

Article

Three-Dimensional Numerical Simulation of Mechano-Electrochemical Coupling Behavior of Q420NS Steel with Different Corrosion Pit Morphologies Under Simulated South China Sea Environment

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Abstract

The mechano-electrochemical coupling behavior of Q420NS steel containing pits in the South China Sea environment was investigated. A three-dimensional numerical model incorporating elastoplastic deformation and corrosion kinetics was developed using COM-SOL Multiphysics. The effects of axial tensile displacement and five typical pit morphologies on the local corrosion behavior were systematically examined, and the threshold displacement at which plastic deformation initiates was determined for each pit morphology. The results indicate that increasing tensile displacement elevates the stress, equivalent plastic strain, and corrosion rate at the pit bottom. Among the five morphologies, conical pits exhibited the earliest plastic yielding, the highest corrosion rate, and the strongest coupling effect, whereas semi-ellipsoidal pits demonstrated the best corrosion resistance. A coupling intensity coefficient K is originally proposed to quantify the intensity of the mechano-electrochemical coupling for different pit morphologies. This coefficient reveals the underlying mechanism by which pit morphology regulates the coupled corrosion process through stress concentration, thereby providing a scientific basis for the defect-tolerant design of marine steel structures.

Keywords: mechano-electrochemical interaction; pit morphology; corrosion; stress concentration; coupling intensity coefficient; defect-tolerant design

1. Introduction

Offshore platforms made of steel are subjected to a wide range of stresses due to tension and bending, and they are in a highly corrosive environment caused by salt and chloride ions in the seawater of the South China Sea. Stress concentration caused by pitting corrosion and electrochemical degradation are the primary reasons for the sudden failure of structural components [1–4]. Q420NS steel is a weather-resistant, low-alloy, high-quality type of steel with good mechanical properties and corrosion resistance that is often used in the construction of marine bridges and seabed facilities. However, the mechano-electrochemical interaction mechanisms underlying pitting corrosion in marine environments still require further investigation [5–7].

A great deal of research has indicated that stress concentration causes localized plastic deformation of the metal surface, causing passive film destruction and the development of corrosion pits. With the development of pits, the mechanical properties of the material



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decline gradually [8–10]. To illustrate, researchers have submerged Q420qD and E690 steels in a 3.5 wt.% NaCl solution under external loading conditions and found that the rate of corrosion has increased by approximately 15 percent and 44 percent, respectively, and there is a decrease in mechanical properties. These observations resulted in the deduction that the mechano-electrochemical coupling phenomenon is crucial [11,12]. Pitting attack begins as a result of metal exposure to the combined effect of extended mechanical loading and seawater corrosion. The geometric characteristics of these pits have a dual regulation role in the growth of corrosion damage. On the one hand, when defects are present, this leads to the redistribution of stresses which alter the potential distribution locally. It increases the potential difference and hence accelerates the anodic dissolution process. However, the enhanced anodic dissolution causes the corrosion defect morphology to become more irregular and the resulting geometrical distortion increases the stress gradient even more. Finally, a synergistic degradation cycle forms: stress concentration → corrosion acceleration → defect evolution → intensified stress concentration [10–14].

The essence of the mechano-electrochemical coupling effect is the alteration of the dynamics of the electrochemical process at the metal surface through the distribution of stress and plastic deformation [15–18]. As suggested by Gutman [19], tensile stress raises the chemical free energy of atoms causing a negative change in the equilibrium potential of the anodic reaction, which elevates the corrosion driving force [20]. At the same time, plastic deformation generates strong dislocation multiplication and lattice distortion, resulting in the rise in the density of surface active sites and the enhancement of anodic exchange current density, which eventually increases the rate of corrosion. Although the stress corrosion behavior of corrosion-resistant steels has been thoroughly addressed, many studies have neglected the presence of defects or only considered a single semi-ellipsoidal pit morphology [5,21–27], which is far from reality regarding the real corrosion circumstances [28–30]. This implies that, to properly evaluate corrosion damage, a characteristic parameter is very crucial whose quantification will help in determining the level of the mechano-electrochemical coupling effect. In the absence of this parameter, comparative analysis of coupling effects between different defect morphology and load magnitudes cannot be easily made, thereby limiting severely the precision of defect tolerance design and safety assessment of offshore steel structures.

Corrosion pits generated under marine service conditions do not share identical morphologies; available types include semi-ellipsoidal, hemispherical, conical, circular-dish, and nested morphology. The stress concentration magnitudes of diverse pit morphologies differ by an order of magnitude, and they negatively affect the initial threshold of plastic deformation and the rate of corrosion. To examine the effects of axial tensile displacement and pit morphology on the electrolyte potential, current density, stress field, equivalent plastic strain, and corrosion rate, a dog-bone-shaped Q420NS steel specimen was chosen as the sample of this research. The threshold displacements needed to cause plastic deformation of the five typical pit morphologies were measured. This paper proposes a parameter K to characterize the mechano-electrochemical coupling intensity. The purpose of introducing this parameter is that it allows researchers to compare the intensity of the coupling between the pits of different morphologies in the same manner regardless of variations in their absolute deformation or their overall corrosion rate. This is the core of the relationship between stress, pit morphology and electrochemical reactions. It gives more theoretical information about the process of corrosion in marine steel structures.

2. Material and Methods

2.1. Material and Experimental Characterization

The Q420NS low-alloy high-strength weathering steel, widely applied in marine engineering structures in the South China Sea, was selected as the research object. Its basic mechanical and electrochemical properties were tested to provide calibrated input parameters for the subsequent numerical coupling model.

Mechanical properties were obtained through uniaxial tensile tests at room temperature. The specimen was machined from a hot-rolled Q420NS steel plate, with dimensions consistent with those of the numerical model. Tensile tests were performed on a CMT5105 universal testing machine (MTS Systems (China) Co., Ltd., Shenzhen, China) at a constant displacement rate. The experimentally measured engineering stress–strain curve is shown in Figure 1a. Key mechanical parameters, such as elastic modulus and yield strength, were extracted.

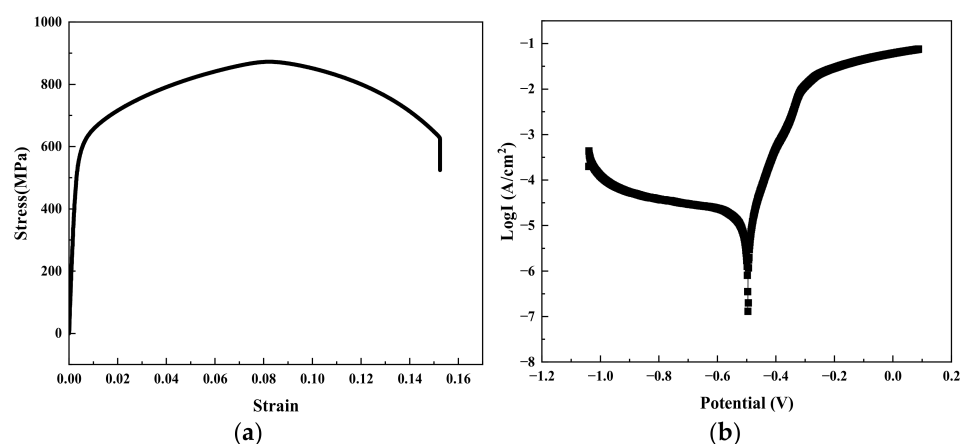


Figure 1. Basic material properties of Q420NS steel. (a) Stress–strain curve. (b) Potentiodynamic polarization curve.

Potentiodynamic polarization tests were conducted to characterize the electrochemical properties in simulated South China Sea seawater at 301.15 K. A standard three-electrode system was used, and all electrochemical measurements were carried out on a CHI760E electrochemical workstation (Chenhua Instrument Co., Ltd., Shanghai, China). The scan was performed from -1.2 V to 0.2 V at a rate of 0.5 mV/s; the resulting curve is presented in Figure 1b. Core electrochemical parameters including corrosion potential, anodic/cathodic Tafel slopes and exchange current densities were obtained via the Tafel extrapolation method: the corrosion potential corresponds to the minimum current point on the curve; Tafel slopes are derived by linear fitting of the strong polarization line segments; exchange current densities are determined by extrapolating the fitted Tafel lines back to the corrosion potential. These parameters were then adopted to define the electrochemical boundary conditions of the coupling model.

