SEISMIC PERFORMANCE ANALYSIS OF REINFORCED CONCRETE FRAMES CONSIDERING NON-UNIFORM STEEL CORROSION

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Abstract

Reinforced concrete structures are often in a working state with cracks due to the long-term effect of load, erosion environment or various coupling factors during their service lives. The interaction between load and corrosion environment will lead to the deterioration of durability of reinforced concrete structures, and the structural degradation caused by corrosion of steel bars is the focus of current research. Over the past decades, a large number of studies at levels from material and component to structure have been done by worldwide researchers, including experiment research, numerical simulation and theoretical analysis. However, most of these studies have been carried out based on accelerated corrosion tests, which are quite different from the actual structural components under load-environment interaction. Moreover, there are relatively few studies on the seismic performance degradation caused by structural durability deterioration. In this paper, the real seismic performance of corroded reinforced concrete frame structure is studied by numerical simulation, considering pitting corrosion of steel bars.

Firstly, the reasonable expressions of mechanical property parameters of corroded steel bars are determined through literature research. Then, the numerical models of corroded reinforced concrete frame structural members are established based on the non-linear finite element software MSC.MARC adopting the appropriate constitutive models of steel bar and concrete, and used to simulate an existing corroded reinforced concrete beam test under load-environment coupling action. During the numerical simulation, two different situations, i.e. uniform corrosion and pitting corrosion of steel bars, are considered respectively. Through the comparison of results between numerical models and tests, the validity of the numerical model and the necessity of considering pitting corrosion of steel bars are verified. On this basis, the numerical analysis models for a serial of reinforced concrete frame structures, which have worked for different years, are established. The relevant parameters of the numerical models are determined, referring to the offshore atmospheric environment of a coastal city in China. Finally, nonlinear time history analyses of these frame structures under different seismic intensity conditions are carried out using a set of earthquake records. And some typical indexes, including storey drift, structural failure mode and collapse probability, are obtained to investigate the seismic performance of corroded reinforced concrete frame structures.

It is shown that the seismic displacement demand of the corroded RC frame structure increases and the structural ultimate deformation capacity decreases as the service time increases. And the Pitting corrosion of steel bars has an effect on furtherly increasing the displacement demands of the corroded RC frame structures and reducing the seismic ultimate deformation capacity, which leads to a worse seismic collapse-resistance performance and lower seismic reliability for the structural models considering the pitting corrosion than those uniform corrosion models.

Keywords: reinforced concrete frame; pitting corrosion; seismic performance; collapse probability.

1. Introduction

The durability of reinforced concrete (RC) structures has been widely concerned, and the corrosion of steel bars is the main factor affecting the durability of RC structures [1]. Due to the coupling effect of the load and the erosion environment, there is non-uniform corrosion, i.e. pitting, in the steel bars of the actual engineering RC structures to a certain extent. And the non-uniform corrosion of the steel bars in the RC structures in coastal area is more serious as a result of the high chloride ion concentration in the atmosphere environment, which leads to the structural performance degradation before the design service life is achieved [2,3]. For decades, a large number of studies at levels from material and structural members to the whole structures have been done by worldwide researchers [4], including experiment research, numerical simulation and theoretical analysis. However, these studies are mostly based on accelerated corrosion tests [5], in which the corrosion state of the steel bars is close to uniform corrosion. So for the RC structures in coastal area, this deviates from the actual situation of pitting corrosion in steel bars to some extent. In addition, the pitting corrosion of steel bars will lead to a decrease in the ductility of the material [6], which in turn reduces the seismic performance of structural members and whole structures. At present, there are relatively few related studies.

In this paper, considering pitting corrosion of steel bars, the seismic performance of corroded RC frame structure in the coastal area is studied by numerical simulation. Firstly, the reasonable mechanical property parameter expressions of corroded steel bars are determined based on the literature research. Then, the effectiveness of the numerical analysis model for corroded RC frame structural members and the necessity of considering pitting corrosion are verified by comparing the results of numerical models with the experimental results of an existing RC beam test study under the load-environment coupling action. On this basis, a five-storey RC frame structure is designed with the offshore atmospheric environment of a coastal city in China as the background. Based on the results of nonlinear time history analysis under a set of ground motion inputs, the seismic performances of corroded structures after different service years are studied, and the influence of pitting corrosion on the seismic performance of structure is discussed. It should be noted that only the corrosion of longitudinal reinforcement is considered in this study, while the corrosion of stirrups and the degradation of concrete materials are not considered for the sake of simplicity.

2. Material parameters of corroded steel bars

In this paper, seismic analysis models for RC frame structures are established by using THUFIBER [7], a fiber-beam-element package that was developed based on the finite element software MSC.MARC. In THUFIBER, the fiber-beam-element is used to simulate the RC frame beam and column members, and the uniaxial material constitutive relationship of the steel bar and concrete fiber is specified by the user. The effectiveness of THUFIBER in the simulation of the nonlinear behavior of uncorroded RC frames under strong earthquakes has been verified by reference [7]. On this basis, the degradation of the mechanical properties of the corroded longitudinal steel bar under chloride erosion is considered, and the material parameters are determined through literature research.

