Preliminary estimation of reduction factors in mechanical properties of steel reinforcement due to pitting simulated corrosion

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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 causes chloride-induced corrosion. Basically, there are two types of steel reinforcement corrosion called general and pitting corrosion. In real corroded reinforced concrete (RC) structures, a mix of the general and pitting corrosion usually takes place. Corrosion decreases the mechanical characteristics of steel reinforcing.

In this study, reduction factors of mechanical properties of steel reinforcement have been estimated through experimental monotonic tensile tests to take into consideration of eccentricity caused by pitting corrosion. Reduction factors have been defined to estimate the effect of corrosion on the reduction in mechanical properties of corroded steel bars. The reduction factors indicate the percentage reduction in the mechanical properties for 1% loss of cross-section area of steel reinforcement.

To meet this aim, pitting corrosion has been simulated by mechanically removing a portion of the cross section form 10mm, steel reinforcement. The reduction factors in terms of yield stress, ultimate stress, module of elasticity and elongation have been estimated from monotonic tensile tests. The relevant deterioration models have been developed based on the experimental results, and have been used for section-level analysis of a reinforced concrete bridge pier. The results of section-level analysis show degradation in moment-curvature and force-displacement of the corroded RC bridge pier due to pitting corrosion.

1 INTRODUCTION

There are a number of causes of corrosion in reinforced concrete (RC) structures including: chloride-induced, carbonation-induced, bacterial-induced and stray current-induced corrosion. Chloride-induced corrosion is generally the most common cause for corroding of RC structures. Chloride-induced corrosion is an electrochemical process that degrades reinforced concrete (RC) structures. While RC structures in pristine condition can be expected to satisfy the code requirement of a given era corrosion of reinforcing steel will degrade the seismic capacity of the structure over time. Therefore, old corroded RC structures become vulnerable to future earthquakes. Past studies have reported some corroded RC bridge in New Zealand (Bruce and Land Transport 2008, Pank 2009, Rogers, Al-Ani et al. 2013). Figure 1 shows examples of real corroded bridge in New Zealand (Rogers, Al-Ani et al. 2013).

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.

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). Pitting corrosion not only decreases cross-section area of steel reinforcement but also does cause reduction in effective mechanical properties of steel reinforcement.

Figure 1. Real-life corroded bridges' deck in New Zealand; Right: corrosion of longitudinal bars; Left: corrosion of post-tension tendons used in beams.

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

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). However, according to the best knowledge of the authors, there is no experimental study on the spherical simulated pitting corrosion. The only approach studies simulated pitting corrosion by removing a part of steel bar's cross-section using hemispherical end mill with a cylindrical shank (Cairns, Plizzari et al. 2005). With respect to accelerated corrosion, a number of methods have been used to corrode RC structures. Ponding members in salt water and applying current electricity named galvanostatic method and artificial climate chamber method are frequently used (Castro, Veleva et al. 1997, Yuan, Ji et al. 2007). Figure 3 shows test setup of these two 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.

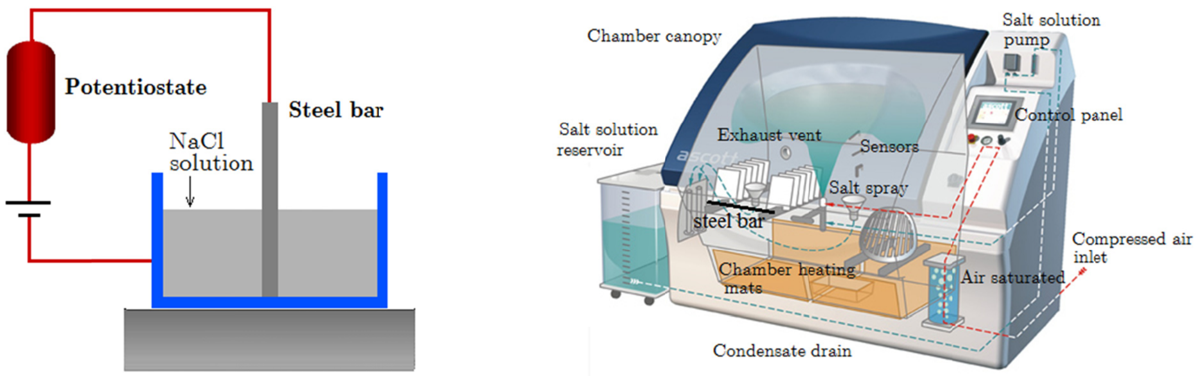

Figure 3. Accelerated corrosion test setup, left: Galvanostatic; right: Artificial climate chamber

