Journal of Constructional Steel Research 185 (2021) 106866

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Load and temperature influence on the post-fire mechanical properties of steel reinforcements

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ARTICLE INFO

Keywords:
Residual properties
Post-fire behaviour
Reinforcement
Steady-state test
Transient-state test
Tensile test

ABSTRACT

An experimental study was carried out to evaluate the residual mechanical properties of steel reinforcements after their exposure to elevated temperatures. In order to reproduce real loading conditions, specimens were simultaneously subjected to a load level and a thermal cycle consisting of heating up to a target temperature and cooling back to room temperature. The target temperature was a percentage of the critical temperature, i.e., the temperature at which a specimen breaks when it is subjected to a constant tensile load and an increasing temperature at a constant rate. After that, the residual mechanical properties were obtained submitting the specimens to tensile testing until failure. Critical temperatures for each load level were obtained by means of transient-state tests. In parallel, unloaded specimens were subjected to the same thermal cycle for comparison purposes, and for the same reason steady-state tests were also performed.

Results indicated that the residual mechanical behaviour of reinforcing bars depended not only on the maximum temperature reached, but also on the load level that was bearing during the thermal cycle. Depending on this combination of variables, the code requirements for a given ductility class of a reinforcement may not be satisfied in a post-fire situation. Considering the lack of information in this issue, the obtained data can be helpful in the assessment of reinforced concrete structures after a fire.

1. Introduction

After a fire, reinforced concrete (RC) or composite steel-concrete structures usually do not collapse due to the insulating properties of concrete, so a decision has to be taken in order to its reinstatement or further demolition [1–3]. In the first case, the remaining elements need to verify the safety requirements of the current performance-based codes, but must of them such as EN 1992-1-2 (Eurocode 2, part 1-2 [4]) do not provide rules in this regard (as an exception, BS 5950-8 [5] prescribed some guidelines for a further reuse of a structure affected by fire) so post-fire evaluation of a RC structure depends mostly on the expertise criteria [6].

In order to evaluate the performance of a RC structure after a fire, the residual mechanical properties of its constituent materials must be analyzed. As it is known, mechanical properties of structural materials decrease with the temperature and, eventually, some of them can be partially recovered after cooling down. These 'residual properties' of materials have to be strongly accounted for in the evaluation of fire damaged structures [7]. Nevertheless, while mechanical properties of structural material at high temperatures have been extensively reported, residual properties have not, which can be the reason for the lack of code recommendations on post-fire assessment of RC structures.

Given that steel reinforcements provide the tensile strength that concrete cannot withstand by itself, its residual properties are critical in the post-fire appraisal of a RC structure. These properties depend on multiple factors [3], such as chemical composition, manufacturing process, heating duration, maximum temperature reached, cooling method, presence of corrosion or the load level carried out at the onset of fire and throughout its duration. The joint analysis of these factors to evaluate post-fire behaviour of steel reinforcements is unaffordable, so previous works have focused in obtaining residual mechanical properties by testing.

Edwards and Gamble [8] tested Grade 60 reinforcing bars, i.e., minimum yield strength of 413 MPa, after heating and cooling. They found that the residual values of yield strength and ultimate strength were practically unaltered after cooling down from 500°C or below (there is currently consensus with this finding) but residual elastic modulus did not experienced substantial changes until cooling down from 800°C.

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https://doi.org/10.1016/j.jcsr.2021.106866
Received 6 May 2021; Received in revised form 14 July 2021; Accepted 15 July 2021
Available online 27 July 2021

Notation

ε_f	Strain at fracture
ε_u	Ultimate strain (strain at tensile strength f_u)
E_s	Elastic modulus
$f_{0.2}$	Proof stress at 0.2% strain
$f_{2.0}$	Proof stress at 2.0% strain
f_u	Tensile strength
f_y	Yield stress
t_s	Soaking time
θ_0	Room temperature
θ_{crit}	Critical temperature
θ	Target temperature

Dias et al. [9] and Neves et al. [10] studied the influence of the reinforcement diameter and the cooling method (by air, water jet or water immersion) after being heated to high temperatures. These parameters affect the cooling rate and, subsequently, the residual values of tensile strength and ultimate strain. The cooling method had a significant influence for temperatures above 600°C, but the influence of the diameter was less significant. If cooling by water jet or water immersion was used, an increase in residual tensile strength and a decrease in residual ultimate strain was observed, which implied a significant reduction of ductility. In both works, the findings were justified from a metallographic perspective. The influence of steel grade and manufacturing process on the residual properties of steel reinforcements (yield stress, ultimate strength and ductility) when heated up to 500°C or higher was demonstrated by Nikolau and Papadimitriou [11], Topçu and Karakurt [12] and Felicetti et al. [13]. It is interesting to point that Topçu and Karakurt [12] registered a dependency of bar diameter on post-fire behaviour stronger than the findings of Neves et al. [10].

Tao et al. [14] conducted an extensive literature survey to statistically compute reduction factors for yield strength, tensile strength and elastic modulus of both structural and reinforcing steels after cooling down from high temperatures. Stress-strain relationships were also obtained for structural and reinforcing steel separately. This work can be considered as the first attempt to formulate a post-fire, stress-strain model of reinforcing steels. Elghazouili et al. [15] performed experimental tests on hot-rolled and cold-worked steel reinforcements after cooling down from high temperatures. Mechanical properties for both steel types remained unchanged up to 400°C but, if a temperature of 600°C (or higher) was reached, residual tensile strength was substantially reduced while residual ultimate strain was increased. This finding is crucial for adequately assess the post-fire ductility of a RC member.

The previous state of the art review illustrates that the post-fire behaviour of reinforcement steels has not been as extensively studied as the behaviour at high temperatures. Moreover, the heating-cooling thermal cycles performed in the previous works were applied to unstressed specimens, which does not represent a realistic situation. Fire is an accidental situation during which the structure supports a fraction of the service load, so it is expected that reinforcing bars bear certain load

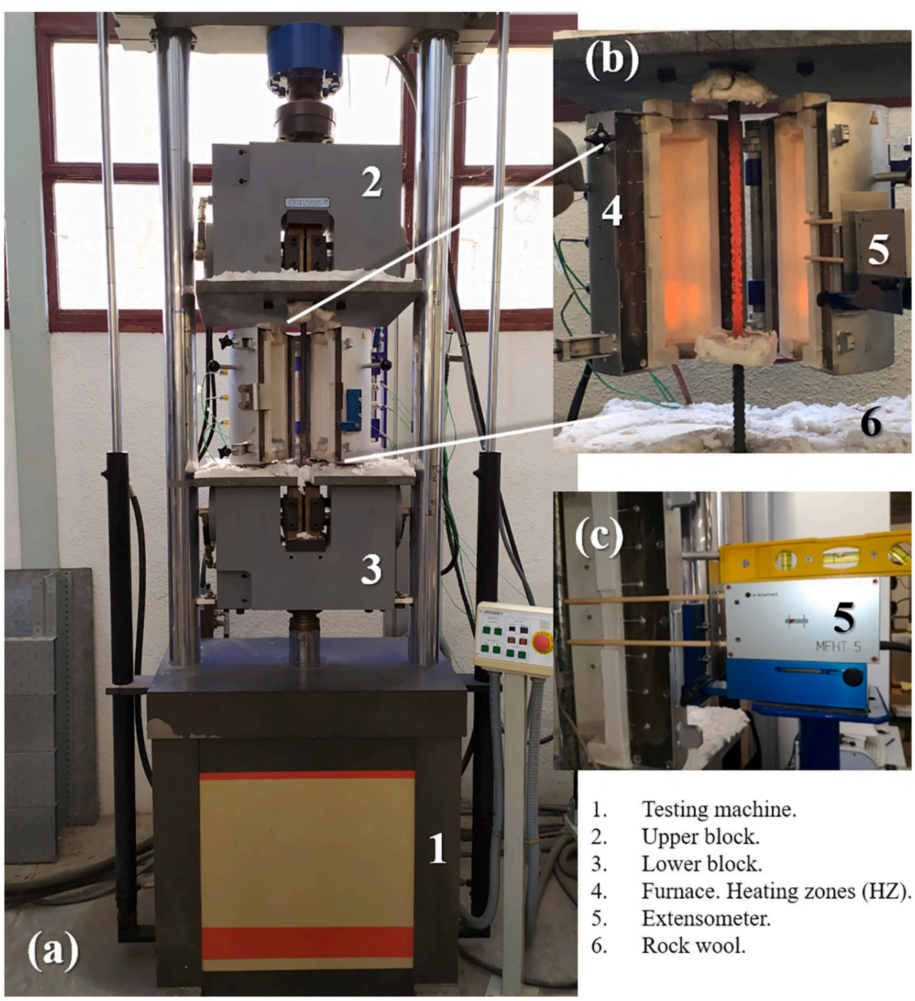


Fig. 1. Test setup. (a) Overview of the furnace mounted on the testing machine. (b) Detail of the furnace during an experiment. (c) Detail of the extensometer.

level during fire and after cooling down. Surprisingly, there is very limited information concerning post-fire mechanical behaviour of reinforcing steel bars subjected to the combined action of high temperature and load level. Holmes et al. [16] tested specimens after being subjected to load level combined with heating-cooling thermal cycles. Although residual values of yield strength, ultimate strength and elastic modulus were not reduced with respect to the measured at room temperature, it has to be mentioned that specimens were tested at a load level corresponding to the 55% of the yield stress (corresponding to a safety factor of 1.8) and the highest temperature reached was 600°C during the tests. Besides, according to Tao et al. [14], in the work of Cao [17] structural steels were subjected to a combination of load level (corresponding to 40%–100% of yield stress) and high temperatures within the range 240°C–600°C. However, since current RC regulations may require a fire resistance of 90 min or more for an element, the reinforcement temperature during a fire of this duration can easily reach 600°C, especially if spalling has occurred.

