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Finite element analysis of mechanical property of steel gabled frames after corrosion in warm and humid marine-atmosphere environment

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Abstract. The paper focuses on the condition in which the structure of steel gabled-frame factory building is corroded in ocean-atmosphere environment and leads to reduction of component's effective cross section and degradation of mechanical property, which thus reduces the bearing capacity and leads to a safety problem of the whole structure. By referring to the existing experimental data and research results regarding the corroded steel's mechanical property, the steel structures of different spans before and after the corrosion are modeled to analyze the structural performances after 2 to 20 years of corrosion. The effects of corrosion on damage of the component's cross section and the degradation of mechanical properties of steel are considered. The results show that after corrosion the influence of the reduction of cross section on the bearing capacity is more significant than that of the reduction of stiffness, and the latter is nearly linear.

Keywords. Gabled frame, corrosion, finite element, weight loss ratio, stress ratio

1. Introduction

The steel gabled frame of light-weight factory building is a kind of structure which has been developed rapidly in recent years. Compared with the traditional concrete structure, it has better economical efficiency and applicability, and thus it is more in line with the strategy of national sustainable development[1]. In practical engineering, the steel structure often suffers the corrosion especially caused by marine atmosphere and polluted atmosphere. Many engineering accidents of steel structure show that the corrosion not only causes economic loss, but also threatens the safety of industrial and civil buildings.

It is difficult to implement anti-corrosion maintenance on the structure during the design service life, and so the effect of corrosion on industrial steel structure's performance during the service life is a key problem to solve. Much research work has been done on the corrosion resistance of steel structures around the world, but the foci are mainly on materials themselves, and the components and structures are less involved. The components and structures involved are mainly steel bridges, marine steel structures, etc. The research results for them have limited reference value for the industrial factory buildings which are almost completely exposed to outdoors.

Corrosion of steel can result in the reduction of effective cross-section of the component and decrease in strength and ductility. The pits caused by corrosion can lead to stress concentration[2], which has especially more significant impact in places near the sea in high temperature. For example, a steel structure in Xiamen is 250 meters away from the sea, and after 5 years of service, the yield strength and ultimate strength of some components decreased to 84.1MPa, and the ratio of the yield strength to ultimate strength is 1.0, namely the safety margin is 0[3]. Therefore, it's necessary to study from the structural perspective in order to understand the factors that lead to decrease of the bearing capacity and ductility of the load-carrying components and change of overall structural performance, and the law of corrosion duration's impact on the structural degradation.

The research results in recent years show that it is feasible to analyze the structural performance after corrosion with finite element numerical simulation method[4,5]. Based on the experimental data regarding the degeneration of mechanical property of steel and the reduction of cross section after corrosion in the references[6, 7], in this paper the finite element numerical simulation is used to analyze and predict the change in bearing capacity and deformation of the steel structure of coastal gabled-frame factory buildings after corrosion in moist marine atmosphere, and then the adverse effects of corrosion on the steel-structure factory buildings can be assessed to some degree, and some meaningful reference can be provided for further exploration of the corrosion protection of the steel structure of coastal industrial factory buildings.

2. Section design of component with PKPM

The design herein is based on Technical Specification for Steed Structure of Light Weight Buildings with Gabled Frames (CECS 102:2002) and Code for Design of Steel Structures (GB50017-2003). The design software named PKPM is adopted herein to design the common single-span single-storey gabled frame with span of 18m to 31m in Xiamen. The column space is 6.0 meters. The roof slope is 1/10. The roof is equipped with 40mm-thick glass-wool insulation layer. The column foot is hinged, and the column tapers downward. The beams with span of 18m and 24m are in uniform cross section, and those with span of 30m and 36m are in variable cross section.

According to Load Code for Design of Building Structures (GB5009-2012), when designing the factory building, the dead load (including that of roof, beam, column, support, and purline) shall be 1.31 to 1.47kN / mm^2 for different spans. The live load of the roof is 0.3kN / mm^2. The grade of roughness of the ground is B. The basic wind pressure is 0.8kN / mm^2. Q235B steel is adopted. The dimensions of components are listed in Table.1. With such dimensions, the strength, overall stability and local stability of all beams, columns and joints can meet the relevant requirements, so can slenderness ratio, the lateral displacement of the column top, and the deflection of beams. The projection method of other spans' section are similar.

