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Experimental study of the effects of corrosion on seismic performance of un-bonded post-tensioned rocking bridge piers with replaceable external dissipaters

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ABSTRACT: The importance of bridges as the most vulnerable components of traffic networks in earthquakes, and the fact that bridge failures typically result in fatalities, traffic disruption, and expensive and lengthy repairs, causes to demand of earthquake resilient bridges. Low damage technologies such as un-bonded post-tensioned rocking bridge pier provide a remedy for aforementioned problems. However, corrosion weakens structural elements and increases their vulnerability to seismic events. Therefore the investigation on the effects of corrosion on seismic performance of structures and structural elements is critical. The external dissipaters are the most vulnerable components in corrosion attacks. Therefore, in this paper the effects of corroded external dissipaters on seismic performance of the rocking bridge pier have been experimentally studied. To meet this aim, the well-known accelerated corrosion method called galvanostatic method was employed to corrode the dissipaters. Then quasi static cyclic tests on 1:3 scale rocking bridge pier have been carried out with non-corroded and corroded dissipaters. The results clearly show corrosion induced deterioration significantly affect seismic performance of the un-bonded post-tensioned rocking bridge pier indicating life time seismic analysis of bridges are critically essential to evaluate structural performance of existing and design of new bridges.

1 INTRODUCTION

Housner (1963) presented the theory of rocking systems. Following Housner’s work, a simplified design method proposed by (Priestley, Evison et al. 1978). McManus (1980) validated the proposed design method using experimental tests. The first pure rocking bridge constructed in New Zealand was the “stepping” rail bridge over Rangitikei River completed in 1981. A number of studies have been carried out on the controlled rocking system (Nigel Priestly 1991, Priestley 1996, Nigel Priestley, Sritharan et al. 1999). The concept of the controlled rocking pier has been further extended for bridge pier by (Palermo, Pampanin et al. 2005). In this contribution further studies coordinated by the University of Canterbury were carried out (Palermo, Pampanin et al. 2007, Marriott, Pampanin et al. 2009).

Corrosion is a time dependent process causing structural element degradation leading to significant reduction in mechanical properties and structural or seismic response of corroded structures. On the other side there is no study on the effects of corrosion of seismic performance of the controlled rocking piers. Therefore the importance of study on the effects of corrosion on seismic performance of corroded bridge piers is clear. This research is a part of a research project named” Long-term seismic performance of RC bridge pier due to corrosion” that is in progress at the University of Canterbury.

In this paper a controlled rocking bridge pier having four external dissipater and un-bonded post-tensioned tendon located at the centre of the pier was employed. Eight dissipaters were manufactured by machinery operation to provide a fuse length, and four dissipaters out of the eight dissipaters were corroded using the accelerated corrosion method called galvanostatic method. A series of three cycles at increasing level of drift followed by a half single cycle was applied through a horizontal hydraulic actuator. Two quasi-static cyclic tests were carried out on the pier with non-corroded and corroded dissipaters. Load-displacement responses of the pier with non-corroded dissipaters were compared with those with corroded dissipaters. The results exhibit corrosion of dissipaters causes reduction in seismic capacity of the pier.

2 ROCKING BRIDGE PIER

Hybrid or controlled rocking concept is included sufficient ratio of self-centring (nonlinear static behaviour) provided by un-bonded post-tensioned tendon and energy dissipation (elasto-plastic or similar behaviour) provided by external dissipaters. This system exhibits a special hysteresis behaviour called “flag-shape”. The advantages of this system are damage resistance limitation of maximum drift and no residual displacement. While in traditional solutions moderate to severe earthquakes causes extensive cracks in plastic hinge region, in the controlled rocking solution, the inelastic deformation is accommodated at the pier-foundation interface through the gap opening and closing and yielding external dissipaters. Figure 1 shows the view and details of the rocking bridge pier. A 70mm diameter hole at the centre of the pier is used to post-tension tendon. 10mm thick steel shell at the base has confined concrete cover at 500mm length. A 12mm thick steel shell ring was employed at the bottom of the column to protect concrete when pier is rocking. External shear keys welded to 10mm thick steel shell were employed to transfer base shear at the critical intersection.

