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RESIDUAL LIFE PREDICTION AND DESIGN CORRECTION METHOD OF CORRODED CIRCULAR STEEL TUBES BASED ON TIME-VARYING RELIABILITY

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ABSTRACT

Current research on the effects of corrosion on the safety of steel members is primarily focused on the degradation of the ultimate bearing capacity, and there is a lack of research on the reliability-based service life assessment. In this paper, a modified reliability function and an uncertainty model for each parameter considering the effects of corrosion are established based on the reliability analysis method of the GB50068-2018 design specification. The effects of the corrosive environment category, wall thickness, and slenderness ratio on the time-varying reliability of axially compressed round tubes are analyzed. The results indicate that an increase in the corrosion duration and the environmental category can cause a decrease in the reliability index of the component, and the smaller the wall thickness, the faster the corrosion-related degradation of the reliability index. However, with the increase of the slenderness ratio, the corrosion-related degradation of the reliability index gradually decreases. In the end, a residual life prediction method and a design correction method for corroded components based on the reliability index are proposed. Moreover, the values of the corrosion life and corrosion coefficient of circular steel tubes for different environmental categories, slenderness ratios, and thicknesses are determined. This paper provides a technical reference for the residual life prediction and full life design of round steel tubes considering local corrosion.

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1. Introduction

As the service life of a large number of steel structures progresses, durability issues[1-3] related to corrosion problems come to the fore[4,5]. However, there are no operational assessment and design correction methods that take into consideration the development and effects of corrosion under different environments. Therefore, it is of high importance to conduct research on this issue.

Previous studies [6-8] have paid extensive attention to the effects of corrosion on the durability of reinforced concrete structures, focusing on characteristics including the corrosion development rate, surface crack length and width, and stray currents.

In contrast, there is a distinct lack of research on the durability of steel structures after corrosion, with available studies focusing mainly on the degradation of the load bearing capacity of components. A number of scholars have shown that corrosion has a non-negligible effect on the load-bearing capacity and structural safety of steel components. For example, Khedmati et al. [9] derived a semi-empirical equation based on a finite element model to predict the relationship between the axial compressive bearing capacity and the corrosion of circular steel tubes. Zhang et al.[10] analyzed the axial bearing capacity of irregularly corroded tubes and presented a recommended engineering assessment method. Wu et al [11] used an outdoor cycling spray and found that the corrosion duration had a strong effect on the ultimate bearing capacity of the specimens and a small effect on their stiffness. Jie et al [12] used hemispherical notches to simulate pitting damage and performed and analyzed the effect of small corrosion points on the fatigue performance of cross-shaped joints. Yang et al [13] investigated the performance degradation of offshore sheet pile walls using a corrosion model that could approximate the actual conditions.

It should be noted that the above studies mainly concern the degradation of the carrying capacity rather than the change in the failure probability. However, most of the current design codes [14-16] are based on the reliability theory and do not take into account the effect of corrosion on design [17,18]. In response to this conflict between research and design, Lin et al [19] employed the Monte Carlo method to analyze the uncertainty of pitting corrosion in submarine pipelines. Their study revealed that the uncertainty of the corrosion process is crucial to the study of corrosion effects. Ma et al. [20] calculated the failure probability of corroded pipelines based on the critical and working pressures. Zelmati et al. [21] concluded that the reliability of gas transmission steel pipelines was reduced by 40% when the defect length of the pipeline increased to 55 mm. While the loading form considered in the above studies is internal pressure, the main loading form for circular tubes in spatial structures is axial pressure[22,23].

In view of the above limitations, this paper takes the axially compressed circular steel tubes in spatial steel structures as the research object. In the analysis of the reliability indices, the effect of corrosion is taken into account. On the basis of the existing liability function, the uncertainty of the generation and effect of local corrosion are taken into consideration. The variation trend of the reliability index of corroded axially compressed circular steel tubes under different load combinations is analyzed. Finally, based on the reliability index requirements, the residual life of steel tubes under different corrosion environments and the corrosion coefficient value for structural design modification are determined.

2. Reliability calculation model

2.1. Reliability function

According to GB50068-2018 [24], the basic variables to be considered when calculating the reliability index of a structure include the material strength K_M, geometric dimensions K_G, resistance calculation mode K_P, effect calculation mode K_B, and action effect S. The action effect in the reliability function can be divided into the constant load effect S_G, live load effect S_{LR}, and wind load effect S_W. Using these essential variables, the reliability function can be obtained, when the corrosion effect is not taken into account.

$$Z = R - S = K_P R(K_M, K_G) - K_B(S_G + S_{LR} + S_W) \tag{1}$$

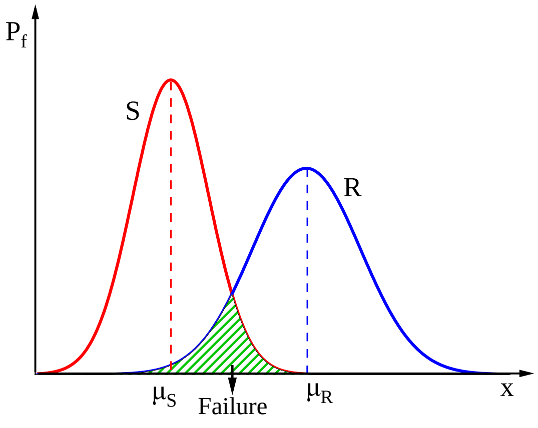

Fig. 1 Uncertainty of corrosion effect

As illustrated in Fig. 1, both the resistance R of the structure and the action S of the load are stochastic in nature. When the resistance R is larger than the effect S (Z>0), the structure is in a safe state; when the resistance R is smaller than the effect S (Z<0), the structure is in a failure state; and when the resistance R is equal to the effect S (Z=0), the structure is in a marginal state. The green area in Fig. 1 is the probability of the failure state.

