PREDICTION SEISMIC PERFORMANCE (LCF) OF CORRODED REINFORCING STEEL BARS

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Abstract

In this study, the impact of corrosion in S400 grade of reinforcing steel bar as for the mechanical performance on seismic loads (low-cycle fatigue LCF) was investigated. The mechanical performance and life expectancy of S400 grade of reinforcing steel bar on seismic loads was evaluated based on the strength degradation (reduction of maximum strength) during its loading time period, under corrosion or not circumstances. The results show that corrosion level, as a parameter, has a negative influence on the seismic performance of steel bar. Therefore, a phenomenological hysteretic model of non-corroded and corroded steel bar was also conducted considering two levels of imposed deformation (±2.5 % & ±4 %). The effectiveness of material model was validated through comparison with experimental data being in a good agreement with the observed experimental results. At this point, a lower limit value (threshold) of upper tensile and compression load was also introduced, in order to predict the performance and the useful life duration (number of cycles) of a Reinforced-Concrete (R/C) member. That could lead to warning signs of awakening in order not to use unreliable parts of R/C in existing structures, prior to their life expectancy.

Keywords: Steel rebar, corrosion, seismic performance, material model, life expectancy

1. INTRODUCTION

It is well known that corrosion effect is an electrochemical nature phenomenon which constitutes one of the basic factors of degradation of reinforcing concrete structures. In the past, lots of studies have presented the negative circumstances of corrosion effect, such as the local decrease of cross section and the respective mass loss. Meanwhile, corrosion effect has an impact on the mechanical behavior of steel bar due to the reduction of strength properties, the ductility and the bonding between the concrete and the steel bar. The corrosive factor in correlation with the effect of seismic loads plays an important role in the mechanical performance of structures. Sheng and Gong [1] studied and showed that the effect of seismic loads can be simulated, in a laboratory, in low cycle fatigue conditions. This effect can induce a reduction of steel bar's loading ability as well as their failure. Corrosion effect appears to begin from chloride ions penetration through the pores of concrete either through the action of capillary voids of water or a combination of them. An important percentage of chloride concentration, on corrosion effect, is about 0.4 % of concrete's weight [2]. In case of corrosion effect, and the generation of pits (chlorides penetration), the tension rate of stress and also the stress concentration rate increases, resulting in the formulation and the development of micro-cracking which, in concert with seismic loads, causes the material's failure. Although a significant number of researchers have presented the consequences of mechanical degradation of steel bar due to seismic loads and corrosion effect, the international design regulations of structures, apart from the Portuguese and Spanish regulations, do not include adequate technical requirements for the reinforcing steel bars. Furthermore, the negative effect of the buckling phenomena in steel rebar is not taken into consideration. A plethora of mathematical models have been proposed that are mainly influenced by material model such as the Guiffre-Pinto [3] and Menegotto-Pinto model [4] that simulates the inelastic fatigue behaviour of steel bars.

Based on the results of an extensive experimental study, in which steel bars in various seismic loads (Low Cycle Fatigue in ±2.5 %, and ±4 % deformation range values [5]) were examined, an effort of predicting the fatigue behaviour of corroded and non-corroded steel bars S400 is made. More specific the degradation of maximum strength and the life expectancy were examined, based on LCF tests. Furthermore, a simplified hysteretic model was conducted so as to simulate the non-linear dynamic response of reinforcing bars representing at the same time the effect of inelastic buckling and LCF strength degradation as well. At this point, a complementary study of predicting the performance and the useful service life of a Reinforced Concrete (R/C) member was demonstrated by introducing an upper tensile and compression load threshold of steel reinforcing bar.

2. EXPERIMENTAL

2.1. Low-cycle fatigue test

The experiments were conducted on S400 grade reinforcing steel, specially produced for the needs of the current investigation by a Greek steel mill. The chemical composition of steel S400 is (in wt. %): 0.35C, 0.94Mn, 0.026S, 0.013P, 0.26Si, 0.10Ni, 0.16Cr, 0.42Cu, 0.002V, 0.023Mo, 0.01N. Though S400 steel (widely known as StIII or BSt420) has officially been withdrawn since the late 1990's from production, it still holds as the backbone of reinforced structures aging from 20 to 50 years. The steel rebars were delivered in the form of 10 mm nominal diameter ribbed bars according to Apostolopoulos and Pasialis [5] study. Specimens with 170 mm total length and 60 mm in gauge length were cut for the LCF tests. Prior to the tests, the specimens were corroded using accelerated laboratory corrosion test in salt spray environment. Salt spray tests were conducted according to the ASTM B117-94 specification. For a detailed description of the spray chamber configurations and the artificial environmental conditions, the reader may refer to [5]. The duration time of exposure was 45, 60 and 90 days. **Table 1** presents the low cycle fatigue test results (in different amplitudes of deformation ±2.5 and ±4 %).

