Effect of steel reinforcement with different degree of corrosion on degeneration of mechanical performance of reinforced concrete frame joints

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ABSTRACT. Beam-column joints which shoulders high-level and vertical shearing effect that maintains balance of beam and column end is the major component influencing the performance of the whole framework. Post earthquake investigation suggests that collapse of frame structure is induced by failure of joints in most cases. Thus, beam-column joints must have strong bearing capacity and good ductility, and reinforced concrete structure just meets the above requirement. But corrosion caused by long time use of reinforced concrete framework will lead to degeneration of mechanical performance of joints. To find out the rule of effect of steel reinforcement with different corrosion rate on degeneration of bearing capacity of reinforced concrete framework joints, this study made a nonlinear numerical analysis on fifteen models without stirrup in the core area of reinforced concrete frame joints using displacement method considering axial load ratio of column end and constraint condition. This work aims to find out the key factor that influences mechanical performance of joints, thus to provide a basis for repair and reinforcement of degenerated framework joints.

KEYWORDS. Reinforced concrete; Mechanical performance of joints; Corrosion of steel reinforcement.

INTRODUCTION

In China, most framework structures has been degenerated [1]. During construction of old building, core area of building framework joints is usually placed with less or even no stirrup due to the limitation of building science and technology and insufficient understanding on importance of putting stirrup in the core area of framework, which influences quality of old framework joints [2, 3]. Framework joints involving complex force situation can influence overall framework performance. Therefore, studying degradation of mechanical performance of old framework joints is of great and practical significance.

It has been found that, steel reinforcement corrosion is the leading cause for function degeneration of old building structure [4].

Besides decrease of mechanical property, performance of steel reinforcement corrosion also includes cracking and even spalling of concrete, weakening of bound stress and decrease of adhesive property. Currently, structure damage or instability induced by corrosion of steel reinforcement in concrete has been one of major issues concerned by the world; it occupies a leading role in factors influencing durability of structure [5]. For building which needs continued construction, steel reinforcement corrosion will further develop and finally result in engineering accidents if no thorough examination and effective treatment are carried out on corrosion condition of steel reinforcement [6]. Hence it is necessary to detect steel reinforcement corrosion and evaluate durability and reliability of corroded component. Research on corroded reinforced concrete in China and abroad [7] mainly focuses on beam and column, and few concerns joints of corroded reinforced concrete framework. On this account, we made a simulation study on mechanical performance of framework joints without stirrup under statistic load and obtained degeneration rule of bearing capacity of reinforced concrete framework under the influence of different corrosion rate of steel reinforcement which can help guiding repair and reinforcement of old framework joints.

FINITE ELEMENT MODEL AND ANALYSIS METHOD

Concrete Constitutive and Corroded Steel Reinforcement Relationship

Unilateral compressive stress-strain relationship reflects mechanical property of concrete under stress [8]. Its expression is as follows:

$$\sigma = (1 - d_c) E_c \varepsilon \tag{1}$$

If disturbance effect in coal yielding is considered, introduce disturbance factor d into the formula, then the formula change to:

$$d_c = \begin{cases} 1 - \dfrac{\rho_c n}{n - 1 + x^n}, x \le 1 \\ 1 - \dfrac{\rho_c}{\sigma_c (x-1)^2 + x}, x > 1 \end{cases} \tag{2}$$

$$\rho_c = \frac{f_{c,r}}{E_c \varepsilon_{c,r}} \tag{3}$$

$$n = \frac{E_c \varepsilon_{c,r}}{E_c \varepsilon_{c,r} - f_{c,r}} \tag{4}$$

$$x = \frac{\varepsilon}{\varepsilon_{c,r}} \tag{5}$$

$f_{c,r}$ (N/mm²)	25	30	35	40	45	50
$\varepsilon_{c,r}$ (10^{-6})	1560	1640	1720	1790	1850	1920
σ_c	1.06	1.36	1.65	1.94	2.21	2.48
$\varepsilon_{cu} / \varepsilon_{c,r}$	2.6	2.3	2.1	2.0	1.9	1.9
$f_{c,r}$ (N/mm²)	55	60	65	70	75	80
$\varepsilon_{c,r}$ (10-6)	1980	2030	2080	2130	2190	2240
σ_c	2.74	3.00	3.25	3.50	3.75	3.99
$\varepsilon_{cu} / \varepsilon_{c,r}$	1.8	1.8	1.7	1.7	1.7	1.6

Note: ε_{cu} refers to the compressive strain of concrete when the stress in descending branch of stress-strain curve is equal to 0.5 $f_{c,r}$.

Table 1: Reference values of parameters relating to concrete single-axial compressive stress - strain curve.

In the formula, σ_c refers to parameter value of descending branch of single-axial compressive stress - strain curve of concrete (refer to Table 1); $f_{c,r}$ refers to representative value of axial compressive strength of concrete, and its concrete value is determined based on actual structural analysis; $\varepsilon_{c,r}$ refers to peak compressive strain of concrete corresponding to axial compressive strength of concrete $f_{c,r}$ (refer to Table 1); d_c refers to concrete single-axial compressive injury evolutionary parameter; σ refers to compressive stress of concrete; ε refers to compressive strain of concrete; E_c refers to elasticity modulus of concrete.

