Research Article

Experimental Research and Simulation on the Mechanical Performance Degradation of Corroded Stud Shear Connectors

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Electrochemical accelerated corrosion and tensile tests were conducted on six series of 30 stud specimens in this study to assess the various mechanical properties in corroded stud connectors. The results indicate that there is a gradual decline in mechanical properties (e.g., yield strength, ultimate strength, and plasticity) as stud corrosion rate increases. Degradation equations for these parameters were established via fitting analysis on the test data. A Gurson–Tvergaard–Needleman (GTN) constitutive model describing the tensile behavior of corroded studs was established based on mesodamage mechanics and finite element analysis. In the GTN model, the corrosion rate equals the original void volume fraction; the trial-and-error method was adopted to determine the relationship between the corrosion rate and material failure parameters. The finite element simulation results are in good agreement with the experimental results. The GTN model accurately simulates the uniaxial tensile behavior of the corroded stud.

1. Introduction

In steel-concrete composite beams, the stud connectors are key components which ensure shear transfer with the reinforced concrete slab. They are often structural failure points [1–3]. In the daily operation of an engineered bridge, traffic loads and temperature loads readily cause interface cracks among materials or cracks in the concrete slab. Upon the formation of cracks, the aggressive medium can easily reach the stud position further leading to stud corrosion, as shown in Figure 1. Corrosion degrades the mechanical properties of the studs and the bond performance between the concrete and studs, which ultimately degrades the structural performance of the entire bridge [4]. Correct, precise, and comprehensive understanding of the mechanical properties of corroded studs is the basis of durability assessment, life prediction, and the computer simulation analyses for steel-concrete composite bridges.

Many researchers have explored corrosion problems in a variety of steel components. Nakai et al. [5], for example, performed a corroded I-beam bending performance test

using an artificial drilling method to simulate rust. They found that flexural capacity and ductility decrease sharply with the increase of the depth and the density of corrosion pits. Almusallam [6] adopted the constant current method to accelerate the corrosion of steel bars in a concrete structure, where the mass loss ratio was used to calibrate the corrosion rate. They found that when the corrosion rate exceeds 12%, the steel bar presents brittle fracture. Garbatov et al. [7] obtained the material parameters of corroded beam specimens through a regression analysis of tensile strength test data. Feng et al. [8] discussed the influencing factors of stress-induced corrosion in steel bars. The results showed that the corrosion behavior of the rebar in mortars is strongly affected by the deterioration of the interface between the concrete and rebar. Chen et al. [9] investigated the behavior of corroded steel fibers with various levels of corrosion levels to find that the nominal tensile strength of the fibers decreases as corrosion increases. Pitting corrosion is also shown to reduce the actual tensile strength of steel fibers, while uniform corrosion has little effect. Zhang et al. [10] studied the effect of corroded prestressed steel bars/

FIGURE 1: Stud corrosion in the steel-concrete composite beam.

strands on the fatigue behavior of partially prestressed concrete beams. They found that deflection and cracks develop quicker and grow wider in corroded beams as stiffness degradation increases compared to that of uncorroded beams. Guo et al. [11] used probabilistic finite element analysis to evaluate time-dependent reliability in strengthened PSC box-girder bridges. They effectively simulated concrete shrinkage, creep and cracking, and corrosion and stress relaxation in steel materials. Liu et al. [12] proposed a stochastic time-variant reliability assessment method considering the combined effect of corrosion and cyclic loading to evaluate the safety of suspenders. Previous studies on corroded steel components have mainly centered on plates and bars, while the corrosion problem in the stud connectors of steel-concrete composite structures is yet unresolved.

Most finite element simulations of corroded steel components are conducted from the macro perspective [13, 14]. Because of the particular scale of the mesovoid, explicit modeling is not suitable for simulation analysis [15]. It is practical, however, for using damage variables to describe corrosion evolution characteristics from the mechanics point of view. The key point in any damage constitutive model is effectively introducing mesodefects into the macrovolume element. Such a damage constitutive model can also help to predict the macroconstitutive relationship [16]. Gurson proposed a model in which the constitutive relationship is analyzed by the mesomechanic homogenization method; he investigated an isolated spherical void in a continuum media and derived the pressure dependent yield function accordingly. However, the Gurson model does not account for intervvoid effects. Tvergaard and Needleman modified the Gurson model to include a yield condition which encompasses the interaction among voids, the Gurson-Tvergaard-Needleman (GTN) model [17, 18]. The GTN model can also be used to describe the tensile behavior of corroded studs.

