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Cyclic behaviour of uncorroded and corroded steel reinforcing bars

Silvia Caprili *, Walter Salvatore

Dept. of Civil and Industrial Engineering, University of Pisa, Italy

HIGHLIGHTS

- Analysis of the mechanical properties of different reinforcing steels under monotonic loads.
- Analysis of the low-cycle fatigue (LCF) behaviour of different typologies of reinforcements.
- Influence of corrosion on the monotonic behaviour of bars, in terms of strength and ductility.
- Analysis of the combined effects of corrosion phenomena and low-cycle fatigue.
- Influence of production process on the ductile behaviour of bars.

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ABSTRACT

In the present work the results of a wide experimental test campaign on steel reinforcing bars, including monotonic tensile and low-cycle fatigue tests, the last ones able to reproduce the stress–strain condition induced by seismic events, are presented. The main aim of the research work consists in the analysis of the combined effects of seismic action and aggressive environmental conditions on the ductile behaviour of steel reinforcements: as a consequence, mechanical tests were executed also on samples previously subjected to exposure in salt spray chamber, evaluating the residual mechanical properties and dissipative capacity.

1. Introduction

The ductile behaviour of reinforced concrete (r.c.) buildings in seismic areas is strictly dependent on the ductile properties of steel reinforcing bars located in those sections where the development of plastic hinges is expected, in agreement to the capacity design approach [1–3]. The investigation of the ductility of steel bars is necessary to understand the behaviour of both r.c. elements (beams, columns and sub-assemblages) and of the whole structure under seismic actions. Following what presented in Eurocodes 8 and 2 [1,4] for concrete structures, steel bars adopted in modern buildings shall be able to guarantee a sufficient level of *ductility*, expressed in terms of strain (A_{gt} – elongation to maximum load) and hardening ratio (R_m/R_e); the minimum values of the ductility parameters A_{gt} and R_m/R_e are defined in relation to three different classes, called “A”, “B” and “C” and characterized by increasing levels of the above mentioned parameters ($\geqslant$2.5%, $\geqslant$5.0% and $\geqslant$7.5% for A_{gt}, $\geqslant$1.05, $\geqslant$1.08 and $\geqslant$1.15 and $\leqslant$1.35 for R_m/R_e). The design requirements imposed by Eurocodes are not directly translated into an harmonized European standard able to codify strength and ductility classes: this results in a large variety of steel grades, different for yielding and tensile strengths (R_e, R_m), hardening ratio and minimum values of elongation (A, A_{gt}). For sake of clarity, Table 1 shows the most common steel grades in Europe and Mediterranean area and their corresponding mechanical properties.

Actual European standards for reinforcing steels do not provide indications for the control of the cyclic behaviour of bars: only some Countries, like Spain and Portugal [5,6], introduce low-cycle fatigue (LCF) tests for the characterization of the cyclic performance of bars. The proposed testing procedures differ for the frequency, the number of cycles to execute, the imposed deformation and the free length of the specimens. This fact is mainly due to the lack of information about the behaviour of bars in r.c. structures during earthquake events and to the following representation of the seismic condition: despite of the wide scientific documentation on the seismic behaviour of r.c. elements, structures and sub-structures [7–9], only few data are available regarding the ductile behaviour of bars [10]. A codified procedure

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* Corresponding author.
E-mail addresses: silvia.caprili@ing.unipi.it (S. Caprili), walter@ing.unipi.it (W. Salvatore).

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for the control of the cyclic performance of steel bars is then necessary, according to what required in Mandate M115 [11] inside the revision of EN10080:2005 [12], that aims to solve the problems related to the definition of "*the methods (calculation, test methods or others) or a reference to a standard containing the methods for the determination of such characteristics*", including the individuation of the cyclic performance necessary for earthquake prone areas.

Nowadays, the ductile requirements imposed by design standards [1,4] are mainly satisfied through the adoption of TempCore steel bars, characterized by good levels of ductility and strength due to the production process: the two following phases of quenching and tempering lead to the development of an external tempered martensite layer and of a more soft and ductile central region with a typical ferritic – perlitic microstructure, with excellent mechanical properties towards moderate production costs, if compared to other processes. For instance, Micro-Alloyed steels, characterized by the addition of alloy elements such as Vanadium, Molybdenum and others, offer even higher levels of ductility and strength despite the increase of the costs related to the production process.

Several works in the current literature [13–15] evidenced durability problems in structures with TempCore reinforcements exposed to aggressive environmental conditions: the decrease of the mechanical properties of corroded bars and the deterioration of the cover result in the early degradation of concrete buildings with reduction of the residual service life. Rodriguez et al. [15] evidenced that two kinds of corrosion phenomena usually affect r.c. structures: carbonation of concrete and chlorides' penetration; in both the two situations, the pH of the solution in which bars are embedded drops below 12.8, with the following cracking of the protective passive layer, the initiation and propagation of the corrosion process.