Degeneration of mechanical property of corroded steel reinforcement mainly reflects on decrease of yielding strength, ultimate strength and elongation ultimate of concrete. With the increase of corrosion rate, ultimate deformability weakens and yielding platform shortens and even disappears. Based on the feature, we propose stress-strain relationship model for corroded steel reinforcement as shown in Figure 1. When corrosion rate of steel reinforcement is small and yielding platform has not disappeared, Figure 1 (a) is used; and when corrosion rate exceeds certain critical point and yielding platform disappears, Figure 1(b) is used. f_{yc} and f_{uc} refers to nominal yield strength and nominal ultimate strength of corroded steel reinforcement respectively; ε_{sc} and ε_{sc} stands for stress and strain of corroded steel reinforcement respectively; ε_{syc} and ε_{suc} stands for yielding strain and hardening strain of corroded steel reinforcement.

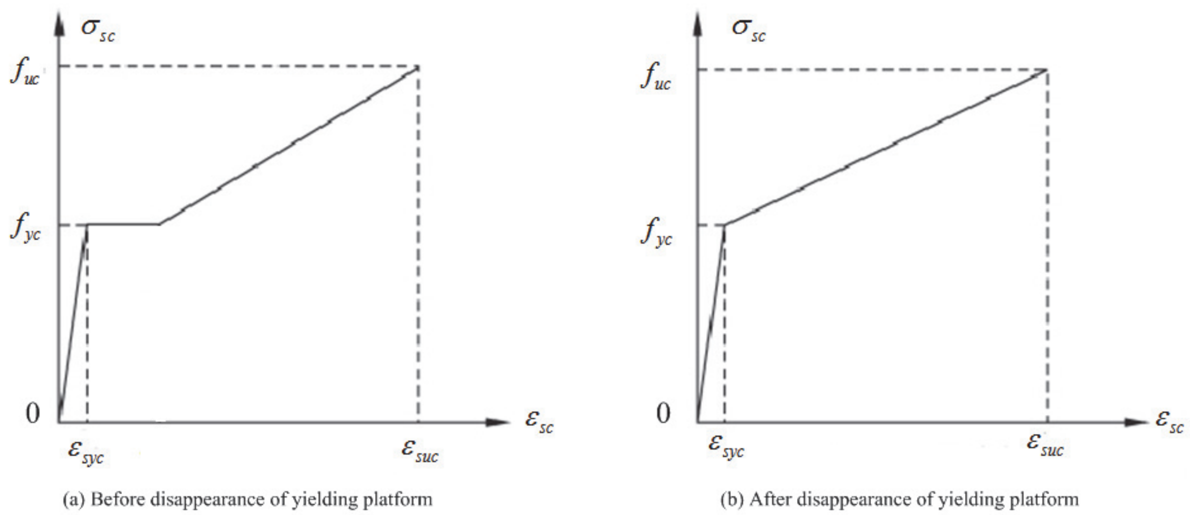


Figure 1: Constitutive relation curves for corroded steel reinforcement before and after disappearance of yielding platform [8].

Finite Element Model and Grid Generation

Cruciform frame joints of reinforced concrete is taken as the finite element model (Figure 2). Size of test beam (simply supported beam) used for modeling is b×h×l = 120×200×1900 mm. Span of the beam is 1.7 m. Two concentrated forces are applied on midspan and the distance between two forces is 50 mm. Concrete cover of main reinforcement is 2.5 mm thick. Detailed size of the beam and reinforcement are shown in Figure 3.

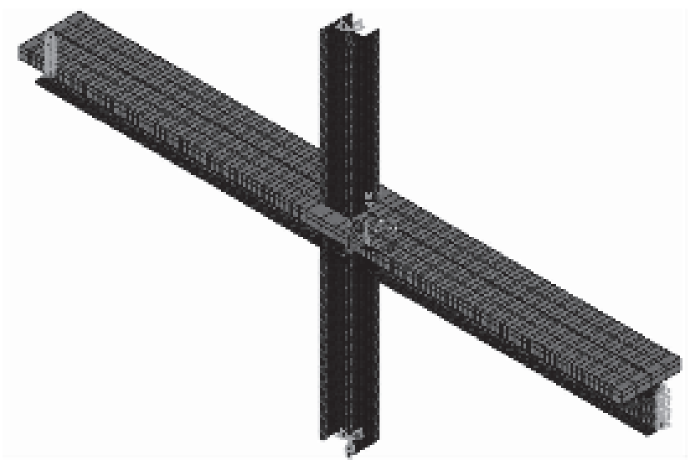


Figure 2: Frame joint model.