Table 1 Low Cycle Fatigue test results

Days of corrosion	Strain (%)	Cycles to Fracture	Dissipated Energy [MPa]
0	±2.5 / ±4.0	40 / 11	1059 / 537
45	±2.5 / ±4.0	24 / 10	629 / 470
60	±2.5 / ±4.0	24 / 7	627 / 337
90	±2.5 / ±4.0	24 / 7	587 / 272

2.2. Modeling of low-cycle fatigue behaviour

The adopted method to analyze the non-linear behavior of steel rebar submitted to cyclic loads, constitutes an aspect of well-known Guiffre-Menegotto-Pinto model, that was initially proposed by Guiffre and Pinto (1970) [3] and implemented later by Menegotto and Pinto (1973) [4]. The initial form of this model does not take into consideration the Bauschinger phenomenon. In this model, the cyclic behavior via stress-strain relation of steel rebars is represented. The envelop curve related to loading, unloading and reloading is described by the following equation form:

$$f' = b\varepsilon' + \frac{(1-b)\varepsilon'}{\left(1+\varepsilon'^{R}\right)^{1/R}} \tag{1}$$

The accompanying terms consist of a modified form of that proposed by Filippou et al. [6] and are defined as:

$$\varepsilon' = \frac{\varepsilon_s-\varepsilon_Q}{\varepsilon_P-\varepsilon_Q},\ f' = \frac{f_s-f_Q}{f_P-f_Q},\ b = \frac{E_{sh}}{E_s} \tag{2}$$

The objective of the above modification i.e. the insertion of an extra parameter “Q”, was not only to improve the accuracy of the model but also to incorporate an extra point that contributes to the approach of the Bauschinger effect, in case where buckling phenomenon does not exist.

The above equation represents a curved transition from a straight line asymptote with slope E_s to another asymptote with slope E_{sh}. The position of the asymptotes correspond to the yield surface is assumed to be constantly shifted and the slope E_s to remain constant (**Figure 1**). It should be pointed out that even though the slope of E_s is actually shifted in an experimental procedure, this change is so limited as to neglect it, and thus it was received as constant.

The parameters f_Q and ε_Q are stress and strain at the inception point of envelop curve. It should be noted that the unloading part of hysteresis branch initially takes place along a line parallel to elastic region. The end of this linear unloading part constitutes the inception point of transition branch that refers to Q point. The parameters f_P and ε_P are stress and strain at the point where the two asymptotes of the branch under consideration meet (point P). From that point, the transition from tension to compression (and vise-versa) follows a branch curve that forms a smooth “knee”, that is located at the point of theoretical yielding point in case of monotonic loading. The term b is the strain hardening ratio defined as the ratio between slope E_{sh} and E_s R is a parameter that influences the shape of the transition curve.

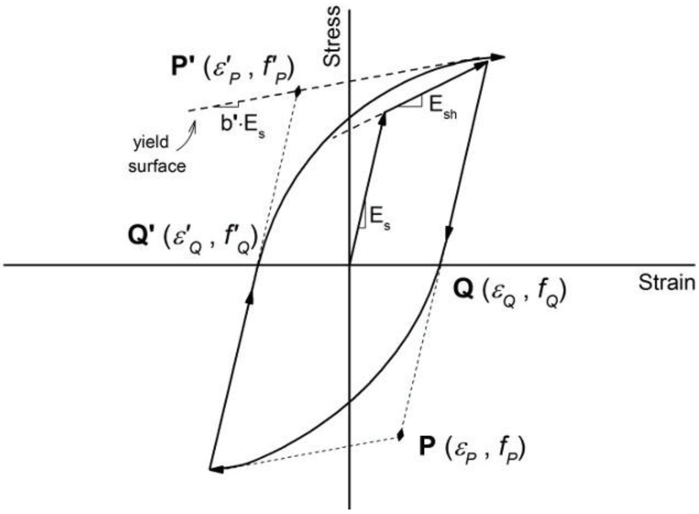

Figure 1 Representation of model and parameters

The main reason of adopting the model of Menegotto and Pinto rely on the fact that each parameter defines a different geometry of the envelop curve and therefore the parameters can be easily determined from the experimental data.

