Assessment of the Residual Strength of Fire-Damaged Steel-Rebars

R. Felicetti and P.G. Gambarova

Abstract Concrete structures are known to exhibit a good behaviour in fire, thanks to the low thermal diffusivity of the material, which provides an effective protection to steel reinforcement. Moreover, a significant strength recovery occurs when the bars cool down to room temperature, though this markedly depends on their metallurgical properties. Since the surviving structure is still required to bear the noticeably-higher loads assigned by the ultimate limit state, the post-fire strength of the reinforcement has to be carefully weighed up. To this purpose, two different Non-Destructive Techniques are investigated in this study. The first one is the Dynamic Hardness Test (also known as Leeb Test), which is quite sensitive to steel decay. The test can be performed onsite by means of a small specifically-designed device, provided that the surface of the bar has been smoothed prior to testing. The second technique is based on the continuous monitoring of the drilling resistance via a special setup, which allows to measure the thrust to be exerted on the bit in order to keep a constant feed rate. This latter method requires no sample preparation, but the correlation with steel decay is rather uncertain, due to the conflicting effects of the decreasing yield strength and the increasing hardening and strain capacity of fire damaged steel. The pros and cons of these two methods are discussed in the paper, in view of their practical implementation for assessing the post-fire safety of actual structures.

Keywords Damage • Drilling • Fire • Hardness • Rebars • Steel

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R. Felicetti (✉) • P.G. Gambarova
Dept. of Structural Engineering, Politecnico di Milano, Milano, Italy
e-mail: roberto.felicetti@polimi.it

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Introduction

Concrete structures have good chances to survive a fire, thanks to the low thermal diffusivity of the material, to the redundancy of their scheme and to the reduced level of variable loads which are likely to concur in such an exceptional event. Although the damage undergone by concrete cover is mostly irreversible and some repair measures are often needed to restore the required durability, steel rebars are expected to recover an sizeable share of their original strength when cooled down to room temperature. This recovery is critical, as the reinforcement is still required to bear the noticeably higher loads associated with the ultimate limit state. Being generally the weakest link in cross-sections designed for flexural ductility, the assessment of the residual mechanical properties of steel rebars is an important and - to authors' opinion - not adequately addressed issue in Civil Engineering.

The original strength of metals and their sensitivity to the heating/cooling cycle caused by a fire markedly depend on microstructure [1], and then on a) average size of iso-oriented crystalline regions (grains); b) number of defects at the atomic scale (dislocations); c) presence of any embedded alloying elements and d) production process (e.g. hot-rolled vs. cold-worked steel). In a recent study by the authors [2], Quenched and Self-Tempered bars (QST bars) were shown to be more sensitive to temperatures above 550°C than the "old" carbon-steel bars. On the other hand, stainless-steel exhibited a very good behaviour when the bars are hot-rolled, but the opposite was found in case of cold-worked bars.

In consideration of this wide assortment of possible material types, exposed to the highly variable heating conditions associated with real fire scenarios, fast and responsive assessment methods are needed, possibly not requiring a prior knowledge of the metallurgical properties of the examined rebars. To this purpose, two different techniques have been investigated in this study: the measurement of the dynamic hardness via a portable tester and the monitoring of the drilling resistance via an instrumented drill. The implementation and the sensitivity of these two methods are discussed in the following sections.

Steel Types and Experimental Programme

In the present study, both off-the-shelf and old high-bond bars were considered. In more details, the following reinforcement types have been investigated (Table 1):

Quenched and Self-Tempered bars (QST - Ø = 10 and 16 mm). It is presently the most extensively used reinforcing steel in Europe. The bar surface is quenched with water sprays as it exits the rolling mill, leading to a hard, tempered martensitic outer layer, and a soft, more ductile ferrite-pearlite core. In this way the average yield strength is increased while the carbon content can be kept at a rather low level, to the advantage of ductility and weldability.

Table 1 Reference strength values and ND parameters for unheated rebars

rebar type	QST 10	QST 16	MA 10	SS 12	CS 12/20
yield strength f_y (MPa)	524	529	453	701	463
Tensile strength f_t (MPa)	642	624	614	812	710
Leeb number	477	481	474	562	476
drilling thrust (N)	46.1	-	33.4	61.9	40.3