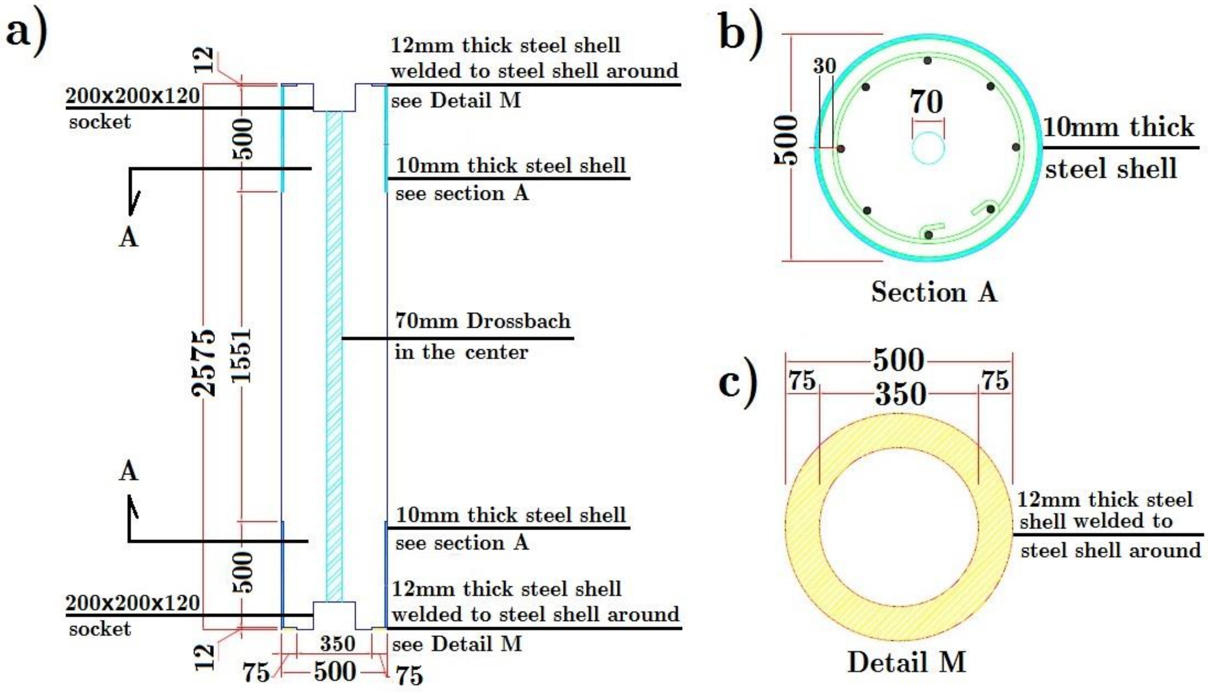

Fig.1: a) Overview of the rocking bridge pier, b) Details of cross-section at section A, c) Details of 12mm thick steel shell welded to 10mm thick steel shell around

2.1 Dissipater details

Diameter size of 24mm plain steel reinforcement grade 300 were employed to manufacture dissipaters with machinery operation. Figure 2 shows the details of the dissipater called 3 cut dissipater. The 435mm total length of the dissipater included 245mm fuse length that the cross sectional area is equivalent of the area of 17mm plain reinforcing steel. To prevent buckling of the dissipater, a pipe with sub-millimetre gap between the dissipater and the pipe was employed.