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. A machined simulated pit is an accelerated method to simulate corrosion, because natural pitting corrosion may take several years. Three different pit levels associated with low, medium and sever pitting corrosion have been simulated. In this regard, a pit causes up to 10%, 15%- 30% and more than 35% reductions in cross-section area is considered as low, medium and sever pitting corrosion. The deterioration models of reduction in the four mechanical properties of steel reinforcement have been developed based on the tensile test results. Then they have used in section level analysis of a RC bridge pier to investigate the effect of pitting corrosion on the moment-curvature model. The preliminary results show pitting corrosion has a critical impact on seismic behaviour of RC bridge piers.

2 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 4 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, 4mm and 5mm pit depth corresponding to low, medium and severe pitting levels have been simulated on 10mm deformed steel reinforcement using machinery operation.

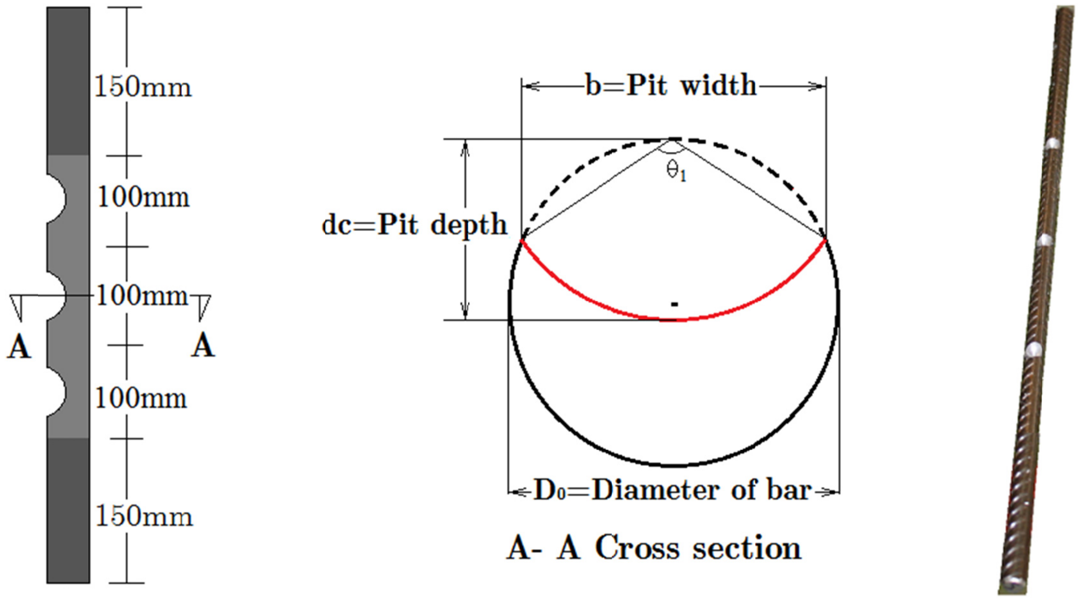

Figure 4. Left: geometry of pitting corrosion Middle: cross-section details of samples; Right: steel bar prepared for tensile tests

To take into consideration the effects of spatial variability of pitting corrosion, a pit at every 10mm distance (3 pits in total) on the surface of the steel bars have been considered (Stewart and Al-Harthy 2008, Stewart 2009)

Three different pit sizes have been shown in the figure 5. In the research, three different dimensions, 2mm, 4mm and 5mm pit depth have been simulated using machinery operations. The associated maximum percentage loss of cross section areas are 7.3%, 26.5% and 39% respectively. Assuming general corrosion, the average cross-section loss percentages are 0.14%, 0.97% and 1.73% for 2mm, 4mm and 5mm 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. According to the literature, general corrosion up to 1% reduction in cross-section does not affect mechanical properties of steel reinforcement (Maslehuddin, Allam et al. 1990, Allam, Maslehuddin et al. 1994).