In this paper, different corrosion rates of studs were selected through an accelerated corrosion method and assessed as per their effects on the mechanical properties of stud connectors via the tensile test. The change laws of various mechanical properties (e.g., yield strength, ultimate strength, and elongation) of corroded stud connectors were analyzed accordingly. The tensile behavior of corroded studs

was also investigated by the GTN constitutive model based on mesodamage mechanics and finite element simulation.

2. Electrochemical Accelerated Corrosion Test

2.1. Electrochemical Accelerated Corrosion Mechanism. The stud connectors were immersed in 5% NaCl solution [19] with a DC power supply. The positive terminal and the negative terminal of the DC power supply were connected with the stud connectors and the copper plate, respectively. Water in the electrolyte was electrolyzed into hydrogen ions and hydroxyl ions (i.e., H^+ and OH^-) once the DC power supply was switched on. H^+ moved to the cathode and OH^- moved toward the anode while the stud lost an electron and an oxidation reaction occurred, whereas the cathodic material obtained an electron and a reduction reaction occurred. A stable current eventually formed leading to a closed loop, as shown in Figure 2. The reaction equation is as follows:

Rust formation is a step-wise process. Fe^{2+} meets with OH^- in the transmission process and $Fe(OH)_2$ is generated. Further, $Fe(OH)_2$ and O_2 are reacted to produce $Fe(OH)_3$. As time progresses, $Fe(OH)_3$ further turns into $nFe_2O_3 \cdot mH_2O$ (red rust). A loose rust layer thus forms on the surface of the stud.

2.2. Equation of Electrochemical Accelerated Corrosion Test Control. Faraday's Law [20] is needed to control the corrosion rate of studs, where the amount of a substance present at an electrode in the battery is proportional to the total electric charge passed through the substance. This can be expressed as follows:

$$Q = mF, \quad (2)$$

where Q is the total electric charge, m is the amount of the substance, and F is the Faraday constant (96484 C/mol).

Assuming the value of the anode current per unit anode area is i ($i = Q/t$), the mass of the corroded iron per unit time is then given by

$$w = \frac{Mm}{nt} = \frac{MQ}{ntF} = \frac{Mi}{nF}, \quad (3)$$

where w is the mass loss of the stud per unit area and per second, the unit is g/s; t is the corrosion time; n is a metal valence, the valence of iron is 2; and M is the relative molecular mass of the metal or the relative atomic mass.

If the stud surface area is A and the current is I , the mass loss for stud (Δm) on corrosion time t is expressed as

$$\Delta m = A \cdot t \cdot w. \quad (4)$$

Meanwhile,

$$I = A \cdot i. \quad (5)$$

By equations (3)~(5), it can be obtained that

FIGURE 2: Experimental setup of the electrochemical accelerated corrosion test.

$$\Delta m = M \frac{I}{nF} t. \quad (6)$$

Equation (6) can be used to calculate the required time t to achieve a predetermined corrosion rate.

2.3. Corrosion Test. Stud type (M13 $\times$ 180) applied in the actual bridges was selected. Its actual diameter is 12.96 mm and the actual length is 178 mm. The material type is ML-15. The specific chemical composition of the stud is listed in Table 1.

The stud specimens were preprocessed prior to the corrosion test. To conveniently chuck clamp the studs during the tensile test, the heads were removed. Numerous threads were carved in the head and tail of each stud to increase the friction force between the chuck and the stud. The studs were then washed with absolute alcohol, and both ends were sealed with an epoxy resin and a heat shrinkable tube; the middle exposed length of the stud was 70 mm. Finally, 30-cm copper wires were welded in one end of the stud. Figure 3 shows the preparation and the electrochemical corrosion test process.

