ce/papers Proceedings in civil engineering
Ernst & Sohn A Wiley Brand
Check for updates
ORIGINAL ARTICLE
eurosteel AMSTERDAM 2023
Ernst & Sohn A Wiley Brand

Influence of load and high temperature on the post-fire behaviour of high-strength structural steels

Andrés Lapuebla-Ferri[1] | David Pons[1] | Manuel L. Romero[2] | Leroy Gardner[3]

Correspondence

Dr. Andrés Lapuebla-Ferri
Universitat Politècnica de València
Department of Continuum Mechanics and Theory of Structures
Camí de Vera, s/n
46022 València, Spain
Email: anlafer0@mes.upv.es

[1] Department of Continuum Mechanics and Theory of Structures - Universitat Politècnica de València, Valencia, Spain
[2] ICITECH, Universitat Politècnica de València, Valencia, Spain
[3] Imperial College, London, United Kingdom

Abstract

In this work, an experimental campaign was carried out to evaluate the post-fire mechanical performance of high-strength steel specimens (grade S700) when being subjected simultaneously to different combinations of tensile load and elevated temperature. To this end, transient-state tests were firstly carried out to obtain the 'critical temperature', i.e., the temperature at which a specimen failed while being simultaneously subjected to tensile load and heated at a constant temperature rate. Secondly, post-fire tests were performed on unloaded as well as loaded specimens. For that purpose, specimens were heated to temperatures below the critical temperature, cooled down in air and finally submitted to tensile testing. In order to investigate the influence of production route, specimens were extracted from cold-formed circular hollow sections and hot-rolled sheets. Moreover, coupons with five different thicknesses were tested to investigate the influence of section thickness on the post-fire behaviour. Residual values of yield strength, ultimate strength, elastic modulus and ductility were determined from the tests and discussed.

Keywords

Post-fire behaviour, High-strength steel, Transient-state tests, Residual properties, Production route, Yield strength, Ultimate strength, Elastic modulus, Ductility

1 Introduction

Conventionally, steels whose yield strength is higher than 460 MPa are known as high-strength steels (HSS). In the last years, the structural use of HSS has become more and more frequent, especially in structural applications such as long-span buildings or pipelines. Structural engineers can take advantage of the increased strength-to-weight ratio of HSS, allowing for lighter elements compared to conventional steels. Consequently, reduced expenses in transport and erection of structures can be expected, so the use of HSS is interesting in terms of economic benefits and environmental protection.

Besides, steel performance is highly dependent on the working temperature, so fire hazards are a cause of special concern in the design of HSS structures [1-2]. Experimental studies have been performed in the past to study the variation of mechanical properties of HSS with the temperature (steady-state tests) and the combination of temperature and tensile load level (transient-state tests) such as [3-5]. Nevertheless, limited attention has been focused on the post-fire behaviour of structural HSS and its eventual reuse after cooling down. To the authors' knowledge, previous works and code and practical recommendations in this field are scarce for HSS [6].

In this work, an experimental campaign was carried out to evaluate the post-fire performance of HSS. To do this, different tests were performed. Firstly, transient-state tests allowed the 'critical temperature' θ_{crit} at which a specimen failed under tensile load and increasing temperature to be obtained (described in Section 3). Secondly, post-fire tests were performed, as described in Section 4. In these tests, specimens were subjected to a tensile load and heated to a proportion of θ_{crit} prior to being cooled back down to room temperature. Then, tensile tests were performed, so that residual properties of the material (yield and ultimate strength, elastic modulus and ductility) could be obtained; the results are discussed.

It has been reported in previous works [3-6] that the production route of HSS (i.e., the composition and the manufacturing process) has a significant influence in the response of the material at high temperatures. So, the influence of the production route (as well as the thickness) on post-fire response of HSS is also considered in this work by testing sets of specimens from different sources.

2 Materials and methods

The experimental setup used in this work is described in Sub-section 2.1. Sub-section 2.2 below describes the geometrical and mechanical features of the specimens.

https://doi.org/10.1002/cepa.2491

2.1 Experimental setup

The experimental setup is depicted in Figure 1 and it was used in previous works of the authors [7-8]. It consisted of a hydraulic universal testing machine equipped with a 200 kN load cell, controlled by a closed-loop system. The upper and lower blocks of the machine incorporated hydraulic flat jaws, so the specimens could be laterally clamped to prevent slipping. In a tensile test, while the upper block remained fixed, the lower moved downwards. Specimens were heated by means of an attached electric furnace with three heating zones, each one with a thermocouple connected to a control unit. An extensometer located in the central section of a specimen was used to measure its modulus of elasticity.

Figure 1 Experimental setup. 1: Upper block. 2: Lower block. 3: Electric furnace. 4: Extensometer.