Figure 5. The sizes of pits on the surface of 10mm deformed bars

The relationship between pit depth and pit width have been defined as follows:

$$b = 2d_c\sqrt{1-\left(\frac{d_c}{D_0}\right)} \tag{1}$$

The maximum corroded area (shown in the A-A cross section in figure 1) can be calculated as follows:

$$A_{pit}(t) = \begin{cases} A_1 + A_2 & d_c \le \frac{D_0}{\sqrt{2}} \\ \frac{\pi D_0^2}{4} - A_1 + A_2 & \frac{D_0}{\sqrt{2}} < d_c \le D_0 \\ \frac{\pi D_0^2}{4} & d_c \ge D_0 \end{cases} \tag{2}$$

Where, b, d_c and D_0 are pit width, pit depth and diameter of sound steel reinforcement respectively, and A_1 and A_2 are estimated as follows:

$$A_1 = \frac{1}{2}\left[\theta_1\left(\frac{D_0}{2}\right)^2 - b\left|\frac{D_0}{2} - \frac{d_c^2}{D_0}\right|\right] \tag{3}$$

$$A_2 = \frac{1}{2}\left[\theta_2 d_c^2 - b\frac{d_c^2}{D_0}\right] \tag{4}$$

$$\theta_1 = 2\sin^{-1}\left(\frac{b}{D_0}\right) \tag{5}$$

$$\theta_2 = 2\sin^{-1}\left(\frac{b}{2d_c}\right) \tag{6}$$

3 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, 12 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 6 shows the test setup. The results have been used to develop the relevant deterioration models.

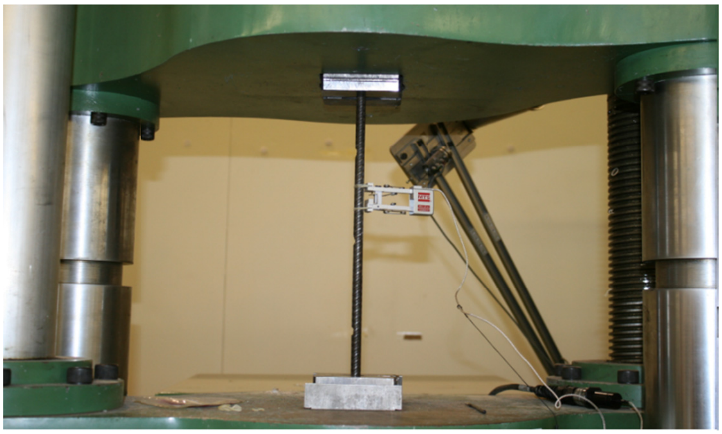

Figure 6. Monotonic tensile test setup

4 RESULTS

The effective stress strain curves of monotonic tensile tests have been presented in figure 7. 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 (mm^2)	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
PL3	8.66	5	30.7	39

