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Research Paper

A metal atmosphere corrosion in the industrial zones - Reliability and durability prediction models of steel structures

Ngoc-Long Tran [a]***, Van-Tien Phan*** [a]***, Trong-Ha Nguyen*** [a,*]

[a] *Department of Civil Engineering, Vinh University, Vinh 461010, Vietnam*

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Currently, the steel structure has been popularly used in industrial zones due to cost advantage and fast construction time. However, the industrial zone is an area with complex corrosive agents in the environment such as sulfur dioxides and chlorides. This paper presents a reliability prediction model considering atmosphere corrosion at the industrial zones. The prediction model is a combination of metal atmosphere corrosion (MAC), finite element method (FEM), and Monte Carlo (MC) simulation. Thereafter, that predictive model is applied for reliability and durability assessment of the steel structures due to atmosphere corrosion in the industrial zones until a life-service of 100 years. The result reveals that the safe probability of the steel structure is reduced to approximately 90 and 80% after 50 years and 100 years, respectively. It implies that the time-varying structural degradation at the design step should be considered.

1 Introduction

Impact assessment of corrosion on the structural mentioned in the design standards of some countries and EN ISO: 9223, these recommendations depend on each standard. The European structural design codes recommend for design structures [1, 2]. However, there is not a specific process with quantitative goals aimed at determining the reliability and durability of steel structures during exploitation.

The industrial zone is an area with complex corrosive agents in the atmosphere. There are many studies that investigated the effects of atmospheric corrosion on steel structures. Townsend [3] presented the effects of alloying elements on the corrosion of steel in industrial atmospheres. Meanwhile, Nguyen et al. [4] proposed an assessment of the effects of the climate change on atmospheric corrosion rates of steel structures, in which the effects of atmospheric corrosion due to changes in the

* *Corresponding author. Tel.: +084 942809698.*
E-mail address: trongha@vinhuni.edu.vn

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environmental temperature, carbon dioxide, relative humidity, wind, rainfall, and pollution were considered. A study on atmospheric corrosion of MnCuP weathering steel in a simulated coastal-industrial atmosphere was performed by L. Hao et al. [5].

Anti-corrosion techniques are interesting topics to worldwide researchers. Anti-corrosive properties and quantum chemical study was conducted by Elmsellem et al. [6]. They introduced the inhibitive action of the (E)-4-methoxy-N-(methoxy benzylidene) aniline (P1) and (E)-N-(4-methoxy benzylidene)-4-nitroaniline (P2) to the corrosion of steel in molar hydrochloric acid. Meanwhile, Douche et al. [7] investigated the anti-corrosion performance of 8-hydroxyquinoline derivatives for mild steel in acidic medium including gravimetric, electrochemical, DFT, and molecular dynamics simulation. A corrosion protection enhancement was proposed by Ziouche et al. [8] for aluminum and magnesium alloy using Mo-CeO2 conversion coating. A study of electrochemical and tribological behavior of surface-treated titanium alloy Ti–6Al–4V was performed by Attabi et al. [9]. In addition, a new and green synthetic anti-corrosive inhibitor for mild steel in 1.0 HCl using 2, 3-(2-alkylthio)-6, 7-bis (2-alkylthio) TTF was presented in the study of Jeroundi et al. [10]. Meanwhile, corrosion inhibition potential of $2-\left[\left(5-\text{methylpyrazol}-3-\text{yl}\right)\ \text{methyl}\right]$ benzimidazole against carbon steel corrosion in 1 M HCl solution: Combining experimental and theoretical studies in [11].

The reliability and durability of the structures considering metal corrosion have been studies numerously. Robert et al. [12] performed the structural reliability assessment of ships, offshore structures, and pipelines considering essential theoretical concepts and realistic data. Akio et al. [13] conducted research on the corrosion behavior of one-fifth scale lid models of a transport cask submerged in the sea bottom. The reliability assessment of the structure is also an interesting subject to researchers. Omishore and Kala presented a reliability analysis of steel structures with imperfections, in which the design reliability of a steel element was verified according to the concepts of standards Eurocode 3 and EN 1990 [14]. A similar approach was used to assess the reliability analysis of stainless-steel structures [15]. Meanwhile, Nguyen [16, 17] used Monte-Carlo simulations for assessing the reliability of steel frames with semi-rigid joints considering random input variables. However, the reliability and durability of steel structures accounting for metal corrosion in the industrial zone are not thoroughly investigated. Additionally, the reliability and durability prediction models have not been proposed yet.