2.2 Test specimens

Different sets of S700 grade specimens were considered, corresponding to various production routes. Two sets were obtained by cutting by laser 8 mm and 12 mm S700 MC sheets (hot-rolled structural steel for cold forming) and four cold-formed, circular hollow section (CHS) HSS tubes were cut longitudinally to obtain a set for each tube. Unlike the specimens cut from sheets, the specimens obtained from CHS tubes incorporated permanent strains induced by folding the original plate in the manufacturing process, which could be observed in the curved shape of the specimens. Each specimen had a length of 800 mm. Geometrical features of the specimens are shown in Table 1.

Table 1 Geometrical features of specimens. CF: cold-formed. TR: thermomecanically rolled. HR: hot-rolled. w: width. t: thickness.

Production route		**Shape**	**w** (mm)	**t** (mm)
C1L6	CF+TR	Rectangular	27	4
C2L2	CF+TR	Rectangular	20	4
C3L3	CF+TR	Rectangular	18	5
C4L5	CF+TR	Rectangular	18	6
Steel sheet	HR	Coupon	20 15	8 12

A set of 3 specimens from each production route was subjected to tensile testing in order to obtain its mechanical properties at room temperature. These properties are presented in Table 2.

Table 2 Mechanical properties of specimens at room temperature. f_y: yield strength; f_u: ultimate strength; E: modulus of elasticity; ε_u: ultimate strain (strain at f_u); ε_f: strain at fracture.

	Plate specimens		**CHS specimens**			
	t8	**t12**	**C1L6**	**C2L2**	**C3L3**	**C4L5**
f_y (MPa)	777.3	721.5	754.8	707.6	714.1	769.3
f_u (MPa)	853.5	829.1	842.9	793.3	773.6	824.8
E (MPa)	205000	201000	209070	218500	219500	221000
ε_u (%)	10.46	10.20	3.74	3.41	2.15	1.76
ε_f (%)	13.00	12.36	4.74	4.17	2.90	2.77

Stress-strain curves obtained from tensile tests at room temperature are depicted in Figure 2. Although the steel grade is the same for all sets, it is evident that ductility of the material from the CHS specimens is much less than that cut from plates. One of the ductility requirements given by Eurocode 3, part 1-12 [9] states that strain at fracture must not be less than 10%, which is not fulfilled by the specimens extracted from the CHS tubes. This is probably due to the manufacturing process of the CHS tubes, and it will have implications in the post-fire behaviour of specimens, as will be discussed later.

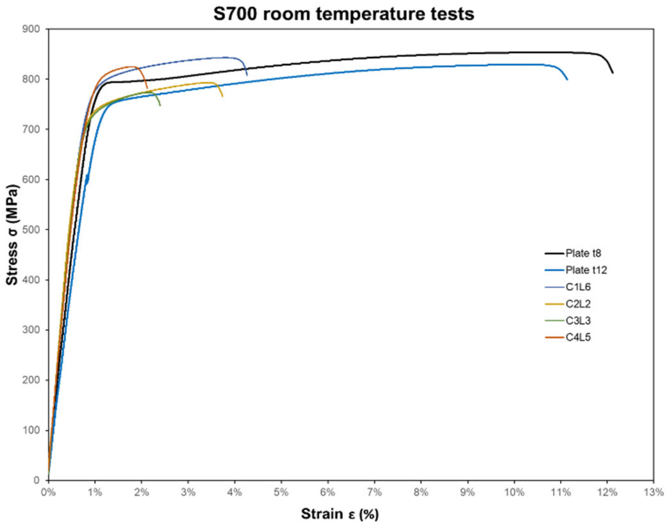


Figure 2 Material properties of specimens at room temperature.

3 Transient-state tests

In the transient-state tests, specimens were placed in the testing machine and subjected to a tensile load, in such a way that the stress level σ_t was a proportion of the yield strength f_y of the material at room temperature. The tensile load was held constant while the specimen was heated at a constant temperature rate of 10 ºC/min until its failure (or the machine stroke was reached without failing). In both cases, the temperature at the surface of the specimen (critical temperature θ_{crit}) was recorded. Figure 3 depicts the temperature and stress histories. These tests reflect a real situation, because a structure is loaded (not necessarily fully) during a fire event. In Eurocode 3, part 1-2 (EN 1993-1-2 [10]), the stress level carried by a steel member during a fire event can be computed through the 'degree of utilisation' parameter μ_0:

$$\mu_0 = \frac{E_{fi,d}}{R_{fi,d,0}} \quad (1)$$

where $E_{fi,d}$ is the design effect of the action in the fire situation and $R_{fi,d,0}$ is the design value of the resistance in the fire situation at time t = 0 (at the onset of fire). So, the ratio of the stress level to the yield strength at room temperature of a specimen will also be regarded as degree of utilisation μ_0, assuming that failure is strength, rather than stability governed.