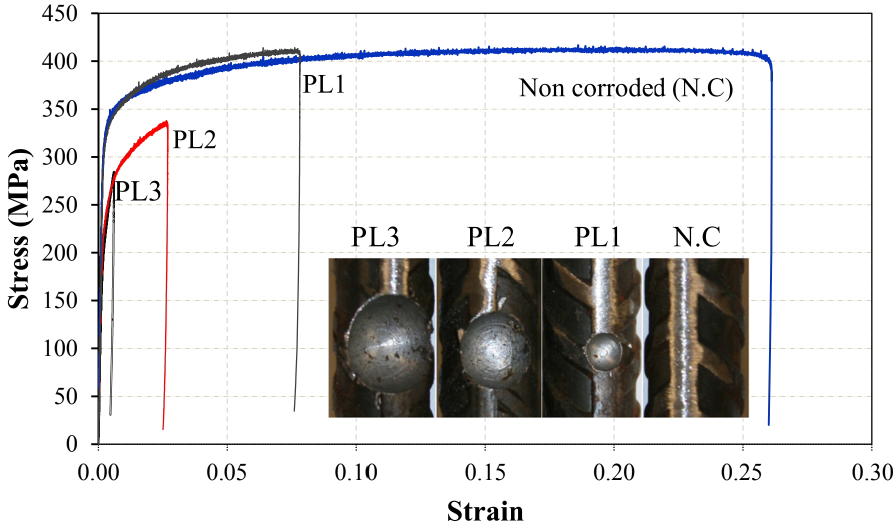

Figure 7. Stress-strain curves of 10mm deformed steel reinforcement of various degree of pitting corrosion

5 DEVELOPING DETERIORATION MODELS

Several deterioration models based on mathematical relationships showing how mechanical properties of corroded members or materials degrade due to corrosion exist in the literature (Morinaga 1996, Cairns, Plizzari et al. 2005, Lee and Cho 2009, Oyado, Kanakubo et al. 2011). However, usually, general corrosion has been adapted for estimating the reduction factors. Moreover, the results presented in the literature have a wide variation indicating the need for further studies. The existing deterioration models in the literature have been presented based on linear regression of experimental results. The equation 7 shows the general form of deterioration models for corroded steel reinforcement that has been used for both general and pitting corrosion:

$$\frac{\beta_c}{\beta} = y = [1 - \alpha \times Q_{corr}] \qquad (7)$$

Where, β_c: mechanical properties of corroded bars, α: relevant reduction factors, Q_{corr}: amount of corrosion in the term of reduction percentage of mass, and β: mechanical properties of sound bars. The equation 7 is independent from type of corrosion, and the mechanical properties of corroded bars can be calculated by given relevant parameters. Figures 8 and 9 show deteriorated modulus of elasticity, elongation, yield stress and ultimate stress for different amount of cross section reduction. Assuming linear regression, reduction factors for each of these properties have been calculated using equation 7 as 0.65, 2.78, 1.19 and 0.81 respectively. The results indicate that further studies are needed to estimate the reduction factors of mechanical properties of reinforcing steel, and linear regression presented by past studies is not suitable in case of pitting corrosion. While all reduction factors have been estimated based on linear regression in the literature, the results show that with exception of ultimate stress and modulus of elasticity, the linear regression are not suitable methods basically for variation of reduction factors for different amount of corrosion. The reduction in elongation, for example, for up to 7.3% corrosion in much higher than that for corrosion between 7.3% and 26.5%, and the reduction for corrosion greater than 26.5% is relatively low. The results indicate further investigation to estimate reduction factors based dependent on amount of corrosion.

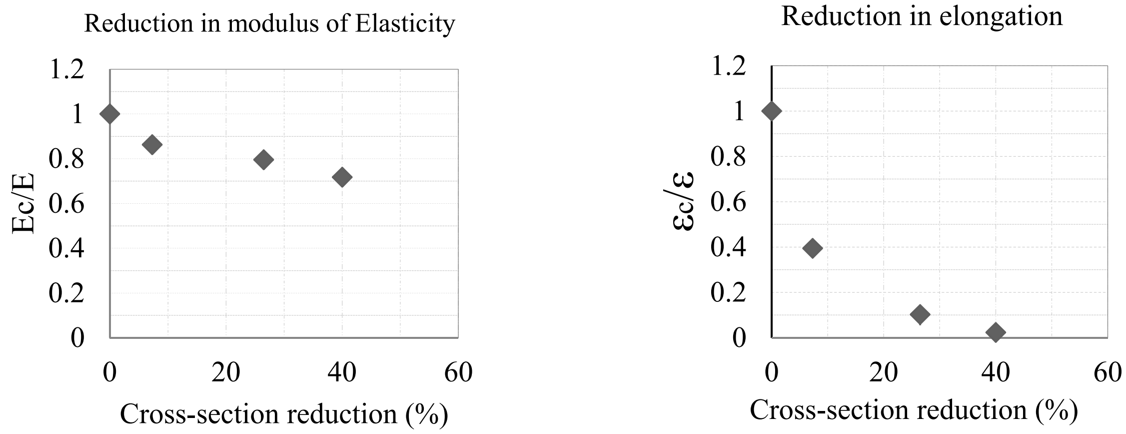

Figure 8. Relationship between corrosion and reduction in left: module of elasticity, right: elongation

