Review on Corrosion Mechanism and Mechanical Properties Degradation of Building Structural Steel

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Abstract: Steel structure is favored by many designers because of its light weight, high strength, short construction period and good seismic performance, and is widely used in high-rise, super high-rise and long-span structures, but the shortcomings of steel structure corrosion are gradually highlighted. In the past 20 years, literature in relevant domestic and foreign journals, conference proceedings, and electronic databases were searched. The mechanical properties of corroded components were studied and summarized from the corrosion mechanism, corrosion influencing factors and rust pit morphology. It is found that the dangerous area of stress concentration of corroded steel is in the middle of the pit, and the maximum stress value is located at the lower edge of the pit mouth. The bearing capacity and ductility of the corroded steel structure are deteriorated, which seriously affects the structural safety under dynamic load. Due to the complexity of correlation analysis of atmospheric corrosion test of metal materials, it is still necessary to improve the corrosion data of existing steel grades and newly developed steel grades in natural environment. At present, there are few researches on corrosion of high strength steel, molded steel plate and prefabricated buildings. With the increasing application of high-strength steel, further research is needed to obtain the latest research results and apply them in practical engineering.

1. Introduction

In recent years, with the continuous improvement of the type and quantity of steel in China, steel has been used more and more widely in the construction field, and steel structure has become one of the most important structural forms in China due to its advantages of convenient construction, high strength, plasticity and good seismic performance [1]. The inherent potential of steel structure requires the excavation of architects and engineers. Such as "Bird's Nest", "Water Cube", Shanghai Jinmao Tower, Shanghai Yangpu Bridge, Hong Kong Qingma Bridge, Hangzhou Bay cross-sea Bridge, Famen Temple Pagoda, the emergence of these representative buildings, marking the steel structure in the theory and design of the increasingly mature. But in addition to the joy, we also have to face up to the vigorous rise of steel structure at the same time, due to its own material, design method, construction and its environment and other defects, steel structure often has chemical or electrochemical interaction with the surrounding environment (medium)caused by damage[2], Many large-scale steel structure projects (such as Bridges, large industrial buildings, large reservoir gates, offshore oil production facilities, etc.) have been corroded for a long time.

The investigation in literature [3] found that a copper electrolysis plant could not be put into normal use due to corrosion problems after it was put into service for many times, resulting in significant economic losses. The rail in a tunnel has high maintenance cost due to chemical corrosion. The boiler tubes of East China Power grid leak out due to corrosion. Many oil production systems, due to corrosion caused by pipeline perforation, burst and so on. Literature [4] analyzed the causes of corrosion of steel structure components in the workshop of Taiyuan Coal Preparation Plant. Since the equipment in the workshop mainly works with water, and the water used in the equipment often contains weakly acidic chemicals, a large amount of coal dust accumulated in the root of the steel column in the workshop during the washing process, resulting in serious losses in the long term. Literature [5] points out that the world's largest ancient stone Buddha statues, Leshan Giant Buddha in Sichuan, China, and the Statue of Liberty in the United States, were seriously corroded by acid rain and wind. Greek Acropolis monuments and sculptures with cracks and markings due to vulcanization. Literature [6] found that after a refinery in Anqing was put into use, corrosion and perforation occurred in most of the oil tanks. After investigation, uniform corrosion occurred in the gas phase parts of the oil tanks, and serious ulcerative point corrosion, pitting and perforation occurred at the bottom of the tanks. Literature [7] analyzed that after the steel silo of a grain depot in Qingdao was built and put into use, perforation corrosion occurred in many places of the silo cover due to certain corrosive environment, and the rust layer was obvious. Many domestic and foreign steel structure accidents [8] show that corrosion not only causes direct and indirect losses to the national economy, but also

