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Procedia Engineering 114 (2015) 800 – 807

Procedia Engineering

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1st International Conference on Structural Integrity

Strength and Ductility of Damaged Tempcore Rebars

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Abstract

The Tempcore rebars behaviour results from the interaction of the three layers that compose them, with different initial stresses. Therefore, their mechanical properties study is important for the understanding of the rebar overall behaviour. In this paper it is presented and discussed the results of hardness, strength and ductility obtained in tensile and hardness tests of several samples from Tempcore rebars (with high ductility) with various damage levels. The assessment of strength and ductility in locally damaged rebars concluded that the ultimate strain decrease is the main anomaly, mainly due to the hardening of steel that allows overcoming the yield stress decrease until damages of 20%.

Peer-review under responsibility of INEGI - Institute of Science and Innovation in Mechanical and Industrial Engineering

Keywords: Corrosion, Damage, Tempcore, Strength, Ductility

1. Introduction

The minimum material requirements to be applied in the civil engineering works have progressed over the years with a view to improve their safety and durability, as well as to reduce their working associated costs. In the particular case of reinforced concrete (RC) structural elements, such requirements have been overcome with the development of materials (concrete and steel) with improved properties, particularly in terms of strength, ductility and durability; as well as the introduction of new materials and the increase of prefabrication.

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Peer-review under responsibility of INEGI - Institute of Science and Innovation in Mechanical and Industrial Engineering
doi:10.1016/j.proeng.2015.08.029

The verification of these requirements is an increasingly factor to take into account, such that for decades the different regulations and scientific codes have specific chapters, only concerning materials, covering topics such as the manufacture, its durability, and their physical and mechanical properties.

In order to fulfil these requirements, the production of steel rebars has changed in time. After several decades of steel production in blast-furnaces, the electric oven was used, due to environmental reasons, as a replacement; its operation and feedstock led to a final product with higher quality [1]. On the other hand, and coupled with this change, the usual hardening performed during the steel cold rolling, to obtain higher mechanical strength, was almost completely replaced by more suitable thermal treatments.

One of the most effective thermal treatments, revealed and implemented in the world, is the Tempcore system developed in Liege, Belgium, which main idea consists in superficially cooling the rods with water, in a short time, during the manufacturing process (process called TEMPer). After this phase the rebar back to red hot at the surface by the heating of the CORE, followed by a slow cooling up to room temperature.

The Tempcore heat treatment gives to the rebars a cross-section formed by three layers (Fig. 1), comprised of different iron-carbon alloys: i) core (ferrite with pearlite), ii) transition layer (tempered martensite, tempered bainite and ferrite with pearlite), and iii) surface layer (tempered martensite). Various alloys have very different mechanical properties, for example, ferrite is highly ductile but somewhat hard while martensite is extremely hard but very little ductile.

Thus, in a Tempcore rebar the hardest component is located in the surface layer. In addition, after a Tempcore treatment, as the rebar first cools in the surface layer and then in the core, self-balanced stresses are induced in the bar cross section, being the surface layer in compression and the core in tension.

These features are very beneficial for the lateral stability of the rebar as it can be observed in the bending-unbending test by the absence of significant transverse cracks, or by the number of complete cycles of the alternating cyclical supported hysteresis test. For these reasons these rebars are suitable for earthquake resistance [2].

In the early 1990s Tempcore rebars began to be produced and marketed in Portugal on a large scale. By the early 2000s after several improvements in the manufacturing process, the special ductility rebars appeared, also known as anti-seismic, since its main progress against the previous was not the exceptional increase in ductility but their suitability for earthquake resistance, as previously mentioned.

The production of special ductility rebars is regulated by the specifications LNEC 455 and 460 [3, 4], which requirements satisfy all ductility classes provided in the Eurocodes; especially Eurocode 2 - Part 1.1 [5] considering that the other Eurocodes redirect to the first: the definition of rebars properties. The Portuguese (and European) name for these steel bars are: A400 NR SD (B400C) and A500 NR SD (B500C).