Six series of corrosion tests with different corrosion rates were designed for this study. In each series, five studs were subjected to corrosion over the same time period with the same electric current. After the experiment, the corroded stud was first cleaned with hydrochloric acid solution (12% concentration) and then neutralized with saturated lime-water. The cleaned stud was dried for four hours in an oven, and then its mass was weighed on an electronic said (0.01 g accuracy). Here, it was assumed that corrosion only occurs in the exposed length range of the stud and that the mass of the stud is uniformly distributed along its length direction. Thus, the stud corrosion rate can be calculated as follows:

$$\rho = \frac{m_0 - m_p}{m_0 (l/L)}, \quad (7)$$

where m_0 is the initial mass of the stud, m_p is the mass of the corroded stud, l is the exposed length (70 mm), and L is the total length of the stud.

Table 2 shows a comparison between the test and theoretical prediction results. The theoretical prediction

corrosion rate is very close to the actual corrosion rate, which indicates that the equation to control the stud corrosion rate is feasible. Additionally, when the corrosion rate is less than or equal to 7%, the theoretical prediction corrosion rate is slightly underestimated; when the corrosion rate is more than 7%, the theoretical prediction corrosion rate is slightly overestimated. This is mainly due to the adsorption of iron oxide on the surface of the stud during the test. At the beginning of the test, the energization was strong and the electrochemical reaction was stable and intense; thus, the actual corrosion rate was greater than the theoretical prediction. However, as the reaction progressed, a large amount of iron oxide adhered to the studs and the copper plate, hindering the reaction and driving the theoretical rate above the actual corrosion rate.

Figure 4 shows the appearance of the stud specimens after testing at different corrosion rates. The corrosion surface of the stud appears to have grown increasingly uneven as the corrosion rate increased, accompanied by rust pits on the surface.

2.4. Tensile test. It is true that stud connectors are shear-based components in actual use, but tensile strength is more easily obtained under normal conditions. In EC4 and AASHTO codes, the tensile strength of studs is used as an index for calculating the shear strength of studs. The tensile mechanical properties of the studs were tested in this paper.

Tensile tests were conducted in this study to assess the mechanical behavior, including strength, elongation, and elastic modulus of studs under different corrosion rates.

Before the test, every 5 mm within the $5d$ range of the stud was marked with a color pen in order to measure the elongation. The experiment was run on a microcomputer hydraulic universal testing machine with a loading rate of $5 \text{ N/mm}^2 \cdot \text{s}^{-1}$, as shown in Figure 5.

Three material parameters, yield strength, ultimate strength, and elongation, were determined by experiments and expressed in nominal terms. The nominal strength is the ratio of the actual load to the nominal section area. The relative elongation can be expressed as a relatively nominal uniform elongation. In this study, elongation was calculated as follows:

$$\delta = \frac{L_s - 5d}{5d} \times 100\%, \quad (8)$$

where δ is the elongation (%), $5d$ is the original mark distance, and L_s is the measured length between notches after fracture.

2.5. Test Results and Analysis. Figure 6 shows where the stress-strain relationship curve of the studs corroded at different rates trends steadily downward as corrosion rate increases. Regardless of the extent of corrosion, the stress-strain curve shows continuous yielding with no obvious yield point. To this effect, the yield strength can be determined by the residual strain of 0.2% after unloading [21].

Moreover, it was found that the stress-strain relationship of the corroded studs can be divided into three stages: an

TABLE 1: Chemical composition of ML-15.

Elements	Contents (%)
C	0.12~0.16
Si	0.05~0.08
Mn	0.32~0.38
Alt	0.034~0.040
P	0.012~0.016
S	≤0.009
Ni	≤0.010
Cr	≤0.023
Cu	≤0.010

elastic stage, elastoplastic stage, and plastic stage. In the elastic stage, the stress increases from zero to the yield strength. The relationship between stress and strain is linear and the slope reflects the nominal elastic modulus. In the elastic-plastic stage, the stress increases to the ultimate strength nonlinearly. In the plastic stage, the strain increases sharply while the stress slowly decreases.

2.6. Degradation Model of Corroded Stud Mechanical Properties. The mechanical properties of the studs are altered by corrosion, which is reflected in the constitutive model. As shown in Figure 6, the mechanical parameters of the stud degraded considerably as the corrosion rate changed throughout the experiment.

A regression model was determined according to the trends observed in the test. The parameters were calculated via the principle of the least square method, and a regression curve equation was obtained.

