Flexural Experiment and Stiffness Investigation of Reinforced Concrete Beam under Chloride Penetration and Sustained loading

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Abstract: This paper presents an experimental study conducted to characterize the effect of corrosion and sustained load on structural behavior of reinforced concrete (RC) beam. The effects of loading level on corrosion of reinforcing steel, the flexural deflection and residual loading capacity of the test beams were investigated. **In the first scenario, two non-corroded beams were tested to determine the maximum load levels that were required by the beams to reach their deflection limits and that were also tested for the sustained levels of the applied loads. For the second experiment, the corrosion was accelerated through the application of external direct current whilst the beams were under the load equivalent to 0%, 50%, 65% and 80% of the ultimate load.** The results indicate that load levels have a significant effect on the rise of steel corrosion level, the decrease of flexural stiffness and the degradation of flexural capacity. The mechanical properties like the strength and ductility are significantly impaired due to simultaneous effect of loading and corrosion in comparison to the effect of the single parameter at a time. Considering the corrosion situation of different position of steel bar, the formula of the ratios of the different position of steel bar corresponding with different sustained loading levels was given. An equation was deduced to calculate the flexural stiffness of corroded reinforced concrete and can be served as a reference for deflection calculation of corroded reinforced concrete beams.

Keywords: chloride; flexural deflection; flexural stiffness; sustained load; reinforced concrete; residual loading capacity;

1. Introduction

Reinforcement corrosion is one of the major causes for structural deterioration of reinforced concrete bridges [1,2]. The mechanical performance, residual strength, the frequency of use, maintenance, and service life of these structures with corroding reinforcements should be fully understood for the economic and robust design and construction.

Several experimental studies have been carried previously on the corrosion of reinforcement in reinforced concrete dealing with various issues which included corrosion process, its initiation, damaging effects of corrosion, and the prediction of time-to cover cracking of concrete due to corrosion [3-7]. These studies have found that the bond stiffness increases with corrosion up to a certain level of reinforcement corrosion, but with further increase in corrosion, the bond stiffness progressively decreases. However, previous studies were carried out in such a way that the reinforcements in concrete beams were first corroded to an expected extent, before the concrete beams were loaded to failure to assess the variation of their mechanical behaviour due to corrosion.

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These concrete beams were subjected to a separate loading test and reinforcement corrosion. However, the corrosion of reinforcement occurs simultaneously with the applied loads in the real practice; the previous studies have only considered it separately.

Heavy loading is now one of the common ways to maximize the benefits in China. However, the heavy load results in the emergence of cracks within the concrete surface causing the stiffness to reduce of the cracked section. Thus, the deflection limit of the beam is reached earlier than under the normal loading conditions and would cause the beam to no longer satisfy the requirements for its serviceability limits. The AASHTO road test result [8] also indicates that if the axle load increases twice, the damage to the road could be 16 times higher. The engineering practice shows that although the accidental heavy load does not necessarily cause significant structural damage on bridge, but effect of repeated heavy load would cause the damage of bridge aggravated, which increases the failure risk of structures, and improve the cost of maintenance.

Recently, the effects of load and corrosion on the structural performance have been reported [9-13], these investigations are mainly focused on the behavior of concrete beam at its corrosion propagation, surface cracks, instead of ductility, ultimate strength, and the relationship between loading and corrosion. In addition, the investigations for the simulation of reinforcement corrosion are mainly focus on the middle span [9-13], and the effect of shear reinforcement corrosion were ignored, and the level of sustained loads applied on the beams was only about 8% and 12% of beam ultimate capacity [11-12], which are smaller than that in actual structures. Malumbela et al.[11] have however shown that for beams that are corroded whilst under a sustained load, after a certain level of corrosion, the stiffness of the beams become degressive with a continued increase in the level of corrosion. However, it does not show the model which can be used to calculate the deflection of corroded RC beams.

This paper presents the results of experiments conducted to investigate the structural behavior of reinforced concrete beams subjected to simultaneous sustained load and reinforcement corrosion. Investigation on deflection, residual capacity, and ductility rate of an RC beam is also carried out. The corrosion of different regions of an RC beam is also compared and theoretical model of the flexural stiffness is proposed.