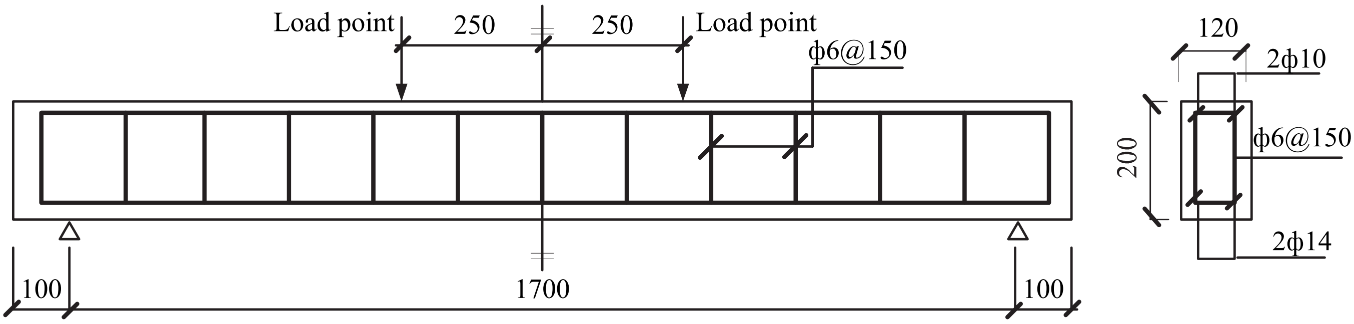


Figure 3: Size of test beam and reinforcement

(1) Boundary condition
Considering symmetry of the structure, half of the mid-span section of the beam is taken for modeling. Mid-span section is set to be symmetry constraint. Cushion block is placed at the position of support and support constraint is exerted on cushion block. Moreover, constraints in X and Y direction is exerted in the direction vertical to the beam. Free deformation of beam along beam direction is allowed.
(2) Load application
Self weight: the model considers self weight of the structure; specific gravity of concrete and steel are 25 kN/m^3 and 7.85 kN/m^3 respectively; acceleration of gravity is taken as 9.81 m/s^2.
Vertical load: as finite element analysis needs to consider descending branch of the stress-strain relationship curve, displacement loading is applied, in order to ensure calculation convegence. Vertical displacement is applied on loading site of the test beam until the beam breaks. Then the external force exerted is calculated according to load-displacement relationship of the loading point.

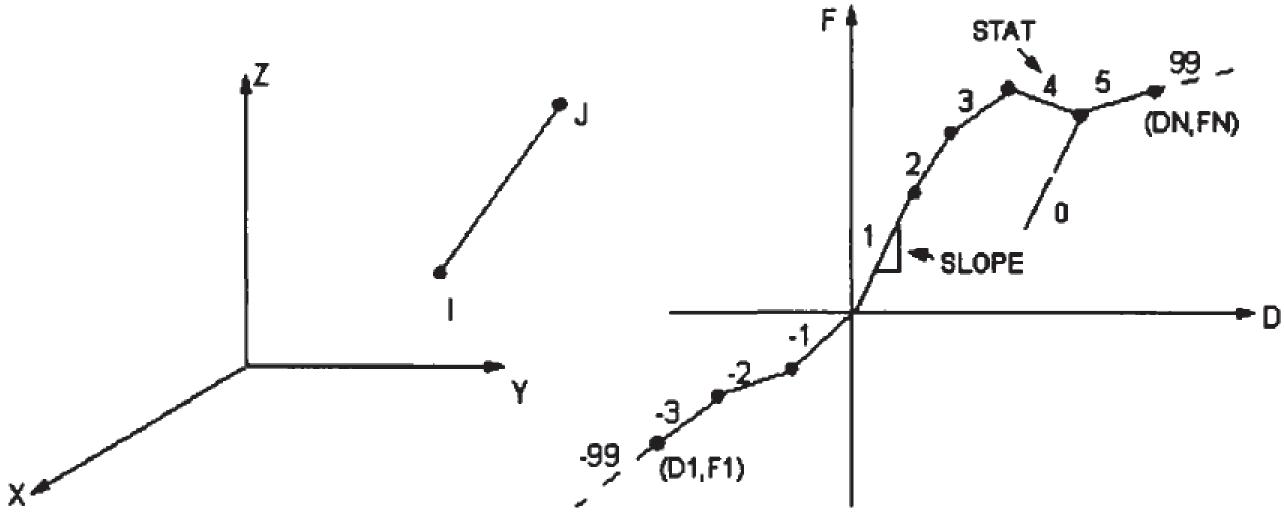


Figure 4: Nonlinear spring unit.

The core area of frame joints is not equipped with stirrup; steel reinforcement and concrete are modeled using C3D8R unit (C3D8R refers to type of the unit; C refers to entity unit; 3D refers to three dimension; 8 refers to number of nodes in that unit; R means the unit is a reduced integration unit); to simulate the interaction between corroded steel reinforcement and concrete better when making three-dimensional finite element analysis on corroded steel reinforced concrete structural element, three nonlinear springs with different stiffness and vertical to each other (K_x, K_y, K_z) are placed between unit joint of steel reinforcement and unit joint of concrete. Stiffness matrix of the nonlinear spring K_e is:

$$\left[K_e\right] = K^{tg}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad (6)$$

where K^{tg} refers to slope of unit force of spring - relative displacement (Figure 4).

