Stress-Strain Response of Corroded Reinforcing Bars under Monotonic and Cyclic Loading

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SUMMARY
Corrosion of embedded reinforcement is the most common cause of deterioration of reinforced concrete (RC) structures and a major economic cost for maintenance of national infrastructures. This will affect the residual capacity of the RC structures and therefore is of concern to those who are in charge with ensuring safe operation of concrete structures. In addition, if the structure is located in an earthquake prone region, in the seismic assessment and evaluation of the structure consideration needs to be given to ductility of reinforcement in tension, and it's buckling response in compression. This paper reports results from experimental investigations on the behaviour of corroded reinforcing bars in tension, compression and under cyclic loading (including buckling). The test results show that corrosion affects the response of reinforcing steel in tension. Pitting corrosion also affects the buckling load of reinforcing bars under monotonic compression loading and changes the behaviour of corroded bars under cyclic loading.

Keywords: Reinforcing steel; Corrosion; Inelastic buckling; Postbuckling; Cyclic Behaviour

1. INTRODUCTION

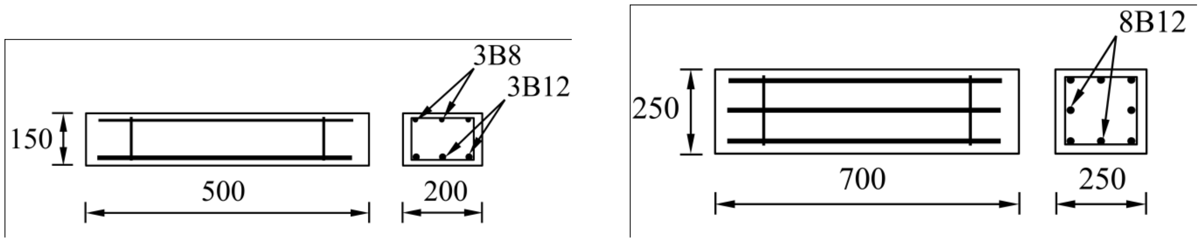
Corrosion of embedded reinforcement is the most common cause of deterioration of reinforced concrete (RC) structures and a major economic cost for maintenance of national infrastructures. This will affect the residual capacity of the RC structures and therefore is of concern to those who are in charge with ensuring safe operation of concrete structures. In addition, if the structure is located in an earthquake prone region, in the seismic assessment and evaluation of the structure consideration needs to be given to ductility of reinforcement in tension, and it's buckling response in compression. Currently there is a gap in our knowledge that how corrosion affects the non-linear behaviour of RC structures subject to seismic loading. Furthermore, in recently developed methods of nonlinear analysis of RC structures subject to seismic loading, a lot of attention has been given to the fibre element technique where the member cross section is discretized into a number of steel and concrete fibres at the selected integration points. In this method the material nonlinearity is modelled using uniaxial constitutive material models of steel and concrete. Various researchers have made efforts to improve the accuracy of this method by developing nonlinear material models. Accordingly, in order to use this method for the seismic analysis of RC structures suffering from corrosion of reinforcement we need to understand how corrosion of reinforcement changes the constitutive behaviour of reinforcing steel under monotonic and cyclic loading.

There is a large amount of literature on the corrosion of reinforcement which is mainly focused on corrosion induced cover cracking, corrosion prevention and repair of corrosion damaged structures. In the recent years researchers have studied the effect of corrosion on residual capacity and mechanical properties of reinforcing bars (Almusallam 2001, Du et al. 2005, Cairns et al 2005, Apostolopoulos 2007). In most previous studies researchers have used accelerated corrosion techniques on bare bars and bars embedded in concrete to simulate the corrosion procedure in the laboratory environment (Almusallam 2001, Du et al. 2005) as well as taking reinforcing bar samples from corroded bridges (Palssom and Mirza 2002). A key aspect that almost all these researchers agree on is that the corrosion does not change the mechanical properties (e.g. modulus of elasticity) of reinforcing steel; however unsymmetrical pitting corrosion along the bar does change the load-extension response of reinforcement in tension test.