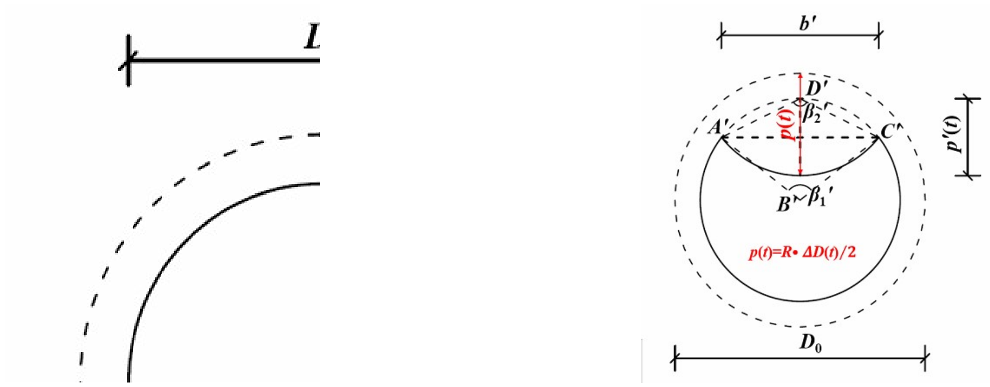
2.1 Cross-section corrosion rate of steel bars

According to the literature [8], the cross-section area model shown in Fig.1 (a) can be used to represent the uniform corrosion that uniformly occurs along the radial direction of the steel bar. And the model in Fig.1 (b) can be used to show the non-uniform corrosion (pitting corrosion), i.e. corrosion in the form of a sphere to the interior of the steel bar on the basis of uniform corrosion.

The cross-section corrosion rate η_s for a certain section of steel bar is the loss rate of the area after corrosion relative to the uncorroded area, and is determined by Eq. (1):

$$\eta_s = \frac{A_0 - A_r}{A_0} \qquad (1)$$

where A_0 and A_r are the cross-section areas of the uncorroded and corroded steel bars, respectively, and A_r can be obtained according to the different description models of corrosion cases shown in Fig.1[8].



(a) Uniform corrosion

(b) Pitting corrosion

Fig. 1 –Description models of different corrosion cases

For the uniform corrosion case, according to Faraday's law, the reduction in steel bar diameter at time t can be expressed as Eq. (2):

$$\Delta D(t) = D_0 - D(t) = 0.0232(t - t_i) I_{\text{corr}} \tag{2}$$

where I_{corr} is the corrosion current density [8]. t_i is the initial corrosion time of the steel bar [9], which can be determined by Eq. (3):

$$t_i = \sqrt[1-m]{\frac{X^2}{2D_{28}T_{28}^m \left\{\Phi^{-1}\left[\frac{1}{2}\left(1-\frac{C_{\text{cr}}}{C_0}\right)+0.5\right]\right\}^2}} \tag{3}$$

where, X is the distance between the outer edge of the target steel bar in the concrete member and the concrete surface. D_{28}, C_{cr}, and C_0 are environment-related parameters, which are determined according to reference [10] and specific environments.

Therefore, for the uniform corrosion case, the remaining cross-section area of the steel bar at time t ($t > t_i$) can be calculated by Eq. (4):

$$A_r(t) = \frac{\pi\left[D_0 - \Delta D(t)\right]^2}{4} \tag{4}$$

For the pitting corrosion case, the pitting depth outside the ring at time t ($t > t_i$) as shown in Fig.1 (b) can be expressed by Eq. (5):

$$p'(t) = 0.0116(t - t_i) I_{\text{corr}} R - \frac{1}{2}\Delta D(t) \tag{5}$$

where, R is the ratio of the total pitting depth $p(t)$ to the uniform corrosion depth $\Delta D(t)/2$, as shown in Fig.1, and the range of R for the pitting corrosion case is usually 4~8 [10].

Therefore, for the pitting corrosion case, the remaining cross-section area $A_r(t)$ can be calculated by Eq. (6):

$$A_r'(t)=\begin{cases}\dfrac{\pi\left(D_0-\Delta D(t)\right)^2}{4}\text{-}A_1'\text{-}A_2' & p'(t)\le\dfrac{D_0-\Delta D(t)}{\sqrt{2}}\\ A_1'\text{-}A_2' & \dfrac{D_0-\Delta D(t)}{\sqrt{2}}<p'(t)\le D_0-\Delta D(t)\\ 0 & p'(t)>D_0-\Delta D(t)\end{cases} \qquad (6)$$

where, A_1 'and A_2' are the areas enclosed by the arc $A'C'D$ 'and the dashed line segment $A'C'$, the arc $A'B'C'$ and the dashed line segment $A'C'$ in Fig.1 (b), respectively; b 'is The chord length at the intersections of the corroded hemisphere and the round section of the steel bar.