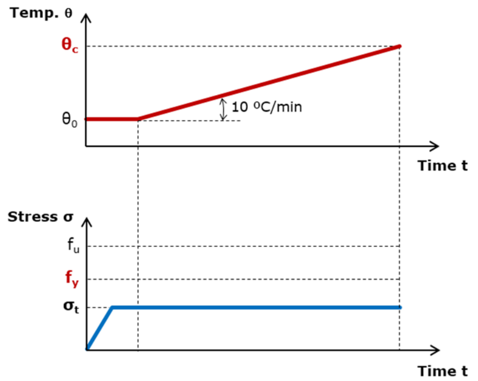


Figure 3 Transient-state tests; temperature and stress histories.

Figure 4 shows the variation of critical temperature with the degree of utilisation for each specimen set. For the plate specimens, logarithmic curves were fitted to the experimental values of θ_{crit}, as can be seen in the figure.

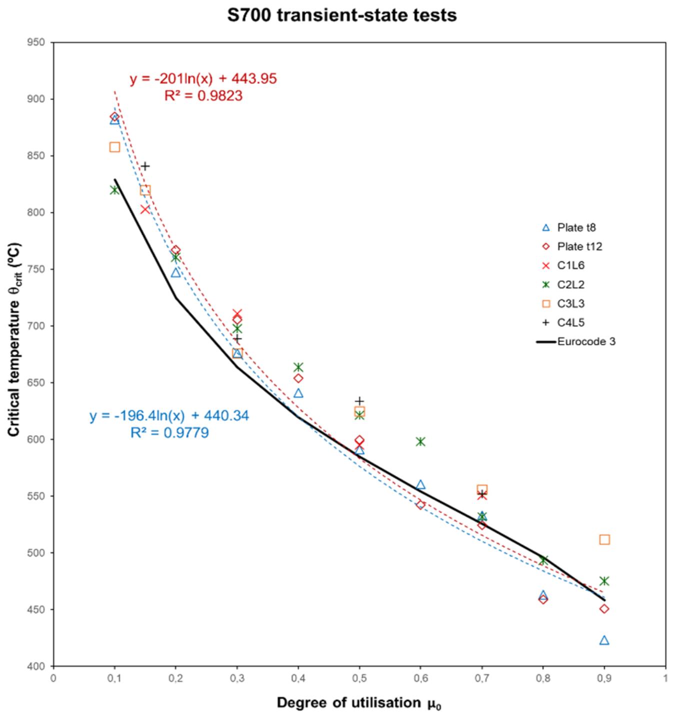


Figure 4 Transient-state tests; θ_{crit} - μ_0 relationships.

In Figure 4, the curve found in EN 1993-1-2 that relates θ_{crit} with μ_0 for carbon structural steels is also presented. The transient-state tests performed on the HSS specimens provide results that generally follow but do not fully correspond to the code expression. The curves fitted to the plate tests results intersect the EN 1993-1-2 curve at approximately μ_0 = 0.4 (t = 8 mm) and μ_0 = 0.47 (t = 12 mm). At higher degrees of utilisation, critical temperature values obtained from EN 1993-1-2 curve are unconservative. Besides, the specimen thickness appears to have some influence. Regarding the CHS tubes, the curve of EN 1993-1-2 is conservative in almost the entire range of degrees of utilisation.

4 Post-fire tests

Post-fire tests are intended to obtain the residual mechanical properties of steel members heated to high temperatures and subsequently cooled down.

The test procedure is depicted in Figure 5. Steel specimens were preloaded at room temperature to a stress level $\sigma_t = \mu_0 \cdot f_y$. The same degrees of utilisation μ_0 used for transient-state tests were considered. Then, the specimen was heated to a target temperature $\theta_t < \theta_{crit}$ at a heating rate of 10 ºC/min. When reaching θ_t, it was held for a soaking time t_s = 30 min until the entire specimen was evenly heated. Following this, the furnace was turned down and gradually opened, so the specimen cooled 'naturally' down in air back to room temperature. During the heating and cooling cycle, the stress σ_t remained constant. Finally, when the specimen attained room temperature θ_0, the tensile load was increased until the failure of the specimen.

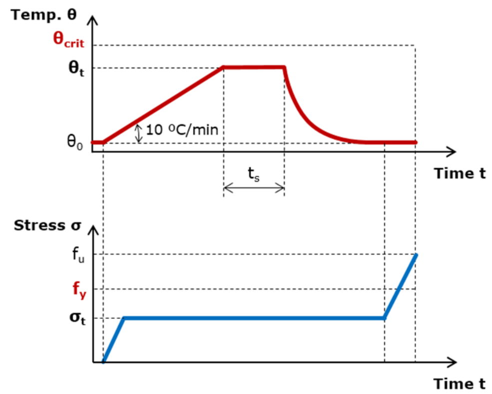


Figure 5 Post-fire tests; temperature and stress histories.

In order to study the influence of the target temperature θ_t and the degree of utilisation μ_0 on the post-fire behaviour of HSS, two types of post-fire tests were performed. In the first one, μ_0 = 0 (post-fire, unloaded tests, PFU, Sub-section 4.1). In the second one, μ_0 > 0 (post-fire, loaded tests, PFL, Sub-section 4.2).

