Time-Dependent Reliability Assessment of a Continuous I-shaped Steel Beam Considering Corrosion Effects

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Abstract-Among other fields, climate change has a great influence on metal corrosion that reduces the durability and reliability of steel structures. A time-dependent reliability analysis includes time-dependent climate scenarios and deterioration processes as well as random variables, material properties, and dimensions. The extent of corrosion damage is calculated by tracking the evolution of the corrosion process using Monte Carlo simulations. The current paper presents a time-dependent reliability assessment of a continuous I-shaped steel beam, considering the corrosion effects of climate change in Vietnam. The results showed that the safety probability of a continuous steel beam considering metal corrosion from the pristine to 100 years reduces from 96.77% to 63.08%. These findings can be used to assess and provide a cost-technical analysis of climate adaptation measures.

Keywords-time-dependent reliability; continuous I-shaped steel beam; corrosion damage; Monte Carlo simulation

I. INTRODUCTION

Continuous steel beams that contain two or more spans are typically used in steel frame buildings and bridges. The design of continuous beams not only ensures the strength condition but also minimizes their weight and material costs. A steel beam can be influenced in the long term by corrosion, leading to an acceleration of structural deterioration. Therefore, a time-dependent reliability assessment of continuous steel beams is very important, especially in the context of climate change. The assessment of the reliability and durability of steel structures for metal corrosion attracted the interest of many studies. The structural reliability of ships, offshore structures, and pipelines takes into account essential theoretical concepts and realistic data [1]. An investigation of corrosion behavior was conducted on a scale of 1:5 of a transport container sunk in a seabed [2]. Evaluations and surveys on structural reliability considering metal corrosion in steel frame structures and steel-concrete composite beams were conducted in [3-6]. Meanwhile, an assessment process was proposed to consider the effects of climate change on the atmospheric corrosion rate of steel structures, taking into account changes in ambient temperature, carbon dioxide, relative humidity, wind, precipitation, and pollution [7]. However, the structural reliability and durability of continuous I-shaped steel beams with corrosion damage have not been assessed so far. This study aimed to evaluate the time-dependent reliability of continuous I-shaped steel beams, considering the effects of corrosion based on a climate change scenario. The climate change scenario was assumed from 2020 to 2120 with Time Of Wetness (TOW), sulfur dioxide (SO_2), chlorides (Cl), and Temperature (T) as input parameters, and adopted the corrosion model proposed in [8]. The time-dependent reliability assessment was a combination of the Monte Carlo (MC) simulation and the Finite Element Method (FEM), estimating the corrosion loss of the cross-section of a steel beam. The computations were conducted in MATLAB. The numerical results of the corrosion reliability and durability behaviors were determined for exposure times of 10 to 100 years.

II. THEORETICAL BACKGROUND

A. *Climate Change Scenario*

This study considered a climate change scenario that included TOW, SO_2, Cl, and T as input parameters [9]. Their ranges were as follows:

- $445.40 \leq \text{TOW} \leq 518.80$ h/year

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- $80.00 \leq SO_2 \leq 98.26$ μg/m^3
- $25.85 \leq Cl \leq 36.78$ μg/m^2/day
- $25.53 \leq T \leq 28.10$ °C.

Figure 1 shows the curves of the environmental parameters, each one corresponding to a scenario of climate change.

