

Effects of sustained loading and corrosion on the performance of reinforced concrete beams

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Abstract

This paper presents an experimental investigation on the behaviour of reinforced concrete (RC) beams under simultaneous loading and reinforcement corrosion. Corrosion of reinforcements within beams were created by an accelerated method using a 5% NaCl solution combined with a constant impressed current. Three different corrosion durations at 5, 10 and 20 days and four levels of sustained loading at 0, 15%, 30% and 60% of ultimate loading capacity were applied to the beams. Totally 13 RC beams were tested to examine the corrosion of reinforcements, cracking of beams, and structural behaviour of the corroded beams. Test results indicate that corrosion of reinforcements increases with the sustained loading but undergoes an initially increasing rate followed by a decreasing rate. Higher loading level and longer corrosion period are prone to cause the brittle failure of RC beams. Increasing the sustained loading extends the longitudinal crack but not the crack width. The joint effects of sustained loading and corrosion duration, compared to the single effect of either one factor, are more significant on the performance of RC beams in terms of corrosion of reinforcements, failure mode, ultimate loading capacity, and deformation ability. At a higher sustained loading level, beams' ultimate loading capacity and deformation ability decrease more significantly with the corrosion periods. It is also found that a lower loading increases the flexural stiffness of RC beams, but a higher loading level instead decreases it.

Keywords: Corrosion; RC beam; sustained loading; corrosion period

1 Introduction

Corrosion of reinforcements has been recognized as one major cause of structural degradation in reinforced concrete (RC) structures [1]-[3], especially for those exposed to the marine environment. This is mainly attributed to the reduction of reinforcement section area as well as cracking and/or spalling of concrete induced by the expanded corrosion products [4]. Probabilistic models considering corrosion of reinforcements have also been proposed to predict the service life of RC structures [5]-[7]. Corrosion variability of reinforcements in the structures is properly considered in their models, leading to more accurate predictions for RC structures. Wang *et al.* [8] reported that the width, density and tortuosity of cracks are the main parameters affecting the chloride diffusion of concrete. Moreover, corrosion of reinforcements causes the bonding deterioration between the reinforcements and the concrete, which significantly affects the safety and service life of the infrastructures [9]. Therefore, it is necessary to estimate the performance of RC structural members subject to different levels of corrosion.

A large number of studies have been focusing on investigating the behaviour of RC beams in the presence of corrosion and loading [10]-[12]. Longitudinal tensile strains on the tensile surface of corroded beams under the service loadings would increase monotonically with the corrosion periods at a decreasing rate [10]. It has been known that the joint action of corrosion and loading would increase the deflection of corroded RC beams [11]. Nevertheless, the joint effect of corrosion and loading on the performance of RC beams could be further studied, such as flexural stiffness. It was previously found that a low-level corrosion could enhance the bond between reinforcements and concrete [13] as well as increase the flexural stiffness of the beam [14]. As the further increase of corrosion, the flexural stiffness of the corroded beams under a constant loading was found to become constant. This is mainly attributed to the secondary longitudinal strains of reinforcements from the expansive corrosion products, which supersedes the increase in bond between reinforcements and concrete [15]. However, it remains unclear how would the flexural stiffness of RC beams be affected when the loading is further increased. Corrosion rate of reinforcements within the RC beams would significantly affect the service life of RC structural members. Currently, there are controversial findings regarding the corrosion rate of beam reinforcements subject to various levels of sustained loading. Yoon *et al.* [16] stated that the corrosion of RC beams would increase at an increasing rate under high

levels of sustained loads. While other researchers (e.g., Liu and Weyers [17]; Weyers [18]) found that the corrosion rate of reinforcements would decrease as the corrosion level increased. Differently, Zhe *et al.* [19] reported that the corrosion of reinforcements within RC beams developed in a stochastic manner. Therefore, the effect of sustained loading on the corrosion rate of reinforcements within RC beams needs further study.

Existing studies demonstrated that crack width on corroded beams under sustained loading was wider than that without loading. However, most studies (e.g., Zhu et al., [12]; Du et al., [20]; Yin et al., [21]) focused on studying the cracking behaviour of RC beams after corrosion process. Cracks would propagate on the corroded beams subject to a constant loading as the corrosion period increased. There has been limited research investigating the development of cracks for the RC beams with different corrosion levels. The effect of sustained loading on the cracking behaviour of corroded RC beams remains unclear.

The objectives of this research lie in that: (1) to investigate the effect of sustained loading on the corrosion rate of reinforcements within RC beams; (2) to characterize the cracking behaviour of corroded RC beams under multiple sustained loadings and corrosion periods; and (3) to analyse the joint effects of sustained loading and corrosion on the flexural behaviour of RC beams, specifically, to study the flexural loading capacities and load-displacement response of the corroded beams. The research findings would provide insights on the joint effects of sustained loading and corrosion levels on corroded RC beam's behaviour, especially at high loading levels (i.e., 30% to 60% of ultimate loading capacity).

2 Experimental program

2.1 Specimens

Totally 13 RC beams with the same reinforcement details and concrete strength were prepared for experimental tests. Each beam had the cross-section of 120 mm × 200 mm and the length of 1,700 mm. The beam section was reinforced with two T12 in the tension zone and two R8 in the compression zone. T12 is the HRB335 high strength steel bars with the nominal diameter of 12 mm while R8 is the HPB235 round steel bars with the diameter of 8 mm. The longitudinal reinforcements in the tension zone extended beyond both ends of the RC beam, and the extended portion of reinforcements were polished, bonded with copper wires, and sealed by epoxy resin. Stirrups R6.5 were provided along the beam at spacing of 80 mm except the constant moment zone in the middle of beam. R6.5 is the HPB235 round steel bars with the

diameter of 6.5 mm. The clear span of each beam was 1,500 mm. The dimension and reinforcement details of the beam are shown in Figure 1.