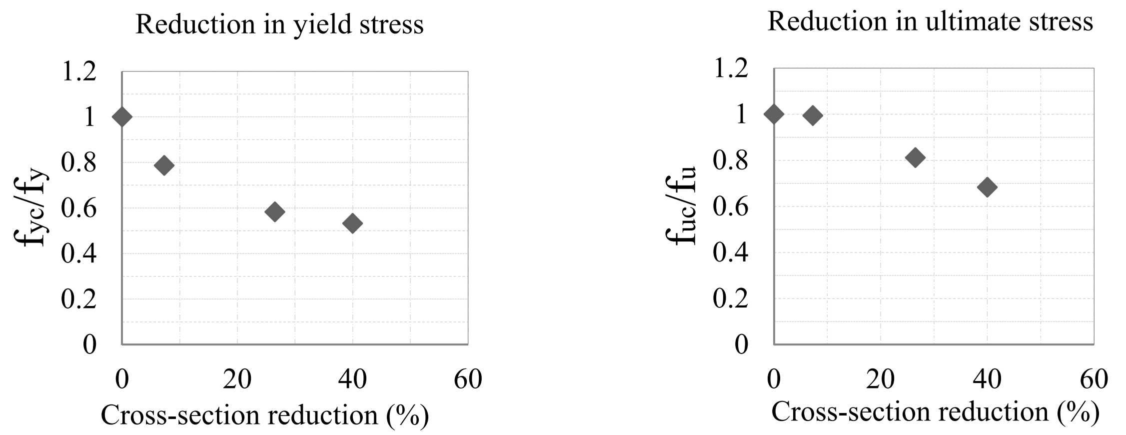

Figure 9. Relationship between corrosion and reduction in left: yield stress, right: ultimate stress

6 CROSS SECTION ANALYSIS OF A CORRODED RC 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, Biondini, Camnasio et al. 2013). Corrosion is usually modelled by decreasing cross-section area of steel reinforcement and causing reduction in effective mechanical properties of steel reinforcements which leads to reduction in the seismic capacity. The moment-curvature and force-displacement relationship have been utilized to evaluate the effects of corrosion on seismic performance of a corroded bridge pier (Montejo 2007). 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 tests in the section 5 are implemented in CUMBIA (Montejo 2007). Authors acknowledge that this is just a preliminary investigation and more tests and numerical analyses are needed. Therefore, a research program named "Long-term seismic performance of corroded bridge pier" is in progress at the University of Canterbury. To achieve the objectives of the project, 10mm, 16mm and 25mm deformed and 10mm plain reinforcing steel and reinforcing steel grade 500 will be examined.

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 10 shows details of the cross section and mechanical properties of concrete and steel. The moment-curvature relationship is shown in the left side. 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 14.3%, 25% and 36% for pitting corrosion decreasing 7.3%, 26.5% and 39% 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%, 0.97% and 1.73% respectively. The corresponding curvature has been decreased by 19%, 66% and 92%. The yielding curvature has not changed, this means that the curvature ductility drops exactly the same as the ultimate curvature.