Unit grid generation is an important step in modeling which can transform geometrical model into finite element model composed of joints and units. Result of grid generation directly determines preciseness of computation result and computation time [9, 10]. In the study, we adjust grid density for many times during computation process. Dense grids cannot ensure calculation convegence, especially when beam is severely fractured; and discrete grids will result in poor computational accuracy. Figure 5 shows grid generation of concrete unit.

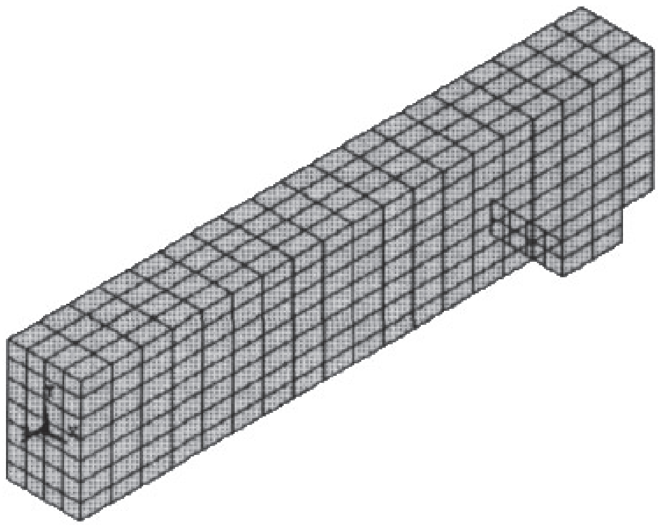


Figure 5: Grid generation of concrete unit.

Parameters of Model

The analytical model uses parameters including axial compression ratio (ratio of design value of axial pressure of column (wall) to product of full sectional area of column (wall) and design value of compressive strength of concrete column) and corrosion rate of steel reinforcement [11]. C30 concrete is used as model; longitudinal steel used is HRB335; stirrup used is HPB235. Corrosion rate of longitudinal steel is 0, 2%, 5%, 10% and 15%; axial compression ratio is 0.2, 0.4 and 0.6.

LOADING MEANS AND BOUNDARY CONDITIONS

Corrosion expansion of steel reinforcement is stimulated by exerting radial displacement on holes of concrete. Assume that the steel reinforcement is evenly eroded, R_1 refers to initial radius of steel reinforcement, R_2 refers to external radius of corrosion product; R_3 is radius of remaining steel reinforcement section. Corrosion rate of steel reinforcement β is:

$$\beta = 1 - \left(\frac{R_3}{R_1}\right)^2 \quad (7)$$

Assume corrosion product is τ times as large as original steel reinforcement and δ_0 is the space between non-corroded steel reinforcement and concrete, then the relationship between corrosion rate of steel reinforcement β and radial expansion displacement of concrete ω can be expressed as:

$$\beta = 2\frac{\delta_0 + \omega}{(\tau - 1)R_2} \quad (8)$$

When corrosion occurs, corrosion product first fills the space between non-corrosive steel reinforcement and concrete. Then corrosion quantity increases and volume becomes larger, resulting in extrusion on concrete around steel reinforcement [12, 13]. Model of exerting radial displacement on concrete around steel reinforcement is shown in Figure 6. The model exerts displacement load on concrete around steel reinforcement at frame joints by such kind of loading means.

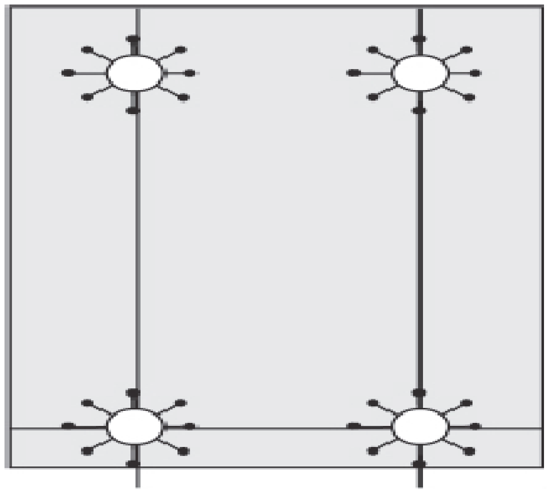


Figure 6: Radial displacement loading model.

ANALYSIS OF RESULTS

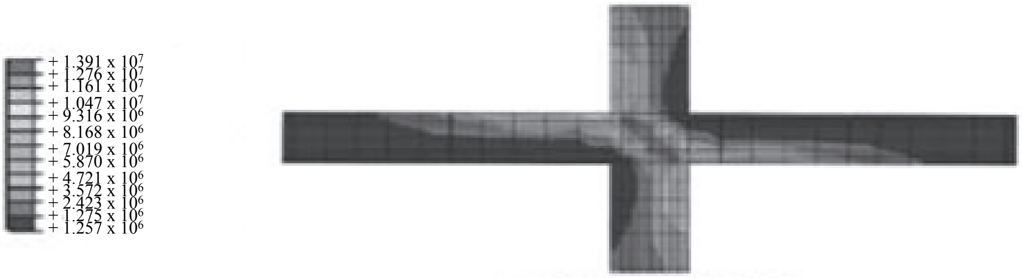
Stress Analysis

Nephogram of concrete stress (kg/cm²) under different corrosion rate when axial compression ratio is 0.2 is shown in Figure 7.