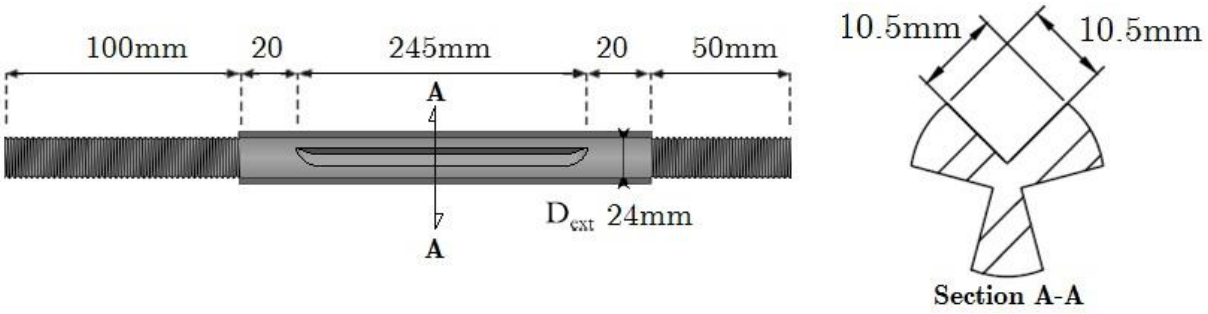

Fig. 2: Details of the “3-cut dissipater” and cross section of fuse length

3 EXPERIMENTAL PROGRAM

The experimental program consisted of two phases: corroding of dissipaters, and quasi-static cyclic test of the rocking bridge pier. Four dissipaters out of 8 manufactured dissipaters were corroded by the accelerated corrosion technique called galvanostatic technique. Two quasi-static cyclic tests were carried out on a cantilever single bridge pier with a controlled rocking connection with four external dissipater at the base. The first set of tests were carried out with four non-corroded dissipaters and the second set of tests carried out with the four corroded dissipaters.

3.1 Corrosion test setup of dissipater

Ponding samples in NaCl solution and applying electricity are main steps have to be done when the Galvanostatic method employed to corrode the samples. The objective was corroding fuse length part of the dissipaters. To meet this aim, four dissipaters were placed in 3.5% Na Cl solution and current electricity was applied. The corrosion density, the ratio of current electricity to corroded area, was 900 $\mu A/cm^2$. Figure 3 shows the photo of corrosion test setup and a non-corroded and corroded dissipater. The details of corrosion test setup have been presented in table 1.

Fig. 3: a) Corrosion test setup of dissipater, b) a non-corroded dissipater, and c) a corroded dissipater

After corroding the dissipaters, the corrosion percentage for each dissipater was calculated as follows:

$$corrosion\,(\%) = \frac{original\ weight\ of\ dissipater - weight\ of\ dissipater\ after\ corrosion}{original\ weight\ of\ diddipater} \qquad (1)$$

Table 1: Details of corrosion test setup of dissipaters

Sample name	Exposure length of dissipaters (mm)	Time of exposure (days)	Corrosion density i($\mu A/cm^2$)	Corrosion (%)
D5	285	19	900	20.4
D6	285	20	900	21
D7	285	19	900	20.7
D8	285	18	900	20

3.2 Quasi-static cyclic test of the post-tensioned rocking bridge piers

Figure 4 shows quasi-static cyclic test setup of the rocking bridge pier. The controlled rocking connection of the pier at the base consisted of four external dissipater at 90° interval around the circumference. The load cell and tendon anchorage at the top of the column provided 150KN vertical load, and the lateral hydraulic ram employed to push and pull the bridge pier. The tests were carried out using controlled drift method. A series of three cycles at increasing level of drift followed by a half single cycle was applied through a horizontal hydraulic actuator. Figure 5 shows configuration of 1.8% drift. Maximum displacement was estimated by multiplying the vertical distance of hydraulic ram from pier-foundation interface and the given drift. The external dissipaters are replaceable so the same column was used for non-corroded and corroded dissipaters.