The relative value of yield strength k_y , relative value of ultimate tensile strength k_t , relative value of elongation k_e , and relative value of elastic modulus k_{em} can be defined as shown in equations (9)–(12), respectively:

$$k_y = \frac{\sigma_s}{\sigma_{s0}}, \quad (9)$$

$$k_t = \frac{\sigma_b}{\sigma_{b0}}, \quad (10)$$

$$k_e = \frac{\delta}{\delta_0}, \quad (11)$$

$$k_{em} = \frac{E}{E_0}, \quad (12)$$

where σ_s is the yield strength of corroded studs, σ_b is the ultimate strength of corroded studs, δ is the elongation of corroded studs, E is the elastic modulus of corroded studs, and σ_{s0} , σ_{b0} , δ_0 , and E_0 are the corresponding uncorroded stud parameters.

Figure 7 gives the variation of several mechanical properties with the corrosion rate. According to Figures 7(a) and 7(b), the yield strength and ultimate strength of the corroded stud were less than those before corrosion, which exhibited a linear degradation with the corrosion rate. There are two main reasons for the degradation: (1) an effective

area reduction of the corroded stud and (2) the stress concentration caused by the stud's uneven surface. It is worth noting that the dispersion degree of the stud strength was larger in the case of high corrosion rate. Evidently, when the corrosion rate is relatively high, the corrosion morphology of the stud has a significant influence on the stud's strength.

Figure 7(c) shows where the elongation decreased nonlinearly as the corrosion rate increased, i.e., ductility reduction occurred over the course of the test. Elongation was reduced at a higher rate than nominal strength, which is consistent with the change law of corroded steel bars [22, 23].

Figure 7(d) shows that the nominal elastic modulus also decreased as the corrosion rate increased, however, the decline is not significant. The fitting coefficient of determination is also fairly low (only 0.7518), indicating sizable fluctuations. The minimum value of elastic modulus is 196.0 GPa across all the specimens, and the error is less than 2% compared with the initial value. In effect, the elastic modulus of the stud is basically not influenced by the corrosion rate.

The mechanical properties of the corroded studs tested in this study degraded in a similar manner to those of ordinary steel bars. The degradation is not only related to the corrosion rate but also to the precise corrosion morphology of the studs. The fitting results shown in Figure 7 were used to establish the mechanical degradation model for the corroded studs:

$$\begin{aligned} \sigma_s &= \sigma_{s0} k_y = \sigma_{s0} (0.9986 - 1.3506\rho), \\ \sigma_b &= \sigma_{b0} k_t = \sigma_{b0} (1.0038 - 1.1914\rho), \\ \delta &= \delta_0 k_e = \delta_0 (0.9613e^{-2.09\rho}). \end{aligned} \quad (13)$$

2.7. Finite Element Analysis

2.7.1. Gurson–Tvergaard–Needleman (GTN) Model. For most engineering alloys, ductile fracture usually occurs in three stages: void nucleation, void growth, and void coalescence [24], as shown in Figure 8.

Gurson–Tvergaard–Needleman (GTN) constitutive model can be used to describe the effect of voids on the plastic properties of the metal materials. Assuming that the mass loss rate of the corroded stud is equal to the original void volume fraction, finite element analysis can be applied to describe the tensile behavior of the corroded studs by introducing the GTN constitutive model. It is expressed as

$$\Phi = \frac{\sigma_{eq}^2}{\sigma_0^2} + 2q_1 f^* \cosh\left(\frac{3q_2 \sigma_m}{2\sigma_0}\right) - (1 + q_3 f^{*2}) = 0, \quad (14)$$

where σ_{eq} is the macroscopic mises equivalent stress, σ_m is the macroscopic hydrostatic stress, σ_0 is the equivalent yield stress, and q_1 , q_2 , and q_3 are the proposed model parameters [25], respectively. While q_3 is equal to q_1^2 . f^* is the void volume fraction.

FIGURE 3: Stud electrochemical accelerated corrosion process.

TABLE 2: Comparison between experimental and theoretical stud corrosion rate values.