2. Experimental program

The experimental program consists of three parts: a. test program; b. data collection and analysis and c. formula derivation and model examination. The complete methodology has been shown in Fig. 1

Fig. 1 The work sequence

2.1 Beam specimen and material properties

Twelve reinforced concrete beams with a dimension of 150*250*2000mm were tested in this program. The reinforcement details of the beams are shown in Fig. 1. Each beam was reinforced with two 22mm deformed bars in tension, and two 10 mm plain bars in compression. The concrete cover is 30 mm. and 10mm stirrups with a space of 100 mm within the shear span. There are no stirrups in the middle span. The stirrups were wrapped by epoxy resin to avoid corrosion.

Fig.2 Dimension and Reinforcement of Specimen Beam (Unit: mm)

The concrete was designed to yield a 28 days compressive strength of 40MPa. The water cement ratio was 0.42 and the maximum aggregate size of the concrete was 20mm. The fine aggregate was the sand that the fineness modulus was 2.8, quality of the concrete mix ratio equal to w(cement): w(sand) : w(pebble): w(water) was 1:1.42:3.15:0.42. The compressive strengths, elastic modulus of the beams, the yield strength, and ultimate strength of the steel were shown in Table 1.

Table.1 Material properties

Diameter	Steel		Concrete	
	Yield strength/MPa	Ultimate strength/MPa	Compressive Strength/MPa	Elastic modulus/GPa
φ 8	335	482	45.4	33.6
φ 10	342	492		
φ 22	383.7	572.6		

2.2 Testing program

In the previous studies, the levels of sustained loading applied on the beam were usually smaller than the actual loading. However, in order to investigate the mechanical properties of the RC beam under normal state, there is a need of determination of the sustenance level of the beam for the applied load.

The first experiment was designed to test the strength and deflection of two concrete beams only for loading levels without being tested for corrosion with the chloride penetration. The testing was conducted using the testing Rig 3 under the displacement control. The flexural behavior of RC beam consists of three distinct stages: in first stage, the majority of applied stress on the beam is balanced by the concrete and not by the steel bars. Also, there are no cracks on the surface of the concrete and the stress level is much lower as compared with the normal state. In the second stage, the applied tensile stress on the concrete is more than the tensile strength of concrete itself and therefore, the concrete cracks due to the increased tension. It is well known that the maximum deflection limit is $l/600$ mm, which is considered appropriate for the RC beams [14]. Therefore, the loading level for the normal state was chosen to be 50% of the ultimate load and that 50% corresponds to a deflection of 3mm. The loading setup for the conducted experiment is shown in Fig 3.

Fig.3 Static loading frame (Unit: mm)

The specimens were divided into five groups: the first group was without the loading; the second simulated the normal state; the third simulated the heavy load I state; the fourth simulated the heavy load II state; the fifth simulated coupling time influence on the RC beam. Table.2 shows the details of test beams.

Table.2 Details of test beams

Beams no.	Sustained Loading level/%	Coupling time/d
CL00-10-1	-	10
CL00-10-2	-	10
CL50-10-1	50(normal state)	10
CL50-10-1	50(normal state)	10
CL60-10-1	65(loading I)	10
CL60-10-1	65(loading I)	10
CL80-10-1	80(loading II)	10
CL80-10-2	80(loading II)	10
CL80-15-1	80(loading II)	15
CL80-15-2	80(loading II)	15

All the concrete beams were cured in a water tank for 15 days, before they were subjected to sustained load. The beams were placed in the water tank which was filled with a 5% solution of NaCl, and the beams were separately subjected to sustained load equivalent to 0%, 50%, 65%, and 80% of the ultimate capacity of a virgin beam. The load was measured and monitored using a load cell that was positioned between the screw block and the loading beam. The load cell was connected to a data logger to monitor the applied load so that the load could be adjusted to the target level once the load decreased, as illustrated in Fig 4.

Fig.4 Loading rig

The DC power supply was applied to accelerate the corrosion process to obtain the desirable corrosion level. The tensile steel bar and the stainless steel bar were connected to the DC power supply. The maximum voltage used in the test was 25V, and the maximum current was 2.5A. In the circuit, the $\phi 22$ reinforcing bars in a concrete beam lost electron acted as anode, the stainless plate gained electrons which was transformed from the steel served as cathode. The amount of charge which passed through the steel was calculated by the Faraday's Law. The time of corrosion was determined to attain desirable level of corrosion of the tensile steel bars in the concrete beams.

