SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

TENSILE AND CYCLIC BEHAVIOR OF CORRODED 10MM DEFORMED STEEL REINFORCEMENT-PRELIMINARY RESULTS

Kaveh ANDISHEH[1], Allan SCOTT[2] and Alessandro PALERMO[3]

ABSTRACT

In recent years, growing attention has been given to the effects of corrosion on reinforced concrete structures. Marine environment and de-icing salt are two main phenomena that cause chloride-induced corrosion. Basically, there are two types of steel reinforcement corrosion called uniform and pitting corrosion. In real corroded reinforced concrete (RC) structures, a mix of the uniform and pitting corrosion always takes place. Pitting corrosion critically degrades RC structure. Corrosion decreases the mechanical characteristics of steel reinforcing.

Corrosion changes mechanical properties of steel reinforcement including stress, force and strain in yield and ultimate point. Changing strain has an important impact on seismic behaviour of structures.

In this study, mechanical properties of steel reinforcement have been estimated through experimental monotonic tensile and cyclic tests to take into consideration of eccentricity caused by pitting corrosion.

To meet this aim, pitting corrosion has been simulated by machinery operation for 10mm deformed steel reinforcements. Reduced mechanical properties of the reinforcing steel in terms of ultimate stress and strength and yield stress and strength have been estimated from monotonic tensile tests. Low cycle fatigue behaviour of corroded the corroded steel reinforcement has been investigated through cyclic test, in order to simulate the effect of earthquakes on dynamic behaviour of steel reinforcement. The results can be used to develop deterioration models for corroded RC structures.

The relevant reduced mechanical properties of reinforcing steel based on the experimental results, and have been used for section-level analysis of two reinforced concrete bridge piers. The results of section-level analysis show degradation in moment-curvature and corresponding ductility of the corroded RC bridge piers due to pitting corrosion.

INTRODUCTION

In recent years, growing attention has been given to the effects of corrosion on reinforced concrete structures. According to National Association of Corrosion Engineers (NACE), the direct annual cost of corrosion of infrastructure was more than $22 billion in the US in 2002 (Virmani 2002). American Society of Civil Engineers (ASCE) has reported that the US should invest $2.2 trillion over

---

[1] PhD candidate, University of Canterbury, Christchurch, New Zealand, kaveh.andisheh@pg.canterbury.ac.nz, kavehandisheh@gmail.com

[2] Senior Lecturer, University of Canterbury, Christchurch, New Zealand, allan.scott@canterbury.ac.nz

[3] Senior Lecturer, University of Canterbury, Christchurch, New Zealand, alessandro.palermo@canterbury.ac.nz

the next five years to repair and upgrade more than 300,000 bridges in the US that are approaching the end of their design life (Hansen 2009).

Corrosion of steel embedded in concrete is an electrochemical process. A number of anodes and cathodes are formed on the surface of steel reinforcement, which are connected together electrically through the body of the steel. The electrochemical reaction takes place between each couple of anode and cathode. The process is initiated when aggressive ions such as chloride penetrate the concrete cover and reach the steel reinforcement. Once the corrosion process commences, not only does cross sectional area of the corroding reinforcing steel decrease but also corrosion by-products such as rust are formed. The volume of rust is 2-4 times greater than that of the steel. Therefore, formation of corrosion by-product causes volume expansion, developing tensile stresses in concrete, which ultimately results in propagating cracks and leads to spalling of the cover concrete and softening of the concrete core (Vu and Stewart 2000, Coronelli and Gambarova 2004). Moreover, the cohesive force between steel and concrete decreases (Stanish, Hooton et al. 1999, Fang, Lundgren et al. 2006, Kivell 2012). Figure 1 shows the electro-chemical process of corrosion and its main effects on deterioration of RC members.

