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A REVIEW OF LOW-CYCLE FATIGUE OF CORRODED STEEL BARS

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Abstract: Low-cycle fatigue (LCF) represents an important material degradation phenomenon that may compromise structural performance under strong earthquakes. A large number of studies have been performed over the past two decades to fully understand and model the LCF behaviours of steel reinforcement, including the combined effects of corrosion and buckling on LCF. This paper presents a critical review of the experimental and theoretical work to forge a converging view on the influential factors of the low-cycle fatigue behaviour with an emphasis on corroded rebars. Testing protocols, major experimental findings, and model development were reviewed. The review finds that the objective of experimental studies has been extended from the sole prediction of fatigue life to more thorough characterization of cyclic behaviours such as strength and stiffness degradation, energy dissipation, and pinching in hysteresis loops, whereas the LCF model has become a submodule of steel rebar's constitutive law under cyclic loadings. It is also found that corrosion does not only reduce the fatigue life drastically, but also significantly affects strength degradation and energy dissipation. Moreover, the presence of corrosion aggravates the synergetic effects of buckling on LCF. It is suggested that future studies should aim to establish LCF model based on measurement of pitting corrosion (e.g., pit depth), rather than that of general corrosion.

1 INTRODUCTION

Under the modern performance-based design philosophy, reinforced concrete (RC) structures in seismic areas need to satisfy various seismic requirements. This means structures should possess sufficient ductility and deformability at material, element and system levels to survive small, medium and large earthquakes within a targeted damage or performance target. Under strong earthquakes, this target is achieved by allowing plastic hinges at the ends of structural members without a significant loss in strength. The inelastic deformation in these regions causes severe tensile and compressive strain reversals in longitudinal reinforcing steel bars. At extreme cases, the steel rebars may rupture, causing the corresponding member to fail prematurely and even the overall structure to collapse. This material failure is called low-cycle fatigue (LCF) failure of rebar (Mander et al. 1994).

To study the LCF of steel rebars, a large number of experimental and theoretical studies have been conducted. The LCF performance of different types of uncorroded rebar has been investigated experimentally (Mander et al. 1994; Brown and Kunnath 2004; Hawileh et al. 2010a) and several LCF models were proposed (Kunnath et al. 2009; Kim and Koutromanos 2016). As structural durability and performance of aged RC structures gained more and more research attention, recent LCF studies have been transitioned to the investigation of the effects of corrosion on LCF behaviours. Representative work includes Apostolopoulos (2007b), Hawileh et al. (2011), Caprili and Salvatore (2015) and Kashani et al. (2015a). Nevertheless, a comprehensive review of the LCF work is lacking.

The purpose of this paper is to glean verified evidences from existing experimental and theoretical investigations on the LCF behaviours of steel rebars. It is hoped that the review will lead to an improved understanding of LCF behaviours of both uncorroded and corroded rebars. For this purpose, the review is conducted and organized as follows: First of all, the corrosion of rebars in concrete is briefly reviewed in Section 2. Although this subject is not directly related to the LCF studies, some basic comprehension of rebar corrosion is important to understand subsequent experimental studies and modeling for the prediction of LCF life of rebars in practical structures. Secondly, the experimental studies, which include both testing protocols and major findings, are reviewed in Section 3. Finally, analytical modeling based upon empirical and theoretical development is reviewed in Section 4. Section 5 concludes the paper.

2 CORROSION OF REBARS IN CONCRETE

Normally, embedded rebars in concrete are in both physical and chemical protection. Physical protection is provided by the dense and relatively impermeable concrete cover, while the thin oxide film formed during concrete hydration guarantees an extra chemical protection. This protective layer prevents the rebar surface from aggressive ions and acts as an alkaline buffer to balance the surrounding pH, making the steel stay passivated. If the alkalinity of pore solution decreases due to concrete carbonation and/or chloride ions penetrating through the concrete cover, depassivation of the oxide film may occur (Moreno et al. 2004). Advancing corrosion brings the reduction of cross-section area and expansion of the volume of oxidation products, causing internal stresses which lead to cracking or detachment of concrete cover and in turn, those breakages will further accelerate the corrosion rates (Andrade et al. 1993).