Previous studies have focused mainly on the effect of corrosion on the residual capacity and ductility of reinforcement in tension and there have been no studies on the effect of corrosion on the inelastic buckling of bars in compression. Buckling of reinforcement is a very important limit state (performance criteria) in seismic assessment of RC structures in earthquake regions. Based on the recent experimental studies on the cyclic behaviour of corroded RC columns and beams corrosion has a significant effect on the buckling behaviour of reinforcing bars and changes the global response of RC elements (Ou et al. 2011, and Ma et al. 2012). Accordingly, this paper reports results from experimental investigations on the behaviour of corroded reinforcing bars in tension, compression and under cyclic loading

2. ACCELERATED CORROSION PROCEDURE

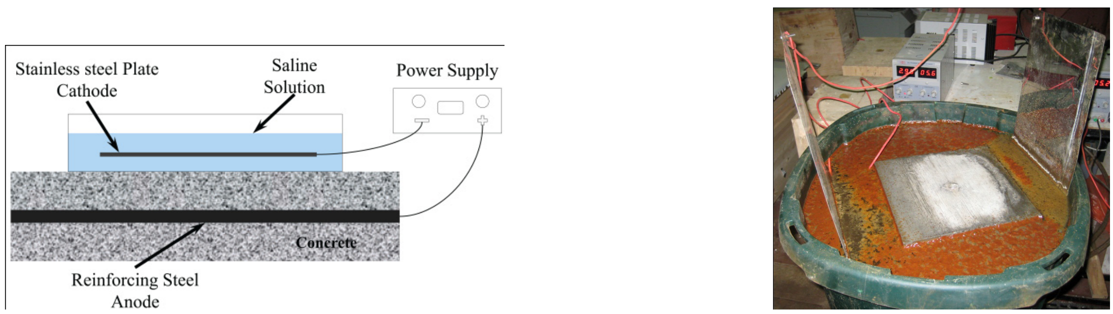
A total of ten reinforced concrete specimens were cast. Two specimens dimensioned $200 \times 150 \times$ 500mm designed for tension tests incorporated 8mm and 12mm diameter reinforcing bars and eight specimens dimensioned $250 \times 250 \times 700$mm designed for buckling and cyclic tests incorporated 12mm diameter reinforcing bars as shown in Fig. 1. The concrete mix was designed to have a mean compressive strength of 30MPa at 28 days with a maximum aggregate size of 12mm. The specimens were cast with nominal cover of 25mm.



(a) **(b)**

Figure 1. Corrosion Specimens (a) Tension Specimens (b) Compression Specimens

An accelerated corrosion procedure is used to simulate the corrosion in the laboratory. The concept of using external currents is very simple and consists of forming an electrochemical circuit using an external power supply. The reinforcing bars act as an anode in the cell and an external material acts as the cathode as shown in Fig. 2.



(a) **(b)**

Figure 2. Corrosion Procedure: (a) Schematic Illustration of Accelerated Corrosion Process, and (b) Accelerated Corrosion Test Setup in the Laboratory

The time of desired corrosion level is estimated using the well known Faraday's 2nd Law of Electrolysis. The detailed discussion of accelerated corrosion procedure is reported elsewhere (Kashani et al. 2012a). Assuming a uniform mass loss, the mean reduced diameter of reinforcement may be estimated using Eq. (1) which represents an average residual diameter of reinforcement relative to the mass loss:

$$D_{Corr} = D_0\sqrt{1-(0.01\psi)} \quad \textbf{(1)}$$

where, D_0 is the initial diameter of uncorroded bar and ψ is the measured mass loss in percentage based on the following equation:

$$\psi = 100\left(\frac{m_0 - m}{m_0}\right) \quad \textbf{(2)}$$

where, m_0 is the mass per unit length of the original steel bar, m is the final mass per unit length of the original steel bar after removal of the corrosion products.

