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The Influence of Corrosion Damage on Low Cycle Fatigue Life of Reinforcing Steel Bars S400

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Abstract

In this study the influence of corrosion and seismic load (low-cycle fatigue LCF) in the mechanical performance of reinforcing steel bars of S400 grade with 10 mm nominal diameter was investigated. There took place 140 tensile, LCF and salt spray tests which performed on reinforcing bars in different conditions. The results show that the corrosion level and surface conditions are the main parameters which affect to the low-cycle fatigue life of reinforcing bars. Moreover, through a non-linear regression analysis of the experimental data, a model of predicting the expectancy life of the corroded rebars was conducted.

This prediction was based on two models: the first model was about an imposed of (total) strain amplitudes (ε_α) and the second model on predicting the strength degradation per cycle of fatigue in correlation with the plastic strain amplitudes (ε_p). Both the experimental study and the prediction modeling conducted for the same steel grade S400 with and without ribs. The model prediction of non-linear regression analysis, show a good agreement with the observed experimental results and adequately confirmed the experimental results showing that from the first levels of corrosion, the degradation of their life expectancy was obvious as well the rebars without ribs (smoothed) which present more advanced mechanical behavior and life expectancy against to the respective ribbed rebars.

Keywords: Steel Reinforcement bar; Fatigue Behavior; Corrosion; Nonlinear Analysis; Low-Cycle Fatigue model

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 past, lots of studies [1-5] 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 mechanic performance of structures. Sheng and Gong [6] 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 with chlorides through the pores of concrete, 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 [7]. In case of corrosion effect, occurring through pits (chlorides), the tension rate of stress and also the concentration rate of stress increase and as a result the formulation and the development of micro - cracking which, in combination with the fatigue, cause the material's failure. Although a significant number of researchers [8-10] presented the consequences of mechanical degradation of steel bar due to seismic loads and corrosion effect, the international design regulations of structures, except for the Portuguese and Spanish regulations [11,12], did not include similar technical requirements for the reinforcing steel bars. Moreover, special well known life expectancy predicting models of metal materials belong to Coffin-Manson [13,14] and Koh–Stephens [15]. Based on the above models, in this study there is an effort of predicting the life expectancy of steel bar S400. In more detail, based on the results of an extensive experimental study, in which steel bars in various seismic loads (Low Cycle Fatigue) were examined, before and after several periods of time exposed to an artificial imposed of accelerated corrosion effect in salt spray chamber. Steel bars S400 with and without ribs have undergone some fatigue tests in monotonic sinusoidal loading of 0.5 Hz frequency in various deformation range values such as ± 1%, ± 2.5%, and ± 4% [16]. S400 steel bar category, even though today has a limited usage, the last decades constituted the main material of many structures in Mediterranean countries (Greece – Italy - Turkey). Therefore, the potential for predicting the life expectancy of steel bars in already existing structures (of various level of corrosion) is really interesting fact for the engineer researchers because it contains useful information about the level of steel bars' mechanical performance and for the level of reliability of crucial structural elements of constructions (such as the columns).

Experimental Procedure

The experiments were conducted on S400 steel grade reinforcing steel, specially produced for the needs of the current investigation by a Greek steel mill. Chemical composition of steel S400, is shown on Table 1. S400 steel (widely known as StIII or BSt 420) 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 material was delivered in the form of 10 mm nominal diameter ribbed bars according to Apostolopoulos and Pasialis [16] study. Specimens