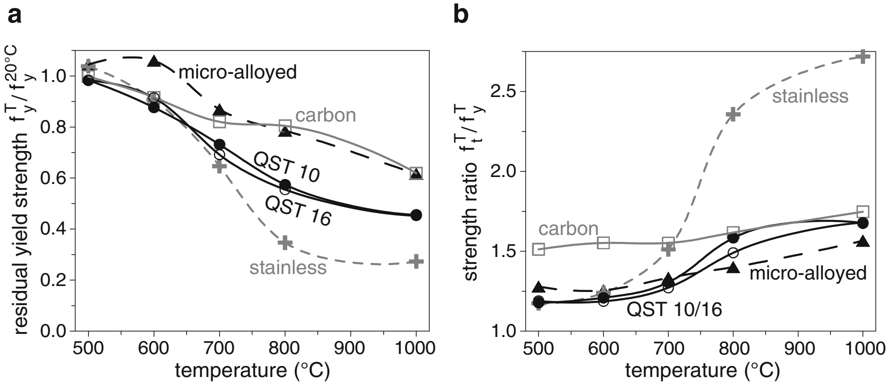

Fig. 1 Yield-strength decay and hardening growth of the investigated steels

Micro-Alloyed bars (MA - Ø = 10 mm). The mechanical properties are enhanced by incorporating alloying elements like Niobium and Vanadium in the molten metal, at increased cost but with the advantage of a homogeneous bar cross-section in terms of microstructure, strength and ductility.

Cold-worked Stainless-Steel bars (austenitic AISI 304L steel - SS - Ø = 12 mm). Corrosion resistance is achieved with chrome content exceeding 10.5% and carbon content lower than 0.07% (EN 10088-1). In spite of the higher material cost (from 4 to 8 times as much as ordinary rebars), the use of stainless steel is strategic for improving the durability of bridges, viaducts and marine structures.

Square-section, Carbon-Steel bars (CS - side = 12 and 20 mm). Currently produced in Italy in 1950-70, these bars exhibit a higher strength [2], but are more fire sensitive than old smooth hot-rolled carbon-steel bars.

All types of bars were cut in 0.6 m samples, to be tested in tension, and 0.2 m pieces for the implementation of ND techniques. The samples were heated at 3°C/min up to T_{max} = 500, 600, 700, 800 and 1000°C. The target temperature was maintained for one hour and then the samples were cooled at the same rate.

As concerns the tensile properties, two repeated tests were performed for each case, with almost identical results. All samples were unaffected by exposure up to 500°C (Fig. 1). Beyond this threshold, different decays occurred depending on the steel type, with carbon and micro-alloyed rebars exhibiting the best endurance and cold-drawn stainless-steel rebars confirming their remarkable sensitivity to high temperature [2]. The above trends are made evident by the reduction of the residual yield strength (Fig. 1a), whereas a smoother response characterizes the tensile strength. This translates into an increasing hardening ratio f_t/f_y (Fig. 1b), which partly offsets the overall weakening of the material. It has to be remarked that at any temperature all carbon steels showed a well defined yielding point, followed by a plateau up to about 1% strain. On the contrary, stainless-steel required the introduction of a conventional proof strength (0.2% non-proportional extension).

Dynamic Hardness Tests

Hardness testing is a recognized indirect way to assess the quality of metals (tensile strength, wear resistance, ductility, etc). The principle is to indent the material surface by gradually applying an assigned force to a hard indenter (sphere, cone or pyramid) and then to measure the size or depth of the ensuing imprint. Unfortunately, the classic static methods (Brinell, Rockwell, Vickers) are generally not suited for onsite application, since they require an accurate sample preparation (roughness < 0.1-0.3 μm) and they are implemented on bench-mounted testers fitted with a precise optical measuring system.

An interesting alternative is provided by the dynamic hardness test (Leeb method), where a body fitted with a hard spherical tip (Ø = 3 mm) impacts the test surface under a spring force [3]. The impact and rebound velocities are measured at approximately 1 mm from the test surface, through the electric potential induced in a coil by a permanent magnet mounted inside the impact body (Fig. 2a). The ratio of these velocities, multiplied by a factor 1000, is defined as the Leeb hardness number. As there is no need to apply any external thrust nor to measure any imprint, the Leeb method allows to develop compact handheld devices that can be easily positioned on the tested rebar (Fig. 2b). The method still requires a smooth surface, though with less stringent limits (average roughness < 2 μm). Moreover, the sample should be firmly restrained, so to prevent any vibration during the impact, which

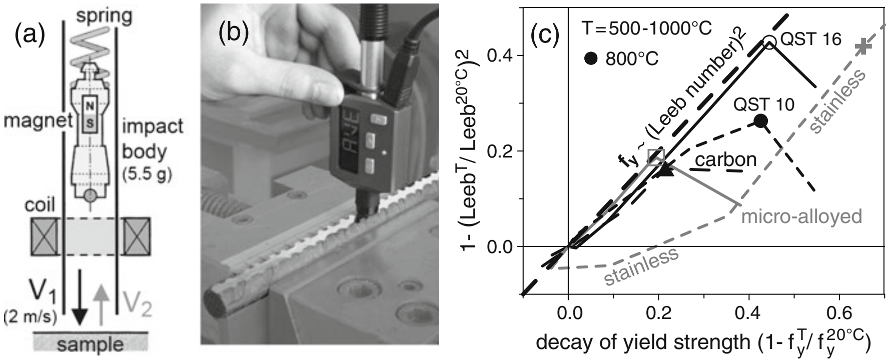

Fig. 2 **a)** Scheme of the Leeb hardness tester, **b)** handheld device (type D) and **c)** relation between the residual yield strength and the Leeb number squared

may reduce the apparent hardness of the tested material. This may be not the case of small rebars embedded in a severely damaged concrete cover.

