On the extremely low cycle fatigue behavior of the concrete reinforcing bar B450C (FeB44k) steel

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ABSTRACT. Under extreme seismic conditions, engineering structures experience small numbers of very large displacement cycles. Reinforcing bar steel properties under very large displacement cycle loading can be studied by means of low cycle fatigue (LCF) test. In this study, we developed a low cycle fatigue testing system, which enables to study the low cycle fatigue strength of concrete reinforcing steel bars in the extreme large strain field; under such conditions the number of reversal to failure is well below one hundred cycles. A further advantage of this system is represented by the fact that the specimen is subjected to bending deformation. The obtained extremely low cycle fatigue (ELCF) strength for B450C (FeB44k) steel ribbed bars was compared with the results from smooth bars in order to assess the effect of ribs on the extremely low cycle fatigue behavior; further smooth bars were also subjected to heat treatments different from Tempcore, or surface modified by shot peening or by atmospheric corrosion.

SOMMARIO. In presenza di forti scosse di terremoto le strutture civili vanno soggette ad un piccolo numero di cicli di sollecitazione caratterizzati da spostamenti particolarmente estesi. Le proprietà degli acciai utilizzati come rinforzo nelle strutture in cemento armato possono essere studiate attraverso prove di fatica a basso numero di cicli (LCF). In questo lavoro sperimentale si è messo a punto un sistema per prove di fatica a basso numero di cicli per studiare il comportamento di tondo da cemento armato in un intervallo di deformazioni estremamente elevate. In tali condizioni il numero di cicli a rottura risulta ben inferiore al centinaio. Un ulteriore vantaggio del sistema di prova impiegato è costituito dal fatto che le barre di tondo da cemento armato sono sollecitate in flessione. Il comportamento a fatica a numero di cicli estremamente basso (ELCF) di barre nervate di acciaio B450C (FeB44k) è stato misurato ed è stato paragonato con i risultati di prove analoghe su barre lisce dello stesso acciaio al fine di valutare l'effetto di concentrazione delle tensioni promosso dalla nervatura; ulteriori prove di fatica a basso numero di cicli sono state poi effettuate su barre lisce sottoposte a trattamento termico differente da quello Tempcore, o su barre modificate superficialmente mediante pallinatura o a seguito di corrosione atmosferica.

KEYWORDS. Concrete reinforcing bar; B450C (FeB44k) steel; Low cycle fatigue

INTRODUCTION

Under extreme seismic conditions, engineering structures experience small numbers of very large displacement cycles. This form of loading is of particular importance for those structural members that are designed to play the role of dissipative elements. The behavior of these structural members under this form of loading is obviously expected to be controlled by their geometry and by the hysteretic properties of the constituent material, which can be assessed through fatigue testing at high strain amplitudes.

Strain-controlled LCF and ELCF testing at high strain amplitude is considered a valuable method of testing steel under cyclic loading. The results can be utilized to estimate the remaining life of steel that may also contain cracks, notches, holes, ribs, fillets, and other discontinuities, and which in many instances are due to corrosion, material flaws or poor design. Correlation of the life expectancy of materials to fatigue strength and damage parameters, such as stress, strain, plastic, and strain energy density, has been investigated in the past for a number of alloys and application fields.

In reinforced concrete structures in seismic areas, where the kinetic energy transferred to the structure by the grounds motion has to be dissipated in the so called "plastic hinge" essentially by the steel cage, the reinforcing bar behavior under loading cycles characterized by very large displacements deserves careful attention.

Reinforcing bar steel properties under very large displacement cycle loading can be studied by means of low cycle fatigue (LCF) test. Earthquakes, in fact, cause stress events on the reinforcing steel in the region of low cycle fatigue as confirmed by Sheng and Gong [1] who investigated seismic ruins of Tangshan (China) and concluded that the failure mode of building structural steels under earthquake loading is LCF.

Fatigue tests can be categorized by considering the applied strain amplitude, which can be decomposed into elastic and plastic components [2]. Testing regimes in which the elastic strain amplitude is higher than the plastic strain amplitude are generally referred to as high cycle fatigue (HCF); such tests are usually stress controlled and typically involve more than 10^6 cycles to cause failure. Conversely, the term low cycle fatigue (LCF) is applied when plastic strain dominates, and the number of cycles to failure generally ranges from 10^2 to 10^4. Low cycle fatigue testing is generally strain-controlled (either by total or plastic strain), since hardening or softening of the material complicates load- or stress-controlled testing.

It has been observed that plastic strain-life data from LCF tests fall approximately on a straight line when plotted on a log-log scale. This observation forms the basis of the Coffin-Manson relationship [3, 4], which is expressed as:

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f \, (2N_f)^c \tag{1}$$

where $\Delta\varepsilon_p/2$ is the plastic strain amplitude, ε'_f is the fatigue ductility coefficient, c is the fatigue ductility exponent and $2N_f$ is the number of reversals to failure.