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threatens the safety of industrial facilities, life and transportation facilities. For example, in less than 20 or 30 years of use, corrosion of different parts of highway Bridges appear, steel bar rust, and steel cables fracture under the combined action of tensile stress, fatigue and atmospheric media. Corrosion will also cause varying degrees of damage to mechanical equipment, after the corrosion of equipment, perforation, fracture and other phenomena will cause many sudden accidents, such as: building collapse, fire, explosion, gas dispersion, material loss, etc., resulting in serious environmental pollution problems. The corrosion of steel structure leads to some urgent scientific problems related to it, and it is especially necessary to form innovations and breakthroughs in the aspects of "surface characteristics and section loss law of corroded steel structure", "stress characteristics of corroded steel structure materials, components and structures", and "load bearing performance evaluation method of corroded steel structure". It has been pointed out that the surface morphology has a significant influence on the wear, lubrication, friction, fatigue, sealing, coating quality, corrosion resistance, electrical conductivity, thermal conductivity and reflection properties of the friction surface. Surface roughness, waviness and random contour features such as surface peaks, valleys and furrows comprehensively affect surface friction, wear, contact stiffness, fatigue strength and other properties [9]. Therefore, it is particularly important to study the corrosion of steel structure and even high-strength steel, and the study of corrosion mechanism is the basis of the whole process of research, and the results of rust pits are not many, so this paper discusses and analyzes the above problems.

2. Corrosion mechanism and influencing factors

When the steel structure is in a harsh environment for a long time, the steel is very easy to have electrochemical corrosion with the corrosive medium in the air, and the corrosion mechanism and products are different in different environments, and the time-varying law of corrosion is also different.

2.1. Corrosion definition

Many famous scholars have defined corrosion. Before the middle of the 20th century, the definition of corrosion was limited to the corrosion of metals, which refers to the chemical reaction, electrochemical reaction or physical dissolution of metals and surrounding media (mainly liquid and gas). With the rapid development of non-metallic materials (such as polymer synthetic materials), since the 1950s, many scholars or research institutions who study corrosion tend to expand the definition of corrosion to all materials. Indeed, non-metals also have corrosion phenomena, such as weathering of masonry, decay of wood, aging of plastics and rubber, etc., are corrosion problems. Since metals and their alloys are still the most important structural materials that are vulnerable to corrosion, this paper mainly discusses the corrosion and protection of metal materials. Considering the nature of metal corrosion, metal corrosion is usually defined as the destruction or denaturation caused by chemical or electrochemical action between the metal and the surrounding environment (medium).

2.2. Corrosion type

The corrosion of the steel structure will cause the section of the component to become smaller, the bearing capacity to decrease, and eventually lead to failure. There are many types of corrosion classification of steel structure, among which uniform corrosion (or total corrosion) and pitting corrosion in local corrosion are the research focus of most scholars. In atmospheric environments, uniform corrosion and pitting corrosion are the most common types of corrosion for steel used in building structures, and often occur simultaneously [10].Over time, the two types of corrosion result in loss of component thickness and formation of surface pits, respectively(Figure1). According to the corrosion process of the material, the corrosion of steel structure can be divided into electrochemical corrosion, chemical corrosion and stress corrosion. Under normal circumstances, the corrosion of steel structure is mainly electrochemical corrosion. Figure 2 shows the proportion of various corrosion forms [11].