In order to ascertain the sensitivity of this method to the strength loss exhibited by heated steels, 0.2 m rebar pieces of the types listed in Table 1 were clamped in a heavy machine vice. The top side of each sample was milled and then polished with sandpaper. About 30 tests were performed on two samples for each steel-temperature combination, with fairly repeatable results (coeff. of var. < 5%).

As regards the interpretation of the results, several studies are available in the literature, presenting either empirical, numerical or closed-form correlations with the yield strength. Among them, the linear relationship with the rebound kinetic energy (namely Leeb number squared) proposed by Stilwell and Tabor for the conical indenter (see [4]) is in good agreement with the experimental results concerning carbon steels exposed up to 800°C (Fig. 2c). At higher temperatures an increasing hardness and larger dispersion are observed, probably because of grain coarsening in the crystalline microstructure. A totally different behaviour characterizes cold-drawn stainless-steel, due to lack of a true yield point and to the remarkable strain hardening exhibited by damaged rebars (see Fig. 1b).

Drilling Resistance Tests

The continuous monitoring of drilling resistance is a promising technique for the condition assessment of construction materials, like timber, mortar, concrete and stones [5]. As for metals, the principle is to cut shavings of assigned thickness by imposing fixed rotational and feed rates, while measuring the thrust to be applied to the work-piece. This latter parameter exhibited a good correlation with the

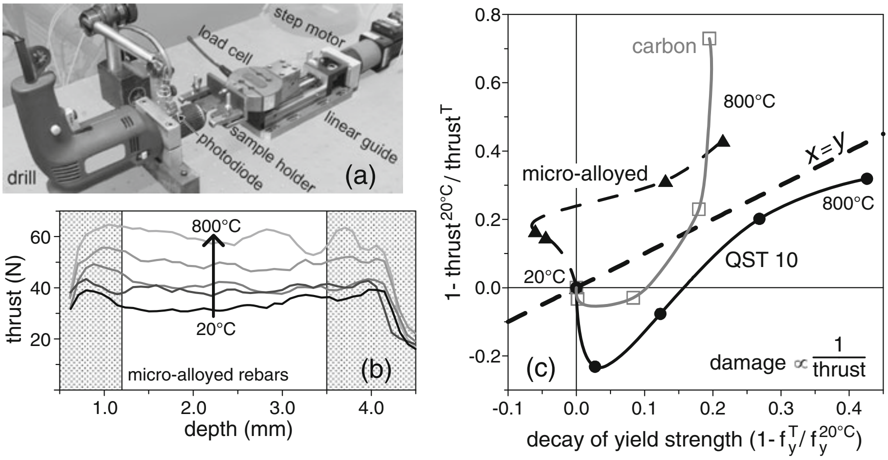

Fig. 3 **a)** Drilling resistance test setup, **b)** plots of the exerted thrust at increasing thermal damage and **c)** relation with the residual yield strength

Vickers hardness in the range 200-900 HV and was successfully applied to check the treatment thickness in superficially hardened steel [6].

According to the cited reference, a special setup was arranged, based on a ordinary pistol-grip drill fixed to a bench (Fig. 3a). The advance of the sample was driven by a step motor fitted with a linear guide and a load cell (0.01 mm/rev, hole depth ~ 4 mm). The tools were Titanium Carbo-Nitride coated bits (Ø = 2 mm), which proved to give repeatable results for more than 50 holes in unheated QST rebars.

Surprisingly, thermally damaged steels proved to be more difficult to drill (Fig. 3b), probably because of the increased strain capacity and the pronounced hardening behaviour. This makes the material harder to cut, to the point that drilling was not possible for carbon steels exposed to 1000°C and cold-formed stainless-steel subjected to temperatures above 500°C. Although the exerted thrust proved to be markedly affected by damage, no clear relation with the yield strength could be recognized (Fig. 3c).

Concluding Remarks

In this study two assessment methods for fire damage in steel rebars were investigated, namely the dynamic hardness and the drilling resistance tests. The main conclusions can be summarized as follows. The dynamic hardness proved to be a viable and sensitive inspection technique for the problem at issue. An easy and general relation with yield strength was found for carbon steels up to 800°C, that is the usual range for practical applications. The requirements of a smooth surface and an effective restraint of the tested rebar are the main limitations to consider in the implementation of the method. These restrictions do not apply to the drilling resistance technique, though a special tester should be developed for onsite applications. On the other hand, no simple correlation with the residual mechanical properties was found. The above results cannot be extended to cold-drawn stainless-steel, though their noticeable sensitivity to fire should be carefully weighed in the assessment of residual structural safety.

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