More recently, Tao et al. [18] carried out a similar approach studying the post-fire behaviour of concrete-filled stainless steel tubular columns subjected to a combination of load and high temperature. Likewise Holmes et al. [16] and Cao [17], it was concluded that the influence of load level could be ignored in the post-fire damage evaluations for temperatures lower that 600°C. Nevertheless, additional tests should be conducted in order to verify that this trend is kept for reinforcement steels at 600°C (or higher) temperatures and different load levels. The authors also indicated that the influence of load level and high temperature on the residual values of another key properties (such as ductility) should be addressed. Regarding composite steel-concrete structures, Han et al. [19] presented a numerical study on post-fire behaviour of steel reinforced concrete columns, which highlights the necessity of this research.

In the present work, an experimental campaign was conducted to evaluate the post-fire behaviour of reinforcing steel bars after being subjected to a combination of load level and high temperature. To this end, specimens were heated to temperatures comprised between room temperature and 1000°C and, in some tests, heating was applied together with a load level corresponding to a percentage of the yield stress at room temperature. Afterwards, specimens were naturally cooled down in furnace to room temperature and submitted to tensile testing. Steady-state tests and transient-state tests were also conducted to compare post-fire with in-fire behaviour of reinforcing bars, as it was done in previous works on carbon steel reinforcements (Dotreppe [20], Kowalski and Kisielinski [21] and Elghazouli [15], among others) and stainless steel reinforcements (Gardner et al. [22]).

The results for each test are presented and discussed, including measurements of key mechanical properties (yield stress, tensile strength, elastic modulus and ultimate strain). An especial attention is put on the post-fire residual ductility, which is a critical issue for RC elements affected by fire in buildings located in high seismic risk areas, and its compliance with the requirements of the current structural codes.

2. Experimental program

2.1. Test apparatus

The apparatus adopted in this work for testing the steel reinforcement bars is depicted in Fig. 1. It comprised a hydraulic universal testing machine (Fig. 1a) equipped with a 196.2 kN calibrated load cell and controlled by a closed-loop system based on load or displacement measurements. Each specimen was laterally clamped at both ends to avoid slip by hydraulic flat jaws located in the upper and lower blocks. The lower block was able to displace downwards while the upper block remained in the same position, thus submitting the specimen to tensile load. For each performed test, a series of loading-unloading cycles served to check the axial alignment of the specimen in the machine.

An electric furnace able to heat up to 1000°C (Fig. 1b) was attached

Table 1
Averaged mechanical parameters of reinforcing steel bars at room temperature.

Parameter	Value
Yield stress f_y (proof stress at 0.2% strain)	563.46 MPa
Ultimate strength f_u	665.17 MPa
Ultimate strain ε_u	13.27%
Strain at fracture ε_f	16.83%
Elastic modulus	198,130 MPa

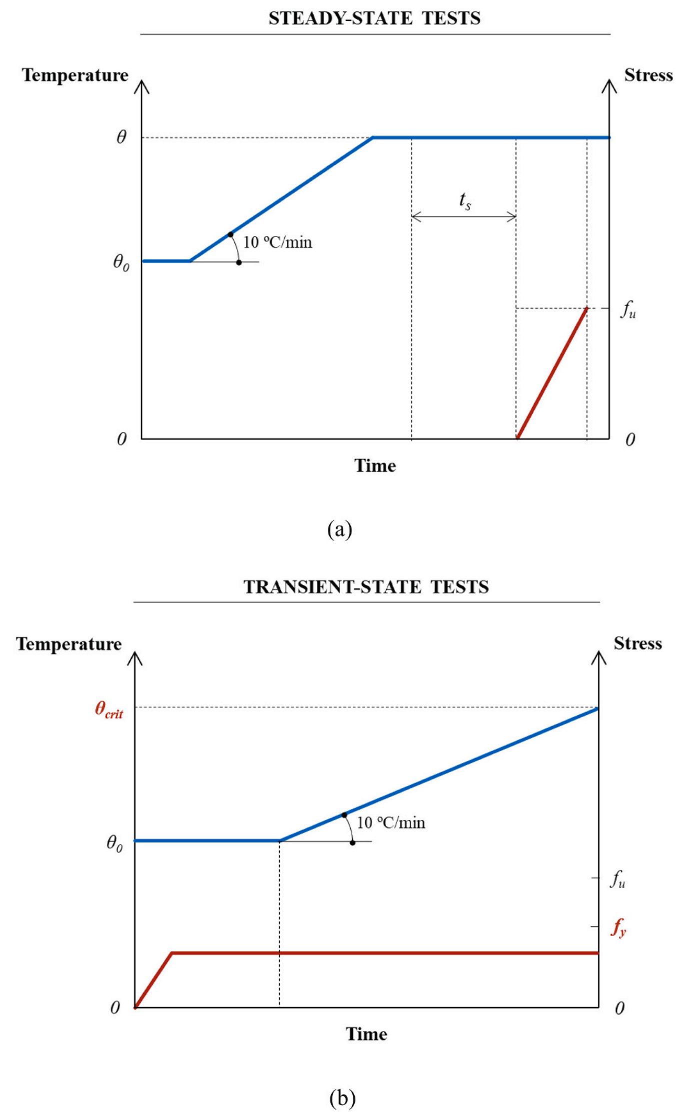
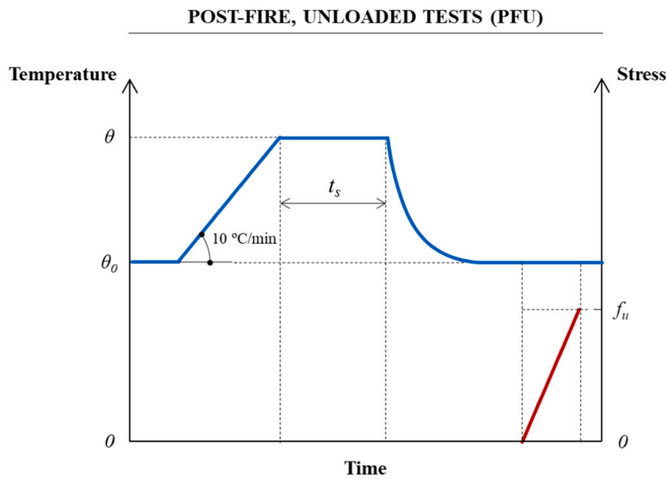


Fig. 2. Temperature and tensile loading histories for testing in-fire properties of steel reinforcements. (a) Steady-state tests. (b) Transient-state tests.

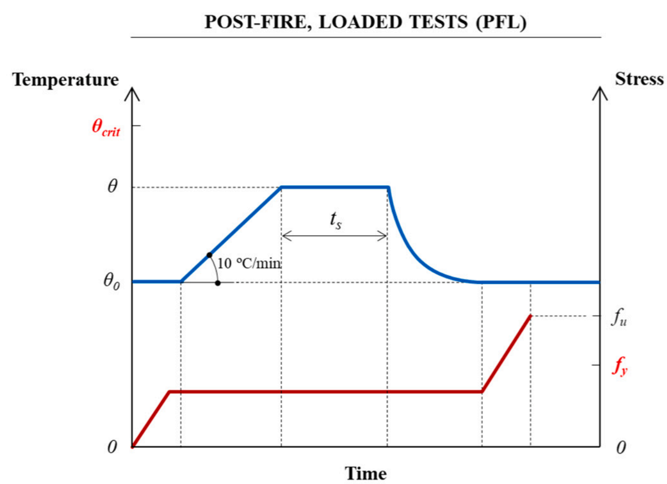
to the frame of the testing machine. The furnace had 3 independently controlled heating zones, located in the upper, the middle and the lower parts of the heating chamber. In order to maintain the target temperature evenly distributed inside the furnace, holes at both ends were filled with rock wool insulation to avoid convective flows.

With the exception of transient-state tests, a high-precision extensometer with a gauge length of 50 mm (Fig. 1c) was used. The extensometer was provided with corundum rods which allowed strain measurements at elevated temperatures. The rods kept in contact with the specimen surface in the central heating zone until plastic strains were reached. Then, the extensometer was removed to avoid breakage.

K-type thermocouples located in the middle of each heating zone



(a)



(b)

Fig. 3. Temperature and tensile loading histories for testing post-fire properties of steel reinforcements. (a) Unloaded specimens (PFU tests). (b) Loaded specimens (PFL tests).

were attached to each tested specimen to record surface temperatures, which were treated as feedback variables in the heating control. Machine measurements (applied load and displacement of the lower block), thermocouple readings and extensometer data were recorded by means of a digital acquisition system (2 Hz of sampling frequency) connected to a PC.

2.2. Material properties at room temperature

Tests were performed on specimens that met the specifications of EN 1992-1-1 [23], corresponding to bars whose steel grade, manufacturing process and diameter can be easily found in conventional RC structures throughout Europe. All the specimens were obtained from the same casting and bars batch.