In order to study the behavior of reinforcing bar steels, seismic loads acting on the load bearing elements of structures in the form of high strain reversals, have been usually simulated as single axis low cycle fatigue [1], either on the rebar itself or on machined specimens, cylindrical or hourglass [5-15].

In reinforced concrete structures the strength of column bases is crucial when seismic actions occur. The results of the seismic action is the gradual bursting and detachment of the covering concrete, which finally leaves the reinforcing steel bars as the exclusive load-bearing element, Fig. 1 [6]. When this occurs, reinforcing steel bars undergo severe bending moments. Since these bending moments, in turn, produce axial forces on the reinforcement which alternate from tensile to compressive during the seismic action, these high-strain reversals have been generally simulated as single-axis low-cycle fatigue.

Figure 1: Column base damage of concrete and reinforcing bars in low cycle fatigue test on reinforced concrete column prototype [6] .

However, low-cycle fatigue tests are generally performed at limited strain levels, in order to avoid specimen buckling while, according to test observations the low-cycle fatigue failure mode of the longitudinal reinforcing bars is associated with relatively large displacement amplitudes, in excess of 4%.
Till now, there are few data on the extremely low cycle fatigue strength of concrete reinforcing steel, particularly in the large strain field corresponding to a fatigue life well below 100 cycles.
In this study, we developed a low cycle fatigue testing system, which enables to study the low cycle fatigue strength of concrete reinforcing steel bars in the extreme large strain field. A further advantage of this system is represented by the fact that the specimen is subjected to bending deformation, i.e. the behavior of the steel is assessed under a loading condition that is more close to those encountered during extreme seismic conditions. Strain in the specimen is geometrically imposed by the radius of the mandrel around which the specimen is bent. The obtained low cycle fatigue strength for B450C (FeB44k) steel ribbed bars was compared with the results from smooth bars in order to assess the effect of ribs on the extremely low cycle fatigue behavior; further smooth bars were also subjected to heat treatments different from Tempcore, or surface modified by shot peening or by atmospheric corrosion.

EXPERIMENTAL PROCEDURES

The starting material for the assessment of the low cycle fatigue behavior of concrete reinforcing bar steel is given by a hot rolled and Tempcore treated B450C (FeB44k) steel in the form of 8 mm diameter ribbed and smooth rebar. The depth of the Tempcore layer, the tempered martensite microstructure of the external layer, and the ferritic-pearlitic microstructure of the bar core are shown in Fig. 2. The wt.% chemical composition of the steel is reported in Tab. 1.