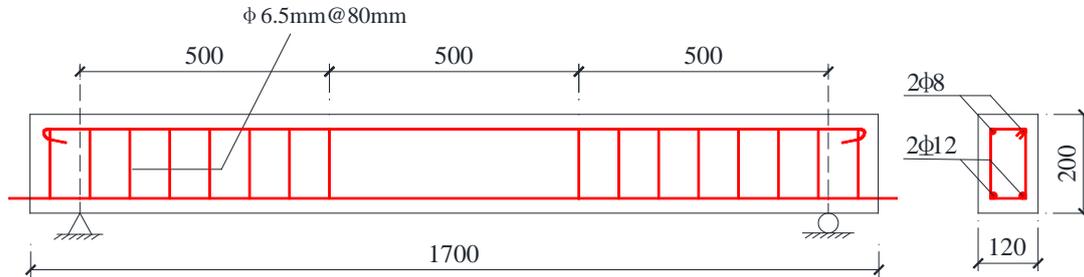


Figure 1. Dimension and reinforcement details of the beam specimen (unit: mm)

The C40 concrete was used to cast the RC beams. In the concrete mix, the ordinary Portland cement 42.5 was used. The natural gravel with the maximum size at 20 mm was adopted as the coarse aggregate and the river sand with the fineness modulus at 2.6 was used as the fine aggregate. To guarantee the same concrete strength, all beams were cast by one batch of ready-mix concrete and were cured under the same condition. The HRB335 high strength steel bars were used as the longitudinal reinforcements while mild steel bars were adopted as the stirrups. The specimens are exposed to different sustained loadings and corrosion conditions. Four levels of sustained loadings at 0, 15%, 30% and 60% of ultimate loading capacity of the beam were adopted. Under each loading level, three levels of corrosion durations at 5, 10 and 20 days were applied to the beams. In addition, one RC beam without sustained loading and corrosion exposure was included as the control specimen. Further detailed experimental programme can be found in Table 1.

Table. 1 Details of experimental programme

Specimen	Loading condition	Corrosion condition	Corrosion duration (days)	Note
BL-0-0	-	-	-	Control
BL-0-1	-	5% NaCl solution with dry-wet cycling	5	Non-sustained loading
BL-0-2	-	5% NaCl solution with dry-wet cycling	10	Non-sustained loading
BL-0-3	-	5% NaCl solution with dry-wet cycling	20	Non-sustained loading
BL-15-1	15% M_u	5% NaCl solution with dry-wet cycling	5	Sustained loading

BL-15-2	15% M_u	5% NaCl solution with dry-wet cycling	10	Sustained loading
BL-15-3	15% M_u	5% NaCl solution with dry-wet cycling	20	Sustained loading
BL-30-1	30% M_u	5% NaCl solution with dry-wet cycling	5	Sustained loading
BL-30-2	30% M_u	5% NaCl solution with dry-wet cycling	10	Sustained loading
BL-30-3	30% M_u	5% NaCl solution with dry-wet cycling	20	Sustained loading
BL-60-1	60% M_u	5% NaCl solution with dry-wet cycling	5	Sustained loading
BL-60-2	60% M_u	5% NaCl solution with dry-wet cycling	10	Sustained loading
BL-60-3	60% M_u	5% NaCl solution with dry-wet cycling	20	Sustained loading
Note: M_u stands for the ultimate loading capacity of the RC beam.				

2.2 Corrosion setup

The test setup for the beam consists of a sustained loading system and an accelerated corrosion system as illustrated in Figure 2. The load was applied through a mechanical jack installed between the specimen and the reaction frame. A load cell was installed to monitor the loading level for each beam. After reaching the loading level for each beam, the sustained loading level was maintained through adjusting the jack during the corrosion process.

The accelerated corrosion system comprises of a direct current (DC) source and a salt water spray cycling. The DC source supplied the maximum voltage and current of 30 V and 3.0 A, respectively. The current applied on each RC beam was controlled by a separate DC source. The bottom reinforcements were connected to the positive electrode of the DC supply. A stainless steel plate with the length of 1,450 mm was set at the bottom of the RC beam and connected to the negative electrode. The corrosion current was controlled by the steady flow. The current density of the RC beam reinforcements was calculated at 0.01 mA/mm² according to the Faraday's law. The 5% NaCl solution was sprayed to the RC beam to simulate wet-dry cycling, which was designed to provide the RC beams with corrosion environment. Two PVC pipes were installed at both sides of the beam along the longitudinal direction. Sprinklers were placed at 100 mm spacing along the PVC pipes, which were connected to the pump through hoses. As shown in Figure 2(b), the accelerated corrosion system could form the water circulation to provide controllable spraying. The wet-dry alternate condition was set in the 24-hour wetting followed by 24-hour drying cycle.



Figure 2. Test setup for (a) sustained loading, and (b) water spray for corrosion

2.3 Measurement of reinforcement corrosion

Two measurement methods were employed to determine the corrosion levels of reinforcements, including cross-section area loss and mass loss of reinforcements. According to JTJ270-98 Testing Code of Concrete for Port and Waterway Engineering [22], the corroded reinforcements were first immersed in acid solution for 30 mins before being sent to alkali solution for another 10 mins. Subsequently, reinforcements were wetted followed by the drying process. The samples were weighted at the precision level of 0.01g. The mass loss of reinforcements is calculated by Equation (1).

$$\text{Mass loss} = \frac{W - W_c}{W} \times 100 \quad (1)$$

where W and W_c are the mass of reinforcements before and after the corrosion, respectively. For cross-section area method, the area of cross-section was calculated based on the averaged diameter of six measurements for the corroded reinforcements. Cross-section area loss of reinforcements can be calculated by Equation (2).

$$\text{Section area loss} = \frac{F - F_{\min}}{F} \times 100 \quad (2)$$

where F and F_{\min} are the cross-section areas of reinforcements before and after the corrosion, respectively.