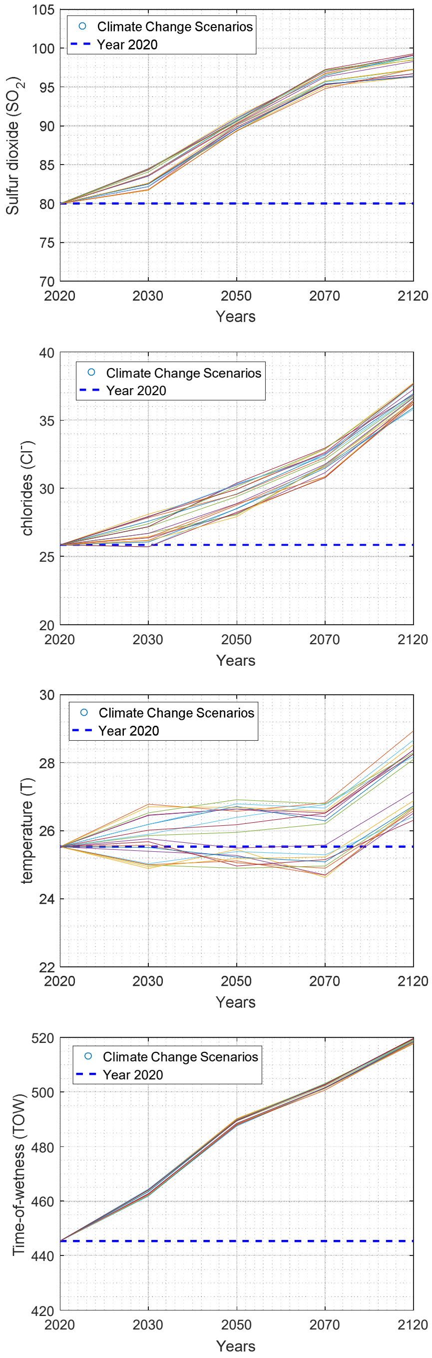

Fig. 1. Climate change scenarios assumed from 2020 to 2120.

B. Atmospheric Corrosion Rate Model

Metal atmospheric corrosion is a complex process and depends on a large number of interacting environmental factors. The atmospheric corrosion of carbon steel in various environments was intensively studied and proposed in [8]. This study adopted this corrosion model to evaluate the reliability of the structures. The following model was used to estimate corrosion loss:

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

where $d(t)$ is the corrosion depth in μm, t is the exposure time in years, TOW is the Time Of Wetness in h/year, $[SO_2]$ is the sulfur dioxide concentration in μg/m^3, $[CL]$ is the chloride deposition rate in μg/m^2/day, T is the avenge temperature in °C, T_0 is an empirical coefficient, and A, B, C, D, E, F, G, H, J are numerical values, which can be found in [8].

C. Nominal and Distributions of Material Properties

The nominals and distributions of material properties were based on [10], while the cross-sections and loadings were adopted from [11].

D. Safety Condition of the Continuous Steel Beam

The safety condition of the continuous steel beam was based on the Eurocode design of steel buildings EC3-1-1 [12]. The safety condition is given by:

$$G(X) = \begin{cases} \left(\frac{M_{Ed}}{M_{c,Rd}} - 1,0\right)\frac{1}{n} \leq 0 \\ \left(\left[\frac{M_{y,Ed}}{M_{pl,y.Rd}}\right]^{\alpha} + \left[\frac{M_{z,Ed}}{M_{pl,z.Rd}}\right]^{\beta} - 1,0\right)\frac{1}{n} \leq 0 \\ \left(\frac{V_{Ed}}{V_{c,Rd}} - 1,0\right)\frac{1}{n} \leq 0 \\ \left(\left(W_{pl,y} - \frac{\rho A_W^2}{4t_w}\right)\frac{f_y}{\gamma_{M0}} - M_{y,c,Rd}\right)\frac{1}{n} \leq 0 \end{cases} \quad (2)$$

E. Monte Carlo Simulation

The MC simulation method is based on the use of pseudo-random numbers and the law of large numbers to assess the reliability of any system. If the safe domain is defined by the condition $f(X)>0$, where X is a random vector containing all input random variables, the unsafe probability of the system is determined by:

$$P_f = \int I_{f(\mathrm{X})<0} f_{\mathrm{X}}(x)dx = E\left[I_{f(\mathrm{X})<0}\right] \quad (3)$$

where $I_{f(X)<0}$ is the indicator function, defined by

$$I_{f(\mathrm{X})<0} = \begin{cases} 1 & \text{if} \quad f(\mathrm{X}) < 0 \\ 0 & \text{if} \quad f(\mathrm{X}) \geq 0 \end{cases} \quad (4)$$