Specimens were hot-rolled, diameter Ø16 mm weldable steel bars with a nominal yield stress of 500 MPa and a ductility class C. This class involves the highest ductility requirements according to EN 1992-1-1: a ratio f_u/f_y comprised between 1.25 and 1.35 (were f_u is the tensile strength and f_y is the yield strength) and a ultimate strain ε_u of 7.5% or higher. Specimen length was 800-mm length, which was necessary to exceed the furnace height in order to be clamped at both ends in the

Table 2
Number of specimens for each test type.

Test type	Number of specimens
Steady-state	36
Transient-state	30
Post-fire (unloaded) (PFU)	40
Post-fire (loaded) (PFL)	24

testing machine. The total heated length of the bar was 300 mm.

A total of 5 tests were performed in order to obtain the mechanical properties of the specimens at room temperature. The corresponding averaged values can be found in Table 1, which were taken as reference values to compare the results of the different tests. It has to be considered that although specimens were hot-rolled steels, proof strength corresponding to 0.2% strain was considered as the yield strength, because the yielding plateau is not always clearly visible at high temperatures or after cooling down.

2.3. Test procedures

Material properties at high temperatures are needed to know the mechanical response of structural materials during fire or after cooling down. Each material behaves differently in each scenario, so the respective material properties must be obtained from different tests which temperature and stress histories are depicted in Figs. 2 and 3.

In order to simulate possible situations of a reinforcement during fire, steady-state tests and transient-state tests were performed (Fig. 2). These tests and the corresponding results are described in Sections 3 and 4, respectively. From transient-state test, it was obtained the value of the 'critical temperature' θ_{crit} at which a reinforcement bar fails when subjected to a simultaneous tensile stress. On the other hand, to obtain the post-fire behaviour of steel reinforcing bars, specimens were subjected to heating and cooling cycles in order to evaluate its residual properties after a fire (Fig. 3). Tests on unloaded specimens (PFU) and their results are described in Section 5. Section 6 deals with post-fire tests on loaded specimens (PFL) which were heated up to a percentage of the corresponding θ_{crit} while bearing different load levels. PFL tests are supposed to reproduce realistically the post-fire conditions of a reinforcement when the RC element it belongs to has not failed during the fire event.

In each test type, 2 identical specimens were tested for each combination of load level and high temperature, and the obtained results were averaged. If remarkable differences were observed, a third test was carried out. Tensile tests were performed according to current ISO standards for room temperature [24] as well as for high temperature [25]. Due to the complexity of PFL tests, only one specimen was tested for each combination of load level and temperature. The number of specimens used in each test type is specified in Table 2.

3. Steady-state tests

3.1. Description

A steady-state test is the classical way to determine the mechanical properties of a steel reinforcement when it is subjected to a constant target temperature θ, so they are also known as 'isothermal' tests. Steady-state tests were performed in this work in order to compare the properties of reinforcement bars at high temperatures with those obtained after cooling down. The temperature and loading regimes applied are depicted in Fig. 2a.

In this work, in order to perform steady-state tests, each specimen was placed in the testing machine and only its lower part was clamped, so it was not subjected to any load and it was allowed to deform freely when heated up. According to Fig. 2a, the specimen was heated up from room temperature θ_0 to a target temperature (θ) at a constant rate of 10°C/min, for the reason explained in sub-section 4.1. The temperatures

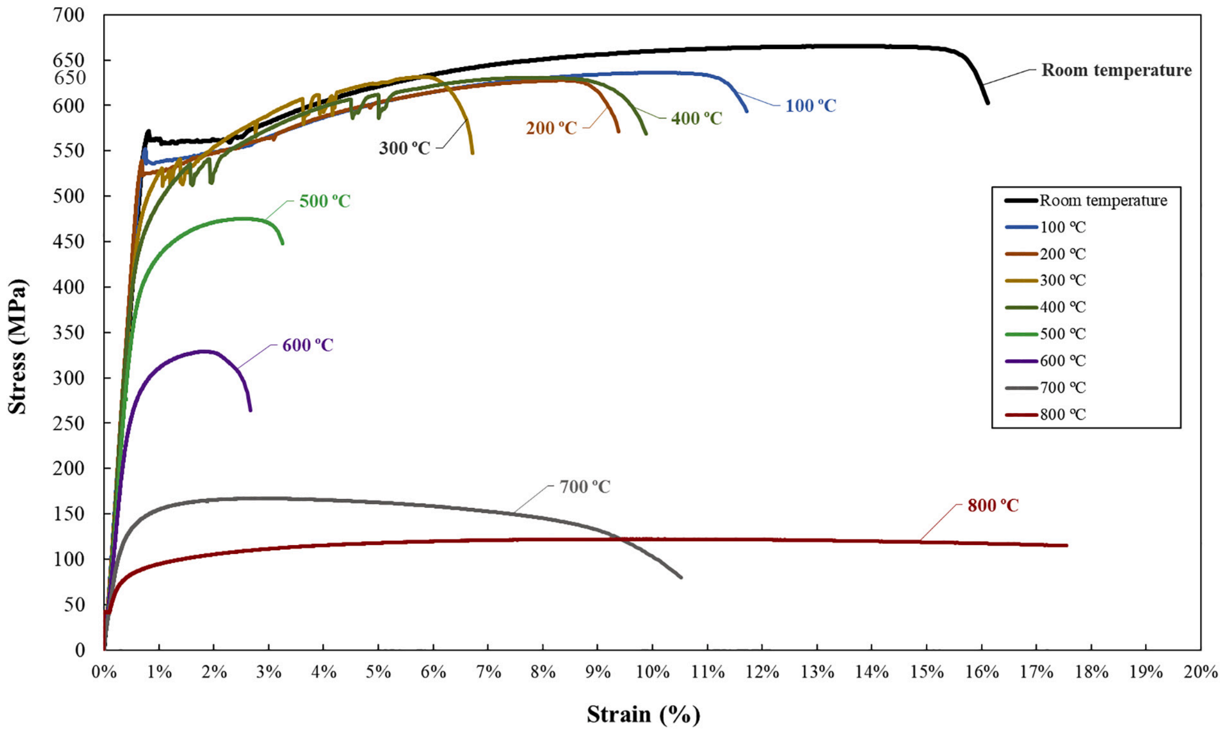


Fig. 4. Steady-state tests. Stress-strain curves at isothermal conditions.

Table 3
Steady-state tests. Mechanical characteristics of reinforcing bars as a function of temperature.

θ(°C)	$f_{0.2}$ (MPa)	$f_{2.0}$ (MPa)	f_u (MPa)	ε_u(%)	ε_f(%)	E_s (MPa)
100	536.36	548.04	636.07	10.11	12.39	197,488
200	512.13	541.33	623.69	6.64	7.97	189,256
300	506.86	553.86	631.65	5.79	7.17	173,119
400	457.21	524.47	630.75	7.77	10.30	173,119
500	410.71	471.35	475.13	2.54	3.63	126,312
600	286.03	327.91	328.90	1.82	2.93	80,282
700	109.46	165.32	167.11	2.82	11.56	53,327
800	80.77	105.39	122.25	9.24	17.56	31,316

ranged from room temperature to 800°C, at steps of 100°C. Considering the thermal inertia, once the target temperature was achieved it was held during a soaking time (t_s) of 30 min to allow the entire sample to be evenly heated. As it was stated by Smith et al. [1], the material deterioration by heating depends on the maximum temperature reached, but it is irrespective on the heating duration at that temperature. Following t_s, the specimen was clamped at his upper end, the testing machine was set to displacement control and the specimen was subjected to a tensile load until its failure.

3.2. Stress-strain curves

Steady-state tests allow plotting stress-strain curves of reinforcing steel bars when isothermal conditions are reached at high temperatures (Fig. 4). In this figure, it can be observed that the curve becomes highly nonlinear as the temperature rises. Reinforcing steel is a ductile material, so the yielding plateau is clearly visible at room temperature, even it shrinks quickly until 200°C [26] [27]. At 300°C or higher, the yielding plateau disappears and the stress-strain curve is similar to the plotted for cold-formed steel at room temperature. Considering that the yield strength can be defined as the lower boundary of the yielding plateau, it is convenient to assume the 0.2% proof strength as the yield strength of steel at elevated temperatures.

On the other hand, the curves of Fig. 4 show a marked reduction in the ductility when target temperature increases, as can be inferred from the area enclosed by each curve. At 400°C there is an apparent recovery in ductility with respect to the curve at 200°C. At 500°C, however, ductility declines abruptly, as well as mechanical performance in general, and shows a decreasing trend again until 600°C. At 700°C and 800°C a strong reversal is observed instead.

From the stress-strain curves, the values of the main mechanical characteristics of the reinforcements as a function of the target temperature are computed and shown in Table 3.

3.3. Reduction factors

A 'reduction factor' is the value of a certain mechanical property at a target temperature θ, normalised to the value of that property at room temperature θ_0. The reduction factors at increasing temperatures θ were computed for yield stress f_y, tensile strength f_u, elastic modulus E_s, strain at ultimate stress ε_u and strain at fracture ε_f.

The trends of the reduction factors with the temperature are depicted in Fig. 5. When available, the reduction factors found in EN 1992-1-2 [4] are also represented, and similarities between experimental and code values are evidenced. Broadly, it can be noted a strong decrease of the mechanical features from 500°C and above (the simplified calculations in the design codes propose 500°C as a critical temperature for steel reinforcements). When temperature overpasses 700°C, yield stress, tensile strength and elastic modulus decay rapidly.

