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Numerical Simulation Analysis for Mechanical Properties of Corroded Reinforced Concrete Beams

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Abstract: *In order to analyze the influence of rebar corrosion on the mechanical properties of concrete beams, Abaqus software was used to simulate the static loading conditions of reinforced concrete T beams with different corrosion rates, and get the load-deflection curve of the corroded reinforced concrete T-beam, as well as the change law of key indicators such as yield load, ultimate deflection, and ultimate load. The results show that corrosion has almost no effect on the elastic stage and cracking load of the beam, but the overall load and yield deflection of reinforced concrete T beams decrease with the increase of the corrosion rate, and the yield stage is no longer obvious, the yield load and ultimate load obviously decrease following the increasing corrosion rate, and both are linear correlation with the corrosion rate. Furthermore, the ultimate deflection is negatively linear correlation with the corrosion rate when the corrosion rate is low, but when the corrosion rate reaches 10%, the corrosion rate of the rebar is positively linear correlation with the ultimate deflection.*

Keywords: *Reinforced concrete T beam, corrosion rate, static loading, Abaqus numerical simulation*

1. Introduction

As a century-old project in the construction of transportation infrastructure, bridges have the characteristics of long service periods, complex environmental conditions, and many reinforced concrete bridges. From the current bridge construction and existing bridge inspections, it is not difficult to find that even if the performance of concrete materials is continuously optimized with the improvement of technology, but many built bridges still have developed functional diseases when they are far from reaching their expected service life, even collapse accidents. These are mostly due to the bearing capacity reduction of the bridges caused by the rebar corrosion[1][2][3].

Among them, in 2000 the Motor Speedway Bridge in northern California collapsed due to the damage of corroded rebar[4]. In order to be able to issue a timely warning of danger during the use of the structure, it is necessary to accurately obtain the changes in the structural mechanical properties of the reinforced concrete beams before and after corrosion.

Therefore, this paper conducts numerical simulation analysis on the mechanical properties of reinforced concrete T-beams after different degrees of corrosion. Abaqus software was used to establish a reinforced concrete T-beam model, and the effect of rebar corrosion was simulated by modifying the cross-sectional area and yield strength of the rebar [5],[6]. The static nonlinear analysis of the reinforced concrete T-beams under different corrosion rates was carried out to obtain the load-deflection curve which is used to analyze the influence of rebar corrosion on the bearing capacity of reinforced concrete beams.

2. Basic Model Information

For the reinforced concrete T-shaped beam rib bottom width b=200 mm, top flange full slab bf=500 mm, flange thickness hf=150 mm, beam total height h=450 mm; rib beams are arranged with 6 longitudinal bars and 2 rebars at the bottom of the flange. The cross-sectional area of the tensioned longitudinal bar As=986.5 mm2, the cross-sectional area of the compressed longitudinal bar As'=339.3 mm2, and the reinforcement ratio ρ =1.89%. The distance from the resultant point of the compressive

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longitudinal bars on the top to the edge of the concrete is as'=40 mm, and the effective height is h0=275 mm. The cross section and reinforcement drawings are shown in Figure 1~2.

The concrete adopts C50 concrete, the standard value of compressive strength fck=33.4 MPa, the standard value of tensile strength ftk=2.64 MPa, and the modulus of elasticity Ec=34500 MPa.

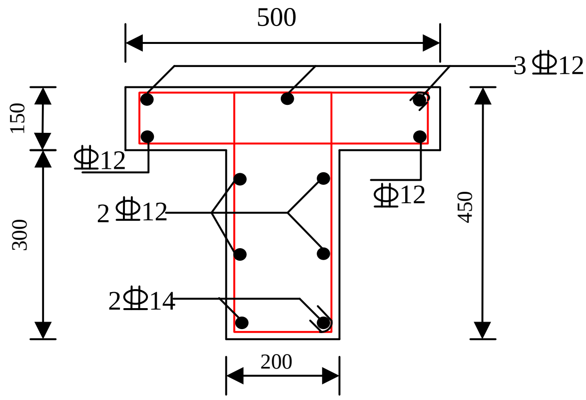

Figure 1: Reinforcement diagram of model beam normal section (Unit: mm).

