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LOW CYCLE FATIGUE BEHAVIOR OF CORRODED FUSE-TYPE DISSIPATERS FOR POST-TENSIONED ROCKING BRIDGE PIERS

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Abstract

This paper presents tensile and low cycle fatigue experimental results of dissipaters used in post-tensioned rocking bridge piers with varying degree of corrosion. The effects of varying degrees of chloride corrosion on the mechanical properties and low cycle fatigue life of dissipaters were studied via quasi-static axial and cyclic tests respectively. The use of bridge pier with permission to rocking motion in its lateral direction at the interface with its foundation is recognized as rocking pier. The rocking motion is controlled by axial post-tensioned load through use of dissipaters mounted to the rocking section to eliminate post-earthquake damage and limit residual drift after an earthquake event. The dissipaters, providing energy dissipation capacity, are uniaxial, tension-compression yielding mild steel bar elements, restrained against bucking and externally placed at the rocking section.

The dissipaters were fabricated from 24mm diameter plan steel reinforcement and provided with reduced diameter to achieve 16mm equivalent diameter over a 245mm fused length. To meet this aim, three grooves were induced by milling along the fused length at 120º interval around the circumference of the plain steel reinforcement. To corrode dissipaters within a reasonable time period, an accelerated corrosion rate of 800 $\mu A/cm^2$ was achieved by applying a constant electrical current to the dissipaters by a power supply. The two degrees of corrosion in terms of mass loss percentage were selected to corrode the dissipaters. The average mass loss percentage for low and high degree of corrosion were (≈ 7%) and (≈ 22%) respectively. The static tensile tests were conducted for 3 non-corroded and 6 corroded dissipaters. This investigation has resulted in clear quantification of the relationship between the degree of corrosion and the mechanical properties of the dissipaters. The cyclic (tensile-compression) tests were conducted for 6 non-corroded and 12 corroded dissipaters using two different deformation rates.

The low cycle fatigue life of the dissipaters was obtained from correlated with the equivalent strain amplitude. The Four-point correlation (4-PC) method was used to estimate fatigue parameters that precisely predicted the low cycle fatigue life of the dissipaters. The deterioration models, developed for reduction in mechanical properties of the dissipaters based on the tensile tests, were employed to modify the fatigue properties presented in the 4-PC method. The proposed fatigue properties can be applied for low cycle fatigue prediction of both corroded and non-corroded dissipaters. The proposed fatigue life prediction method was validated through experimental results. The results can be used in seismic design, seismic evaluation and life cycle analysis of the post-tensioned rocking bridge piers subjected to earthquakes and corrosion.

Keywords: Chloride corrosion, Dissipater, Static tensile test, Mechanical properties, Low cyclic fatigue

1. Introduction

Chloride induced corrosion is one of the major causes of premature deterioration in infrastructure, resulting in considerable maintenance costs. Chloride induced corrosion can cause significant reduction in the cross-sectional area of steel bars, affecting the safety and performance of structures [19].

Corrosion alters the effective mechanical properties of steel bars. To study the effects of corrosion on the mechanical properties of steel reinforcement, a number of monotonic tensile tests on bare bars and RC elements and bending tests on RC beams and slabs were carried out. The results were used to estimate the reduction factors corresponding to the mechanical properties including yield and ultimate (stress or force) strength, elongation, and module of elasticity. The reduction factors indicate the percentage of reductions in the mechanical properties that will occur for 1% reduction in sectional area. They were estimated from experimental results and reported in past studies [12, 4, 7, 13]. There are many studies on the effects of corrosion on the mechanical properties of steel; nevertheless, there is a large variation in the results of the studies for the same amount of corrosion. Moreover, there is no study on the effects of corrosion on the mechanical properties of dissipaters.