Steel corrosion in RC structures usually can be divided into two categories: general corrosion due to the reduced surrounding alkalinity induced by concrete carbonation and pitting corrosion induced by the penetration of chloride ions. Concrete carbonation is time-consuming, and it takes decades to make pH of pore solution drop to a certain value. For structures located in coastal areas and other places with high concentration of aggressive ions (mostly chloride ions), such as cold regions where deicing salts are widely used, pitting corrosion may take the main form of corrosion. Generally, corrosion induced by chloride penetration will be faster and more harmful than concrete carbonation. An investigation found that the mass loss of corroded rebar was as high as 18% in 27 years and the problem of corrosion in chloride contaminated structures was more severe than expected (Apostolopoulos et al. 2006).

To investigate the effects of corrosion on the LCF behaviour of rebars, the first task is to prepare corroded rebar specimens. Accelerated corrosion techniques are often used. The common accelerated corrosion methods in laboratory can be categorized based on the surrounding medium of rebars and the way corrosion medium is applied (Table 1). Generally, salt spray tests represent conditions for more uniform corrosion while pitting corrosion can be simulated by current density control. Cyclic wetting and drying method, with or without imposed current, is limited by higher requirements for testing condition and time cost. It is worth noting that even the executed method of accelerated corrosion tests was exactly the same, the mass loss obtained from different laboratories could be very different.

Another important task of corrosion testing in LCF study is to choose the proper measure or measures that describe the extent of corrosion and correlate the best the change in LCF life. So far, the most widely adopted measure is percentage mass loss. The measure works well for general corrosion. More recently, researchers (Caprili et al. 2015; Apostolopoulos and Matikas 2016) pointed out that pitting corrosion in terms of pit depth is more of a controlling parameter for LCF than the percentage mass loss. Some even suggested to use more detailed pit characterization such as pit distribution (Kashani et al. 2014; Kashani et al. 2015a). Another interesting suggestion was the use of cross section uniformity index, which is defined as the ratio of the minimum cross section area to the maximum cross section area of the corroded rebar along the whole testing specimen. If the uniformity index is less than 0.8, the corrosion is defined pitting corrosion; otherwise, it is deemed to be general corrosion. Nevertheless, the majority of the current

LCF models for corroded rebars still consider mass loss as the key measure for corrosion, which might be one thing that needs to be corrected in future. This issue will be further discussed in Section 4.

Table 1: Categorization of accelerated corrosion techniques

		SURROUNDING MEDIUM	
		Air (bare rebars)	Concrete (embedded rebars)
CORROSION METHODS	Salt spray chamber	Apostolopoulos and Michalopoulos (2007), Apostolopoulos and Papadakis (2008), Caprili and Salvatore (2015), Apostolopoulos and Matikas (2016)	Apostolopoulos et al. (2013b), Apostolopoulos and Matikas (2016)
	Electro-chemical circuit	Du et al. (2005b), (2005a), Xia et al. (2013)	Du et al. (2005b), (2005a), Kashani et al. (2013), Kashani et al. (2015a), Fernandez et al. (2016)
	Cyclic wetting & drying	None	Lee and Cho (2009) Cairns et al. (2005), Xia et al. (2013)

3 EXPERIMENTAL STUDIES

3.1 Testing Protocols

Normally, the LCF tests can be conducted by a universal material testing machine with grips that are powerful enough to avoid any slippage. The relative vertical displacement between grips is recorded to calculate the average strain across the entire unsupported length of the specimen. The test is set to displacement control using an axial sinusoidal wave loading pattern. In order to obtain the real effects of corrosion, the specimens should not be machined or treated before tests.