This paper aims to develop the reliability and durability prediction model of steel structures considering the metal atmosphere corrosion in the industrial zones. The prediction model is a combination of atmospheric corrosion under local geographical conditions of the industrial zones, finite element method (FEM), and Monte Carlo (MC) simulation. Based on the predictive model, a computational program is established using MATLAB. The numerical results of reliability and durability behaviors under corrosion are determined for exposing time from 10 to 100 years. Finally, the effects of input parameters on structural reliability are also investigated in this study.

2 Theoretical background

2.1 Atmospheric corrosion rate model in the industrial zones

As mentioned above, the metal atmospheric corrosion in the industrial zone has a complex process, which is related to a large number of interacting environmental factors. The atmospheric corrosion of carbon steel in various environments was intensively studied and proposed by Klinesmith *et al.* [18]. We adopted this corrosion model to evaluate the reliability of structures in this study. The following model form was used to estimate corrosion loss, expressed as Eq. (1).

$$d(t) = A.t^{B}\left(\frac{TOW}{C}\right)^{D}.\left(1+\frac{[SO_2]}{E}\right)^{F}.\left(1+\frac{[Cl]}{G}\right)^{H} e^{J(T+T_0)} \qquad (1)$$

where $d(t)$ is the corrosion depth (μm); t is the exposure time (years); TOW is the time-of-wetness (h/year); SO_2 is the sulfur dioxide concentration (μg/m^3); Cl is the chloride deposition rate (μg/m^2/day); T is the avenge temperature (ºC); T_0 is the empirical coefficient; *A*, *B*, *C*, *D*, *E*, *F*, *G*, *H*, *J* are numerical values, which can be found in Klinesmith *et al*. [19].

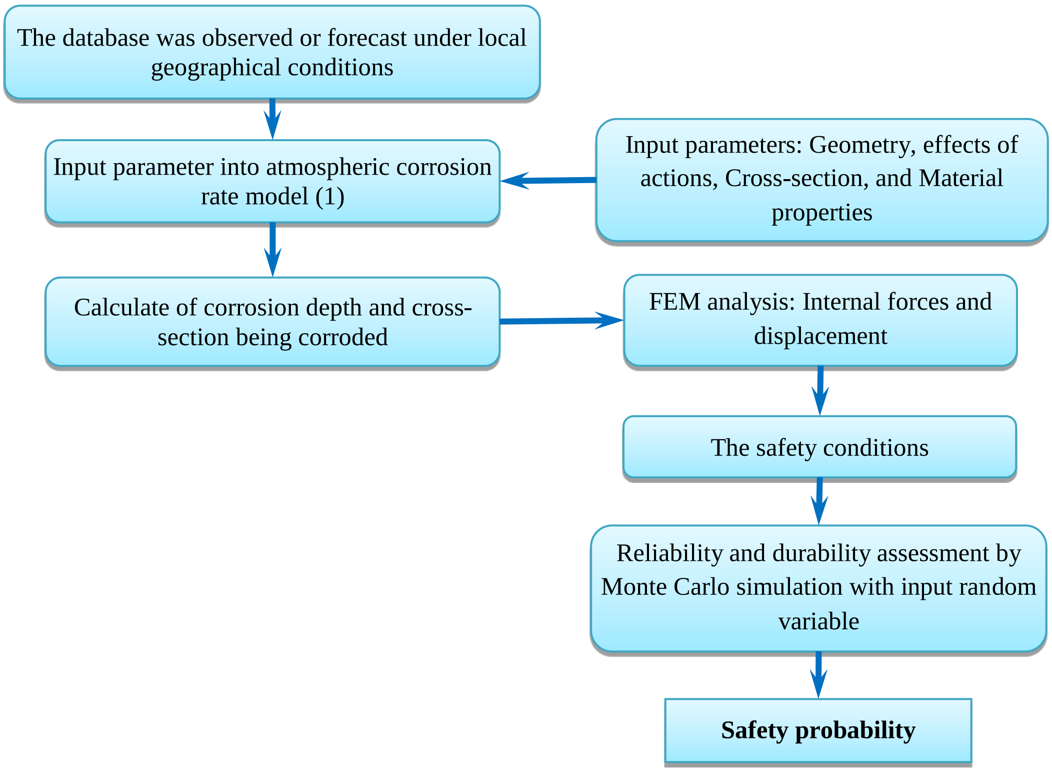

Fig. 1 – Flowchart of the prediction model is a combination of atmospheric corrosion under local geographical conditions of the industrial zones, finite element method (FEM), the Monte Carlo simulation (MC), and the safety condition of the steel structures.