2.2. Numerical Simulation Model

A three-dimensional mechano-electrochemical coupling finite element model was developed using COMSOL Multiphysics 6.3. The model consists of three modules—the solid mechanics module, the secondary current distribution module, and the deformed morphology module—which together enable bidirectional interaction between the mechanical field and the electrochemical field. In the solid mechanics module, an elastoplastic constitutive model based on the von Mises yield criterion is employed to describe the plastic deformation behavior. The secondary current distribution module calculates the potential and current density fields by solving the Butler–Volmer equation at the steel–

seawater interface. The deformed morphology module uses the moving mesh method to track the dynamic evolution of the corrosion front, thereby enabling closed-loop feedback between mechanical deformation and electrochemical corrosion. All numerical simulation parameters are listed in Table 1.

Table 1. Numerical Simulation Parameters.

Parameter	Symbol	Value
Elastic modulus of steel	E	207 GPa
Yield strength of steel	σ_m	585 MPa
Anodic reaction equilibrium potential (unstressed)	$\varphi_{eq,a}$	−0.68 V
Cathodic reaction equilibrium potential (unstressed)	$\varphi_{eq,c}$	−0.65 V
Anodic exchange current density (unstressed)	i_a	6.3×10^{-5} A/m ²
Anodic Tafel Slope	b_a	0.06 V
Cathodic reaction exchange current density (unstressed)	i_c	2×10^{-2} A/m ²
Cathodic Tafel slope	b_c	−0.35 V
Charge transferred by anodic dissolution reaction	n	2 [31]
Molar molecular volume of steel	V_m	7.13×10^{-6} m ³ /mol
Coefficient	α	1.67×10^{11} cm ^{−2}
Molar mass of steel	M	55.845 g/mol
Density of steel	ρ	7.87 g/cm ³
Conductivity of seawater	σ_l	5.3 S/m
Electrical conductivity of steel	σ_s	5×10^6 S/m
Initial dislocation density (before plastic deformation)	N_0	1×10^8 cm ^{−2} [32]
Direction factor	v	0.45 [33]

2.2.1. Geometric Model, Mesh Generation and Boundary Conditions

The coupling model consists of the steel specimen domain and the simulated seawater electrolyte domain, as shown in Figure 2. The seawater domain dimensions are 400 mm × 200 mm × 90 mm, which are large enough to eliminate the boundary effect on the electrochemical field. The steel specimen has a standard dog-bone shape with a total length of 220 mm, a width of 70 mm, a thickness of 10 mm and a transition radius of 35 mm at both ends. A single surface corrosion pit was prefabricated at the center of the specimen's upper surface. Five typical pit morphologies were designed, namely, semi-ellipsoidal, hemispherical, conical, circular-dish and nested, whose cross-sectional profiles are shown in Figure 3b. The semi-ellipsoidal pit was selected as the reference morphology. To exclude the interference of dimensional differences, the opening area of all pits was uniformly set to 113 mm² and the pit depth was fixed at 2 mm. The coupling mechanism under tensile load is illustrated in Figure 3a: anodic iron dissolution occurs at the stress-concentrated pit bottom, while cathodic oxygen reduction takes place at both ends of the steel plate.

For the boundary conditions, the left end of the steel specimen was fully constrained in the solid mechanics module, and a uniaxial tensile displacement was applied to the right end to simulate axial loading. In the electrochemical field, the left end of the steel plate was defined as the electrical ground, and all external boundaries of the electrolyte domain were set as electrically insulated.

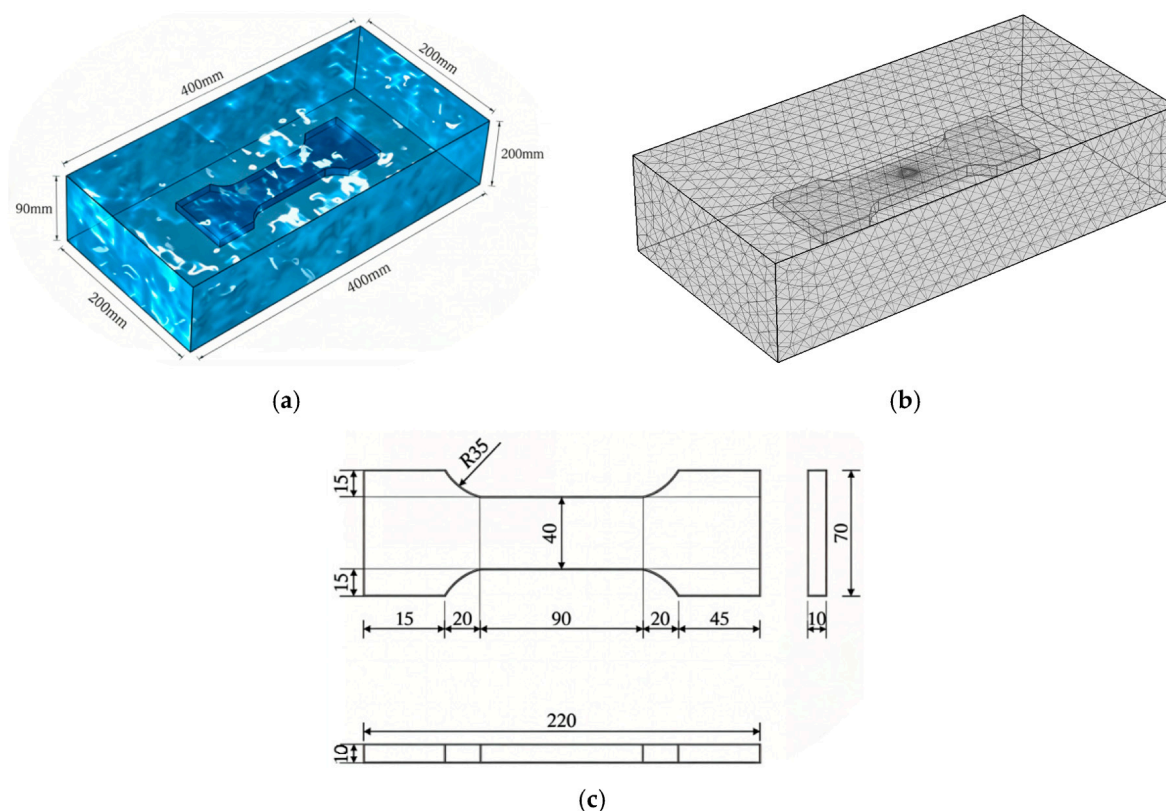


Figure 2. Mechano-electrochemical coupling model of Q420NS steel in simulated seawater. (a) Geometric model. (b) Mesh generation. (c) Specimen dimensions.

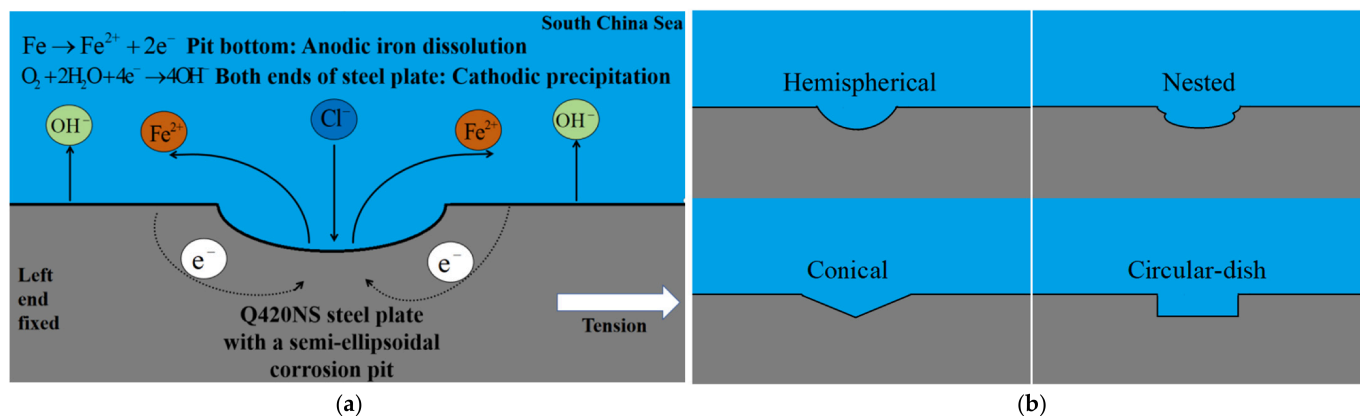


Figure 3. Schematic of mechano-electrochemical coupling for Q420NS steel with various pit morphologies. (a) Coupling mechanism under tensile loading. (b) Cross-sectional profiles of four pit types.