According to the theory of statistics, if there are N realizations of the random vector X by propagating the randomness, a sample of N realizations of the indicator function can be obtained. The expected value of the indicator function can be approximately determined by taking the mean of the sample, as expressed in:

$$\hat{P}_f = E\left[I_{f(\mathrm{X})<0}\right] = \frac{1}{N}\sum_{i=1}^{N} I_{f(\mathrm{X})<0}^{i} \quad (5)$$

A 95% confidence interval for the estimation was defined in [13] as:

$$\hat{P}_f\left(1-1.96\sqrt{\frac{1-\hat{P}_f}{N\hat{P}_f}}\right) \le P_f \le \hat{P}_f\left(1+1.96\sqrt{\frac{1-\hat{P}_f}{N\hat{P}_f}}\right) \quad (6)$$

Reliability assessment was evaluated using MC simulations in MATLAB. The verification of the MATLAB code has already been presented in [3, 4, 14-16].

III. TIME-DEPENDENT RELIABILITY COMBINING FEM, METAL CORROSION MODELING, AND MONTE CARLO SIMULATION

The computational program for the reliability assessment of the continuous steel beam was developed using FEM, the corrosion model with input parameters based on the climate change scenario, and the MC simulations.

A. Convergence of the Monte Carlo Simulation at Pristine

A continuous I-shaped steel beam with 3-spans was examined, having the geometry of structure and cross-section as shown in Figure 2. The nominal values and distributions of the random variables are shown in Table I. The nominal values and the distributions of the material properties were adopted from [10], while the cross-sectional dimensions and applied load were adopted from [11]. Reliability assessment was applied in pristine conditions ($t = 0$ years). Figure 3 shows the convergence tests of the MC simulations at the design time ($t = 0$) for the continuous steel beam. The convergence test of the continuous steel beam was achieved after 2340 samplings in 28.5min, and the safety probability of the structure was up to 96.77%. The test was conducted using an Intel® Core™ i7-3930 CPU at 3.20-4.20Hz. This result also shows that although there was a safety factor of 1.15 in the analysis, the reliability of the structure was only $P_s = 96.77\%$, because of the randomness of input parameters. Thus, the assessment of the structure's reliability is necessary, especially considering the metal corrosion over time.

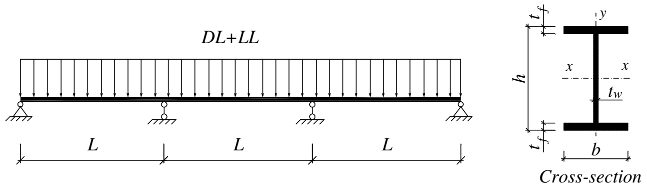

Fig. 2. Continuous I-shaped steel beam with 3-spans.

TABLE I. STATISTIC PROPERTIES OF RANDOM VARIABLES FOR RELIABILITY ASSESSMENT

Properties	Variables	Nominal	Mean/ nominal	COV	Distribution	Ref.
Geometric	L	6000 (cm)	-	-	Deterministic	-
Material	f_y	248.0 (GPa)	1.10	0.06	Lognormal	[11]
	E	200.0 (GPa)	1.10	0.06	Lognormal	[11]
	G	81.0 (GPa)	1.10	0.06	Lognormal	[11]
Loading	DL^*	50.0 (kN/m2)	1.05	0.10	Normal	[10]
	LL^*	30.5 (kN/m2)	1.05	0.10	Normal	[10]
Cross-section beam	B	200.0 (mm)	1.00	0.05	Normal	[10]
	H	480.0 (mm)	1.00	0.05	Normal	[10]
	t_f	20.0 (mm)	1.00	0.05	Normal	[10]
	t_w	10.0 (mm)	1.00	0.05	Normal	[10]