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with 170 mm total length and 60 mm in gauge length were cut for the LCF tests. The gauge length was equal to six times the nominal diameter of steel specimens. Prior to the tests, the specimens were pre-corroded using accelerated laboratory corrosion tests in salt spray environment. Salt spray tests were conducted according to the ASTM B117-94 specification. For the tests, a special apparatus, model SF 450 specially designed by C and W. Specialist Equipment Ltd. was used. The salt solution was prepared by dissolving 5 parts by mass of sodium chloride (NaCl) into 95 parts of distilled water. The duration times of exposure were 10, 20, 30, 45, 60 and 90 days. Upon completion, the specimens were washed with clean running water to remove the remaining salt deposits from their surfaces and then were dried. The oxide layer was removed using a bristle brush, according to the ASTM G1-90 specification. In order to make a more comprehensive study of the mechanical behavior of the steel, except of LCF tests, additionally tensile tests on ribbed bars were performed, before and after, corrosion. The mean value tensile test results (corroded and non-corroded) are shown in Figure 1 and Table 2. Table 3 presents the low cycle fatigue test results (in different amplitudes of deformation ± 1, ± 2.5, and ± 4%).

Modeling low-cycle fatigue life of steel bar

It is well known that the low-cycle fatigue life of reinforcing bars without the effect of corrosion has been studied by several researchers. The current study examined the life prediction, based on Coffin-Manson's and Koh-Stephen's models, which are more popular among researchers. Coffin-Manson model relates the plastic strain amplitude (ε_p) to fatigue life.

$\varepsilon_p = \varepsilon'_f (2N_f)^c$, where ε'*f* is the ductility coefficient i.e., the plastic fracture strain for a single load reversal, c is the ductility exponent and $2N_f$ is the number of half-cycles (load reversals) to failure. Koh-Stephen extended the Coffin-Manson's model for modeling the low-cycle fatigue life of materials based on the total strain amplitude (elastic strain + plastic strain) as described in the following equation.

$\varepsilon_\alpha = \varepsilon_f (2N_f)^\alpha$, where ε_f is the ductility coefficient i.e., the total fracture strain for a single load reversal, α is the ductility exponent and $2N_f$ is the number of half-cycles (load reversals) to failure.

Between these two models, Koh-Stephen's model is used for the analysis and the prediction of low-cycle fatigue life of reinforcing bars. Furthermore, the influence of corrosion on fatigue material constants εf and α is also explored. The Koh-Stephen equation is fitted with the observed experimental data of each exposure time to calibrate the fatigue material constants (ε_f and α). In a similar way, using the Coffin-Manson model, the prediction of strength loss of hysteresis loops was conducted. The prediction of strength degradation of reinforcing bars is made by using a type expression, $\varepsilon_{pl} = \varepsilon_d (f_{SR})^\alpha$, where, ε_d and α are material constants and f_{SR} is the strength loss factor per cycle as measured in a fatigue test at a constant plastic strain amplitude of ε_{pl}. The results of Fatigue Life material and Strength loss material coefficients are shown in Tables 4 and 5.

Results and Discussion

Mass loss measurements for several periods of time exposed to salt spray chamber 10, 20, 30, 45, 60 and 90 days led to 1.58%, 2.50%, 3.77%, 5.18%, 7.23% and 8.48% percentage mass loss respectively. The results of mechanical tensile tests of ribbed bars are presented in Table 2. They show that the decrease of strength properties is (about) equivalent to mass loss decrease, opposite to the ductility properties where a dramatic decrease is presented in. It is known that corrosion of embedded steel

C %	Mn %	S %	P %	Si %	Ni %	Cr %	Cu %	V %	Mo %	N %
0.35	0.94	0.026	0.013	0.26	0.26 0.10	0.16	0.42	0.002	0.023	0.01

Table 1: Chemical composition of S400.

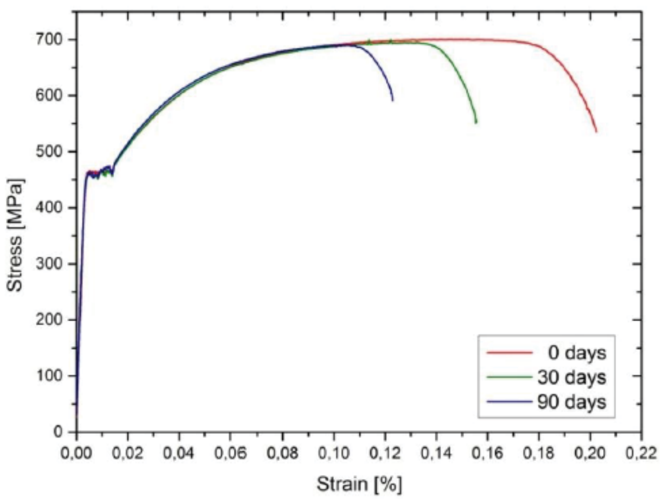

Figure 1: Stress-strain curves of ribbed bars.

