JMEPEG (2007) 16:236–241
DOI: 10.1007/s11665-007-9038-y

1059-9495/$19.00

Mechanical Behavior of Reinforcement Stirrups BSt 500_s at Corrosive Environment

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(Submitted June 22, 2006)

To date, there is no widely accepted regulation on the minimum required diameter of the bending drums, which shape the stirrups of the main concrete reinforcing bars, varying between 4 and 12 times the diameter of the bent bar, and thus resulting in various plastic strains. In the present work, the influence of the degree of plastic strain on the mechanical properties of steel bar of Class BSt 500_s for concrete reinforcement stirrups is investigated, under the additional implication of laboratory corrosive conditions. The increase of the degree of the plastic strain of the stirrup bar had as a result a significant decrease in the ductility properties of the steel. Moreover, it is shown that the combination of plastic strain and corrosion causes additional damages, as strain fractures were recorded lower than that defined by the current specifications for concrete reinforcement, indicating the need for a new review of the relative specifications.

Keywords corrosion, mechanical properties, plastic strain, steel bars BSt 500_s, stirrup

1. Introduction

Deterioration of concrete in service may be the result of a variety of mechanical, physical, chemical, or biochemical processes (Ref 1-3) In the majority of concrete structures steel reinforcement is used. In reinforced concrete, the most serious deterioration mechanisms are those leading to corrosion of the reinforcement (Ref 4, 5) Reinforcing bars are protected from corrosion by a thin oxide layer that forms on their surface due to high alkalinity of the surrounding concrete. Corrosion may start when this layer is destroyed (Ref 6, 7):

- either by chloride penetration and when the chloride content exceeds a critical value,
- or due to a reduction in the pH of concrete to values below 9. Such a reduction in alkalinity is the result of carbonation of the $Ca(OH)_2$ in the concrete mass, i.e., of its reaction with the atmospheric CO_2 that diffuses through the concrete pores.

In marine or coastal environments, and when de-icing salts come in contact with the concrete surface, chloride penetration is the main mechanism that paves the way to initiation of reinforcement corrosion. In many other cases, and especially in CO_2-rich urban areas, carbonation of concrete is the main mechanism leading to steel corrosion, whereas for corrosion propagation the presence of both moisture and oxygen is required.

Corrosion of steel reinforcement impairs not only the appearance of the structure, but also its strength and safety, due to the reduction in the cross-sectional area of the reinforcement and the deterioration of bond with the surrounding concrete. One of the most complex matters faced by the international scientific groups involved in the structural rehabilitation of such structures is the precise knowledge of the actual mechanical characteristics of the main construction materials, such as the reinforcing steel and concrete, as well as the wear mechanisms which cause the degradation of the mechanical properties (Ref 8-11).

A specific case that has to be individually investigated is the corrosion of the perimeter steel bars that have been bent in order to be used as stirrups of the main straight steel reinforcing bars of the concrete element, see Fig. 1. Such a stirrup bar has been bent at 90° angle on the corners and at 135° on the anchorage points. It is known that the required anchorage length of a reinforcing bar depends mostly on the developing coherence stresses in the interface among the two materials, concrete and steel. In order to decrease this length, the edges of the bars are shaped into rectangular or semicircular hooks. Any of the above-mentioned bending results in a permanent plastic strain of the bar material. Especially, the diameter of the drum, around which the rectilinear bar will be bent to receive the expedient angle, defines the size of the imposed strain. The diameter of the bending drum varies for each national regulation, i.e., Greek ELOT 971, DIN 488, EN 10080-3/99 (Ref 12-15). In Greece, that diameter should be between 4 and 12 times the diameter of the shaping bar. In addition, this drum diameter should be adequate to avoid failure during bending, i.e., bar fracture or cracking of the essential outer layer of the bar. The use of such a bending, however, decreases the capability of a further deformation. This is shown schematically at a typical diagram of stress-strain for steel, Fig. 2, where the shaping procedure brings the steel at a position B and further, after the release of the imposed shaping force, at a position E. The shaped steel follows then a mechanical behavior according

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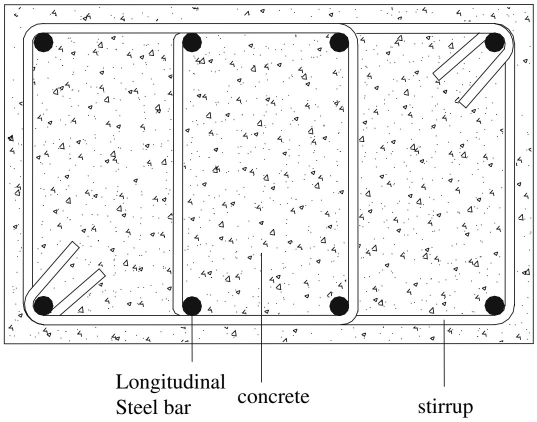