2.4 Loading scheme



Figure 3. Flexural testing setup

Upon the completion of the corrosion process, the corroded RC beams were washed before being placed in the flexural testing setup shown in Figure 3. The four-point load was applied to the beam. The maximum loading capacity of the frame was 5,000 kN. The applied load and deflection at the mid of the beam were collected for analysis.

3 Experimental results and discussion

3.1 Corrosion of reinforcements

The corrosion of reinforcements within the beams subject to different sustained loadings and corrosion periods was examined. Figure 4 shows the typically corroded reinforcements taken from different beams. It was observed that the outer surface of the reinforcement (close to concrete cover) exhibited more severe corrosion as compared to the inner surface of reinforcement. This would promote the formation of corrosion caused by the oxygen concentration between the outer and the inner surfaces of reinforcements, and also accelerate the corrosion process [23]. Expansion of reinforcements due to the accumulation of corrosion products would subsequently induce cracks on the beams. For beams under a constant sustained loading (e.g. 60% of ultimate loading capacity) as seen in Figure 4, corrosion levels of reinforcements increased with the corrosion period. At the advanced stage of corrosion, the pitting corrosion could be found at a certain location along the reinforcement. When the corrosion level further increased, the significant reduction in the cross-section area of reinforcements due to the pitting corrosion was found (e.g. specimen BL-60-3).

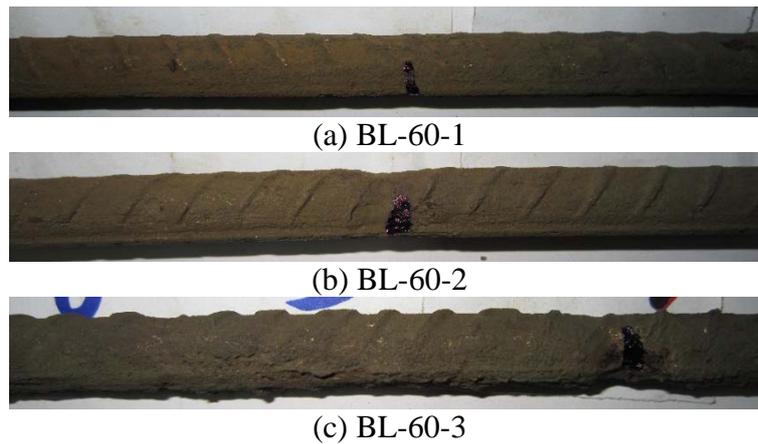


Figure 4. Corroded reinforcing bars

The corrosion level of reinforcements was quantitatively assessed in terms of mass loss and section area loss as shown in Table 2. Two types of corrosion were identified for the reinforcements, including the surface corrosion and the pitting corrosion. For the specimens corroded on surface only (e.g. specimens in series BL-0 and BL-15), ratio of mass loss to section area loss was approximated to be 1.0, which indicated that both mass loss and section area loss of reinforcements could reflect the corrosion level of reinforcements. When reinforcements were corroded in a uniform manner, both methods were effective to measure the corrosion states. For the specimens corroded with pits, however, the ratio of mass loss to section area loss was much smaller than 1.0. Thus, mass loss of reinforcement could not appropriately represent the corrosion levels as the occurrence of pitting corrosion significantly affected mechanical property of reinforcements due to the reduction of section area. Therefore, it is recommended to examine the corrosion level of reinforcements through section area loss especially for reinforcements with pitting corrosion.

Table 2 Corrosion level of reinforcements

Specimen	Corrosion type	Corrosion level		Mass loss/section area loss
		Mass loss (%)	Section area loss (%)	
BL-0-1	Surface	1.98	1.37	1.443
BL-0-2	Surface	4.62	4.86	0.951
BL-0-3	Surface	8.78	10.65	0.824
BL-15-1	Surface	2.58	2.45	1.055
BL-15-2	Surface	5.72	5.52	1.037
BL-15-3	Pitting	10.10	13.57	0.745
BL-30-1	Pitting	2.97	9.40	0.316
BL-30-2	Pitting	6.24	11.37	0.549
BL-30-3	Pitting	11.10	21.85	0.508
BL-60-1	Pitting	3.12	13.03	0.240
BL-60-2	Pitting	6.63	22.86	0.290

BL-60-3	Pitting	10.87	29.01	0.375
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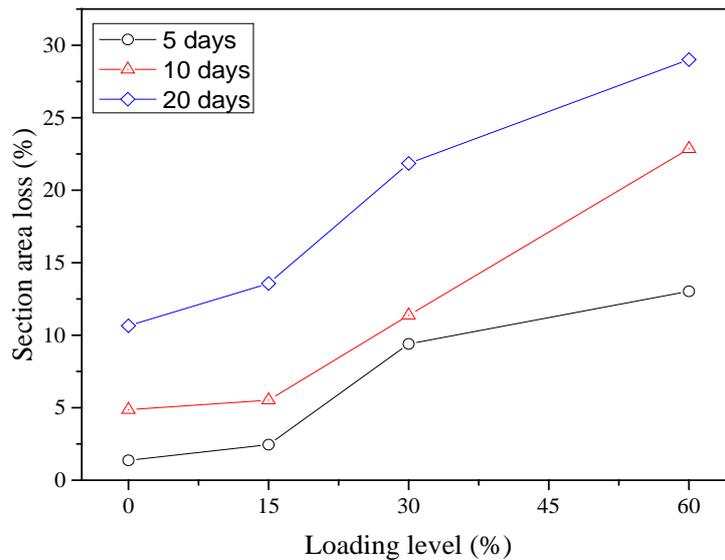