2.2 Monte Carlo simulation

Monte Carlo simulation method is based on the use of pseudo-random numbers and the law of large number to assess the reliability of any system. If the safe domain is defined by the condition, $f(\boldsymbol{X}) > 0,$ where ***X*** is a random vector containing all input random variables, the unsafe probability of the system is determined by Eq. (2).

$$P_f = \int I_{f(\mathrm{X})<0} f_{\mathrm{X}}(x)\, dx = E\left[I_{f(\mathrm{X})<0}\right] \tag{2}$$

where $I_{f(\mathrm{X})<0}$ is the indicator function and is defined by Eq. (3).

$$I_{f(\mathrm{X})<0} = \begin{cases} 1 & \text{if} \quad f(\mathrm{X}) < 0 \\ 0 & \text{if} \quad f(\mathrm{X}) \geq 0 \end{cases} \tag{3}$$

According to the theory of statistics, if we have N realizations of the random vector X by propagating the randomness, we obtain a sample of N realizations of the indicator function. The expected value of the indicator function can be approximately determined by taking the mean of the sample, as expressed in Eq. (4).

$$\widehat{P}_f = E\left[I_{f(\mathrm{X})<0}\right] = \frac{1}{N}\sum_{i=1}^{N} I^{i}_{f(\mathrm{X})<0} \tag{4}$$

A 95% confidence interval of the estimation is defined by Eq. (5) [19]

$$\widehat{P}_f\left(1-1.96\sqrt{\frac{1-\widehat{P}_f}{N\widehat{P}_f}}\right)\leq P_f\leq\widehat{P}_f\left(1+1.96\sqrt{\frac{1-\widehat{P}_f}{N\widehat{P}_f}}\right) \tag{5}$$

In this study, the reliability assessment using Monte Carlo simulation is constructed in MATLAB. The verification of the MATLAB code was already presented in some studies of the authors [16, 17, 20-26].

2.3 The safety condition of steel frame structures

The safety condition of the steel structures must simultaneously satisfy two requirements: (1) the safety condition of cross-section beams and (2) the safety condition of cross-section columns based on Euro codes - Design of steel buildings EC3-1-1 [2].

3 A reliability prediction model considering atmosphere corrosion in the industrial zone

In the industrial zones, metal atmosphere corrosion factors are usually existing in terms of TOW, sulfur dioxide, chlorides, and temperature, which are observed or forecasted under local geographical conditions. In this study, TOW, sulfur dioxide, chlorides, and temperature are considered as input parameters for the atmospheric corrosion rate model. The prediction model is a combination of atmospheric corrosion under local geographical conditions of the industrial zones, finite element method (FEM), and Monte Carlo simulation (MC). This model has to be satisfied the safety condition of the steel structures (beam and beam-column) based on EC3-1-1 [2]. The flowchart of the reliability and durability prediction model of steel structures is shown in Fig. 1. MATLAB is used to perform algorithms to develop the predictive model.

4 Numerical examples

4.1 Input parameters of environmental industrial zones

Climate change scenarios were assumed from 2020 to 2120 with *TOW*, sulfur dioxide (SO_2), chlorides (*Cl*), and temperature as input parameters (*T*), as shown in Table 1. This is the author's climate change scenario were assumed based on the climate change scenario in Vietnam.

Table 1 - Input parameters of TOW, sulfur dioxide, chlorides, and temperature

Input parameters/years	2020	2030	2050	2070	2120
SO_2 (μg/m^3)	80.00	83.52	90.25	96.30	98.26
Cl^- (μg/m^2/day)	25.85	27.16	29.40	32.12	36.78
TOW (h/year)	445.40	463.50	489.40	502.30	518.80
T (ºC)	25.53	25.86	25.95	26.21	28.10

4.2 Configurations, applied load, and material properties of steel structures

The proposed prediction model has used for reliability assessment of a plane steel frame, as shown in Fig. 2, and a space steel frame, as shown in Fig. 3. Statistical properties of input random variables are shown in Table 2. The nominals and distributions of material properties are based on the suggestion of Ellingwood et al. [25], while the cross-sections and loadings are adopted the study of Bartlett et al. [26].