Fig. 5a deals with the retention factors corresponding to the experimental values of yield stress ($f_{0.2}$, proof stress at 0.2% strain). Considering that steel can reach a strain level of 2% or higher in a fire scenario, a proof stress $f_{2.0}$ at 2% strain is also considered, because the yielding plateau vanishes at elevated temperatures. Comparing the reduction factors obtained experimentally with those found in EN 1992-1-2, the first are conservative for temperatures up to 400°C, but unconservative for temperatures of 600°C and 800°C. For 500°C and 700°C, the experimental retention factors corresponding to $f_{0.2}$ are conservative, but unconservative for the retention factors regarding $f_{2.0}$. In Fig. 5b, the reduction factors corresponding to the ultimate stress f_u are represented.

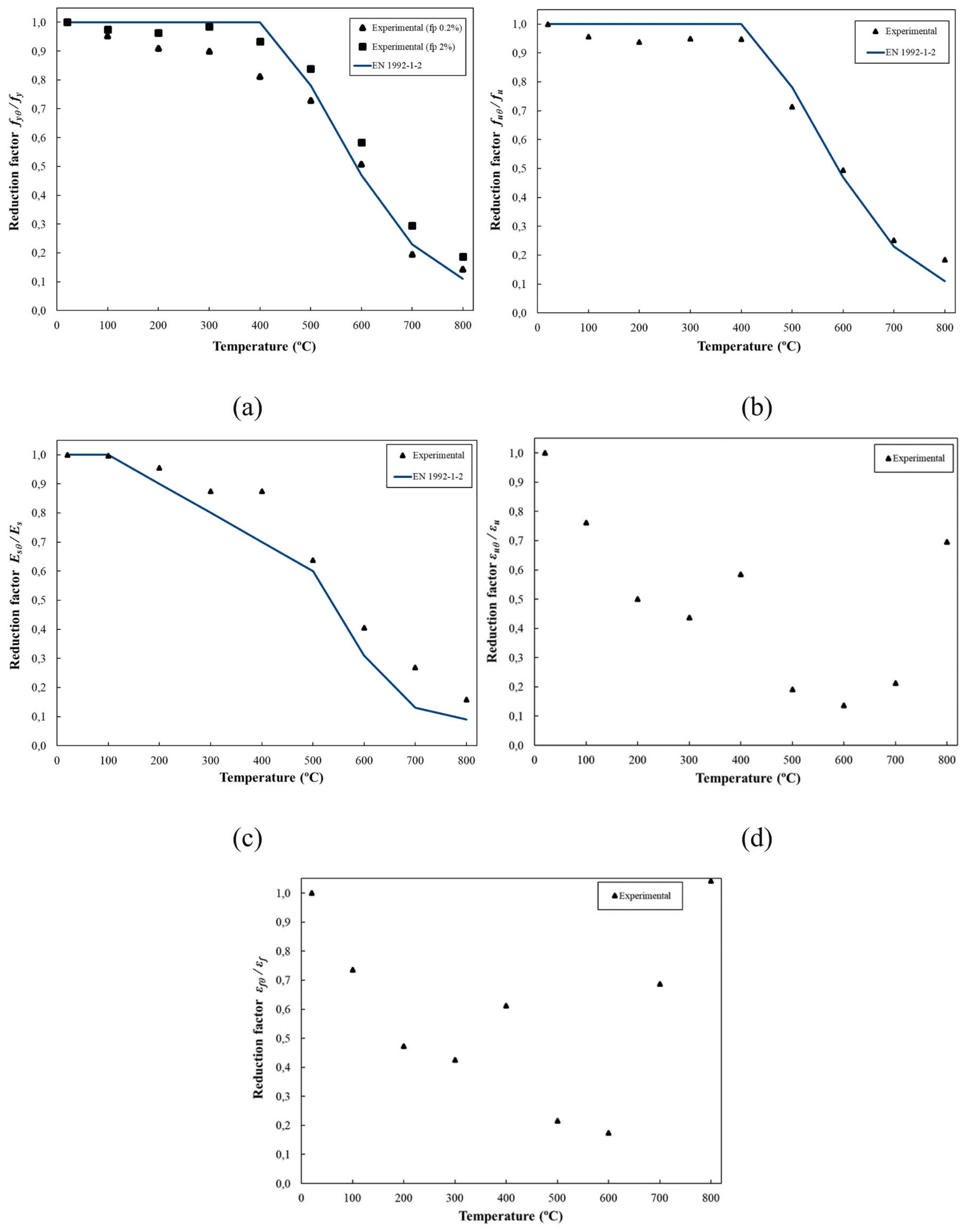


Fig. 5. Steady-state tests. Reduction factors for: (a) yield stress (proof stress at 0.2% strain and 2% strain); (b) tensile strength; (c) elastic modulus; (d) ultimate strain and (e) strain at fracture.

The reduction factors computed experimentally follow very closely those found in EN 1992-1-2. Fig. 5c depicts the reduction factors corresponding to the elastic modulus E_s. In this case, the reductions factors of EN 1992-1-2 are conservative when compared to those found experimentally.

Fig. 5d and e show, respectively, the reduction factors for ultimate strain ε_u and strain at fracture ε_f. A certain scatter of the values can be noted, similarly to the findings of Edwards and Gamble [8]. No reduction factors for these features are provided in EN 1992-1-2, but its inclusion in this work is mandatory since these parameters are related to the ductility class requirements of a reinforcement. In both figures, a decreasing trend can be observed except for values corresponding to 400°C, 700°C and 800°C. It is believed that this behaviour is related to metallographic transformation. The point increase in ductility at 400°C

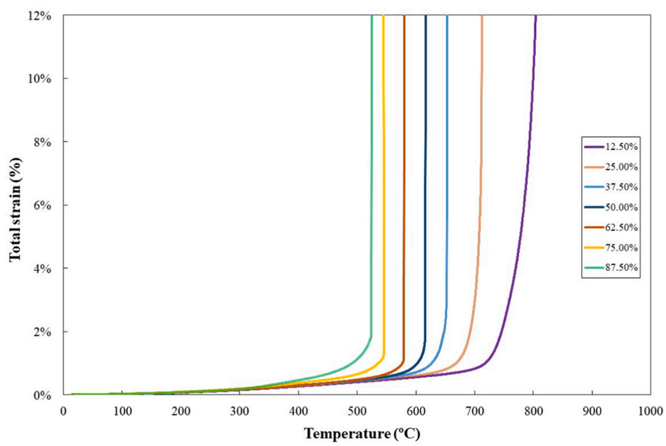


Fig. 6. Transient-state tests. Strain-temperature curves recorded of each stress level.

Table 4
Transient-state tests. Critical temperature of the reinforcement bar as a function of the applied tensile stress

Applied stress		Critical temperature θ_{crit} (°C)		$(\Delta\varepsilon/\Delta t)_{crit}$ (s^{-1})
% f_y	Value (MPa)	Predicted	Experimental	
12.5	70.43	> 800°C	811.24	0.0033
25.0	140.87	758.50	712.37	0.0277
37.5	211.30	672.69	653.24	0.0438
50.0	281.73	629.16	616.46	0.0373
62.5	352.16	584.09	580.24	0.0449
75.0	422.60	533.75	545.05	0.0364
87.5	493.03	488.49	524.95	0.0433

is accompanied by a loss of yield strength and ultimate strength at this temperature and above (see Fig. 5a and b). The increasing trend of ε_u and ε_f that starts at 700°C is also observed in the corresponding stress-strain curves (Fig. 4). This behaviour is probably related to the phase changes that take place when the target temperature is near the eutectoid temperature of carbon steel (around 723°C).

4. Transient-state tests

4.1. Description

Unlike steady-state tests, transient tests are able to capture more realistically the complex and combined effects of load and variable temperature that take place in a reinforcement during a fire. In a transient-state (or 'anisothermal' test, Fig. 2b) the specimen was placed in the furnace with both ends clamped to the testing machine, which was set to load control in order to subject the specimen to a tensile load throughout the test. Assuming that the fire begins when the structure is in service, the load was kept constant during the test. The load level corresponded to a percentage of the yield stress f_y (proof stress $f_{0.2}$ at 0.2% strain at room temperature) of the material at room temperature θ_0: 12.5%, 25%, 37.5%, 50%, 62.5%, 75% and 87.5%. Afterwards, the temperature was increased at a constant rate of 10°C/min until specimen failure, which occurred at maximum value known as 'critical temperature' θ_{crit}. According to Dotreppe [20], this heating rate corresponded closely to the experienced by a reinforcement bar in a column of 30 × 30 cm with a concrete cover of 3 cm and submitted to the ISO 834 standard temperature-time curve, which is a usual practical situation.

4.2. Results

In each of the transient-state tests, it was recorded the variation of the strain with the temperature. The resulting curves are depicted in Fig. 6. It has to be noted that all of them began at zero strain because it was not accounted the initial strain of the bar when the tensile stress was applied at the beginning of the tests. It is observed that for a given load level, the strain rate rises along with temperature.