4. UNIAXIAL TENSION TEST OF REINFORCING BARS

For tension testing of bars a universal testing machine with 600KN capacity and V-groove jaws with course tooth pattern was used. The speed of testing was set to 2mm/min based on the ASTM E8. A 100mm gauge length extensometer with maximum stroke of 25mm used to measure the bar extension to failure.

4.1. Observed Stress-Strain Response in Tension

Mechanical properties of the original reinforcing bars calculated using the result of tension tests on uncorroded bars. A summary of properties of the original reinforcement are shown in Table 1.

Table 1 Mechanical Properties of Uncorroded Reinforcement

Reinforcement Type		8 mm (B8)	12mm (B12)
Yield Strength	f_y (MPa)	510	520
Modulus of Elasticity	E_s (Mpa)	194881	212099
Yield Strain	$\varepsilon_y = f_y/E_s$	0.00261	0.00247
Ultimate Strength	f_u (MPa)	645	616
Ultimate Strain	ε_u	0.04660	0.06033
Strain Ratio	$\varepsilon_u/\varepsilon_y$	17.85	24.42
Strength Ratio	f_u/f_y	1.27	1.18
Total Elongation at Maximum Force	λ (%)	4.66%	6.03%
Unit Mass	m (kg/m)	0.396	0.874

Fig. 3 shows the representative observed mean stress-strain response for the 8mm diameter bars tested in this experiment. In addition the boundaries of minimum code requirements (BS 4449) are also shown in the graph which indicates the significance of corrosion on the residual capacity and ductility of corroded bars. In many cases the rebar fracture occurred within the gauged section but because the point of fracture depends on the pitting corrosion the fracture sometimes occurred outside the gauge, as indicated in the Fig. 4. This issue is also reported by other researchers who previously did tension tests on corroded bars (Du et al. 2005b, Palssom and Mirza 2002).
The results show that corrosion level up to about 15% doesn't have significant effect on stress-strain response. However, once the corrosion level is greater than 15% a significant drop occurs in plastic

deformation and residual capacity of the corroded bars. This is similar to the results of previous studies which used British manufactured reinforcement (Du et al. 2005).

However these results contrast with results reported by researchers from other countries. Andrade et al. (1991) reported that corrosion doesn't have significant effect on the stress-strain curve of bars in tension. In contrast Zhang et al (1995) reported that up to 21% corrosion shortened the yield plateau on the load–extension response of corroded reinforcement. In another study Almusallam (2001) reported that reinforcing steel bars with 12.6% or more corrosion indicated a brittle behaviour. They also reported that the elongation limit of bars with more than 12% corrosion was less than the 9% specified by ASTM A 615. Palssom and Mirza (2002) reported that due to non-uniform loss in cross section area, a 20% difference between greatest and smallest cross section area along the bar can cause 50% reduction in ultimate strain at failure. These differences may be related to the differences in steel grades used in each test.

In all of the previous studies most researchers agree that if the corrosion induced mass loss was uniform along the length of corroded bars it wouldn't have a significant effect on the stress-strain response in tension. Therefore, the change in the stress-strain response is caused by non-uniform distribution of pits along the length of corroded bars (Du et al. 2005). The reason is that the corroded reinforcement starts yielding at the location of the smallest cross section while other parts are still elastic. Once the next weak section along the bar starts yielding the first yielded section is already in the strain hardening region. This will result in a non-uniform stiffness distribution along the bar and subsequently affect the yield and ultimate strength and ductility of corroded bars.

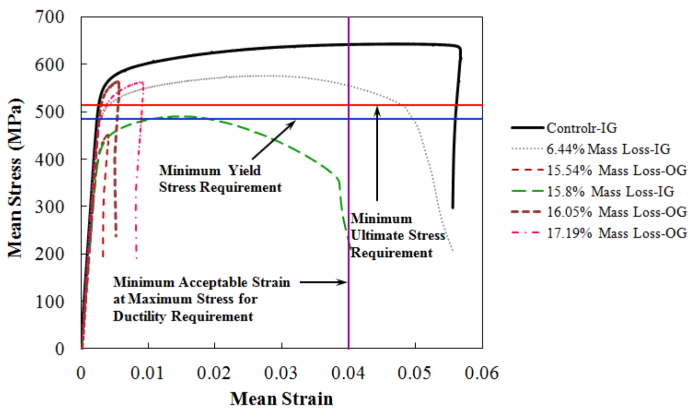


Figure 3. Mean Stress-Strain Curves of Tension Tests for the 8mm Diameter Bars (IG = Failure Inside the Gauge, OG = Failure Outside the Gauge)