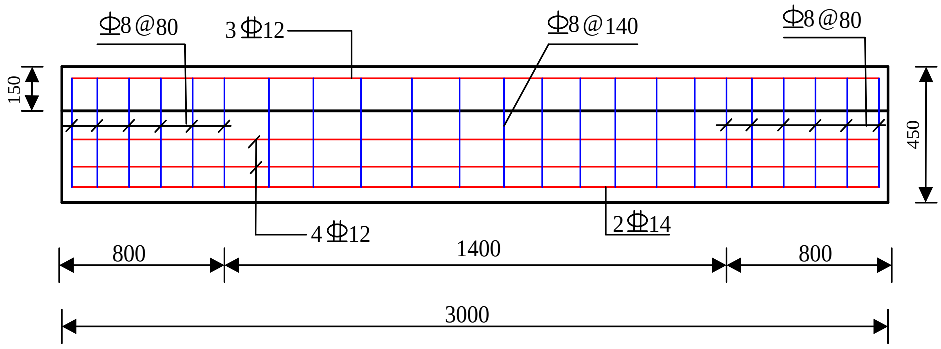

Figure 2: Elevation diagram of model beam (Unit: mm).

3. Numerical Model Establishment

3.1. Element Type

The reinforced concrete beams simulated by Abaqus software are mainly divided into two main parts, concrete and rebar. Concrete Damaged Plasticity Model (CDP) is used for simulating concrete and rod element elastic-plastic model is used for simulating rebar. In the CDP model, the C3D8R element, which is an eight-node linear hexahedral element, is used to describe the concrete, and this element is controlled by reducing integral and hourglass. The elastoplastic model of rebar uses T3D2 element, which is a two-node linear three-dimensional truss element.

3.2. Constitutive Model

In the Concrete Damaged Plasticity Model, the following constitutive curves are mainly used:

The concrete compressive and tensile stress-strain curve mainly adopts the uniaxial tension and compression stress-strain curve from "Code for Design of Concrete Structures" GB 50010-2010[7].

The plastic damage factor of concrete mainly adopts energy-equivalent damage calculation[8] and proportional strain damage calculation method[9]. In this paper, the method of proportional strain is used to describe the plastic damage factor of concrete;

The constitutive relationship of the rebar adopts the tensile stress-strain curve of the rebar without yield point from "Code for Design of Concrete Structures" GB 50010-2010, with the yield strength and ultimate strength of the rebar as the boundary point, and is described by means of a double broken line.

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The bond strength between rebar and concrete adopts the bond stress-slip curve from "Code for Design of Concrete Structures" GB 50010-2010.

The components in Abaqus software are connected together by "Interaction" function, the bonding between rebar and concrete is realized by spring element and the rigid cushion and the concrete are connected together by a face-to-face "binding" manner, which is as practical as possible. The established finite element model is shown in Figure 3.

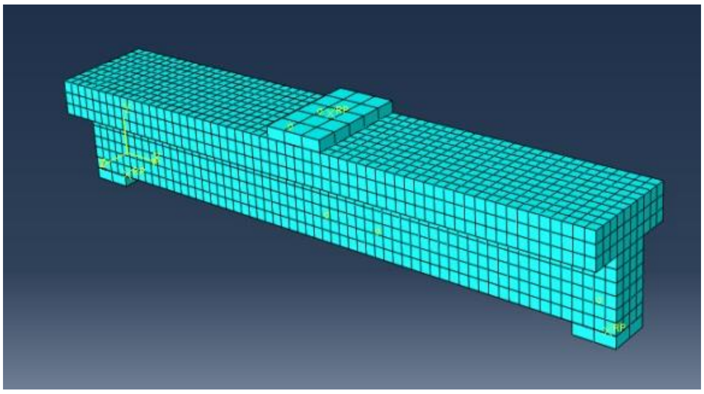

Figure 3: Finite element model of reinforced concrete T beam.

3.3. Corrosion Model

Based on the existing research, it is assumed that the corrosion does not affect the concrete, and the effect on the rebars is mainly reflected in the following four aspects[10]:

a) Degeneration of elastic modulus of rebars;

b) Reduction of the cross-sectional area of rebars;

c) Degeneration of rebar strength;

d) Deterioration of the bonding strength between rebar and concrete.

(1) Degeneration of elastic modulus of rebars. Weiping Zhang[11] counted a lot of test data and found that the elastic modulus of rebars hardly changes with the corrosion rate.