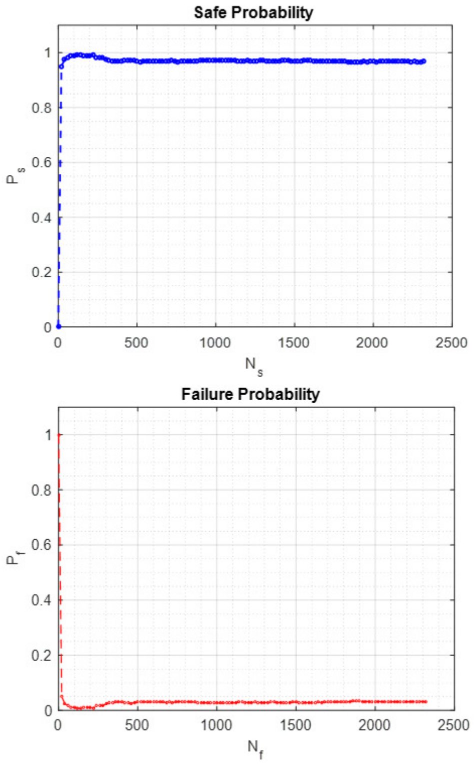

Fig. 3. Convergence of the safety probability (above) and failure probability (below) in the Monte Carlo simulation of the continuous steel beam at the design time ($t = 0$).

B. Effect of Metal Corrosion on the Safety Probability

The reliability assessment of the continuous steel beam was carried out for different corrosion durations of 10, 20, 50, and 100 years. The summary of the safety probability in the Monte Carlo simulation of the continuous steel beam, considering its metal corrosion, is shown in Table II and Figure 4.

TABLE II. SAFETY PROBABILITY OF THE CONTINUOUS STEEL BEAM FROM 0 TO 100 YEARS

Years	0	10	20	50	100
Safety probability (%)	96.77	81.44	75.91	68.61	63.08

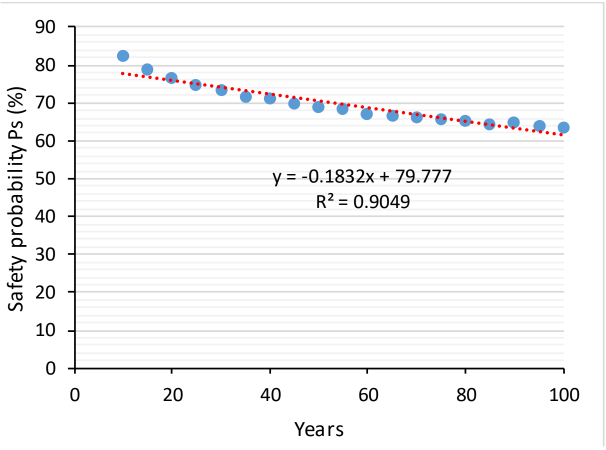

Fig. 4. Reliability decline of the continuous steel beam in 0-100 years.

Table II and Figure 4 show that the safety probability of the continuous steel beam, considering metal corrosion from the pristine to 100 years using MC simulation, reduced from 96.77% to 63.08%. In other words, the safe probability after 10, 20, 50, and 100 years of corrosion reduced by 15.33%, 20.86%, 28.16%, and 33.69% respectively. It should be noted that the used convergence criteria of 1.5% justify the confidence of the estimated reliability.

IV. CONCLUSION

This study evaluated the time-dependent reliability of a continuous I-shaped steel beam, considering the influence of metal corrosion. The numerical results were based on the corrosion model with input parameters from the climate change scenario and Monte Carlo simulation. In the structural reliability assessment, a wide range of corrosive exposure times from 10 to 100 years was considered. The findings of this study can be summarized as follows:

- A climate change scenario in Vietnam from 2020 to 2120 was considered in the structural reliability assessment of a continuous I-shaped steel beam.
- A computational program was developed in MATLAB to assess the time-dependent reliability of a continuous I-shaped steel beam, considering corrosion effects.
- The safety probability of the continuous I-shaped steel beam, considering the metal corrosion from pristine to 100 years, reduced from 96.77% to 63.08%.

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