Figure 5. Section area loss of reinforcements

Figure 5 shows the variation of section area loss of reinforcements within the beams under different loading levels and corrosion periods. Generally, section area loss of reinforcement increases with the loading level and corrosion period. Loading at a low level (e.g. 15% of ultimate loading capacity) joint with a short corrosion period (e.g. 5 or 10 days) would not significantly accelerate the corrosion of reinforcements. Their section area losses were less than 5%. For the beams subject to 20 days' corrosion, the section area loss would significantly increase, as much as doubled to that of the beams with 10 days' corrosion. For the beams subjected to a higher loading level (i.e. 60% of ultimate loading capacity), section area loss of reinforcements at 5 days' corrosion was equivalent to that of beams under 15% of ultimate loading capacity and 20 days' corrosion. It indicated that high level of sustained loading significantly accelerated the corrosion of reinforcements within the RC beams.

Corrosion rate of reinforcement varied slightly when increasing the loading level from 0 to 15% of ultimate loading capacity of the beam. However, a sharp increase in section area loss was observed when increasing loading level from 15% to 30% of ultimate loading capacity. The corrosion rate of reinforcements increased with the sustained loading if the load was below 30% of ultimate loading capacity. However, a further increase of sustained load to 60% of ultimate loading capacity would not continuously increase the corrosion rate of reinforcements. This was probably attributed to the constant width of cracks when increasing the sustained load to 60% of ultimate loading capacity, which limited the ingress of moisture and oxygen to the reinforcements [24]. It indicated that the RC beams subject to a medium level of loadings (e.g.

15% or 30% of ultimate loading capacity) experienced the fastest corrosion of reinforcements as indicated by the largest slopes of corrosion rate lines between 15% and 30% of ultimate loading capacity in Figure 5. It means that the corrosion rate of reinforcements of the beams under loading level from 15% to 30% was higher than other levels. The highest corrosion rate of reinforcements initiated at loading level at 15% of ultimate loading capacity. This loading level could be identified as the critical loading for accelerating the corrosion of reinforcements in beams. In general, corrosion rate of reinforcements within the RC beams would first increase with sustained loading to a medium level, but then decrease with further increase of the sustained loading.

3.2 Cracking behaviour

Cracking behaviour of the RC beams under various loadings and corrosion periods was characterized into three stages, including corrosion without cracking, corrosion of longitudinal reinforcements and leakage of corrosion products. Figure 6 shows a typical example of the beam under 15% of ultimate loading capacity and different corrosion periods. The first stage started from corrosion till the occurrence of cracks on the beams. During this stage, the stress caused by the corrosion of reinforcements was smaller than the tensile strength of concrete, which in turns to no cracking on the beam as shown in Figure 6(a). The corrosion of reinforcements could not be determined by the appearance inspection but by the half-cell potential measurement. This stage was recognized as the best time to conduct proper repair and strengthening for the corroded beams. The second stage of cracking started from the corrosion of longitudinal reinforcements as shown in Figure 6(b). A short horizontal crack was observed along the longitudinal direction of the beam. The corrosion of reinforcements during this stage developed quickly in terms of the length and the width of crack. The width of cracks in this stage was around 0.06 mm. Moreover, the occurrence of cracks provided the channels for oxygen, chloride and water to access the reinforcements inside the beams. Expansion of reinforcements due to the accumulation of corrosion products promoted the formation of the first longitudinal crack along the beam on the fifth day with the accelerated corrosion shown in Figure 6(c). The crack width ranged from 0.15 to 0.3 mm. As seen in Figures 6(c)-(d), the corrosion products leaked out from the beam through the cracks in this stage. The corrosion of reinforcements aggravated as the increase of time in the third stage as show in Figures 6(e)-(f). As more corrosion products leaked out from the beam, there would be a significant degradation in the section area of reinforcement, the yielding strength of reinforcements, and the bonding between reinforcement and concrete, leading to a dramatic decrease in the loading capacity of

beams. As a result, the corroded beams could not sustain the applied load (i.e., 60% of ultimate loading capacity) when the crack width was larger than 2.0 mm.