	0 days	30 days	90 days
Yield Stress [MPa]	454,86	452,53	437,61
Tensile Strength [MPa]	695,12	695,29	674,93
Plastic Strain Ag [%]	15,53	12,88	9,00
Total Strain Agt [%]	19,73	15,33	10,53
Energy Density [MPa]	126,56	97,98	63,98

Table 2: Tensile test results.

Days of corrosion	Strain	Ribbed bars		Smoothed bars	
		Cycles to Failure	Dissipated Energy [MPa]	Cycles to Failure	Dissipated Energy [MPa]
0	± 1.0% ± 2.5% ± 4.0%	1280 40 11	7103 1059 537	1435 51 12	7420 1334 579
30	± 1.0% ± 2.5% ± 4.0%	509 26 9	2902 694 423	750 27 9	3905 705 423
90	± 1.0% ± 2.5% ± 2.5%	349 24 7	1862 587 272	365 24 7	2040 626 344

Table 3: Low cycle fatigue test results.

Days of corrosion	Mass loss	Smoothed Bars			Ribbed Bars		
		ε_f	α	R^2	ε_f	α	R^2
0	0	0,10363	-0,296	0,994	0,10405	-0,314	0,986
10	1,58	0,11075	-0,33	0,989	0,11103	-0,351	0,952
20	2,5	0,10602	-0,337	0,973	0,11388	-0,367	0,985
30	3,77	0,10635	-0,339	0,985	0,11531	-0,372	0,981
45	5,18	0,09286	-0,331	0,987	0,12121	-0,391	0,975
60	7,23	0,11727	-0,388	0,971	0,10321	-0,361	0,998
90	8,48	0,11511	-0,393	0,999	0,10389	-0,363	0,998
Mean*		0,10806	-0,353		0,11142	-0,368	

*(not including 0 days of corrosion)

Table 4: Fatigue life material coefficients.

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bar initially (for mass loss rates 1,5% to 2%) has a positive impact on bonding between concrete and steel bar. As a consequence, the prediction of seismic loads behavior (low cycle fatigue) will have as a reference some experimental results with higher level percentage of mass loss. However, the analysis of experimental tests of low cycle fatigue results, through the statistical regression analyses showed that there are fatigue life prediction models for 0-10% mass loss.

Figures 2 and 3 present the curves of prediction model with dashed line. Table 3 represents the low cycle fatigue test results. In Table 4, the calibrated constants of fatigue material ε_f, a in consequence of regression analysis are presented in. The results of modeling, show high convergence reliability (values of R^2). The analysis of empirical constants (mean) εf and a of life prediction models reflects the influence of the corrosive factor in corrosion levels of concrete. For both types of steel (ribbed and smoothed), based on these mean values the prediction model was resulted from. The curves of the two prediction models are in a good agreement with the experiment results as they take into account the fatigue phenomena and corrosion damage. As it was expected, the corrosion affected negatively the life expectancy of steel specimens.

It is obvious, from Figures 2 and 3, that increasing exposure time, the life expectancy of specimen material is steadily decreased. From the first exposure times of specimens, in smaller strain amplitude (mainly in ± 1%, ± 2.5%), shorter life expectancy is recorded. On the contrary, in larger strain ranges (± 4%) Kashani's study results are confirmed [17], in which additional negative phenomena highlighted due to the effect of inelastic buckling.