A free tetrahedral mesh was adopted for the whole model, as shown in Figure 2b. Because the stress and current density gradients are substantially higher in the pit region, a region-based meshing strategy was employed to balance accuracy and efficiency: the maximum element size was set to 16 mm for the seawater and steel matrix domains, while the pit region was locally refined to reduce numerical errors. To further eliminate discretization errors and ensure the reliability of the calculation results, a mesh independence study was carried out under four tensile displacements (0.1, 0.5, 1, 2 mm) covering the elastic, initial plastic and severe plastic deformation regimes. Three mesh schemes were created: a coarse mesh (42,445 elements), a baseline mesh (105,613 elements) and a refined mesh (142,119 elements). Five core metrics—maximum stress, maximum equivalent plastic

strain, maximum corrosion rate, maximum electrolyte potential and maximum current density—were quantitatively compared, as listed in Table 2. All metrics exhibit monotonic convergence with an increasing number of elements. With the refined mesh as the reference, the relative errors of the baseline mesh are all below 2.2%, well under the widely accepted 5% threshold, and the largest error (approximately 2.11%) occurs in the maximum stress at 2 mm displacement. The baseline mesh achieves a favorable balance between accuracy and efficiency, and is therefore applied to all subsequent simulations.

Table 2. Mesh sensitivity analysis.

Tensile Displacement (mm)	Number of Elements	Maximum Stress (MPa)	Maximum Equivalent Plastic Strain	Maximum Corrosion Rate (mm/a)	Maximum Electrolyte Potential (mV)	Maximum Current Density (A/m ²)
0.1	42,445	186	0	-8.07×10^{-5}	−553.4763	8.79×10^{-5}
	105,613	184	0	-8.32×10^{-5}	−553.4764	8.59×10^{-5}
	142,119	185	0	-8.42×10^{-5}	−553.4764	8.67×10^{-5}
0.5	42,445	639	4.98×10^{-3}	−0.0143	−553.3297	0.0123
	105,613	639	4.63×10^{-3}	−0.0134	−553.323	0.0116
	142,119	643	4.62×10^{-3}	−0.0134	−553.3219	0.0116
1	42,445	685	0.0737	−0.0619	−558.7904	0.0533
	105,613	663	0.0752	−0.0627	−558.7375	0.054
	142,119	657	0.0754	−0.0628	−558.7381	0.054
2	42,445	647	0.203	−0.0899	−563.4752	0.0775
	105,613	695	0.211	−0.0923	−563.3448	0.0794
	142,119	710	0.212	−0.0926	−563.3397	0.0797

2.2.2. Governing Equations of Mechano-Electrochemical Coupling

Stress concentration usually happens at the corrosion pits of the steel plate, which causes local plastic deformation near the pits. Hence, as part of the modeling, a equivalent plastic strain model is considered together with the von Mises yield criterion and isotropic hardening model in order to provide such mechanical behavior of the model that would be closer to the real-life behavior [22]. The hardening function (σ_{yhard}) is defined as follows:

$$\sigma_{\text{yhard}} = \max \left[0, \sigma_{\text{exp}} \left(\varepsilon_p + \frac{\sigma}{E} \right) - \sigma_m \right] \quad (1)$$

where σ_{exp} is the stress–strain function obtained experimentally, ε_p is the equivalent plastic strain, σ is the Von Mises stress, E is the elastic modulus, and σ_m is the yield strength.

The effect of applied load on the cathode potential is negligible [34]; thus, the anodic and cathodic overpotentials are given by:

$$\begin{cases} \eta_a = \varphi_a - \varphi'_{\text{eq},a} \\ \eta_c = \varphi_c - \varphi_{\text{eq},c} \end{cases} \quad (2)$$

where η_a denotes the anodic reaction overpotential; φ_a denotes the anodic electrode potential; $\varphi'_{\text{eq},a}$ denotes the anodic equilibrium potential under applied load; η_c denotes the cathodic reaction overpotential; φ_c denotes the cathodic electrode potential; $\varphi_{\text{eq},c}$ denotes the cathodic equilibrium potential in the absence of applied load.

When steel is subjected to applied mechanical loads, the work done by internal forces induces a change in the free energy of the system, which in turn alters the anodic

electrochemical potential and shifts the anodic equilibrium potential [18]. The anodic equilibrium potential under loading is given by:

$$\begin{aligned}\varphi'_{\text{eq,a}} &= \varphi_{\text{eq,a}} + \Delta\varphi^e + \Delta\varphi^p \\ &= \varphi_0 + \frac{RT}{nF} \ln \frac{a_{\text{ox}}}{a_{\text{red}}} + \Delta\varphi^e + \Delta\varphi^p\end{aligned}\quad (3)$$

where $\varphi_{\text{eq,a}}$ denotes the anodic equilibrium potential in the absence of applied load; $\Delta\varphi^e$ denotes the shift in anodic equilibrium potential induced by elastic strain; $\Delta\varphi^p$ denotes the shift in anodic equilibrium potential induced by equivalent plastic strain; φ_0 denotes the anodic equilibrium potential under standard conditions; R denotes the ideal gas constant, with a value of 8.315 J/(mol·K); T denotes the absolute temperature, with a value of 301.15 K, which is the same as the annual surface water temperature of the South China Sea.; n denotes the number of electrons transferred in the reaction; F denotes the Faraday constant, with a value of 96,485 C/mol; a_{ox} denotes the activity of the oxidized species; a_{red} denotes the activity of the reduced species.

When the anode of steel is in an elastic state, the isothermal-isobaric free energy has a linear relationship with stress P . In the equation of state, the molar volume V is expanded into a power series in terms of stress. Steel possesses low compressibility, so only the zero-order term is retained. The shift in anodic equilibrium potential induced by elastic strain is given by [35,36]:

$$\Delta\varphi^e = \frac{\int_{P_1}^{P_2} V(P) dP}{nF} = \frac{\int_{P_1}^{P_2} V_m e^{(-\chi^P)} dP}{nF} \approx -\frac{V_m \Delta P}{nF} \quad (4)$$

where V_m denotes the molar volume of steel; ΔP denotes the absolute value of hydrostatic pressure in the stress tensor.

$$\Delta P = \begin{cases} \sigma/3, & \varepsilon_p = 0 \\ \sigma_m/3, & \varepsilon_p > 0 \end{cases} \quad (5)$$

When the anode of steel is in a plastic state, the deformation resistance of the material is determined by the different orientations of its grains. Dislocation clusters form on grain surfaces and raise the flow stress. The rise in thermal potential energy during dislocation generation elevates the electrochemical potential of steel. The shift in anodic equilibrium potential induced by equivalent plastic strain is given by:

$$\Delta\varphi^p = -\frac{RT}{nF} \ln \left(\frac{v\alpha}{N_0} \varepsilon_p + 1 \right) \quad (6)$$

where v denotes the Schmid factor; α denotes the coefficient; N_0 denotes the initial dislocation density of steel prior to plastic deformation.

The anodic equilibrium potential induced by elastoplastic strain is given by [21]:

$$\varphi'_{\text{eq,a}} = \varphi_{\text{eq,a}} - \frac{V_m \Delta P}{nF} - \frac{RT}{nF} \ln \left(\frac{v\alpha}{N_0} \varepsilon_p + 1 \right) \quad (7)$$

Studies have shown that stress accelerates the cathodic reaction rate. A semi-empirical formula incorporating stress effects into the exchange current density is adopted to characterize the mechano-electrochemical effect. The exchange current densities of the anode and cathode are expressed as [26]:

$$\begin{cases} i'_a = i_a \times 10^{\frac{\eta_a}{b_a}} \\ i'_c = i_c \times 10^{\frac{\sigma V_m}{6F(-b_c)}} \end{cases} \quad (8)$$

where i'_a denotes the anodic exchange current density under applied load; i_a denotes the anodic exchange current density without applied load; b_a denotes the anodic Tafel slope; i'_c denotes the cathodic exchange current density under applied load; i_c denotes the cathodic exchange current density without applied load; b_c denotes the cathodic Tafel slope.

Faraday's law states that the mass of substances undergoing chemical reactions at the steel/electrolyte interface is proportional to the current intensity and energization time:

$$m = KI_a t = \frac{M}{nF} I_a t \quad (9)$$

where m denotes the dissolved mass of corroded steel; K denotes the electrochemical equivalent; I_a denotes the anodic exchange current; t denotes the corrosion time; M denotes the molar mass of steel.

Combining Equation (9) with the definition of corrosion rate, the normal corrosion velocity at the interface is derived. This velocity corresponds to the steel corrosion rate calculated from the dissolved corrosion mass, namely the nominal corrosion rate [27]:

$$V_n = \frac{M}{nF\rho} i'_a \quad (10)$$

where V_n denotes the nominal corrosion rate; ρ denotes the density of steel.