When the corrosion effect is taken into consideration, K_C is introduced to represent the resistance degradation caused by corrosion; thus, the modified function becomes:

$$Z = K_P K_C R(K_M, K_G) - K_B(S_G + S_{LR} + S_W) \tag{2}$$

For axially compressed components, the resistance is related to the material strength f, the cross-sectional area A_n, and the stability coefficient φ. The action effect can be considered according to the provisions of the load sub-factor in GB50009-2012 [25]. As a result, the resistance and effect of corrosion can be determined by:

$$R_{\mathrm{d}} = \varphi A_{\mathrm{d}} f_d \tag{3}$$

$$S_d = \gamma_0(\gamma_G S_{GK} + \gamma_{LR} S_{LRK} + \psi \gamma_W S_{WK}) \tag{4}$$

where the subscripts k and d denote the standard and design values, respectively, S_{GK} is the standard value of the constant load effect, S_{LRK} is the standard value of the live load effect, S_{WK} is the standard value of the wind load effect, γ is the load sub-factor, ψ is the combined value factor, and γ_0 is the structural importance factor, which is taken as 1.

In the design of building structures, when the components are in the ultimate state, the design value of the resistance is equal to that of the load effect, which can be expressed as:

$$R_{\mathrm{d}} = S_d \tag{5}$$

Consequently, when φ, A_d, and f_d are known, the load effect design value S_d can be determined, and the standard load effect value generated by each load can be determined according to the load ratio relationship commonly used in engineering practice. Subsequently, the relationship between the standard value of each load, its mean value, and its variation coefficient is used; that is, the probability distribution pattern of each load is obtained. The specific process of the above reliability index calculation can be found in the literature [26-28].

Taking the corrosion effects into consideration, the equation of state for axially compressed round steel tubes can be further expressed as:

$$Z = K_P K_C K_G K_M R - K_B(S_G + S_{LR} + S_W) \tag{6}$$

where K_C is the bearing capacity reduction factor due to corrosion. To determine the reasonable value of K_C, experimental and numerical simulation studies were performed in our previous work [29]. The factors considered in the study included the dimensions of the steel tubes and the size of local corrosion, as well as the location of random corrosion. A comparison of the experimental and simulation results is illustrated in Fig. 2.

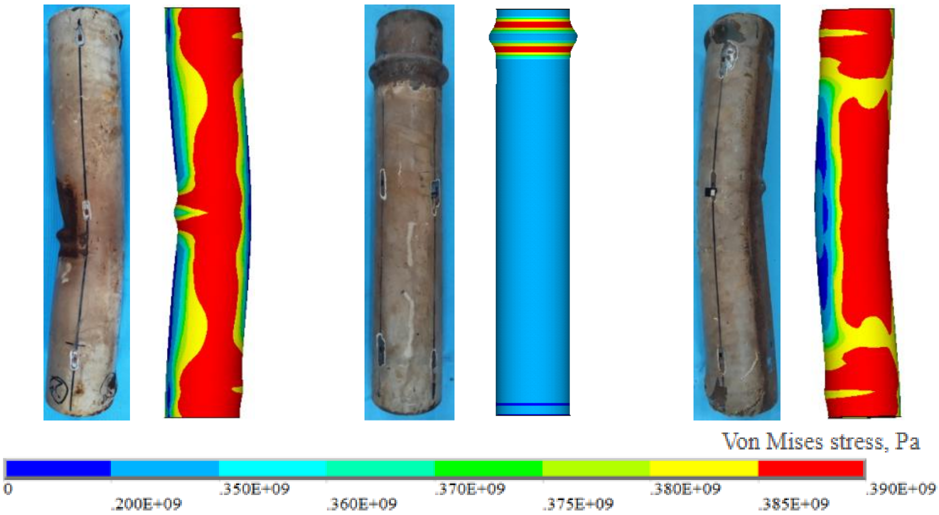

Fig. 2 Comparison of experimental and simulation results

Under the protective effect of the external coating, it has been determined that the main form of corrosion of steel members is localized corrosion. Based on the experimentally validated model, the reduction factor K_C for locally-corroded round steel tubes was determined by parametric analysis using the following equation [30]:

$$K_C = \begin{cases} 0.01*(-19*D_C + 19*H_C^2 - 13H_C - 7*L_C - 109D_C*H_C) + 1 & \lambda < 70 \\ 0.01*(-34*D_C + 22*H_C^2 - 22H_C + 0.08*\lambda - 17*L_C - 62D_C*H_C) + 1 & 150 \geq \lambda \geq 70 \end{cases} \tag{7}$$

where λ is the slenderness ratio of the tube, H_C is the circumferential ratio of corrosion, L_C is the axial ratio of corrosion, and D_C is the depth ratio of corrosion.

2.2. Calculation method

The Monte Carlo method was utilized for random sampling, and according to the law of large numbers, when the number of samples is substantially large, the probability value obtained statistically after random sampling is equal to the actual probability value. A more detailed description of the Monte Carlo method and its application in corrosion prediction can be found in the literature [19, 31].