The critical temperature θ_{crit} for each load level is the temperature reached by the specimen in the instant of failure. As a criterion, it was considered that the specimen lost its load bearing capacity when the strain rate reached a maximum during all the heating story, which was referred to as 'critical strain rate' $(\Delta\varepsilon/\Delta t)_{crit}$. The values of critical temperatures and critical strain rates for each load level are summarized in Table 4. As it was expected, the higher the load level, the lower the critical temperature; this is, the critical temperature of a steel reinforcement depended on the load level it was subjected to. Linear interpolation between the values of f_u in Table 4 served to compute the predicted value of θ_{crit} for each load level applied. Critical temperatures

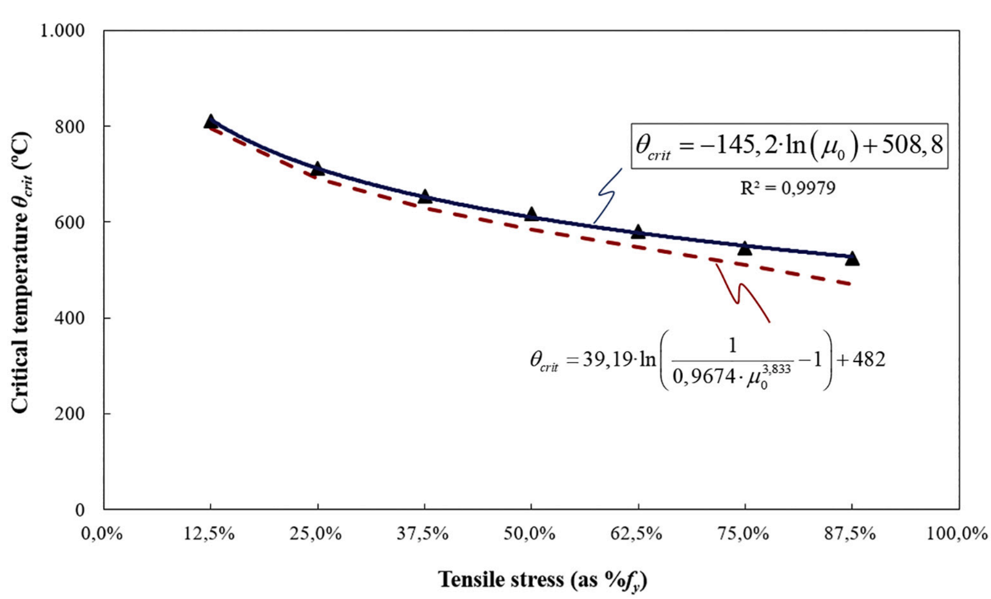


Fig. 7. Transient-state tests. Relationship between applied tensile stress and critical temperature.

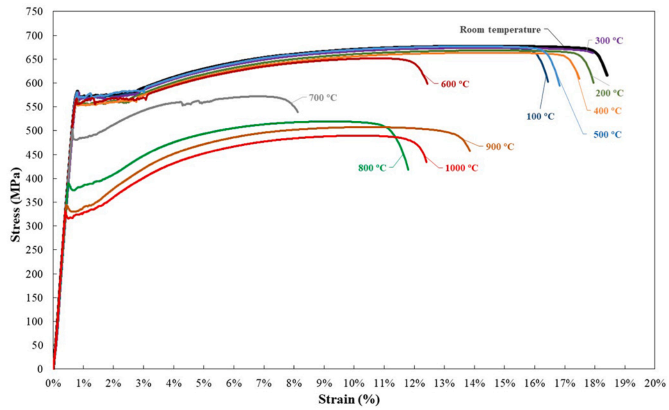


Fig. 8. Post-fire, unloaded tests (PFU). Residual stress-strain curves.

obtained from transient-state tests were validated, even a small discrepancy appeared for the test performed at 87.5% f_y. Finally, it can be seen in Table 4 that the critical strain rate slightly increases with the load level, although it seems to stabilize around 0.04 for 50% f_y and above.

Fig. 7 shows that, for load levels comprised from 12.5% to 87.5% of f_y, the critical temperature of a specimen can be computed by using the logarithmic Eq. (1), which fits very closely to the experimental values obtained by testing ($R^2 = 0.9979$).

$$\theta_{crit} = -145.2 \cdot ln(\mu_0) + 508.8 \quad (1)$$

where μ_0 is the ratio of applied stress related to f_y, which is known as 'degree of utilization' according to UNE 1993-1-2 [28]. In this standard, a logarithmic expression allows to compute the critical temperature θ_{crit} in carbon structural steels or hot rolled reinforcements as a function of μ_0, which is represented in Fig. 7. It can be seen that both curves are almost coincident.

5. Post-fire, unloaded tests (PFU)

5.1. Description

In these tests (Fig. 3a) each specimen was placed in the testing machine and clamped at both ends, but it was not subjected to any load and was allowed to deform freely otherwise. The specimen was heated up to a target temperature θ at a constant rate of 10°C/min. In PFU tests, the heating rate was not as significant as it was in transient-state tests, but the same value was chosen to avoid introducing another variable when comparing results between test modalities.

When the desired value was reached, it was held during a soaking time t_s of 30 min to have the specimen evenly heated. Afterwards, the furnace was turned down and opened, so the specimen was allowed to be 'cooled in air' (according to Tao et al. [14]) during 12 h until the specimen reached room temperature. Then, it was tested under tensile load until its failure.

5.2. Residual stress-strain curves

Fig. 8 shows the residual stress-strain curves obtained from PFU tests for target temperatures θ ranging from 100°C to 1000°C at intervals of 100°C. Quantitatively speaking, different residual properties are observed after cooling down depending on the maximum temperature reached in the specimen:

- The linear portion of the stress-strain curve seems to keep the same slope for the entire temperature range. Indeed, up to 500°C the shape of the stress-strain diagram is kept. The mechanical properties of the specimens are supposed to be fully recovered after the heating-cooling cycle.
- At 600°C and above the stress-strain curve gets progressively smaller, i.e., yield stress and tensile strength decrease as the temperature rises. This phenomenon can be associated to a noticeably ductility loss, as it will be discussed later. The yielding plateau of the specimens recovers almost completely after cooling down from temperatures up to 600°C.
- At 600°C and 700°C the stress-strain curve shortens, i. e., residual strain at fracture ε_f decreases. From 700°C and above, a small plateau seems to appear following the linear portion of the stress-strain diagram, but this is less obvious.
- At 800°C and 900°C the specimen seems to increase its ductility, which is roughly kept at 1000°C. Crystallographic transformations of carbon steel near the eutectoid temperature (around 723°C) would explain this change in the stress-strain curves.

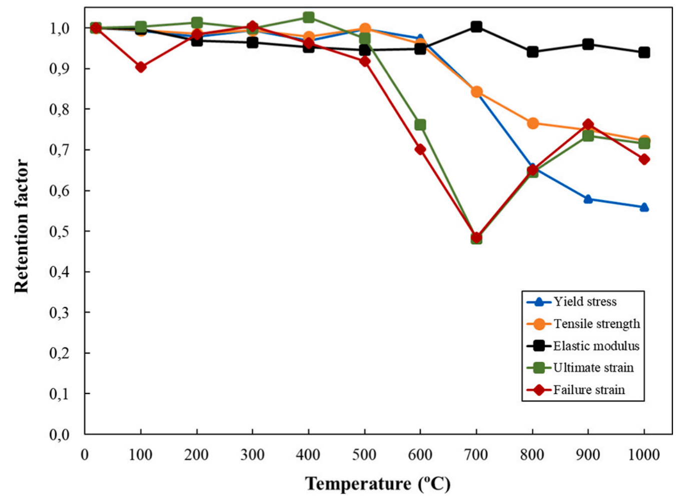


Fig. 9. Post-fire, unloaded tests (PFU). Retention factors.

5.3. Retention factors

Post-fire mechanical properties of a reinforcing steel need to be addressed quantitatively. So, a 'retention factor' of a given mechanical property is defined as the value of that property that is kept following the heating-cooling cycle carried out in a PFU test, normalised to the value of that property at room temperature. Fig. 9 depicts the variation of the retention factors with the maximum temperature reached in the specimen.

As it was mentioned before, hot-rolled steel reinforcement bars retain almost the full values of f_y and f_u at room temperatures when heated up to 500°C. However, when heated to 600°C or higher, retention factors reduce, being for f_y lower than for f_u. These observations agreed with those stated by Felicetti and Gambarova [29], for example. These authors showed that elastic modulus was unaffected by temperature after cooling down, this is, the original value was recovered after cooling down. Also, Holmes et al. [16] reported that the elastic modulus of reinforcement steels remained unaltered when heated up to 700°C and cooled down. In this work, this feature was also verified.

In Fig. 10, retention factors experimentally obtained for yield stress f_y, tensile strength f_u and elastic modulus E_s are compared with the retention factors computed by Tao et al. [14]. For f_y (Fig. 10a) and f_u (Fig. 10b) there is a practical coincidence of retention factors up to 600°C and 700°C, respectively. From this temperature and above, there can be found a clearly decreasing trend, even the retention factors computed experimentally are somehow conservative. With regard to E_s (Fig. 10c) the retention factors are near 1 for the entire tested temperature range.