Days of corrosion	Smoothed bars			Ribbed bars		
	ε_d	α	R^2	ε_d	α	R^2
0	0,01762	0,369	0,934	0,01693	0,411	0,979
10	0,01696	0,421	0,958	0,01617	0,444	0,981
20	0,01465	0,490	0,992	0,01455	0,507	0,978
30	0,01479	0,466	0,974	0,01383	0,516	0,981
45	0,01291	0,531	0,994	0,01353	0,477	0,972
60	0,01235	0,593	0,991	0,01314	0,554	0,973
90	0,01189	0,535	0,986	0,01241	0,521	0,972
Mean*	0,01392	0,506		0,01394	0,503	

Table 5: Strength loss material coefficients.

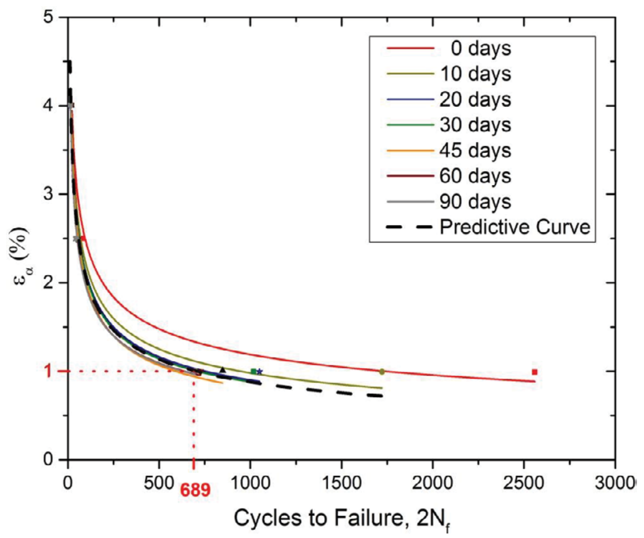

Figure 2: Fatigue life of ribbed bars.

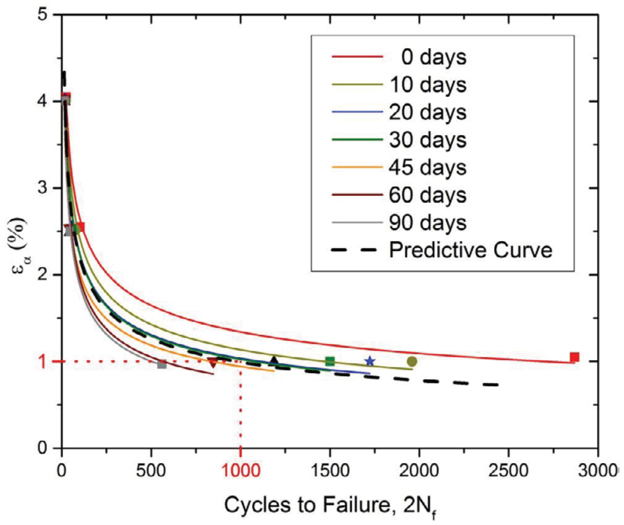

Figure 3: Fatigue life of smoothed bars.

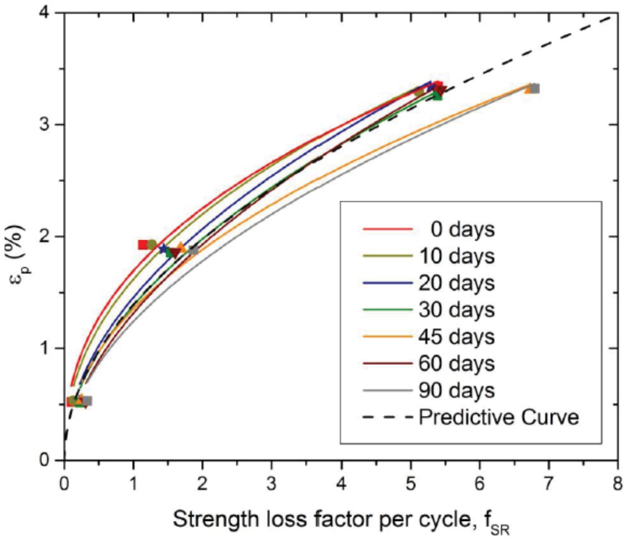

Figure 4: Strength loss of ribbed bars.