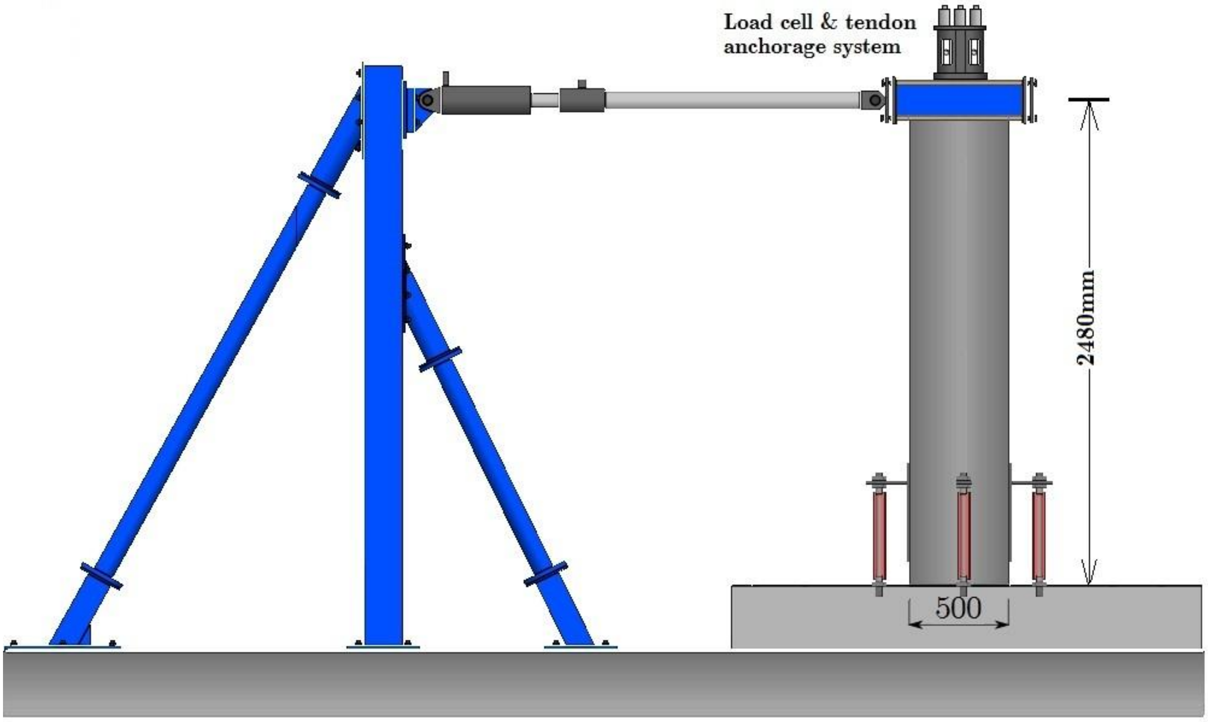

Fig. 4: Quasi-static test setup of the rocking bridge pier

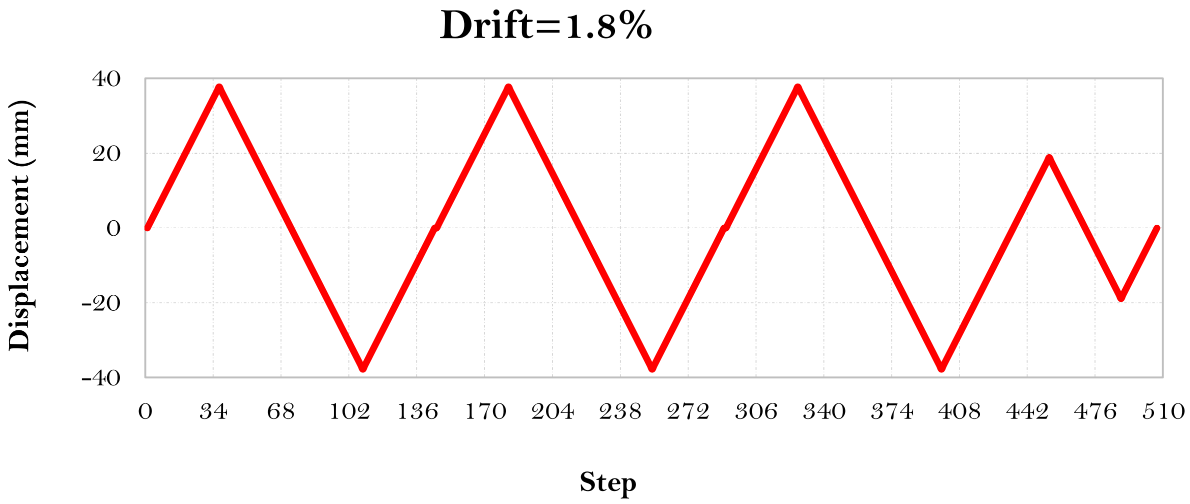

Fig. 5: Loading configuration for

4 RESULTS

The pier with non-corroded dissipater show excellent load-displacement response up to 2.8% drift, whereas dissipater failure observed for the pier with corroded dissipater in 2.8% drift.

Force-displacement of the rocking pier for 0.5%, 1%, 1.8%, and 2.8% drift for the pier with non-corroded and corroded dissipaters have been presented in this paper. Figure 6 shows force-displacement relationship of the pier with non-corroded dissipaters for 1.8% drift. The figure 6 clearly shows flag-shape hysteresis loop of the pier. Dissipating of energy inversely depends on the number of cycles of a given drift. On the other hand, for a given drift, maximum energy is dissipated in the first cycle. The controlled bridge pier has exhibited Flag-shape hysteresis responses. Figures 7-10 compare force displacement of the pier with non-corroded and corroded dissipaters for aforementioned drift prototypes. The results show corrosion of dissipaters lead to reduction in stiffness of the pier. The results also clearly show that corrosion of dissipaters causes reduction in load is needed for a given displacement, indicating corrosion of dissipaters degrades seismic capacity of the bridge.

The results clearly show that the 20% average reduction in maximum lateral force was observed for approximately 20% corrosion percentage. This means the reduction factor of 1 can be used for quantifying corrosion induced deterioration in the maximum lateral force. Reduction factors indicate that the percentage of reductions in mechanical properties that will happen for 1% corrosion. A general form of deterioration model for maximum lateral load is represented as follows:

$$\mathrm{F_L^c} = [100 - \alpha_{FL} \times \mathrm{Q}_{corr}\%]\mathrm{F_L} \qquad (1)$$

Where: $\mathrm{F_L^c}$, is the maximum lateral force of the pier with corroded dissipaters, α_{FL}, is their associated reduction factors, $\mathrm{Q}_{corr}\%$ is the corrosion percentage, and $\mathrm{F_L}$, is maximum lateral force of the pier with non-corroded dissipaters.

Using reduction factor of 1, the equation 1 is represented as follows:

$$\mathrm{F_L^c} = [100 - \mathrm{Q}_{corr}\%]\mathrm{F_L} \qquad (2)$$

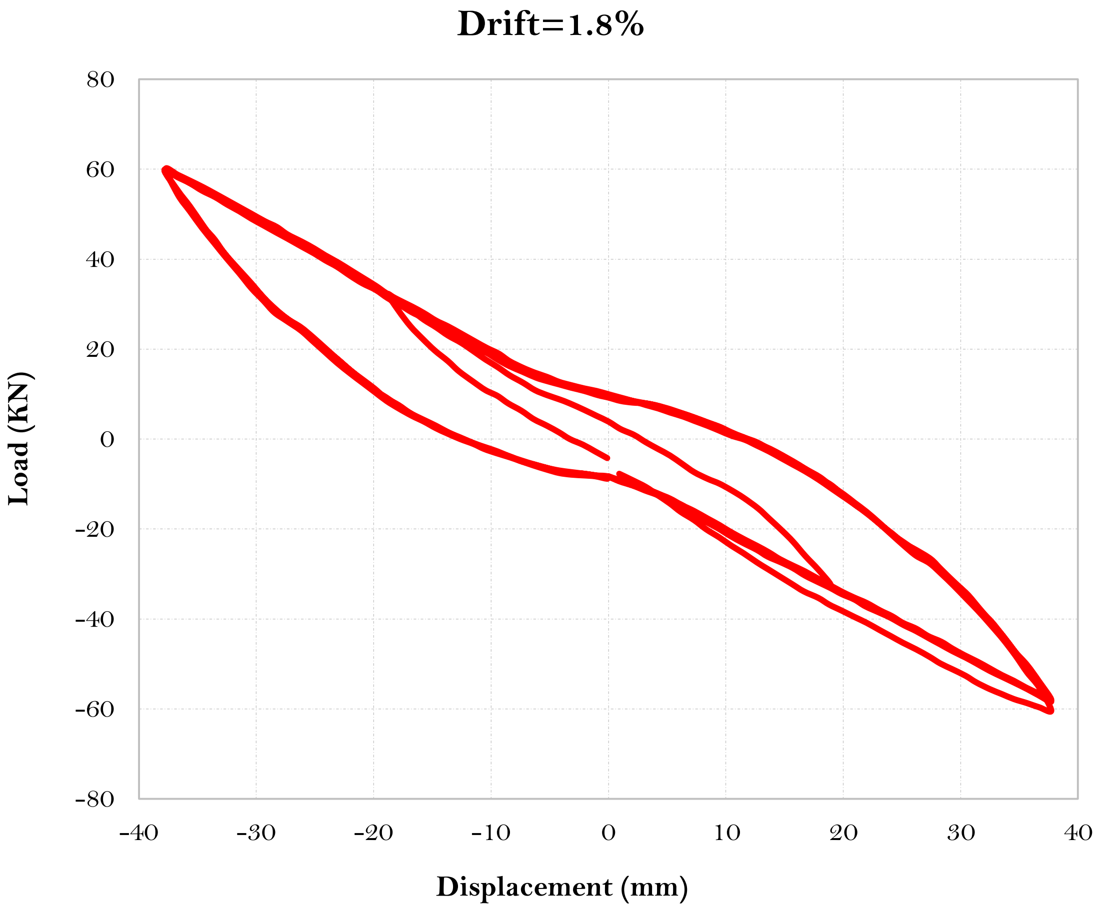

Fig. 6: Force-displacement response of the bridge pier with non-corroded dissipaters

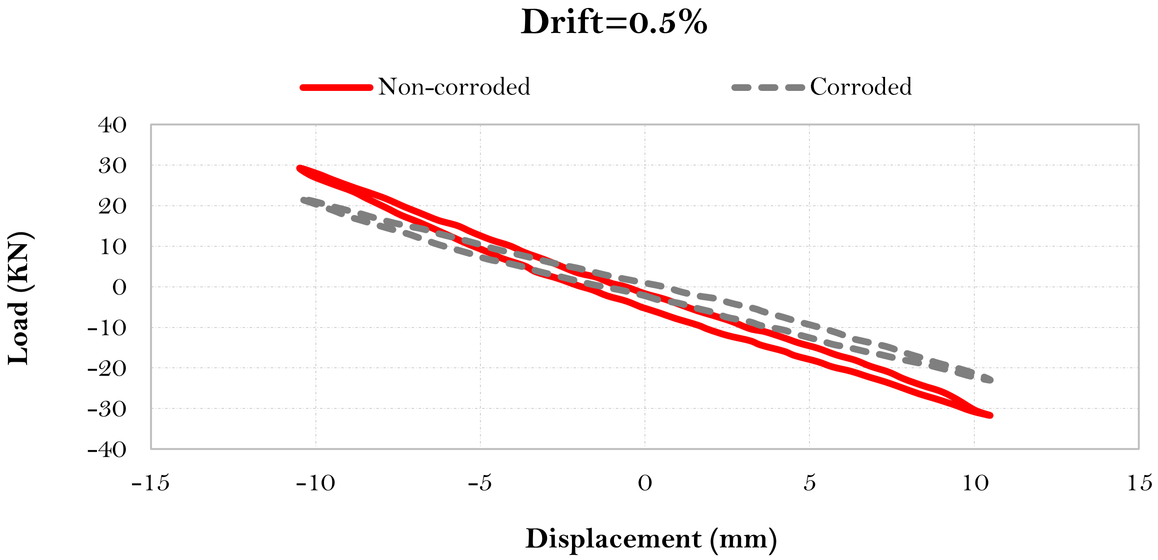

Fig. 7: Comparison Force-displacement responses of the bridge pier with corroded and non-corroded dissipaters for 0.5% drift