(2) Reduction of the cross-sectional area of rebars. Fujian Tang[12] used a Three-dimensional laser scanner to project each data of 46 rebars with different corrosion rates within 0.2 mm of the cross-section onto a plane, and obtained a relationship between quality corrosion rate and cross-sectional corrosion within a certain corrosion range of the rebar with a fitting degree of 0.95. Its specific formula is as follows:

$$\eta_{(avg\text{-}mass)}=-0.71+1.03\cdot\eta_{avg} \quad (1)$$

in which $\eta_{(avg\text{-}mass)}$ and η_{avg} are the corrosion rate of rebar quality and the average cross-sectional corrosion rate respectively.

(3) Degeneration of rebar strength. Weiping Zhang[11] used the corrosion test to study the degradation law of the mechanical properties of the corroded rebars, and obtained the relationship formulas between the yield strength, ultimate stress, ultimate strain and section loss rate of the corroded rebars:

$$f_{yc}(\eta_s)=(1.000-1.092\eta_s)f_{y0} \quad (2)$$

$$f_{uc}(\eta_s)=(1.000-1.152\eta_s)f_{u0} \quad (3)$$

$$\varepsilon_{uc}(\eta_s)=\varepsilon_0\cdot e^{-2.556\cdot\eta_s} \quad (4)$$

where

$f_{yc}(\eta_s)$ and $f_{uc}(\eta_s)$ denote respectively the nominal yield strength and ultimate strength of corroded rebars;

f_{y0} and f_{u0} denote respectively the yield strength and ultimate strength of uncorroded rebars;

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$\varepsilon uc(\eta s)$ and $\varepsilon 0$ denote respectively the ultimate strain of corroded rebars and the ultimate strain of uncorroded rebars;

ηs denotes corrosion rate of rebar average section.

(4) Deterioration of the bonding strength between rebar and concrete. Faifei Wang[13] fits the relationship formula between the bond strength of rebar and concrete by the pull-out test of ribbed rebars with different corrosion rates and concrete:

$$\eta = 1.000 - 2.7352\rho \quad (5)$$

where η and ρ denote respectively the bonding strength between rebar and concrete, and the quality corrosion rate of rebar.

3.4. Calculation Conditions

After the reinforced concrete beam undergoing rebar corrosion, a static nonlinear analysis is carried out to obtain its load-deflection curve in which the change law of yield load, ultimate deflection, ultimate load and other indexes can be obtained. In order to verify the feasibility of using Abaqus software, firstly, carry out the numerical simulation of the bearing capacity of reinforced concrete beams with specific test data comparison and then the static loading of the corroded reinforced concrete T beams were simulated, and the corrosion rate of the rebar quality was 0%, 3%, 5%, 8%, 10%, 13%,15%, a total of 7 working conditions.

4. Analysis of Simulation Results

4.1. Model Verification

In order to ensure the accuracy of Abaqus software for simulating concrete beams, before simulating the corrosion conditions, the test beams in the literature[14] under non-corrosion conditions were statically loaded and compared with the test data to verify rationality of the established model. The test values of the yield load, ultimate load and ultimate deflection are compared with the simulation values, which are listed in Table 1, and the load-deflection curve is shown in Figure 4.

Table 1: Comparison table of test data and simulation data.

Item	Test value	Simulation value	Difference percentage
Yield Load	88 kN	84 kN	-4.55%
Ultimate Load	92 kN	90 kN	-2.17%
Ultimate Deflection	13.4 mm	13 mm	-2.99%

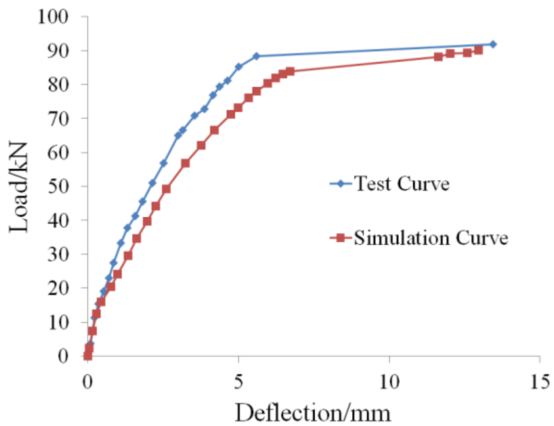

Figure 4: Comparison of simulation curve and test curve.