2.2 Constitutive relationship of corroded steel bar

Based on the constitutive relationship of uncorroded steel bars in THUFIBER [7], the yield strength f_y, ultimate strength f_u, and ultimate tensile strain ε_{su} of the rebar are modified to simulate the effect of corrosion on these mechanical properties. According to literature research, different relationship between the degraded mechanical properties and the corrosion rate η_s of corroded steel bars have been established by worldwide scholars through experiments. In this paper, the degradation model proposed by Zhang [6] are adopted, which is based on experimental data of several scholars, as shown in Eq. (7):

$$k_{yc}=\frac{f_{yc}}{f_{y0}}=\frac{1\text{-}1.049\eta_s}{1\text{-}\eta_s} \qquad (7\text{-a})$$

$$k_{uc}=\frac{f_{uc}}{f_{u0}}=\frac{1\text{-}1.119\eta_s}{1\text{-}\eta_s} \qquad (7\text{-b})$$

$$\alpha_{uc}=\frac{\varepsilon_{suc}}{\varepsilon_{su0}}=\mathrm{e}^{-2.501\eta_s} \qquad (7\text{-c})$$

where the subscripts “0” and “c” correspond to the mechanical parameters of the uncorroded and corroded steel bars, respectively. k_{yc}, k_{uc} and α_{uc} are the reduction coefficients of the yield strength, ultimate strength and ultimate strain of the corroded steel bar relative to the uncorroded one, respectively. η_s is the average loss rate of the cross-section area within the length of the rebar sample during the test, and is generally calculated by weighing the rebar sample. For an element of the numerical analysis model of this paper, the section area parameters of steel bar in the case of uniform corrosion and pitting corrosion can be calculated by Eq. (1) - (6). And the mechanical property degradation parameters of the steel bar are determined according to Eq. (7).

3. Numerical model validation based on corroded RC beam test

An existing corroded RC beam test [11] is selected for numerical simulation, whose performance is degraded under the load-environment coupling action. Based on the material constitutive relationship determined in the previous section, the numerical modeling method for corroded RC frame members used in this paper is further explained. The validity of the numerical model and the necessity of considering pitting corrosion are verified by comparison with experimental results.

3.1 Test Overview

In the simulated test, a RC beam that had been corroded for 26 years under the load-environment coupling action in the laboratory, marked as beam BC, was tested with a three-point loading system until failure. Test was also performed on an uncorroded reference beam with the same age, marked as beam BR. The mid-span load-displacement curves of the two beams were recorded. The diameter losses of the steel bars and the tensile property test results of the uncorroded steel bars are available. The test beam is 3000 mm long and the concrete cover is 10 mm thick. Some information about member size and reinforcement configuration of the test beam is shown in Fig.2. More details about this test can be found in reference [11].

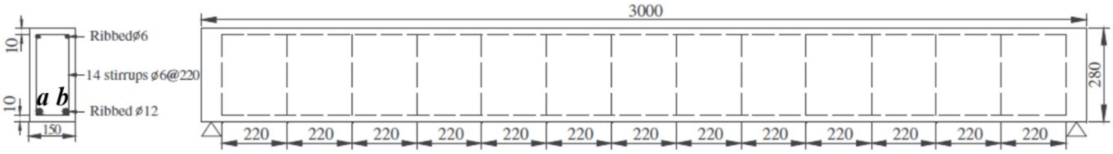


Fig. 2 – Member size and reinforcement configuration of the test RC beam

3.2 Numerical Modeling

3.2.1 Determination of element size

In structural nonlinear analysis involving material elastoplasticity, the element size of the model has an important influence on the analysis results. In this paper, the plastic hinge length l_p of the RC frame member is taken as the corresponding element size [12]. And the adopted empirical formulas to calculate the plastic hinge length of RC frame beam and column are shown in Table 1.

Table 1 – Empirical formula of the plastic hinge length

Structural member type	Proposer	Formula
beam	Hu[12]	$l_\mathrm{p} = \frac{2}{3}h_0 + a < h_0$
column	Pauley[12]	$l_\mathrm{p} = 0.08H + 0.022 f_\mathrm{y} d_\mathrm{s}$

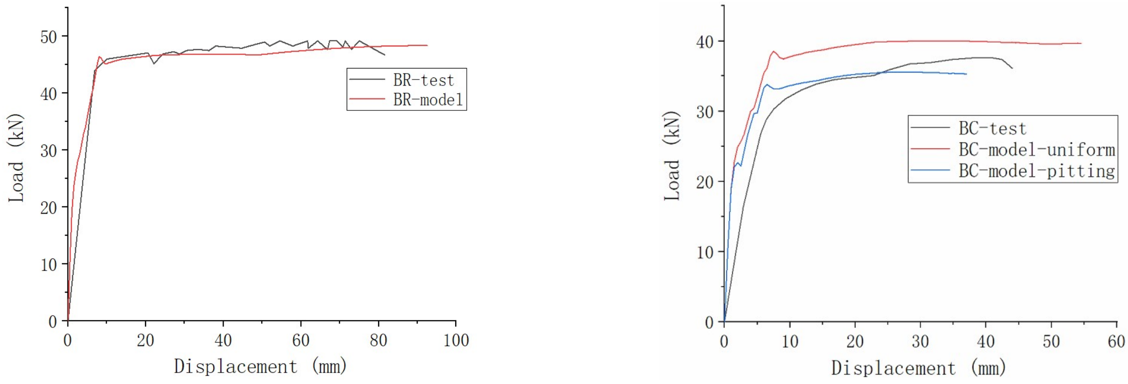
The element size of the numerical model for this RC beam is 175mm, an approximate value calculated according to the formula of Hu in Table 1.