As indicated in **Figure 1**, the coordinates P (ε_P,f_P) and Q (ε_Q,f_Q) are updated after each strain reversal. The parameters P′ and Q′ refer to anion transition curve.

The determination of the coordinates Q and P, as for cation branch, and Q′ and P′, as for anion branch of envelop curve, were based on experimental data. By isolating the cation and the anion envelop curve from each cycle in combination with the modified mathematical model, the parameters R and b and R′ and b′ were specified, respectively. For the purpose of simplifying the modeling process, the variance of parameters was basically approached through linear fitting. As depicted in **Figures 2 - 4** the implementation of simplified functions sufficiently approaches the experimental results.

3. RESULTS AND DISCUSSION

In **Figure 2** (left) is depicted the radius R and R′ of the curve of transition branch. Based on the fact that the fluctuation of the values is limited, it does not significant effect the prediction and therefore the parameter R and R′ were represented by horizontal lines of average value R_{av} and R'_{av}, respectively. In **Figure 2** (right) is depicted the variation of parameter b as a function of number of loading cycles.

From the investigation of the function of the transition branch it was observed that b parameter significantly influences the envelop curve and the maximum load value (strength degradation). Therefore, the parameters b refer to cation transition branch can be adjusted through an exponential type function, while the parameters b′ of anion transition branch through a linear type function in case of corroded and non-corroded, steel bars.

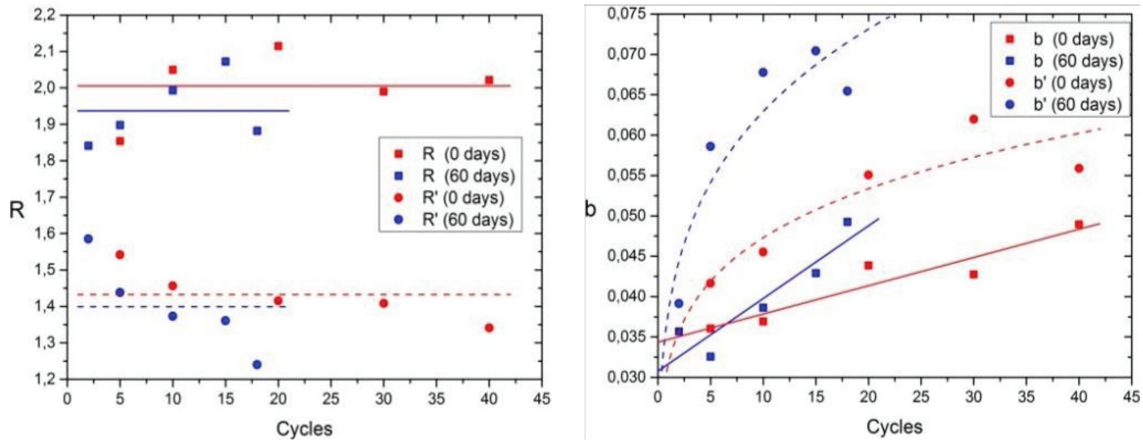

Figure 2 Parameter R and R′ (left) and Parameter b and b′ (right) as a function of number of cycles for corroded (60-days) and non-corroded rebar

In **Figures 3** is depicted the distribution of the coordinates of point Q and Q′ defined as the point of the section of linear branch of the material and the inception part of transition branches. According to the fact that the ability of material for elastic deformation is reduced in the long run, the coordinates of Q point show an algebraic degreased behavior and the respective of Q′ point an increased behavior (**Figure 3**). The approach of the coordinates Q and Q′ was based on linear type functions.