Test number	Number of tests	Corrosion current density (mA/cm ²)	Corrosion time (h)	Theoretical corrosion rate ρ_f (%)	Measured corrosion rate ρ_s (%)	ρ_f/ρ_s
T-1	5	0	0	0	0	0
T-2	5	1.5	77	5	5.66	0.88
T-3	5	1.5	108	7	7.25	0.97
T-4	5	1.5	154	10	9.36	1.07
T-5	5	1.5	232	15	14.21	1.06
T-6	5	1.5	309	20	18.83	1.06

FIGURE 4: Studs at different corrosion rates. (a) 0%. (b) 5.66%. (c) 7.25%. (d) 9.36%. (e) 14.21%. (f) 18.83%.

FIGURE 5: Tensile test equipment.

FIGURE 6: Stress-strain curves for studs with different corrosion rates.

FIGURE 7: Continued.

FIGURE 7: Mechanical properties varying with corrosion rate. (a) Yield strength. (b) Ultimate strength. (c) Elongation ratio. (d) Elastic modulus.

FIGURE 8: Schematic diagram of ductile fracture mechanisms of the porous metal. (a) Void nucleation. (b) Void growth. (c) Void coalescence.

FIGURE 9: Finite element analysis model of the stud.

TABLE 3: GTN model parameters.

Material parameters			Void nucleation			Void propagation/coalescence		
q_1	q_2	q_3	ϵ_N	S_N	f_N	f_0	f_c	f_E
1.5	1	2.25	0.3	0.1	0.04	ρ	$0.08 + \rho$	$0.12 + \rho$

FIGURE 10: Stud damage evolution under different corrosion rates in the tensile process. (a) $f_0 = 5.66\%$. (b) $f_0 = 9.36\%$. (c) $f_0 = 18.83\%$.

FIGURE 11: Comparison of the failure modes between test and finite element analyses. (a) $f_0 = 5.66\%$. (b) $f_0 = 9.36\%$. (c) $f_0 = 18.83\%$.

The void volume fraction f^* is expressed in the following formula:

$$f^* = \begin{cases} f, & f \leq f_c, \\ f_c + \frac{f_u - f_c}{f_F - f_c} (f - f_c), & f > f_c, \end{cases} \quad (15)$$

where f_c is the critical void volume fraction at the beginning of the void polymerization, f_F is the void volume fraction for the disrupted materials, and f_u^* is the critical void volume fraction when the stress bearing capacity is zero.

The porous propagation of materials includes the void growth rate and the void nucleation rate, as shown in equation (16).

$$\dot{f} = \dot{f}_{\text{growth}} + \dot{f}_{\text{nucleation}}. \quad (16)$$

The growth rate is expressed by equation (17) under the assumption of incompressible plasticity of the matrix material. The nucleation rate of the void can be expressed by equation (18).

$$\dot{f}_{\text{growth}} = (1 - f) \dot{\epsilon}_{\text{kk}}^p, \quad (17)$$

where $\dot{\epsilon}_{\text{kk}}^p$ is the plastic hydrostatic strain.

$$\dot{f}_{\text{nucleation}} = A \dot{\epsilon}_0 = \frac{f_N}{S_N \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\epsilon_0^p - \epsilon_N}{S_N} \right)^2 \right] \dot{\epsilon}_0, \quad (18)$$

where ϵ_N is the average strain at void nucleation, S_N is the standard deviation of nuclear strain, f_N is the volume fraction size of a nuclear particle, and A is the void nucleation coefficient.

2.7.2. Finite Element Model. A finite element model of the middle stud (70 mm) was established. In view of the geometric symmetry of the stud, the 1/2 model was thus established and the symmetric boundary conditions were applied, as illustrated in Figure 9. The eight-node solid element C3D8R was used [26]. According to the meshing size

of the unit in the references [16, 27], the model was meshed with the unit size of $1 \text{ mm} \times 1 \text{ mm} \times 1 \text{ mm}$.

In this model, the A end is a fixed end and the B end is a loading end. The displacement loading method was adopted, and the loading direction is shown in Figure 9. The displacement value was 6 mm.