4.1 Post-fire, unloaded tests (PFU)

PFU are the traditional post-fire tests used in the literature [11] since they are easy to perform, but they are unable to capture the combined influence of load and peak temperature in the post-fire behaviour of steels.

Figure 6 shows the residual stress-strain curves of the specimens from the 8-mm plate when heated to $\theta_t \in$ [300, 1000] ºC at intervals of 100 ºC and cooled back down to θ_0. Similar curves were obtained for t = 12 mm. Qualitatively speaking, the mechanical properties seem to be unaltered when specimens were heated up to θ_t = 600 ºC. Only the ductility was marginally affected. When heated to 700 ºC and above, the deterioration of the material is evident. At 900 ºC, even the yield strength and ultimate strength decline dramatically, and ductility increases but without recovering the value at room temperature. The elastic modulus remains essentially constant for all cases.

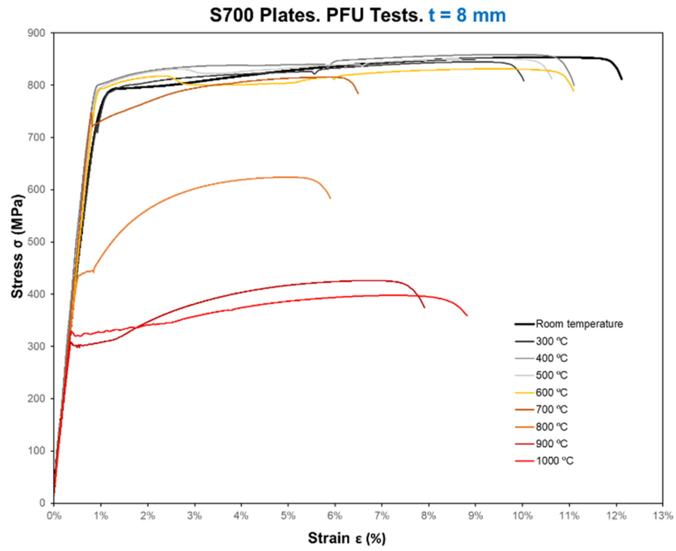


Figure 6 PFU tests on S700 plate (t = 8 mm); residual stress-strain curves (similar curves and trends were obtained for t = 12 mm).

4.2 Post-fire, loaded tests (PFL)

The combined influence of load and temperature in the post-fire behaviour of steel has been studied in a few works on mild steel [7-8] but there are no works concerning HSS.

4.2.1 Results of PFL test on plates

The PFL tests carried out are summarized in Table 3. The first two rows show the degree of utilisation μ_0 and the corresponding critical temperature θ_{crit}. The same range of target temperatures used in the PFU tests was chosen to perform the PFL tests: $\theta_t \in$ [300, 1000] ºC. Given a target temperature θ_t, the intersection of the respective row with a column for a given μ_0 provides a percentage value, which is the amount of θ_{crit} that is θ_t for that μ_0. For example, if a specimen is loaded (μ_0 = 0.5) and heated up to 500 ºC, this is 85% of the critical temperature (591 ºC).

Not all combinations θ_t – μ_0 given in Table 3 were tested, corresponding to the shaded cells. There are three arguments for this. The first one is obvious: a test could not be performed if $\theta_t > \theta_{crit}$ (blank cells). The second is that the PFU tests revealed that a target temperature θ_t = 300 ºC barely influenced the post-fire behaviour of HSS (a similar reason applies with respect to a degree of utilisation μ_0 = 0.1). Finally, the red values indicated tests that could not be finished because the specimen failed during the soaking time, most probably due to thermo-mechanical creep.

Table 3 PFL Tests. Different combinations of degrees of utilisation and target temperatures for S700 plates (**t** = 8 mm). This table is also used for 12-mm specimens, because the shaded cells are the same and the difference between values is less than ±2%.

μ_0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
θ_{crit}(ºC)	882	747	676	641	591	561	533	463
θ_t (ºC)	**% θ_{crit}** (ºC)							
300	34%	40%	44%	47%	51%	53%	56%	65%
400	45%	54%	59%	62%	68%	71%	75%	86%
500	57%	67%	74%	78%	85%	89%	94%	
600	68%	80%	89%	94%				
700	79%	94%						
800	91%							

Figures 7 and 8 show the stress-strain residual curves from the PFL tests (θ_t = 400 ºC and θ_t = 500 ºC, respectively) for both thicknesses. Stress-strain curves at room temperature and from the PFU test at that θ_t are also plotted as references.

For θ_t = 400 ºC and t = 8 mm (Figure 7a) the residual stress-strain curve at μ_0 = 0 (PFU test) exhibits lower ductility than the curve at room temperature. Increasing μ_0 up to 0.4, the specimen ductility continues to reduce, but its yield and ultimate strengths remain essentially constant. For μ_0 = 0.5 and μ_0 = 0.6 the strength reduces. For μ_0 = 0.7 the curve exhibits even lower ductility. In the case of t = 12 mm specimens (Figure 7b) the trend is less evident. In all the range of μ_0, stress-strain curves maintain similar strengths as the room temperature curve, but ductility slightly increases for μ_0 = 0.6 and μ_0 = 0.7.