5. MONOTONIC COMPRESSION TEST OF CORRODED REINFORCING BARS

A total of 57 monotonic compression tests were carried out on corroded bars with different effective lengths and mass losses. The buckling length of bars considered in the experiment chose based on the ratio of spacing of horizontal ties (L) in the common construction of RC columns to bar diameter (D) known as L/D ratio. The L/D ratios tested in the monotonic experiment are 5, 8, 10, 15 and 20. A 250KN universal testing machine with hydraulic grips was used in compression and cyclic tests of reinforcing bars. The machine is instrumented by a built in LVDT to measure the grips displacement. A 50mm extensometer with maximum stroke of ±5mm was used to measure the average axial strain of reinforcement in the linear range. An additional external LVDT with maximum stroke of ±10mm was connected to the grips to measure the average displacement over the entire length of the bar as shown in Fig. 4. Before the main experiment some sample tests carried out on reinforcement with different diameter and lengths to make sure that there will be no slip within the grips during the test. The data readings from the external LVDT, built in LVDT and extensometer of the sample tests were compared. It was found that no slip occurred during the sample tests; therefore the data reading of the external LVDT has been used throughout this paper which provides an average strain over the entire length of the bar.

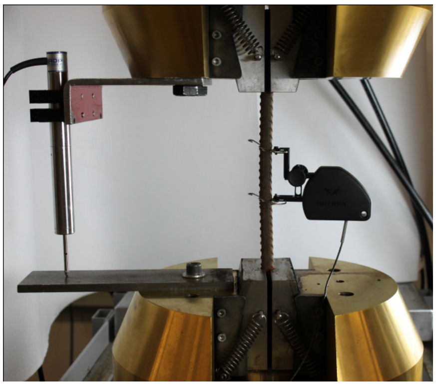


Figure 4. Buckling Test Setup

5.1. Observed Stress-Strain Response in Compression

The detailed results of the effect corrosion on buckling mechanism and buckling load of corroded bars are reported in Kashani et al. (2012a) and a summary of observed stress-strain responses are reported here.

As expected the bars with L/D ratio of 5 were not prone to buckling and generally had a stable behaviour under compression loading. The observed stress-strain response was almost identical to the tension response. Only some of the heavily corroded bars or bars with highly localised pits showed a small buckling which resulted in a slight change in post-yield behaviour. Figure 5 shows the observed stress-strain curve of bars with L/D=5. It should be noted that calculated stresses are based on the average reduced cross section and is called Mean Stress. The strain is the average strain over the entire length of bars and is called Mean Strain.

