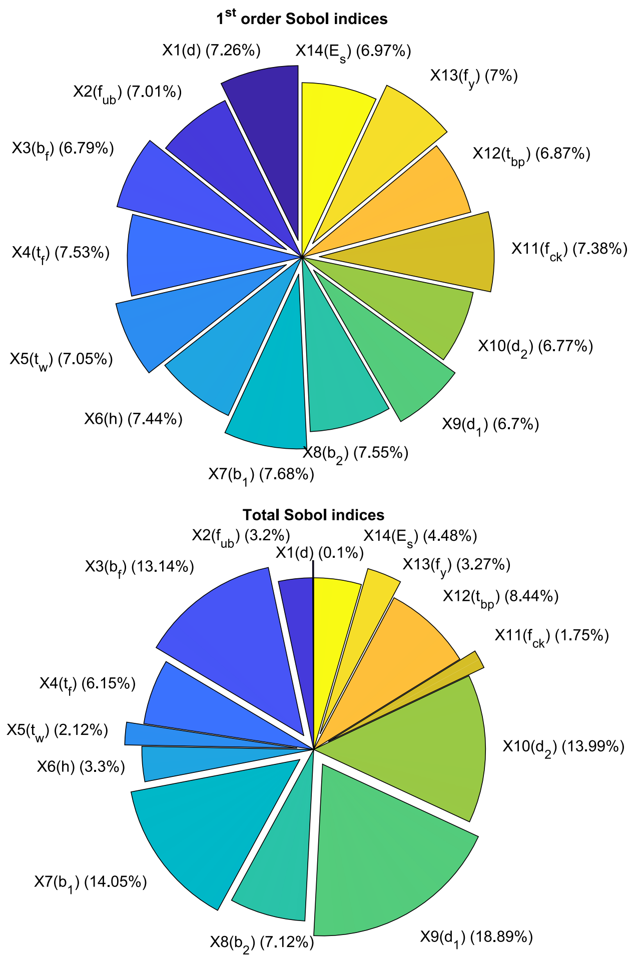
(a) At pristine condition

(b) After 100 years corrosion in rural environment

(c) After 100 years corrosion in urban environment

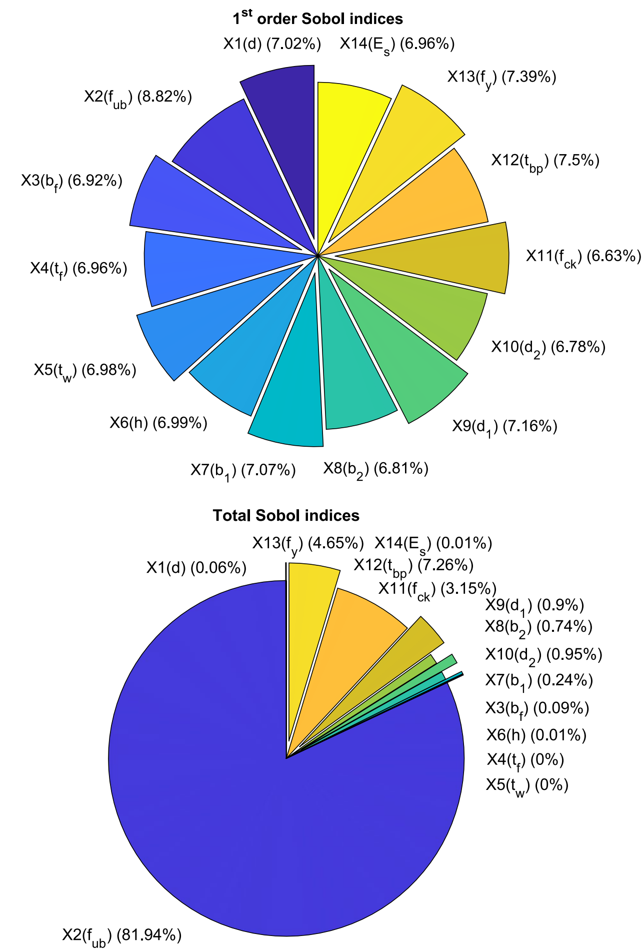
(d) After 100 years corrosion in marine environment

Fig. 11 Histograms of reliability index in various scenarios



(a) without corrosion.

Fig. 12 Sensitivity Sobol's indices for bending resistance of column base plates in various conditions