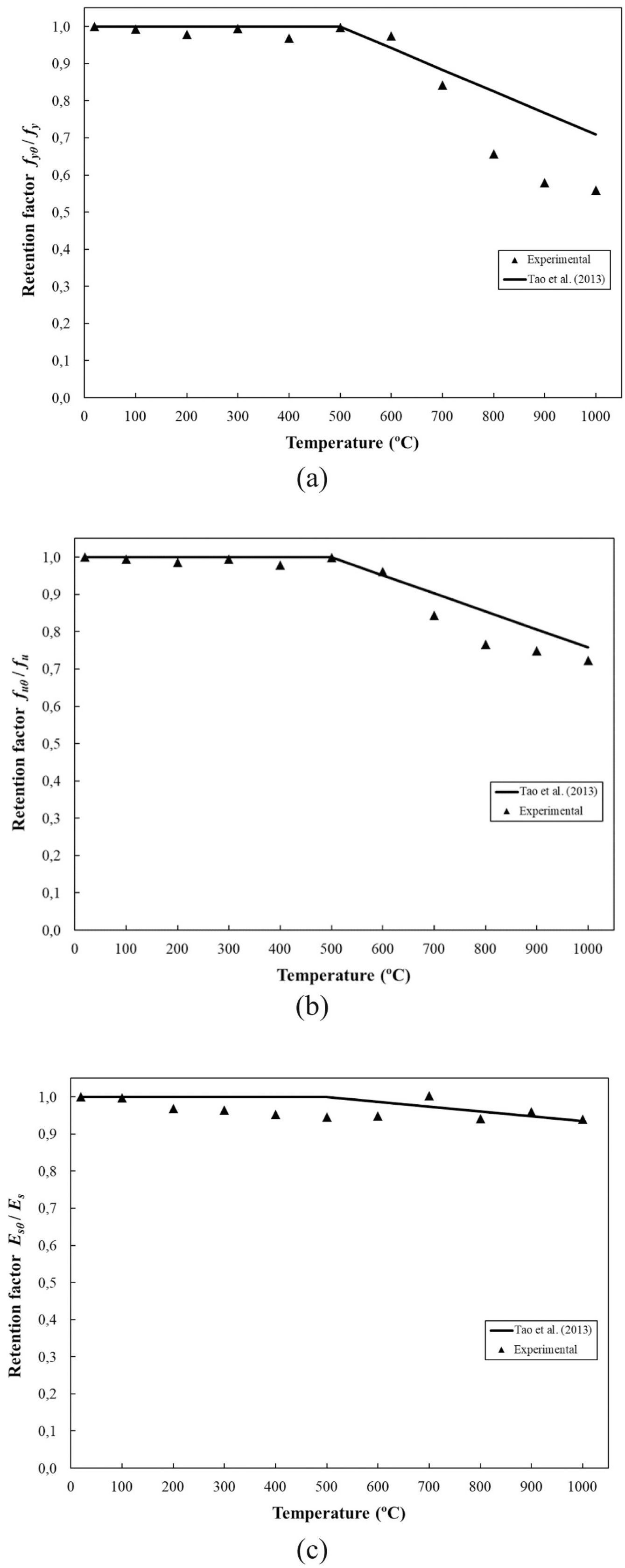


Fig. 10. Post-fire, unloaded tests (PFU). Retention factors for: (a) yield stress f_y, (b) tensile strength f_u and (c) elastic modulus E_s.

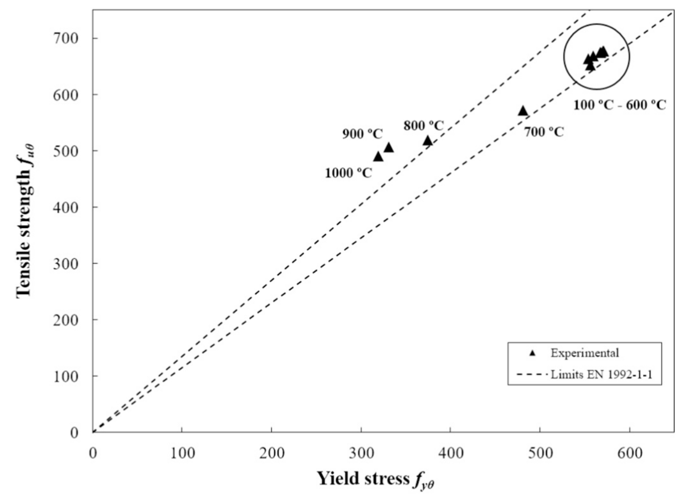


Fig. 11. Post-fire, unloaded tests (PFU). Relationships between residual values of yield stress and tensile strength at different temperatures with respect to ductility prescriptions from EN 1992-1-1.

5.4. Residual ductility

As it is known, 'ductility' refers to the ability of a material to withstand plastic deformations before failure. Roughly speaking, the presence of a yielding plateau and the strain range covered by the stress-strain curve are regarded as ductility indicators. This property is crucial in a RC structure since it permits moment redistribution or an adequate response to seismic loads. Nevertheless, the residual ductility of reinforcing steel bars after a fire has not been sufficiently studied.

As it is stated in EN 1992-1-1 [23], the ductility of reinforcing steel is specified by two parameters: the ratio f_u / f_y of the tensile strength f_u to the yield stress f_y and the ultimate strain ε_u (at f_u). C-class reinforcement bars meet the highest requirements: $1.15 \leq f_u / f_y \leq 1.35$ and $\varepsilon_u \geq 7.5\%$. Since the relationship between f_u and f_y must be limited in order to guarantee the ductile behaviour of steel, these limits are shown in Fig. 11 together with the f_u / f_y ratios computed experimentally after heating to a target temperature θ. Only three points fall outside of the bounds, corresponding to 800°C, 900°C and 1000°C.

Besides, Fig. 9 shows that the retention factor corresponding to ε_u stays above 0.9 until 500°C. From this temperature, it falls sharply until a minimum value of 0.48 is reached for 700°C. At 800°C the trend is reversed (the same phenomenon was observed in the residual stress-strain curves, Fig. 8). From this point, ductility is regained until 1000°C, which corresponds to a retention factor of 0.72. Taking into account that the value of ε_u measured at room temperature is 13.27% (see Table 1), the minimum value admitted according to EN 1992-1-1 is $\varepsilon_u = 7.5\%$, which corresponds to a retention factor of 0.56. According to the PFU tests, only the residual ultimate strain at 700°C falls below the prescribed value. It is noteworthy to see that when heated up near to the eutectoid temperature and posteriorly cooled down, the residual ductility of the specimens does not meet the code requirements for a C-class reinforcement bar, since the f_u / f_y ratio and ε_u limits have to be satisfied simultaneously.

Previously, Neves et al. [10] considered the influence of the residual values of f_u and ε_u in the residual ductility of reinforcements: if a decrease of residual ε_u is followed by an increase of residual f_u, the material becomes brittle, and ductile on the contrary. Nevertheless, those results were not contrasted with the code requirements. In addition, the relative contribution of f_u and ε_u to the reinforcement ductility is still under discussion, even for room temperature.

Table 5
Post-fire, loaded tests (PFL) performed at different stresses and target temperatures.

Load level %f_y	12.5%	18.75%	25%	30%	37.5%	50%	62.5%	65%	75%	87.5%
θ_{crit} (°C)	811	752	710	684	651	609	577	571	551	528
θ (°C)					**% θ_{crit}**					
100	12%	13%	14%	15%	15%	16%	17%	18%	18%	19%
200	25%	27%	28%	29%	31%	33%	35%	35%	36%	38%
300	37%	40%	42%	44%	46%	49%	52%	53%	54%	57%
400	**49%**	**53%**	**56%**	**59%**	**61%**	**66%**	**69%**	**70%**	**73%**	**76%**
500	**62%**	**67%**	**70%**	**73%**	**77%**	**82%**	**87%**	**88%**	**91%**	**95%**
600	**74%**	**80%**	**84%**	**88%**	**92%**	**98%**				
700	**86%**	**93%**	**99%**							
800	99%									
900										
1000										

6. Post-fire, loaded tests (PFL)

6.1. Description

In PFL tests (Fig. 3b) each specimen was placed in the testing machine and clamped at both ends. The specimen was subjected to a tensile load corresponding to a percentage of its yield strength at room temperature (f_y) and subjected to a heating rate of, again, 10°C/min until a target temperature θ was reached. In Section 4, it was shown that in a transient-state test (by applying a constant tensile load and an increasing temperature at a constant rate) a specimen failed when the corresponding critical temperature θ_{crit} was reached. Since critical temperature is the upper bound specimen under certain load can be heated to without failure, PFL tests were performed by heating at a target temperature $\theta < \theta_{crit}$. They were used the same load levels applied in transient-state tests (12.5%, 25%, 37.5%, 50%, 62.5%, 75% and 87.5% of f_y) and also for 30% of f_y. When the target temperature was reached, it was maintained during the same soaking time t_s of 30 min, as in previous tests. Then, the furnace was turned down and opened, so the specimen gradually cooled down in air back to room temperature. During all the test, the stress applied to the specimen remained constant by means of the testing machine, which was set to load control for this purpose. Finally, the machine was set to displacement control and the tensile load was increased until its failure at f_u.

Table 5 summarizes the PFL tests carried out. The first two rows show the load level and the corresponding critical temperature θ_{crit}. The critical temperature for 30% f_y was predicted by means of Eq. (1). In order to compare the post-fire behaviour of unloaded with loaded specimens, the same target temperature range was used in PFU and PFL (from 100°C to 1000°C at 100°C intervals) as can be seen in the first column of Table 5. The target temperature θ the specimen is heated up is a percentage of the critical temperature θ_{crit} for each load level applied, whose value is also reflected in Table 5. For example, for a specimen loaded at 30% f_y, a heating up to $\theta = 500$°C corresponds to 73% of θ_{crit}.

It has to be taken into account that only the PFL tests at target temperatures from 400°C to 700°C (bold percentages of Table 5) were performed for two main reasons. First of all, tests for target temperatures of 100% θ_{crit} or higher could not be obviously performed (these tests correspond to the empty cells of Table 5). On the other hand, preliminary tests performed for load levels of 50% f_y and 75% f_y showed that the mechanical properties of specimens remained unaltered when heated up to 300°C and posteriorly cooled down to room temperature.

6.2. Residual stress-strain curves

Fig. 12 depicts the residual stress-strain curves obtained for different load levels and target temperatures of 400°C, 500°C and 600°C. The corresponding residual stress-strain diagram obtained from PFU test at each temperature is also represented for the sake of comparison. It is noted that the curves begin at non-zero stress according to the load level applied.