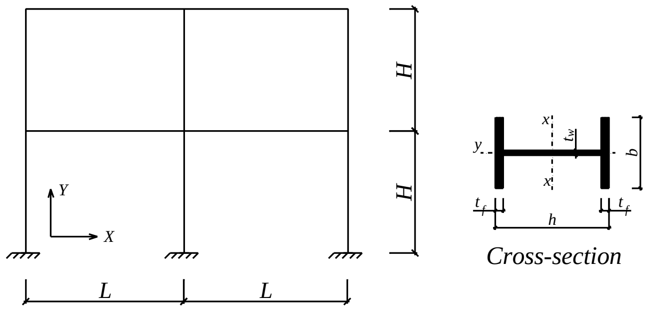

Fig. 1 - A two-bay two-story steel frame

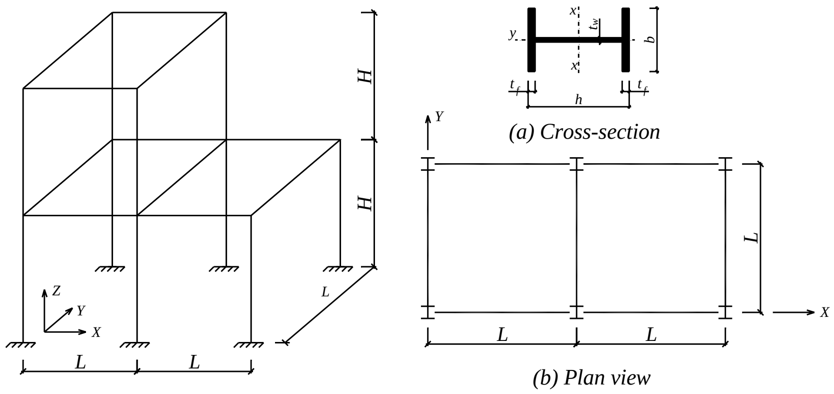

Fig. 2 - Two-story space steel frame

Table 2 - Statistical properties of random variables for reliability assessment

Properties	Variables	Nominal	Mean/nominal	COV	Distribution	Ref.
Geometric	H	400 (cm)	-	-	Deterministic	
	L	400 (cm)	-	-	Deterministic	
Material	f_y	248.0 (GPa)	1.10	0.06	Lognormal	[26]
	E	200.0 (GPa)	1.10	0.06	Lognormal	
	G	81,0 (GPa)	1.10	0.06	Lognormal	
Load	DL^*	50.0 (kN/m^2)	1.05	0.10	Normal	[25]
	LL^*	30.5 (kN/m^2)	1.05	0.10	Normal	
	WL^*	30.0 (kN/m^2)	0.92	0.37	Gumbel	
Cross-section of beam and column	b	250.0 (mm)	1.00	0.05	Normal	
	h	380.0 (mm)	1.00	0.05	Normal	
	t_f	15.0 (mm)	1.00	0.05	Normal	
	t_w	8.0 (mm)	1.00	0.05	Normal	

4.3 Convergence of Monte Carlo Simulation at the design time

Convergence tests of Monte Carlo simulations at the design time design (i.e., t = 0) for the two-bay two-story plane and two-story space steel frames are shown in Fig. 4 and Fig. 5, respectively

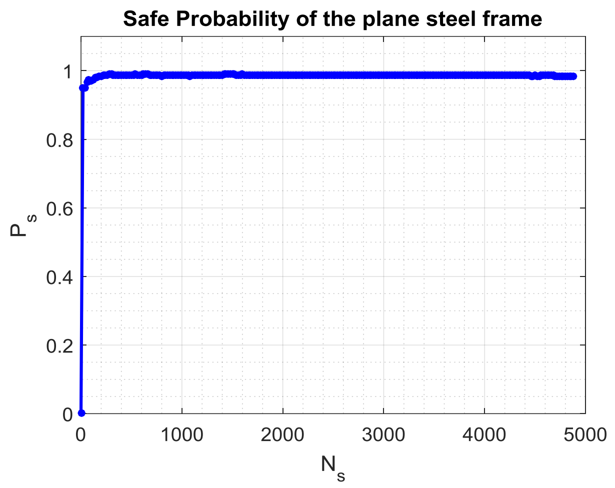

Fig. 3 - Convergence of the safety probability in the MC simulation of the plane frames at the design time (t = 0)