As far as construction method of bridges are concerned, Traditional cast in place (CIP) construction for RC bridges is time consuming and can result in quality, maintenance, and post-earthquake repair issues [11]. Unavoidable significant damages were observed in traditional CIP bridge piers subjected to severe earthquakes as a result of inelastic behavior [16]. Bridges are important lifelines that must remain usable soon after occurrence of natural disasters such as earthquakes [14]. Advanced Bridge Construction (ABC), employing precast concrete component technology, is an alternative approach for CIP. ABC has a number of advantages if compared with CIP including, improved quality and durability and decreased construction time and disruption to public transportation [2]. Taking into consideration ABC advantages over CIP, the use of ABC substructures in low seismicity regions is growing [1]. However, using ABC substructures in moderate to high seismicity regions is limited due to concerns about the seismic performance of connections, and further investigations need to be conducted [6, 20]. The ABC connections are categorized into two groups: energy dissipating and deformable connections [11]. Emulative precast connections imitating behavior of CIP connections in severe earthquakes are energy dissipating, and non-emulative precast connections are deformable connections [11]. Considering the critical need for earthquake resilient bridges, non-emulative connections such as dissipative controlled rocking (DCR) have a number of advantages over emulative connections [14]. The DCR connections designed with controlled damage philosophy ensure localized damage in easy access predetermined components called dissipaters [15, 10]. Among the advantages of DCR connections are predetermined repair plans and post-earthquake repair which is rapid and cost effective [5, 17, 9]. The key features of DCR connections are unbounded posttensioned tendons and external dissipaters [15, 9]. The posttensioned tendons clamp precast components and provide self-centering capability, and dissipaters dissipate seismic energy [5, 17, 9, 20].

In this paper, the effects of corrosion on the static monotonic tensile and cyclic (tension-compression) behavior of dissipaters subject to two different deformation rates are determined for a range of corrosion degrees and dissipater configurations. The experimental results of tensile tests were used to develop corresponding reduction factors and deterioration models for corroded dissipaters. A fatigue life prediction model was analytically developed for corroded dissipaters based on Basquin-Coffin-Manson model. The experimental results of cyclic tests were used to validate the proposed fatigue life prediction model. It is worth noting that the dissipaters used in this paper are probably smaller than those used in some real structures. Nevertheless, according to the literature, the effects of type (plain or deformed type) and diameter of reinforcing steels on reduction factors can be neglected [4]. Therefore, the results obtained in this paper can be directly used for real corroded DCR connections.

2. Dissipaters in rocking system

The use of a bridge pier that ensure rocking motion in its lateral direction at the interface with its foundation is recognized as a "rocking pier" [18]. The rocking motion is controlled by axial post-tensioned load through use of dissipaters mounted on the rocking section. Hence, the DCR is employed to eliminate post-earthquake damage and limit residual drift after an earthquake event [14].

In fact, implementation of cost efficient replaceable dissipaters is a crucial key feature of the DCR system. The dissipaters, providing energy dissipation capacity, are uniaxial, tension-compression yielding mild steel bar elements, restrained against buckling and externally placed at the rocking section. Therefore, the dissipaters can be easily replaced after an earthquake event [9]. In this paper, the studied dissipaters are fused-type dissipaters, mild steel round bar milled to a reduced cross-sectional area to concentrate yielding in fused length. Figure 1 shows schematic of a type of fused-type called groove type dissipaters [20]. In this type of dissipater, the fused length was created by milling along the length at 120° interval around the circumference of the plain steel reinforcement. Figure 1 also shows the cross section of the dissipater with anti-buckling system.