3. Results and Discussion

3.1. Effect of Tensile Displacement on Mechano-Electrochemical Coupling Behavior

3.1.1. Evolution of Stress and Equivalent Plastic Strain Fields

Figure 4 displays the von Mises stress contours of the specimen containing a semi-ellipsoidal pit, subjected to axial tensile displacements of 0.1, 0.3, 0.5, 0.7, 1, and 2 mm. The stress concentration invariably appears at the pit base and the transition fillets of the specimen—these two locations are the most susceptible to structural failure.

When the tensile displacement was 0.1–0.3 mm, the stress reached a maximum of 184 MPa and 552 MPa, respectively. This indicates that the material was still in the elastic deformation stage but was already approaching its yield strength. However, when the displacement reached 0.5 mm, the stress had already exceeded the yield strength, reaching 639 MPa. It can be observed that yielding first occurred at the bottom of the pit, followed by the gradual expansion of the high-stress region along the axial tensile direction. As the displacement subsequently increased to 2 mm, the stresses rose to 645 MPa, 663 MPa, and 695 MPa, respectively. The specimen in the central region clearly entered a state of global plastic deformation accompanied by work hardening, with plastic flow fully developed.

Figure 5 presents the equivalent plastic strain fields for the Q420NS steel specimen with a semi-ellipsoidal pit at displacement levels of 0.5, 0.7, 1, and 2 mm. At the earlier stages (0.1 and 0.3 mm), the specimen stays purely elastic without any detectable plastic strain. When the displacement was 0.5 mm, the maximum equivalent plastic strain at the bottom of the pitting was only 4.63×10^{-3} . As the displacement increased to 0.7 mm, the plastic zone expanded significantly, and the peak strain rose to 0.0333. Subsequently, at displacements of 1 mm and 2 mm, the peak strain reached 0.0752 and 0.211, respectively, with plastic deformation fully developed and spreading outward. The equivalent plastic strain field closely coincided with the high-value regions of the von Mises stress field. When the tensile displacement reaches 2 mm, the peak equivalent plastic strain (0.211) approaches the critical value for ductile fracture of Q420NS steel, posing a risk of microcrack initiation at the bottom of the pitting corrosion pit. Since this paper focuses on pre-fracture force-electrochemical coupled corrosion behavior and the fracture mechanics module was

not incorporated into the model, the maximum displacement was limited to 2 mm; all conclusions drawn are valid within this range.

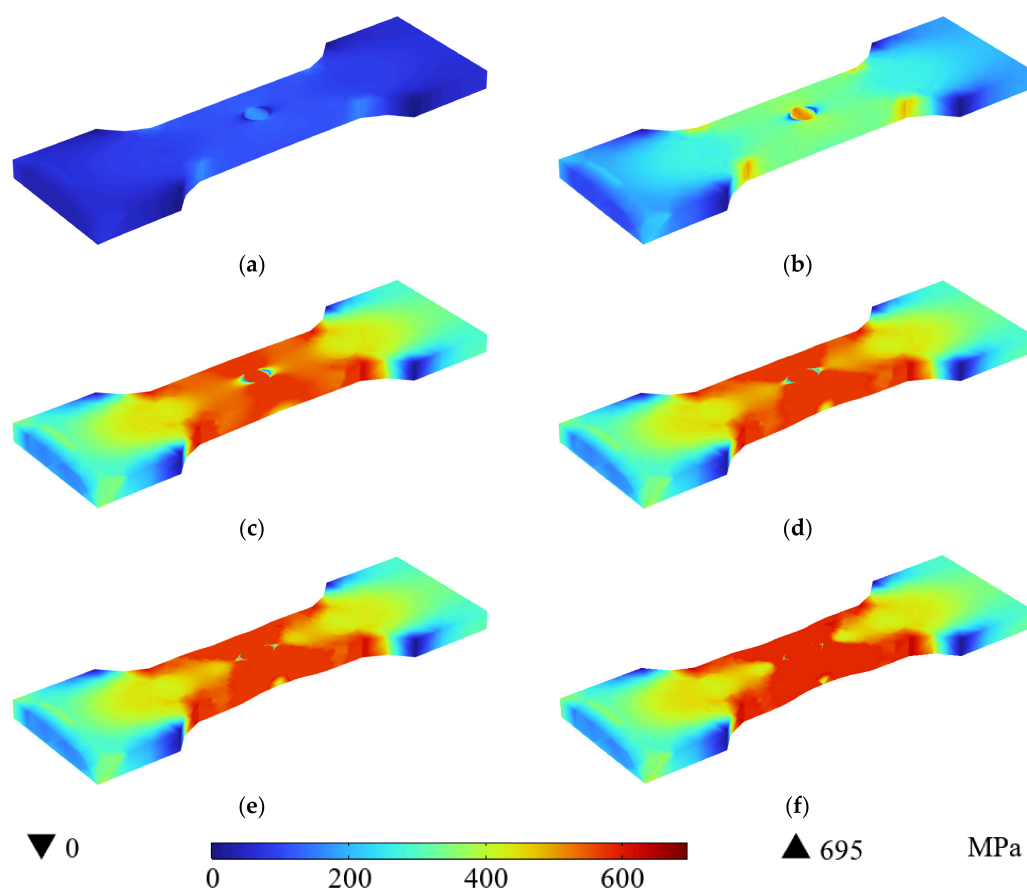


Figure 4. Von Mises stress distribution in Q420NS steel plate specimens at different tensile displacements: (a) 0.1 mm, (b) 0.3 mm, (c) 0.5 mm, (d) 0.7 mm, (e) 1 mm, (f) 2 mm.

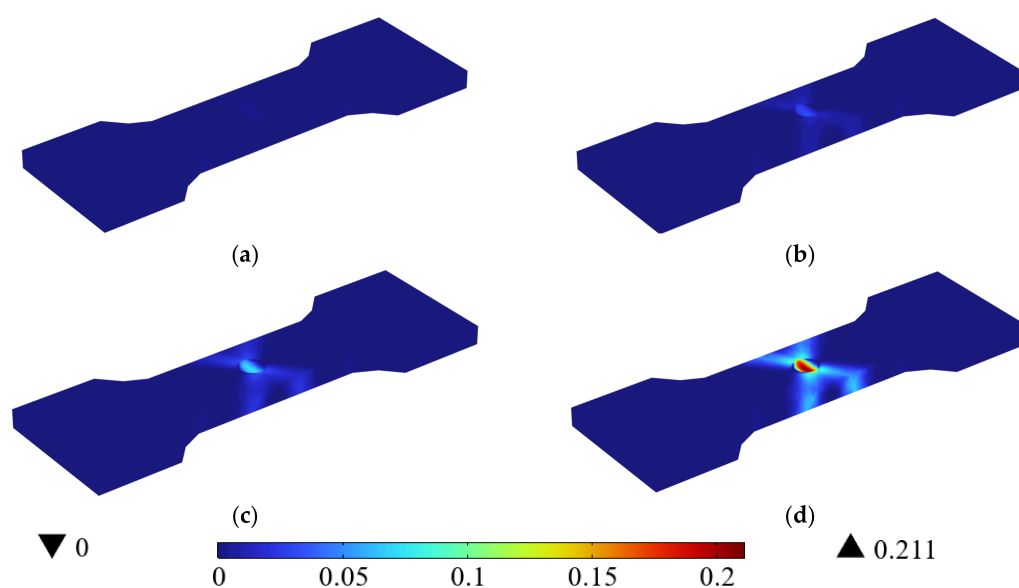


Figure 5. Distribution of equivalent plastic strain in Q420NS steel plate specimens at different tensile displacements: (a) 0.5 mm, (b) 0.7 mm, (c) 1 mm, (d) 2 mm.

3.1.2. Evolution of Corrosion Potential and Current Density Fields

Figure 6 displays the three-dimensional corrosion potential field within the electrolyte for the dog-bone-shaped Q420NS steel specimen containing a semi-ellipsoidal pit, tested under six tensile displacement levels (0.1–2 mm) in simulated South China Sea seawater. In the contour plots, red corresponds to a more negative potential (indicating higher electrochemical activity and a stronger anodic tendency), while blue represents a more positive potential. As the applied displacement increases, the potential distribution becomes progressively more non-uniform, and the most negative potential value always appears at the location of peak stress concentration adjacent to the pit.