2.3 Measurement of steel corrosion rate

The steel was immersed into 2.5% hydrochloric acid solution for 30mins, and then the specimens were taken away from the acid solution, washed in water to remove the acid and dried by a dryer. The steel was cut into specimens of 200mm, and weighed on an electronic scale. The mass of the specimens would be as the initial mass. At the end of the residual capacity test, the corroded steel bars were removed from the test beams. The steel wire brush was used to remove the rust that was on the surface of the steel and then the specimens were weighed in the similar way as described above. Fig.5 shows the steel coupons of corroded bars. The percentage gravimetric mass loss of steel coupon was calculated from the following equation:

$$\eta = \frac{m_u - m_c}{m_u} \times 100\% \quad (1)$$

where m_u is the average mass of uncorroded steel coupon; and m_c is the mass of corroded coupon.

Fig.5 Steel coupons of corroded bars

3 Results and discussions

3.1 Corrosion of steel under sustained loading

Fig.6 shows the corrosion rates under different loading conditions.

The corrosion rate was determined corresponding to the level of sustained load, and the speed of corrosion was accelerated with increasing load. The corrosion rate for the loading I was 50% higher than that for normal state, and the corrosion rate for loading II was 74% higher than that under loading I. The corrosion rate increased with the increase of load levels. In the actual engineering conditions, most concrete structures consist of cracks, and the open cracks provide the channel for oxygen and moisture and the steel gets corroded further. The increased loads lead to the further increment in crack width and the number of the cracks also increases, resulting in more severe corrosion loss. Hence, the load has a significant impact on corrosion speed. The middle span of the beam suffered more cracks than the other sections of the beam; hence the rate of corrosion was also larger than other sections of the test beam.

Fig.6 Variation of corrosion rate along the steel

The corrosion modalities of tensile under different load levels were given in Fig.7. It is clear to observe in Fig.8 that the extent of corrosion or the modality of corrosion of the beams was affected by load. Previous studies suggested that local corrosion usually occurred in the natural environment, and general corrosion occurred in accelerate corrosion. However, the general corrosion and local corrosion occurred simultaneously under sustained load. Hence, the corrosion shape was changed by the loading.

Fig.7 Corroded steel

3.2 Structural performance under loading and corrosion

As shown in Fig.8, the structural performance of reinforced concrete beams under simultaneous loading and corrosion can still be divided into three different stages. This is similar with a lot of published work mentioned earlier on corroded beams. But the slope of the curve decreased with increasing loading levels. The result of CL80-15-2 indicated that the flexural capacity suddenly decreased and the steel reached the yield stage, whilst the concrete in the compression zone was not crushed.

Fig.8 Load-deflection curves of beams tested to failure

In the earlier working stage of RC beams (i.e. Stage), the deflections of specimens applied on different levels of sustained load were nearly the same. When the deflection reached the limit of

the specification [14] ($f = \frac{l}{600} = 3mm$), the average load of the CL50-10, CL65-10, CL80-10,

and CL80-15 was 110.3kN, 102.6kN, 92kN, and 114kN respectively. These results indicated that the increment of deflections under the heavy load state was significantly faster than that under normal state, and the growth rate was corresponding to the increment of the loading levels. The reason for this phenomenon is that the oxide film on the surface of steel was destroyed by the erosion of chloride ions, as a result, damaged surface and undamaged surface became the cathode and anode of electrochemical reaction, respectively. Since, the area of anode was larger than the cathode, the density of anode current was also larger, hence the corrosion of reinforced cross-section further increased. The effective area of steel decreased, and the extent of corrosion under heavy loading state were more severe than the normal state, therefore, the flexural stiffness of beams under higher load was lower.

In the later working stage of RC beams, the yield load significantly decreased. The ductility rate was defined as the vertical displacement of yield-to-destruction ratio. Fig.9 shows the corrosion rate and the ductility rate of the test beams. The ductility ratio of CL65-10 and CL80-10 was 2.4% and 13.15% lower than the CL50-10 specimen, respectively and the deduction of ductility performance of RC beams was significantly induced by sustained loading and reinforcement corrosion. This was attributed to decrease in the diameter of ribbed bar under reinforcement corrosion, which decreased the bond force between steel and concrete. For the beam CL80-15-2, the under-reinforced beam of brittle failure replace the anticipated ductile flexural failure. The reduction in ductility of corroded reinforcement and non-uniform corrosion along the length of a corroded bar [13]. In practice, the engineering structures with corroding reinforcements are still being used and playing important role in our society. Hence, the corroded structures that are still being used should be inspected regularly with their residual strength to avoid catastrophic accidents.