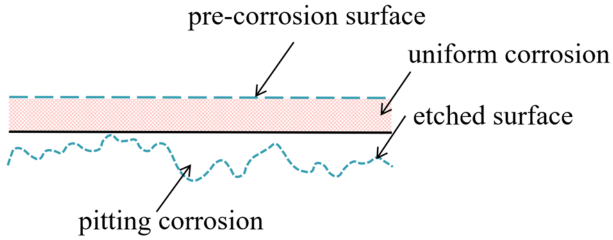

Fig. 1. Diagram of uniform corrosion and pitting

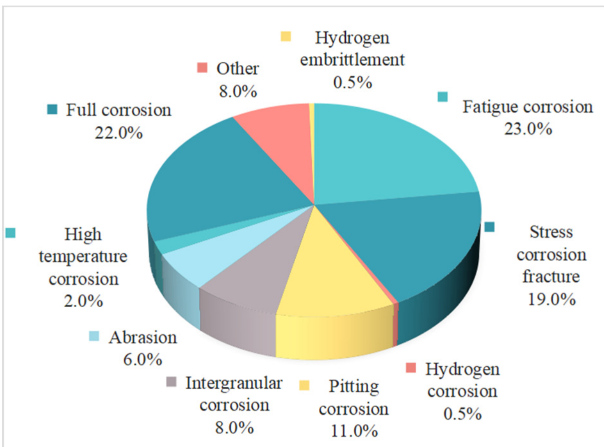

Fig. 2. The proportion of different corrosion forms

2.3. Corrosion mechanism

The corrosion mechanism of steel structure is mainly divided into electrochemical corrosion, chemical corrosion and stress corrosion. Among them, the essence of electrochemical corrosion is: the iron element in the steel as the anode of the battery, release electrons to form iron ions, and finally produce $Fe(OH)_2$, and through a series of reactions to produce $Fe(OH)_3$, and finally through dehydration reaction to produce Fe_2O_3, Fe_2O_3 is the main component of rust.

Chemical corrosion is the chemical reaction that occurs when the steel structure is exposed to acid, concentrated alkali and salt solutions.

Stress corrosion: refers to the acceleration of steel corrosion under stress. Stress corrosion can seriously reduce the bearing capacity of steel structures and affect the durability of structures. The mechanism of stress corrosion and electrochemical corrosion is basically the same, but the former also has the influence of additional stress elements. When the steel member under stress is in the corrosive medium, micro-cracks will appear on the surface of the steel member under the action of stress, and when the corrosive medium contacts the surface of the steel member, local corrosion will first occur at the position of micro-cracks. With the progress of local corrosion, the width and depth of micro-cracks are further increased, so the phenomenon of stress concentration at the crack is more and more serious, which promotes the development of cracks, which provides more sufficient space for corrosive media.

2.4. Corrosion test

The corrosion process is slow and time-consuming. To study the corrosion mechanism of steel and the properties of steel after corrosion, it is necessary to complete the corrosion process and obtain the corrosion products. In addition to the study of steel structures in service, corrosion tests can also be carried out. There are two types of corrosion test, one is the atmospheric corrosion test of steel structure exposed to the natural environment, which refers to the direct placing of steel specimens with known parameters in the atmospheric environment. This test method can truly and accurately reflect the corrosion of steel specimens at the test site, and the reliability of the test results is strong. The test is also the basis for studying the atmospheric corrosion process of metal materials. However, the test cycle is too long, ranging from a few years to decades [12-14]; the second is the indoor test through artificial simulation to accelerate the corrosion of steel structure, which refers to the corrosion of materials in the artificially set corrosive environment, the advantage of this test is that the cycle is short, there is no strict requirements for the area, and the simulated accelerated corrosion test is often carried out indoors or in a specific test instrument. In recent years, a variety of simulated accelerated corrosion test methods have been proposed according to different environmental characteristics [15,16], such as acid test, humid heat test, immersion test, salt spray test, multi-factor cyclic composite test, etc. Among them, immersion test and salt spray test are the most widely used.

2.5. Influencing factors of corrosion of steel structure

From the corrosion mechanism, the main factors affecting the corrosion of steel structure can be roughly attributed to the environmental factors of steel and steel alloy elements.

2.5.1 Environmental factor

The environment of steel structure is mainly divided into atmospheric environment, seawater environment and soil environment.

Atmospheric environment: Atmospheric corrosion of steel structures is the most common type of corrosion. The main environmental factors affecting atmospheric corrosion are: atmospheric relative humidity, temperature, harmful gases in the atmosphere, dust in the atmosphere and so on.

Under normal circumstances, steel is difficult to corrode in a dry environment, and the corrosion speed will be accelerated only when the relative humidity of the atmosphere reaches the critical humidity. The adsorption of water in the atmosphere on the surface of the steel structure to form a water film is the decisive factor of steel corrosion. The atmospheric temperature will affect the condensation of water on the steel surface, the solubility of various gases and salts in the water film, the conductivity of the water film, and the speed of electrochemical reaction. With the different environment, the dust in the atmosphere also has different properties, mainly in its solubility and corrosion. Corrosive dust dissolved in water film will participate in corrosion reaction. Some non-corrosive dust can absorb corrosive substances, and when it is dissolved in water film, it brings corrosive substances.