Very interesting results came from exploring the roles of steel ribs. Comparing Figures 2 and 3, it is observed that for the same number of reversals ($2N_f$), the maximum deformation of specimens without ribs are higher than the ribbed specimens. On the other hand, for a given range deformation (e.g. ± 1.0%) the number of reversals of the ribbed bars is presented lower than the smoothed bars.

According to the modified Coffin-Manson's equation that is referred to terms of plastic deformation and the coefficient strength loss per cycle of fatigue [18], comes up a prediction model of strength loss which is related to loading cycles. In equation, $\varepsilon_{pl}=e_d (f_{SR})^{\alpha}$, e_{pl} is the plastic strain amplitude, f_{SR} is strength loss coefficient per cycle and εd and α, are the empirical coefficients which are based on the material. In this analysis, the f_{SR} measurement was calculated by deriving the total strength loss from the total number of failure cycles. The experimental procedure led to prediction modeling of strength loss per cycle fatigue at S400 steel with and without ribs. The diagrams of Figures 4 and 5 are related to this, showing the prediction curves (dashed lines). In the

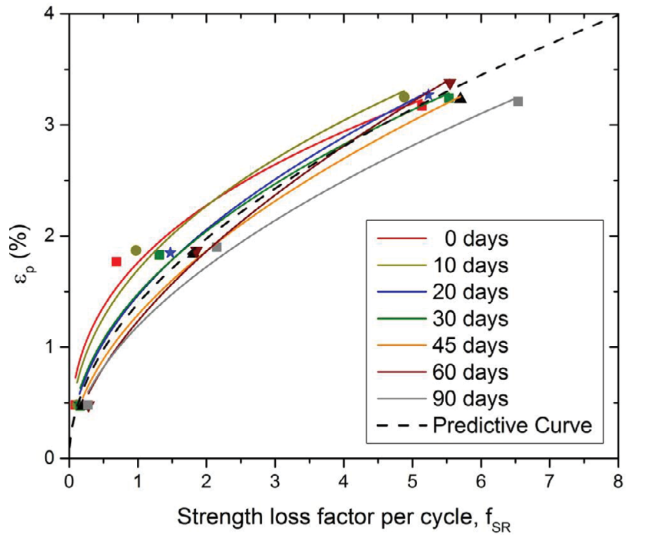

Figure 5: Strength loss of smoothed bars.

following diagrams, (Figures 4 and 5) the modified Coffin-Manson equation is displayed fitted to the experimental data using non-linear regression analysis. The results of regression analyses are summarized in Table 5. Herein, it observed that the impact of corrosion causes a shift in curves, in ribbed and also in smoothed steel bars, as the value of strength loss factor increases. The increase of strength loss factor rate is combined with lower percentage increase of ε_{pl} (plastic strain). The dashed line represents a mean curve condition of corroded bars.

Conclusions

1. The effect of corrosion has significant impact on low-cycle fatigue behavior of S400 reinforcing bar. As the duration of exposure increased the LCF life decreased and therefore the energy dissipation capacity of the bar under cyclic loading reduced.
2. The non-corroded bars show a ductile failure mechanism compare to corroded bars. This is also observed in case of smoothed compared to ribbed bars. However, as the strain amplitude increases the influence of ribs are reduced and the fracture of bars is mainly governed by the stress concentration of buckling phenomena.
3. The predictive models combine the effect of corrosion (concerning mass loss), the morphology of outer surface of rebars (ribbed -smoothed) and low-cycle fatigue degradation of S400 steel rebar. These results of prediction refer to mass loss rate less than 10% because after this rate, the strength bonding loss is too high. At these circumstances (mass loss > 10%) the study of mechanical performance and durability of RC structures serves no purpose.

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