For an in-service building structure, the failure probability is about 10^{-5}, and then, when the sampling number is 10^7, it can be guaranteed that the error is less than 20% with a confidence level of 95% [26, 32]. Consequently, the number of samples used in the subsequent study of this paper was $3*10^7$, and when the failure probability has been determined, the corresponding reliability index can be deduced from the standard normal distribution. The reliability index calculation results can be found in Section4.

3. Uncertainty of parameters

3.1. Load and resistance uncertainty

A large number of engineering applications and measurements have indicated that there is significant randomness and variability in both load and resistance. The uncertain statistical parameters of loads according to the provisions of "Unified Standard for Reliability Design of Building structures" GB50068-2018 [4], "Code for load of Building structures" GB50009-2012 [25], and "Technical Specification for Spatial Grid structures" JGJ7-2010 [33] are shown in Table 1.

On the other hand, the uncertainty regarding the structural resistance to load mainly includes the effect of several aspects, such as the geometric dimension uncertainty K_G introduced above, the uncertainty of the material properties K_M, and that of the resistance calculation model K_P. The uncertainties of each parameter for mild steel [34, 35] are listed in Table 2.

Table 1
Load uncertainty

	Mean/standard value	Variation coefficient	Distribution type
Constant load	1.06	0.07	Normal distribution
Live load	0.644	0.233	Extreme value type I distribution
Wind load	0.908	0.193	Extreme value type I distribution
Snow load	1.14	0.225	Extreme value type I distribution
Effect calculation model	1.0	0.05	Normal distribution

Table 2
Resistance uncertainty

	Mean/standard value	Variation coefficient	Distribution type
Wall thickness	1.0	0.05	Normal distribution
Diameter	1.0	0.03	Normal distribution
Yield strength	1.19	0.096	Normal distribution
Young's modulus	1.02	0.01	Normal distribution
Resistance calculation model	1.0	0.05	Normal distribution

3.2. Corrosion uncertainty

In addition to the aforementioned uncertainties, corrosion of steel structures occurs inevitably with the progress of service life. The reaction process and speed of corrosion are also associated with strong randomness. Based on the specification "Corrosion of Metals and Alloys—Corrosivity of Atmospheres— Classification, Determination and Estimation" ISO 9223:2012 [36], the relationship between corrosion amount depth and time can be expressed as follows:

$$d_t = \begin{cases} \gamma_{corr} t^n & t < 20 \\ \gamma_{corr}(20^n + n(20^{n-1})(t-20)) & t \geq 20 \end{cases} \tag{8}$$

where t is the duration of the corrosion process, d_t is the corrosion volume of the t^{th} year (mm), γ_{corr} is the corrosion volume of the metal in the first year, and n is the environmental characteristic parameter of the metal in the corrosion model. It reflects the inhibitory effect of corrosion products on the corrosion rate. Taking a value less than 1, its distribution can be simplified to a normal distribution with a mean value of 0.523 and a standard deviation of 0.026 [37-39].

The corrosion environment can be divided into 6 categories [36]. Among them, C5 has a wide range of corrosion rate, which here has been divided into C5A and C5B. The corrosion rate range for each category in the first year and the corresponding environment type are given in Table 3.

Table 3
Corrosion environment category

Category	One year after exposure		Reference environment case
	Loss of weight ($g\cdot m^2$)	Loss of thickness (μm)	
C1 Very low	<10	<1.3	Atmospheric environments with very low levels of pollution and very short periods of humidity, e.g., deserts, Antarctica, etc.
C2 Low	10-200	1.3-25	Atmospheres with low pollution levels in rural areas or terminals with low humidity levels
C3 Medium	200-400	25-50	Moderately polluted urban and industrial atmospheres or low-pollution areas in the temperate subtropics
C4 High	400-650	50-80	Highly polluted urban and industrial areas, medium salinity coastal areas, or swimming pools
C5 Very high	650-1100	80-140 (C5A)	Highly polluted industrial environments, high salinity seaside areas, or tropical or subtropical seaside industrial environments
	1100-1500	140-200 (C5B)	
CX Extreme	>1500	>200	Specific marine environments, e.g., tropical offshore environments, or production spaces with almost permanent condensation

In addition to the corrosion rate, it is also necessary to take the uncertainty of the corrosion area size into consideration. Through statistical analysis of corrosion observation data[26,27], the probability distribution patterns of the corrosion annular size, longitudinal size, and depth ratio have been determined (Table 4).

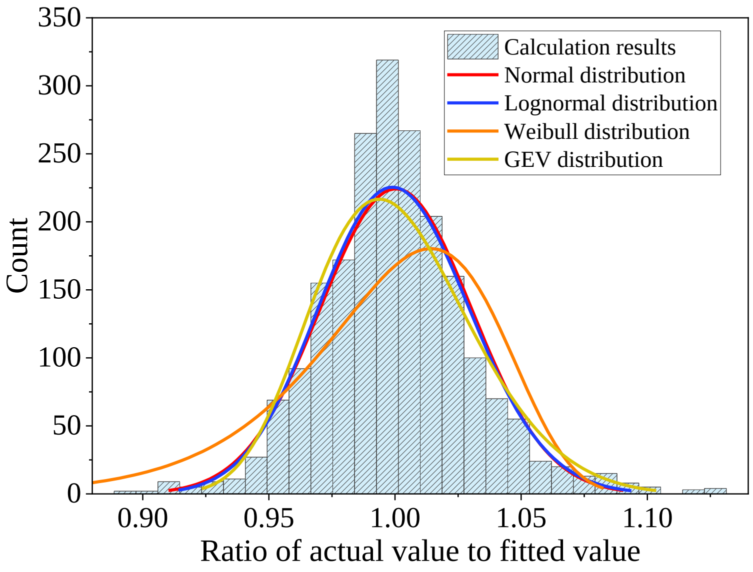

Fig. 3 Corrosion effect uncertainty

Table 4
Corrosion size uncertainty

Corrosion size direction	Corrosion size-to-depth ratio		
	Mean value	Standard deviation	Distribution type
Circumferential	150	25	Normal distribution
Longitudinal	550	70	Normal distribution