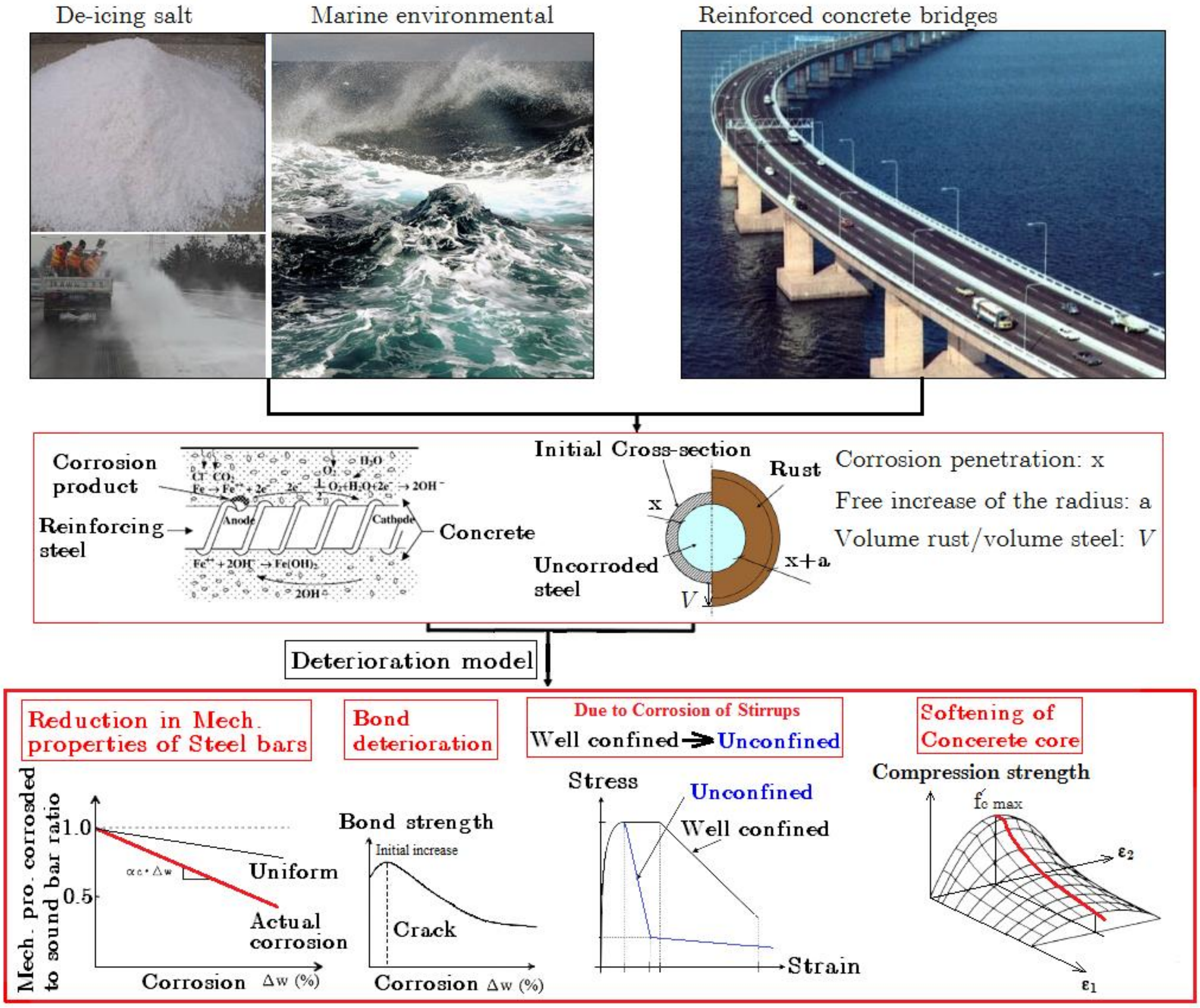

Figure 1: Electrochemical process of corrosion and its effect on RC members

There are two corrosion configuration named general corrosion and pitting (or localized) corrosion. Figure 2 shows configuration of pitting and general corrosion simulated by accelerated corrosion technique. Figure 3 shows corroded bridge piers

Figure 2: Corrosion configuration: Left: general corrosion; Right: Pitting corrosion

Figure 3: Corroded bridge piers (Akiyama and Frangopol 2013, Ou, Fan et al. 2013)

According to the literature, there are a number of studies on general corrosion, while few investigations have been carried out on pitting corrosion. Pitting corrosion significantly decreases cross-section area of steel bars and affects the service life of RC structures. It is worth to note that, diameter size of bar affects pit depth. Increasing diameter of reinforcing steel raises pit depth (Stewart and Al-Harthy 2008, Stewart 2009). İt has been shown that pitting corrosion not only decreases cross-section area of steel reinforcement but also does cause reduction in effective mechanical properties of steel reinforcement (Andisheh et al, 2014).

Three different techniques are utilized to corrode steel reinforcement including machined, accelerated and marine environment (natural) corrosion. Machined and accelerated corrosion techniques are always artificial methods to simulate marine environment corrosion because natural corrosion is a long-term process that is not feasible to be used for research programs. Past studies, to simplify the problem, have theoretically modelled pitting corrosion as a part of sphere that is very similar to realistic pitting corrosion (Stewart 2004). Figure 4 shows test setup of these accelerated methods. It should be stated that with exception of machinery operation, simulation of only pitting corrosion is not possible using accelerated corrosion, because they lead to a combination of both general and pitting corrosion.