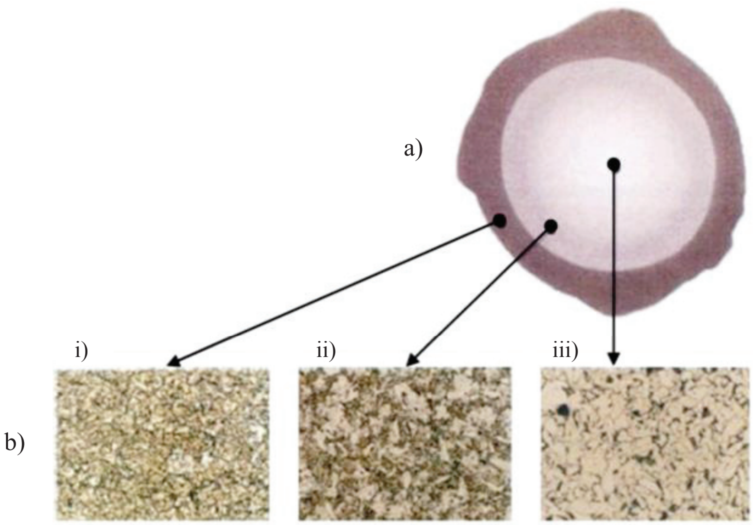


Fig. 1. a) Cross-section of Tempcore rebar [6]. b) Zoomed photo (500x): i) surface layer, ii) transition layer, iii) core.

The Tempcore rebars behaviour is a result of the complex interaction of their three layers with different initial stresses and therefore, the study the different layers properties is important for the understanding of the rebar overall behaviour. This paper presents and discusses the results of hardness, strength and ductility obtained from tensile and hardness tests on several samples from special ductility rebars and with various levels of damage.

Nomenclature

L_0	initial length
D	rebar diameter
r	rebar radius after abrade
R	rebar radius
f_u	ultimate strength
K	proportional constant
HV	hardness

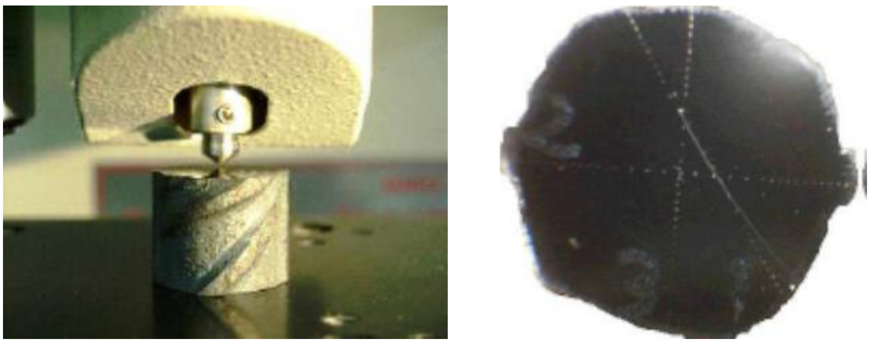
2. Experimental Work

The performed experimental campaign can be divided in three parts: i) assessment of the hardness in depth ii) assessment of strength and ductility in depth and iii) assessment of strength and ductility of damaged rebars. The first two were aimed to study the behaviour of the rebars in depth, while the third aimed to quantify the ductility of special ductility rebars occasionally damaged, simulating pitting corrosion.

2.1. Assessment of Hardness in Depth

The hardness of a material, in this case of the steel, is defined as the stress which the material has to undergo to achieve a plastic deformation on its surface. From this parameter, which is easy and low cost to obtain, it is possible to estimate others, like the mechanical strength. In this work, given the small dimensions of the cross section of the rebar and the need of an exhaustive hardness characterization in depth, a microhardness test was performed, instead of a conventional hardness test, to guarantee a larger data sample in a short tested area. The type of the test carried out was the Vickers penetration test, in which the diamond indenter presents a pyramid shape.