It can be seen from Figure 4 that in the elastic stage, the test value and the simulated value are basically the same. After the concrete tension zone cracks, the curve of the two has an inflection point. Before the simulated reinforced concrete structure reaches the yield strength, its load-deflection value curve has been slightly lower than the test value, indicating that the stiffness of the model is slightly

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less than the stiffness of the actual concrete. When the load reaches the yield load, the curve produces an inflection point, indicating that the tensile rebar yields.

On the whole, the simulation curve tends to coincide with the test curve, and the error of key numerical nodes does not exceed 5%, indicating that it is feasible to use Abaqus software to analyze the mechanical properties of reinforced concrete beams.

4.2. Analysis of Mechanical Properties of Corroded Reinforced Concrete T Beams

4.2.1. Load-deflection Curve of the Corroded Beam

The load-deflection curve of each reinforced concrete beam under different corrosion rates is plotted in Figure 5 to observe the change law of the deflection of the reinforced concrete T-beam with increasing load, and to observe the properties of the reinforced concrete T-beams under different corrosion rates.

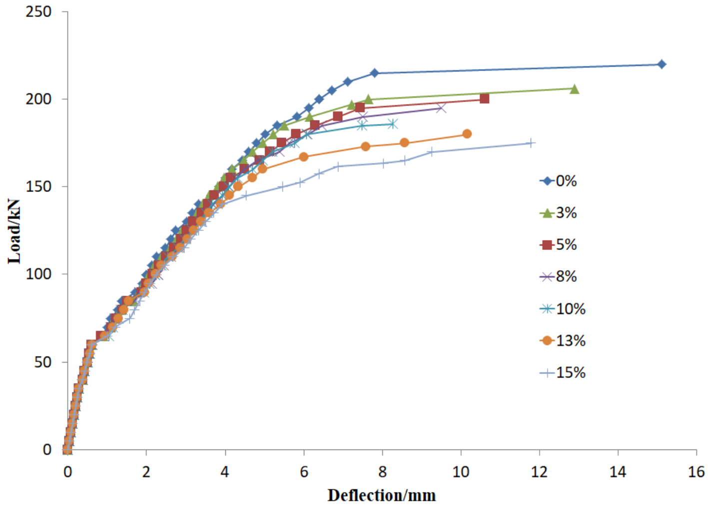

Figure 5: Load-deflection curve after corrosion.

There are some conclusions from Figure 5 as follows:

Before the reinforced concrete T-beam reaches the cracking load, the load-deflection curve changes linearly. At this time, the component is in an elastic working state, and the numerical curves of the reinforced concrete beams with different corrosion rates basically overlap and the cracking loads are all at the same level, indicating that in the elastic stage, the corrosion rate has almost no effect on the reinforced concrete beam;

After the concrete tension zone cracks and before reaching the yield load, as the corrosion rate increases, the rigidity of the reinforced concrete beam will slightly decrease, and the curves will begin to make a difference.

Both the yield load and ultimate load of reinforced concrete beams continue to decrease as the corrosion rate increases; when the bottom rebar yields, the load-deflection curve of the beam does not change significantly. Only the rebars near the effective height yield, the load-deflection curve will enter the yield stage, and as the corrosion rate increases, the yield stage is no longer obvious.

At the range of 10% mass corrosion rate, with the increase of corrosion rate, the ultimate deflection is significantly reduced. When the mass corrosion rate is greater than 10%, as the corrosion rate increases, the stiffness of the model beam decreases rapidly, and the ultimate deflection is positively correlated with the corrosion rate of rebars.

4.2.2. Cracking Deflection, Yield Deflection and Ultimate Deflection of the Corroded Beam

The changes of the beam's cracking deflection, yield deflection and ultimate deflection with the corrosion rate are shown in Figure 6. It can be seen that the effect of corrosion on the cracking deflection of reinforced concrete T-beams is very small and can be ignored. However, the yield deflection of reinforced concrete beams decreases with the increase of corrosion rate, and the relationship is basically linear.

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When the corrosion rate of rebar quality is below 10%, the ultimate deflection decreases with the increase of the corrosion rate, showing a linear relationship; but when the corrosion rate is above 10%, the ultimate deflection and the corrosion rate are in a positive linear relationship. It is speculated that when the corrosion rate exceeds 10%, the bond strength between the rebar and the concrete is too low, resulting in an increase in the ultimate deflection.