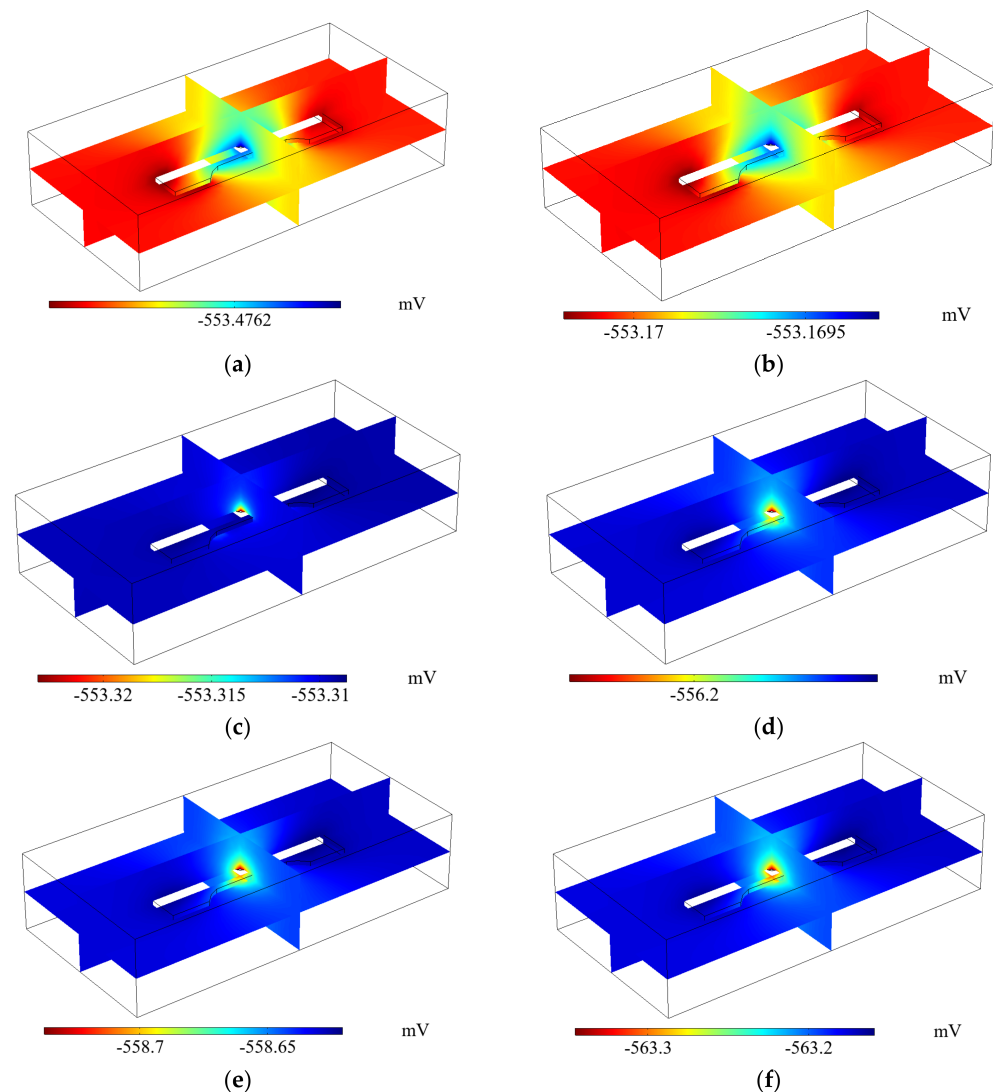


Figure 6. Three-dimensional distribution contours of corrosion potential in the electrolyte solution under different tensile displacements: (a) 0.1 mm, (b) 0.3 mm, (c) 0.5 mm, (d) 0.7 mm, (e) 1 mm, (f) 2 mm.

During the elastic regime (0.1–0.3 mm), the overall potential distribution stays largely homogeneous. At 0.1 mm, the potential difference between the pit bottom and the surrounding matrix is only 0.0003 mV, and this value rises slightly to 0.0009 mV at 0.3 mm, with negligible anodic/cathodic separation. Such behavior arises because elastic deformation causes only a minor negative shift in the anodic equilibrium potential through free energy variations, resulting in a very weak modulation of electrochemical activity.

It can be seen that plastic deformation exacerbates the potential non-uniformity. When stretched to 0.5 mm, the potential difference between the corrosion pit and the matrix reached 0.0142 mV (15.8 times the maximum difference observed during the elastic stage), with the corrosion pit acting as a significant anode; at 0.7 mm, the potential difference rose to 0.0742 mV (82.4 times that at 0.1 mm), and the system potential shifted negatively by approximately 3 mV, forming a macroscopic corrosion galvanic cell with a large cathode and a small anode, in which the corrosion pit acted as a strong anode and the matrix as a cathode.

As the displacement further increases to 1 mm and 2 mm, the potential difference widens to 0.117 mV and 0.1857 mV, respectively. The overall potential intervals shift toward more negative values: -558.74 to -558.62 mV at 1 mm and -563.34 to -563.16 mV at 2 mm. These changes are accompanied by continuously enhanced anodic features at the pit bottom and an amplified driving force for macro-galvanic corrosion.

The essence of this phenomenon lies in a mechano-electrochemical coupling mechanism: tensile stress increases the chemical free energy of metal atoms, causing the anodic equilibrium potential to shift negatively; at the same time, plastic deformation triggers extensive dislocation propagation, increasing the density of active sites on the metal surface. The combined effect of these two mechanisms significantly enhances the tendency for anodic dissolution at the bottom of stress-concentration pits.

Figure 7 shows the three-dimensional distribution of the corrosion current density across the surface of the Q420NS steel specimen at various tensile displacements. At a displacement of 0.1 mm, the maximum corrosion current density is merely 8.59×10^{-5} A/m²; nevertheless, the value at the pit is approximately three times that of the surrounding matrix. This indicates that the stress concentration at the pit bottom already enhances localized corrosion susceptibility during the early elastic deformation stage.

With increasing tensile displacement, the maximum corrosion current density grows exponentially: 2.63×10^{-4} A/m² at 0.3 mm (3.1 times the 0.1 mm value), 0.0116 A/m² at 0.5 mm (135 times), 0.0372 A/m² at 0.7 mm (433 times), 0.054 A/m² at 1 mm (629 times), and 0.0794 A/m² at 2 mm (924 times). The high-current region expands continuously from the pit area toward both ends, while the current density at the specimen ends remains the lowest. At 0.7 mm, a cross-shaped high-current zone matching the equivalent plastic strain distribution forms, with local current density over 80 times higher than that of the matrix. As displacement further increases to 1 mm and 2 mm, the high-current zone spreads outward and the pit-bottom corrosion current keeps rising, reflecting progressively intensified local corrosion.

These results confirm that the corrosion-accelerating effect of tensile stress strengthens rapidly with displacement, and plastic deformation is a dominant driver of the abrupt rise in corrosion rate.

3.2. Effect of Mechano-Electrochemical Coupling on Corrosion Rate

Figure 8 illustrates the three-dimensional corrosion rate distribution across the Q420NS steel surface under various tensile displacements. Here, negative values denote anodic dissolution, whereas positive values signify cathodic deposition of corrosion products.

At a displacement of 0.1 mm, the most intense dissolution occurs along the pit opening periphery, with a peak dissolution rate of -8.32×10^{-5} mm/yr. Relative to this baseline, the maximum dissolution rate is amplified by factors of 3.0, 161, 520, 754, and 1109 at displacements of 0.3, 0.5, 0.7, 1, and 2 mm, respectively. Concurrently, the zone of highest corrosion migrates from the pit rim toward the pit bottom, evolving into a cross-shaped region of strong anodic activity. This anodic zone continues to expand at displacements of 1–2 mm, accompanied by intensified localized dissolution.