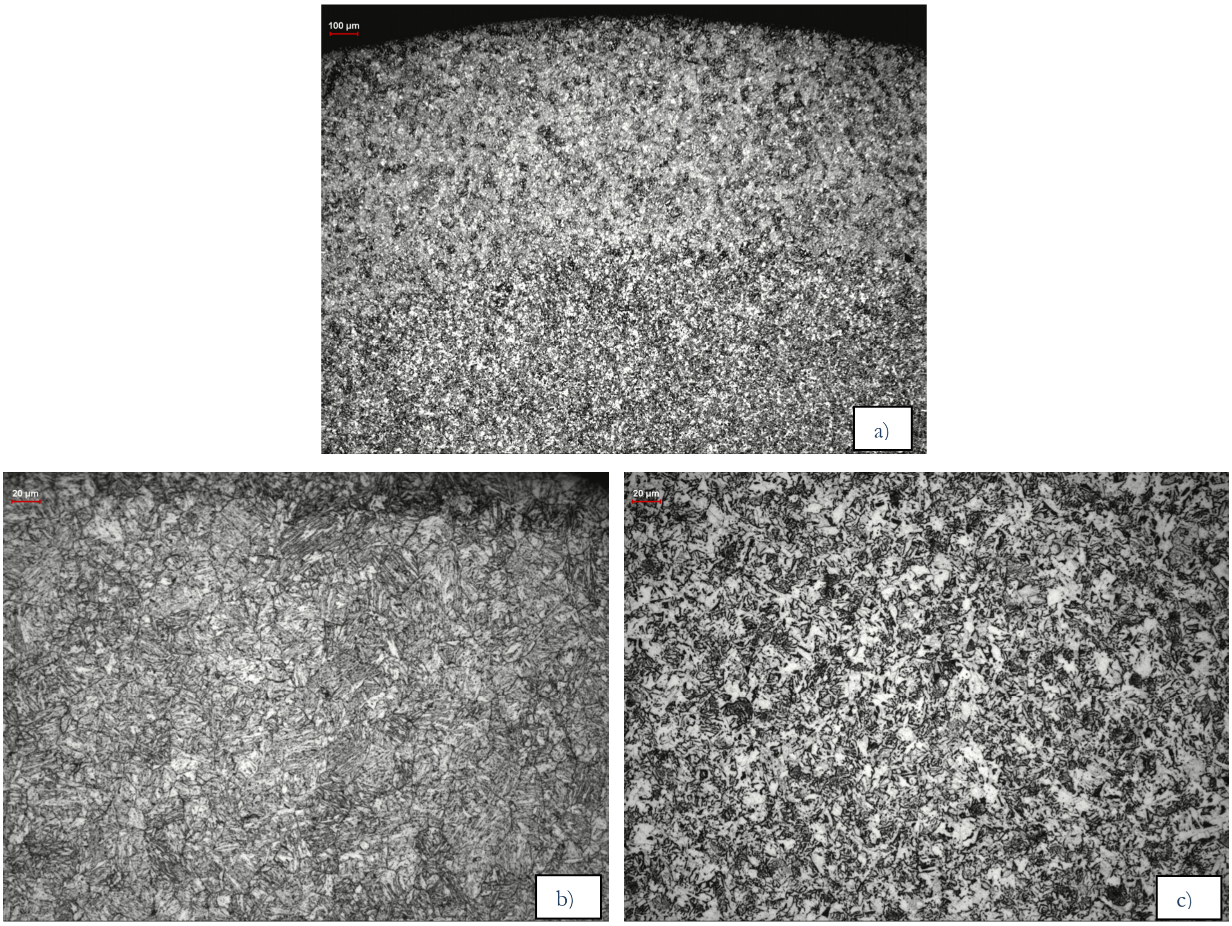

Figure 2: Microstructure of the B450C (FeB44k) steel; a) low magnification aspect of the Tempcore layer; b) and c) external layer and central microstructures respectively .

C = 0.2	Si = 0.22	Mn = 0.67	P = 0.023	S = 0.03	Cu = 0.44	Cr = 0.14
Ni = 0.1	Sn = 0.019	Mo = 0.03	Al = 0.004	V = 0.004	N = 0.0081	

Table 1: wt.% chemical composition of the concrete reinforcing B450C (FeB44k) steel bar, 8 mm diameter, used for the low cycle fatigue experiments.

In addition to the standard Tempcore treatment, that was kept close to the lower bound of the prescribed requirements for the strength level, a slightly different Tempcore treatment has been given to a billet of the same heat by adjusting the treatment parameters in order to obtain a deeper thickness of the transformed surface layer, with strength properties close to the upper bound of the prescribed requirements. The rebars in these two different experimental conditions have been referred to as Rebar B (or ribbed standard Tempcore) and Rebar C (or ribbed improved Tempcore) respectively.
Furthermore, in order to eliminate the influence of the notch effect given by the ribs on the low cycle fatigue behavior, one billet of the same heat has been hot rolled into a 8 mm diameter smooth wire rod, which has been given the same standard Tempcore treatment as the ribbed rebar C. In the present research work this smooth wire rod has been considered the reference material for the study of the low cycle fatigue behavior of the B450C (FeB44k) steel and has been referred to as Rebar A (or smooth standard Tempcore).
A certain amount of the smooth wire rod has then been given a couple of different heat treatments. The first treatment is a normalizing treatment by austenitizing at 870 °C for 20 minutes followed by air cooling. The second treatment is a water quenching from the same austenitizing condition down to room temperature, followed by a tempering treatment adjusted in order to obtain the same surface hardness as rebar A. These differently heat treated smooth rebars have been identified as Rebar D (or smooth normalized) and Rebar E (or smooth quenched and tempered) respectively. Finally, the surface of smooth bar was modified by shot peening (Rebar F) and by atmospheric corrosion by simple exposure in air for six months (Rebar G); both surface modifications are known to have an important influence on the fatigue life.
The test apparatus for low cycle fatigue test on reinforcing bar steel is shown in Fig. 3.
The ribbed or smooth rebar to be tested is first fixed in the testing apparatus by holding its lower end within a grooved small lock plate which is screwed to a base plate, not shown in the figure. Two cylindrical mandrels are also screwed on the same base plate as shown in the figure. Finally, a loading apparatus clutches the opposite end of the test bar and moves it alternatively from one side to the opposite one, making the bar to conform with the geometric profile of the mandrel. The mandrel radius R has been previously calculated in order to determine a total strain in the range from 8% to 25%, well beyond the limit of 3 - 4% that has to be complied with in order to avoid buckling in uniaxial fatigue.