3.2.2 Modeling method for uniform corrosion and pitting corrosion

During the numerical simulation of the test reference beam BR, uniform corrosion of steel bars is assumed. However, two different cases, i.e. uniform corrosion and pitting corrosion are considered respectively in the numerical simulation of the test corroded beam BC. In the case of uniform corrosion, the cross-section area data and mechanical property parameters of the rebars in the element are set directly based on the average corrosion rate data provided in the literature. In the numerical model considering pitting corrosion, the following simplified scheme is adopted as the information of parameters to quantitatively calculate the residual area of steel bars after pitting based on Eq. (1)-(6) is incomplete in the literature of this test. Acoording to existing research, the average corrosion rate is higher in the parts with larger bending moments [13], and the pitting corrosion phenomenon is also more serious in the parts with higher average corrosion rates [14]. Therefore, it is assumed that pitting corrosion only occurs at the two elements in the middle of the numerical model where the bending moment is the largest for such a simply supported beam for the sake of simplicity. Furthermore, the corrosion rate of these two pitting elements here is obtained by enlarging the average corrosion rate of the whole rebar provided in the literature by 1.5 times. Then the constitutive parameters of the corroded rebars are calculated according to Eq. (7).

3.3 Results and discussion

The mid-span load-displacement curves of the uncorroded beam BR and the corroded beam BC are shown in Fig.3. As shown in Fig.3, for uncorroded beam BR, the ultimate load-bearing capacity and deformation capacity results from the numerical simulation curve and the test curve agree well. For the corroded beam BC, compared with the uniform corrosion simulation curve, the pitting simulation curve is more in agreement with the test curve. Therefore, for the RC structures and members that are actually subjected to the load-environment coupling effect, it is necessary to consider the effect of the pitting corrosion of the steel bar on its mechanical performance when the corrosion rate of the steel bar is relatively high.



(a) beam BR

(b) beam BC

Fig. 3 – The load-displacement curve results

4. Seismic performance analysis of corroded RC frames

According to the current Chinese design code [15,16], a five-storey RC frame structure example is designed with the background of the offshore atmospheric environment 200m away from the coast in Luohu District, Shenzhen City, China. And the service period of the structure *t* is set as 0, 10, 20, 30, 40 and 50 years, respectively. Seismic numerical analysis models are established for the structures after different years of service in accordance with the modeling methods described in Sections 2 and 3, considering uniform and pitting corrosion of steel bars respectively. Based on a set of 22 far-field ground motion records recommended in ATC-63 [17] and the widely used EI-Centro ground motion, the nonlinear time history analysis is carried out to investigate the structural seismic performance.

4.1 Design information of RC frame Structure

The five-storey RC frame structure example is assumed to be in a common category with Site Class III (medium soft soil site). The design seismic intensity level is 7 degree and the corresponding design peak ground motion acceleration (PGA) is 0.10g. The structure has a regular layout of plan and elevation. The plan layout of the structure is shown in Fig.4. Cross-section sizes and reinforcement of members are shown in Fig.5. The concrete grade is C30, corresponding to a characteristic compressive strength of 20.1MPa. And the grade of steel bar is HRB400 with a yield strength of 400MPa.

4.2 Numerical model

The environmental parameters of the structure example are: D_{28}=7.94x10^{-12}m^2/s, C_{cr}=1.5kg/m^3, C_0=3.35kg/m^3. Substituting the above parameters into Eq. (3), the initial corrosion time t_i of longitudinal rebars is 5.80 years.

For the case of structural model assuming uniform corrosion of steel bars, the residual recross-section areas of the rebars after different service time are calculated according to Eq. (2) and (4). For the pitting corrosion model, the similar simplified modeling scheme is adopted here, i.e. pitting corrosion only occurs at the end element of the frame beam and column members, as the the bending moment at this place is larger than the other places of the structural member under the action of gravity. Then the value of R is set as 6 here for the element considering pitting corrsion of steel bars and the remaining areas after different service time are calculated according to Eq. (2), (5) and (6). Then the constitutive parameters of the rebars of frame beams and columns are calculated according to Eq. (1) and (7).

Table 2 lists the longitudinal rebar parameters of frame structural members for all the numerical models corresponding to both cases of uniform corrosion and pitting corrosion after different service period, including the corrosion rate η_s, the ultimate strain ε_{suc}, and the cross-sectional area of each longitudinal bar A_r.