The hardness measurement (Fig. 2a)) was done in a 20 mm diameter sample of A500 NR SD of, after smoothing the surface of the cross-section successively through polishing with finer sand-paper. Three hardness profiles were performed on the sample. In other words, the hardness was measured successively along three straight lines, as showed in Fig. 2b), wherein it was used 1 mm spacing in the central zone and 0.5 mm in the lateral areas of the sample. The hardness test was executed with a Struers Duramin machine according to the EN ISO 6507-1: 2005.



a) b)

Fig. 2. a) Hardness test execution. b) Performed hardness profiles.

2.2. Assessment of Strength and Ductility in Depth

The assessment of the rebars strength and ductility was carried out using the conventional rebar tensile tests, according to the NP EN 10002-1. For these tests, a Shimadzu machine was used, which rebar strains measurement system consisted of numerical computation of digital images from two video cameras accurately oriented to the measuring marks (references).

Samples of rebars for tests were obtained from A500 NR SD steel type of 20 mm diameter. Before, samples were abraded (Fig. 3a) concentrically from their surface up to their final diameter. Several final diameters were chosen to be tested: 20 mm (with no abrade), 19 mm, 18 mm, 17 mm, 14 mm and 11 mm. For each selected final diameter, three samples of rebars were tested.

The initial length of each sample followed the specifications of the previous mentioned standard and consisted in five times the sample diameter (L_0 = 5D).

2.3. Assessment of Strength and Ductility of Damaged Rebars

The study of damaged rebars consisted of tensile tests of rebars locally damaged. Induced damage into the rebars consisted in locally abrading, with a half circle shape, perpendicularly to the rebars (Fig. 3b), in order to simulate the effect of pitting corrosion.

Three sets of five 16 mm diameter rebars samples were tested, being the first series with no damage, and the second and third series with a damaged of 10% and 20% of the rebar cross-section, respectively. The test procedures were identical to those used in the previous section.

a) b)

Fig. 3. a) Rebars abraded concentrically. b) Damaged rebar locally abraded.

3. Experimental Results

3.1. Assessment of Hardness in Depth

Fig. 4 shows the results obtained for the three hardness profiles. From the results observation it is clear that the distinction between the different curves sections indicated three layers (surface, transition and core). It is noted that in the main layers (surface and core) the hardness values are practically constant, whereas in the transition layer occur a variation of the hardness firstly soft near the core, but relatively abrupt near the surface layer.

The hardness has values of 164 HV in the core and 262 HV in the surface layer, that is, the surface layer is about 60% harder than the core. Another important feature obtained in the results was the low scatter, which results not only by the fact that the three profiles were obtained of the same sample, but also because the high quality of the production process of rebars.

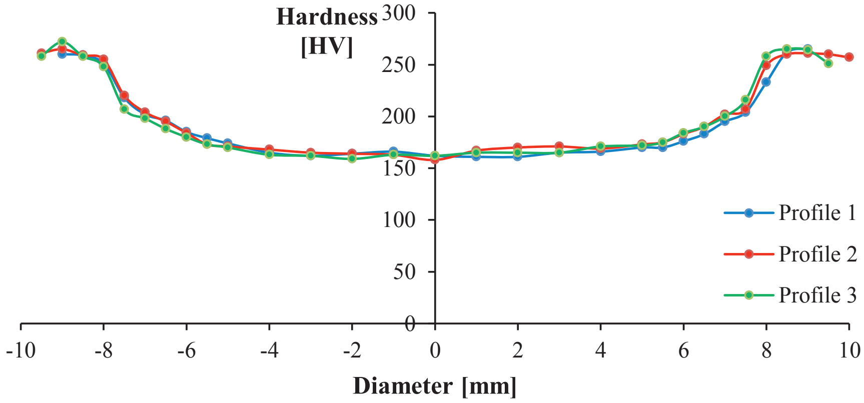


Fig. 4. Hardness of the 20 mm diameter rebar A500 NR SD.

3.2. Assessment of Strength and Ductility in Depth

Figs. 5 and 6 represent the average values of results obtained from each group of samples. The dimensionless parameter r/R in the horizontal axis is the normalized radius of each sample group. For example, for final diameter of 11 mm, r/R=0.55.