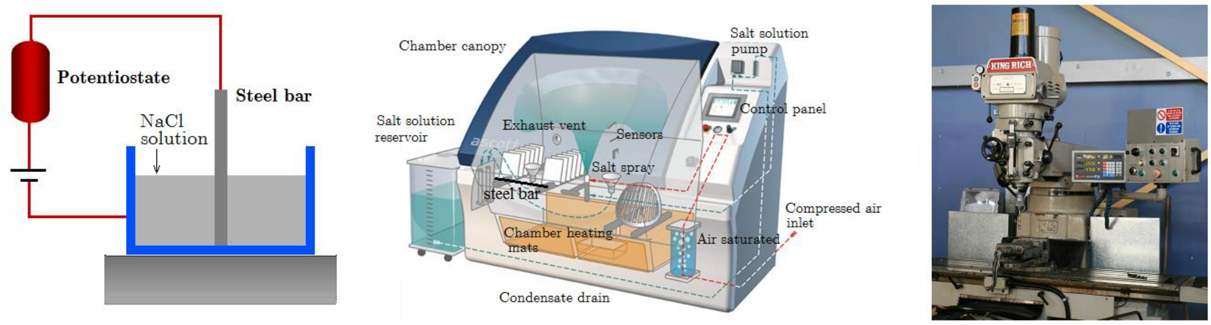

Figure 4: Accelerated corrosion test setup, left: Galvanostatic; middle: Artificial climate chamber; right: machining operation

In this paper, the effect of pitting corrosion on reduction in yield and ultimate stress, module of elasticity and elongation has been investigated through experimental monotonic tensile tests. To meet this aim, pitting damage on 10mm deformed steel bars has been simulated by mechanically removing a part of steel cross-section using a spherical cutter. The results have been used for section-level analysis of a circular and a rectangular cross section arrangement bridge pier. Moreover the effects of small pits on low cycle fatigue behavior of 10mm deformed reinforcing steel have been investigated. The resulrs show pitting corrosion reduce mechanical properties and low cycle fatigue properties of reinforcing steel leading to reduction in moment and cuvature and corresponding ductility of RC bridge piers.

EXPERIMENTAL METHOD TO SIMULATE PITTING CORROSION

Corrosion simulated by machining the reinforcement is a very simple technique which can be used to accurately create a given geometry and reduce the cross-section. Figure 5 shows the geometry of pitting corrosion. As shown in the figure, pit width and depth are two main geometry factors representing the severity of pitting corrosion. The samples of length 600mm (300mm gauge length) were cut for tensile tests. In this research, 2mm and 4mm pit depth corresponding to low and medium pitting levels have been simulated on 10mm deformed steel reinforcement using machinery operation.

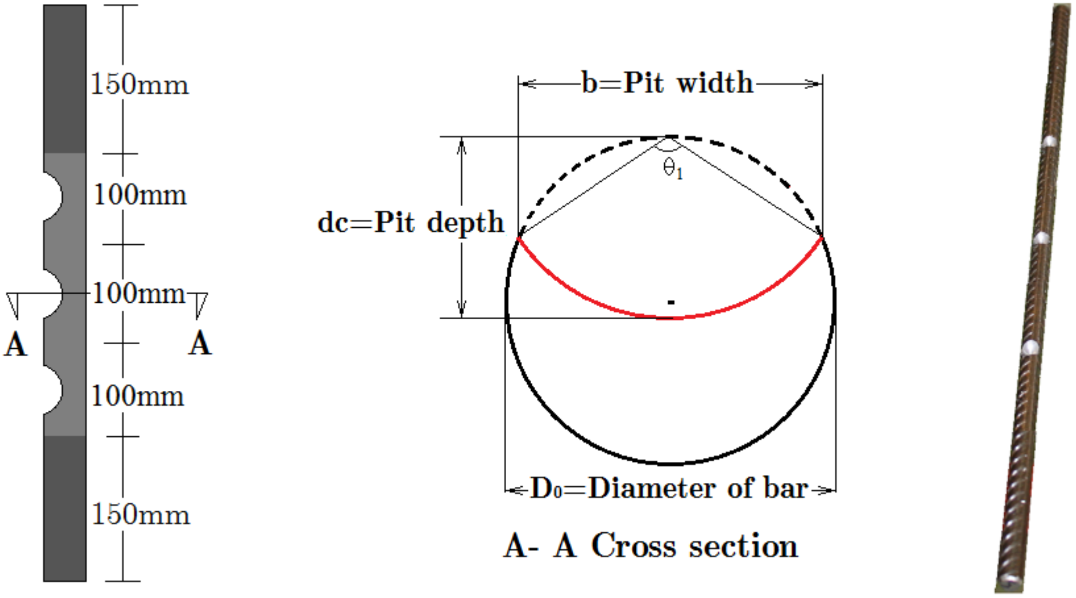

Figure 5: Left: geometry of pitting corrosion Middle: cross-section details of samples; Right: steel bar prepared for tensile tests (Andisheh et al, 2014)