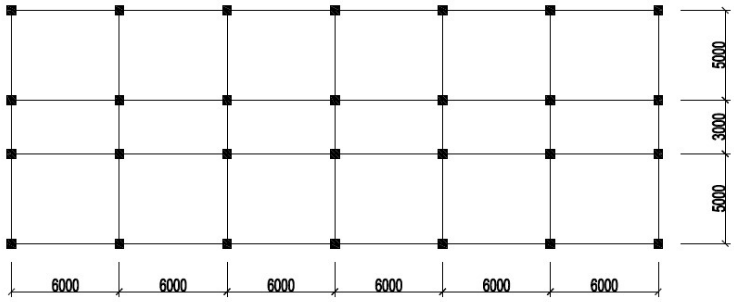
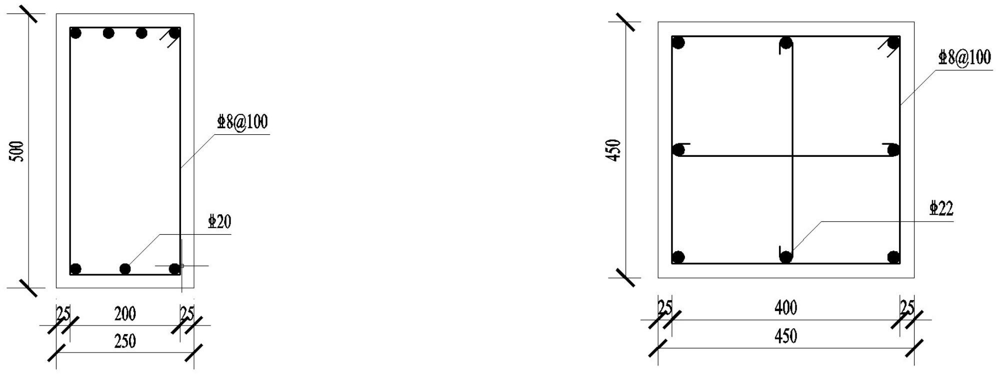


Fig. 4 – Plan Layout of the designed RC frame example (unit: mm)



(a) Beam (b) Column

Fig. 5 – Cross-section sizes and reinforcement of structural members (unit: mm)

Table 2 – The longitudinal rebar parameters of the members

t (year)	Corrosion model	Frame beam			Frame column		
		η_s (%)	ε_{suc}	A_r (mm^2)	η_s (%)	ε_{suc}	A_r (mm^2)
0	-	0.00	0.0800	314	0.00	0.0800	380
10	uniform	1.94	0.0762	308	1.76	0.0766	373
	pitting	2.06	0.0760	308	1.86	0.0764	373
20	uniform	6.48	0.0680	294	5.90	0.0690	358
	pitting	7.79	0.0658	290	6.98	0.0672	354
30	uniform	10.91	0.0609	280	9.95	0.0624	342
	pitting	14.60	0.0555	268	13.02	0.0578	331
40	uniform	15.24	0.0546	266	13.90	0.0565	327
	pitting	22.38	0.0457	244	19.87	0.0487	305
50	uniform	19.46	0.0492	253	17.77	0.0513	313
	pitting	30.99	0.0369	217	27.44	0.0403	276

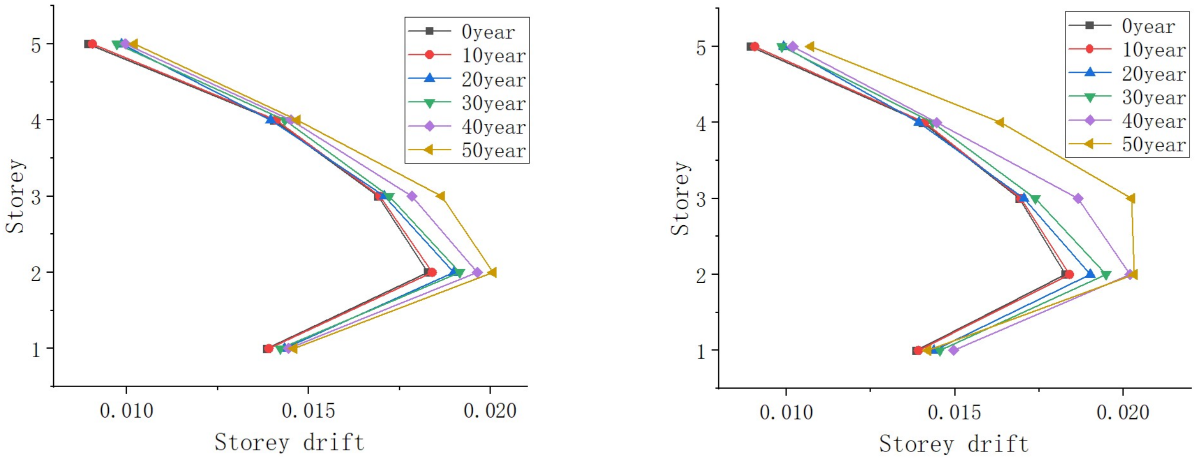
4.3 Structural elastoplastic displacement demands under strong earthquakes

The ground motion is input along the short side of the structure, and PGA is used as the ground motion intensity index. The PGA is set to 0.62g, which has exceeded the ground motion intensity of maximum considered earthquake for the design seismic intensity level of 7 degree according to Chinese seismic code. The results of the maximum storey drift distributions of each structural model are calculated to examine the effect of the service year and pitting corrosion on the structural seismic displacement demands.