For θ_t = 500 ºC and t = 8 mm (Figure 8a) a similar trend as for θ_t = 400 ºC is observed, but the yield and ultimate strengths seem to slightly reduce up to μ_0 = 0.5. In the case of t = 12 mm, however (Figure 8b) the yield and ultimate strengths, as well as the ductility, seems to keep unaltered for all the range of μ_0.

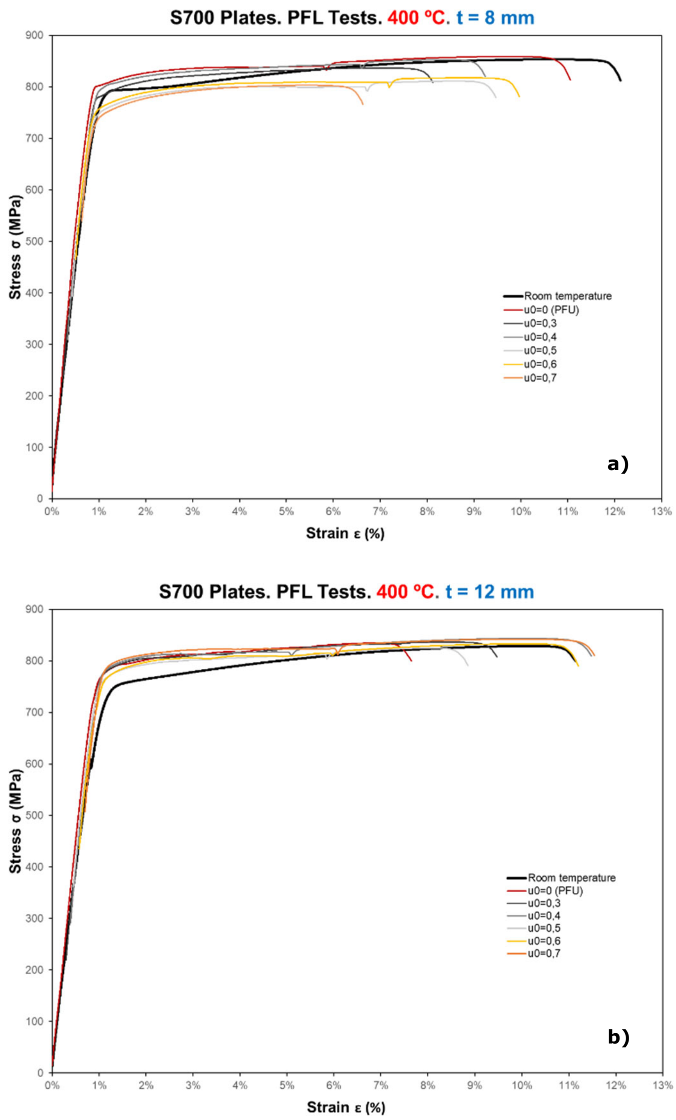


Figure 7 PFL tests on S700 plate; residual stress-strain curves for 400 ºC and different degrees of utilisation. a) t = 8 mm. b) t = 12 mm.