Table 1. The dimensions of components of gabled frames

No.	span(m)	The cross section of columns(mm)	The cross section of beams(mm)	
1	18	H(250~450)×200×8×10	H300×200×8×10	
2	24	H(300~600)×200×8×12	H400×200×8×12	
3	30	H(400~800)×250×8×12	H(800~400)×250×8×12	H(400~700)×250×8×12
4	36	H(400~900) ×250×10×14	H(900~600) ×250×10×14	H(600~800) ×250×10×14

3. Influence of corrosion on structural performance of steel gabled frames

In this paper, the single-span single-storey gabled frames with span varying from 18m to 36m are modeled with ANSYS 15.0 to analyze the adverse effect of the corrosion of load-bearing steel structures on the bearing capacity and deformation.

3.1 The establishment of finite element model

The element of Beam188 in ANSYS, taking the effects of shear deformation into account, is suitable for analyzing beam structures that are slender or moderately stubby and short. With command such as sectype, the dimensions of different cross sections can be defined and thus it is very suitable for modeling components with variable cross section. Therefore, it is adopted herein.

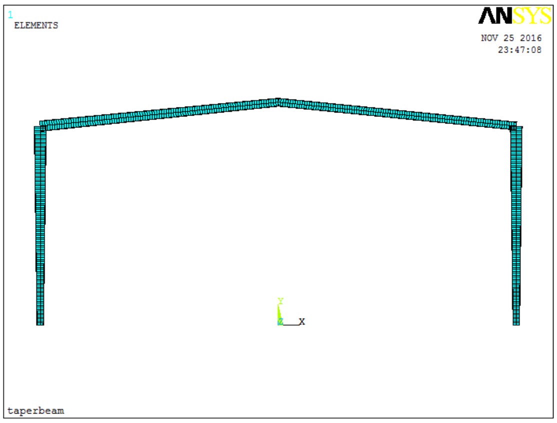

Figure 1. Model for span of 18m and 24m

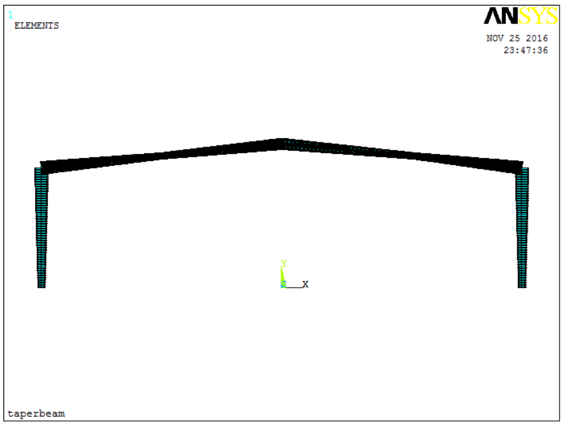

Figure 2. Model for span of 30m and 36m

Many studies have shown that in corrosive environments, the dimension of components changes with time. Liang Caifeng etc.[9] obtained the law of atmospheric corrosion development of steel with the method of stepwise regression in 4a, 8a and 16a exposure tests on 17 types of steel in 7 sites in domestic as follows.

$$D = A^{tn} \tag{1}$$

Where D, t , A and n denote corrosion depth (mm), exposure time, and constants, respectively.

In 2001, in the same way, Townesend[10] obtained quantitative relationship between steel corrosion and the year of corrosion in different typical climates. The method is proved to be very effective.

Table 2. The value of A and n in some typical environments

	Beijing	Qingdao	Wuhan	Jiangjin	Guangzhou	Qionghai	Wanning
A	0.030	0.057	0.049	0.074	0.056	0.022	0.032
n	0.420	0.610	0.240	0.410	0.410	1.050	1.400

For example, Wanning City is a coastal city, with the annual average temperature of 24°C, small annual temperature difference and high average relative humidity, which belongs to tropical moist maritime climate[11]. According to ISO 12944-2:1998[12], the category of atmospheric corrosive environment of outdoor steel-structure factory building in this area belongs to C5-M. The values of A and n listed in table 2 can be used to calculate the corrosion depth of steel in hot coastal areas. For Q235 steel with protective coating, according to equation (1), D=0.084mm(after 2 years), 0.305mm(after 5 years), 0.804mm(after 10 years), and 2.12mm(after 20 years), respectively.