Fig. 1 Schematic representation of a steel stirrup that retain together the main longitudinal steel bars of concrete reinforcement

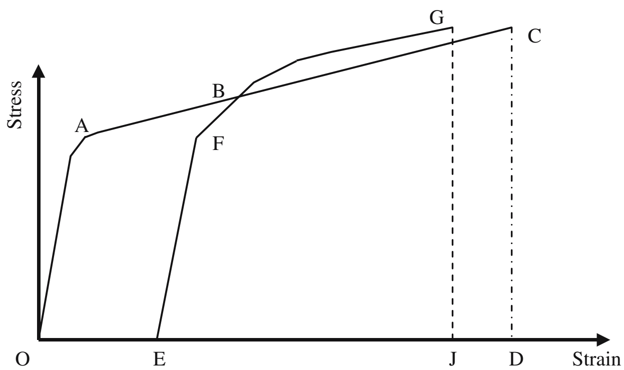

Fig. 2 Stress-strain curves for a steel bar before (OABC) and after (EFBG) a plastic strain

to the new curve of EFBG. Note that the residual strain is reduced dramatically as EJ < OD, and likewise the capability of energy absorption of the building element.

On the other hand, a stirrup is much more exposed to a corrosive environment due to reduced concrete cover and to a subsequent damage than the main reinforcing bars, as it is placed on the outer surface of these bars nearest to the concrete outer surface and corrosive agents, see Fig. 3. Moreover, it has usually a considerably lower size than the main reinforcing bars, resulting thus to higher mass losses in the case of a corrosion attack. According also to recent results (Ref 16) the chloride-induced corrosion of the steel bars causes a significant reduction in the ductility properties enough prior to the other degradation consequences (critical reduction in the cross-sectional area of the reinforcement and deficiency to the bond with the surrounding concrete). Recognizing the importance of the stirrups to the structure serviceability and performance, an experimental work is further required to investigate the mechanical behavior of various bent steel bars, especially under the additional attack of a corrosive environment.

This work presents the results of an experimental study for assessing the effect of gradually accumulating corrosion damage due to laboratory salt spray corrosion on the mechanical behavior of steel bars S500s tempcore (Ref 12) or equivalently Class BSt500$_s$ (Ref 14). Some of these bars had been deformed by various tensile strains, simulating the stirrup plastic strains when the bars are bent in order to connect the main longitudinal steel bars of concrete reinforcement. A significant reduction of the tensile ductility of the material was observed, indicating the need for a new review of the specifications for the bending of concrete reinforcing bars, especially when the structure is exposed to a severe corrosive environment. We have to emphasize that the present results may be different in the case when the steel bars are embedded in the concrete. However, the present results are a first indication of the influence of both plastic deformation and corrosion on steel ductility properties.

2. Experimental Investigation

2.1 Materials

Steel bars of class BSt 500$_s$ tempcore (Ref 14) (S500s according to the Greek Standards (Ref 12) and cross-section nominal diameter of 8 mm were used. The steel bars were delivered in the form of ribbed bars from the producer Greek industry. The maximum contents (%) of C, P, S, and N of the alloy BSt 500$_s$ are 0.24, 0.055, 0.055, and 0.013, respectively. Steel bar specimens of 240 mm in length were cut by using a metal cut wheel.

2.2 Experimental Procedure

Some of these specimens were subjected to a plastic strain of 1%, 2%, and 4% by applying a uniform tensile force and using a servo-hydraulic machine MTS 250 KN with a loading rate of 0.5 mm/min. The bar deformation was recorded by using a specific length-recorder.

Reference (non-deformed) and deformed steel specimens were exposed to a laboratory corrosion environment using a chloride salt spray for 10, 20, 30, 40, 50, 60, and 90 days (exposure duration). Salt spray (fog) tests were conducted according to the ASTM B117–94 specification (Ref 17). For the tests, a special apparatus, model SF 450 made 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 pH of the salt spray solution was such that when dissolved at 35 °C the solution was in the pH range from 6.5 to 7.2. The temperature in the zone of the reinforcement material exposed inside the salt spray chamber was maintained at 35 °C + 1.1−1.7 °C. When the exposure was completed, the specimens were washed with clean running water to remove any salt deposits from their surfaces, and then were dried. In Fig. 4, a non-corroded and two corroded specimens are shown.