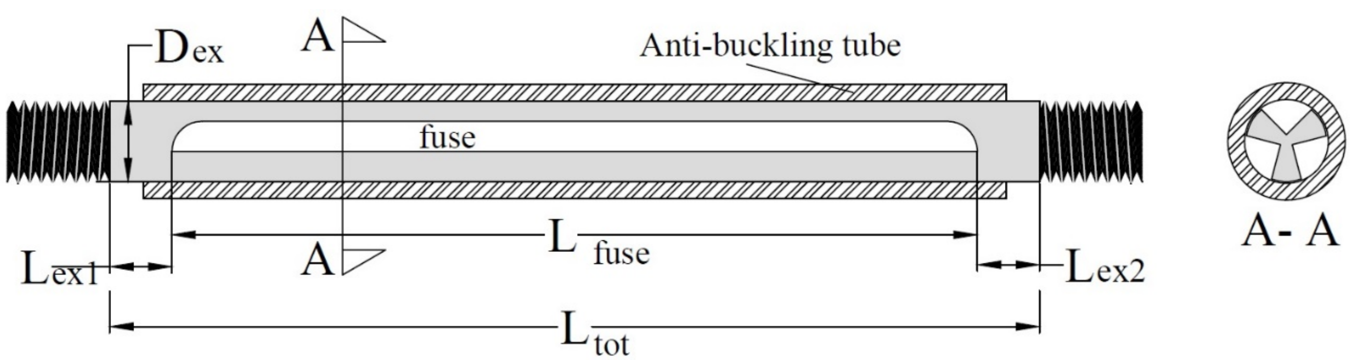

Figure 1: Schematic figure of a groove type dissipater

Figure 2 shows qualitative behavior of a DCR bridge pier with particular focus on the behavior of the dissipater symbolized as "i". When the post-tensioned bridge pier is subjected to horizontal loading, the column will bend in an elastic range without gap opening. A small gap opens at the pier foundation interface when bending moment due to the lateral load reach the decompression bending moment. Increasing gap opening causes to yield the dissipaters. In the unloading, the gap deceases, and at the end of unloading the gap is closed. The dissipaters yield in tension and compression during cyclic lateral loads, and energy dissipates by the dissipaters.

Table 1 shows the details of geometrical parameters of the dissipaters used in this research.

Table 1: Details of geometrical parameters of the dissipaters according to the Fig.1

D_{ex} (mm)	L_{ex1} (mm)	L_{ex2} (mm)	L_{fuse} (mm)	L_{tot} (mm)	Equivalent diameter of the fused-length part (mm)
24	20	20	245	285	17