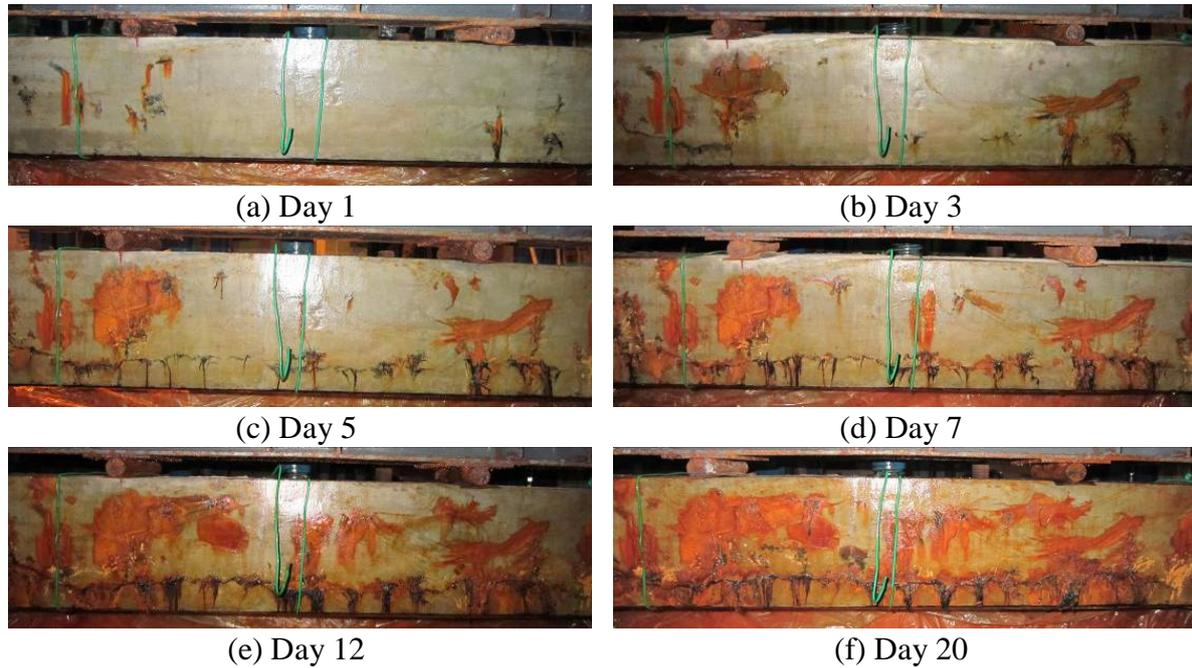


Figure 6. Development of corroded cracks

Figure 7 shows the crack patterns and widths for the beams under different loading levels. It was noted that only the beam exposed to 5 days' accelerated corrosion is shown in Figure 7 for demonstration purpose. It was readily seen that cracks observed along the longitudinal direction on the side and bottom of RC beams. The crack widths on the beams under different loadings varied but within 2.0 mm. It was further found that the crack width did not increase with the sustained loading level. This was mainly due to the leaking out of corrosion products during the corrosion process, which suspended the volumetric expansion of reinforcements for crack propagation. Generally, the cracks on beams under simultaneous loading and corrosion formed and propagated along the longitudinal direction. Increasing the loading level would result in longer longitudinal cracks rather than wider cracks as shown in Figure 7.

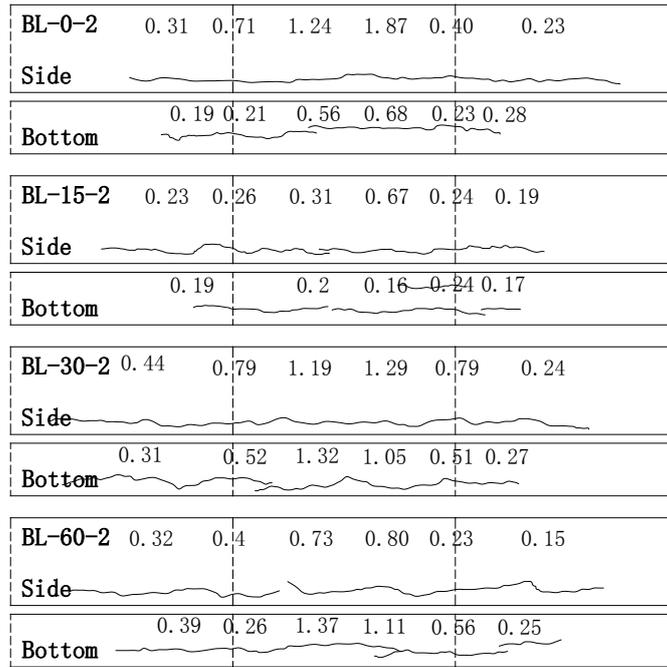


Figure 7. Crack pattern of the corroded beams

Note: the numbers shown in Fig.7 are the crack width, with the unit of mm.

3.3 Structural behaviour of corroded beams

3.3.1 General behaviour and failure modes

Flexural test was performed to examine the structural performance of RC beams after exposing to different levels of corrosion. Three types of failure mode for the corroded beams were identified. In the first type, the corroded beams failed upon the fracture of tensile reinforcements. It occurred to the beams under severe corrosions only (e.g. 29.01% section area loss in reinforcements). After the yielding of the corroded longitudinal reinforcements, the development of flexural cracks in the constant moment zone was negligible as the applied load increased. Once the applied load reached around 90% of ultimate loading capacity, several main cracks formed quickly followed by the sudden fracture of longitudinal reinforcements. The specimen failed in a brittle manner and possessed the lowest loading capacity, e.g. for specimen BL-60-3 as shown in Figure 8(a). In the second type, the RC beam failed with concrete crushing in the compression zone after the yielding of longitudinal reinforcements, which commonly happened to the beams with limited corrosion. The main cracks were observed in the constant moment zone of the beam after the yielding of longitudinal reinforcements. As the applied load increased, cracks developed in both length and width followed by the crushing of concrete in compression zone as shown in Figure 8(b). The third failure mode was similar to the second type. Although the RC beam had severely corroded

reinforcements, it failed with the concrete crushing in the compression zone after longitudinal reinforcements yielded. Different from the first failure mode, cracks in the beam grew gradually until concrete crushed in the compression zone as shown in Figure 8(c). Generally, failure mode of the corroded RC beams would not be altered when they were under low to medium corrosion. Beam with severe corrosion would fail in a brittle manner due to the dramatic loss of reinforcement area.