In the sequence, tensile tests were performed in order to investigate the effect of the degree of the plastic strain on the mechanical properties of the steel, at various corrosion levels. The minimum length of specimens between the grabs was 120 mm and for the tensile tests the specification DIN 488–3 (Ref 14) was applied. For each measurement, three specimens were used and the mean value is presented.

3. Results and Discussion

As expected and shown in Fig. 5, the corrosion damage increases with the exposure duration to salt spray. The exposure

Fig. 3 Photos of deteriorated concrete structures due to reinforcement corrosion (a) Ladopoulos papermill, Patras, Greece (73 years old) (b) General Hospital, Lixouri, Greece (51 years old)

Fig. 4 Uncorroded steel bar (left) and steel bars after 30 days (middle) and after 90 days (right) exposure at a chloride-rich environment

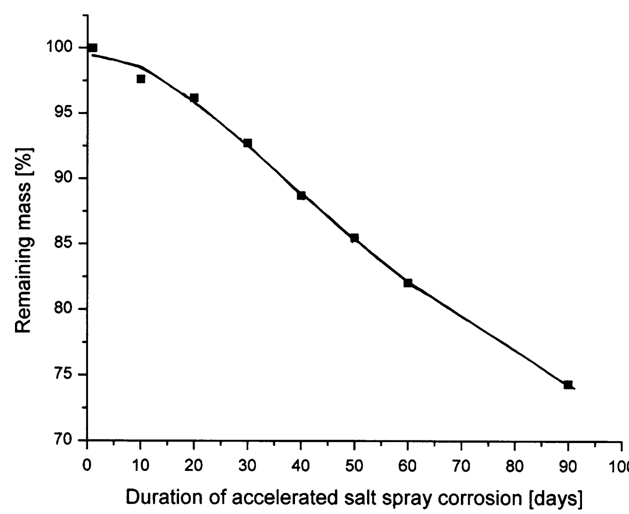

Fig. 5 Remaining mass of specimens as a function of the corrosion duration (mean values from all deformed and non-deformed specimens)

of the specimens to the salt spray environment causes the production of an oxide layer, which covers the specimen. Removal of the oxide layer by using a bristle brush, according to the specification ASTM G1–90, has shown extensive pitting of the specimens already after 10 days of exposure to salt spray. In parallel, corrosion has as a result the elimination of bar ribs and thus the reinforcement looses its bonding with the surrounding concrete, see Fig. 4. It has, however, to be emphasized that these bars are not embedded in concrete and thus a different behavior could be observed in that case. It was also observed, that the difference in mass loss between specimens with various degrees of plastic strain (0%, 1%, 2%, and 4%) was negligible; in other words this low degree of plastic deformation does not influence the corrosion rate, at least in the present accelerated tests.

Typical stress-strain diagrams for all deformed specimens were developed and for various exposure periods at the corrosive environment. It was found and shown in Fig. 6, 7 that the imposition of the plastic strain and the corrosion process result in a significant alteration on the mechanical properties of the initial uncorroded steel. The increase in the plastic strain has as a result the initial increase in strength properties; however the ductility properties and the energy density (the area under the curve) have been reduced significantly.

In order to receive more quantitative results some important tensile properties were derived from the experimental results and presented in the following; yield strength stress R_p, ultimate stress R_m, elongation to fracture f_u, and energy density W. Energy density is calculated from the area under the true stress—true strain curve. In the present work, as an engineering approximation, the energy density has been evaluated from the engineering stress—engineering strain curves as follows:

$$W = \int_{0}^{f_u} \sigma d\varepsilon \qquad \text{(Eq 1)}$$

In Fig. 6a and b, the yield stress R_p and ultimate stress R_m are presented, respectively, over the duration of salt spray exposure, and for the various degrees of plastic strain. As observed, the imposition of the plastic strain at the steel bar increases both the yield and ultimate stress. This increase of strength properties is due to the workhardening phenomenon of the material and it is higher as the deformation degree increases (Ref 18). It is also obvious that at a corrosive environment, the deformation retains this increase in both yield and ultimate strength. It has also to be emphasized that the data presented are the effective values. Note the two different determinations, effective stress and apparent stress. The effective stress is the quotient of the load capacity divided by the true cross section of the corroded specimens, which is calculated as a function of the mass and length of each specimen. The apparent stress is calculated as the quotient of the load capacity, divided by the initial, uncorroded cross section of the steel bars. This demonstrates the stress, according to the standards, which considering the mass, and therefore the cross-sectional area of the specimens remains constant over time.