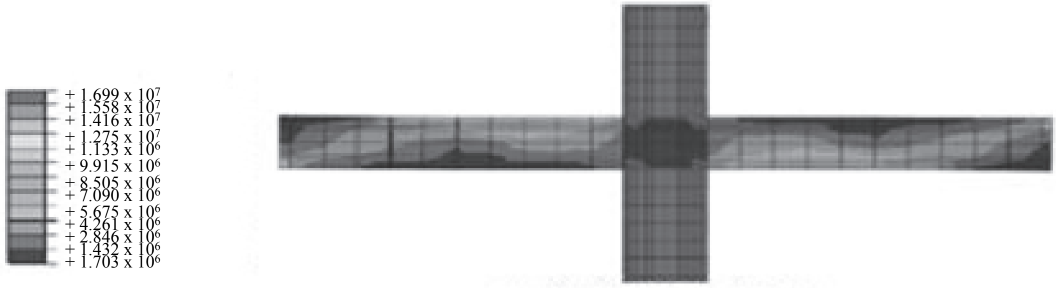
It can be seen from Figure 7(a) that, stress at the intersection of concrete beam column is the maximum when corrosion rate is 0; and at that moment, cracks appear and extend to the core area of joints, leading to shear failure; upper part of left beam and lower part of right beam in the core area of concrete joints shoulders larger stress under the influence from antisymmetric monotonic load. Figure 7(b) demonstrates that, middle part of beam shoulders the maximum stress when corrosion rate is 2%. That is because concrete holes around steel reinforcement shoulders radial displacement load from middle part of left beam to middle part of right beam. Figure 7(c) suggests that, changes of stress on concrete beam when corrosion rate is 5% is basically the same with that when corrosion rate is 2%, but the stress is unevenly distributed. That is because that, joints can still shoulder radial displacement load though protective layer of concrete beam has cracked; stress on concrete column at the moment is much higher than that when corrosion rate is 2%; concrete column shows no obvious stress changes due to the large stress on beam. Figure 7(d) shows the maximum stress on concrete joints when corrosion rate is 10% is smaller than that when corrosion rate is 5%; maximum stress on concrete reaches its peak when corrosion rate is 5% and moreover, stress on concrete column changes sharply (column end shoulders large stress and stress in core area of joints is larger than beam end). We can know from figure 7(e) that, the stress nephogram of concrete joints changes slightly when corrosion rate is 15%; and maximum stress on concrete is approximately equal to that when corrosion rate is 10%.

Effect of Changes of Corrosion Rate on Bearing Capacity

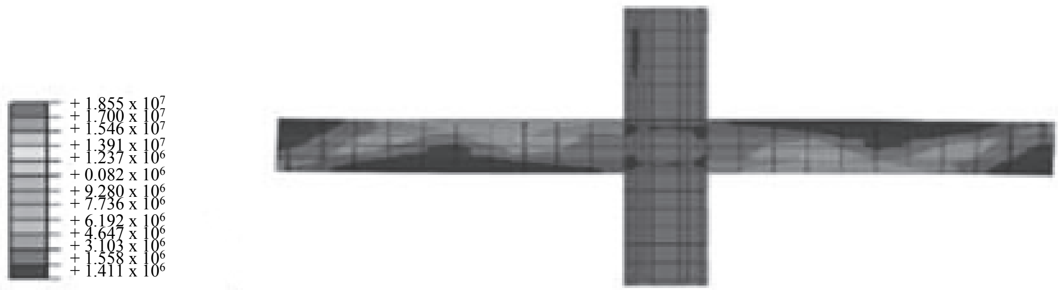
To discuss over effect of changes of corrosion rate of steel reinforcement on bearing capacity of component under fixed axial compression ratio, we divide fifteen stimulation analysis results into three groups according to axial compression ratio. Figure 8 ~10 give load-displacement curves of different test specimen.



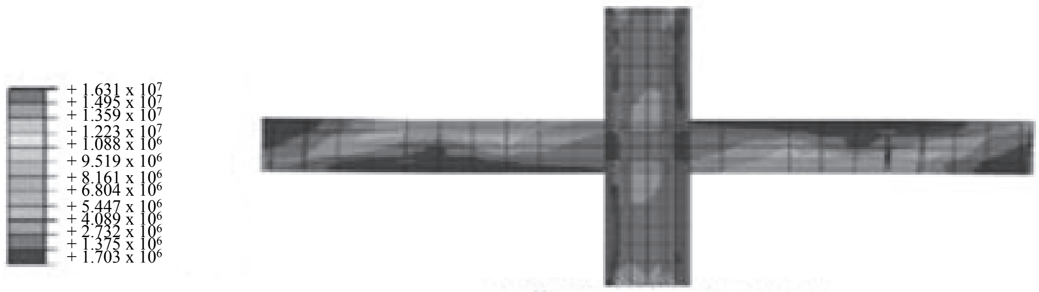
(a) Corrosion rate of steel reinforcement 0