Fig.9 Ductility ratio vs. corrosion rate

3.3 Residual flexural capacity

Table.3 shows the flexural ultimate capacity, the deduction of bending strength and the failure modes of the beams. The ultimate flexural capacity loss is relative to the average ultimate flexural capacity of two reference beams (R1 and R2) which is equal to (214.35 kN). Table.3 indicates that corrosion of reinforcement decreases the ultimate strength of a concrete beam, which is consistent with the results reported by previous researchers [16,17,20].

Table.3 also shows that the reduction of ultimate strength of corroded beams varied not only with the amount of corrosion, but also with the load level which was applied on the RC beams. The flexural ultimate capacity of beams under normal state was accounted for 92.1% of the reference beam. When the beams were applied on the 65% of the virgin beam ultimate capacity, the flexural ultimate capacity decreased to 87.5% of the reference beam. For the beams which were with 80% of ultimate strength and corrosion for 10 days, their ultimate strengths decreased about 17.3%. For the beams with 80% of ultimate strength and corrosion for 15 days, the ultimate strength was reduced by 23.3%.

The reason behind this is that corrosion is not uniformly distributed in the beam and the load also has a significant effect on the reduction of ultimate strength. For the CL00 and CL50 beams, since the cracks width occurred are within or nearby their mid-span, and the number of cracks was few, the corrosion loss was low, hence, the reduction of ultimate strength was not evidently. For the CL65 and CL80 beams, however, since the severe corrosion took place in the mid-spans, the smallest residual section of their tensile bars likely coincided with the position of their maximum bending moment. As a result, a large reduction in their ultimate strength was induced. For the CL80-15-2 beam, since the corrosion of tensile bar occurred asymmetrically along the length, with the maximum corrosion occurred in the shear moment. This may lead to decrease in friction between the concrete and tensile bar, once the friction decreases below the tensile, a sudden collapse is likely to happen without any significant signs of warnings.

As a brief summary, the magnitude of the reduction of beam capacity depend on the amount of reinforcement corrosion, the position where the corrosion takes place, and the distribution of bending moment of the beam under sustained loads. To estimate the ultimate capacity, the distribution of corrosion properties and should be taken into account.

Table.3 Ultimate strength and failure mode of corroded beams

beam	Ultimate strength(kN)	Bond loss/%	Failure mode
R1	216.7	-	ductile failure
R2	212	-	ductile failure
CL00-10-1	205.4	4.17	ductile failure
CL00-10-2	207.6	3.15	ductile failure
CL50-10-1	198.4	7.44	ductile failure
CL50-10-2	196.3	8.42	ductile failure
CL65-10-1	184.7	13.83	ductile failure
CL65-10-2	190.5	11.13	ductile failure
CL80-10-1	178.8	16.59	ductile failure
CL80-10-2	175.7	18.03	ductile failure
CL80-15-1	169.3	21.02	ductile failure
CL80-15-2	159.8	25.45	brittle failure

3.4 Theoretical method of calculating the flexural stiffness

3.4.1 Relation of strain compatibility

The compatibility of strain between steel bar and concrete was changed by the expansive corrosion products which were similar for all corroded RC beams. The strain of steel bars lagged behind concrete strain which was due to the corrosion, hence, the function of strain coordination was defined as follows:

$$k(\eta_s) = \frac{\varepsilon_{cs}}{\varepsilon_s} \quad (2)$$

where $k(\eta_s)$ was the function of strain coordination between steel bar and concrete after corrosion; ε_{cs} was strain of concrete which was around the steel; ε_s was strain of steel bar;

The $k(\eta_s)$ reflects the variation between steel and concrete corresponding to the corrosion rate, ZHANG[21] gave the fitting formula:

$$k_c = 0.918 + 0.160\eta_s \quad (3)$$

$$k_m = 2.368 + 0.122\eta_s \quad (4)$$

where k_c is the function of strain in the middle of steel, k_m is the strain function of margin.