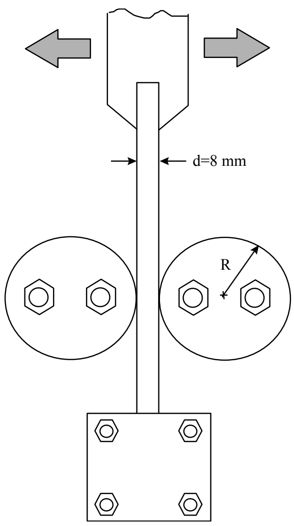

Figure 3: Schematic drawing of the testing apparatus for low cycle fatigue tests in alternate bending. R = mandrel radius.

RESULTS AND DISCUSSION

Tab. 2 summarizes the results of tensile tests. Not all the differently treated rebar steel specimens can be classified either as B450C or FeB44k according to the new and the old standard requirements. In fact, as it can be observed, Rebar D (smooth normalized) has too low yield strength to comply with both FeB44k and B450 C/A requirements ($f_y \geq 430$ MPa and ≥ 450 MPa in the old and new standard respectively) and Rebar E (quenched and tempered) has to be classified as B450A because of its low uniform elongation at maximum load (Agt ≥3%, but not ≥7%).

Fig. 4 shows the strain-life relationship for smooth FeB44k steel 8 mm diameter bars in the standard Tempcore treatment state (Rebar A). Despite the number of the experimental points that are plotted in the figure, a minimum of five specimens have been used for each test conditions, as well as throughout all the experiments.

Total strain amplitude has been reported in the diagram; it has been calculated on the basis of the deformation given by the bending of the bar against the mandrel of the testing apparatus; the strain amplitude is related to the maximum strain experienced by the outer fibers of the bar with respect to the neutral axis. Some attempts were carried out in order to measure the elastic strain by measuring the curvature of the bar after removal of applied load; the method proved to be inaccurate and the total strain was preferred as the loading parameter. The total strain amplitude was also used by other Authors [14] who concluded that, based on the standard error, the prediction of fatigue life based on the total strain amplitude is more accurate than that of the plastic strain amplitude.

From Fig. 4 it can be observed that the Manson & Coffin relationship fits very well the experimental points. The fatigue ductility coefficient ε'_f and the fatigue ductility exponent c of the Manson & Coffin relationship are reported in the figure along with the standard deviation of the data fitting curve.

	UTS (f_t) [MPa]	YS (f_y) [MPa]	$(f_t/f_y)_k$	Uniform elongation at maximum load (Agt) [%]	complies with
Rebar A	606	497	1.22	13.6	FeB44k - B450C
Rebar B	649	495	1.31	15.8	FeB44k - B450C
Rebar C	693	593	1.17	11.9	FeB44k - B450C
Rebar D	510	305	1.67	19.6	-
Rebar E	701	668	1.05	6.1	FeB44k - B450A
Rebar F	639	530	1.21	13.6	FeB44k - B450C
Rebar G	610	505	1.21	12.3	FeB44k - B450C

Table 2: Tensile properties of the concrete reinforcing FeB44k steel bar, 8 mm diameter.

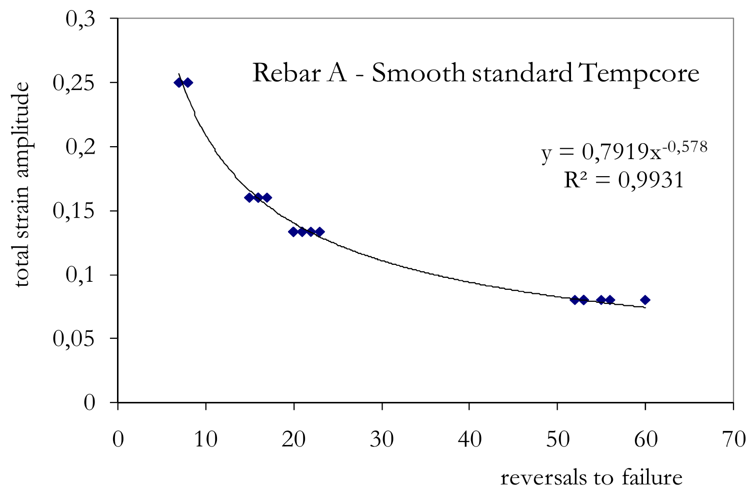

Figure 4: Strain-life relationship for smooth B450C (FeB44k) steel bars in the standard Tempcore treatment state (Rebar A).