The LCF performance is affected by many different factors. Thus, a feasible and reasonable protocol for LCF tests is required. Only a few European countries, such as Spain (UNE 36065 EX: 2000) and Portugal (LNEC E455-2010), have introduced specific LCF testing protocols for steel rebars. However, such protocols are defined empirically, without reliable background studies. Nevertheless, a consensus seems to have reached that the following four main parameters collectively define an LCF testing protocol:

- the slenderness ratio L_0/ϕ, where L_0 represents the free length of the rebar specimen and ϕ the nominal diameter;
- the amplitude of imposed strain ($\Delta\varepsilon$),
- the testing frequency (f), and
- the number of cycles to execute (N_{cycles}).

With the consideration of all these factors, an elaboration of common procedure for assessing the LCF behaviour of rebars can be developed.

3.1.1 Strain Amplitudes

The strain amplitude is the most important parameter that directly controls the LCF life of rebars. In moderate to severe earthquakes, typical strain amplitudes of rebars in load-bearing members can easily exceed 2% and the recorded strain value is as high as 28% (Apostolopoulos and Rodopoulos 2010). Numerical analyses presented in Braconi et al. (2013) showed that the maximum level of deformation in rebars due to earthquake events in tension and compression was averaged around 6% and -4%, respectively. Based on these, different strain amplitudes have been used in LCF tests. These include:

- A range between ±1% and ±5% (Brown and Kunnath 2004; Kashani et al. 2015a).
- ±2%, ±5% and ±8% (Apostolopoulos and Rodopoulos 2010) according to the typical seismic response reported by Franchi et al. (1996).

- ±1.5% for $\phi \geq 25$mm, ±4% for $\phi \leq 16$mm, and ±2.5% for rebars in between (Braconi et al. 2013)
- ±2.5% and ±4.0% (Apostolopoulos et al. 2013a).

It is important to recognize that here the strain amplitude refers to the amplitude of total strain including elastic and plastic strains. In LCF modeling, some researchers prefer to use only the plastic strain to relate the LCF performance.

3.1.2 Slenderness Ratios

Both field failures and laboratory observations have confirmed that LCF of steel rebars is often complicated with buckling failure, particularly when the rebar has a high slenderness ratio. Current design codes (e.g. Euro Code, (UNI EN 1998-1 2005) and Chinese Code (GB50011 2010)) prescribe the maximum distance between adjacent stirrups to 6 or 8 times of nominal rebar diameter (ϕ) for buildings designed in high or medium ductility class, respectively. For this reason, the free length of testing specimens of 6ϕ or 8ϕ is commonly used. The European standard (BS EN 10080 2005) suggests 10ϕ as the free length for LCF tests. In literature, the actual slenderness ratio of the free length to diameter is found to vary from 2 (Hawileh et al. 2011) to greater than 15 (Fernandez et al. 2016). This wide range of slenderness ratio allows one to perform comprehensive studies of the interaction between local buckling and LCF. It is cautioned, however, that the actual slenderness ratio becomes very difficult to define for corroded rebars, particularly when pitting corrosion prevails.

3.1.3 Testing Frequency

The power spectra of ground motion records showed that the dominant frequency was approximately 2.0Hz (Apostolopoulos et al. 2008). To simulate the characters of earthquake loading, the Spanish test standard, (UNE 36065 EX: 2000) suggests that a frequency from 1.0 to 3.0Hz be used, whereas the Portuguese standard (LNEC E455-2010) is fixed to 3.0Hz (Apostolopoulos et al. 2013a). The frequencies adopted in tests from current literatures are summarized in Table 2.

Table 2: Frequencies adopted in LCF experiments

Uncorroded specimens		Corroded specimens	
Source	*f* (Hz)	Source	*f* (Hz)
Mander et al. (1994)	0.025-0.15	Apostolopoulos and Rodopoulos (2010)	1.0
Rodriguez et al. (1999)	0.005	Hawileh et al. (2011)	0.05
Hawileh et al. (2010a)	0.05	Caprili et al. (2015)	0.05, 2.0
Hawileh et al. (2016)	0.05	Kashani et al. (2015a)	0.1-0.5

3.1.4 Failure Criteria

To determine the exact LCF life in terms of the number of cycles, one needs to determine a priori the LCF failure criteria. Commonly, complete rupture signifies the failure (Apostolopoulos 2007a; Kashani et al. 2015a). However, other failure criteria were used. For example, Mander et al. (1994) and Brown and Kunnath (2004) defined a failure as initiation of a fatigue crack in the test specimen. In that instant the corresponding number of cycle is taken as the LCF life. In another case, Hawileh et al. (2011) defined LCF failure at the instant when the stress in the last cycle dropped to 50% of the maximum stress achieved in the first cycle. These disparate failure criteria used in experiments may affect empirical modeling when one combines data from different sources.