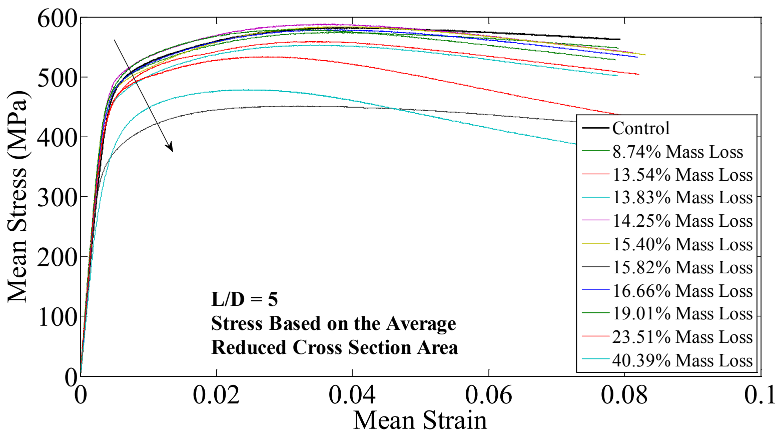
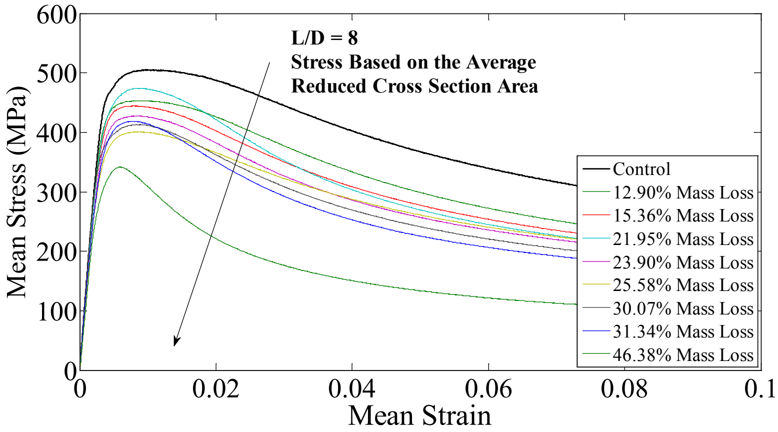


Figure 5 Observed Stress-Strain Response of Corroded Reinforcement in Compression with L/D=5

Fig. 6 shows the observed stress-strain response of bars with L/D = 8 and 10. As it is shown in Fig. 6, three types of behaviour observed. Those bars with highly localised pitting corrosion showed a smooth transition from linear elastic to nonlinear plastic which took longer compare to the uncorroded bars and followed by post-yield softening. This behaviour is due to the premature yielding and squashing of the weakest section under compression before buckling starts. The post-buckling softening of these bars showed generally similar trend to the original uncorroded bar with a significant reduction in the buckling load. Those bars with more uniformly distributed corrosion with relatively lower mass loss showed a similar behaviour to the original uncorroded bars with a small reduction in buckling stress. However, the bars with high percentage of mass loss and relatively uniformly distributed pits showed a quicker transition from linear elastic to the nonlinear plastic. These bars had a big reduction in buckling stress and had a steeper post-yield softening branch. This indicates that more uniform corrosion is resulted in a change in the overall slenderness ratio of corroded bars.

The observed stress-strain response of bars with L/D=15 and 20 are shown in Fig. 7. The uncorroded control specimens of this group of bars also showed relatively stable behaviour up to the stress close to yield stress with a sharp and steep post-yield softening branch.

The corroded bars with L/D=15 are generally showed a quick and smooth transition from linear elastic to the post-yield softening branch compare to shorter bars. The bars with L/D=20 showed a very sharp transition from linear elastic at the point of buckling stress which followed by a very steep post-yield softening branch. This is primarily due to effect of corrosion on slenderness ratio of corroded bars. In addition, corrosion induced imperfection in the bar has more significant effect in bars with a longer length.