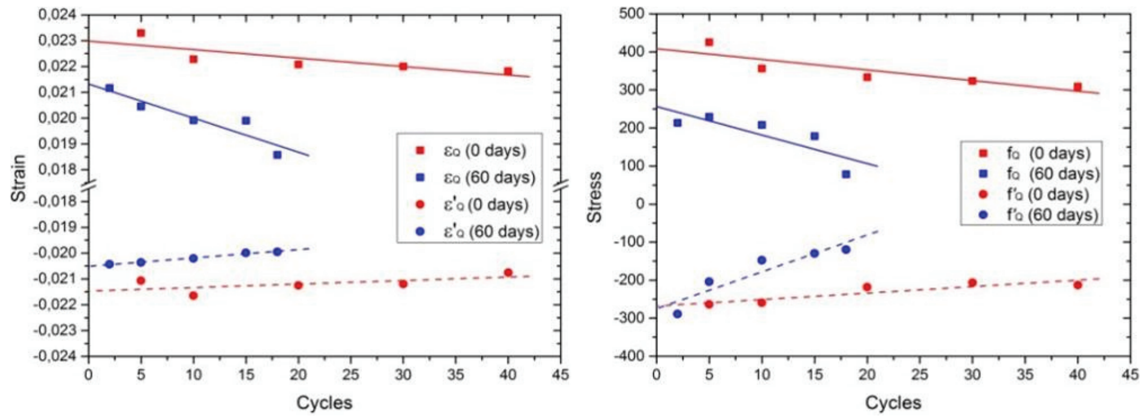

Figure 3 Parameter of strain (left) and Parameter of stress (right) at point Q as a function of number of cycles for corroded (60-days) and non-corroded rebar

In **Figure 4** it is depicted the variation of the coordinates of point P and P′ defined as the theoretical yielding points. The position of P and P′ is directly influenced by the strength degradation per loading cycle. As a result, the coordinates of P shows an increased behavior while the coordinates of P′ shows a degreased behavior. For the needs of prediction, the adjustment of the coordinates was made through linear type function. Herein, it is observed that the linear function refers to strain of corroded steel does not show any difference in comparison with that of non-corroded rebar. On the contrary, in the case of stress it is observed a differentiation of inclination between the corroded and non-corroded rebar in case of cation branch in the same way as for anion branch. Relied on the adjusted curves from the above graphs, the prediction behavior of steel bar (of hysteretic branch) established through the use of a code in a MatLab programming language. In this code the adjusted functions for a certain strain level are inserted in case of non-corroded and corroded for 60 days, respectively.

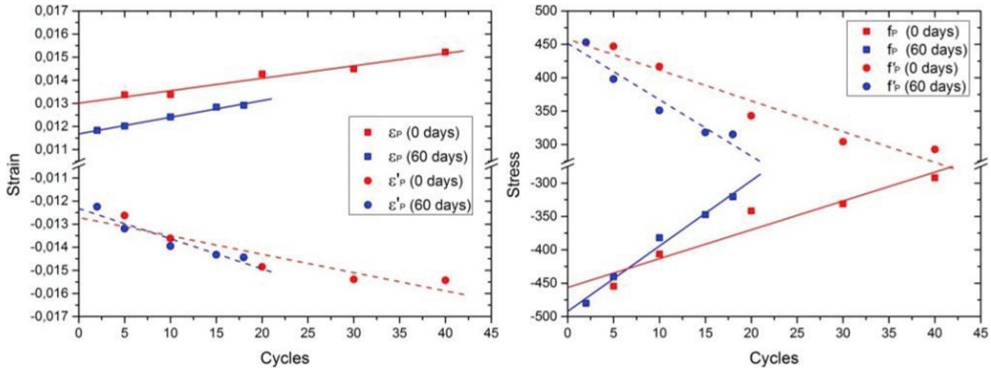

Figure 4 Parameter of strain (left) and Parameter of stress (right) at point P as a function of number of cycles for corroded (60-days) and non-corroded rebar

The connection of cation and anion transition braches in each cycle of the model is accomplished in order to draw the stress-strain dependence of hysteretic braches according to low-cycle fatigue diagram. A comparison between the experimental results and the aforementioned prediction material model follows, based on the parameters developed in this study. In **Figures 5** (left & right) is depicted the comparison of the experiment and the model for imposed deformation rate ±4 % of non-corroded and corroded for 60 days.