In previous investigations, in the very low cycle regime, referred to also in this paper as extremely low cycle fatigue (ELCF), an over-estimation of fatigue life by the Manson & Coffin relationship has been observed [16,17].
Models accounting for the combined effects of ductile and fatigue damage have been proposed to establish strain life relationships that cover both the LCF and ELCF regimes. This has been achieved, for example, by combining an exponential function with the power law of the Manson & Coffin relationship [16], partitioning the damage into ductile and cyclic damage components [17,18] or by employing plastic void growth and coalescence models [19]. In the case of the present results, as it will be discussed also later on, all the experimental data fall in the regime of ELCF and show a unique and homogeneous damage mode by ductile microvoid growth and coalescence.
Fig. 5 shows the strain-life relationships for FeB44k steel 8 mm diameter ribbed bars in the standard Tempcore treatment state (Rebar B) and in the improved Tempcore treatment state (Rebar C).
By comparing the behavior of smooth and ribbed reinforcing steel bars (Rebar A vs. Rebar B) produced from the same heat and hot rolled and Tempcore treated under the same conditions it is clear the absence of ribs leads to an increase in the number of fatigue cycles before failure of the material.
An analogous conclusion was reported in (10) where, after removal of the ribs by means of filing, it was observed that removal of the ribs greatly improved the number of cycles to failure, as well as of the dissipated energy. In that case the effect was more evident at relatively low strain amplitudes, whereas according to present results the detrimental effect of ribs is well evident also at very high strain amplitudes.
Fig. 6 shows the strain-life relationships for smooth FeB44k steel 8 mm diameter bars in the normalized treatment state (Rebar D) and in the quenched and tempered treatment state (Rebar E).

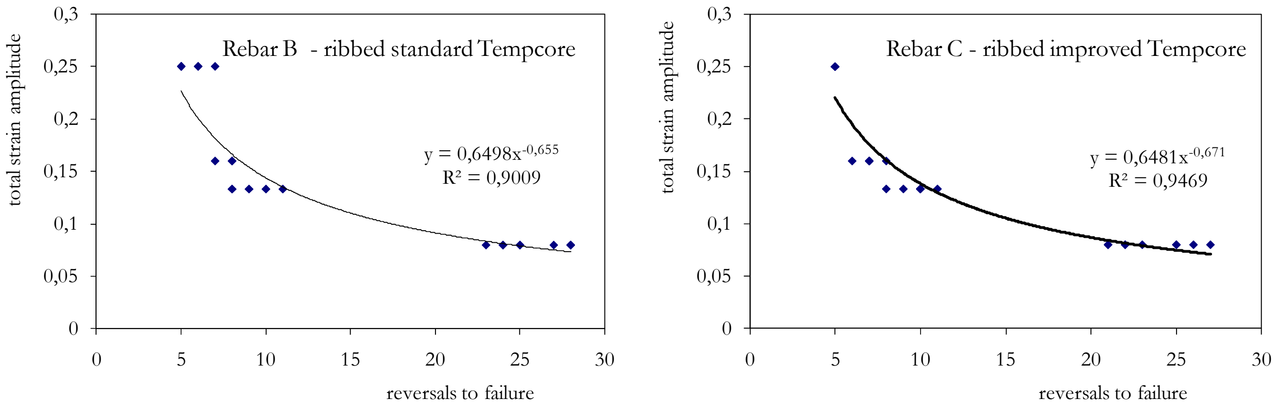

Figure 5: Strain-life relationship for ribbed B450C (FeB44k) steel bars in the standard Tempcore (Rebar B) and improved Tempcore (Rebar C) treatment state.

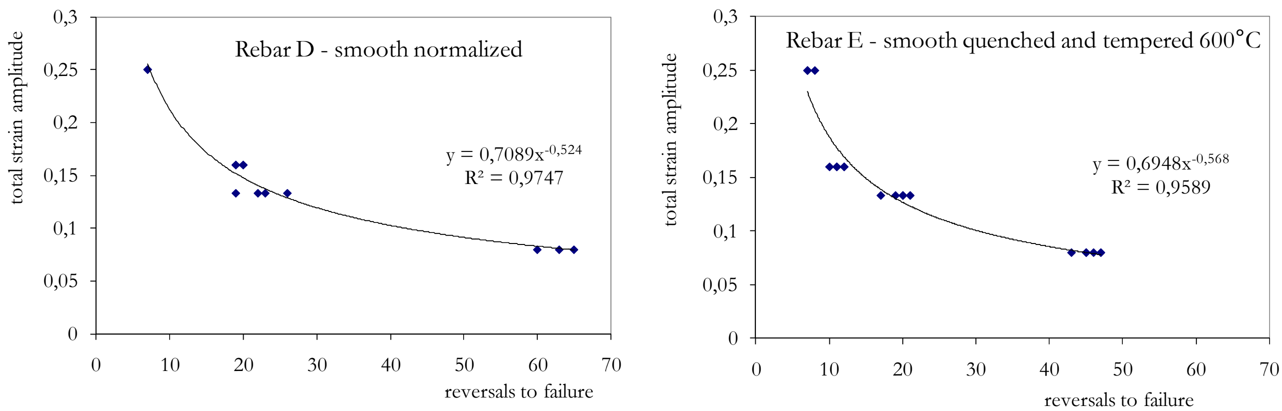

Figure 6: Strain-life relationship for smooth B450C (FeB44k) steel bars in the normalized (Rebar D) and quenched and tempered (Rebar E) treatment state.