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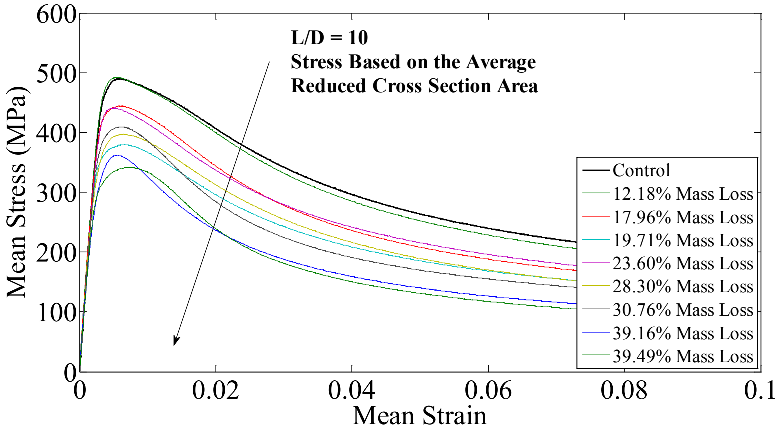
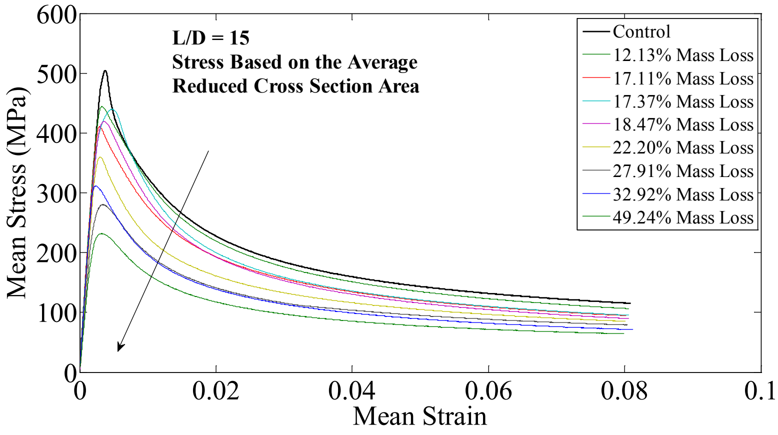


(b)

Figure 6 Observed Stress-Strain Response of Corroded Reinforcement in Compression with L/D=8 and 10



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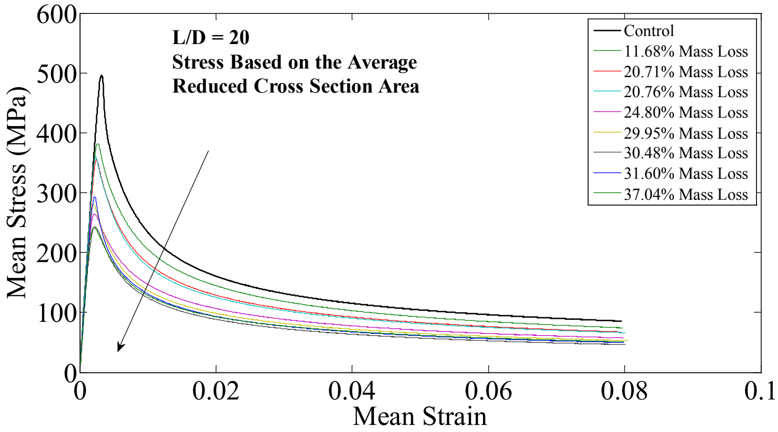


(b)

Figure 7 Observed Stress-Strain Response of Corroded Reinforcement in Compression with L/D=15 and 20

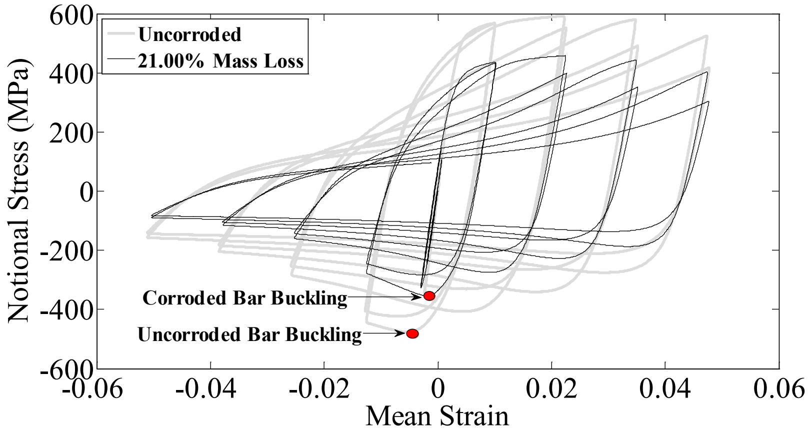
4. CYCLIC TEST OF CORRODED REINFORCING BARS

A total of 40 cyclic tests were carried out on corroded bars with different effective lengths. The loading protocol adapted was a two cycle reversed symmetrical strain history. The slenderness ratios this experiment were L/D=5, 10, and 15. Three control (uncorroded) specimens were tested for each slenderness ratio. The detailed discussion of the results of cyclic test are available in Kashani et al. (2012b) and only a summary of observed hysteresis responses are reported here.