Fig. 5 shows the results obtained for the ultimate force and yield force for each group of samples abraded, while Fig. 6 shows the results for permanent strains at yield plateau and the ultimate strain.

Relatively to the Fig. 5, the overall shape of results is typical of a circular section specimen, wherein its area, and therefore also the force, increases with the square of the diameter. There is an increase in the difference between the two forces curves as the rebar is complete. Through an analysis of Fig. 10 it can be seen that the hardening, relationship between the ultimate and the yield force, ranges between 1.21 (r/R=1) and 1.35 (r/R=0.55), indicating that the hardening of rebars increases as they become abraded.

In Fig.6 it is observed that the ultimate strain (at maximum force), except for a group of samples (probably negligible), shows very similar values, and slightly exceeding to 10%. The permanent strain at the yield plateau manifests a slight decrease as the rebar is complete, varying from 1.7 to 1.1%.

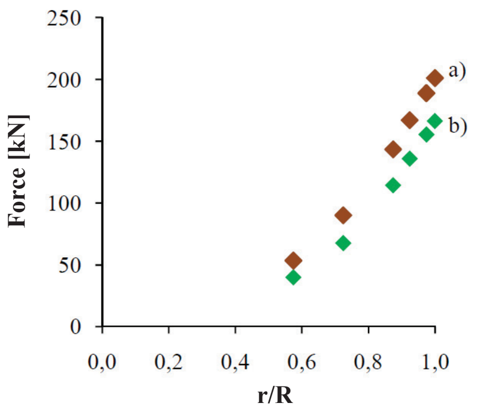


Fig. 5. Axial force as function of normalized radius.
a) Ultimate load.
b) Yield load.

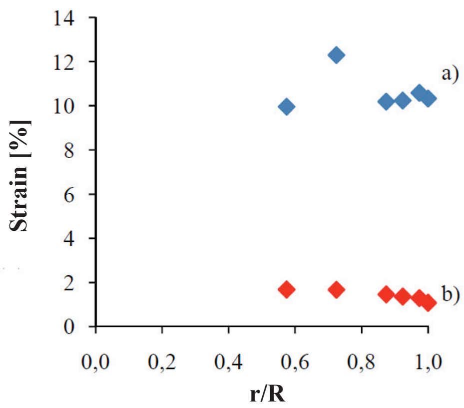


Fig. 6. Axial strain as function of normalized radius.
a) Ultimate strain.
b) Permanent strain at yield plateau.

3.3. Assessment of Strength and Ductility of Damaged Rebars

Fig. 7 shows the rebars tensile tests results for each group of selected samples (0, 10 and 20% damage). The main anomaly observed was a pronounced decrease in the ultimate strain (at maximum force) in the damaged rebars. However, even with rebars with 20% damage was possible to achieve an ultimate strength of rebars higher than the yield strength of rebars without damage, that is, the base value for which the rebars are design.

Figs. 8 and 9 present the average values of the results obtained for the various mechanical properties of each group of samples. Comparatively to the undamaged rebars, the yield strength reductions were 14 and 24%, respectively, while for the ultimate strengths, these decreases were only 7 and 15%, respectively, that is, the reductions in the yield strength are greater than those that would be obtained by the theoretical values by applying a factor corresponding to the area reduction.