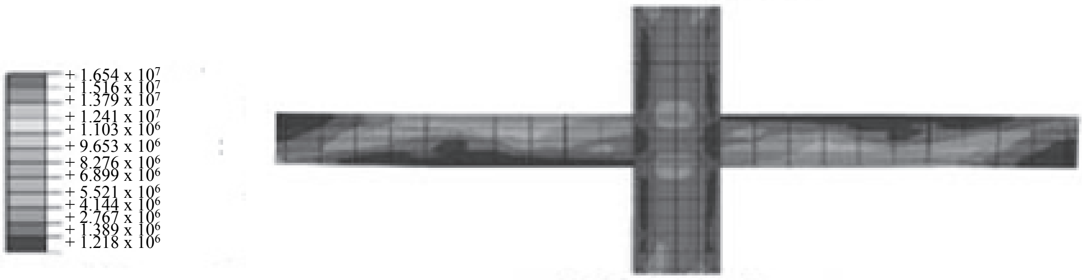
(b) Corrosion rate of steel reinforcement 2%



(c) Corrosion rate of steel reinforcement 5%



(d) Corrosion rate of steel reinforcement 10%



(e) Corrosion rate of steel reinforcement 15%

Figure 7: Nephogram of stress on joints of concrete.

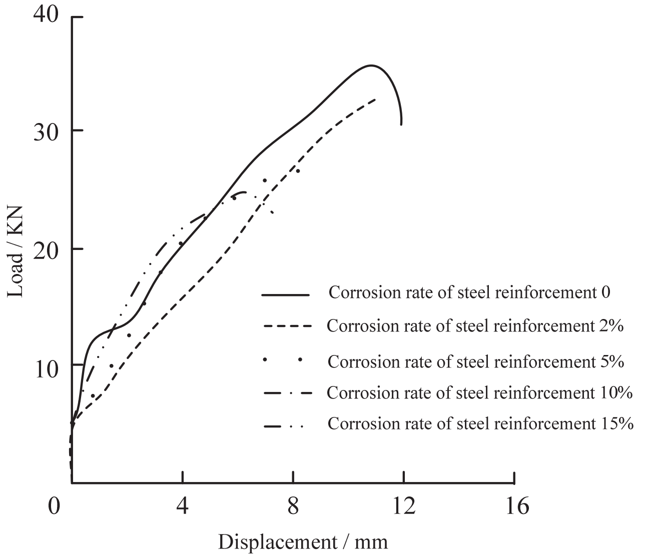


Figure 8: Curves of load-displacement (axial compression ratio 0.2).

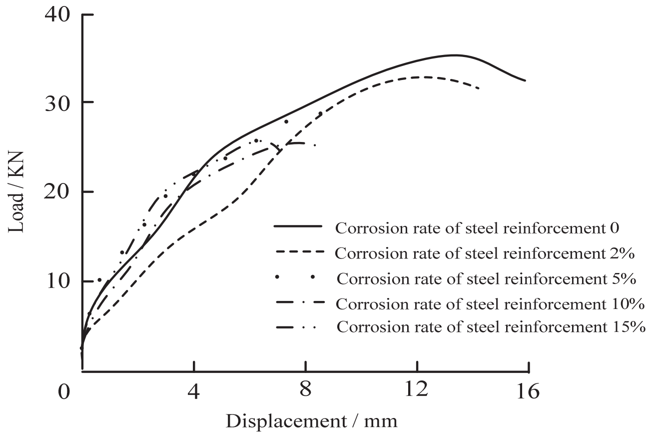


Figure 9: Curves of load-displacement (axial compression ratio 0.4).

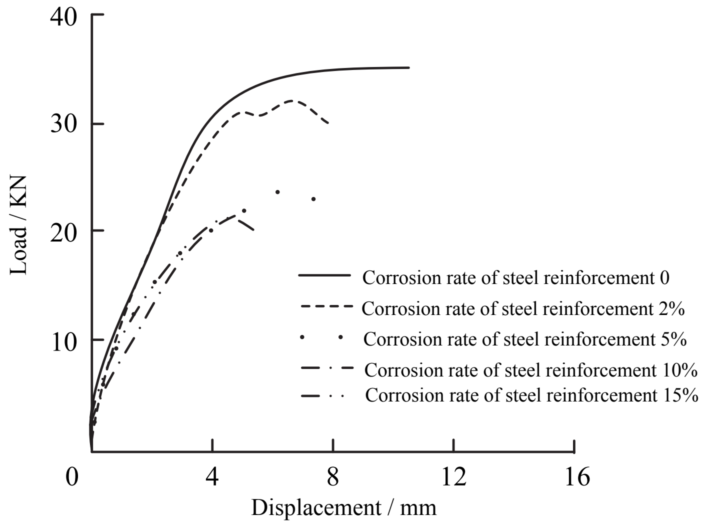


Figure 10: Curves of load-displacement (axial compression ratio 0.6).