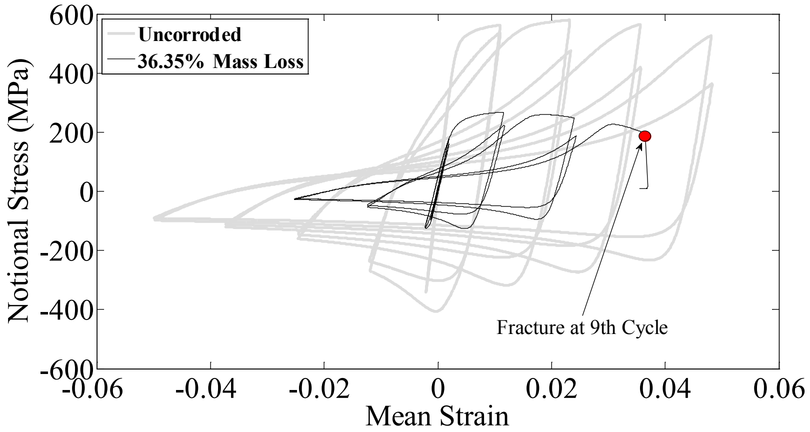
5.1. Observed Cyclic Stress-Strain Response

The slenderness ratio has a significant effect on the hysteresis response of reinforcing bars. In general corrosion resulted in a significant reduction in the area of hysteresis curves, energy dissipation and premature fracture of bars in tension.

The uncorroded bars with L/D = 5 had a symmetric hysteresis response with kinematic hardening. As the level of corrosion increased the hysteresis response of this group of bars a pinching effect in the stress-strain graph was seen. In other words, corrosion increases the slenderness ratio of the corroded bars. The observed results showed that localised pitting corrosion has a significant effect on premature fracture of bars in tension and reduction of hysteresis area. This effect was more significant in the group of bars with bigger slenderness ratios (L/D ≥ 10). However, in some cases more uniform corrosion did not cause the fracture of bars in tension but had a significant effect on the shape of hysteresis cycles due to changing the slenderness ratio of bars and buckling effect. This complexity in the results is due to the random distribution of corrosion along the bars. Fig. 8 shows a representative observed hysteresis responses of corroded bars with L/D = 10 and 15 with different failure modes. It should be pointed out that the calculated stress in Fig. 8 is based on the original uncorroded cross section of bars, therefore it is called *Notional Stress*.



(a)



(b)

Figure 8 Observed Cyclic Stress-Strain Response of Corroded Reinforcement with L/D=10 and 15: (a) Buckling of Corroded bar (b) Fracture of Corroded Bar in Tension after Buckling in Compression

6. CONLUSION

Corrosion has a significant effect on buckling mechanism of corroded bars. The observed buckling modes showed that the buckling mechanism of corroded bars is a function of mass loss due to corrosion and distribution of pits along the buckling length. It was found that the distribution of pits along the length of corroded bars is the most important parameter affecting the stress-strain response in both tension and compression. This is more critical in compression where the load eccentricity and imperfection have a significant influence on the buckling load of bars.

Experimental results of cyclic tests showed that corroded bars with pitting corrosion will fracture earlier in tension after buckling in compression. This is due to the combined effect of low-cycle fatigue and premature yielding of bars at pitting locations. Furthermore, based on the results of the recent experimental studies on the cyclic behaviour of corroded beams and columns (Ou et al. 2011, and Ma et al. 2012) there are evidence that the buckling and/or fracture of corroded bars had a significant effect on the global response, plastic rotation capacity and plastic hinging mechanisms of the corroded RC elements. As a result in the seismic assessment and evaluation of existing corroded structures consideration needs to be given to the buckling of bars even if the structure is originally designed to have sufficient level of confinement and anti-buckling reinforcement.

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