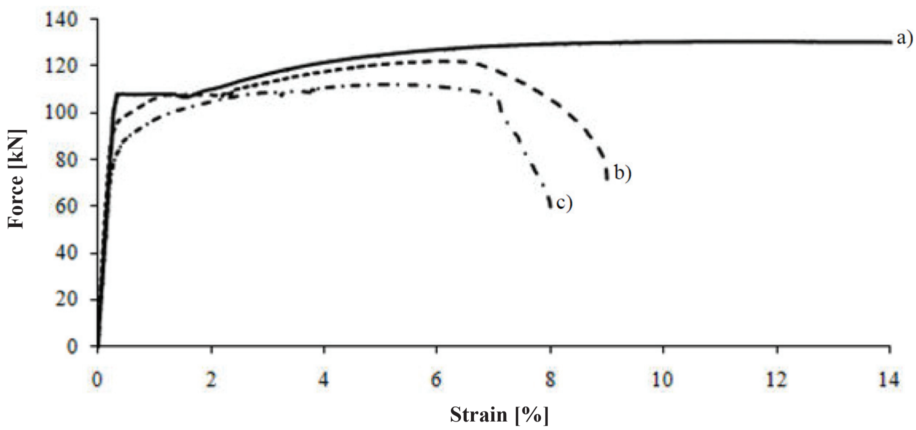


Fig. 7. Tensile test for the16 mm diameter rebars of A500 NR SD.
a) Rebars without damage. b) Rebars with 10% Damage. c) Rebars with 20% Damage.

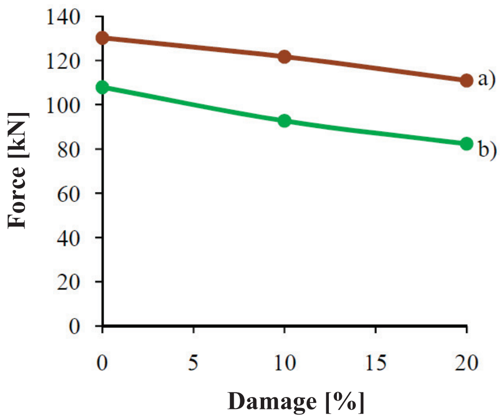


Fig. 8. Force as function of normalized radius.
a) Ultimate load.
b) Yield load.

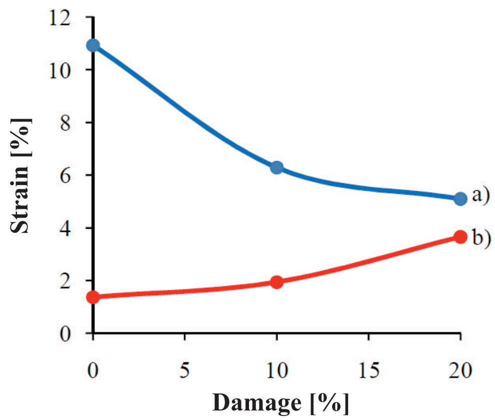


Fig. 9. Strain as function of normalized radius.
a) Ultimate strain.
b) Permanent strain at yield plateau.

With the damage introduced, the ultimate strain (at maximum force) (L_0 = 5D) decreased by 42% and 53%, respectively, while the permanent strain at the yield plateau increased by 42% and 167%, respectively. This last parameter, in this study with damaged rebars (10 and 20%), does not mean a permanent strain at yield plateau; in fact no yield plateau occurred in the damaged bars, since these rebars had a typical behaviour of a brittle steel. Thus, this parameter only represents the strain to which it is observed from the first change in shape of the curve, as happens in the non-damaged rebars where the yield plateau gives rise to a parabolic curve that culminates into the rebar rupture. For this reason the analysis of this parameter should be carefully analysed.

4. Discussion of Results

The results showed in Fig. 4 for the hardness in depth are typical of steel rebars produced by the Tempcore system. Other authors, such as Son [6] or Zheng and Abel [7] had already published works with steels, produced in other countries, which presented hardness curves very similar to results obtained even for steel bars of the A400 class.

As mentioned in Section 2.1 it is possible to estimate other properties of the materials from the correlations using appropriate hardness measurements, such as yield strength or ultimate strength of the material. For the steels case, it is current to estimate the yield stress from a standard hardness tests.

Several standards such as ASTM E140 [8] and SAE J417 [9] have conversion tables between the various ranges of hardness and yield strength. Moreover, other authors have hardness conversion formulas to other properties. One of the most used equations is shown in Eq. (1), which presupposes a directly proportional relationship between hardness and ultimate strength for a given range of values.

$$f_u = K \cdot HV \tag{1}$$

where f_u represents the ultimate strength, K is a proportional characteristic constant, and HV, the material surface hardness. According to Yavuz and Tekkaya [10], who evaluated this relationship for many types of steel, the parameter K is about 3.0 for the type of iron-carbon alloys presented in steel rebars.