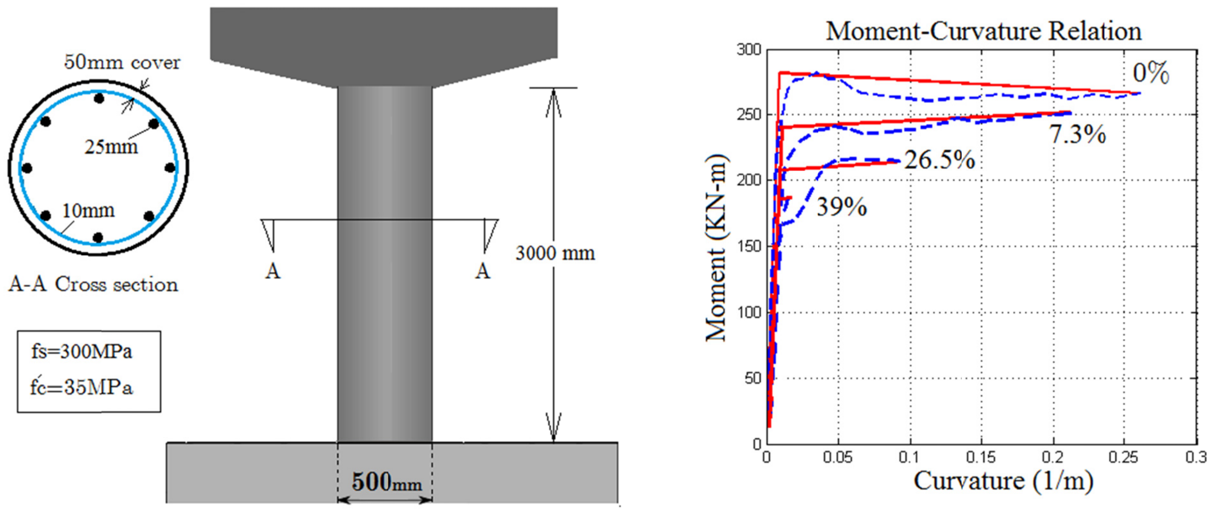

Figure 10. Right: details of cross-section of the bridge pier; Left: Moment- curvature relationship for different percent loss of cross section area of steel reinforcements in the bridge pier

Force-displacement relationship has been analysed using the model presented by Paulay and Pristley (Paulay and Priestley 1992). Figure 11 shows force-displacement relationship of the bridge pier for different amount of cross-section loss due to pitting corrosion. The pitting corrosion causes reduction in lateral load carrying capacity and in elongation leading to decrease of consequence displacement ductility. The results show base shear capacity has been decreased by 21%, 75% and 58% for 7.3%, 26.5% and 39% loss of cross section area respectively. The equivalent reduction by general corrosion is 0.14%, 0.97% and 1.73% respectively. The corresponding reduction in displacement ductility is 11%, 71% and 93% respectively. The effects of pitting corrosion on ductility in terms of reinforcing steel strain, curvature and lateral displacement of the bridge pier are shown in the table 2. The results show few small pits significantly reduce the ductility which impact seismic performance of bridges.

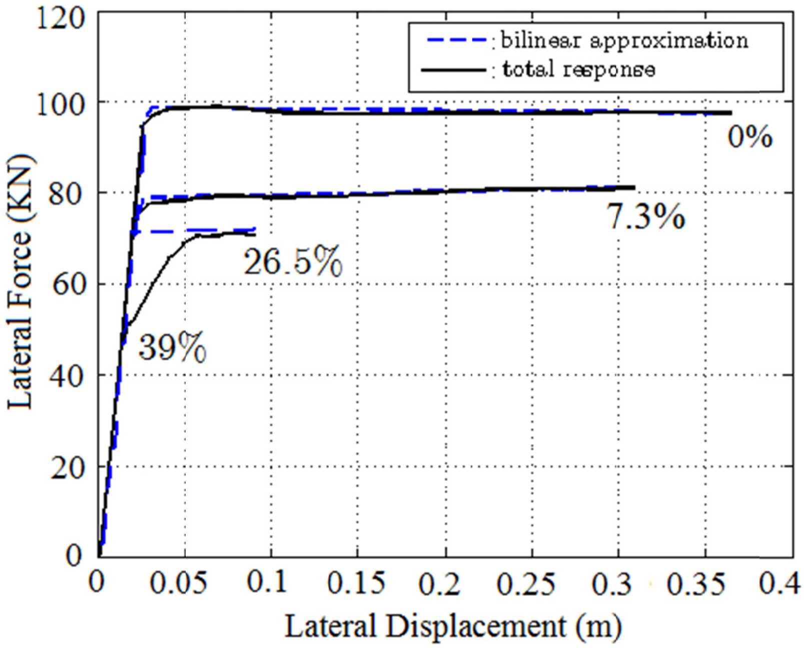

Figure 11. Lateral force-displacement relationship for different percent loss of cross section area of steel reinforcements in the bridge pier