The normalizing treatment greatly improves the ductility behaviour of the steel; at the same time, its strength properties are also affected and their values are too low in order to comply with both FeB44k and B450 C/A requirements. From the point of view of the ELCF behavior, on the contrary, by comparing the number of reversals to failure at the same total strain amplitude for Rebar A in Fig. 4 and Rebar D in Fig. 6, the increase in the steel ductility is notably beneficial for the resistance against very high strain amplitude loading cycles. On the other hand, quenching and tempering treatment results in a decrease in the steel ductility, that in turns impairs the ELCF behaviour (Rebar E).
Finally, Fig. 7 shows the strain-life relationships for smooth FeB44k steel 8 mm diameter bars in the standard Tempcore treatment with additional shot peening treatment (Rebar F) and with additional surface corrosion damage (Rebar G).
Notwithstanding shot peening is expected to improve the fatigue behavior due to the generation of a compressive surface residual stress field and to the improvement in the rough surface finish given to the bars by the standard manufacturing process, it is confirmed that when the concrete reinforcing bars are submitted to complex and high loads with associated very large displacements, as in the case of earthquakes, the beneficial effect of surface compressive residual stresses is almost null or becomes even negative. A similar observation was already reported by Real and coworkers [20] who investigated the fatigue behavior of duplex stainless steel reinforcing bars subjected to shot peening.
The detrimental effect of surface corrosion (Rebar G) on the LCF is confirmed by results in Fig. 7 also in the range of large strain amplitudes. A lot of investigations about the effect of corrosion have been published [7-11, 15] because of its relevance for the in service corrosion of reinforcing bars in reinforced concrete structures.

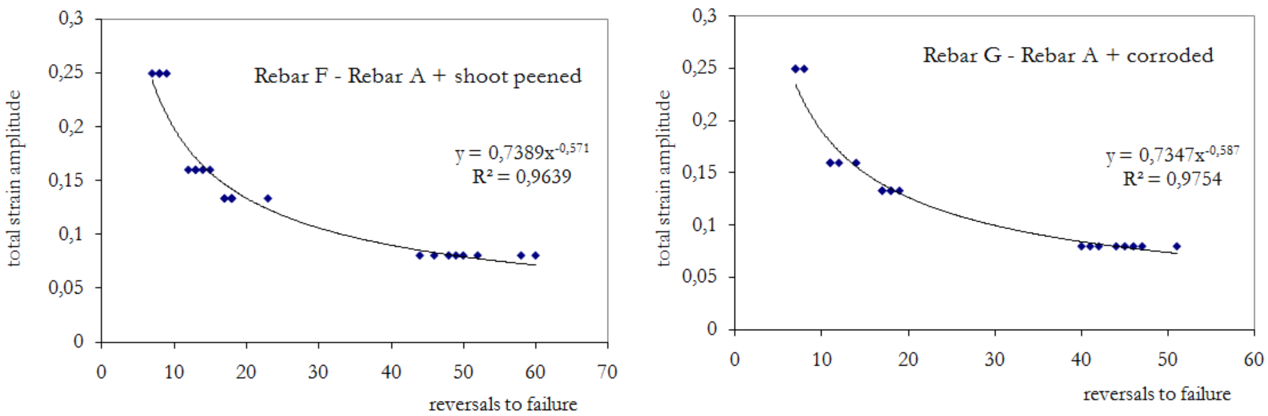

Figure 7: Strain-life relationship for smooth B450C (FeB44k) steel bars in the standard Tempcore with additional shot peening treatment (Rebar F) and in the standard Tempcore with additional surface corrosion damage (Rebar G).

Fig. 8 shows the fracture appearance of a smooth Rebar A specimen at the end of the low cycle fatigue test with a maximum strain of 8% and R = – 1; bending of the specimen occurred in the vertical direction. The fracture appearance in Fig. 8 can be considered representative of the damage development in the ELCF tests carried out on B450C (FeB44k) steel bars in the different test conditions. From the general appearance of the fracture surface (Fig. 8 a) it can be observed that fracture occurs on different planes and that only a small portion of it, nearly at the centre of the bar, is normal to the bar axis. Correspondingly, the micro fracture appearance, whose mechanism is always by microvoid nucleation and coalescence, is characterised by equiaxed dimples in the central area (Fig. 8 b), whereas on the other slanted fracture paths microvoids are elongated in a specific direction (Fig. 8 c,d).
From the fracture appearance it can be argued that, as the cyclic reverse loading begins, damage occurs in the form of plastic strain accumulation in both the compression and tension strained sides; major cracks nucleate when strain cannot be longer sustained, while secondary cracks, perpendicular to the main crack plane, may eventually form under the transverse tensile stress acting perpendicularly to the bending plane. Considering the strain amplitude range used in the present investigation, it is to be expected that, in the case of the highest strain amplitude, extremely severe damage and rupture initiation most probably occur since the first loading cycle. Major cracks propagate cyclically across the section from the most tensile strained side towards the centre, forming coarse slanted areas by a slip mechanism with dimple oriented in the slip direction; only in the centre of the fracture surface, almost equiaxed dimples are developed under the axial loading component that leads to the final separation in two halves.