Fig.10 shows the measured corrosion rate in the middle and margin of steels. The variation of corrosion rate with different load levels is also presented. The results and correlation coefficient were compared in order to determine the best fitting formula as follows:

Fig.10 Relation of M and η

By comparing the fitting degree index, the polynomial fitting curve matched the test datum best with the highest correlation coefficient. Hence, the polynomial regression was used to be the expression of the load and corrosion rate.

The strain coefficient between steel and concrete can therefore be presented in terms of the loading as follows:

$$\begin{aligned} k_c &= 2.538M^2 - 0.796M + 1.128 \\ k_m &= 1.24M^2 - 0.4M + 2.48 \end{aligned} \quad (5)$$

3.4.2 The flexural stiffness of corroded RC beam

Previous studies [17-19] were mainly focused on the pure bending of concrete beam and ignored the contribution of shear moment regions to the stiffness. Fig. 11 shows the section stiffness and sectional curvature of RC beam. The number 1 curve is the section curvature which is used in previous stiffness calculated formula, and the number 2 curve is the section curvature that considers the shear moment regions. The shaded area in Fig.11(b) was ignored when the previous method was used to calculate flexural stiffness. Hence, the calculation result was higher than actual stiffness. In order to make the calculated results more accurate, the stiffness of shear moment regions need to be considered.

Fig.11 The distribution of cross-section curvature

Considering the situation of RC beam under symmetrical load, the shear of arbitrary section can be expressed as the following equation:

$$\frac{d^2 y}{dx^2} = \frac{1}{GA} \frac{dQ(x)}{dx} \quad (6)$$

where G =modulus of rigidity. Due to $\frac{dy}{dx} = \frac{Q(x)}{GA}$, i.e. $y = \int_0^x \frac{Q(x)}{GA} dx + C_1$, and the equation satisfies the boundary conditions, $y = \frac{Px}{3GA}$. For middle span, $y = \frac{Pl}{6GA}$. The deflection of RC beam induced by moment is $y = \frac{6.81Pl^3}{384EI}$, the ratio of shear deformation and bending deformation is 0.04.

The stiffness of flexural is calculated from the following equation:

$$B = \frac{M}{\phi} \quad (7)$$

where B is the section stiffness; M is the bending moment; ϕ is the sectional curvature;

(a) Diagram of section strain

(b) Stress pattern of mid-span

Fig.12 Simplified Calculation Diagrams

1) Calculation of curvature

The average curvature of cross-section can be calculated using the following equation:

$$\phi = \frac{\bar{\epsilon}_c + \bar{\epsilon}_{cs}}{h_0} \quad (8)$$

where $\bar{\varepsilon}_c$ is average compressive strain of compression area in the mid-span; $\bar{\varepsilon}_{cs}$ is average strain of concrete around the steel; h_0 effective height of cross-section;

Combining equation (2) and equation (6):

$$\phi = \frac{\bar{\varepsilon}_c + k(\eta_s)\bar{\varepsilon}_s}{h_0} \quad (9)$$

where $\bar{\varepsilon}_c$ is the average concrete strain in compressive area, $\bar{\varepsilon}_s$ is the average strain of steel

The non-uniform coefficient of steel bar can be adjusted by the binding coefficient β^E :

$$\psi' = 1 - \beta^E(1 - \psi) \quad (10)$$

where ψ' expresses the non-uniform coefficient after corrosion; ψ is the non-uniform coefficient before corrosion. β^E is the binding coefficient. Considering the contribution of the shear section, take $\bar{\varepsilon}_c = \varepsilon_c$, and the average strain of steel can be expressed as following equation:

$$\bar{\varepsilon}_s = [1 - \beta^E(1 - \psi)]\varepsilon_s \quad (11)$$

Hence, the average curvature of cross-section is

$$\phi_{avg} = \frac{\varepsilon_c + \bar{\varepsilon}_s(k(\eta_s^c)\psi'_c + 0.04k(\eta_s^m)\psi'_m)}{h_0} \quad (12)$$

where ϕ_{avg} is average curvature of cross-section; η_s^c and η_s^m express the corrosion rate in the middle and end of steel respectively; ψ'_c and ψ'_m express the non-uniform coefficient of middle and margin of steel bar.