Apostolopoulos and Papadakis [14] showed the detrimental effects of corrosion on steel reinforcements Bst420 (∅10 mm), typically used in Greece during the 1960s, reproducing corrosion with exposition in salt spray chamber and executing monotonic tensile and cyclic tests on corroded specimens. The results of tests evidenced a reduction of the ductility in terms of total elongation (*A*) up to the 50% and, on the other hand, a lower decrease of yielding and tensile strength. Al Hashemi et al. [16] executed tensile and high cycle fatigue tests on corroded TempCore bars B450C (∅16 mm), typically adopted in Italy; corrosion was induced through the application of an anodic current to bars embedded in chloride contaminated concrete blocks. The results of tensile tests evidenced a big decrease (around the 60%) of the ductility of the samples in terms of ultimate elongation, both in the case of localized and uniform corrosion; the effects on the high cycle fatigue behaviour of steel reinforcements were quite negligible, especially in the case of uniform corrosion. Similar results were also found by [17,18].

What already presented highlights the necessity of a detailed investigation of the mechanical behaviour of corroded bars: experimental data present in the scientific literature are mainly related to TempCore steel reinforcements [13] or to steel bars coming from existing buildings, nowadays no more produced. The large variety of steel grades adopted in Europe underlines the need to execute an experimental test campaign on the most common production processes, diameters and steel grades, in order to analyze the effects of corrosion and to evaluate the ability of corroded specimens to withstand the seismic demand, preventing the rapid decrease of the bearing capacity of the whole structure and the deterioration of the ductility of the sections to which the ductile behaviour is devoted.

In the present work, developed inside the European research project *RUSTEEL "Effects of Corrosion on Low-Cycle Fatigue (Seismic) Behaviour of High Strength Steel Reinforcing Bars"* [19], the results of a wide experimental test campaign on uncorroded and corroded bars, representative of the actual European production scenario, are presented. The main aim of the research project consisted in the evaluation of the combined effects of corrosion phenomena and seismic action on the ductile behaviour of steel reinforcing bars, analyzing the ability of corroded specimens to satisfy the ductile demand due to earthquake events.

In the present paper the results of tensile and LCF tests on uncorroded and corroded bars are provided. A sample of steel reinforcements, representative of the actual European scenario of bars' production, was subjected to monotonic and cyclic tests, following the prescriptions imposed by EN 15630-1:2010 [20] and a specific procedure able to represent the effects of seismic action on the base of what actually provided by current standards and scientific literature [19,21–23]. Specimens were artificially corroded through the execution of accelerated tests in salt spray chamber considering two exposure periods in order to obtain different levels of damage. The evaluation of the ductile capacity of corroded steel reinforcing bars was evaluated in terms of reduction of the mechanical properties (R_e, R_m, A_{gt}, A and R_m/R_e for monotonic tests and dissipated energy and number of cycles to failure for LCF tests) in relation to the obtained mass loss ($\Delta M/M_{uncorr}$). A simplified scheme of the procedure adopted is presented in Fig. 1.

2. Mechanical characterization of uncorroded steel bars

2.1. Selection of specimens

In order to characterize the mechanical behaviour of steel reinforcements, a representative sample of reinforcing bars was selected for experimental tests. Different steel grades (with nominal R_e equal to 400, 450 and 500 MPa), different ductility classes (*A*, *B* and *C*), different diameters (between 8 and 25 mm) and different production processes (TempCore – TEMP, Micro-Alloyed – MA, Stretched – STR, Cold Worked – CW) were considered to cover the large variability of properties already discussed (Table 1).

Steel reinforcing bars were provided by two European producers involved as partners of the research project (hereafter indicated as "producer 1" and "producer 2"), allowing to take into account possible differences in the same steel grade due to producers and plants. Table 2 presents the complete set of steel reinforcements selected for the execution of mechanical experimental tests. The number of bars used for mechanical monotonic and cyclic tests for each steel grade, diameter, process and producer is specified in the following paragraphs. Before presenting the data, it shall be noted that the experimental results discussed in the present paper are only part of the global investigation executed inside the European research project Rusteel [19], in which a statistical analysis of the results on a bigger sample of reinforcements (with about 50 specimens for each steel grade, diameter, ductility class and kind of load) was executed adopting *Anova* technique.

2.2. Mechanical characterization under monotonic loads

Tensile tests were executed according to EN 15630-1:2010 and using two servo-hydraulic testing machines. For each steel grade, diameter, process and producer three tensile tests were executed on three specimens of adequate length. In order to make the paper easier to be read, Table 3 presents only the mean values of the mechanical properties (yielding and tensile strength – R_e, R_m, elongation to maximum load and ultimate – A_{gt}, A) and the corresponding standard deviations, used for the evaluations presented in the following pages.

As visible from Table 3, for bars B450C and B500B 16 mm (TEMP), B450C 12 mm (TEMP) and for bars B500A 12 mm (CW)