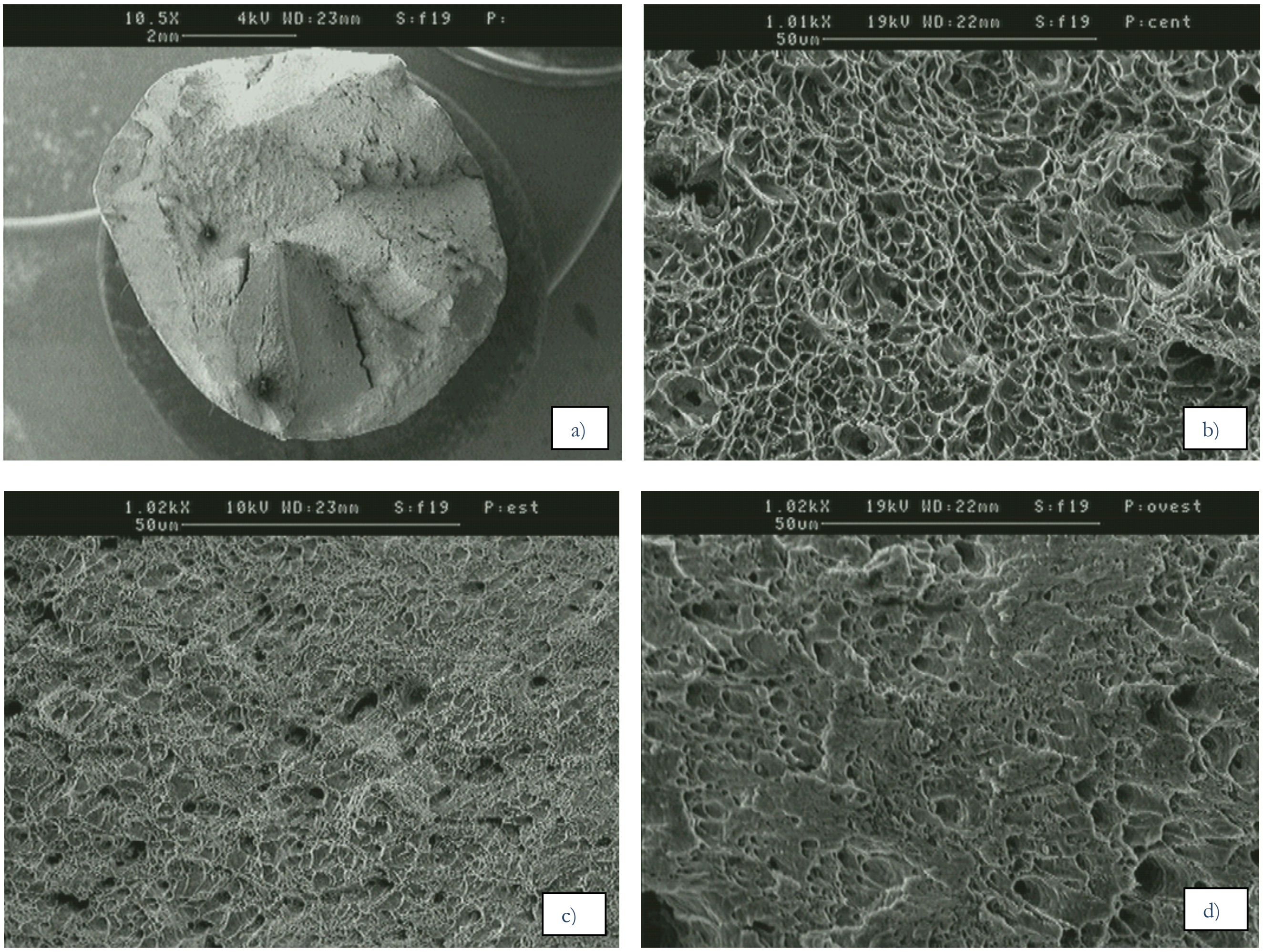

Figure 8: Fracture appearance of a smooth Rebar A specimen at the end of the low cycle fatigue test with a maximum strain of 8% and R = – 1 ; a) general appearance; b), c), and d) centre, left side, and right side of the fracture surface