3.2 Major Experimental Findings

A typical LCF failure in a constant strain amplitude test occurs as follows: In the first few cycles, the peak stress in each cycle drops quickly. After that the stress deterioration slows down, and depending upon the strain level, the peak stress even sometimes remains almost constant over a large number of reversals until incipient failure occurs at the initiation of a fatigue crack. Cycling can still continue for a few times, but the crack propagates quickly with the peak stress dropping rapidly till fracture. As a result of the stress deterioration, the energy dissipation per cycle decreases with increasing number of cycles.

A unique difference between the conventional high-cycle fatigue and LCF lies in the fact that in the former the peak stress in each half cycle always occurs at the extreme strain, whereas in LCF the peak stress may occur before the testing strain amplitude is reached. When this within-cycle strength and stiffness degradation occurs, one knows that the material is approaching the end of fatigue life. This is why some researchers defined the end of fatigue life by the instant when the peak stress occurs before the extreme strain is reached. In addition, this phenomenon is further aggravated by the synergistic effects of inelastic buckling and localize corrosion. Before we summarize the detailed findings of these synergistic effects, let us explain the key performance indicators of LCF and their trends along with strain amplitudes at first.

3.2.1 Performance Indicators of LCF

The most commonly used indicator is the number of cycles to failure, or simply LCF life (N_f). Another important one is the total dissipated energy to failure (W_{fT}), which can be calculated numerically by integrating the area under the hysteretic stress-strain curves. For uncorroded rebars, the most significant parameters affecting N_f and W_{fT} are the applied testing strain amplitude and the free length of the specimens (L_0) (Caprili et al. 2015). Both the LCF life and the total dissipated energy generally decreased with the increase of the level of imposed strain amplitudes and the free length of the specimen. Nevertheless, it is evidenced in Crespi's study that the cyclic behavior is independent from loading rate (Caprili and Salvatore 2015).

For uncorroded rebars, the presence of ribs in deformed bars greatly reduced the fatigue life in comparison with smooth bars; however, the reduction diminished with advancing corrosion and strain levels (Apostolopoulos 2007a). Usually, corrosion initiated at the rib bases and reduced them progressively, making the deformed bars smoother. That is why in several cases of the study from Kashani et al. (2015a), rebars with increased corrosion showed a larger fatigue life. However, it should be noted that such specimens still experienced significant losses in W_{fT}. This is a good representation of the energy storage capacity of the material during seismic event.

For corroded rebars, the general trend between the fatigue life and strain amplitude is similar to uncorroded ones, except that corrosion accelerates the reduction in fatigue life. In a series of studies led by Apostolopoulos, corrosion was found to have more significant impact on fatigue life in low strain amplitude than in high strain amplitude (Apostolopoulos and Papadopoulos 2007; Apostolopoulos et al. 2008). Hawileh et al. (2011) further confirmed that as the level of corrosion damage increased, its impact on fatigue life reduction decreased. In addition, they found that W_{fT} not only dependent on the applied strain amplitude, but also decreased as a result of corrosion damage for all applied strain amplitudes. The energy storage capacity of bars is highly dependent on the imposed stain amplitude (Apostolopoulos and Papadopoulos 2007). For low strain level (1%), there was a strong dependency of W_{fT} on corrosion damage while such dependency diminished in higher strain levels (2.5% and 4%). In addition, an overall reduction was found in the peak stress of corroded specimens for each cycle. It is noted that the corrosion damage being discussed in this section is confined to general corrosion, the effects of localized pitting corrosion will be discussed in next subsection.