Two different pit sizes have been shown in the figure 6. In the research, two different dimensions, 2mm and 4mm pit depth have been simulated using machinery operations. The associated maximum percentage loss of cross section areas are 7.3% and 26.5% respectively. Assuming general corrosion, the average cross-section loss percentages are 0.14% and 0.97% for 2mm and 4mm pit depth respectively. The loss of mass caused by each pit divided by mass of 100mm length of the bar is the equivalent percent of general corrosion (Andisheh et al, 2014). According to the literature, general corrosion up to 1% reduction in cross-section does not affect mechanical properties of steel reinforcement. (Allam, Maslehuddin et al. 1994).

Figure 6: The sizes of pits on the surface of 10mm deformed bars

TENSILE TESTS

Monotonic tensile tests have been carried out on the non-corroded and corroded bars to compare the effects of pitting corrosion on mechanical performance of 10mm deformed bars grade 300. Three tests for each level of corrosion, 9 tests have been performed in total. The tests have been carried out using controlled rate of displacement. The rate of displacement in elastic region was 1mm per minute, and was increased to 2mm per minute in plastic region. An extensometer has been set up between two pits for measuring the strain, force and displacement. Figure 7 shows the test setup. The results have been used to develop the relevant deterioration models.

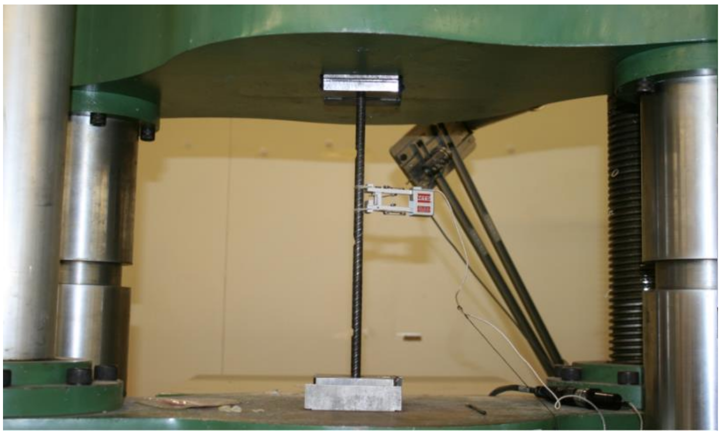

Figure 7: Monotonic tensile test setup

RESULTS OF TENSILE TESTS

The effective stress strain curves of monotonic tensile tests have been presented in figure 8. It can be seen that pitting corrosion alters effective mechanical properties of the steel bar. Table 1 shows the pits' geometry and the associated cross section loss percentage. It should be stated that corrosion does not affect inherent mechanical properties reinforcing steel. It alters effective mechanical properties of corroded bars.

Table 1.Pitting geometry and percent of cross-section loss of samples

Specimen	Pit width (mm)	Pit depth (mm)	Corroded area (mm2)	Cross section loss (%)
Non corroded (N.C)	0	0	0	0
PL1	3.92	2	5.75	7.3
PL2	7.33	4	20.8	26.5

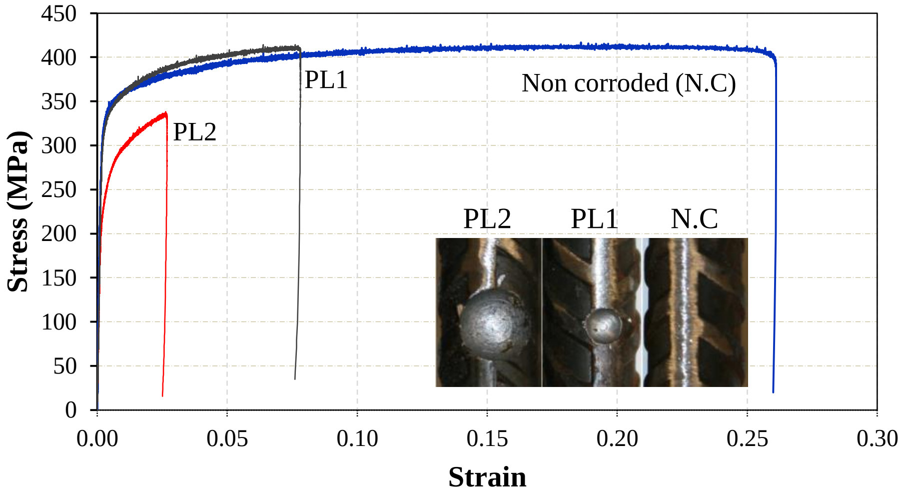

Figure 8: Stress-strain curves of 10mm deformed steel reinforcement of various degree of pitting corrosion

CYCLIC TESTS

Cyclic tests have been carried out on the non-corroded and corroded bars to compare the effects of pitting corrosion on low cycle fatigue behavior of 10mm deformed bars grade 300. The tests have been carried out on non corroded (NC) and pit level 1 (PL-1). The samples of length 125mm (25mm gauge length) were cut for cyclic tests. Three tests for each level of corrosion, 6 tests have been performed in total. The tests have been carried out using strain control method. The strain was 1.1%. Figure 9 shows geometry of samples prepared for the cyclic test.