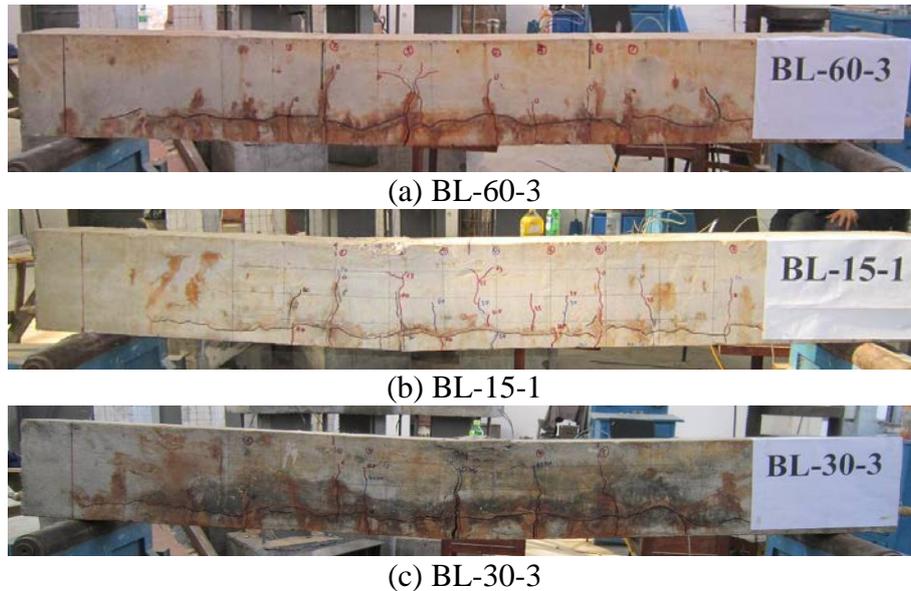


Figure 8. Typical failure modes of corroded beams

3.3.2 Load-displacement behaviour

The load-displacement relationships at the mid-span of the corroded beams are shown in Figure 9. The control beam without the sustained loading and the corrosion exposure (i.e. specimen BL-0-0) is also included in Figure 9 for comparison. Compared to the control beam, structural behaviour of the corroded beams degraded in terms of ultimate loading capacity and deformation ability. This depends on the corrosion level of reinforcements. Increasing sustained loading and/or corrosion period would decrease ultimate loading capacity and deformation of beams. The beams subject to a corrosion only performed similar to the control beam as seen in Figure 9(a), particularly for the beam experienced a short corrosion period (e.g. specimen BL-0-1). As seen in Figures 9 (b)-(d), the ultimate loading capacity and the deformation ability of beams would be further reduced as the sustained loading and corrosion period increased. Apart from the decrease in ultimate loading capacity, deformation ability decreased gradually for the beams under each loading level. As the RC beam subject to 60% of ultimate loading capacity and 20 days' corrosion period underwent the brittle failure, the failure load and deformation were only 25% and 13.2% as that of the control beam, respectively.

There was a joint effect of sustained loading and corrosion period on the ultimate loading capacity and the deformation ability of RC beams.