2) Constitutive equations

The constitutive equations of concrete and steel are:

$$\sigma_c = E_c \varepsilon_c \quad (13)$$

$$\sigma_s = E_s \varepsilon_s \quad (14)$$

where σ_c =compressive stress of concrete in the compressive area. E_c =modulus of elasticity of concrete. σ_s is the stress of steel bar, E_s =modulus of elasticity of steel bar.

3) Balance equation

Ignoring the tensile capacity of concrete in the tensile area, and the balance equation is

$$M = \alpha \gamma \sigma_c b x_c h_0 \quad (15)$$

$$M = \gamma \sigma_s A_{se} h_0 \quad (16)$$

where M =section moment, α =ratio between the height of rectangular stress block and the depth of the neutral axis, γ =the internal lever arm coefficient in cracking cross section(0.87), x_c =the height of compression area, A_{se} =area of steel, considering the degree of corrosion

Combining equation(13)~equation(16), and substituting to equation(12):

$$\phi = \frac{M}{E_s A_{se} h_0^2} \left\{ \frac{\psi'_c k^c(\eta_s) + 0.04 \psi'_m k^m(\eta_s)}{\gamma} + \frac{\alpha_E \rho_{se}}{\alpha \gamma x_c / h_0} \right\} \quad (17)$$

where $\alpha_E = E_s / E_c$, where $\rho_e = \frac{A_{se}}{bh}$, considering the degree of corrosion; [14] gives the some parameters:

$$\frac{\alpha_E \rho}{\alpha \gamma x_{cr} / h_0} = 0.2 + 6\alpha_E \rho_{se} \quad (18)$$

Combining equation (17) and equation (8), the flexural rigidity of corroded RC beam which is under compound effect of load and corrosion is

$$B = \frac{E_s A_{se} h_0^2}{1.15(k(\eta_s^c)\psi'_c + 0.04k(\eta_s^m)\psi'_m) + 0.2 + 6\alpha_E \rho_e} \quad (19)$$

The local corrosion and uniform corrosion occurred simultaneously due to the presence of transverse cracks under the sustained loading. Although the pits were numerous, the depths of pits were shallow which turned the rate of section corrosion into the rate of region corrosion, maintaining the calculation accuracy. In conclusion, when the rate of corrosion was less than 3% and the form of pitting was not significant. The influence of pitting can be ignored when the flexural stiffness of corroded RC beam is calculated. Fig 13 shows the measured deflection at the middle span of beams. Also presented in the figure is the variation of theoretical deflection of different model. The theoretical curves obtained from the theoretical model fitted well with experimental curves; however the curves obtained from Xing' model ignored the contribution of tensile bars when sectional moment of inertia was calculated. Thus, the calculated stiffness becomes too large due to not considering the influence of the margin tensile reinforcement.

Fig.13 Comparison of test results and prediction results

4. Conclusions

Based on the experimental results from the tests, the following conclusions can be drawn:

1. The corrosion rate of loading I was 50% higher than the corrosion rate of normal state, and the corrosion rate of loading II was 74% higher than the corrosion rate of the loading I. Hence, the sustained load accelerated the corrosion of steel bars. **Thus, an attention should be paid to the case where the corrosion of steel takes place, and how to monitor the geometric properties of corrosion pit along the tensile bar.**

2. Under simultaneous loading and reinforcement corrosion, the flexural rigidity of RC beam of heavy loaded state decreased so that the deflection reached the limits earlier than normal state beam. In addition, the ductility ratio was influenced by the corrosion but mostly by the level of simultaneous load. **An anticipated ductile failure can be replaced by a less ductile or even brittle failure.**

3. The ultimate strength of a corroded beam under simultaneous loading and reinforcement

corrosion depended not only on the amount of corrosion, but also on the load level applied on the beam. In this study, when the loading reached 80% of the ultimate strength, the residual strength decreased 76.7% to ultimate capacity. Thus, the beam could no longer satisfy the requirements for its serviceability limit state.

4. The equation for calculating the flexural stiffness of corroded reinforced concrete was verified by the experimental results. Test results showed that the proposed flexural stiffness equation was reliable. The flexural stiffness equation can be used to guide engineering practice.