The uncertainty of the simplified calculation method of the corrosion effect (Eq. 7) should also be taken into consideration. The deviation of the simplified calculation method can be obtained by dividing the results of the finite element model calculation with those of the simplified calculation. Based on the data reported in the literature [30], Figure 3 exhibits the deviation distribution of the calculation method. The distribution of the corrosion effect calculation model resembled that of normal distribution. Using a normal distribution with a mean of 1 and a standard deviation of 0.03 to describe the actual and fitted values, the uncertainty of the corrosion effect calculation model can be suitably amplified, making the calculation results slightly biased toward safety.

The above analysis takes into account the stochastic process of the corrosion area expansion and corrosion depth deepening with the increase of the structure service time. In the first year of service of the structure, the member surface exhibits a small exposure to corrosion, which can be probably attributed to bumping or accidental abrasion of the coating during the transportation of the member[40, 41]. During the subsequent service period, the local corrosion corresponding to the initial exposure is gradually aggravated, which is consistent with the assumption made in the reliability analysis of this paper.

4. Time-varying reliability index calculation

4.1. Loading conditions considered

In engineering design, it is necessary to consider the typical loads for the reliability level analysis of structural members. For the purposes of this paper, three most common forms of load combinations were selected (Table 5). The slenderness ratio is controlled within 150 [14]. The numerical relationships between different load effects on structures are not constant and correspond to a variety of reliability indices. However, relevant studies [42-44] have reported that, when the ratio between variable and constant loads is taken as 0.5 and that between wind or snow loads and variable loads is taken as 0.7, the calculated reliability indices are similar to those obtained by the weighted combination of different load effects. Thus, the above values were used in this study.

Table 5
Selection of load combinations

Condition	Considered loads	Expression [25]
1	Constant load; live load	$1.3S_G+1.5S_{LR}$
2	Constant load; live load; wind load	$1.3S_G+1.5(S_{LR}+0.6S_W)$
3	Constant load; wind load; snow load	$1.3S_G+1.5(S_W+0.6S_N)$

4.2. Effect of corrosion duration and environmental category

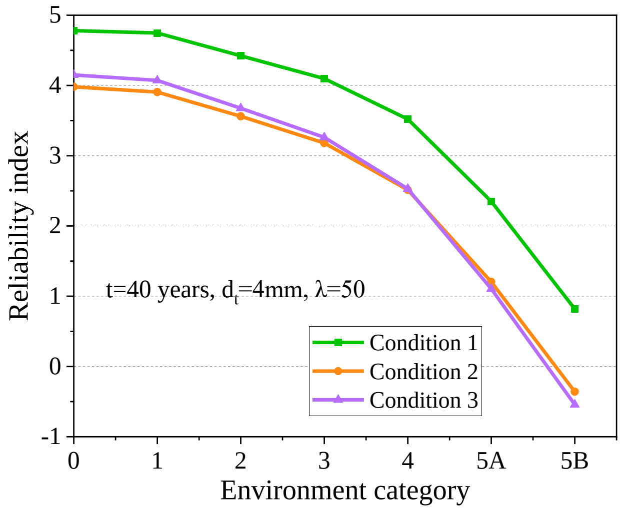

Fig. 5 Reliability index as a function of the environment category

The duration of the corrosion process and the environmental category determine the corrosion depth. According to Fig. 4, when the other factors remained unchanged, the reliability index of an axially compressed circular steel tube changed with increasing corrosion time. It should be noted that d denotes the original wall thickness of the steel tube and λ is its slenderness ratio. It can be observed that with the progress of service time, the reliability index of the circular steel tube under axial compression exhibited a downward trend, indicating that the failure possibility increased gradually. Moreover, the change trend of the reliability index was basically the same under the different load combinations. The curve of the relationship between reliability index and corrosion time was smooth; thus, the index was calculated every 5 years in order to reduce the calculation cost.

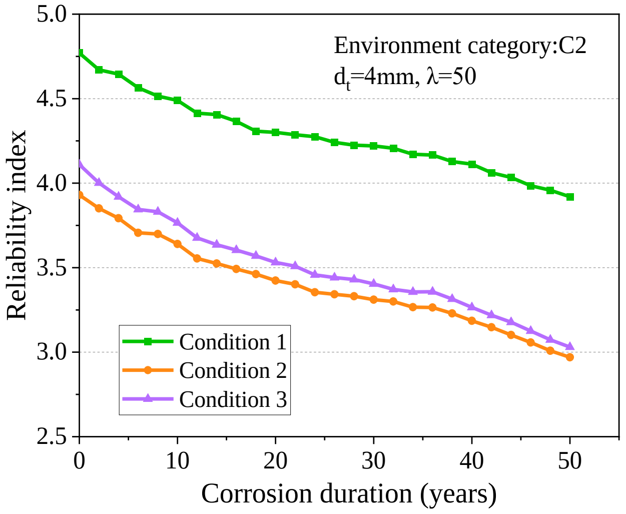

Fig. 4 Reliability index as a function of the corrosion duration

Fig. 5 depicts the reliability index of the axially compressed round steel tube under different corrosive environment categories. It can be observed that, as the corrosive environment category increased, the reliability index of the component exhibited a decreasing trend. When the corrosive environment category was between C1-C3, the change in the reliability index was small, while when it was between C4 and C5, the reliability index decreased sharply.