It can be seen from the above figures that, bearing capacity and ultimate displacement of joints shows a decreasing tendency when axial compression ratio is the same and corrosion rate of steel reinforcement becomes higher; when corrosion rate of steel reinforcement is 2%, bearing capacity and ultimate displacement degenerates insignificantly; when it is 5%, the degeneration is quite obvious; bearing capacity and displacement have little differences when corrosion rate is 10% and 15%, but ultimate displacement degenerates for 50%. Under the same axial compression ratio, load-displacement curves partially coincide before yield point, suggesting corrosion rate of steel reinforcement has no influence on component when beam end shoulder small load. But with the increase of external load, bearing capacity of component declines. When corrosion rate is 10% and 15% particularly, protective layer cracks, which accelerates corrosion of steel reinforcement and severely influence mechanical performance of steel reinforcement and coordinated working between steel reinforcement and concrete. Table 2 shows how corrosion rate influences ultimate bearing capacity and displacement of reinforced concrete framework joints when axial compression ratio is 0.2.

Corrosion rate/%	Bearing capacity/kN	Ultimate displacement/mm	Loss of bearing capacity/%	Loss of ultimate displacement/%
0	35.4	12	—	—
2	32.6	11	8	8.3
5	26.7	9	24.6	25.0
10	24.9	7.3	29.7	39.0
16	24.8	7	30	41.7

Table 2: Bearing capacity and displacement of corroded reinforced concrete frame joints when axial compression ratio is 0.2.

Effect of Changes of Axial Compression Ratio on Bearing Capacity

Axial compression ratio is one of the major factors that influences failure mode and ductility of frame column. Yoon et al. [14] stipulated that limit for axial compression ratio of frame structure (level 1 seismic grade) is 0.65. Thus axial compression ratio is thought to be of great significance to bearing capacity of component. We obtain curves of load-displacement by keeping corrosion rate unchanged and changing axial compression ratio (0.2, 0.4, 0.6) (Figure 11 ~ 15).

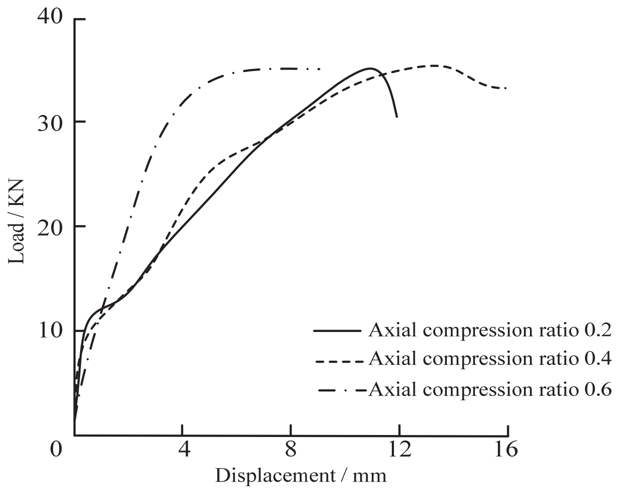


Figure 11: Curves of load-displacement (corrosion rate 0).

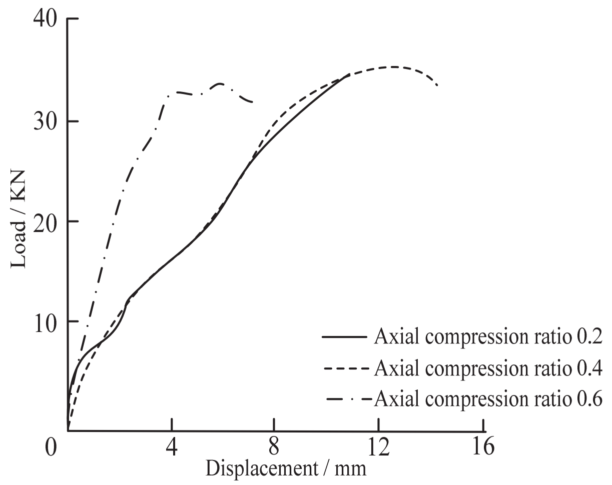


Figure 12: Curves of load-displacement (corrosion rate 2%).

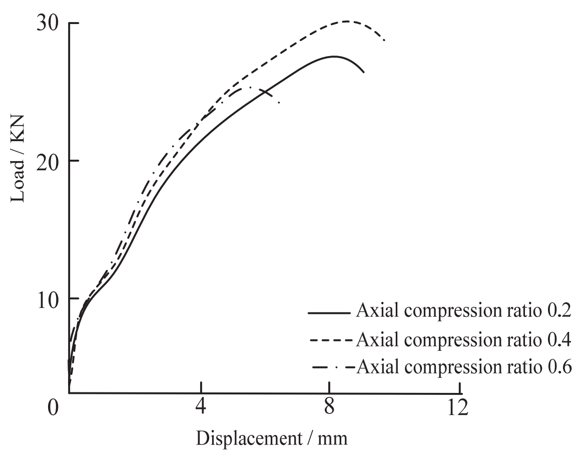


Figure 13: Curves of load-displacement (corrosion rate 5%).