Existing tests have shown a trend that bars with larger diameters provided a longer fatigue life for lower strain amplitudes. However, as the imposed strain increasing, this trend reversed. Furthermore, the deterioration of fatigue life with increasing strain is more severe in larger-diameter bars (Brown and Kunnath 2004).This phenomenon was confirmed by Caprili and Salvatore (2015) and they found that the decrease of the dissipated energy with increasing strain amplitude was lower in smaller-diameter bars.

In conclusion, it is apparent that the LCF life of rebar is dependent upon the loading history, the applied strain amplitude and the extent of corrosion. Corrosion will result in significant reduction in energy dissipation and life expectancy of reinforced concrete structures in a seismic active zone. Moreover, the effects of corrosion on other performance indicators, such as the strength deterioration of corroded rebars, pinching effect, etc. also worth further study.

3.2.2 Effects of Pitting Corrosion

In early period of corrosion, pit depth of embedded bars was much higher than bare ones, with vertical pits in embedded bars comparing to wide, shallow and elliptical shapes in bare specimens (Apostolopoulos and Matikas 2016).

It is reported that the gradual decrease of strength properties was in particular related to the damage of more resistive martensitic outer layer (Apostolopoulos et al. 2008). Partial loss of the martensitic layer occurred at the rib bases of corroded rebars with progressive pitting corrosion, which was considered responsible for the reduction of strength, elongation to fracture, energy dissipation and fatigue life. Also, pitting corrosion induced premature fracture of bars in tension leading to hysteresis area reduction.

In addition, Bauschinger effect in corroded specimens started at smaller strain demands than uncorroded ones, which can be attributed to the changes of tensile response due to nonuniform corrosion along the bar and premature yielding of weak sections (Kashani et al. 2013). Results of component experiments (Ma et al. 2012; Meda et al. 2014) showed that pitting corrosion affected the global response of corroded RC elements under cyclic loading and may change the failure mode of flexural RC elements.

Obviously, pitting corrosion plays an important role in affecting performance of corroded rebars. However, in practical engineering it is very difficult to locate and measure the pits, i.e., the minimum cross-sectional area of corroded rebar. Although non-destructive methods are available to detect the exact localized damage of steel, those techniques have yet to be applied to the LCF studies.

3.2.3 Buckling Behaviour of Corroded Bars under Cyclic Loading

Existing experimental studies have consistently verified the significant role of inelastic buckling in cyclic stress-strain response of steel rebars, whether corroded or not. It is also evident that the cyclic strength degradation is more remarkable in bars with larger slenderness ratios due to geometrical nonlinearity. The fracture mechanism of rebars changed after buckling with increasing strain amplitude and influence of strain amplitude increased by increasing slenderness ratio (Hawileh et al. 2011). Although buckling is unobservable when $L_0/\phi<6$ (Mander et al. 1994), the presence of corrosion increases the effective slenderness ratio and consequently, buckling is more likely. Nonuniform corrosion creates irregular cross-section shapes along the length of rebars resulting in varying strong and weak axes and load eccentricity, which directly affects the buckling behaviour of corroded bars. As a result, corrosion significantly reduces the buckling capacity of corroded bars.

A pinching effect was obtained in the stress-strain curves of rebars with greater slenderness ratios due to buckling. As the level of corrosion increased, the pinching effect in corroded bars also increased (Kashani et al. 2013). Such effect led to significant decrease in the areas of hysteresis curves and subsequently a reduction in energy dissipation capacity. However, the impact of corrosion on energy dissipation capacity of corroded bars reduced with increasing slenderness ratio (Kashani et al. 2015a).