The results of all numerical models show that structure after various service years (both cases of uniform corrosion model and pitting corrosion model) has entered a severe plastic phase, but no collapse has occurred. And the analysis results based on different input ground motions showed a relatively consistent phenomenon. Here the analysis result of EI-Centro ground motion is taken as an example to explain in detail.

4.3.1 Influence of service time on seismic displacement demands of structures

The maximum storey drift distribution results of the structural models after different service years corresponding to uniform corrosion and pitting corrosion are given in Fig.6 (a) and Fig.6 (b), respectively. It can be seen from Fig.6 that no matter what kind of steel bar corrosion model, the structural elastoplastic seismic displacement demand under strong earthquakes increases as the service time increases. The reason is that the cross-section area of longitudinal rebar in the structural member decreases (as shown in Table 2) as the service time increases, resulting in a reduction of seismic bearing capacity of the member and the whole structure. So the structure yields earlier under strong earthquakes, which causes the structural seismic displacement demand increases.



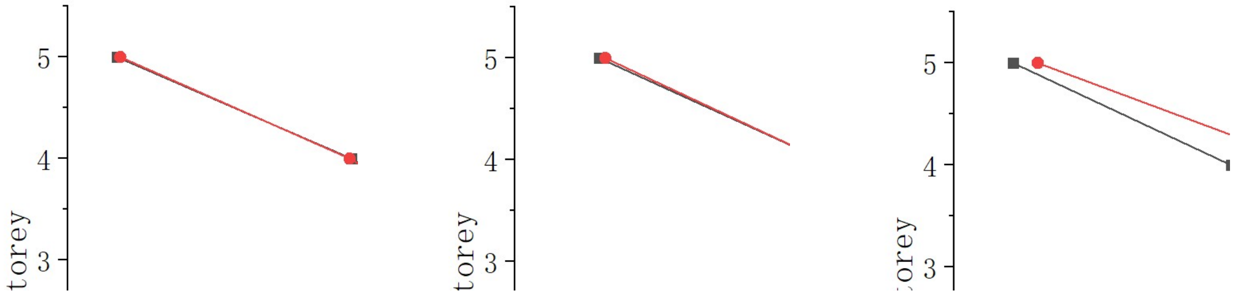
(a) Uniform corrosion model (b) Pitting corrosion model

Fig. 6 – The maximum storey drift distributions of structures after different service times (results of EI-Centro ground motion with PGA of 0.62g)

4.3.2 Effect of pitting corrosion on seismic displacement demands of structures

The structural maximum storey drift distribution results of the two steel corrosion models after a certain period of service are further compared. The comparison results with the service period of 20, 30 and 50 years are given in Fig.7 (a), (b), and (c), respectively.

As shown in Fig.7, after a service period of 20 years, pitting corrosion has little effect on the elastoplastic seismic displacement demands of the structure. However, the storey drift demand of the pitting model begins to exceed that of the uniform corrosion model when t reaches 30 years. And after a service period of 50 years, the storey drift demand of the pitting model is significantly larger than the uniform corrosion model results. The reason is that considering the pitting corrosion of the steel bar, the cross-section area of longitudinal rebar in structural members is smaller than that of the uniform corrosion model after the same service period. This results in a lower seismic bearing capacity and a higher elastoplastic displacement demand of the structural model considering pitting corrosion compared with the uniform corrosion model. Nevertheless, when the service time is short, the difference between the steel bar areas in the two corrosion models is very small. Therefore, only when the service time is long enough, the effect of pitting corrosion on the elastoplastic seismic displacement demands of the structure is obvious.



(a) t= 20 years (b) t=30 years (c) t=50 years

Fig. 7 –The structural maximum storey drift distribution results of the two steel corrosion models (results of EI-Centro ground motion with PGA of 0.62g)

4.4 Structural seismic collapse-resistance performance

In order to study the structural seismic collapse-resistance performance, the PGA of each input ground motion is set large enough to ensure that structural model collapses. In the time history analysis by using THUFIBER, an elemental deactivation technique is employed [7]. The fiber beam element will be eliminated when the ultimate strains of enough rebar fibers of this element are reached, and then the structure will be further damaged until it collapses.