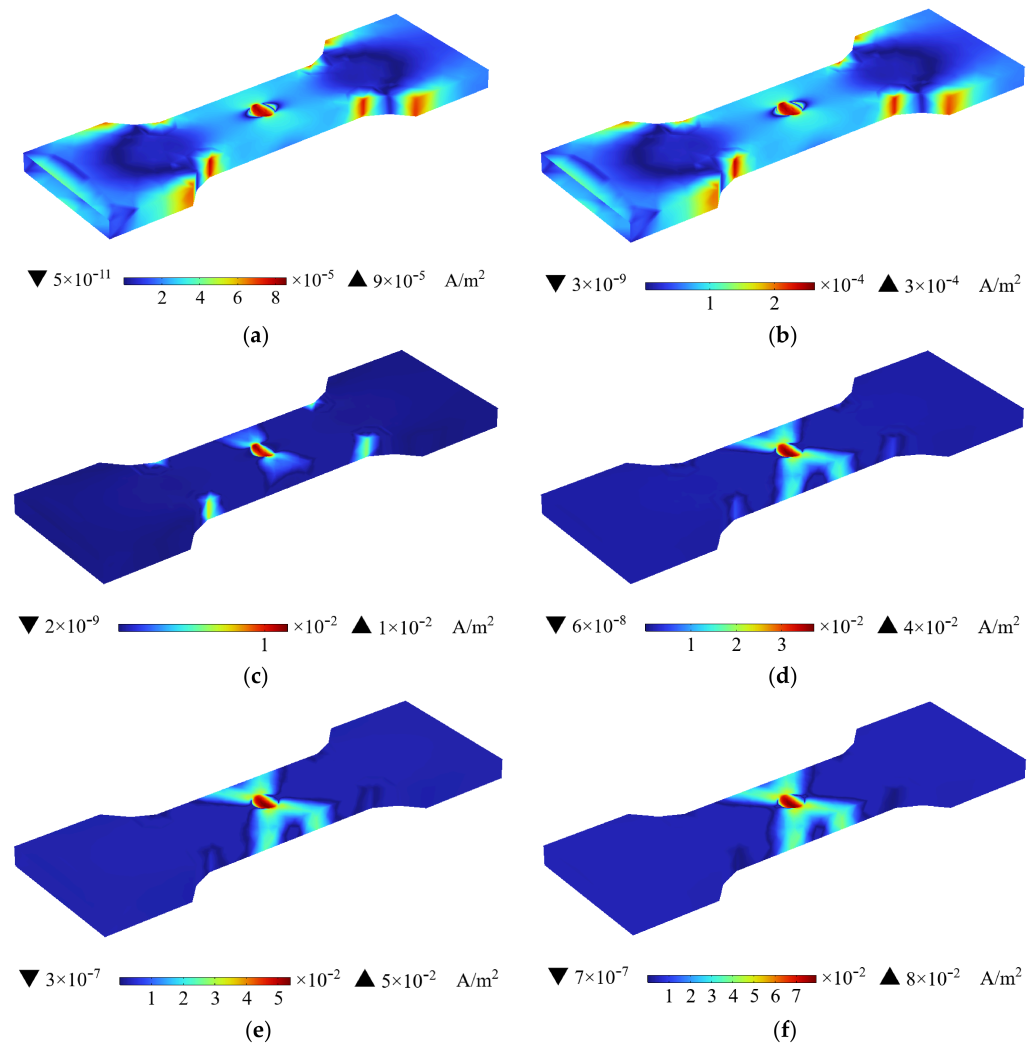


Figure 7. Corrosion current density distribution of the Q420NS steel plate specimen under different tensile displacements: (a) 0.1 mm, (b) 0.3 mm, (c) 0.5 mm, (d) 0.7 mm, (e) 1 mm, (f) 2 mm.

Comparison with Figures 5 and 7 confirms that the corrosion rate evolution matches well with the corrosion current density, and its distribution is highly consistent with the equivalent plastic strain pattern, verifying that local plastic deformation drives the sharp rise in corrosion rate under the mechano-electrochemical coupling effect.

The above studies adopt the widely used semi-ellipsoidal pit assumption. However, actual marine corrosion pits present diverse morphologies including hemispherical, conical, circular-dish and nested, which significantly affect the stress concentration factor and further dominate the plastic deformation threshold and corrosion process. The modulation mechanism of pit morphology on the coupling behavior and unified quantitative metrics remains to be fully elucidated.

3.3. Effect of Corrosion Pit Morphology on Mechano-Electrochemical Coupling Behavior

Under the same tensile displacement (0.7 mm), with the pit mouth area (113 mm²) and pit depth (2 mm) kept constant, the distribution characteristics of the corrosion rate and equivalent plastic strain for pits of different morphologies were compared, thereby discussing the influence of pit morphology on the corrosion behavior.

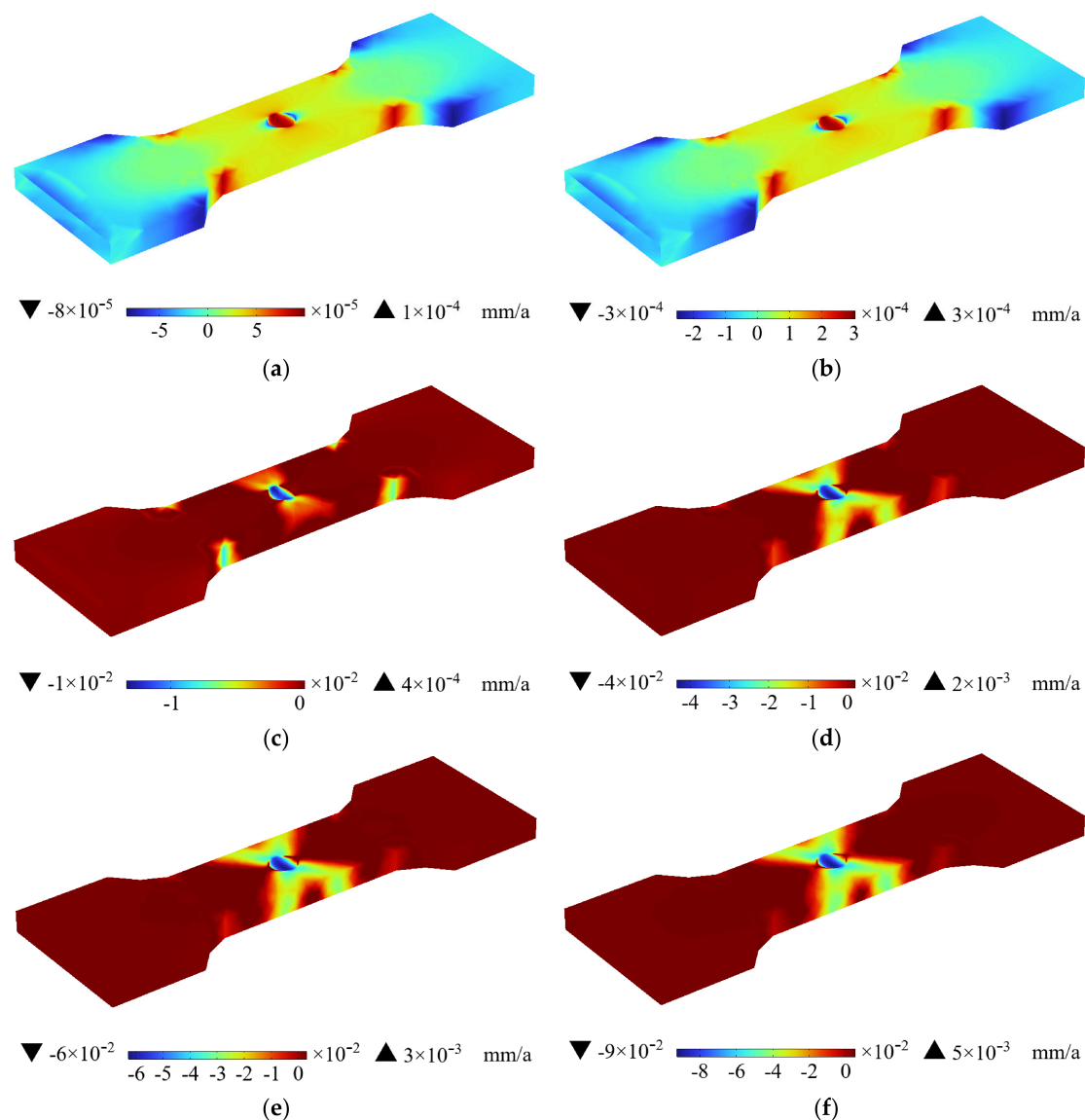


Figure 8. Corrosion rate distribution of Q420NS steel plate specimens under different tensile displacements: (a) 0.1 mm, (b) 0.3 mm, (c) 0.5 mm, (d) 0.7 mm, (e) 1 mm, (f) 2 mm.

Figure 9 displays the corrosion rate distribution for specimens possessing different pit morphologies. The most aggressive corrosion is observed in the conical pit, which yields a peak dissolution rate of -0.077 mm/a, followed sequentially by the nested pit (-0.0522 mm/a), the circular-dish pit (-0.0502 mm/a), the hemispherical pit (-0.0479 mm/a), and the semi-ellipsoidal pit.