To better understand the effect of different corrosion environments and corrosion duration on the reliability index, Fig. 6 demonstrates the relationship between the reliability index, the corrosion rate, and the corrosion duration. It can be seen that, as the corrosion time and harshness of the environment increase, the reliability index decreased significantly. When the corrosive environment category was C1, the reliability index after 50 years of corrosion for a steel tube with 4 mm wall thickness and slenderness ratio of 50 was 3.71. When the environment category was C2, the corresponding reliability index decreased slightly to 3.45, while the reliability indices under the C3 and C4 category corrosive environments were 2.97 and 2.23, respectively. The reliability index for the steel tube in the extremely corrosive environment (C5B) decreased to 1.28 after 50 years, and the failure probability of the component was more than 50% with significant structural risk.

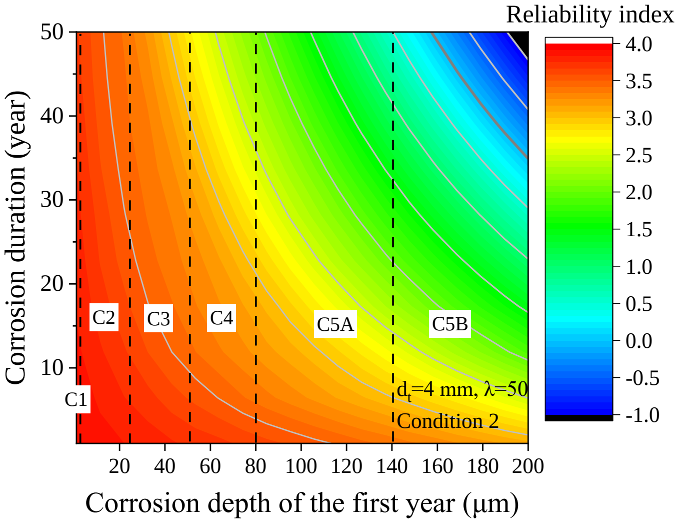

Fig. 6 Reliability index under different corrosion rate and corrosion duration

4.3. Effect of steel tube wall thickness and slenderness ratio

The corrosion depth ratio D_C in Eq. (7) denotes the ratio of the wall thickness loss to the original wall thickness of the steel tube; thus, in addition to the corrosion depth, the effect of the wall thickness of the steel tube should also be taken into consideration. In Fig. 7, it can be observed that, when the wall thickness of circular steel tubes is small, the corrosion can easily cause serious reliability index degradation; however, when the wall thickness is larger, the effect of corrosion is relatively weak. Therefore, in the follow-up parametric analysis, it is necessary to make a more detailed parameter division for steel tubes with small wall thickness.

In Fig. 8, it can be observed that the reliability index of the steel tube increased with the increase of the slenderness ratio. When the slenderness ratio was larger than 70, the effect of corrosion on the reliability index decreased with increasing slenderness ratio. This phenomenon can be attributed to that, with the increase of the slenderness ratio, the initial bending phenomenon of large-slenderness steel tubes becomes increasingly apparent, and the effect of local defects and centroid deviation induced by corrosion on the bearing capacity becomes weaker. Based on the calculation results, when summarizing the reliability index under different conditions, the slenderness ratio can be simply classified into five regions, i.e., less than 40, 40-70, 70-100, 100-130, and 130-150.

5. Residual life expectancy

5.1. Design goals of the GB50068-2018 specification

Currently, the limit state design method based on the probability theory and expressed in terms of sub-factors is commonly used in structural design codes. In GB50068-2018 [19], the reliability requirements of the structure are divided into different security levels according to the possible consequences of structural damage. The corresponding lower limit values of the reliability indices are listed in Table 6.

Table 6
Reliability indices of structural components

Damage Type	Security Level		
	Level I	Level II	Level III
Ductile damage	3.7	3.2	2.7
Brittle damage	4.2	3.7	3.2

Ductile damage means that the structural elements undergo obvious deformation or other precursors prior to damage, while brittle damage is associated with no obvious deformation or other precursors prior to damage. Most of the structures are commonly designed based on security level II, and the damage of steel structures is generally considered to be ductile damage [14]; thus, the lower limit for the reliability index in the design corresponding to this study was $\beta_0 = 3.2$.