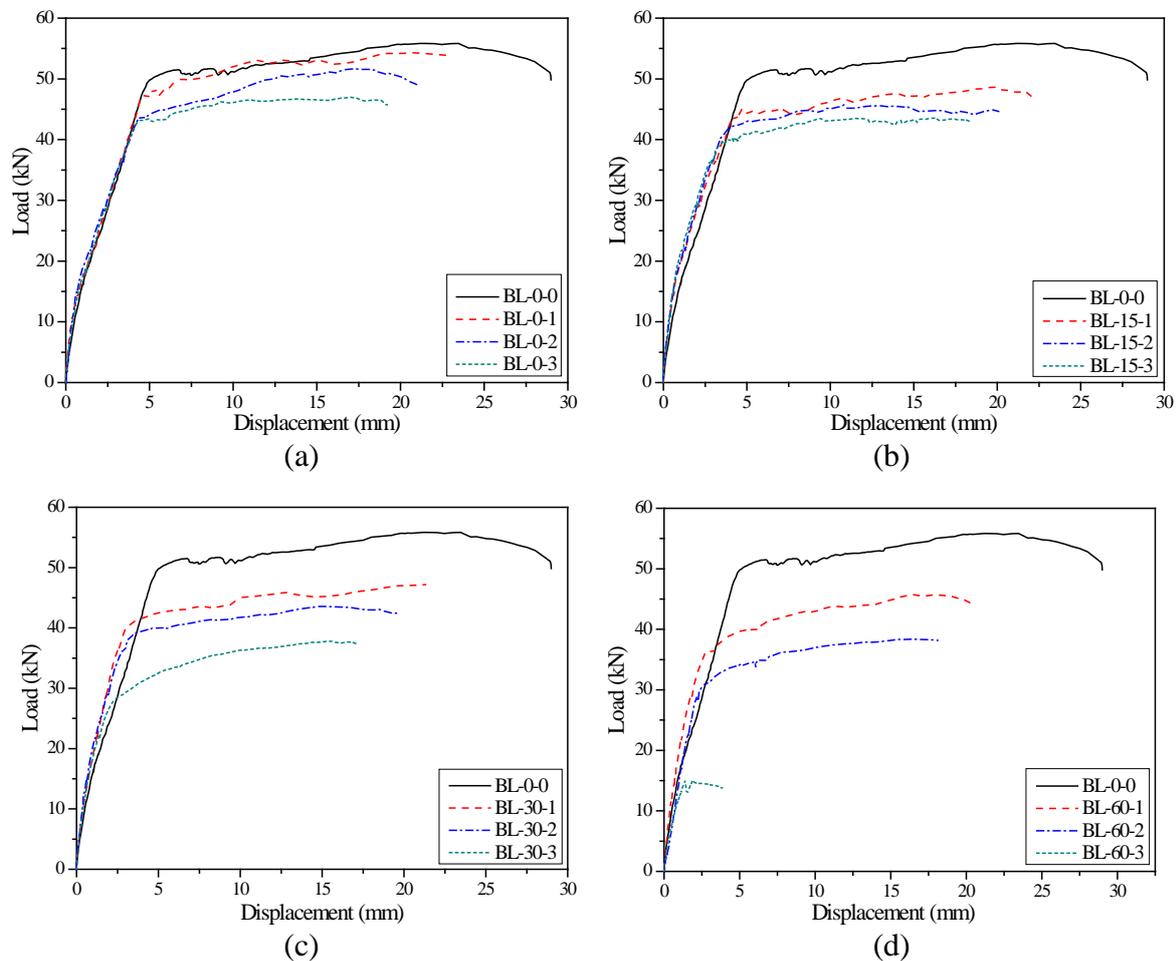


Figure 9. Load-displacement relationship at mid-span of the corroded beams

Figure 10 shows the reduction in the ultimate loading capacity of corroded beams. Reduction ratio of the ultimate loading capacity increased with both sustained loading and corrosion periods. For the beams subject to a constant corrosion period, reduction in ultimate loading capacity varied slightly for short corrosion periods (e.g. 5 or 10 days' accelerated corrosion) as the sustained loading increased. When the corrosion period increased to 20 days, ultimate loading capacity of the corroded beam dramatically decreased as the sustained loading increased. For instance, loading reduction ratio was increased from 30% for beams under 30% of ultimate loading capacity to 70% for that under 60% of ultimate loading capacity. Loading reduction ratio was relatively small for those under low sustained loading level despite the increase of corrosion period. When subject to the higher sustained loading level at 60%, loading reduction was more significant as the corrosion exposure increased. Therefore, deterioration of

the ultimate loading capacity of corroded beam was more significant for those under higher level of sustained loading.

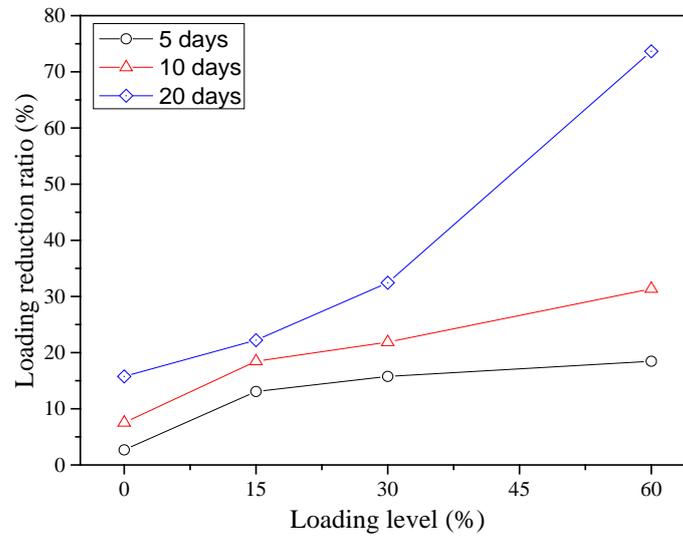


Figure 10. Loading capacity reduction ratio of beams subjected to different levels of loads and corrosions

Flexural stiffness of the corroded beams was examined based on the slope of initial load-displacement relationship shown in Figure 9. Generally, flexural stiffness was enhanced for the corroded beams subject to different levels of loading. The corroded beams without the sustained loading possessed the similar flexural stiffness as the control beam. It indicated that expansion due to the corrosion of reinforcements at this level was not sufficient to change the flexural stiffness of beams. With further increase of corrosion level due to the sustained loading and the corrosion period, flexural stiffness of specimens considerably increased, e.g. in series BL-15 and BL-30. This was mainly attributed to the enhanced bond between the concrete and the corroded reinforcements at the initial stage of corrosion [13]. However, the high level of corrosion would finally reduce the flexural stiffness of beams. It was found that specimen BL-60-2 under 60% of ultimate loading capacity and 10 days' accelerated corrosion exhibited similar flexural stiffness as that of the control beam. This phenomenon was mainly attributed to the cracking of the concrete cover [13], which reduced the moment of inertia of the beam section. To maintain the flexural stiffness of the corroded beams, the critical corrosion level for reinforcements was identified at 22.86% section area loss. Further increasing corrosion level would decrease the flexural stiffness of the beam. This critical corrosion level was slightly higher than 11.7% in the study of Almusallam et al. [14].

4 Conclusions

An experimental study was conducted to investigate the behaviour of RC beams under simultaneous sustained loading and reinforcement corrosion. Afterwards, flexural behaviour of the corroded RC beams was studied. The joint effects of sustained loading and corrosion periods on beam's ultimate loading capacity and deformation were studied. The test results and discussion lead to the following conclusions:

- (1) Corrosion level of reinforcements should be estimated based on the section area loss rather than the mass loss, especially for those with rust pit. Increasing corrosion period and loading level aggregates the corrosion level of reinforcements within beams. Particularly, loading level higher than 15% of ultimate loading capacity significantly accelerates the corrosion of reinforcements. Reinforcements in the beams under loading level of 15% to 30% exhibit the highest corrosion rate.
- (2) Propagation of cracks on the corroded beams are not proportional to the corrosion levels caused by the sustained loading and the corrosion period. Increasing sustained loading would not increase the crack width caused by the reinforcement corrosion, but increase the length of longitudinal cracks.
- (3) The corroded beams mainly fail with the crushing of concrete after the yielding of reinforcements unless severe corrosion of reinforcements occurs. For instance, the corroded beam with 29.01% section area loss in reinforcements fails in the brittle manner.
- (4) Increasing the sustained loading and/or the corrosion period decreases the ultimate loading capacity and deformation ability of the corroded RC beam. Loading reduction ratio of the corroded beams ranges from 10% to 30% when the beams fail with the yielding of longitudinal reinforcements. The beam failed in brittle manner possess 25% of loading capacity of the control beam.
- (5) Flexural stiffness of the corroded beam is similar to that of control specimen while corrosion level is not high. Increasing the corrosion level of reinforcements initially enhances the flexural stiffness and ultimately decreases it for beams under severe corrosion.