The cathodic deposition rates remain essentially indistinguishable across all pit geometries (approximately 2.0×10^{-3} mm/a), indicating that the cathodic reaction is governed by oxygen diffusion and is therefore largely insensitive to the pit morphology. Consequently, the mechano-electrochemical coupling effect modulates the overall corrosion behavior mainly through the acceleration of anodic dissolution.

Figure 10 shows that equivalent plastic strain is highly concentrated at the pit bottom for all morphologies, with near-zero strain in the rest of the specimen. The concentration degree varies significantly: the conical pit has the maximum equivalent plastic strain of 0.0862, which is 2.59, 2.21, 2.02 and 1.92 times that of the semi-ellipsoidal, hemispherical, circular-dish and nested pits, respectively. Comparison with Figure 9 confirms that

the equivalent plastic strain ranking is fully consistent with the corrosion rate ranking, indicating a distinct positive correlation between the two.

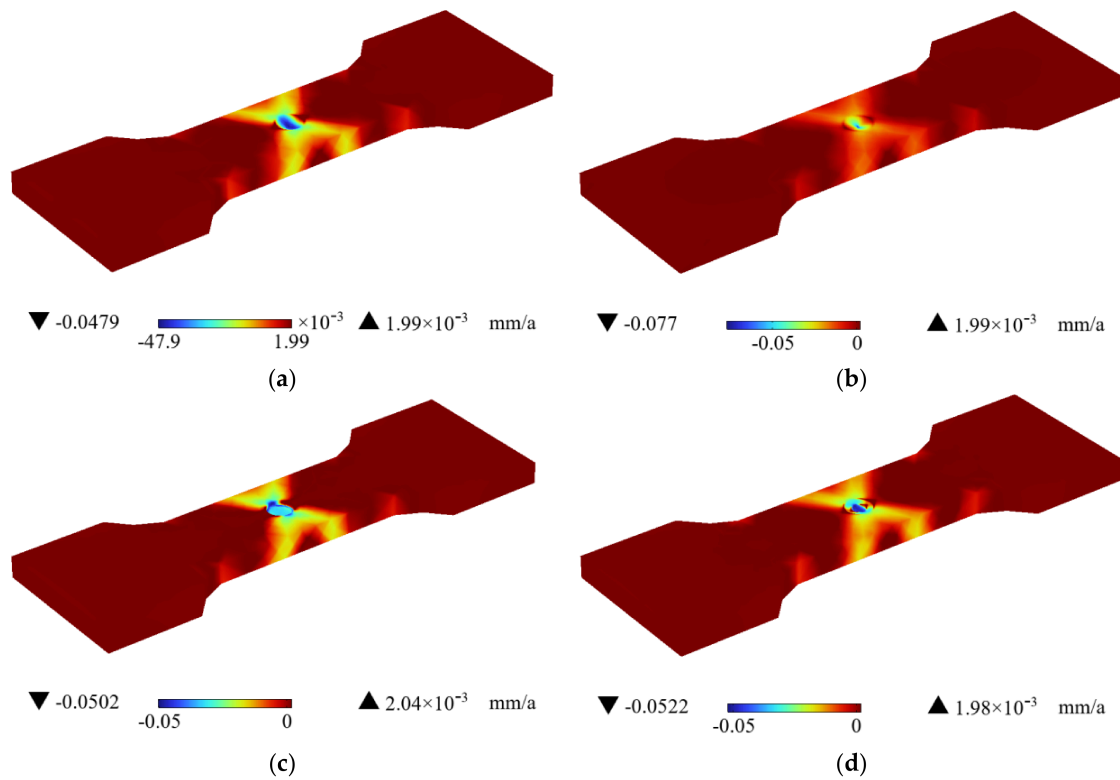


Figure 9. Corrosion rate distribution of Q420NS steel plates containing pits of different morphologies: (a) hemispherical, (b) conical, (c) circular-dish, (d) nested.

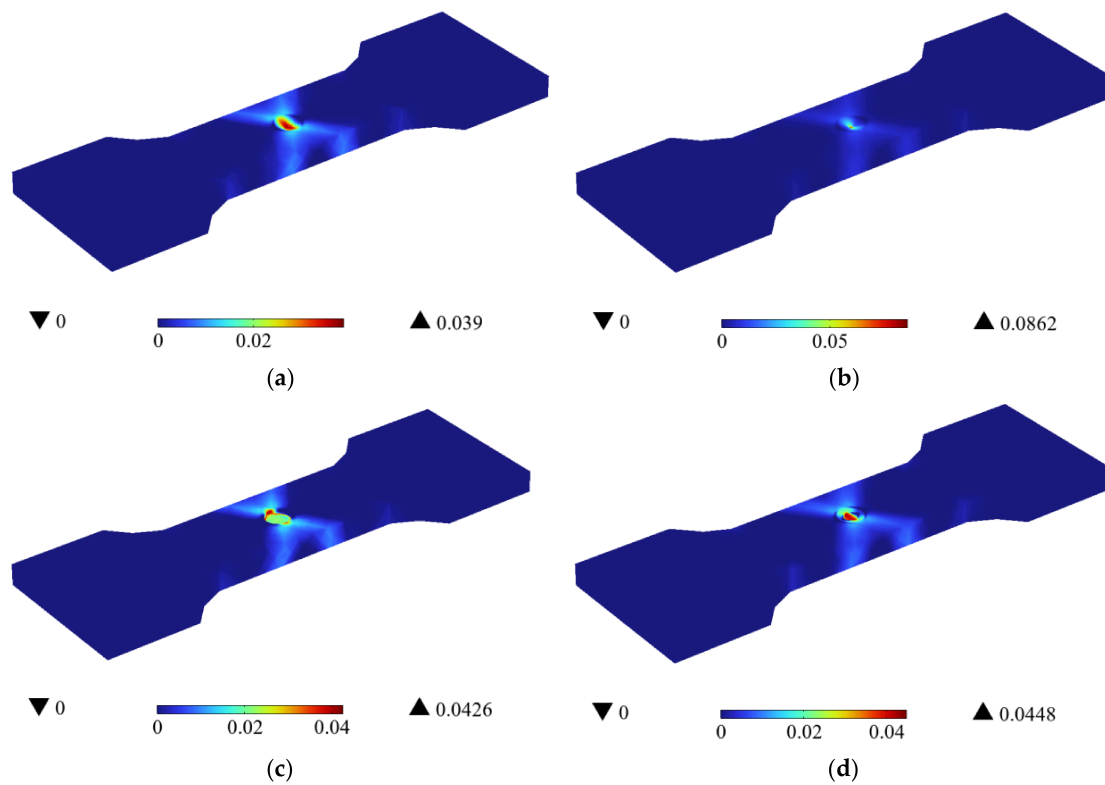


Figure 10. Equivalent plastic strain distribution of Q420NS steel plate specimens with pits of different morphologies: (a) hemispherical, (b) conical, (c) circular-dish, (d) nested.

The variation in pit morphology gives rise to different levels of stress concentration, which in turn governs the evolution of plastic deformation and ultimately dictates the corrosion process. Owing to its smallest bottom curvature radius and the highest stress concentration factor, the conical pit undergoes the earliest yielding, exhibits the fastest expansion of the plastic zone, and generates the greatest dislocation density, thereby yielding the highest corrosion rate. By contrast, the semi-ellipsoidal pit is characterized by the most uniform stress distribution, the least pronounced plastic deformation, and the lowest corrosion rate.

To elucidate how pit morphology affects the mechano-electrochemical coupling behavior, Table 3 summarizes the key parameters of the five pit types from the perspectives of plastic deformation threshold, maximum equivalent plastic strain, maximum corrosion rate, and coupling intensity.

Table 3. Mechano-electrochemical coupling performance parameters for different pit morphologies.

Pit Morphology	Threshold Displacement of Plastic Deformation (mm)	Change in Threshold Displacement Relative to Reference	Maximum Equivalent Plastic Strain	Increase in Equivalent Plastic Strain Relative to Reference	Maximum Corrosion Rate (mm/a)	Increase in Corrosion Rate Relative to Reference	Equivalent Plastic Strain-to-Corrosion Rate Ratio K (a/mm)
Semi-ellipsoidal (Reference)	0.32	-	0.0333	-	-0.0433	-	-0.7691
hemispherical	0.31	-3.13%	0.0390	+17.12%	-0.0479	+10.62%	-0.8142
Conical	0.20	-37.50%	0.0862	+158.86%	-0.077	+77.83%	-1.1195
Circular-dish	0.21	-34.38%	0.0426	+27.93%	-0.0502	+15.94%	-0.8486
Nested	0.25	-21.88%	0.0449	+34.83%	-0.0512	+18.24%	-0.8770

The plastic deformation threshold displacement is strongly negatively correlated with both maximum equivalent plastic strain and corrosion rate: a lower threshold means earlier yielding, more accumulated plastic damage and corrosion active sites, and consequently higher corrosion severity. The conical pit has the lowest threshold of 0.20 mm, 37.50% lower than the reference semi-ellipsoidal pit (0.32 mm), which is the fundamental reason for its highest corrosion rate. Thus, the plastic deformation threshold can be used as a core indicator to evaluate the stress corrosion sensitivity of different pit morphologies.