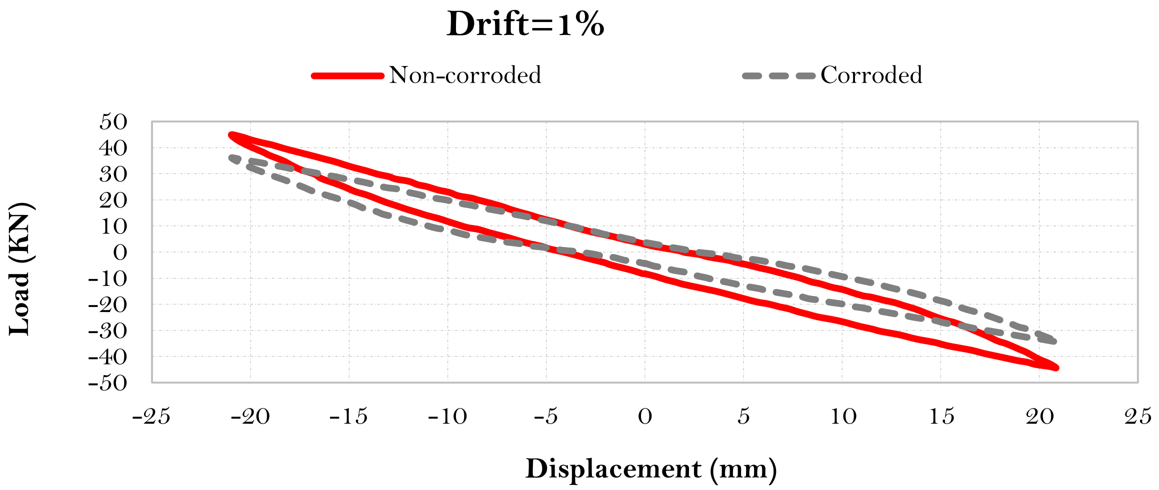

Fig. 8: Comparison Force-displacement responses of the bridge pier with corroded and non-corroded dissipaters for 1% drift

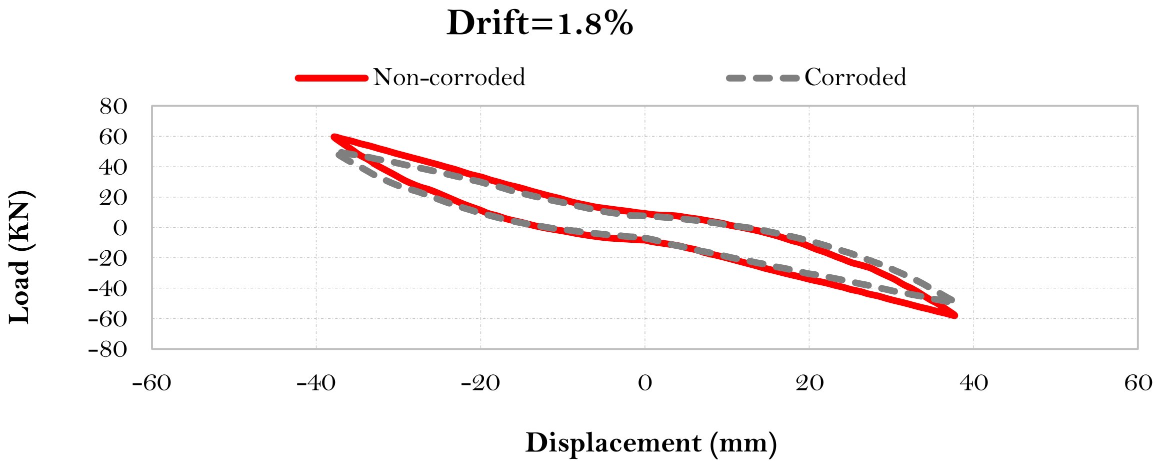

Fig. 9: Comparison Force-displacement responses of the bridge pier with corroded and non-corroded dissipaters for 1.8% drift