Seawater environment: seawater itself is an electrolyte, which dissolves a variety of salts and is acidic. When the steel structure is in seawater, it is difficult to maintain a blunt state, and corrosion will naturally occur. In seawater environment, the main factors affecting the corrosion of steel structure are temperature, oxygen content, pollution, flow rate, Marine biological fouling and so on. In seawater, the above factors affect each other, and under certain conditions, any one of them will become a control factor affecting the corrosion of steel structures.

Soil environment: Soil corrosion is also one of the main types of corrosion of steel structure. Some properties of the soil itself have a great impact on the corrosion of steel, such as porosity, moisture content, corrosive ions and salts, resistivity and pH value. In general, the greater the porosity, the higher the moisture content, the greater the corrosive ion and salt content, and the greater the resistivity, the greater the corrosion rate of steel.

2.5.2 Alloy element of steel

In addition to environmental factors, the corrosion resistance of steel itself will also affect the corrosion of steel structure, but changing the content of alloying elements in steel is an important way to improve the corrosion resistance of steel. The results show that copper and phosphorus can improve the corrosion resistance of steel. At present, according to different corrosion conditions, various types of weathering steel have been developed. And with the development of science and technology, alloy steel with better corrosion resistance will continue to emerge.

2.6. Prevention and control measures for corrosion of steel structure

The commonly used anti-corrosion measures of steel structure are mainly divided into three aspects: improving the corrosion resistance of steel; Use organic, inorganic and metal coatings; impressed current. In large steel structures, these three methods are often used in combination to ensure the safety of the structure.

(1)Improve corrosion resistance of steel. The corrosion resistance of weathering steel is much higher than that of general structural steel. In engineering practice, weathering steel can be used without painting, which is an excellent structural material and can minimize the total cost during the life of the steel structure. In the corrosion process of weathering steel, a dense and continuous inner rust layer can be formed, which can effectively prevent the corrosion medium from spreading to the steel, and can inhibit the anode reaction in the electrochemical reaction, which has a protective effect on the steel.

(2)Use organic, inorganic and metallic coatings. Such anti-corrosion measures are to form a coating or coating on the surface of the steel to isolate the steel, so that the corrosive medium cannot be in contact with the steel, so as to achieve the purpose of anti-corrosion.

3. Corrosion pit study

Corrosion problems are easy to occur in large-scale steel structure projects that have been in corrosive environment such as Marine atmosphere and industrial atmosphere for a long time. Corrosion not only causes the thinning of cross-section size, but also accelerates the initiation and expansion of cracks due to the stress concentration generated by corrosion pits such as pitting and denudation, resulting in the failure and failure of components and shortening the fatigue life of structures. Therefore, the existence of corrosion pits is the most important and dangerous form of corrosion failure [17].

Literature [18] analyzed the samples taken from the cabin and found that the shape of the rust pit on the surface of the component was mainly conical under the Marine atmosphere environment, while the shape of the rust pit caused by seawater corrosion was mainly semi-circular. At the same time, many scholars at home and abroad have studied the corroded steel under various environments and found that the shape of the rust pit on the steel surface is mainly conical and semi-circular. In literature [19], the influence of strip corrosion zone on plate buckling load was studied by taking plate thickness, elastic modulus, corrosion mass loss and the length of corrosion belt in loading direction as basic variables. The results show that the buckling load is related to the elastic modulus and the size of the plate after local corrosion. In literature [20], rectangular pits were used to simulate the shape of pitting corrosion. However, in actual observation, the shape of pitting pits on the surface of steel plates is usually circular. Literature [21] studied the mechanical properties of four-sided simply supported plates under the influence of pitting corrosion. The cylindrical shape was taken as the simulated shape of the pitting pit, and the diameter of the pitting pit was 10-80 mm based on statistical data. In literature [22], the actual shape of pitting corrosion was simulated by a cone pit, and the ratio of cone diameter to diameter depth was 1/8-1/10.

In literature [23], the rust pit artificially generated in the laboratory was used to carry out rotary bending fatigue, tensile and compressive fatigue, torsion fatigue, and tensor-compression combined fatigue tests on the corroded components, respectively. The results showed that the rotary bending fatigue limit decreased by 32%, the tensile and compressive fatigue limit decreased by 10%, and the torsion fatigue decreased by 6%. The cracks all started from the bottom of the pit and were equal to the radius of the pit less than 60um has no effect on the fatigue limit.