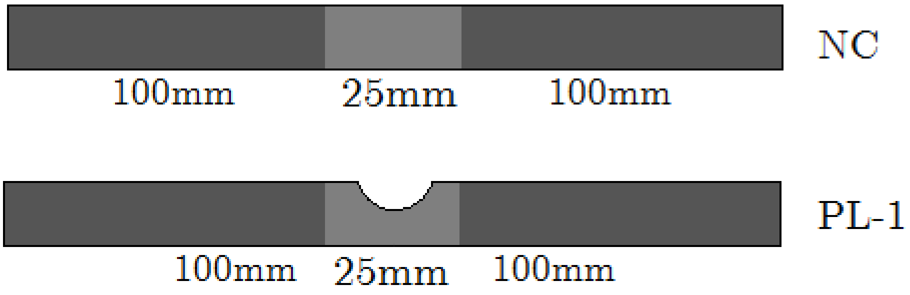

Figure 9: geometry of samples prepared for cyclic test

RESULTS OF LOW CYCLE FATIGUE TESTS

The stress-strain of cyclic loading using in this research has been shown in figure 10. 1.1% strain was applied in both tensile and compression, and the tests cantinued untile failure occued. Fibure 11 compares number of cycles needed to failure for NC and PL-1 samples. The results show a very small pit can decrease number of cycles to failure. PL-1 deceased 7.32% cross section area caused 81.3% reduction in number of cycles needed to failure. The results are very importnat in seismic design and evaluation of RC structures because corrosion usually strats with small pits.