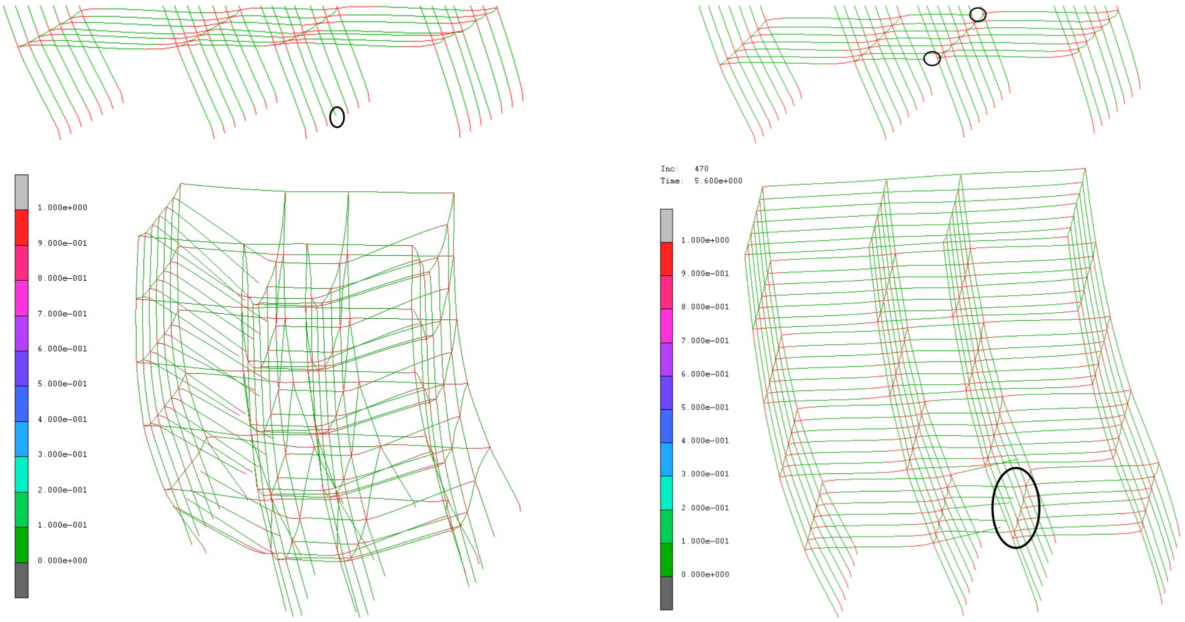
According to the analysis results based on different input ground motions, it is found that the effects of service time and corrosion model on the collapse mode and deformation capacity of the structure are generally consistent. Here the analysis result of EI-Centro ground motion with PGA of 1.6g is taken as an example for specific description. Note that all structural numerical models collapse under EI-Centro ground motion with such a PGA.

4.4.1 Influence of service time on structural collapse mode and deformation capacity

There are two typical structural failure modes when the service time *t* increases from 0 to 50 years. As shown in Fig.8 (a), the whole structure presents a vertical continuous collapse mode due to the compressive failure of bottom column (marked with circles) in the cases with the service period of 0, 10 and 20 years. However, as shown in Fig.8 (b), for structures after the service time of 30, 40, and 50 years, a large number of frame beams (marked with circles) failed due to the ultimate tensile strain of longitudinal rebar reached, which causes the collapse of the whole structure.

This phenomenon can be explained as follows. The cross-section corrosion rate η_s of the steel bars increases and the area of the longitudinal rebars decreases as the service time increases. On the one hand, the frame beam is mainly subjected to bending load, the bearing capacity of the member is more reduced and the demand for bending deformation increases more obviously than those of the frame column member subjected to compression-bending load, which results in a more significant increase of the strain demand of the tensile rebar in the frame beam. On the other hand, the ultimate deformation capacity of steel bars decreases as the corrosion rate η_s increases (see Eq. (7-c)). Therefore, the frame beam in the structure is more prone to failure caused by the achivement of ultimate tensile strain of rebars as the service time increases, which results in the above-mentioned change of the structural seismic collapse modes.

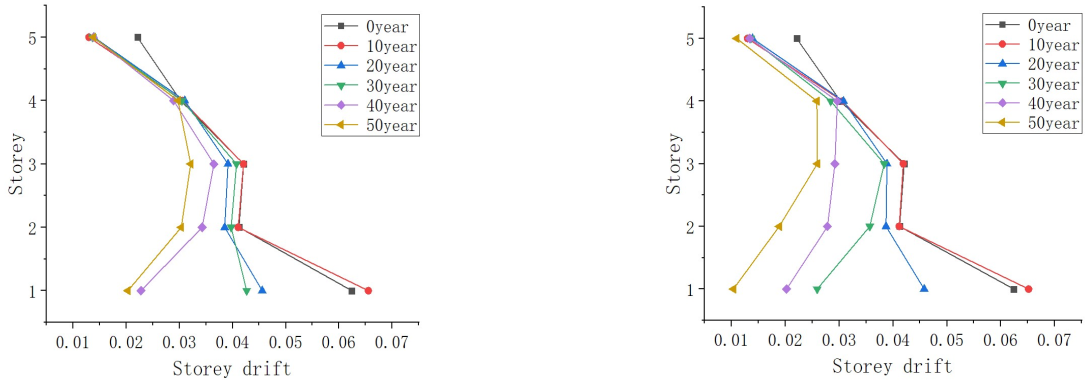
With the increase of service time, the seismic deformation capacity of the structure also declines. The results of the maximum storey drift distributions of the structural model corresponding to uniform longitudinal corrosion and pitting corrosion after different service periods are given in Fig.9 (a) and Fig.9 (b), respectively. Note only the displacement results before the collapse of structure are counted as all the structure models have collapsed under such a strong earthquake. So the storey drift results here can reflect the deformation capacity of the structure to a certain extent. It can be seen from Fig.9 that the seismic deformation capacity of the structure is decreasing as the service time increases for both kinds of corrosion models of steel bar.