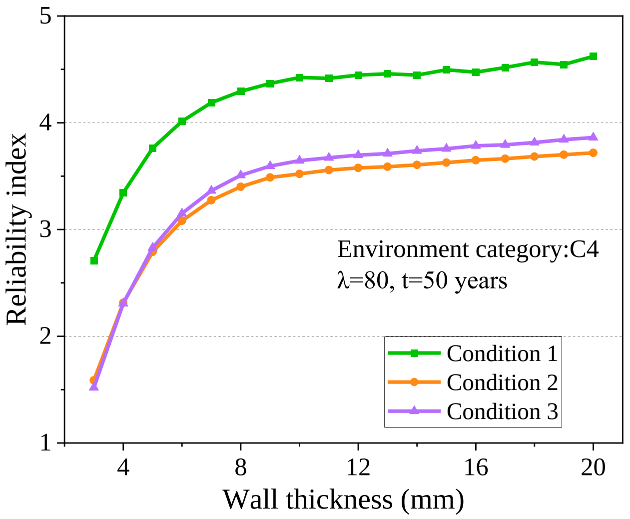

Fig. 7 Reliability index as a function of the wall thickness

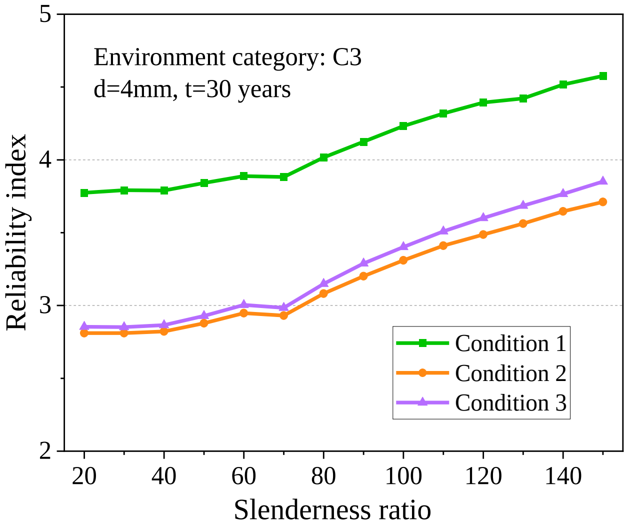

Fig. 8 Reliability index as a function of the slenderness ratio

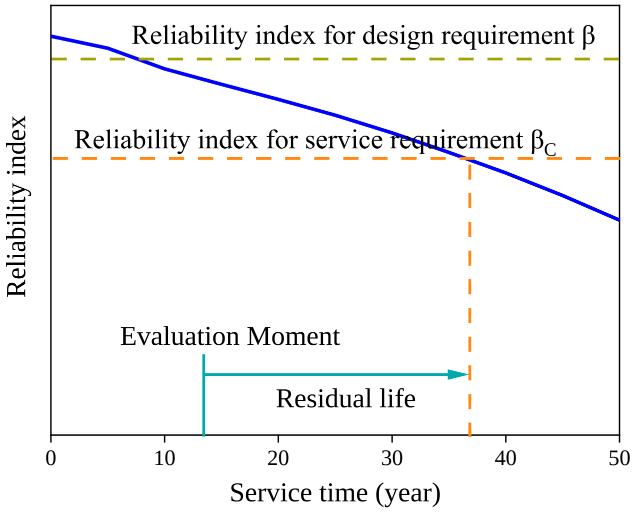

Fig. 9 Relationship between reliability index and remaining life

5.2. Residual life prediction

It should be highlighted that the remaining life of a structural member based on reliability theory is not the time remaining until the structure is destined to fail or be destroyed. In fact, under the reliability theory, just as no structure is completely safe and never likely to fail, no structure is 100% destined to fail. The safety of a structural component is related to a certain probability, and the prediction of its residual life is also based on a certain reliability index, i.e., the end of service life is considered to have been reached when the reliability index of the structure is below a certain level. This reliability index can be called the reliability index for the service requirement β_C, which corresponds to the corrosion duration called the ultimate corrosion duration T_C. For the assessment of in-service structures, the residual life of the members under the reliability index for the service requirement β_C can be determined by subtracting the ultimate corrosion duration from the elapsed in-service time. The relationship between the indicators and the residual life is presented in Fig. 9.

According to the above analysis, determining the reliability index for the service requirement β_C and calculating its corresponding ultimate corrosion duration T_C are the core elements of determining the residual life. Currently, there is no unified conclusion on the reliability index of the endurance limit state, and the design codes [14] provide only a recommended value of 1.0-2.0 for the reliability index of the first type of endurance limit state, e.g., cover damage, steel bar rust, etc. Nevertheless, for the other type of durability limit state, which is directly related to the bearing capacity and structural safety of members, there is no suggestion regarding the appropriate reliability index value. Considering that the problems caused by the third category of durability problems are more severe, the reliability index value of 1.0-2.0 may be on the low side. To meet the safe use requirements of the structure, this paper suggests that β_C should be taken according to the lower security level (Table 1). For instance, for ductile damage members with security level 1, the β_C needs to be designed for ductile damage members with security level 2. Therefore, the β_C corresponding to the ultimate corrosion duration of second-class ductile damage components needs to be used, which is 2.7 (Table 6).

Through linear interpolation of the reliability index, the ultimate corrosion duration T_C of round steel tube components under different corrosion conditions can be determined.

Under C1 and C2 corrosion environments, the reliability index of all components is higher than the value of β_C after 50 years, and the lowest value is 3.15; thus, the T_C can be considered to be more than 50 years. This is mainly due to that the reliability indices specified in the codes are "lower limit values", i.e., any structural calculation results should be higher than this value. After several revisions of the relevant codes, the reliability index for the initial design of the structure is now significantly higher than the target reliability index (3.2). In addition, the code indicates that the current reliability index is high in order to leave room for "environmental factors" [24]. Tables 7 to 10 lists the ultimate corrosion duration of steel tubes in the C3, C4, C5A, and C5B corrosion environments, respectively. It can be found that the severity of the corrosive environment can significantly affect the ultimate corrosion duration T_C. Furthermore, when the wall thickness or slenderness ratio is increased, the ultimate corrosion duration will increase as well, indicating that the structural members can withstand longer corrosion times on the premise of ensuring safety.