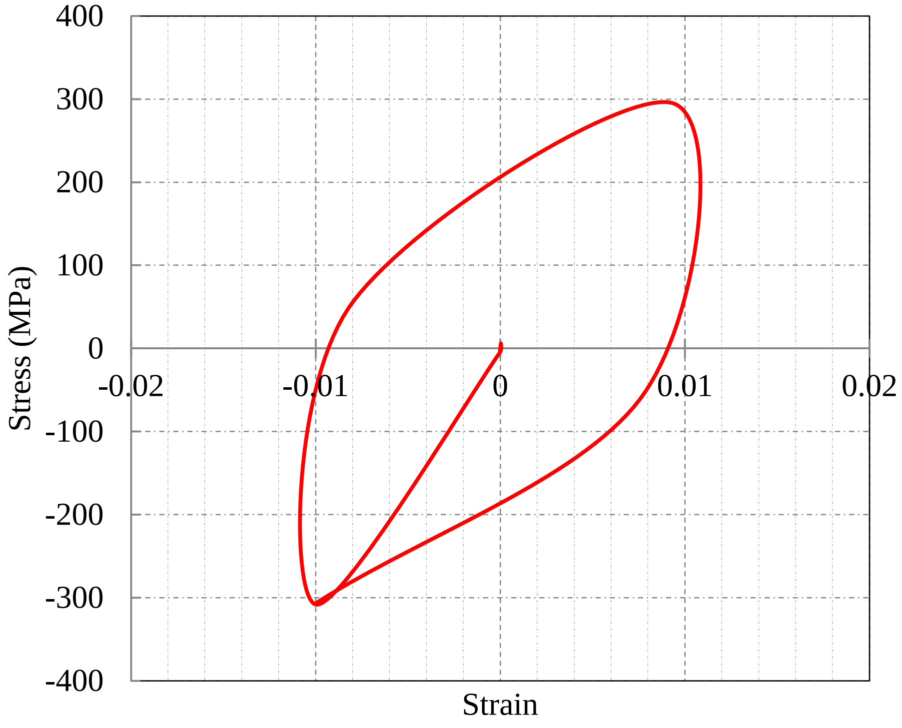

Figure 10: Stress-strain relationship of 10mm deformed bar under cyclic test

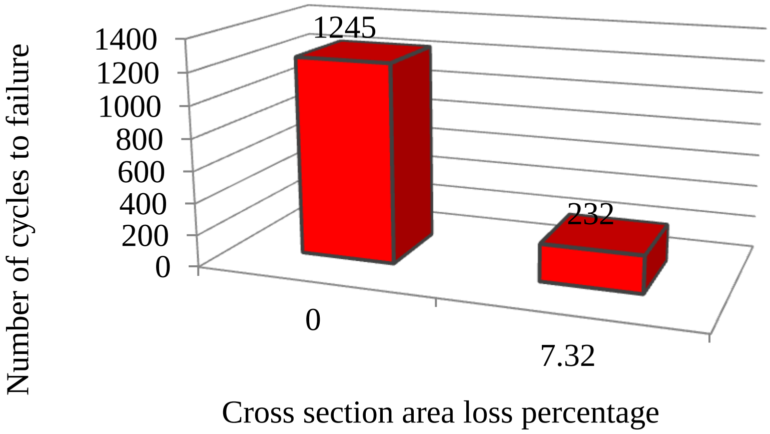

Figure 11: Number of cycles needed to failure; Left: Non corroded and Right: Pit level 1 (PL-1)

CROSS SECTION ANALYSIS OF RC CORRODED BRIDGE PIER

Cross-section analysis is a quite common numerical method to evaluate the key structural parameters for the seismic performance R.C. members. Recently research studies incorporated degradation models for concrete and steel which allows to predict the long term seismic performance of RC bridge piers (Palermo and Pampanin 2008, Ghosh and Padgett 2010)

The cross-section considered is at the bottom of the bridge piers where plastic hinge is forming. The intent is to evaluate how pitting corrosion alters the overall seismic performance of bridge piers in terms of strength and stiffness and more importantly ductility (strain, sectional and structural level). The reduction in the mechanical properties obtained by experimental tensile tests have been implemented in CUMBIA (Montejo 2007).

In this simple case study, a 100 KN vertical load has been applied on the bridge pier to simulate dead and live loads of deck. Figure 12 shows details of the cross section and mechanical properties of concrete and steel for the two bridge piers. The moment-curvature diagrams are shown in figures 13-15 for NC, PL-1 and PL-2. As expected bending moment capacity and corresponding curvature have been decreased basically for decreasing cross section area due to pitting corrosion. The results show that bending moment capacity has been reduced by 9.5% and 21.8% for pitting corrosion decreasing 7.3% and 26.5% cross-section area respectively. The reduction in cross-section areas is just in the location of pits. Having a pit in each 100mm length of steel bar, the equivalent percentage of general corrosion are as 0.14% and 0.97% respectively. The corresponding curvature has been decreased by 54% and 80.5% for circular bridge pier, and 48% and 81.5 for rectangular bridge pier respectively. The yielding curvature has not changed, this means that the curvature ductility drops exactly the same as the ultimate curvature.

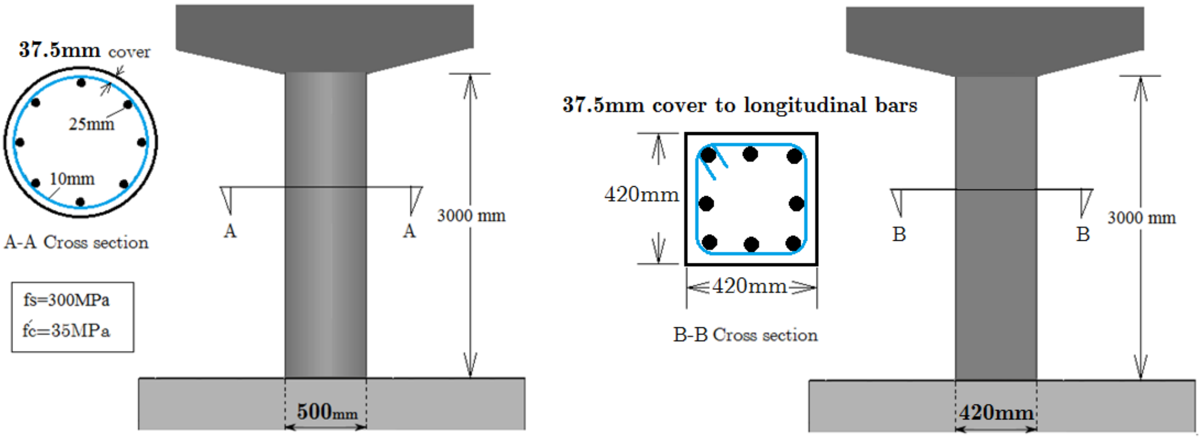

Figure 12: details of cross-section of the bridge piers Right: circular, Left: rectangular cross section