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References

- [1] VIDAL T, CASTEL A, FRANCOIS R. Analyzing crack width to predict corrosion in reinforced concrete [J]. Cement and Concrete Research, 2004, 34(1): 165-174.
- [2] Ma Y, Zhang J, Wang L, Liu Y. Probabilistic prediction with Bayesian updating for strength degradation of RC bridge beams. Structural Safety, 2013, 44: 102-109.
- [3] Morinaga, S. Prediction of service lives of reinforced concrete buildings based on the corrosion rate of reinforcing steel[J]. Proceedings of building materials and components. 1990, 12:5-16.
- [4] Almusallam A A, Al-Gahtani A S, Aziz A R, et al. Effect of reinforcement corrosion on flexural behavior of concrete slabs[J]. Journal of materials in civil engineering, 1996, 8(3): 123-127.
- [5] Torres-Acosta A A, Navarro-Gutierrez S, Terán-Guillán J. Residual flexure capacity of corroded reinforced concrete beams[J]. Engineering Structures, 2007, 29(6): 1145-1152.
- [6] Yoon S, Wang K, Weiss W J. Interaction between Loading, Corrosion, and Serviceability of Reinforced Concrete[J]. ACI Materials Journal, 2000, 97(6): 637-644.
- [7] Liu yang, Jiang nan, Deng yang. Study on flexural experiment of reinforced concrete beams under sustained overloading and corrosion[J]. Journal of Highway and Transportation Research and Development, 2014, 31(10):65-70.
- [8] AASHO. AASHO Guide for Design of Pavement Structures. American Association of State Highway and Transportation Officials, Washington. D. C.1993.
- [9] Ballim Y, Reid J C, Kemp A R. Deflection of RC beams under simultaneous load and steel corrosion[J]. Magazine of Concrete Research, 2001, 53(3): 171-181.
- [10] Ballim Y, Reid J C. Reinforcement corrosion and the deflection of RC beams—an experimental critique of current test methods[J]. Cement and concrete composites, 2003, 25(6): 625-632.
- [11] Malumbela G, Moyo P, Alexander M. Behaviour of RC beams corroded under sustained service loads[J]. Construction and Building Materials, 2009, 23(11): 3346-3351.
- [12] Malumbela G, Alexander M, Moyo P. Steel corrosion on RC structures under sustained service loads—A critical review[J]. Engineering Structures, 2009, 31(11): 2518-2525.
- [13] Du Y, Cullen M, Li C. Structural performance of RC beams under simultaneous loading and

- reinforcement corrosion[J]. *Construction and Building Materials*, 2013, 38: 472-481.
- [14] JTG D-62-2004, Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts[S]. Beijing, China: China Architecture & Building Press.
  - [15] GB 50010-2010, Code for design of concrete structures[S]. Beijing, China: China Architecture & Building Press.
  - [16] Ting S, Nowak AS. Effect of reinforcing steel area loss on flexural behaviour of reinforced concrete beams. *ACI Structure Journal* 1991;88(3):309-14.
  - [17] O' Flaherty FJ, Mangart PS, Lambert P, Browne EH. Effect of under reinforcement on the flexural behaviour of corroded beams. *Materials Structure*, 2008, 41(2):311-21.
  - [18] Wang X, Gu X, ZHANG W. Flexural stiffness of corroded reinforced concrete beams strengthened with carbon fiber composite sheets[J]. *Journal of Building Structures*, 2009, 5: 024.
  - [19] Sun Bin, Niu Di-tao, Wang Qing-lin. Analysis and Calculation flexural stiffness of Corroded Reinforced Concrete Beam[J]. *Building Structure*, 2004, 34(10): 42-45.
  - [20] Azad AK, Ahmad S, Azher SA. Residual strength of corrosion-damaged reinforced concrete beams. *ACI Materials Journal* 2007; 104(1):40-7.
  - [21] Zhang Yong-li, Dong Zhen-ping, Wang Qing-ling, Wang Ying-sheng. Evaluation on the remaining flexural capacity of corroded RC beams[J]. *Concrete*, 2011, 8: 21-26.
  - [22] XING Guohua, NIU Ditao. Analytical model of flexural behavior of corrode reinforced concrete beams[J]. *Journal of Central South University (Science and Technology)*, 2014,45(1):193-201.