When heating up to 400°C (Fig. 12a), the effect of load levels corresponding to 12.5% f_y, 25% f_y, 62.5% f_y, 75% f_y and 87.5% f_y were investigated. The cases corresponding to 37.5% f_y and 50% f_y were not studied to reduce the number of tests. It is observed that, as PFU tests, residual elastic modulus is unaffected by the applied load. In the same way, residual value of yield stress f_y seems to be unchanged, as it can be seen in the position of the yielding plateau. Likewise, residual ultimate strength f_u value is kept constant through the entire range of load levels. Since the ratio f_u / f_y remains virtually constant, ductility is measured through the residual value of ultimate strain ε_u, which decreases slightly with the applied load from 14.41% (without load) to 11.81% when subjected to 62.5% f_y. At 87.5% f_y, ductility seems to increase, but this observation should be caused for slight variations in the tests. As a conclusion, residual values of yield stress, ultimate strength and ductility (measured through residual ε_u) of a reinforcing carbon steel bar seem to be unaffected by load level when it is subjected to a temperature of 400°C and posteriorly cooled down to room temperature.

When heating up to 500°C (Fig. 12b) residual stress-strain curves for load levels corresponding to 12.5% f_y, 25% f_y, 37.5% f_y, 50% f_y, and 62,5% f_y were obtained. It is interesting to note that the residual stress-strain curves for different load levels are always slightly below the residual stress-strain curve obtained from PFU test. This observation implies that residual values of yield stress f_y and ultimate strength f_u decrease when the reinforcement has been subjected to load during fire, which did not occur if the bar was unloaded (see subsection 5.3). Once again, residual elastic modulus E_s was not affected by load level.

It has to be mentioned that a test at 75% f_y was also carried out, but its results are not represented since the specimen broke during soaking time (in this case, 500°C corresponded to 91% θ_{crit} according to Table 5). This premature failure can be attributed to mechanical-thermal creep, and it is expected that a specimen under a load level higher than 75% f_y could fail earlier during soaking time, or even during the heating period. This observation led to perform a test at a load level of 65% f_y, In Fig. 12b it can be seen that, although residual values of f_y and f_u show little variation with those recorded at lower load levels, residual ductility diminishes drastically: residual ε_u reduces from a value of 13.68% without load to 4.76% at 65% f_y. This marked residual ductility reduction is observed at load levels corresponding to 62.5% f_y or even higher.

For a target temperature of 600°C (Fig. 12c) load levels corresponding to 12.5% f_y, 18.75% f_y and 25% f_y were investigated. The load level corresponding to 37.5% f_y was also tested, for whom 600°C was 92% of θ_{crit}, but the specimen failed during soaking time, similarly to the observed for 500°C. The obtained residual stress-strain curves were just below the curve obtained from PFU, even though the residual values of yield stress f_y, tensile strength f_u and elastic modulus E_s remained virtually unchanged, as it happened for 500°C. An additional test at a load level corresponding to 30% f_y was carried out (600°C was equal to 88% θ_{crit}). Residual ductility, practically unaltered for load levels up to 25% f_y, was considerably reduced when the load level was incremented only the equivalent to 5% f_y.

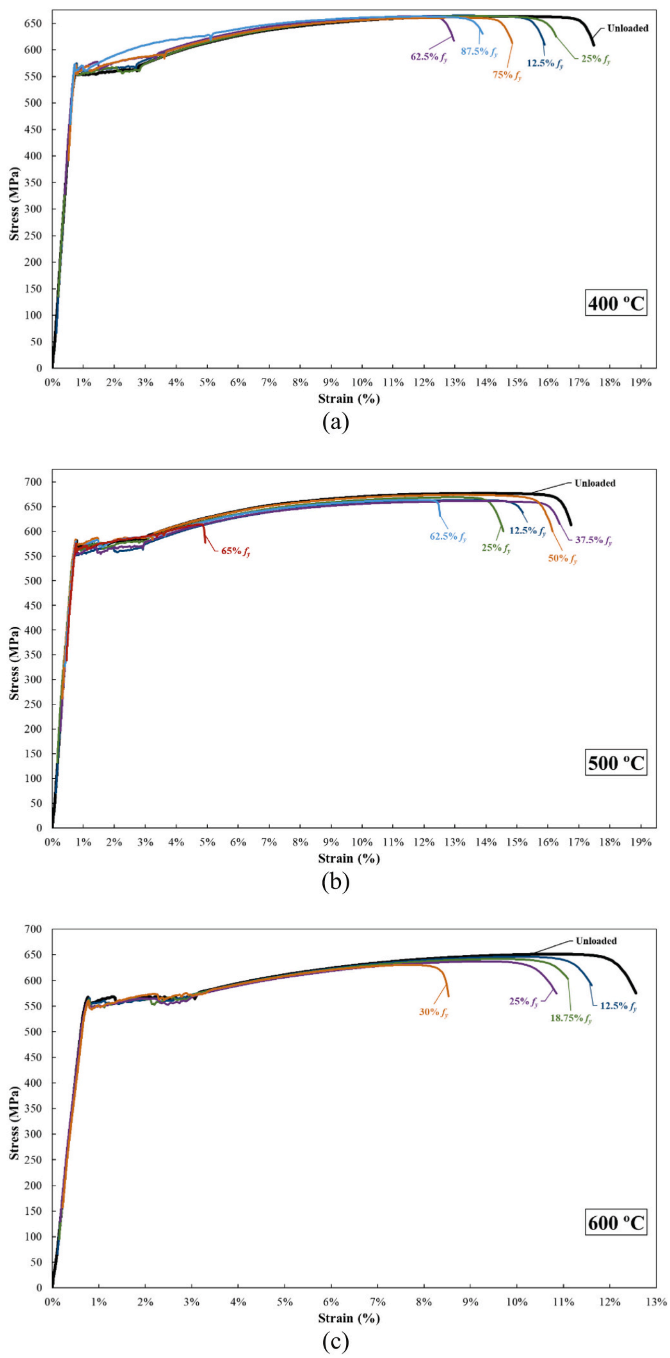


Fig. 12. Post-fire, loaded tests (PFL). Residual stress-strain curves corresponding to different load levels and maximum temperatures of (a) 400°C, (b) 500°C and (c) 600°C.

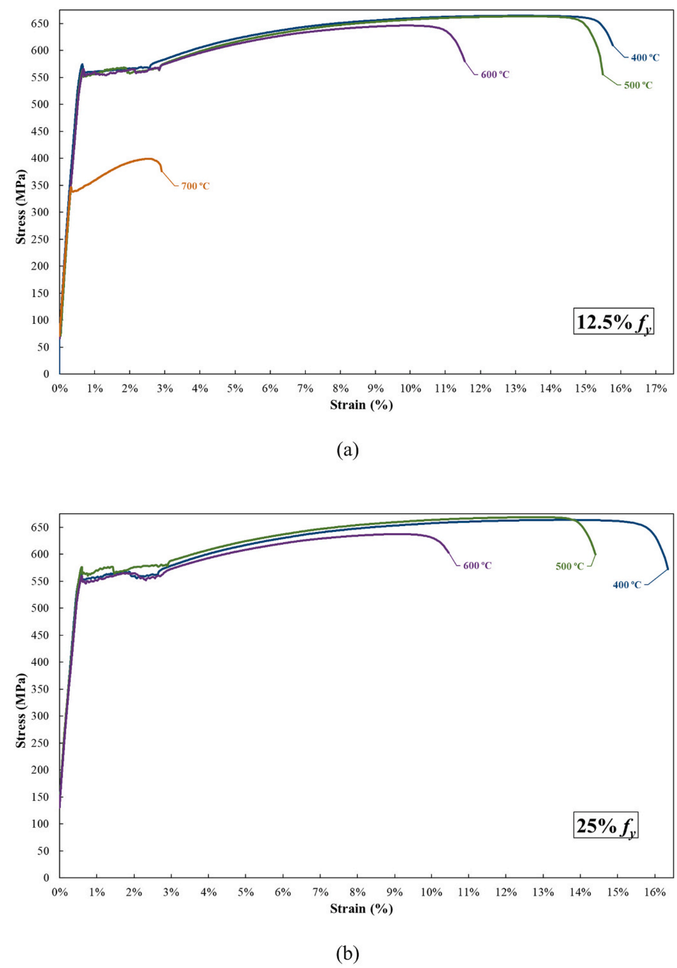


Fig. 13. Post-fire, loaded tests (PFL). Residual stress-strain curves corresponding to different target temperatures and load levels of (a) 12.5% *fy* and (b) 25% *fy*.

Up to this point, some considerations have to be done concerning creep or time-dependent strains. Mechanical-thermal creep effects are strongly related with the amount of time a loaded structure has been subjected to fire. According to Harmathy [30], 'secondary creep' takes place under a combination of stress level and steadily increasing temperature, though this effect can be neglected for maximum temperatures up to 400°C. For higher values, creep effect increases with stress and/or heating rate. This could explain the reason why specimens at 75% f_y and 37.5% f_y failed when heated up to temperatures lower than the corresponding θ_{crit} (500°C and 600°C, respectively).