It is observed from the Fig. 6a, that the minimum requirement of the Greek standard ELOT 971 (Ref 12, 13) of 500 MPa in yield stress for this particular steel, is satisfied from the reference specimens up to a corrosion duration of 42 days. In the case of 4% strain this requirement is satisfied up to corrosion duration of more than 90 days. Similar results are observed in the case of ultimate stress, Fig. 6b. The minimum requirement of the Greek standard ELOT 971 (Ref 12) of 550 MPa is satisfied from all deformed specimens for all corrosion exposure durations; however for the reference specimens this is satisfied only up to corrosion duration of 60 days.

The effect of the increasing corrosion damage and steel deformation degree on the tensile ductility of the investigated steel bars is shown in Fig. 7. Both, elongation to fracture, Fig. 7a, and energy density, Fig. 7b, decrease appreciably with increasing duration of the salt spray exposure, as well as the deformation degree increase.

The elongation to fracture, Fig. 7a, decreases with the duration of exposure to the corrosive environment, and for the reference specimen is almost 57% after 90 days of exposure; whereas after 40 days of exposure ceases to satisfy the

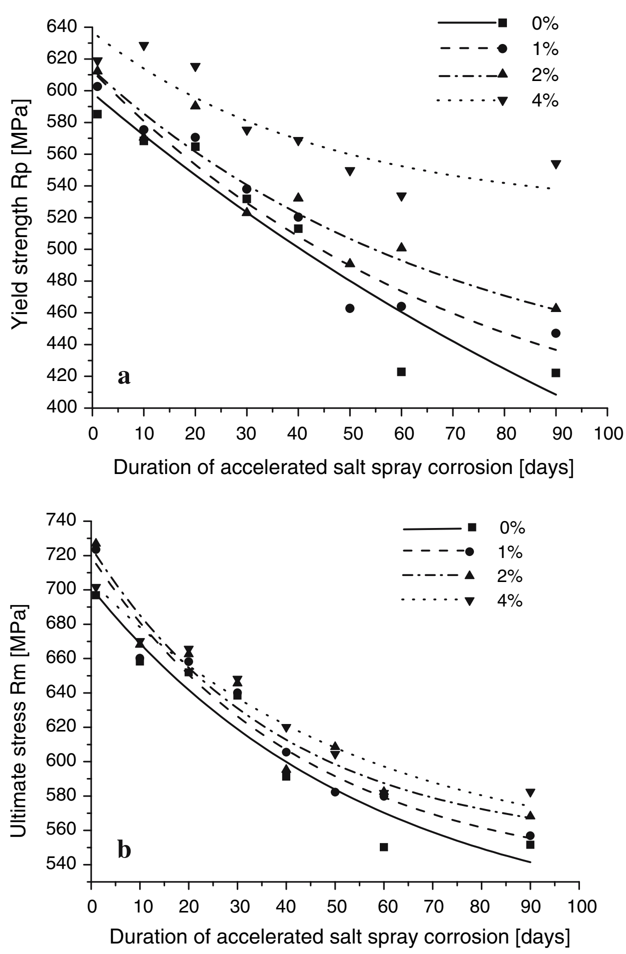

Fig. 6 Effect of plastic strain degree and the corrosion on (a) yield and (b) ultimate stress

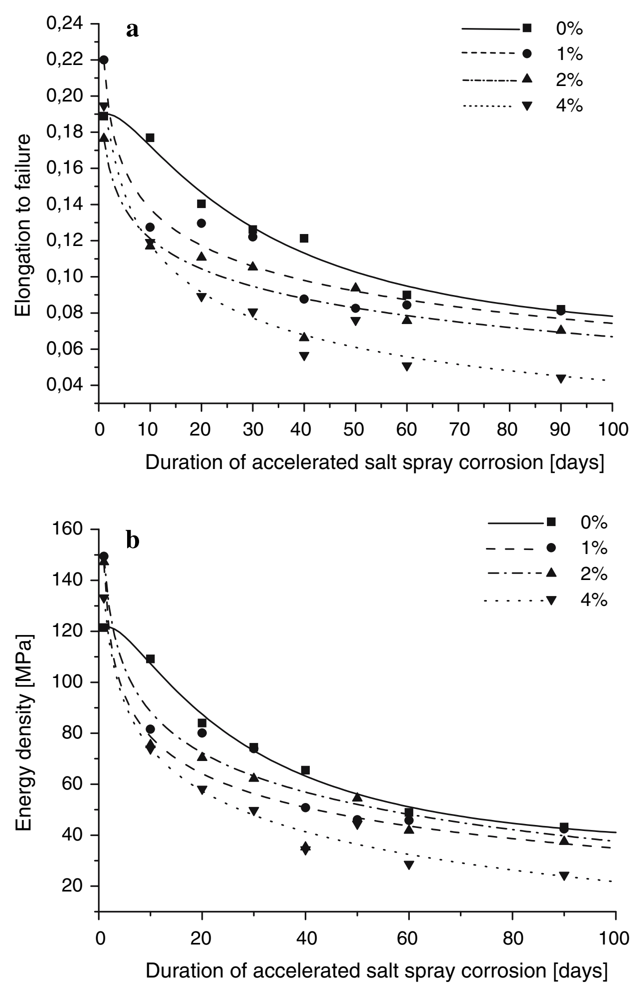

Fig. 7 Effect of plastic strain degree and the corrosion on (a) elongation to failure and (b) energy density