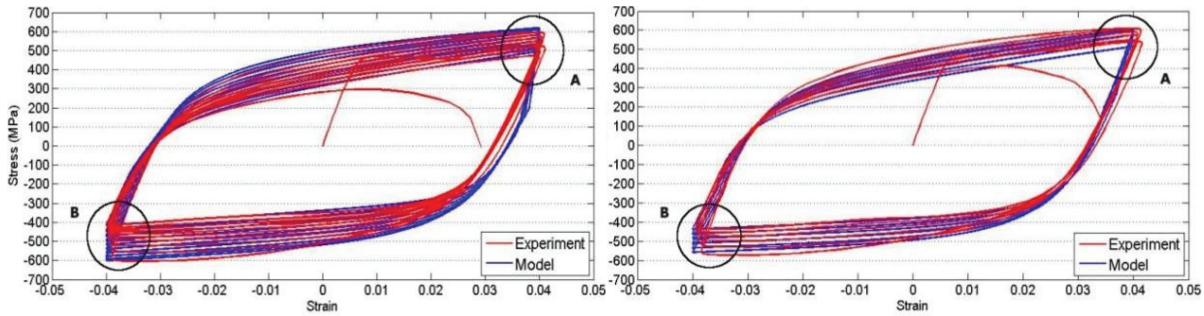

Figure 5 Comparison of the experimental results and the proposed analytical model at ±4 % strain amplitude on non-corroded (left) and on corroded (right) rebar (60-days)

From **Figures 5** it is observed that the prediction model is in a good agreement with the experimental results. The variation of maximum loads level (section A and B), under the progress of cyclic loads, is in the range of 10 - 15 MPa at the most. This variation is acceptable as the experimental results of steel bar differ from test to test. Furthermore, remarkable is the fact that the prediction model is able to simulate the buckling phenomenon in a sufficient manner being in a good agreement with the experimental results.

In **Figure 6** is depicted the gradual reduction of maximum received load per loading cycle in case of imposed strain rate ±4 %. Initially, a rapid increase of the exerted force took place during the first cycle due to hardening of the material. Following that, a gradual reduction of the exerted force was observed for most of the specimens' life followed by a new rapid drop that continues until the failure of the specimen. The reinforcing steel used in RC structures however, is expected to carry a constant load throughout its service life since the loads exerted on the load carrying elements of such structures remain fairly constant over time. By defining a lower limit of 80 % of maximum load, the beneficial number of cycles is dramatically reduced, 66 % loss for 90 days of accelerated salt-pray corrosion. By inserting in as limits the values of 38.95 MPa of tensile branch and -37.94 MPa of compressive branch, the ongoing reduction is considered as strong reason of deconstruction of concrete in the reinforced concrete members. The acceptable limits of maximum tensile and compression receiving loads are depicted in **Figure 6**. In this case, the existing buckling phenomena and the level of corrosion induce a significant reduction of load-bearing capacity and endurance of material.

Table 2 Results of Low-Cycle Fatigue test

Days of salt spray Corrosion	0	45	60	90
Number of Cycles	11 11 12	9 10 11	7 7 8 6	7 7 5 7
Mean	11	10	7	7
Dissipated Energy [MPa]	521 523 568	447 491 551	338 339 384 287	314 285 207 283
Mean	537	470	337	272

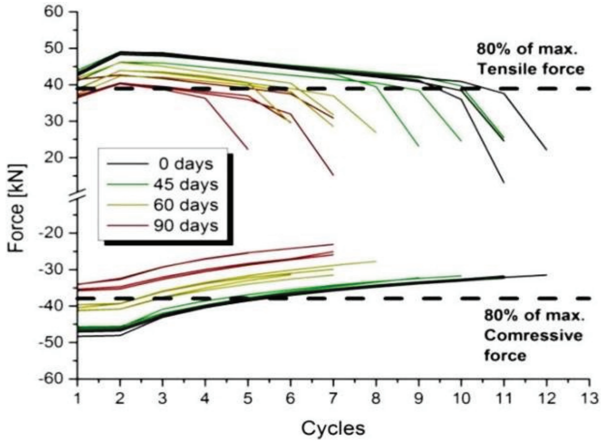

Figure 6 Cycles before load capacity drops below 80 % of the maximum tensile and compressive value for ±4 % strain level

4. CONCLUSION

The main outcomes of this study can be summarized as follows:

- The corrosion phenomenon leads to rapid degradation of steel bars in ±2.5 % strain amplitude. Because of this fact the fatigue life decreases. In ±4 % strain amplitude, the buckling effect plays the main role and, hence, the corrosion does not effect on strength degradation.
- The simplified fitting curves for the parameters of the mathematical model Menegotto-Pinto predict a satisfactory level the experiments including the inelastic buckling phenomena and the corrosion effect.
- The force - fatigue cycles analysis shows that the designer engineer should take into account a part of fatigue cycles and not the total cycles to failure because drop of the 75 % limit of the initial strength can destroy the bond between concrete and reinforcing bars.

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