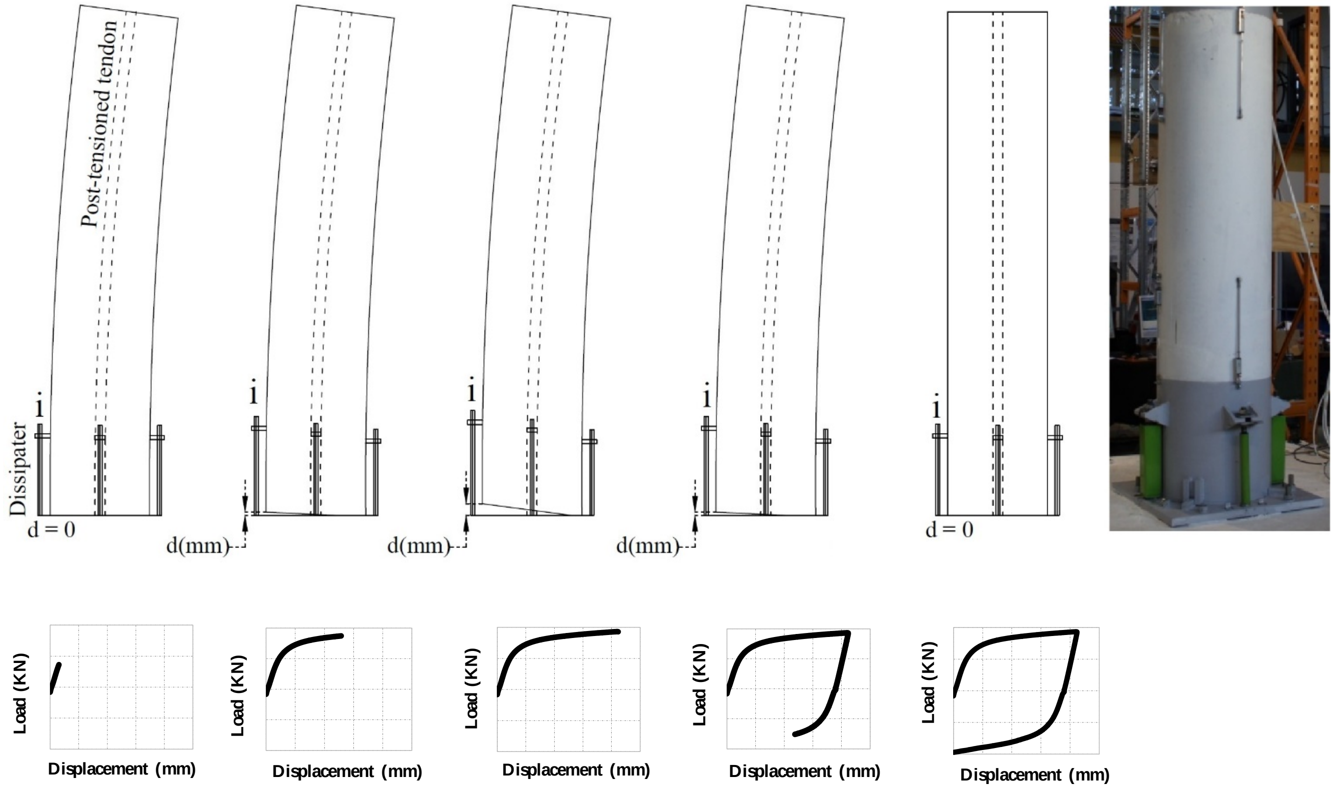

Figure 2: Schematic rocking bridge pier, stress-strain of dissipater i with a photo of a rocking bridge pier

3. Experimental program

The experimental program consisted of three phases: corroding of the dissipaters, Monotonic tensile and cyclic testing. Three testing programs including monotonic tensile, cyclic with deformation rate of 0.75 mm/s, and cyclic with deformation rate of 10 mm/s were conducted. The objective of the tenile tests were determining deterioration model for corroded dissipators. In each testing program nine dissipaters including 3 non-corroded, 3 low-degree corroded, and 3 high-degree corroded dissipaters were tested. Therefore, totally 27 dissipators were tested in this research. All dissipaters were fabricated using Grade 300 mild steel, 24mm diameter, plain reinforcing steel with yield and ultimate stress of 300 MPa and 450 MPa respectively. The length and equivalent cross-sectional area of reduced (fused) length were similar for all dissipaters. A 35 mm (outside diameter) steel pipe with wall thickness of 5 mm was employed as anti-buckling system with 1 mm tolerance between the dissipater and the pipe. The geometrical details of the dissipaters were shown in Figure 1 and Table 1.

3.1. Corrosion test set up

In order to corrode dissipaters within a reasonable time period, an accelerated corrosion method, called electrolytic method, was used in this study. An accelerated corrosion rate of 800 µA/cm2 was achieved by applying a constant electrical current to the dissipaters by a power supply. The dissipaters, immerses in a 3.5% NaCl solution, acting as anode, directly connected to the positive terminal. And stainless steel plates, submerged to the NaCl solution, acting as cathode, directly connected to the negative terminal. The current flowed from the dissipaters to the stainless steel plates through the 3.5% NaCl solution, acting as electrolyte. Figure 3 shows details of corrosion test setup of the dissipaters.