The stress-strain curve of the nondestructive material was applied, as shown in Figure 6, to further explore the model parameters. The elastic modulus E in this case is 200 GPa and Poisson's ratio μ is 0.3. The GTN constitutive model was used to characterize the material's plasticity behavior, where q_1 , q_2 , and q_3 are the constitutive parameters to be determined; ϵ_N , S_N , and f_N are the unknown void evolution parameters and f_c , and f_F are the unknown material failure parameters. There are eight undetermined parameters in this model. The reasonable parameters are directly related to the applicability of the GTN model.

Tvergaard and Hutchinson [25] suggested three constitutive parameters as constants: $q_1 = 1.5$, $q_2 = 1$, and $q_3 = q_1^2$. The void nucleation parameters can be analyzed according to the normal distribution of the nucleation mode. Usually, $\epsilon_N = 0.3$ and $S_N = 0.1$ [28]. The parameter f_N has a certain effect on the softening region in the uniaxial tensile stress-strain curve. It is usually taken as 0.04 [29]. f_c and f_F are not constant; they are related to the initial porosity f_0 and the stress triaxiality Zhang et al. [30] found that f_F affects the shape of the tensile curve in the tightening phase and defines the relationship between f_F and f_0 : $f_F = 0.15 + 2 f_0$. Xu and Qian [16] obtained relevant relationships by means of parameter fitting regression. The relationship between the initial corrosion rate f_0 with f_F and f_c : $f_c = 0.1 + f_0$ and $f_F = 0.15 + f_0$. In the present study, the two were considered to be linear. The finite element simulation was matched to actual test results by trial and error and the following relationship was obtained: $f_c = 0.08 + f_0$ and $f_F = 0.12 + f_0$.

After confirming the values of q_1 , q_2 , q_3 , S_N , and f_N , the corrosion rate was defined as f_0 . Different combinations of material failure parameters were selected, and a regression was carried out to ensure the calculated response curves

FIGURE 12: Experimental versus calculated nominal stress-strain curves for studs corroded at different rates.

agree well with the measured curves. The values of the constitutive parameters and material failure parameters which are applicable on the GTN model for the corroded studs are listed in Table 3.

The tensile processes of the corroded stud were numerically simulated in ABAQUS finite element software. Figure 10 shows the damage evolution processes of three series for different corrosion rates (5.66%, 9.36%, and 18.83%) where VVF represents the void volume fraction. In the initial stage, VVF was the stud corrosion rate. As the test progressed, VVF increased and the necking phenomenon gradually emerged in the local concentration. When the force approached its maximum value, VVF spiked and the stud fractured. The neck shrinkage phenomenon of the stud became less obvious and elongation decreased dramatically as corrosion rate increased. The failure mode of the model transferred from the typical plastic fracture to the brittle fracture mode at this point, which is consistent with the aforementioned results.

Figure 11 shows a comparison of the finite element simulation results with the actual test failure in terms of the failure modes. The failure modes are roughly consistent, but it is worth noting that the actual fracture location basically falls in the middle position. There are changes in the fracture position of the finite element simulation, however, which are mainly attributable to the selection of different GTN model parameters. This conclusion is also consistent with results previously published by Xu and Qian [16].

Figure 12 shows a comparison of the experimental and calculated nominal stress-strain curves for studs corroded at different rates. The results are in close agreement with maximum error less than 5%. These results verify the feasibility of the GTN model for simulating the tensile properties of corroded studs, as well as the correctness of the parameters in Table 3.

3. Conclusions

- (1) An equation for calculating the required time to achieve a predetermined corrosion rate was derived in this study based on Faraday's Law. Experimental results show that the theoretical corrosion rate predicted by this method is very close to the actual corrosion rate; this equation can feasibly be used to control stud corrosion rates. The theoretical prediction is slightly underestimated when the corrosion rate is less than or equal to 7% and slightly overestimated when the corrosion rate is greater than 7%.
- (2) The mechanical properties of the corroded studs were investigated via tensile tests. The results show that the yield strength, ultimate strength, and plastic properties of the corroded stud decrease as corrosion rate increases. However, the modulus of elasticity remains basically unchanged.
- (3) The corrosion rate was characterized by the original void volume fraction and utilized to establish a relationship with material failure parameters. Simulation

results indicate that the finite element calculations are in close agreement with test results. The GTN model can effectively simulate the uniaxial tensile behavior of corroded studs.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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