Because there are various corrosion forms of local corrosion, the occurrence of each corrosion form has great randomness, the corrosion depth of corroded components, the shape, position and quantity of corrosion pits have great randomness, and the corrosion pits have a great impact on the safety of components, so the study of corrosion pits is extremely important. The development of pit mainly includes three processes: initiation, depth development and horizontal development. The corrosion in acidic atmosphere is mainly denudation, the corrosion in alternating dry and wet environment is mainly pitting and the pitting pit is obvious in semi-ellipsoid shape, and the corrosion in neutral salt spray environment is mainly pitting and denudation. It is assumed that the shape of the pit is a common semi-ellipsoid, but the actual shape of the pit is very complex and the surface is not smooth. The depth d is the longitudinal corrosion pit size of the steel plate, the length l is the radius size of the corrosion pit in the stretching direction, and the width w is the radius size of the corrosion pit perpendicular to the stretching direction (Figure3).

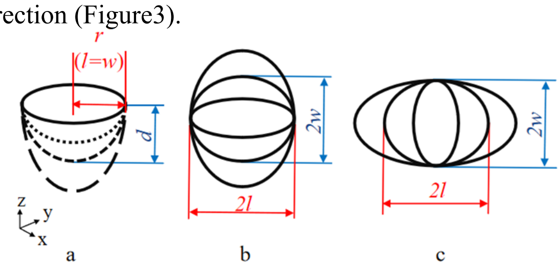

Fig. 3. Schematic diagram of the pit geometry

From the different depth to diameter ratio (d/r) when the length and width are equal, (where, when $l = w$, let $l = w = y$, that is, r is the size of the corrosion pit length or width direction for convenience analysis), and the change of different width to length ratio(w/l)when the depth is unchanged, the influence of the change of the size of the corrosion pit on the stress concentration coefficient and fatigue life is analyzed.

The geometric expression of the ellipsoidal pit is: $(x/d)^2+(y/l)^2+(z/w)^2=1$.

Pitting density D is used as a measure of pitting damage degree. Under the same pitting density D, the influence of different pit depths on the critical strength of elastic shear of pitting damaged plates is discussed. Corrosion thickness damage will lead to loss of elastic shear strength. Under the same D condition, the greater the corrosion depth is, the greater the shear strength loss is. The ratio of width to height of the plate has little effect on the shear strength. Since the intensity of pitting corrosion D will increase the shear strength loss of plates with the same thickness damage, it is necessary to further analyze the influence of D on the shear strength of plates with the same thickness loss. D will lead to the loss of shear strength; under the same thickness loss condition, the greater the D, the greater the strength loss of the shear plate. The aspect ratio α has little effect on the shear strength damage of the plate. Taking the influence of corrosion depth into account, the pitting volume damage degree DV is introduced as the measurement index of pitting damage [24]. Literature [25] carried out loading tests on I-beams with artificial rust pits arranged at the web, and the results showed that the pit fracture caused by the stress concentration in the rust pits would lead to the shear strength obtained by finite element analysis being greater than the actual result. Literature [26] has analyzed the ultimate shear buckling strength of the pitted damaged hull structural plates, and the results show that there is a strong correlation between the ultimate strength of the pitted damaged plates and the corrosion volume. Literature [27] proposed a prediction formula for the ultimate shear strength of pitted plate according to the degree of rust damage and the geometric characteristics of the plate, and believed that the ultimate shear strength of pitted plate was related to D.

4. Influence of corrosion pit on mechanical properties of components

With the vigorous rise of steel structures, more and more attention has been paid to the durability of steel structures. The main reason for the durability reduction of existing steel structures is that the corrosion of steel and the structural resistance caused by corrosion damage decrease with the extension of the use period. Studying the degradation law of material mechanical properties of corroded steel structures is of great significance for mastering the evolution law of structural properties of steel structures during service and the damage pattern of aging structures, correctly evaluating the resistance of existing structures and predicting the service life of existing structures, and reducing maintenance and repair costs on the premise of ensuring sufficient safety of structures [28].