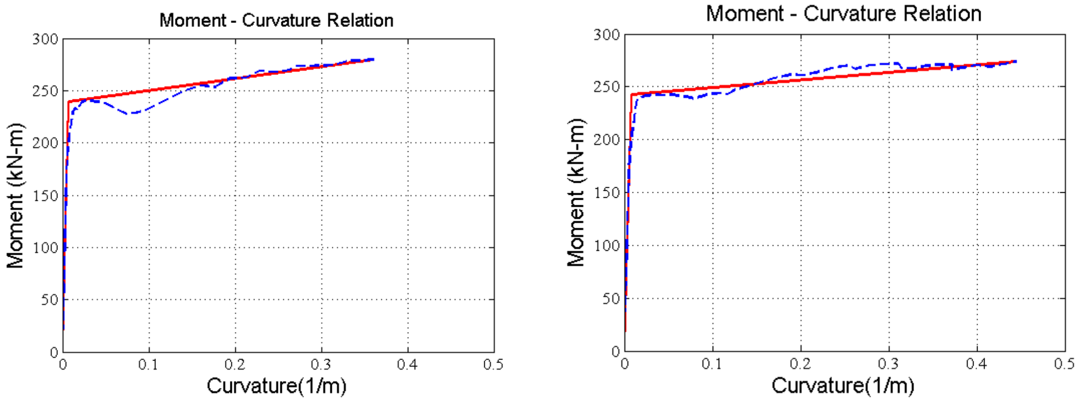

Figure 13: Moment-curvature relationship of NC bridge piers Right: circular, Left: rectangular cross section

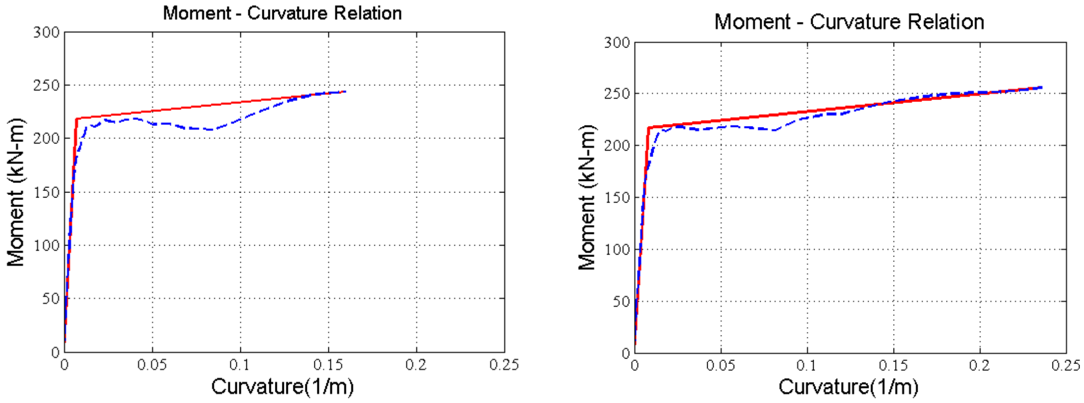

Figure 14: Moment-curvature relationship of PL-1 bridge piers Right: circular, Left: rectangular cross section

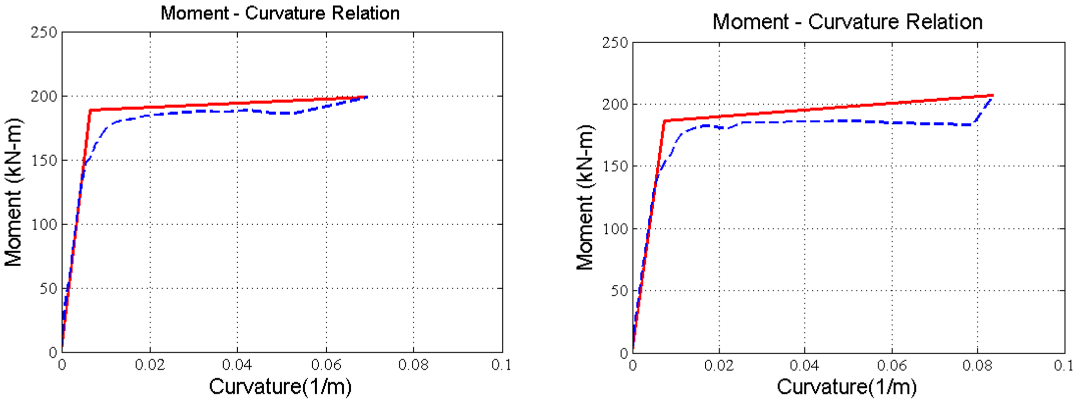

Figure 15: Moment-curvature relationship of NC bridge piers Right: circular, Left: rectangular cross section

The effects of pitting corrosion on curvature ductility of circular and rectangular bridge pier are shown in the table 2. The results show few small pits significantly reduce the ductility which impact seismic performance of bridges.