Table 7
Ultimate corrosion duration in C3 type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	41.8	50+	50+	50+	50+	50+	50+	50+	50+
40-70	46.3	50+	50+	50+	50+	50+	50+	50+	50+
70-100	48.6	50+	50+	50+	50+	50+	50+	50+	50+
100-130	50+	50+	50+	50+	50+	50+	50+	50+	50+
130-150	50+	50+	50+	50+	50+	50+	50+	50+	50+

Table 8
Ultimate corrosion duration in C4type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	19.8	31.9	44.5	50+	50+	50+	50+	50+	50+
40-70	23.1	35.4	47.4	50+	50+	50+	50+	50+	50+
70-100	31.3	40.2	50+	50+	50+	50+	50+	50+	50+
100-130	40	50+	50+	50+	50+	50+	50+	50+	50+
130-150	44	49	50+	50+	50+	50+	50+	50+	50+

Table 9
Ultimate corrosion duration in C5A type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	8	11.4	18.5	25	39.1	50+	50+	50+	50+
40-70	9.9	15.6	21.9	27.4	43.5	50+	50+	50+	50+
70-100	13.9	19.1	26.4	36.3	48	50+	50+	50+	50+
100-130	18.3	27.5	34.8	46.4	50+	50+	50+	50+	50+
130-150	21.1	32.8	42.8	50+	50+	50+	50+	50+	50+

Table 10
Ultimate corrosion duration in C5B type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	4.1	6.8	9.4	13.6	22	32.1	42.8	50+	50+
40-70	5.4	8.7	12.3	17	25.6	34.8	46.3	50+	50+
70-100	8.2	11.5	15.4	22.2	33	41.3	49.5	50+	50+
100-130	10.5	20.9	21.8	27.7	39.5	50+	50+	50+	50+
130-150	11.9	20.3	26.8	32.4	48.5	50+	50+	50+	50+

6. Design correction

6.1. Suggestions for design corrections

According to Eqs. (6)-(8), the limit state design expressions for structural members contain various sub-factors, the values of which are determined by the code values regarding the reliability indicators. These reflect the acceptable level of the risk posed by structural failure. However, these reliability indicators and sub-factors do not take the effect of corrosion into account. When the bearing capacity of structural members is degraded due to corrosion, the reliability index is likely to no longer meet the corresponding reliability index requirement at the time of design, which means that the structural failure risk exceeds the acceptable level.

To tackle this problem, the corrosion coefficient γ_C is introduced into the structural design to consider the bearing capacity degradation and the reliability index decrease induced by corrosion. Accordingly, the load-bearing capacity limit state can be re-written as:

$$\gamma_C \varphi A_d f_d = \gamma_0(\gamma_G S_{GK} + \gamma_{LR} S_{LRK} + \psi \gamma_W S_{WK}) \tag{9}$$

By introducing a corrosion factor γ_C lower than 1, the cross-sectional area required in the design phase of the structure will be increased, enhancing its ability to resist loads. There is a correlation between the corrosion coefficient γ_C and the corrosion time of components, which, in this study, is conservatively determined as the design life of 50 years for ordinary houses and structures. Moreover, its calculation process takes into account the increase in the wall thickness in order to reduce the impact of corrosion. A trial algorithm was adopted to gradually reduce the value of γ_C and calculate the reliability index of the corresponding case until this becomes greater than or equal to the value of 3.2 taken from the specification. It should be noted that this value is taken considering the structural safety. This paper has been relatively conservative to use the reliability index for the design requirement at the limit state of the bearing capacity as the target.

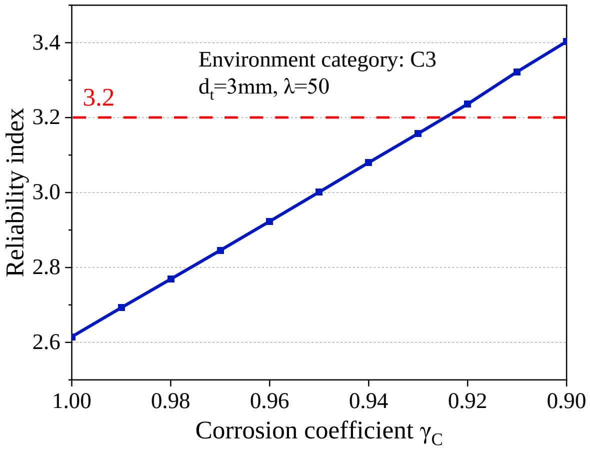

Fig. 10 Reliability index as a function of the corrosion coefficient

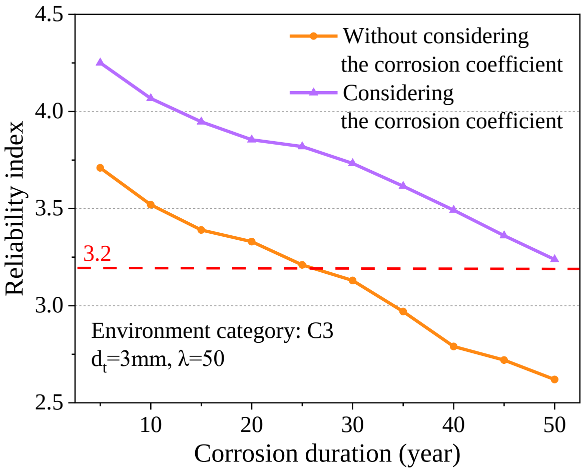

Fig. 11 Corrected reliability index

Fig. 10 plots the reliability index of the structural members for a 50-year corrosion duration as a function of the corrosion coefficient γ_C. Fig. 11 illustrates the trend of the reliability index of the member after correcting the corrosion factor. The analysis results indicated that, by introducing the corrosion factor, the reliability indices of the steel members during the entire service period are greater than the required reliability index, which can guarantee the safety of the structure.