Literature [29,30] points out that corrosion has no obvious effect on the actual yield strength and ultimate strength of steel bars, and the ultimate elongation decreases. When the corrosion rate is relatively small (usually the corrosion rate of cross section is less than 5%), the steel corrosion is more uniform, and the corrosion has little effect on the mechanical properties of the steel bar. When the corrosion rate is large, the steel bar is uneven corrosion, and the actual yield strength and ultimate strength of the steel bar after corrosion are reduced, and the ultimate elongation is also decreased.

Literature[31] analyzed the degradation law of mechanical properties of steel bars under different corrosion rates, and found that when the corrosion rate (cross section loss rate) is less than 5%, its elongation is basically greater than the minimum allowable value of the code; when the corrosion rate is greater than 5%, the stress concentration is more obvious, and the relationship between the elongation after breaking and the corrosion rate is negative exponential and smaller than the minimum allowable value of the code.

In literature [32], sheet tensile tests were carried out on corroded Q235 steel under different environments, and the results showed that the elongation of the member changed negatively with the increase of the corrosion rate, and the ductility decreased with the increase of the corrosion rate. Both yield strength and ultimate strength change linearly with the increase of corrosion rate, and the ultimate strength decreases faster. After corrosion, the stress-strain curve of the component changes in three stages: basically close to the non-corroded state ($\eta_s \approx 5\%$), the yield strength increases($5\% < \eta_s < 10\%$), the yield strength decreases($\eta_s > 10\%$), and the yield platform decreases, there is no obvious yield point, and the yield strength is very close to the tensile strength, which is easy to cause sudden failure of the structure.

5. Conclusion

Corrosion of steel structure is an inevitable natural phenomenon, which causes great economic losses and even leads to engineering accidents, resulting in casualties. Therefore, the anti-corrosion work of steel structure should cause great attention in the steel structure industry. In recent years, although the corrosion of steel in different environments has achieved certain results, due to the complexity of corrosion, there are still many problems that need to be continued research:

(1)At present, scholars have extensively studied the corrosion types, corrosion mechanisms, effects on steel properties, corrosion detection and other aspects of ordinary steel structures, but they mainly focus on the corrosion of common steel structures such as steel bars and shapes, and few research on the corrosion of high-strength steel, molded steel plates and prefabricated buildings.

(2)Due to the complexity of correlation analysis of atmospheric corrosion test of metal materials, in order to clarify the corrosion mechanism of each steel grade and improve the prediction accuracy of atmospheric corrosion of steel, it is still necessary to increase research efforts and continue to improve the corrosion data of existing steel grades and newly developed steel grades in natural environment.

(3)The surface morphology of the steel plate after corrosion in different environments is complex and different. The acid atmosphere corrosion is mainly denudation, the dry and wet alternating environment corrosion is mainly pitting, and the neutral salt spray environment corrosion and denudation, and the early stage is mainly pitting, and the later stage is mainly denudation. Because of the existence of the pit, the stress concentration of the material is obvious and the fatigue life is reduced. In addition, the dangerous area is in the middle of the pit and distributes in a strip shape perpendicular to the stretching direction. The stress amplitude changes greatly along the stretching direction of the pit, and tends to be stable away from the pit, while the stress amplitude changes gently along the edge of the pit perpendicular to the stretching direction, and the maximum stress value lies at the lower edge of the pit.

(4)Due to the multi-directional and random nature of seismic action, the pseudo-static test method is not comprehensive enough to study the seismic performance of steel structures under corrosive environment. In the future, pseudo-dynamic or shaking table test methods which are closer to the actual seismic action can be used to study the seismic performance of corrosion structures.

(5)Test is the most effective and reliable way to study the basic mechanical properties of steel structure and even high strength steel, but it is time-consuming and costly and inconvenient to realize. The perfect design specification should pay more attention to the combination of design method, theoretical science and numerical calculation, and timely supplement the latest research results and engineering application experience of new materials.

(6) The bearing capacity and ductility of the corroded steel structure are deteriorated, and the protective measures of the steel structure should be deeply studied to improve its structural safety under dynamic load and avoid brittle damage, resulting in engineering safety accidents.

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