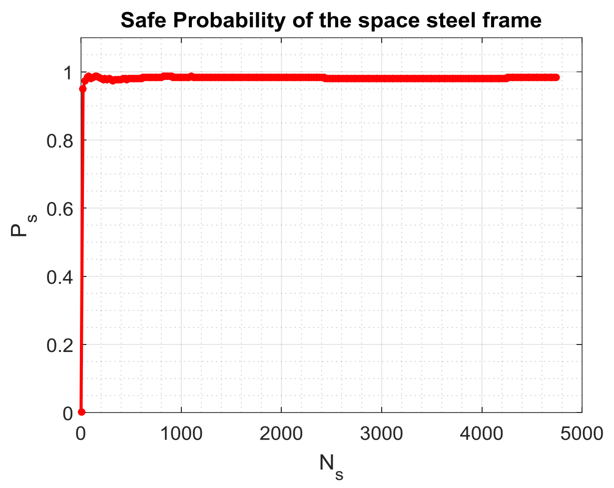

Fig. 4 - Convergence of the safety probability in the Monte Carlo simulation of the space frames at the design time (t =0)

The convergence test of the plane steel frame is reach after 4900 samplings in 110.94 mins, and the safety probability of the structure is up to 97.63%. For the space steel frame, the convergence is achieved after 4760 samplings in 250.5 mins, and the structural reliability is 0.984. It should be noted that the computer system used is Intel® Core™ i7-3930, CPU@3.20Hz 4.20Hz. This result also shows that although we have taken a safety factor of 1.15 in the analysis, the reliability of the structure is only P_s = 97.63% for plane steel frame and P_s = 98.40% for space steel frame because of the randomness of input parameters. Thus, the assessment of the reliability of the structure is necessary, especially considering metal corrosion over time.

4.4 Effect of metal corrosion on the safety probability of the plane steel frame

The proposed prediction model is used for reliability assessment of the plane steel frame (in Fig. 2) considering various corrosion time, which are 10-year, 20-year, 50-year, and 100-year. The summary of the safety probability in the Monte Carlo simulation of the plane steel frame considering metal corrosion is shown in Table 3.

Table 3 - The safety probability of the plane steel frame from 0 year to 100 years

	0 year	10 years	20 years	50 years	100 years
Safety probability (%)	97.63	96.52	93.27	90.14	83.29

From Table 3, the safety probability of the plane steel frame considering metal corrosion from the pristine to 100 years using Monte Carlo simulation is reduced from 97.63% to 83.29%. In other words, the safe probability after 10-years, 20-years, 50-years, and 100-years corrosion is decreased by 1.11%, 4.36%, 6.38%, and 9.98%, respectively. It should be noted that the used convergence criteria of 1.5% justify the confidence of the estimated reliability.

4.5 Effect of metal corrosion on the safety probability of the space steel frame

The proposed prediction model is also applied for reliability assessment of the two-story space steel frame (in Fig. 3) considering 10-years, 20-years, 50-years, and 100-years corrosion. The result of the safety probability in the Monte Carlo simulation of the space steel frame considering metal corrosion is shown in Table 4.

The safety probability of the plane steel frame considering metal corrosion from the pristine to 100 years using Monte Carlo simulation is reduced from 98.75% to 81.40%. In other words, the safe probability after 10-years, 20-years, 50-years, and 100-year corrosion is decreased by 1.45%, 3.47%, 5.14%, and 13.88%, respectively. A convergence criterion of 1.5% justifies the confidence of the estimated reliability. This finding highlight that it is needed to consider the reduction of reliability or durability of steel structures over time.

Table 4 - The safety probability of the two-story space steel frame from 0 year to 100 years

	0 year	10 years	20 years	50 years	100 years
Safety probability (%)	98.75	97.30	95.28	92.16	81.40

5 Conclusion

This paper proposed an algorithm to assess the structural reliability of steel frame structures considering the influence of metal corrosion. The predictive model is combined of metal atmosphere corrosion model (MAC), finite element method (FEM), and Monte Carlo simulation (MC). The predicted model was used for estimating reliability and durability of different steel structures including two- and three-dimensional frames accounting for atmosphere corrosion in the industrial zones until a life-service of 100 years. The following conclusions are drawn.

- A predictive model for assessing the structural reliability of steel structures considering the influence of metal corrosion was proposed.
- A variation of structural reliability with different life-services is quantified. The safe probability is decreased as the exposing time increased. The safe probability of the steel structure is reduced to approximately 90% and 80% after 50 years and 100 years, respectively.
- It is recommended considering input random variables when adjusting the reliability structure at the design time.

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