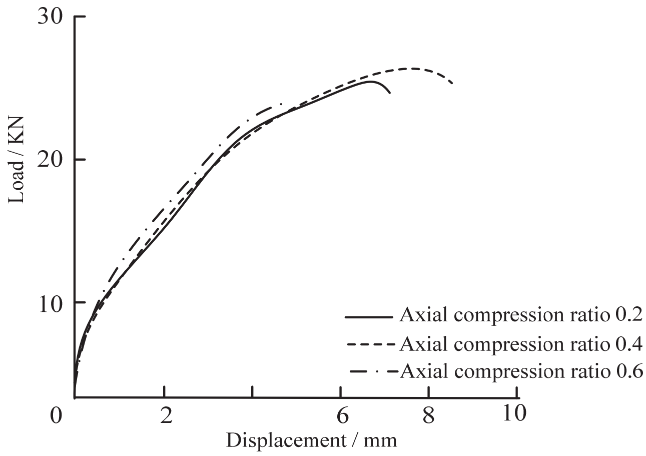


Figure 14: Curves of load-displacement (corrosion rate 10%).

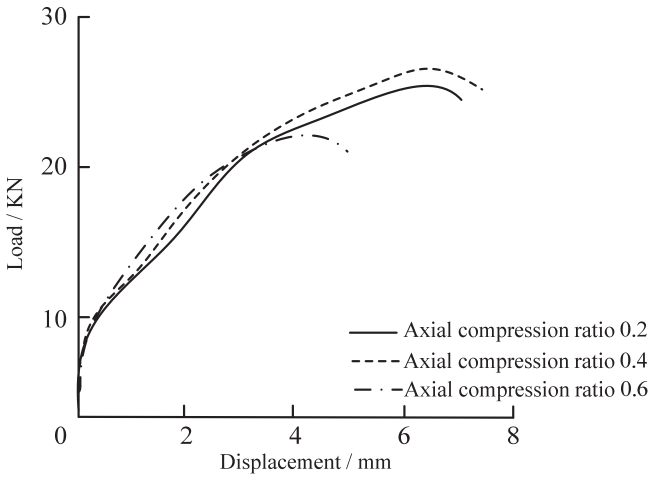


Figure 15: Curves of load-displacement (corrosion rate 15%).

The above figures demonstrate that, bearing capacity and ultimate displacement both decrease with the increase of axial compression ratio; when corrosion is mild, rigidity of component increases with increase of axial compression ratio; component with large axial compression ratio yields early and bearing capacity and ultimate displacement declines greatly. When corrosion rate is low or steel reinforcement is not corroded, curves of load-displacement when axial compression ratio is 0.6 differ greatly with curves when axial compression ratio is 0.2 and 0.4. That is because that, excessively higher axial compression ratio severely affects ducility of the structure. Moreover, when protective layer cracks and corrosion rate is high, bearing capacity and ultimate displacement decline steadily with the increase of axial compression ratio. Under the same corrosion rate, joint model which is not corroded or slightly corroded is less affected by axial compression ratio; the influence is the most notable when corrosion rate is 5%. When axial compression ratio is 0.4, joints have stronger bearing capacity and ultimate displacement. But when axial compression ratio is 0.2, bearing capacity fails to be stronger. When it is 0.6, bearing capacity and ultimate displacement decrease sharply.

CONCLUSION

To sum up, corrosion rate of steel reinforcement and axial compression ratio have large influence on corroded reinforced concrete framework joints; joints show obvious degeneration with the increase of corrosion rate. Changes of mechanical performance can be summarized as declined bearing capacity, degraded rigidity, changed ducility and decreased ultimate displacement. Under coupling effect of inside corrosion and external load, bearing capacity of component remains unchanged, but ultimate displacement decreases obviously, when corrosion rate is excessively large (15%). Corrosion rate is a key factor influencing mechanical performance of component, which can impact endurance quality of old framework.

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NOMENCLATURE

σ_c refers to parameter value of descending branch of single-axial compressive stress - strain curve of concrete;

$f_{c,r}$ refers to representative value of axial compressive strength of concrete, and its concrete value is determined based on actual structural analysis;

$\varepsilon_{c,r}$ refers to peak compressive strain of concrete corresponding to axial compressive strength of concrete $f_{c,r}$;

d_c refers to concrete single-axial compressive injury evolutionary parameter;

σ refers to compressive stress of concrete;

ε refers to compressive strain of concrete;

E_c refers to elasticity modulus of concrete;

ε_{cu} refers to the compressive strain of concrete when the stress in descending branch of stress-strain curve is equal to 0.5 $f_{c,r}$;

f_{yc} and f_{uc} refer to nominal yield strength and nominal ultimate strength of corroded steel reinforcement respectively;

ε_{sc} and ε_{sc} stand for stress and strain of corroded steel reinforcement respectively;

ε_{syc} and ε_{suc} stand for yielding strain and hardening strain of corroded steel reinforcement;

K_e refers to nonlinear spring;

K^{tg} refers to slope of unit force of spring - relative displacement;

R_1 refers to initial radius of steel reinforcement;

R_2 refers to external radius of corrosion product;

R_3 is radius of remaining steel reinforcement section;

β refers to corrosion rate of steel reinforcement;

δ_0 is the space between non-corroded steel reinforcement and concrete;

ω refers to radial expansion displacement of concrete.