Usually, the smaller the thickness of the steel component, the smaller the ratio of superficial area to volume, and thus the greater its cross area, the moment of inertia and section modulus will decrease after its surface layer has peeled off due to corrosion. The beams and columns of gabled frames are all welded H-shaped steel with open cross section. All of them are exposed in air, and thus the influence of corrosion will be serious.

The analysis above shows that both performance and thickness have decreased after corrosion (see Table 3).

Table 3. Sectional dimension of components of Gabled Frames with Span of 18m after Corrosion

Cross Section	After 2 years(mm)	After 5 years(mm)	After 10 years(mm)	After 20 years(mm)
Column	H(249.916~449.916) ×199.916×7.916×9.916	H(249.695~449.695)×199.695 ×7.695×9.695	H299.196×199.196 ×7.196×9.196	H(247.88~447.88) ×197.88×5.88×7.88
Beam	H299.916×199.916 ×7.916×9.916	H299.695×199.695 ×7.695×9.695	H299.196×199.196 ×7.196×9.196	H297.88×197.88 ×5.88×7.88

Some studies show that the influence of the reduction of average cross area, stress concentration caused by uneven corrosion and the change of internal crystal lattice on the degree of degradation of steel can be measured by weight loss rate[4,5] as follows.

$$D_w=(W_0-W_1)/W_0 \tag{2}$$

where D_w is the weight loss rate of corroded steel, W_0 and W_1 are the weight before and after corrosion, respectively.

When the thickness loss is the same, the thinner the larger the weight loss rate will be, and thus the degree of degradation of steel will be greater. If the corrosion loss is the same, the weight loss rates of the steel are listed in Table 4 for the slab with the thickness of 8mm, 10mm, 12mm, and 14mm, respectively.

Table 4. The weight loss rates of slabs with different thickness

	After 2 years	After 5 years	After 10 years	After 20 years
8mm	2.1%	7.625%	20.1%	53.0%
10mm	1.68%	6.1%	16.08%	42.4%
12mm	1.4%	5.08%	13.4%	35.33%
14mm	1.2%	4.36%	11.49%	30.29%
mean	1.60%	5.79%	15.27%	40.26%

Based on the experimental result of mechanical properties of corroded steel, D_w is used to measure the degree of deterioration of mechanical properties of steel after corrosion[7]. According to the experimental data, the linear regression model by the least square method is established to obtain the relation among the decrease of yield strength, tensile strength, and elongation with its weight loss rate for Q235B steel as follows, respectively as follows.

$$f'_y/f_y=1-0.9852D_w \tag{3a}$$

$$f'_u/f_u=1-0.9732D_w \tag{3b}$$

$$\delta'/\delta=1-1.9873\, D_w \tag{3c}$$

Where f_y and f'_y are the yield strengths of uncorroded steel and corroded steel, respectively; f_u and f'_u are the ultimate strength of uncorroded and corroded steel, respectively; δ and δ' are the elongation of uncorroded steel and corroded steel, respectively.

For the steel before corrosion, the elastic modulus, E, is set as 2.06×10^5 MPa herein; for the steel after corrosion, its value is calculated from equation (4) as the following, which was put forward by Lee H. S.[13] and the reduction of elastic modulus with D_w due to corrosion has been taken into accout. The data in Table 5 show that the deterioration of mechanical property gets more and more serious with time. For example, after 20 years the yield strength decreases by 39.66%, which can lead to structural failure under stress.

$$E'_s=(1-0.75D_w)E_s \tag{4}$$

Table 5. Conversion of steel performance index for different weight-loss ratios

	years of service				
	0	2	5	10	20
weight-loss ratio(%)	0	1.60%	5.79%	15.27%	40.26%
yield strength f_y (N/mm^2)	235	231.30	221.59	199.65	141.79
tensile strength f_u (N/mm^2)	380	374.08	358.59	323.53	231.11
Elongation (%)	26	25.17	23.01	18.11	5.20
elastic modulus(MPa)	2.06×10^5	2.035×10^5	1.97×10^5	1.824×10^5	1.438×10^5

3.2 Checking results for structure and components

The single-story gabled frame before and after corrosion is modeled with ANSYS herein, and four cases with different spans from 18m to 36m are calculated based on relevant specifications. The results show that the corrosion influences the stress and deformation of the whole structure and components.