Table 2. Ductility of the D10 reinforcing steel and the bridge pier for different amount of corrosion

Corrosion characteristics		Steel bar	Bridge pier		Ductility			Reduction in ductility		
Corrosion level	Loss of cross section (%)	f_y (MPa)	M (KN.m)	F (KN)	μ_ε	μ_φ	μ_D	$\mu^c_\varepsilon/\mu_\varepsilon$	$\mu^c_\varphi/\mu_\varphi$	μ^c_D/μ_D
N.C	0	374	280	98	13.5	26	14.6	1	1	1
PL1	7.3	294	240	79	4.5	21	13	0.333	0.81	0.89
PL2	26.5	218	215	73	1.78	9	4.3	0.131	0.346	0.294
PL3	39	199	178	53	1.08	2	1.05	0.08	0.077	0.072

7 CONCLUSIONS

The effects of pitting corrosion have been investigated by testing 12 specimens. Pitting corrosion on 9 out of 12 samples has been simulated with mechanically induced defects which represent pitting corrosion. Three levels of pitting corrosion have been simulated. The results show reduction in module of elasticity, elongation, yield stress and ultimate stress. Deterioration models for the mechanical properties have been developed and briefly presented in this paper. Authors acknowledge that the results have been presented in this paper need to be revised based on experimental tests on 16mm and 25mm reinforcing steel. However, it is expected that for the same percent of corrosion, the effect of bar size can be neglected. Finally, moment-curvature and force-displacement analyses of a single column bridge pier for the levels of pitting corrosion have been carried out and the main results have been summarized 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. 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. Pitting corrosion also decreases load carrying capacity and displacement ductility confirming corroded bridge pier are more vulnerable in seismic events.
6. Further investigations are needed to develop deterioration models for pitting corrosion, and linear regression, presented by past studies for general and pitting corrosion, probably is not suitable in case of pitting corrosion.

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REFERENCES

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.

Biondini, F., et al. (2013). Lifetime seismic performance of concrete bridges exposed to corrosion. *Structure and Infrastructure Engineering*(ahead-of-print): 1-21.

Bruce, S. and N. Land Transport (2008). Deterioration of prestressed concrete bridge beams, Land Transport New Zealand.

Cairns, J., et al. (2005). Mechanical properties of corrosion-damaged reinforcement. *ACI Materials Journal* 102(4).

Castro, P., et al. (1997). Corrosion of reinforced concrete in a tropical marine environment and in accelerated tests. *Construction and Building Materials* 11(2): 75-81.

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.

Lee, H.-S. and Y.-S. Cho (2009). "Evaluation of the mechanical properties of steel reinforcement embedded in concrete specimen as a function of the degree of reinforcement corrosion. *International journal of fracture* 157(1-2): 81-88.

Maslehuddin, M., et al. (1990). Effect of rusting of reinforcing steel on its mechanical properties and bond with concrete. *ACI Materials Journal* 87(5).

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

Morinaga, S. (1996). Remaining life of reinforced concrete structures after corrosion cracking. *Durability of Building Materials and Components* 71: 127-136.

Oyado, M., et al. (2011). Bending performance of reinforced concrete member deteriorated by corrosion. *Structure and Infrastructure Engineering* 7(1-2): 121-130.

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.

Pank, W. (2009). Grafton Bridge strengthening. Austroads Bridge Conference, 7th, 2009, Auckland, New Zealand.

Paulay, T. and M. Priestley (1992). Seismic design of reinforced concrete and masonry structures. J. Wiley & Sons, INC USA.

Rogers, R. A., et al. (2013). Assessing pre-tensioned reinforcement corrosion within the New Zealand concrete bridge stock.

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.

Yuan, Y., et al. (2007). Comparison of two accelerated corrosion techniques for concrete structures.