(a) Vertical continuous collapse mode caused by the compressive failure of bottom columns

(b) Collapse due to insufficient flexural ductility of frame beams

Fig. 8 –Two typical structural failure modes



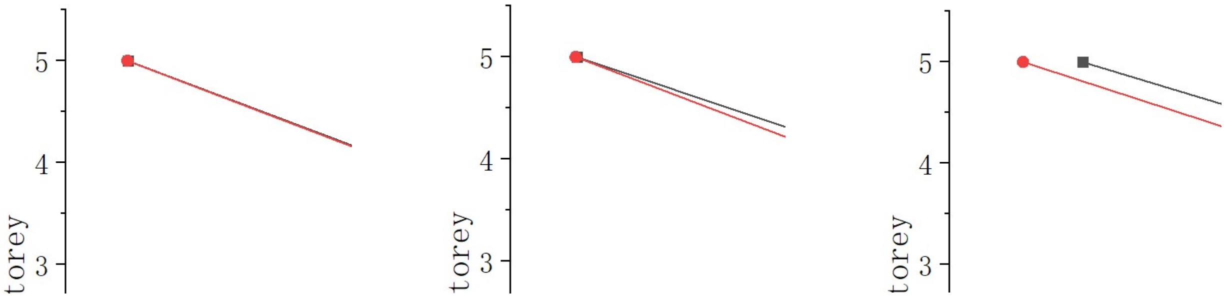
(a) Uniform corrosion model

(b) Pitting corrosion model

Fig. 9 –The maximum storey drift distributions of structures after different service times (results of EI-Centro ground motion with PGA of 1.6g)

4.4.2 Effect of pitting corrosion on structural deformation capacity

The results of the maximum storey drift distributions (before the structure collapse) of structures of the two steel corrosion models after a certain period of service are further compared. The comparison results corresponding to the service time of 20, 30 and 50 years are given in Fig.10 (a), (b), and (c).



(a) t= 20 years (b) t=30 years (c) t=50 years

Fig. 10 – The structural maximum storey drift distribution results of the two steel corrosion models (results of EI-Centro ground motion with PGA of 1.6g)

As shown in Fig.10, when the service time *t* equals to 20 years, the structural ultimate deformation capacities of two steel corrosion models are basically the same. However, when *t* reaches 30 years or more, the structural ultimate deformation capacity of the pitting corrosion model is lower than that of the uniform corrosion model. As metioned above, the cross-section area of longitudinal rebar of pitting corrosion model is smaller than that of the uniform corrosion model under the condition of same service period, and the ultimate deformation capacity of steel bars decreases as the corrosion rate η_s increases. So for the whole structures, it can be inferred that the seismic deformation capacity of the pitting corrosion model is lower than that of the uniform corrosion model. But this phenomenon is only obvious when the service time is long enough as the difference between the steel bar areas of the two corrosion models is very small with a short service time.

4.4.3 Seismic collapse probability results of corroded RC frame structure

Finally, based on the 23 input ground motions whose PGAs are all set to 1g, the corroded RC frame structural example after a service period of 50 years are analyzed for both cases of the two steel bar corrosion models. According to the analysis results, the earthquake-induced structural collapse probability is 57% and 74% for the uniform and pitting corrosion models respectively, showing that the pitting corrosion of steel bars has an effect on reducing the structural seismic reliability. Base on the previous discussion, it is easy to explain such a result. The elastoplastic displacement demand of the pitting corrosion model is higher, while its ultimate deformation capacity is lower, so the seismic collapse-resistance performance of the pitting corrosion model is necessarily worse than that of the uniform corrosion model.

5. Conclusion

Based on comparing with an existing corroded RC beam test with degraded performance under load-environment coupling action, the validity of the numerical model for corroded RC frame structures and the necessity of considering pitting corrosion are firstly verified. Then a five-storey RC frame structure example is designed with the offshore atmospheric environment of a coastal city in China as the background. Based on the elastoplastic time history analysis under 23 ground motion inputs, the seismic performance of corroded structures after different service time is studied, and the conclusions are as follows.

(1) As the service time increases, the elastoplastic seismic displacement demand of the corroded RC frame structure are increases. Moreover, the structural failure mode under strong earthquakes changes from the vertical continuous collapse mode caused by the compressive failure of bottom columns to the collapse due to insufficient flexural ductility of frame beams. And the seismic deformation capacity of the whole corroded RC frame structure also decreases as the service time increases.

(2) Pitting corrosion of steel bars has an effect on increasing the elastoplastic displacement demands of the corroded RC frame structures and reducing the seismic ultimate deformation capacity, which lead to a worse seismic collapse-resistance performance for the structural models considering the pitting corrosion

than those uniform corrosion models. However, this phenomenon is only obvious when the service time is long enough.

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