In the studies of nonlinear stress-strain response of corroded rebar subjected to cyclic loading (Kashani et al. 2013; Kashani et al. 2015a), the location of buckling point depends on the distribution of pits along the specimens. Strain amplitude at inner face of the buckling point with corrosion pit is much bigger than the outer face due to axial plus bending strain, leading to faster crack propagation and earlier rupture. By contrast, if the rebars corroded uniformly, the fracture mode is similar to uncorroded plain bars in smaller diameters. With small diameter and smooth surface, those bars are more ductile than bars with ribs (Apostolopoulos 2007a). By comparing failure modes, Kashani et al. (2015a) suggested that the failure mode of the corroded bars with inelastic buckling under cyclic loading had a significant path dependency.

4 MODELING OF LOW-CYCLE FATIGUE DEGRADATION

A comprehensive description of the performance of reinforcing steel bars consists of monotonic response part, including tension and compression, and cyclic response part. In particular, the effect of buckling on both monotonic compression and cyclic behaviour and the degradation in tension strength due to low-cycle fatigue should be involved. For instance, based on the low-cycle fatigue life relationship established by Brown and Kunnath (2004), Kunnath et al. (2009) developed a generic phenomenological material model for uncorroded rebars consisting of an LCF strength degradation model in tension and Dhakal-Maekawa buckling model (Dhakal and Maekawa 2002) in compression. It also included the Giuffre-Menegotto-Pinto cyclic rules to model the Bauschinger effect. The material model for corroded rebars include additional factors to account for the effects of corrosion on those phenomena.

4.1 Existing LCF Models for Uncorroded Rebars

A typical material model for reinforcing steel bars must be capable of predicting both bar failure and strength degradation. Fatigue life represents the failure of rebar subjected to LCF loading. To predict the bar failure, the well-known Coffin-Manson equation related plastic strain amplitude (ε_{p}) with fatigue life as follows (Mander et al. 1994):

[1] $\varepsilon_p = \frac{\Delta\varepsilon_{\mathrm{p}}}{2} = \theta_f(2N_f)^{-\alpha}$

where $2N_f$ is the number of half-cycles (strain reversals) to failure, θ_f and α are the material constants. Considering the difficulties to define plastic strain amplitudes due to Bauschinger effects, one variant of Eq. 1 using the total strain amplitude (ε_{a}) was developed by Koh and Stephens (1991):

[2] $\varepsilon_a = \frac{\Delta\varepsilon}{2} = M(2N_f)^m$

where *M* and *m* are the material constants. Eq. 1 was adopted by Kunnath et al. (2009) when developing LCF strength degradation model. It was assumed that the strength reduction can also be expressed by a formulation in the form like Eq. 1:

[3] $\varepsilon_{\mathrm{p}} = \theta_{\mathrm{d}}(\delta_{\mathrm{sr}})^{\beta}$

where θ_{d} and β are the material constants, and δ_{sr} is the strength reduction factor corresponding to ε_{p} per cycle, which can be estimated by dividing the total strength loss by the number of cycles corresponding to the cycle preceding failure. The effect of strain history and varying strain amplitudes are involved by the Miner's linear cumulative damage hypothesis and a rainflow counting method may be utilized to compute the cumulative fatigue damage. The material constants in Eq. 1 and Eq. 3 are calibrated based on the tests results obtained by Brown and Kunnath (2004).

In this model, two independent sets of parameters control cyclic degradation and LCF life, respectively. An increase in θ_{d} results in less strength degradation and a smaller value of θ_f will cause fatigue failure in fewer cycles. This model, which incorporates LCF failure and the damage induced by cyclic deterioration, is an advanced description of LCF degradation of uncorroded rebars among current literatures.

4.2 LCF Models for Corroded Rebars

Based on the experimental results, Apostolopoulos and Michalopoulos (2007) suggested that the fatigue life and total dissipated energy were fitted by an exponential decay curve:

[4] $f(\gamma) = C_1 + C_2 e^{(C_3\gamma)}$

where C_1, C_2 and C_3 were material parameters for different corrosion and strain levels. It implies that at higher strain levels, the dominant factor is the applied cyclic strain amplitude whereas corrosion creates the greatest damage on the fatigue life of the material at lower strain levels.