Figure 3 through 6 are the deformation ratios of the overall structure of gabled frames in different time. The results show that the maximum deformation is still the vertical deflection of beam at the roof. The deformation ratio of 2nd year, 5th year and 10th year increases nearly linearly. But the deformation ratio of 20th year increases sharply, and the maximum deformation ratio is close to 1.7. The results show that after a long time of corrosion, the cross section and elastic modulus decreases, and the stiffness of the whole structure is weakened seriously, and therefore a qualitative change happens. It is difficult to determine which of two factors, say, the reduction of the cross section and the decrease of the elastic modulus, is more significant when they act alone. But it can be sure that when they act together, the deformation is significantly greater than that when they act alone.

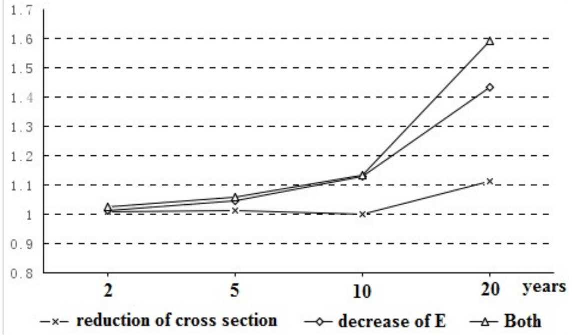

Figure 3. Deformation ratios of structure with span of 18m

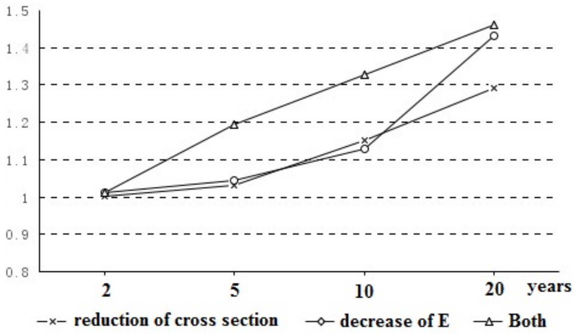

Figure 4. Deformation ratios of structure with span of 24m

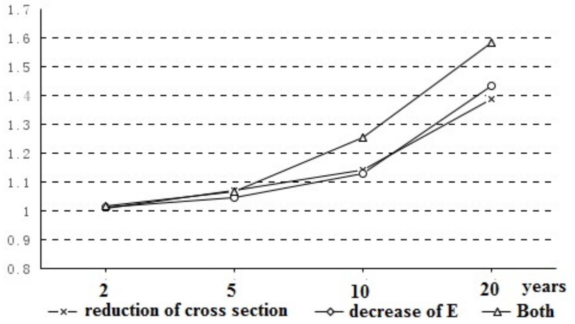

Figure 5. Deformation ratios of structure with span of 30m

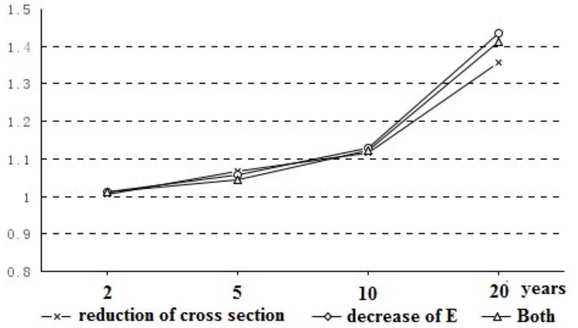

Figure 6. Deformation ratios of structure with span of 36m

Figure 7-10 show the maximum normal stress ratio, which is used to measure the increase of normal stress of component's cross-section after corrosion. It can be seen from the figures that the stress ratio increases with time. When the time is less than 5 years, the normal stress ratio does not increase obviously, and the maximum is 19.33%, which happens to the structure with span of 24m after 5 years. However, after 10 years, the stress ratio of each case has greatly increased, and the maximum normal stress ratio is close to 160%. According to Table 5, the yield strength of steel decreases by 39.66% after 10 years, and the stress has exceeded the designed value of strength, and there has been damage. The reduction of elastic modulus is linear with the increase of stress ratio, and its effect on the component stress is obviously less than that of the reduction of cross section due to corrosion. It shows that the reduction of cross section has a worse impact on the structural stress.