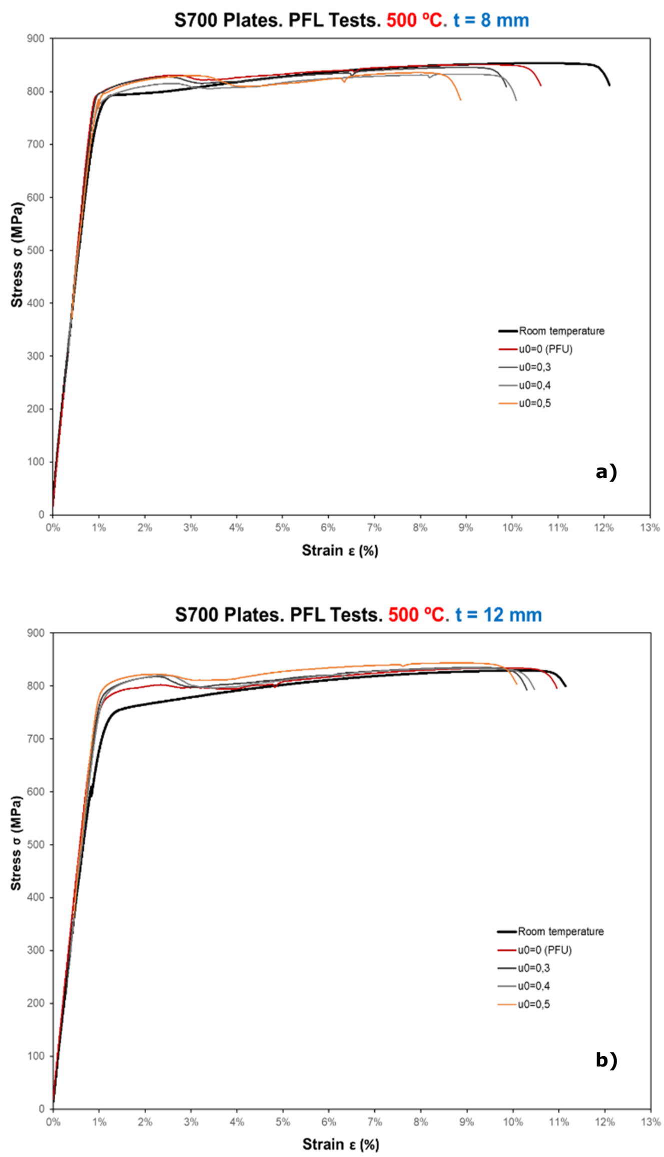


Figure 8 PFL tests on S700 plate; residual stress-strain curves for 500 ºC and different degrees of utilisation. a) t = 8 mm. b) t = 12 mm.

From Figure 8a the residual values of mechanical properties can be obtained, as well as the residual factors (R.F.) for each one (Table 6). A residual factor is the ratio between the value of a property measured in the PFL test to the value of the same property at room temperature. The values corresponding to heating up to 400 ºC (t = 12 mm) and 500 ºC (t = 8 mm and t = 12 mm) are not displayed.

Table 6 PFL tests on S700 plate (t = 8 mm, 400 ºC). Residual values and residual factors (R.F.) of yield strength f_y, ultimate strength f_u and modulus of elasticity E.

μ_0	f_y (MPa)	R.F.	f_u (MPa)	R.F.	E (MPa)	R.F.
0	**801.3**	**1.03**	**859.16**	**1.01**	**217000**	**1.06**
0.3	783.1	1.01	837.0	0.98	207000	1.01
0.4	799.5	1.03	853.0	1.00	209600	1.02
0.5	751.0	0.97	811.4	0.95	216000	1.05
0.6	758.6	0.98	817.7	0.96	208000	1.01
0.7	743.0	0.96	803.2	0.94	198000	0.97

According to the residual factors in Table 6, yield strength, ultimate strength and modulus elasticity seem to recover after being submitted to tensile load along with high temperature and subsequent cooling. Nevertheless, some aspects should be addressed regarding ductility. Current structural codes, such as Eurocode 3 (EN 1993-1-1, [11]) prescribe a minimum ductility for steels. For HSS, extended rules apply (EN 1993-1-12, [13]) so these conditions must be simultaneously fulfilled: 1) $f_u/f_y \geq 1.05$; 2) $\varepsilon_f \geq 10\%$ (ε_f, strain at fracture) and 3) $\varepsilon_u/\varepsilon_y \geq 15$ (ε_y, strain at f_y). From Figures 7-8, the values shown in Tables 7-8 can be determined:

Table 7 PFL tests on S700 plate (400 ºC). Ductility conditions.

μ_0	t = 8 mm			t = 12 mm		
	f_u / f_y	ε_f (%)	$\varepsilon_u / \varepsilon_y$	f_u / f_y	ε_f (%)	$\varepsilon_u / \varepsilon_y$
0	**1.07**	**12.00**	**26.08**	**1.08**	**8.84**	**19.38**
0.3	1.07	**9.04**	18.42	1.07	10.62	21.98
0.4	1.07	10.07	21.60	1.08	12.71	26.44
0.5	1.08	10.31	24.42	1.08	**9.97**	23.23
0.6	1.08	10.83	23.63	1.09	12.26	29.04
0.7	1.08	**7.44**	**13.98**	1.07	12.63	24.46

Table 8 PFL tests on S700 plate (500 ºC). Ductility conditions.

μ_0	t = 8 mm			t = 12 mm		
	f_u / f_y	ε_f (%)	$\varepsilon_u / \varepsilon_y$	f_u / f_y	ε_f (%)	$\varepsilon_u / \varepsilon_y$
0	**1.07**	**11.50**	**24.36**	**1.08**	**12.11**	**18.26**
0.3	1.06	10.73	23.71	1.06	11.59	23.42
0.4	1.06	10.96	22.48	1.06	11.71	23.02
0.5	1.05	**9.72**	21.59	1.05	11.21	22.30

There are some combinations of target temperature and degree of utilisation in which the ductility requirement (mainly that on ε_f) is not fulfilled after cooling down. This result was also found in previous works on mild steels [7-8].

4.2.2 Results of PFL tests on CHS specimens

In the case of CHS specimens, the same number of tests as on plates could not be performed due to the limited number of coupons. The following figures depict the residual stress-strain curves at different values of θ_t: C1L6 (Figure 9) and C4L5 (Figure 10). Curves at room temperature and from the PFU tests are also shown for reference.