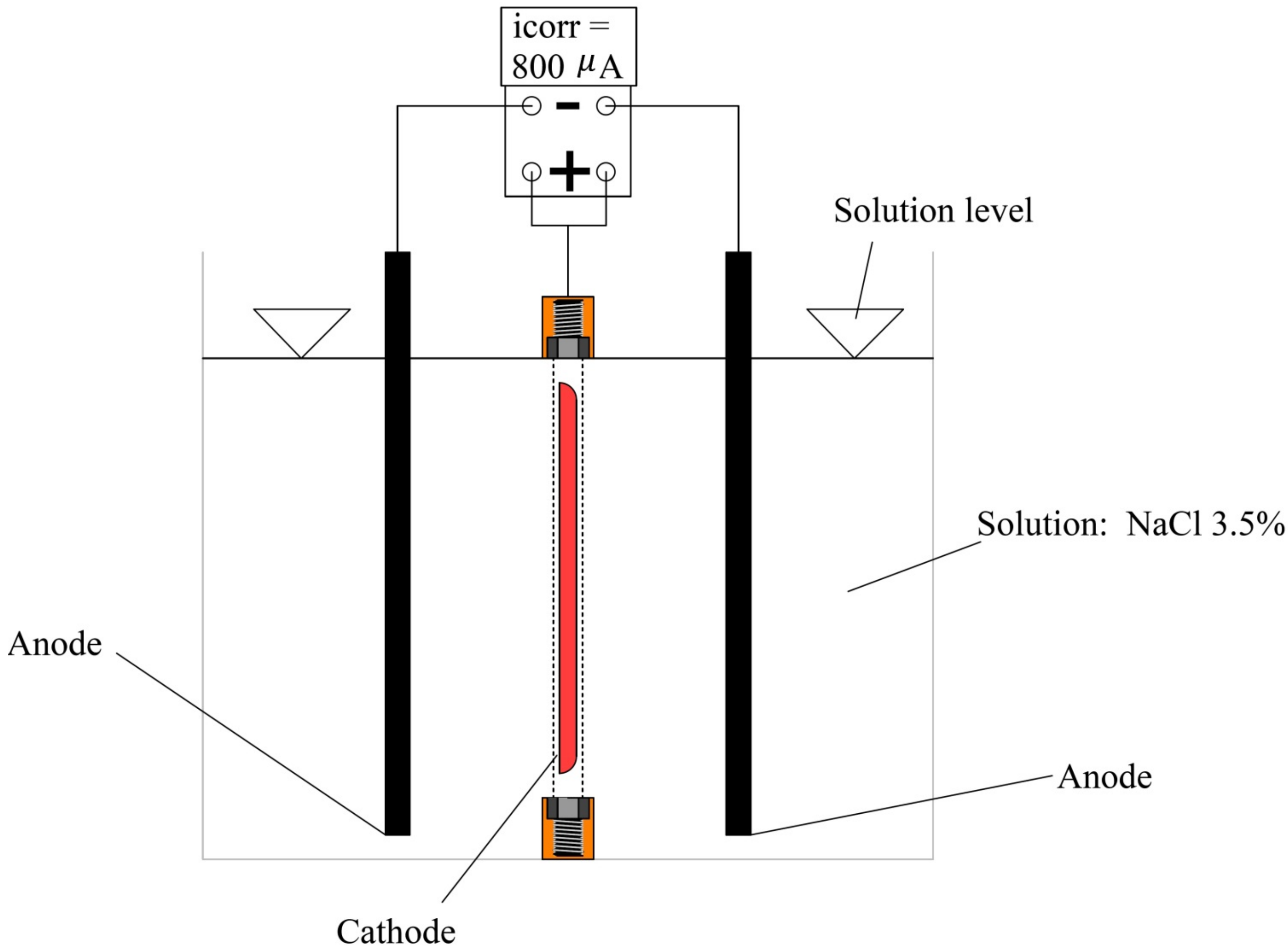

Figure 3: Details of corrosion test setup of the dissipaters

3.2 Tensile test

Nine dissipaters including 3 non-corroded and 6 corroded samples, each 450 mm in total length including 285 mm gauge length, were tested under static tensile tests to failure. The tensile tests were run with a loading rate of 1mm/min in the elastic and 2 mm/min in the plastic range of strain. Three mechanical properties of the dissipaters (ultimate stress, elongation and modulus of elasticity) have been recorded to develop the deterioration models for corroded dissipaters. Strain at the middle of the fuse length of the dissipaters was measured during tensile tests using a contact extensometer. Figure 4 shows the photos of monotonic tensile test setup of the dissipaters.