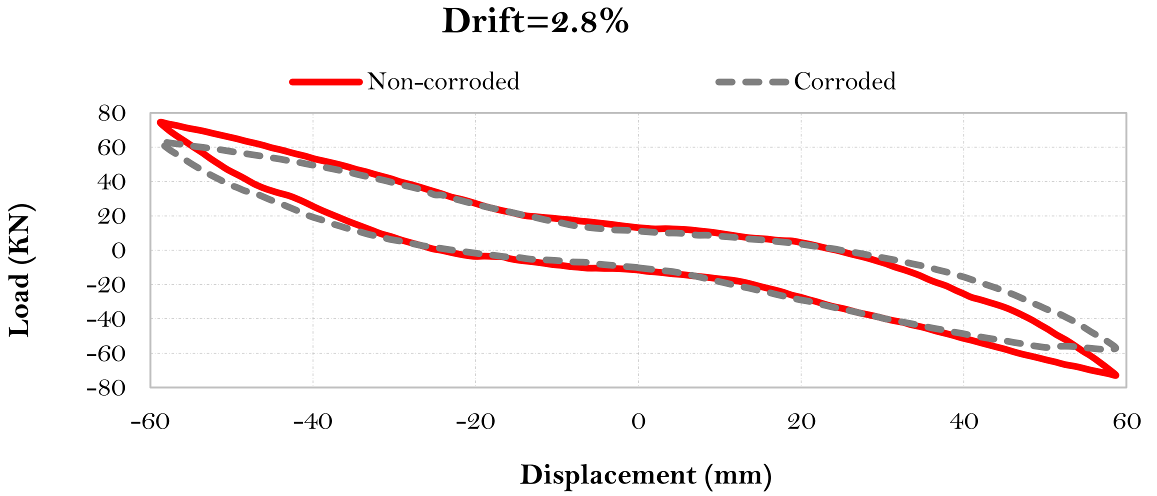

Fig. 10: Comparison Force-displacement responses of the bridge pier with corroded and non-corroded dissipaters for 2.8% drift

The results confirm that corrosion of dissipaters significantly affect seismic response of the rocking bridge pier. However, corrosion monitoring and replacing of corroded dissipaters is quite easy for piers with external dissipaters. Since corrosion is a time-dependent process, life time analysis is needed to analyse bridge piers exposed to corrosion.

5 **CONCLUSION**

In this paper, the effects of corrosion of external dissipaters on seismic performance of controlled rocking bridge pier were studied through experimental tests, and the main results can be summarized as follows:

Corrosion of dissipaters significantly affects seismic response of controlled rocking bridge pier.

While no dissipaters' failure was observed for the pier with non-corroded dissipaters up to 3.4% drift, for the pier with corroded dissipaters one dissipater's rupture occurred in 2.8% drift.

Corrosion of dissipaters caused reduction in stiffness of the rocking bridge pier, and reduction in dissipating energy capability.

Smaller forces are needed for the given displacement response of the pier with corroded dissipaters if compared with non-corroded dissipaters.

A reduction factor of 1 is suggested to estimate the maximum lateral force of the pier with corroded dissipaters as a function of the maximum lateral load of the pier with non-corroded dissipaters.

Corrosion is a time-dependent process affecting service life of bridges, and life-time analysis is needed for assessing existing bridges and also for designing new bridges.

One of main advantages of external dissipaters in controlled rocking bridge pier is that the amount of corrosion can be monitored and to enhance seismic performance of the pier the corroded dissipaters can be easily replaced.

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