In this work, the duration of steady-state tests was relatively low. The maximum target temperature tested (800°C) was reached at 1 h 20 min and, considering soaking time t_s and duration of the tensile stress, the maximum time spent in a steady-state test was less than 2 h. In transient-state test, the longest test lasted 75 min and corresponded to the test in which the critical temperature was 750°C. For this relatively short test time, the combined effects of constant stress and variable temperature were not accounted for, since creep strain was considered to be small compared to the other strain components, so it was neglected. In PFU tests, the specimen was allowed to deform freely, so creep effects were not present. Regarding PFL tests, the cooling phase lasted more than the heating period. For example, for a target temperature of 500°C, the heating phase and the soaking time lasted about one hour and a half, but the cooling phase to room temperature and the subsequent tensile test doubled that duration. So in PFL tests, as well as in a reinforcing bar of a RC element after a fire, the presence of creep strains must be carefully addressed.

The combined influence of load level and target temperature on the residual stress-strain curves is also brought out in Fig. 13, which can be considered as the reverse representation of Fig. 12. There are depicted the residual stress-strain curves for load levels corresponding to 12.5% f_y and 25% f_y for target temperatures ranging from 400°C to 700°C (this last case only for 12.5% f_y). Residual elastic modulus E_s remain unaltered for both load levels and the temperature range tested for each case. For a load level of 12.5% f_y, the residual value of f_y appears to be constant even when cooled down from 600°C. The residual value of f_u seems to be the conserved up to 500°C, as well as the residual ductility measured through residual ε_u. At 700°C, however, all these features are

Table 6
Post-fire, loaded tests (PFL). Residual mechanical properties and retention factors after heating to 400°C and cooling down.

$\%f_y$	Yield stress		Ultimate strength		Elastic modulus		Ultimate strain	
	$f_{y,\theta}$ (MPa)	$f_{y,\theta}$ / f_y	$f_{u,\theta}$ (MPa)	$f_{u,\theta}$ / f_u	$E_{s,\theta}$ (MPa)	$E_{s,\theta}$ / E_s	$\varepsilon_{u,\theta}$ (%)	$\varepsilon_{u,\theta}$ / ε_u
0% (PFU)	553.8	0.98	673.7	1.01	194,802	0.98	14	1.06
12.5%	559.6	0.99	664.5	1.00	199,736	1.01	13.11	0.99
25%	552.9	0.98	663.7	1.00	206,896	1.04	13.71	1.03
62.5%	561.8	1.00	663.6	1.00	203,718	1.03	11.81	0.89
75%	560.7	1.00	660.8	0.99	192,966	0.97	13.04	0.98
87.5%	567.5	1.01	663	1.00	192,207	0.97	11.81	0.89

Table 7
Post-fire, loaded tests (PFL). Residual mechanical properties and retention factors after heating to 500°C and cooling down.

$\%f_y$	Yield stress		Ultimate strength		Elastic modulus		Ultimate strain	
	$f_{y,\theta}$ (MPa)	$f_{y,\theta}$ / f_y	$f_{u,\theta}$ (MPa)	$f_{u,\theta}$ / f_u	$E_{s,\theta}$ (MPa)	$E_{s,\theta}$ / E_s	$\varepsilon_{u,\theta}$ (%)	$\varepsilon_{u,\theta}$ / ε_u
0% (PFU)	570.2	1.01	663.3	1.00	192,706	0.97	14.4	1.09
12.5%	552.5	0.98	663.2	1.00	197,660	1.00	13.46	1.01
25%	563.9	1.00	668.7	1.01	202,520	1.02	12.93	0.97
37.5%	560.6	0.99	660.8	0.99	199,076	1.00	13.35	1.01
50%	555.1	0.99	673.6	1.01	192,866	0.97	13.16	0.99
62.5%	566.4	1.01	663.5	1.00	201,030	1.01	11.71	0.88
65%	566.2	1.00	614.2	0.92	199,689	1.01	4.76	0.36

Table 8
Post-fire, loaded tests (PFL). Residual mechanical properties and retention factors after heating to 600°C and cooling down.

$\%f_y$	Yield stress		Ultimate strength		Elastic modulus		Ultimate strain	
	$f_{y,\theta}$ (MPa)	$f_{y,\theta}$ / f_y	$f_{u,\theta}$ (MPa)	$f_{u,\theta}$ / f_u	$E_{s,\theta}$ (MPa)	$E_{s,\theta}$ / E_s	$\varepsilon_{u,\theta}$ (%)	$\varepsilon_{u,\theta}$ / ε_u
0% (PFU)	556.5	0.99	676.8	1.02	191,288	0.97	13.7	1.03
12.5%	555.4	0.99	646.2	0.97	197,027	0.99	9.97	0.75
18.75%	549.3	0.97	642.0	0.97	199,730	1.01	9.62	0.72
25%	546.2	0.97	637.5	0.96	200,738	1.01	9.26	0.70
30%	546.2	0.97	630.3	0.95	195,897	0.99	7.61	0.57

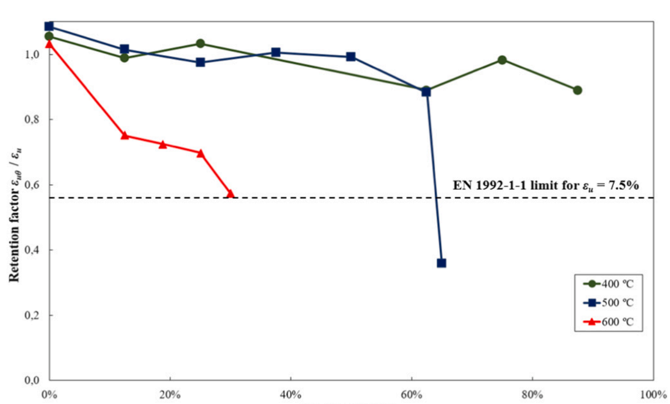


Fig. 14. Post-fire, loaded tests (PFL). Evolution of residual ductility (expressed as the retention factor $\varepsilon_{u\theta}$ / ε_u) with the load level and the maximum temperature.

significantly reduced. At 25% f_y, residual yield stress f_y is maintained in all the temperature range studied, although residual values of f_u and ductility (residual ε_u) start to decay from 600°C.

6.3. Retention factors

Once PFL tests are carried out, retention factors for yield stress f_y, tensile strength f_u, elastic modulus E_s and ultimate strain ε_u can be extracted from residual stress-strain curves. Retention factors are shown in Tables 6–8 for specimens heated up to maximum temperatures of 400°C, 500°C and 600°C, respectively, and posteriorly cooled down back to room temperature. The retention factors have been normalised to the corresponding values at room temperature.

From those values, it can be seen that the retention factors of yield stress f_y, tensile strength f_u and elastic modulus E_s are near 1 irrespective to the maximum temperature reached by the reinforcement. In spite of this, for a given temperature, the residual ultimate strain ε_u reduces considerably with the load level, as it was mentioned in the previous subsection. The evolution of the residual ductility, expressed by means of the retention factor $\varepsilon_{u,\theta}$ / ε_u, is depicted in Fig. 14. If the ductility requirements found in EN 1992-1-1 for a C-class reinforcement are considered [31], it has to be guaranteed a minimum value of 7.5% for ε_u. In the context of the present work, the value of ε_u at room temperature was 13.27% (see Table 1), so a residual ultimate strain of 7.5% corresponds to a retention factor of 0.56 in Fig. 14. Residual ductility requirements are not meet when heating up to 500°C and posteriorly cooled down at a load level corresponding to 65% f_y ($\varepsilon_{u,\theta}$ / $\varepsilon_u = 0.36 < 0.56$). If the maximum temperature reached is 600°C and the load level is equivalent to 30% f_y, the retention factor is barely on the security side with respect to the prescribed limitation ($\varepsilon_{u,\theta}$ / $\varepsilon_u = 0.57 > 0.56$).

7. Conclusions

In this work, an experimental study was carried out in order to evaluate the residual mechanical properties of carbon steel reinforcing bars subjected to a load level after its exposure to elevated temperatures. In order to reproduce real loading conditions of RC structures during a fire scenario, specimens were subjected simultaneously to a constant load level (corresponding to a percentage of the yield stress f_y at room temperature) and a thermal cycle consisting of heating up to a target temperature and cooling in furnace back to room temperature. The target temperature was a percentage of the critical temperature θ_{crit}, this is, the temperature at which a specimen breaks when it is subjected to a constant tensile load and an increasing temperature at a constant rate. After that, the residual mechanical properties were obtained submitting the specimen to tensile testing until its failure.

The following conclusions can be drawn from this work:

- Residual values of yield stress f_y, ultimate strength f_u, and ultimate strain ε_u depend not only on the maximum temperature reached during fire, but also on the load level sustained during the thermal cycle. In the range of target temperatures analyzed in the present work, the residual elastic modulus E_s was unaffected by any combination of load level and target temperature.
- For a target temperature, residual values of yield stress and tensile strength seem unaffected by load level. In this case, residual ductility should be computed by using ultimate strain ε_u instead by the f_u/f_y ratio.
- Reinforcement bars heated up to 500°C and then cooled down exhibited a negligible loss of yield stress and ultimate strength. Nevertheless, residual ductility was reduced significantly at this limiting temperature. In general, a loss of ductility was observed when load level increases, especially for target temperatures of 500°C and 600°C.

Taking into account the lack of information on residual mechanical properties of steel reinforcements in the design codes, as well as in previous works, the obtained data can be helpful in the assessment of RC structures after fire.

Declaration of Competing Interest

None.

Acknowledgements

The authors would like to express their sincere gratitude to the Spanish Agencia Estatal de Investigación (AEI) for the help provided through the Project PID2019-105908RB-I00 and also to the European Union through the FEDER funds.

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