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References

- [1] Roberge PR. Handbook of corrosion engineering. New York: McGraw-Hill; 1999.
- [2] X.H. Wang, X.H. Gao, B. Li, B.R. Deng, Effect of bond and corrosion within partial length on shear behaviour and local capacity of RC beam. *Constr Build Mater* 25(4) (2011) 1812–1823.
- [3] C.Q. Fu, N.G. Jin, H.L. Ye, X.Y. Jin, W. Dai, Corrosion characteristics of a 4-year naturally corroded reinforced concrete beam with load-induced transverse cracks, *Corros Sci* 117 (2017) 11-23.
- [4] W.J. Zhu, R. Francois, C. S. Poon, J. G. Dai, Influences of corrosion degree and corrosion morphology on the ductility of steel reinforcement, *Constr Build Mater* 148 (2017) 297-306.
- [5] Y.F. Ma, J.R. Zhang, L. Wang, Y.M. Liu, Probabilistic prediction with Bayesian updating for strength degradation of RC bridge beams, *Struct Saf* 44 (2013) 102-109.
- [6] A. Duan, J.G. Dai, W.L. Jin, Probabilistic Approach for Durability Design of Concrete Structures in Marine Environments, *J Mater Civil Eng* 27(2) (2015).
- [7] Y.F. Ma, L. Wang, J.R. Zhang, Y.B. Xiang, T.S. Peng, Y.M. Liu, Hybrid Uncertainty Quantification for Probabilistic Corrosion Damage Prediction for Aging RC Bridges, *J Mater Civil Eng* 27(4) (2015).
- [8] H.L. Wang, J.G. Dai, X.Y. Sun, X.L. Zhang, Characteristics of concrete cracks and their influence on chloride penetration, *Constr Build Mater* 107 (2016) 216-225.
- [9] Y.F. Ma, Z.Z. Guo, L. Wang, J.R. Zhang, Experimental investigation of corrosion effect on bond behavior between reinforcing bar and concrete, *Constr Build Mater* 152 (2017) 240-249.
- [10] G. Malumbela, P. Moyo, M. Alexander, Behaviour of RC beams corroded under sustained service loads, *Constr Build Mater* 23(11) (2009) 3346-3351.

- [11] L. Hariche, Y. Ballim, M. Bouhicha, S. Kenai, Effects of reinforcement configuration and sustained load on the behaviour of reinforced concrete beams affected by reinforcing steel corrosion, *Cement Concrete Comp* 34(10) (2012) 1202-1209.
- [12] W.J. Zhu, R. Francois, D. Coronelli, D. Cleland, Effect of corrosion of reinforcement on the mechanical behaviour of highly corroded RC beams, *Eng Struct* 56 (2013) 544-554.
- [13] E.P. Kearsley, A. Joyce, Effect of corrosion products on bond strength and flexural behaviour of reinforced concrete slabs, *J S Afr Inst Civ Eng* 56(2) (2014) 21-29.
- [14] A.A. Almusallam, A.S. AlGahtani, A.R. Aziz, Rasheeduzzafar, Effect of reinforcement corrosion on bond strength, *Constr Build Mater* 10(2) (1996) 123-129.
- [15] G. Malumbela, M. Alexander, P. Moyo, Steel corrosion on RC structures under sustained service loads - A critical review, *Eng Struct* 31(11) (2009) 2518-2525.
- [16] S. Yoon, K.J. Wang, W.J. Weiss, S.P. Shah, Interaction between loading, corrosion, and serviceability of reinforced concrete, *Aci Mater J* 97(6) (2000) 637-644.
- [17] Y.P. Liu, R.E. Weyers, Modeling the time-to-corrosion cracking in chloride contaminated reinforced concrete structures, *Aci Mater J* 95(6) (1998) 675-681.
- [18] R.E. Weyers, Service life model for concrete structures in chloride laden environments, *Aci Mater J* 95(4) (1998) 445-453.
- [19] W.J. Zhu, R. Francois, Y. Liu, Propagation of corrosion and corrosion patterns of bars embedded in RC beams stored in chloride environment for various periods, *Constr Build Mater* 145 (2017) 147-156.
- [20] Y.G. Du, M. Cullen, C.K. Li, Structural effects of simultaneous loading and reinforcement corrosion on performance of concrete beams, *Constr Build Mater* 39 (2013) 148-152.
- [21] S.P. Yin, M.W. Na, Y.L. Yu, J. Wu, Research on the flexural performance of RC beams strengthened with TRC under the coupling action of load and marine environment, *Constr Build Mater* 132 (2017) 251-261.
- [22] JTJ270-98 (1998) Testing Code of Concrete for Port and Waterway Engineering, Tech. Rep., China Communications Press, Beijing, China, 1998.
- [23] X.M. Shi, N. Xie, K. Fortune, J. Gong, Durability of steel reinforced concrete in chloride environments: An overview, *Constr Build Mater* 30 (2012) 125-138.

[24]C. Arya, F.K. OforiDarko, Influence of crack frequency on reinforcement corrosion in concrete, Cement Concrete Res 26(3) (1996) 345-353.