Ranked by hazard degree based on three core indicators at 0.7 mm tensile displacement, the order is: conical pit >> nested pit > circular-dish pit > hemispherical pit > semi-ellipsoidal pit. The hazard ranking is based on how differences in the curvature radius of the pit bottom determine the stress concentration factor. Conical pit bottoms have the smallest curvature, the strongest stress concentration, the earliest yield, and the highest anodic dissolution rate; semi-ellipsoidal contours are the smoothest and exhibit the weakest coupling effect. The curvature of nested, dish-shaped, and hemispherical pit bottoms increases in that order, causing stress concentration to gradually weaken, delaying the onset of plastic deformation, and reducing the corrosion rate, thereby establishing this classification pattern.

Based on the mechano-electrochemical coupling performance parameters of different pit morphologies at a tensile displacement of 0.7 mm (Table 3), the coupling intensity coefficient $|K|$ (the ratio of equivalent plastic strain to corrosion rate) was proposed as a unified quantitative indicator. The coupling coefficient is defined as $K = \varepsilon_{eq,max} / v_{corr,max}$ to enable cross-condition comparison, where $\varepsilon_{eq,max}$ is the peak equivalent plastic strain and $v_{corr,max}$ the maximum anodic corrosion rate at the pit. For each morphology and displacement, these two peak field values are directly extracted for calculation without averaging, and $|K|$ is used to quantify coupling intensity. The $|K|$ value represents the increment in equivalent plastic strain corresponding to a unit increment in corrosion rate. It

eliminates the influence of differences in absolute deformation and corrosion rates among different pit morphologies and directly reflects the intrinsic efficiency of plastic deformation in driving corrosion.

Figure 11 shows the variation of $|K|$ with tensile displacement. The $|K|$ curves for each corrosion pit all exhibit a gradual transition followed by a sustained increase, and can be divided into two stages. During the elastic–plastic transition stage (0.2–0.4 mm), stress levels are relatively low; semi-ellipsoidal and hemispherical pits remain largely elastic, while the bottoms of pits with higher stress concentrations have already undergone localized yielding, resulting in a gradual rise in $|K|$. During the uniform plastic deformation stage (0.4–2.0 mm), all pits enter an elastoplastic state. The accumulation of plastic strain accelerates corrosion; however, since the rate of strain accumulation consistently exceeds the corrosion rate, $|K|$ increases approximately linearly. Conical pits exhibit the highest $|K|$ values throughout the entire process, the shortest plateau phase, the fastest rate of increase, and the greatest sensitivity to displacement; semi-ellipsoidal pits consistently exhibit the lowest $|K|$ values, confirming that morphology plays a key role in regulating the coupling behavior.

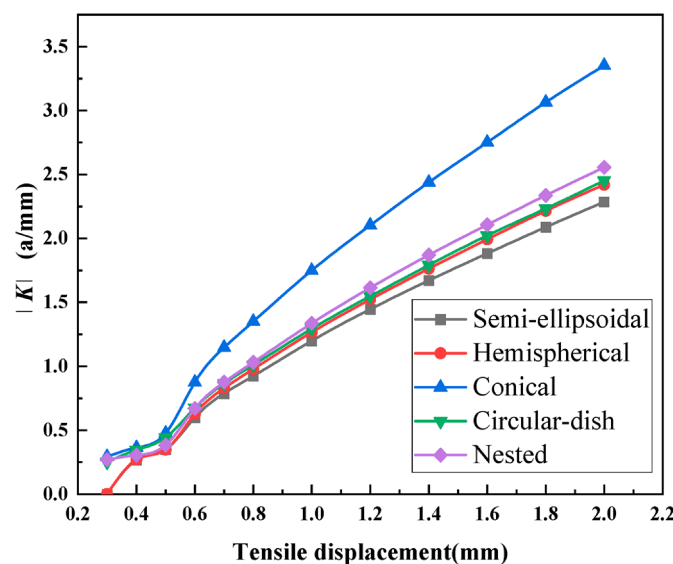


Figure 11. Variation in the coupling intensity coefficient $|K|$ under tensile displacement for different corrosion pit morphologies.

Numerical results validate the reliability of $|K|$: the hazard level rankings derived from $|K|$, plastic strain, and corrosion rate are fully consistent. This consistency follows the “curvature–stress–plasticity–corrosion” chain mechanism—the smaller the curvature at the pit bottom, the greater the stress concentration, the lower the plasticity threshold, the larger the plastic strain, and consequently the faster the anodic dissolution and the higher the coupling strength $|K|$. Furthermore, $|K|$ increases monotonically with displacement, consistent with the mechanism whereby plastic deformation increases the density of active sites and accelerates corrosion; pits with smaller yield critical displacements exhibit higher $|K|$ values, enabling effective evaluation of stress corrosion susceptibility. Table 3 provides characteristic values at key displacement points, complementing the evolution patterns across the entire range shown in Figure 11; in engineering practice, combining known $|K|$ values with the actual strain levels of components allows for rapid estimation of corrosion rates.

4. Conclusions

A three-dimensional bidirectional mechano-electrochemical finite element model has been developed to investigate the corrosion behavior of pitted Q420NS steel immersed in simulated South China Sea seawater. Through a series of numerical simulations, the combined effects of tensile displacement and pit morphology on stress distribution, equivalent plastic strain, electrolyte potential, current density, and anodic dissolution rate are systematically elucidated. A coupling intensity parameter K is originally introduced in this study to quantitatively characterize the magnitude of the mechano-electrochemical coupling. The principal findings are summarized as follows.

Tensile displacement intensifies the coupled degradation process concentrated at pit bottoms. In the elastic regime (0.1–0.3 mm), the coupling is weak, and the anodic dissolution rate grows in a nearly linear fashion. After the onset of plastic yielding, massive dislocation multiplication generates abundant surface active sites, causing the corrosion rate to accelerate exponentially. The regions of high plastic strain and rapid dissolution coincide at the pit bottom and evolve into cross-shaped distributions under large imposed displacements.

The morphology of corrosion pits determines the degree of stress concentration, the plastic yield threshold, and the ultimate severity of corrosion. For pits of the same size, the corrosion hazard is ranked from highest to lowest as follows: conical > nested > circular-dish > hemispherical > semi-ellipsoidal. The smaller the radius of curvature at the bottom of a pit, the stronger the stress concentration effect and the lower the plastic yield threshold. The plastic yield threshold is negatively correlated with the peak equivalent plastic strain and the anodic dissolution rate, and can serve as a reliable indicator for evaluating stress corrosion susceptibility. Traditional models based on semi-ellipsoidal pits significantly underestimate the actual corrosion risk posed by pits with complex geometries in marine service environments.

The coupling strength coefficient $|K|$ is defined by $K = \varepsilon_{eq,max} / v_{corr,max}$ as the ratio of the peak equivalent plastic strain to the maximum anodic dissolution rate. It is extracted directly without averaging, facilitating a unified comparison across all morphologies and displacement conditions. The larger the value of $|K|$, the stronger the driving effect of plastic deformation on anodic dissolution. The $|K|$ value for each corrosion pit increases monotonically with displacement, exhibiting a two-stage characteristic: a slow transition from elastic to plastic behavior, followed by linear growth dominated by plastic flow. Conical corrosion pits exhibit the highest $|K|$ values throughout the entire process and are most sensitive to load, while semi-ellipsoidal corrosion pits exhibit the lowest $|K|$ values.

Tensile loads trigger a self-amplifying degradation cycle: the morphology of the pitting corrosion pits determines stress concentration, which induces plastic deformation; the accumulated plastic strain accelerates anodic dissolution, and the evolution of the pitting corrosion pit contours further exacerbates stress concentration. By combining $|K|$ with the in-service strain level, the local anodic dissolution rate can be rapidly estimated, providing quantitative support for defect-tolerant design, safety assessment, and remaining life prediction of Q420NS marine steel structures.

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