minimum requirement of 12% of Greek standard ELOT 971 (Ref 12). The impressive finding, however, is that the material of the specimens which had suffered a plastic strain of 2% and 4% ceases to satisfy the requirements, after an exposure of only 10 days in the corrosive environment (that corresponds to a mass loss of 2.37%). The decrease in the elongation to fracture for the reference specimens and corrosion exposure of 90 days is about 57%, whereas for the specimens of 4% plastic strain and for the same exposure period is 77%.

Similar is the picture in the case of the energy density, Fig. 7b. The decrease in the energy density for the reference specimens and corrosion exposure of 90 days is about 64%, for the specimens of 1% plastic strain and for the same exposure period is 71.6%, whereas for the specimens of 4% plastic strain is about 82%. Very important is also the recording of the 45% decrease at the energy density in the latter case from the first 10 days of exposure at the corrosive environment. This particular finding is very significant and it has to arouse the civil engineers and constructors to accept for the constructions totally non-corroded reinforcement.

The standards do not require the measurement of the energy density W, Eq. 1, for the assessment of the reinforcing steel. However, energy density is a material property which characterizes the damage tolerance potential of a material and may be used to evaluate the material fracture under both, static and fatigue loading conditions (Ref 19). Note that energy density may be directly related to the plain strain fracture toughness value, which evaluates the fracture of a cracked member under plain strain loading conditions (Ref 20). The observed appreciable reduction in tensile ductility may represent a serious problem for the safety of old and monumental constructions in seismically active areas. As during the seismic loading, the reinforcement is often subjected to low cycle fatigue, the need for a sufficient storage capacity for the material is imperative. The dramatic decrease in energy density and elongation to fracture that is observed only for 4% of plastic strain, and taking into account that even higher values in strain have been reported in practice (Ref 21), does require a thorough review of the specifications for the bending of concrete reinforcing bars, especially when the structure is exposed at a severe corrosive environment.

4. Summary and Conclusions

In the present work, the mechanical behavior of the stirrup of concrete reinforcement was investigated, under the imposition of laboratory corrosive conditions. For this purpose steel bar specimens, class BSt 500s tempcore (Ref 14) and cross-section diameter of 8 mm, that are widely used as common stirrup, were subjected in various degrees of plastic strain that simulate the bar bending in practice. These specimens were exposed at a chloride salt's spray in laboratory for various exposure periods.

The imposition of the plastic strain and the corrosion process results in a significant alteration in the mechanical properties of the initial uncorroded steel. The increase of the degree of the plastic strain of the reinforcing bar had as a result a significant decrease in the ductility properties of the steel, despite the parallel increase in yield and ultimate stress. Both, elongation to fracture and energy density decrease appreciably with increasing duration of the salt spray exposure, as well as the strain degree increases. It was clearly shown that the combination of plastic strain and corrosion causes additional damages, as strain fractures were recorded lower than that defined by the current specifications for concrete reinforcement.

Present day standards for calculating strength of reinforced concrete members do not account for the appreciable property degradation of the reinforcing steel bars due to the gradually accumulating corrosion damage. Although a revision of the standards such as to account for the above corrosion effects on the material properties seems to be required, further extensive investigation is needed to conclude on proper recommendations for such a revision. There is also no widely accepted regulation on the minimum required diameter of the bending drums, that is used in order to shape the steel bars to stirrups of the main reinforcing bars, varying between 4 and 12 times the diameter of the bent steel bar, and thus resulting in various plastic strains on the bar. Recognizing the importance of the stirrups to the structure serviceability and performance, the present experimental work investigates the mechanical behavior of various bent steel bars, especially under the additional attack of a corrosive environment, as the stirrup is most susceptible to corrosion due to its outer placement. The dramatic decrease in energy density that is observed only for 4% of plastic strain, and taking into account that even higher values in strain have been reported in practice, does require a thorough review of the specifications for the bending of concrete reinforcing bars, especially when the structure is exposed in a severe corrosive environment.

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