(b) after 100 years in rural environments

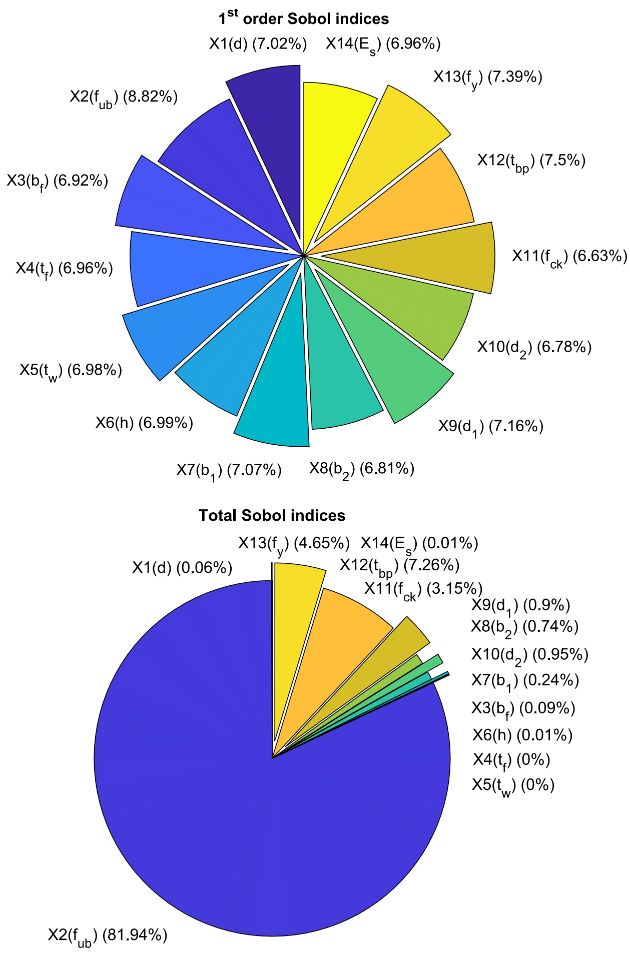
Fig. 12 (continued)

attributed to the reason that the first-order Sobol's index considers independently the effects of each variable, whereas the total-order Sobol's index considers the interaction between the variables. Additionally, the steel structure is corroded more seriously in the marine environments compared to that in the rural and urban environments.

5 Conclusions

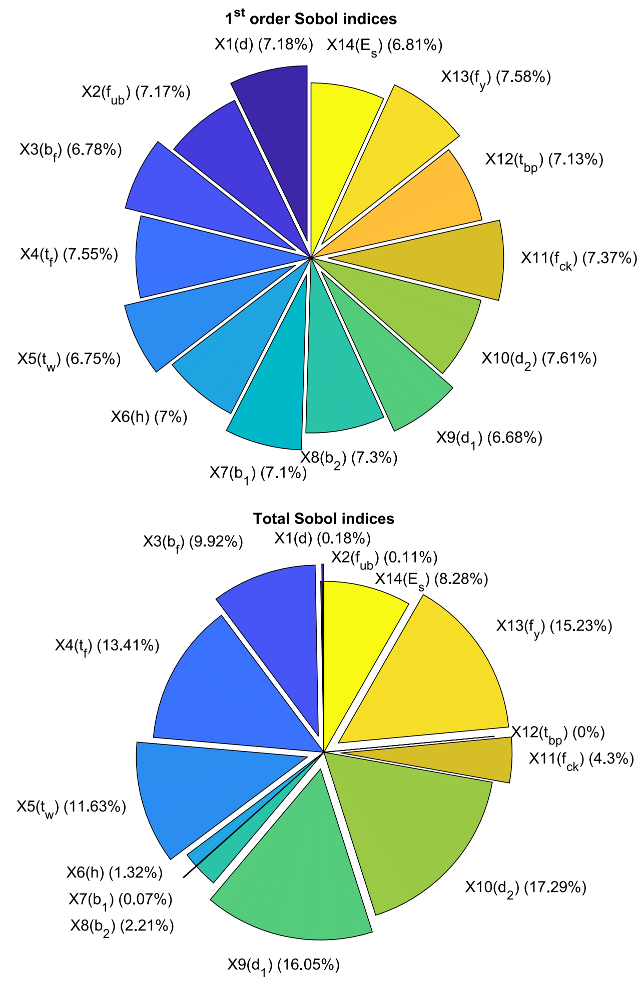
This study proposed an evaluation procedure to investigate the remaining bending resistance of corroded steel column base plates. Three environmental conditions, which are rural, urban, and marine areas, were considered in the evaluation. Two methods were used, in which the deterministic and random approaches were evaluated. The deterministic approach used the component method in EN 1993-1-8 to design the bending resistance of steel column base plates. Meanwhile, the reliability evaluation of the corroded steel structure was conducted using the hybrid artificial neural network- Monte Carlo simulation (ANN-MCS) method. Specifically, the reliability of the steel column base plate up to 100-year life-service was evaluated. Sobol's indices were employed to calculate the sensitivity of the input variables. The following conclusions are drawn.

(1) A procedure for calculating the bending resistance of corroded steel column base plates according to EN 1993-1-8 is proposed.
(2) A hybrid ANN-MCS algorithm is proposed for evaluating the structural reliability of corroded steel column base plates in different corrosion conditions.
(3) The probability of safety $\left(P_s\right)$ of the steel structure is reduced significantly from the pristine condition to the cases of rural, urban, and marine environments.
(4) The sensitivity of input parameters is mostly equal, contributing from 6 to 8%, in terms of the first-order



(c) after 100 years in urban environments

Fig. 12 (continued)



(d) after 100 years in marine environments

Fig. 12 (continued)

Sobol's indices for all environmental conditions. Meanwhile, the sensitivity has changed significantly in the total Sobol's indices. For the cases of pristine condition and marine environments, the dimensions of the base plate and steel column are the most influential variables to the structural reliability, followed by the foundation block dimensions. Moreover, the steel column plate is significantly affected by the strength of anchor bolts (f_{ub}) for rural and urban environments.

It should be noted that this study focused on the evaluation of structural capacity of corroded steel column base plates. The corrosion of other parts was not investigated. However, the material properties and dimensions of steel columns, anchor bolts, and concrete were also considered as random variables.

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Data Availability Data request is considered by the corresponding author.

Declarations

Conflicts of interest The authors declare that they have no conflicts of interest.

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