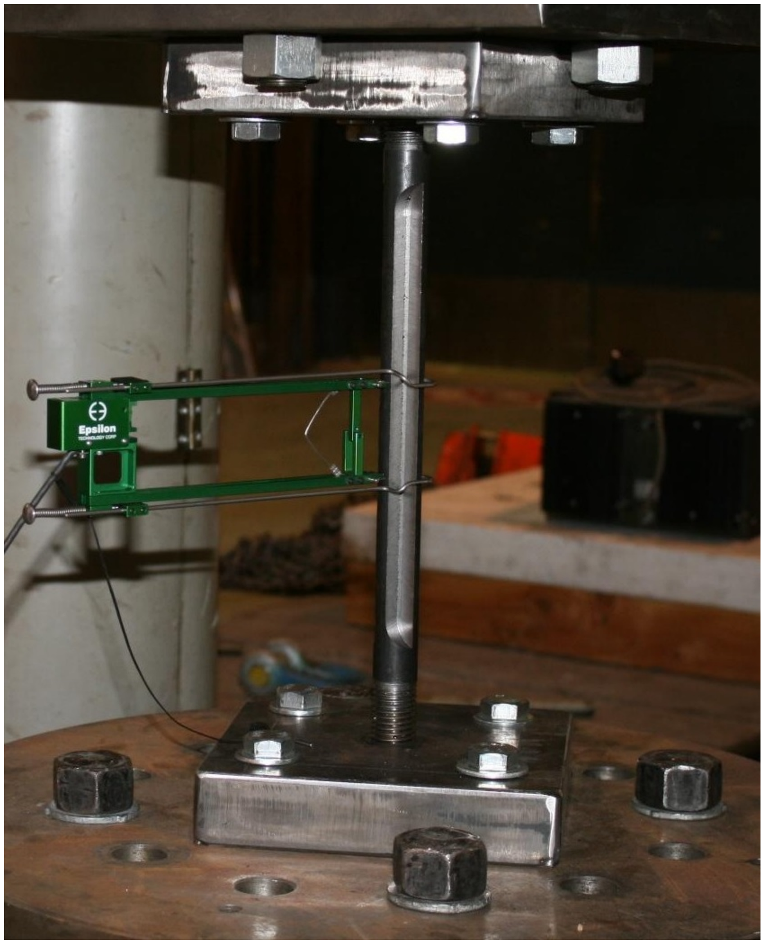

Figure 4: Tensile test setup of groove type dissipaters

3.2 Results of the tensile tests

The effective mechanical properties of steel reinforcement (dissipaters) measured by the machin load cell and the contact extensometer for corroded and non-corroded groove type dissipaters were analyzed for modelling corrosion induced reduction in the effective mechanical properties of the dissipaters. The investigated mechanical properties include ultimate stress, elongation, and modulus of elasticity.
Assuming a linear trend, the relationship between the mechanical properties of corroded and non-corroded dissipaters can be generally expressed as:

$$P_c = [1 - \gamma(W_{corr})] \times P \quad (1)$$

Where, P_c and P are the mechanical properties of corroded and non-corroded dissipater respectively; γ is the corresponding reduction factor that regressed from the test results; and W_{corr} is corrosion percentage.
The results of tensile tests as arelationship between the investigated effective mechanical properties of corroded and non-corroded steel reinforcement and degrees of corrosion were presnted as follows:

$$E_c = [1 - 0.012(W_{corr})] \times E \quad (2)$$

$$\sigma_{u_c} = [1 - 0.0183(W_{corr})] \times \sigma_u \quad (3)$$

$$\varepsilon_{u_c} = [1 - 0.0321(W_{corr})] \times P \tag{4}$$

3.3 Cyclic test

The cyclic tests were conducted using a servo-hydraulic controlled testing machine at two different deformation rates: 0.75 mm/s, and 10 mm/s. The anti-bucking systems were employed during the cyclic tests. Nine dissipaters were tested under unidirectional cyclic at deformation rate of 0.75 mm/s. To study the effects of deformation rate on behavior of corroded dissipaters, nine dissipaters were tested under unidirectional cyclic at deformation rate of 10 mm/s.
A deformation protocol including a series of three cycles at increasing level of displacement was applied through the DARTEC machine. Each cycle includes 100 % target tensile and 10 % target compressive deformation. The used displacement protocol is compatible with the predicted behavior of dissipaters used in rocking bridge pier during actual testing.

The maximum compressive and tensile stress, the maximum strain, the stability, and the number of cycles to failure of the dissipaters were evaluated; particularly with respect to performance of buckling resistant system.
Figure 5 shows the load protocol and a photo of the cyclic test setups of dissipaters. The displacement limit corresponding to the ultimae limit state (ULS) and the maximum creatable earthquake (MCE) have been shown in Figure 5.