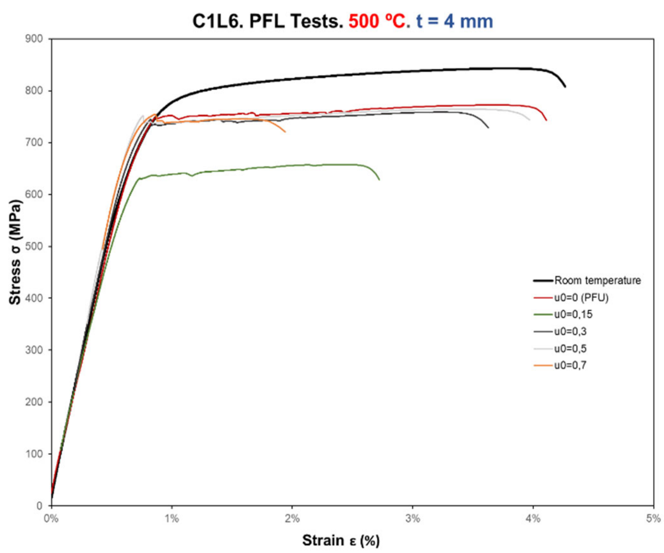
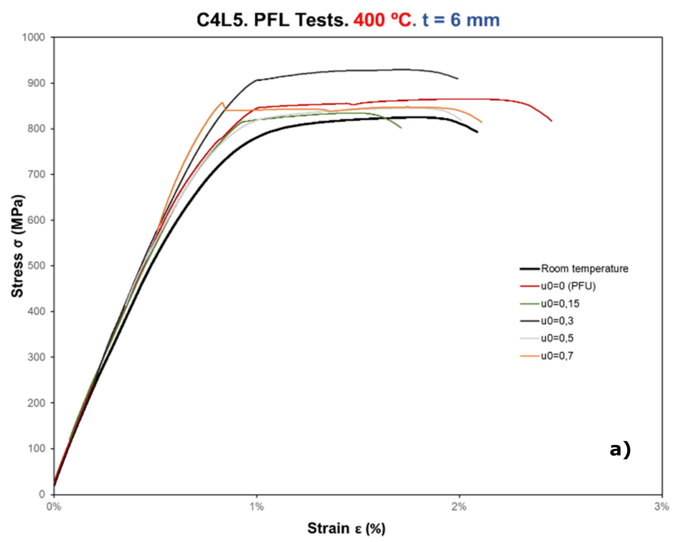


Figure 9 PFL tests on specimens from CHS C1L6 (t = 4 mm); residual stress-strain curves for 500 ºC and different degrees of utilisation.



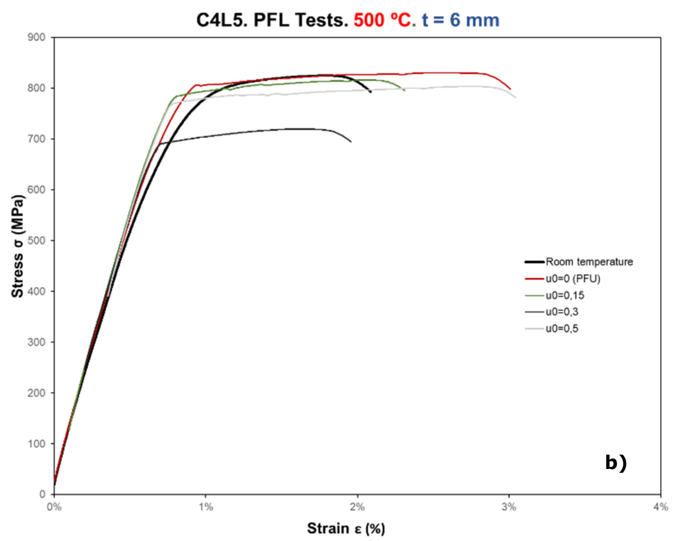


Figure 10 PFL tests on specimens from CHS C4L5 (t = 6 mm); residual stress-strain curves for different degrees of utilisation. a) 400 ºC. b) 500 ºC.

Residual values and residual factors of mechanical properties are presented in Table 9.

Table 9 PFL tests on specimens cut from CHS tubes. Residual values and residual factors (R.F.) of yield strength f_y, ultimate strength f_u and modulus of elasticity E. N/A: data not available (measurement errors).