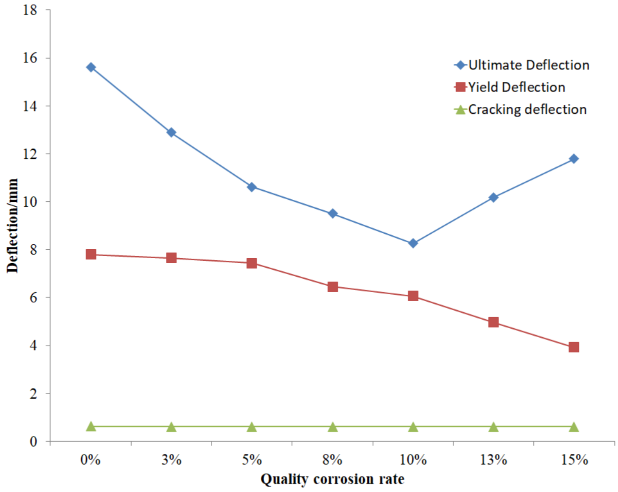

Figure 6: Curve of deflection-corrosion rate.

4.2.3. Yield Load and Ultimate Load of the Corroded Beam

Taking the corrosion rate as the abscissa and the load as the ordinate, the yield load and ultimate load with the corrosion rate are plotted in Figure 7. It can be seen that both the yield load and the ultimate load decrease with the increase of the corrosion rate, and both show a linear relationship with the corrosion rate.

Among them, when the model beam is just corroded, the ultimate load drops faster; when the model beam has a corrosion rate of more than 10%, the yield load drops significantly faster.

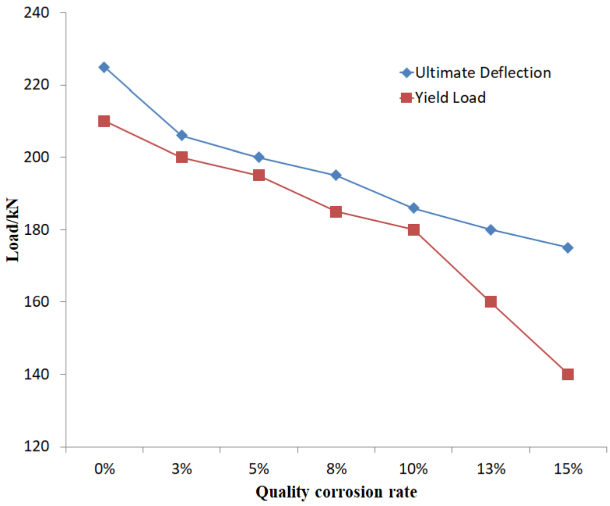

Figure 7: Load-corrosion rate relationship curve.

5. Conclusions

In this paper, Abaqus software is used to numerically simulate the mechanical properties of reinforced concrete T beams with different degrees of corrosion. By analyzing the results under different corrosion rates, the following conclusions are drawn:

(1)The corrosion of rebars will significantly affect the load-deflection curve of reinforced concrete beams, but has little effect on the elastic stage; the yield load, yield deflection and ultimate load decrease with the increase of the corrosion rate; taking 10% corrosion rate as the cut-off point, the ultimate deflection also changes significantly with the increase of corrosion rate.

(2)When the bottom rebars yields, the load-deflection curve of the reinforced concrete T beam does not change significantly. Only the rebars near the effective height yield, the beam load- deflection curve will enter the yield stage, and when the corrosion rate increases, the yield stage is no longer obvious, and the stiffness decreases slightly.

(3)With the increase of the corrosion rate, the yield deflection will be significantly reduced, and it is a linear relationship; when the corrosion rate is less than 10%, with the corrosion rate increases, the corrosion rate of the rebar is negatively linearly related to the ultimate deflection; when the corrosion rate is greater than 10%, with the increase of the corrosion rate, the ultimate deflection is positively linearly related to the corrosion rate.

(4)Both the yield load and the ultimate load decrease significantly with the increase of the corrosion rate, and have a linear relationship with the corrosion rate. At the beginning of corrosion, the ultimate load drops faster; when the corrosion rate is above 10%, the yield load drops significantly faster.

Acknowledgments

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