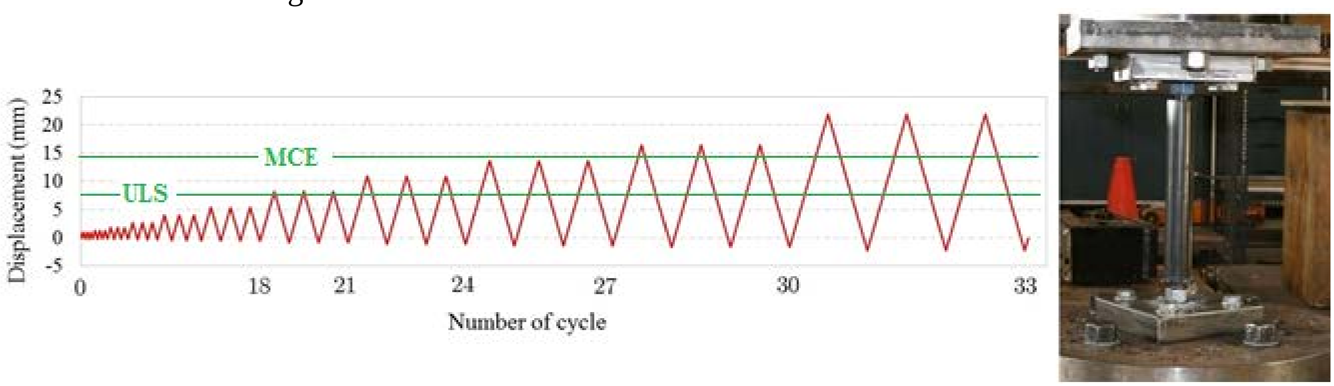

Figure 5: Load protocol and photo of cyclic test setup

4. Low cycle fatigue life prediction of the groove type dissipaters

The fatigue life of the dissipaters can be approximated using Basquin-Coffin-Manson model [21]. The relationship between the total applied stress and the number of cycles based on the Basquin-Coffin-Manson model is as follows:

$$\frac{\Delta\varepsilon_t}{2} = \frac{\acute{\sigma}_f}{E}(2N_f)^b + \acute{\varepsilon}_f(2N_f)^c \tag{5}$$

Where $\frac{\Delta\varepsilon_t}{2}$ is the total strain amplitude, N_f is the number of cycles to failure, E is module of elasticity, $\acute{\sigma}_f$, $\acute{\varepsilon}_f$, b, and c are the uniaxial fatigue properties. A number of methods exist in the literature to estimate the uniaxial fatigue properties.It is noted that the true fracture ductility, ε_f, in some equations can be estimated as follows [3]:

$$\varepsilon_{fc} = \ln(\varepsilon_{uc} + 1) \tag{6}$$

Where, ε_{uc} is the effective ultimate strain for varying degrees of corrosión of the dissipaters.
In this research to estimate the uniaxial fatigue parameters, Four-point Correlation Method was used.

4.1 Four-point correlation method

The Four-point correlation (4-PC) method was suggested by [8] using monotonic tensile properties. The fatigue properties are dependent on the mechanical properties of steel reinforcement inclusing ductility, module of elasticity, and ultimate strength. Therfore, the effective mechanical properties of steel reinforcement for varying degrees of corrosion presented in Eq. (2) to Eq. (4) was used to estimate the fatigue parameters. Finally the fatigue parameters and can be estimated as follows [8]:

$$\sigma'_f = \frac{E_c}{2} \times 10^{b\times\log 2 + \log\left[\frac{2.5\sigma_{uc}(1+\varepsilon_{fc})}{E_c}\right]} \tag{7}$$

Where, σ_{uc} and E_c are the effective ultimate stress and modul of elasticity of the varying degrees of corrosion of the dissipaters respectively.

$$b = \frac{\log\left[\frac{2.5(1+\varepsilon_{fc})}{0.9}\right]}{\log[1/4 \times 10^5]} \tag{8}$$

$$\varepsilon'_f = \frac{1}{2} \times 10^{c\times\log\frac{1}{20} + \log\left(\frac{1}{4}\varepsilon_{fc}^{0.75}\right)} \tag{9}$$

$$c = \frac{1}{3}\log\left[\frac{0.0132 - \Delta\varepsilon^*}{1.91}\right] - \frac{1}{3}\log\left(\frac{1}{4}\varepsilon_{fc}^{0.75}\right) \tag{10}$$

Where $\Delta\varepsilon^*$ is the elastic strain range at 10^4 cycles, and is estimated as follows [8]:

$$\Delta\varepsilon^* = 10^{b\log(4\times10^4) + \log\left[\frac{2.5\sigma_{uc}(1+\varepsilon_{fc}}{E_C}\right]} \tag{11}$$