If the hardness in Fig. 4 is integrated, from the rebar centre up to its surface, and multiplied by K (as Eq. (1)) it is possible to obtain rigorously the results of Fig. 5a), as showed in Fig 11.

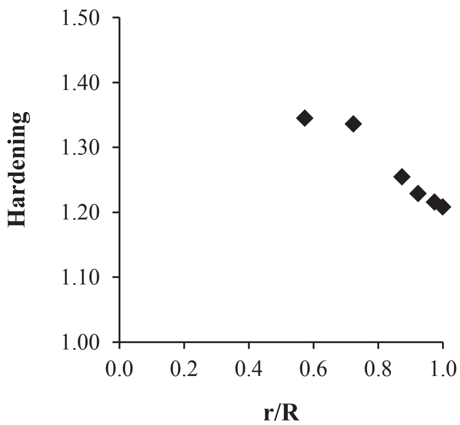


Fig. 10. Hardening of the 20 mm diameter rebar A500 NR SD.

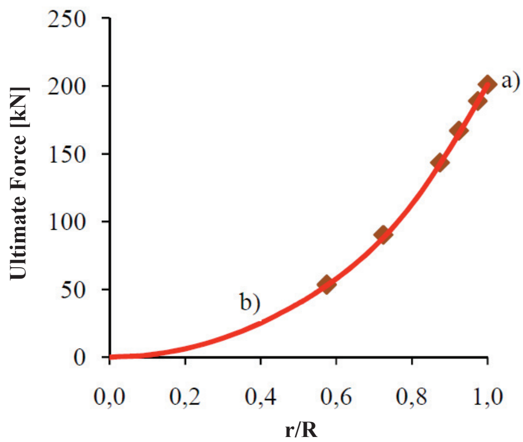


Fig. 11. Ultimate force as function of normalized radius.
a) Tensile test.
b) Correlation from hardness test.

Finally, from the results obtained in Section 3 is presented in Table 1 the results (yield force and ultimate strain) of two extreme corrosion scenarios: generalized corrosion by using the results of Section 3.2, and pitting corrosion, using the results of Section 3.3. For the yield force there is a slightly higher reduction to the sectional area loss (damage), as already mentioned above. For ultimate strain this parameter is not changed by general corrosion, while for pitting corrosion this parameter is strongly affected.

Table 1. Consequences of corrosion in rebars of 20 mm diameter

Damage [%]	Yield Force [kN]		Ultimate Strain (L_0=5D) [%]	
	General Corrosion	Pitting Corrosion	General Corrosion	Pitting Corrosion
0	166	166	10,3	10,3
10	145 (-13 %)	143 (-14 %)	10,4	6,3 (-39%)
20	123 (-26 %)	126 (-24 %)	10,2	5,1 (-50%)

5. Conclusions

The heat treatment gives to the Tempcore rebars a cross-section formed by three layers: core (less strong, more ductile), transition layer and surface layer (stronger, less ductile). The performed experimental campaign enabled assessing better the properties of rebars in depth.

The measured values for hardness ranged from 164 HV (core) to 262 HV (surface layer). With these values it was possible to estimate accurately the local ultimate strength of the material, as confirmed by the results of tensile tests on rebars laterally abraded.

The strength and ductility evaluation in locally damaged steel concluded that the decrease in ultimate strain (at maximum force) is the main anomaly. This happens because the steel hardening allows mitigating the yield strength reduction for damages up to 20%.

Acknowledgements

The first author would like to express their sincere appreciation and gratitude to the ESF – European Social Fund and FCT – Portuguese Foundation for Science and Technology for the received support under the doctoral grant with the reference SFRH/BD/30004/2006. The authors also acknowledge the FCT for the support of the research unit CONSTRUCT - LABEST.

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