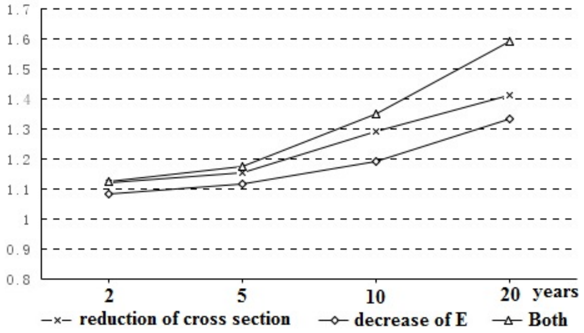

Figure 7. The maximum normal stress ratio of the structure with span of 18m

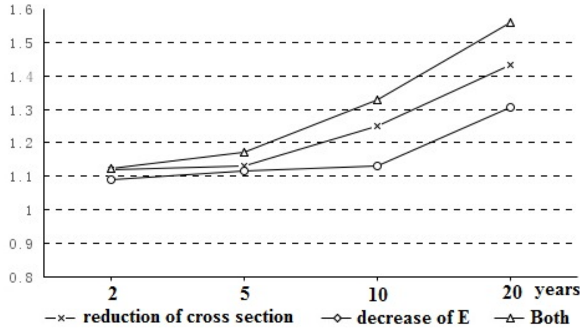

Figure 8. The maximum normal stress ratio of the structure with span of 24m

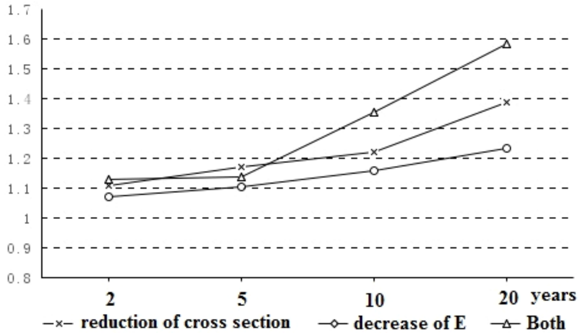

Figure 9. The maximum normal stress ratio of the structure with span of 30m

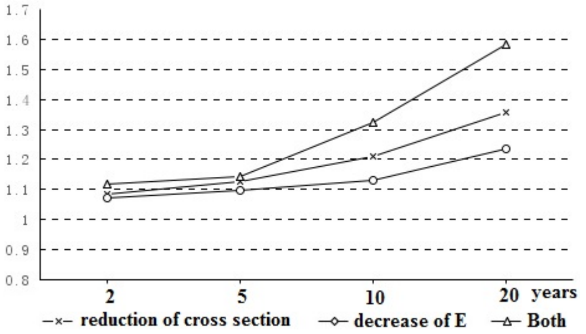

Figure 10. The maximum normal stress ratio structure with span of 36m

4. Conclusion

(1) The result obtained with finite element numerical simulation shows that the bearing capacity of structure and components of gabled frames reduces and the overall stiffness is weakened due to corrosion in warm and humid ocean-atmosphere environment after 2 to 20 years. The vertical deflection ratio at the roof and the maximum stress ratio of the cross section increase observably.

(2) Both the normal stress ratio and the deformation ratio after the corrosion increase greatly with time. The maximum normal stress ratio may exceed the designed value of strength. It even can reach the ultimate state of bearing capacity and lead to failure of structure.

(3) The result shows that the reduction of both cross section and elastic modulus due to corrosion affects the stiffness and bearing capacity of the structure, but the reduction of cross section has a more significant impact on stress increase.

(4) The analysis process and results of this paper show that it is feasible to estimate the reduction of the elastic modulus with equation (4) and the corrosion depth with equation (1). The finite element method can be used to study the effective anti-corrosion measures further.

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