4.2 Evaluation of the method for fatigue life prediction of the dissipaters

The Four-point correlation method was used to predict fatigue life of the groove type dissipaters. To meet this aim, number of cycles to failure for each strain applied in cyclic tests of the dissipaters was estimated for the presented method. As previously mentioned, a series of three cycles at increasing level of strain was applied. Therefore, the used fatigue life for each strain was estimated based on three to the corresponding number of cycles to failure. The total fatigue life was approximated based on accumulate the used fatigue life of all applied strains until failure. The fatigue life predicted using the presented method was compared with the observations of the cyclic tests at 10 mm/s deformation rate for the non-corroded dissipaters. The results of this comparison (shown in Figure 6) demonstrated that the 4-PC method can accurately predict the low cycle fatigue life of the groove type dissipaters. Figure 6 shows comparison of the fatigue life predicted by the 4-PC with observations of the cyclic tests at varying deformation rates and corrosion degrees. Figure 6 shows that the low cycle fatigue life of the dissipaters tested at 10 mm/s was more accurately predicted than that of 0.75 mm/s deformation rate.

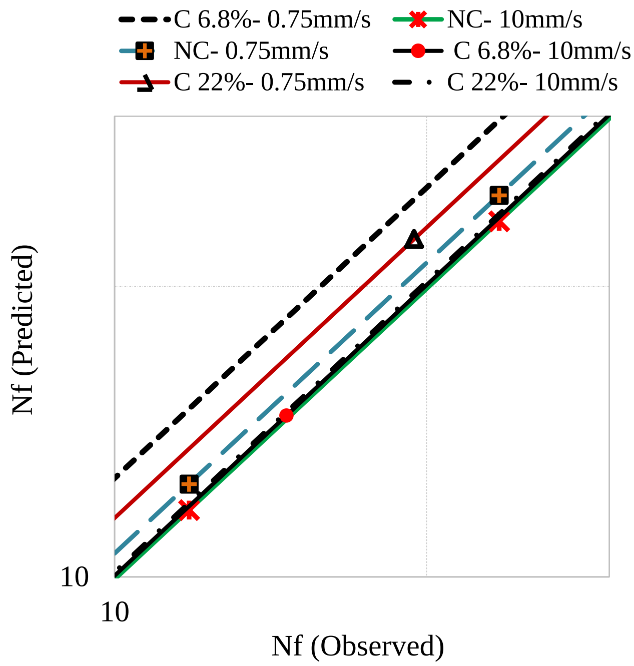

Figure 6: Comparison low cycle uniaxial fatigue life of the dissipaters with varying degree of corrosion predicted by 4-PC, and experiment (observed) with deformation rate of 10 mm/s and 0.75 mm/s

To quantify the accuracy of the 4-PC method, the number of cycles to failure observed in the cyclic tests normalized to that obtained from the 4-PC method is presented in Table 2.

Table 2: Normalized number of cycles to failure for dissipaters with varying degree of corrosion predicted by 4-PC method compared with observed at 0.75 mm/s and 10 mm/s

Fatigue life model	Normalizad number of cycles		
	Non corroded (NC)	6.8% Corroded (C 6.8%)	22% Corroded (C 22%)
Theory	1	1	1
Experimental 0.75 mm/s	1.06	1.33	1.15
Experimental 10 mm/s	0.99	1.07	1.01

The developed analytical model can be used for failure predict of dissipators of post-tensioned rocking columns with dissipators with any level of corrosión. The dissipatos are key feature of dissipating seismic energy, therfore predicting the behavior of dissipators in earthquakes is very important.

5. Conclusions

The paper presented the experimental and analytical study of monotonic tensile and low cycle fatigue behavior of a fuse-type dissipation device (groove type) subjected to corrosion. The dissipaters have been commonly used in damage avoidance seismic solution in precast concrete, steel and timber post-tensioning. The dissipaters are external, so they can be corroded within a short period of time, but they can be replaced after damage easily.

The main objective of the research presented in this paper was to study the effects of corrosion on low cycle fatigue behavior of the dissipation devices.

Deterioration models for mechanical properties of the corroded dissipaters were presented from regression of monotonic tensile tests. The deterioration models were used to predict low cycle fatigue behavior of the dissipaters.

An analytical model was proposed to predict low cycle fatigue behavior of the dissipaters, and the model was validated using experimental tests.

The experimental observations highlighted that the sugessted model to predict low cycle fatigue behavior of the dissipaters have a very good agreement with the experimental results at deformation rate of 10 mm/s. This means the sugessted model may can precisely predict the low cycle fatigue behavior of the dissipation devices in real eathquakes.

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