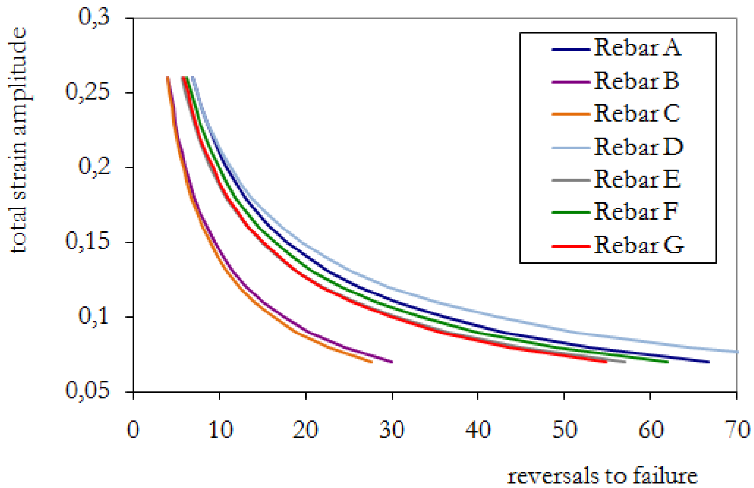

Figure 9: Best fit curves, based on Coffin–Manson (Eq. (1)), for plastic-strain amplitude versus reversals to failure for B450C (FeB44k) steel specimens for $R = -1$ and for the different test conditions.

Fig. 9 shows the best fit curves, based on Coffin–Manson relationship, Eq. (1), for total strain amplitude versus reversals to failure for B450C (FeB44k) steel specimens for $R = -1$. It is observed that for these best fits the fatigue ductility coefficient ε'_f and the fatigue ductility exponent c of the Manson & Coffin relationship range between 0.648 and 0.792, and between −0.524 and −0.671 respectively. Notwithstanding the above best fitted ranges for ε'_f and c have been obtained for test results in the field of ELCF, they are within the common range of metals as demonstrated by Coffin and Manson [3,4].

The regressed power function relationships for the B450C (FeB44k) steel in the different test conditions provide an estimate of fatigue life for a wide range of very high plastic strains; however, their estimate should not probably be extended to lower strain amplitudes, because for the present experiments a ductile rupture mechanism was observed, while for lower strain amplitudes a transition towards a fatigue mechanism is to be expected.

The experimental apparatus that has been used in the present research work, represent a tool to extend the LCF investigations that up to now yielded data for a limited range of strain amplitudes to the field of very large strain amplitudes, (i.e. beyond 3%), that is not possible to explore by conventional uniaxial LCF testing because buckling of the specimen is unavoidable.

Fig. 9 allows a more direct comparison of the ELCF behavior of B450C (FeB44k) steel; with respect to the best fit curve for Rebar A, the standard Tempcore smooth specimen, that has been considered as the reference steel, the most detrimental effect is given by the presence of ribs (Rebar B); Tempcore treatment adjusted to yield strength properties close to the lower and upper bound of the prescribed requirements, Rebar B and Rebar C respectively, doesn't result in a high difference in the ELCF behavior.

Among the smooth bars, the worst behavior is offered by the surface corroded rebars, while it is confirmed the lack of beneficial effects by the shot peening treatment.

The improvement in the number of reversals to failure observed for the normalized reinforcing bars confirms the relevance of the steel ductility in enhancing the ELCF behavior of reinforced concrete structures under extreme seismic conditions.

CONCLUSIONS

In this study, the extremely low-cycle fatigue behavior of B450C (FeB44k) reinforcing steel ribbed and smooth bars was experimentally evaluated. Tests were performed under displacement-controlled bend loading on un-machined bar specimens by means of a simple loading apparatus that allowed to reach very high strain levels. The deformed bars were subjected to cyclic maximum bend strains ranging from 8 to 24% at a strain ratio R of −1.

Total strain amplitude versus reversals to failure relationship based on Coffin–Manson equation proved to be suitable to assess the extremely low cycle fatigue life. The obtained fatigue ductility coefficient ε'_f and fatigue ductility exponent c of the Manson & Coffin relationship are within the common range of metals as demonstrated by Coffin and Manson.

The extremely low-cycle fatigue tests performed indicate that:

- the presence of ribs greatly reduces the performance of the steel bars under cyclic loading
- the most important parameter for enhancing the ELCF resistance is represented by the steel ductility
- shot peening surface treatment has no beneficial effects, or may even be detrimental, for the resistance to ELCF
- corrosion damage is extremely dangerous for the ELCF behavior.

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