CHS, temp.	μ_0	f_y (MPa)	R.F.	f_u (MPa)	R.F.	E (MPa)	R.F.
C1L6 500 ºC	0	749.5	0.99	772.4	0.92	200800	0.96
	0.15	629.9	0.83	657.5	0.78	185800	0.89
	0.3	734.7	0.97	758.8	0.90	N/A	N/A
	0.5	734.4	0.97	764.6	0.91	216700	1.04
	0.7	754.1	1.00	754.3	0.89	N/A	N/A
C4L5 400 ºC	0	838.2	1.09	865.0	1.05	234600	1.06
	0.15	818.3	1.06	834.3	1.01	199000	0.90
	0.3	906.9	1.18	929.2	1.13	202200	0.91
	0.5	818.6	1.06	844.9	1.02	N/A	N/A
	0.7	839.9	1.09	856.8	1.04	N/A	N/A
C4L5 500 ºC	0	804.7	1.05	830.4	1.01	233900	1.06
	0.15	791.3	1.03	816.3	0.99	214600	0.97
	0.3	697.9	0.91	719.9	0.87	160800	0.73
	0.5	775.3	1.01	803.4	0.97	N/A	N/A

In specimens cut from the CHS tubes, the stress-strain curves have a different shape than those obtained for the specimens cut from the plates. In any case, the post-fire behaviour is similar regarding the residual mechanical properties, because the residual factors are close to 1.00. Nevertheless, such factors are less than those computed for the specimens cut from plates. Regarding residual ductility, the values of ε_f remain very low as for room temperature due to the influence of cold working during production [12-13].

5 Conclusions

In the present work, an experimental campaign was performed to evaluate the residual mechanical properties (yield strength, ultimate strength and modulus of elasticity and ductility) of HSS specimens from different production routes. Specimens were exposed simultaneously to tensile load and a heating and cooling cycle. From the results, some conclusions are drawn.

The first one is that the post-fire behaviour of HSS is dependent on the production route and to some extent the thickness of the specimen. This can be seen in the critical temperatures of steels, as well as in the shape of the residual stress-strain curves. According to these findings, structural codes should incorporate residual factors related to the post-fire behaviour of different steel types. The second one is that the combination of tensile load, heating to high temperatures and cooling down seems to not seriously affect the mechanical properties of the specimens. The loaded specimens regain a considerable amount of their initial mechanical properties after cooling down from temperatures up to 500 ºC. Nevertheless, it is observed that some combinations of degree of utilisation and high temperature can strongly reduce the initial ductility of the material. Ductility is a key feature to take into account in steel structures, particularly in zones with high seismic risk, so fire design of HSS structures should take into account the stress level.

Acknowledgements

The authors would like to express their sincere gratitude for the help provided through the Grant PID2019-105908RB-I00.

References

[1] Winful, D.; Cashell, K. A.; Afshan, S.; Barnes, A. M. and Pargeter, R. J. (2017). *Material properties of high strength steel under fire conditions.* ce/papers 1(2-3), 2668-2677. https://doi.org/10.1002/cepa.316

[2] Neuenschwander, M.; Scandella, C.; Knobloch, M. and Fontana, M. (2017). *Modeling elevated-temperature mechanical behavior of high and ultra-high strength steels in structural fire design.* Materials and Design 136, 81-102.

[3] Chen, J.; Young, B. and Uy, B. (2006). *Behavior of High Strength Structural Steel at Elevated Temperatures.* Journal of Structural Engineering 132, 1948-1954.

[4] Qiang, X; Bijlaard, F and Kolstein, H. (2012). *Dependence of mechanical properties of high-strength steel S690 on elevated temperatures.* Construction and Building Materials 30, 73-79.

[5] Shakil, S; Lu, W. and Puttonen, J. (2020). *Experimental studies on mechanical properties of S700 MC steel at elevated temperatures.* Fire Safety Journal 116, 103157.

[6] Li, G.-Q.; Lyu, H. and Zhang, C. (2017). *Post-fire mechanical properties of high strength Q690 structural steel.* Journal of Constructional Steel Research 132, 108-116.

[7] Lapuebla-Ferri, A.; Pons, D. and Romero, M. L. (2021) *Load and temperature influence on the post-fire mechanical properties of steel reinforcements.* Journal of Constructional Steel Research 185, 106866.

[8] Pons, D.; Lapuebla-Ferri, A. and Romero, M.L. (2022) *Post-fire Residual Strength and Ductility of Structural Steels from Hollow Sections*. ce/papers 5, 458-466. https://doi.org/10.1002/cepa.1777

[9] European Comittee for Standardization (2009) *EN 1993-1-12. Eurocode 3: design of steel structures. Part 1-12: additional rules for the extension of EN 1993 up to steel grades S 700*.

[10] European Comittee for Standardization (2005) *EN 1993-1-2. Eurocode 3: design of steel structures. Part 1-2: general rules – structural fire design*. Brussels, Belgium.

[11] European Comittee for Standardization (2005) *EN 1993-1-1. Eurocode 3: design of steel structures. Part 1-1: general rules – rules for buildings.* Brussels, Belgium.

[12] Afshan, S.; Rossi, B. and Gardner, L. (2013) *Strength enhancements in cold-formed structural sections – Part I: Material testing.* Journal of Constructional Steel Research 83, 177-188.

[13] Afshan, S.; Rossi, B. and Gardner, L. (2013) *Strength enhancements in cold-formed structural sections – Part II: Predictive models.* Journal of Constructional Steel Research 83, 189-196.