6.2. Corrosion coefficient value

Tables 11 to 14 list the corrosion coefficient γ_C values which can meet the reliability index requirements of the design code after trial calculations. In practice, the cross-sectional area A_0 obtained without taking the corrosion effect into consideration should be divided by the corrosion coefficient γ_C to determine the cross-sectional area A_1 that satisfies the corrosive environment. Subsequently, the wall thickness of the steel tube should be re-selected according to the new cross-sectional area (Fig. 12). The above adjustment process provides sufficient safety margins for steel members in harsh corrosive environments and meets the current structural design requirements. It should be clarified again that, for steel members in the C1 and C2 environments, the reduction of the load capacity due to corrosion is negligible (see Section 5.2); therefore, no adjustment to the cross-section is required.

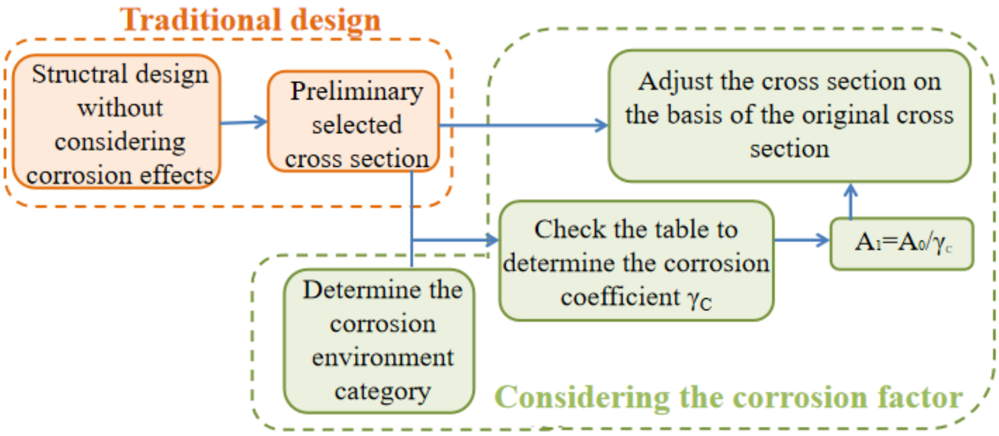

Fig. 12 Consideration of corrosion effects in the structural design process

Table 11
Corrosion factors for C3 type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	0.91	0.96	0.98	0.99	1	1	1	1	1
40-70	0.91	0.97	0.99	1	1	1	1	1	1
70-100	0.94	0.99	1	1	1	1	1	1	1
100-130	0.99	1	1	1	1	1	1	1	1
130-150	1	1	1	1	1	1	1	1	1

Table 12
Corrosion factors for C4 type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	0.82	0.88	0.91	0.95	0.98	1	1	1	1
40-70	0.82	0.88	0.93	0.96	1	1	1	1	1
70-100	0.84	0.91	0.95	0.99	1	1	1	1	1
100-130	0.89	0.95	1	1	1	1	1	1	1
130-150	0.92	0.98	1	1	1	1	1	1	1

Table 13
Corrosion factors for C5A type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	0.68	0.76	0.81	0.85	0.93	0.94	0.96	0.98	0.99
40-70	0.68	0.77	0.81	0.86	0.93	0.95	0.97	0.99	1
70-100	0.7	0.77	0.82	0.86	0.95	0.97	0.99	1	1
100-130	0.74	0.81	0.87	0.92	0.97	1	1	1	1
130-150	0.75	0.84	0.92	0.95	0.99	1	1	1	1

Table 14
Corrosion factors for C5B type corrosive environment

Slenderness ratio	Wall thickness (mm)								
	3	4	5	6	8	10	12	14	16
15-40	0.58	0.67	0.72	0.77	0.84	0.88	0.91	0.94	0.96
40-70	0.58	0.68	0.72	0.77	0.84	0.88	0.92	0.94	0.97
70-100	0.61	0.68	0.74	0.77	0.85	0.92	0.96	0.98	1
100-130	0.62	0.71	0.78	0.81	0.9	0.95	0.99	1	1
130-150	0.65	0.73	0.81	0.86	0.92	0.98	1	1	1

7. Conclusions

In this paper, the time-varying reliability of corroded round steel tubes has been systematically analyzed. Moreover, a method for predicting the residual bearing capacity of members based on the time-varying reliability and a steel tube design correction method have been thoroughly investigated. The following main conclusions can be drawn.

1) A reliability function considering the effect of corrosion was established and the process of local corrosion development under coating protection was considered. Based on the Monte Carlo method, the effects of corrosion duration, corrosion environment category, wall thickness, and slenderness ratio on the reliability index of corroded tubes were analyzed. The reliability indices of various types of round steel tubes under different environmental categories and corrosion durations were determined.

2) Based on the time-varying reliability analysis considering corrosion, a method for predicting the residual life of corroded round steel tubes was proposed, which takes the reliability index for the service requirement β_C into consideration. Furthermore, the ultimate corrosion durations were given for structural evaluation.

3) To meet the requirements regarding the expected reliability indices for round steel tubes in corrosive environments, it has been proposed to modify their cross-section based on the corrosion coefficients. Finally, tables for consulting the corrosion coefficients that can facilitate the engineering design have been provided.

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