Unsurprisingly, there are few analytical models available that describe the LCF degradation of corroded bars. Kashani et al. (2015b) represents the only exception. They used Kunnath et al.'s model shown in Section 4.1 as the base model and introduced γ to modify the material constant for considering the effects of corrosion. Based upon testing data from Apostolopoulos (2007b), Kashani et al. (2013)

performed regression analyses to calibrate the effect of corrosion on the material constants θ_f and α in (Eq. 1) of the corroded bars. They claimed that the effect of corrosion on θ_f in Eq. 1 was negligible while it did change α. The relationship between corrosion level and α was expressed as:

[5] $k = 1 + 0.4\gamma$

where k is the corrosion modification factor on α. The value of α in Kunnath et al.'s model can be modified with k to account for nonuniform pitting on fatigue life. The influence of buckling in the this model was included within the cumulative damage constant θ_d in Eq. 3. The value of θ_d was modified from 0.2 to 0.6 according to the corroded rebar experimental data obtained by Kashani et al. (2013). Such corrosion extended analytical model generally in good agreement with experimental results up to about γ=25%. However, in the implementation of such model for RC element analysis in Kashani et al. (2015b) studies, there was no validation based on actual experiment results. Whether this model can be used for the prediction of the cyclic response of reinforced concrete components with corrosion still needs to verify.

Moreover, it has to be noticed that there are two important assumptions in Kunnath et al.'s model. The strength reduction per cycle is assumed to be uniform and the relationship between strength degradation and fatigue damage is assumed to be linear for simplicity. However, the reduction of strength degradation increases with the number of cycles, and corrosion will further accelerate this process. Therefore, an improved description of strength reduction is needed, particular for corroded rebars. Also, more experimental data are required to validated the linear relationship between strength degradation and fatigue damage including the tests results from corroded rebars.

It should be noted that, the material constants α and θ_f vary for specific types of steel bars. The average estimate value for ASTM A 615 steels obtained by Brown and Kunnath (2004) of α and θ_f are 0.44 and 0.12 respectively. The reported value of α and θ_f for B500 British Standard reinforcing bars by Hawileh et al. (2010b) are 0.54 and 0.219 respectively. The same situation also appears in the value of θ_d.Therefore, a more extensive and comprehensive experimental database for the performance of steel bars could greatly improve the analysis results. From another aspect, if possible, a comprehensive LCF life model for a wide range of rebar types under different situations can be a solution.

5 SUMMARY AND FUTURE RESEARCH NEEDS

The low-cycle fatigue behaviour of corroded steel reinforcement, including the combined effects of corrosion and buckling on LCF degradation is an important part of material mechanical properties studies. The ultimate targets of LCF studies are to develop seismic performance assessment methods of existing corrosion-damaged structures and to predict the performance degradation of structures in aggressive environment and regions with high seismic activities considering rebar corrosion in design. A reliable material model and proper description of corroded rebars for simulated analysis is an essential part of such procedures.

This review concludes that strain amplitude, L_0/ϕ ratio, corrosion rate are the most important factors that affect the LCF behaviours of corroded bars. Whereas earlier LCF studies focused mainly on the prediction of fatigue life, recent studies included strength degradation, energy dissipation and the synergistic effects between corrosion and buckling. In terms of model development, this review found that LCF modeling for corroded rebars had been simply an extension from the practice for uncorroded rebars using mass loss as the additional parameter that measures the extent of corrosion. Our review found that the mass loss can be a poor indicator when pitting corrosion is prevalent. It is thus suggested that future experimental studies measure the maximum pit depth and mass loss for a better prediction of LCF behaviors for corroded rebars. The review has also found that there is limited work in the development of a unified LCF model for both intact and corroded rebars. To this end, it is suggested that a comprehensive database including corroded and uncorroded rebars be developed.

Finally, the developed LCF models need to be further validated at the element and structural levels. Currently, experimental results for degraded RC members and structures with corroded rebars are very rare. Further experiments are therefore highly desired. On the other hand, due to the complexity and random nature of fatigue and corrosion, probabilistic modeling approach for LCF are suggested for further study.

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