Table 2: Curvature ductility of the circular and rectangular bridge pier for different amount of corrosion

Corrosion	Moment-curvature Ductility	
	Circular column	Rectangular column
Non corroded (N.C)	59	60.5
PL-1	26.23	30.26
PL-2	11.39	11.32

CONCLUSIONS

In this paper the effects of pitting corrosion on tensile and cyclic behaviour of 10mm deformed bar grade 300 have been investigated. The results indicate that pitting corrosion alters mechanical properties and low-cycle fatigue behaviour of steel reinforcement and the results have been used to section- level analysis of two arrangement types of RC bridge pier. The main results of the research have been presented as follows:

1. Pitting corrosion causes reduction in mechanical properties of steel reinforcement that should be taken into consideration in the design of RC structures exposed to corrosion.
2. The reduction in elongation is the greatest among all mechanical properties indicating critical negative impact of pitting corrosion on ductility, since the yielding curvature does not change.
3. The experimental results show that even a very small pit causes significant reduction in ductility, tensile and cyclic performance of steel reinforcement. This is very important because corrosion process usually starts with a number of small pits.
4. Pitting corrosion decreases both bending moment and associated curvature indicating decreasing in seismic capacity of corroded RC bridge piers.
5. A small pit (PL-1) decreases singnificantly number of cycles to failure.
6. Reduction in ductility for circular and rectangular cross section of RC bridge pier is similar, indicating reduction in curvature ductility independent from geoemtry figure of cross section.
7. A small pit (PL-1) causes more than 50 % reduction in curvature ductility of RC bridge piers.

REFERENCES

Akiyama, M. and D. M. Frangopol (2013). "Long-term seismic performance of RC structures in an aggressive environment: emphasis on bridge piers." *Structure and Infrastructure Engineering*(ahead-of-print): 1-15.

Allam, I. M., et al. (1994). "Influence of atmospheric corrosion on the mechanical properties of reinforcing steel." *Construction and Building Materials* 8(1): 35-41.

Andisheh, K., Scott, A., Palermo A., (2014), "Preliminary estimation of reduction factors in mechanical properties of steel reinforcement due to pitting simulated corrosion", *New Zealand Society for Earthquake Engineering,* Auckland, New Zealand, 21-23 March.

Coronelli, D. and P. Gambarova (2004). "Structural assessment of corroded reinforced concrete beams: Modeling guidelines." *Journal of Structural Engineering* 130(8): 1214-1224.

Fang, C., et al. (2006). "Bond behaviour of corroded reinforcing steel bars in concrete" *Cement and Concrete research* 36(10): 1931-1938.

Ghosh, J. and J. E. Padgett (2010). "Aging considerations in the development of time-dependent seismic fragility curves." *Journal of Structural Engineering* 136(12): 1497-1511.

Hansen, B. (2009). "ASCE's Infrastructure Report Card Gives Nation a D, Estimate Cost at $2.2 Trillion." *ASCE News* 34(2): 1-4.

Kivell, A. R. L. (2012). Effects of Bond Deterioration Due to Corrosion on Seismic Performance of Reinforced Concrete Structures, MSc thesis, University of Canterbury.

Montejo, L. (2007). Generating set of codes for the analysis of reinforced concrete members, CUMBIA. Technical, report no. IS-07-01.

Ou, Y. C., et al. (2013). "Long- term seismic performance of reinforced concrete bridges under steel reinforcement corrosion due to chloride attack." *Earthquake Engineering & Structural Dynamics*.

Palermo, A. and S. Pampanin (2008). "Enhanced seismic performance of hybrid bridge systems: Comparison with traditional monolithic solutions" *Journal of Earthquake Engineering* 12(8): 1267-1295.

Stanish, K., et al. (1999). "Corrosion effects on bond strength in reinforced concrete." *ACI Structural Journal* 96(6).

Stewart, M. G. (2004). "Spatial variability of pitting corrosion and its influence on structural fragility and reliability of RC beams in flexure" *Structural Safety* 26(4): 453-470.

Stewart, M. G. (2009). "Mechanical behaviour of pitting corrosion of flexural and shear reinforcement and its effect on structural reliability of corroding RC beams." *Structural Safety* 31(1): 19-30.

Stewart, M. G. and A. Al-Harthy (2008). "Pitting corrosion and structural reliability of corroding RC structures: Experimental data and probabilistic analysis" *Reliability Engineering & System Safety* 93(3): 373-382.

Virmani, Y. (2002). Corrosion costs and preventive strategies in the United States, Federal Highway Administration, Report FHWA-RD-01-156 BIOGRAPHICAL SKETCH.

Vu, K. A. T. and M. G. Stewart (2000), "Structural reliability of concrete bridges including improved chloride-induced corrosion models" *Structural Safety* 22(4): 313-333.