MECHANICAL PROPERTIES OF STRUCTURAL STEEL EXPOSED TO PASSIVE FIRE

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Abstract

Non-seismically designed existing reinforced concrete (RC) structures are susceptible to any thermal effect. Indeed, difficulties arise even more in understanding the performance of buildings in fire due to the inherent complexity in the behavior of composite materials at elevated temperatures. This paper deals with the determination of mechanical properties of hot rolled structural steel under thermal effect. A focus on the influence of the passive fire to the structural steel is thus provided. The specimens were firstly heated up to a certain level of temperature (i.e. in a range of 300-700 °C) and then cooled down to room temperature. After that, the dog-bone shape steel tensile test samples were taken from reinforcing bar of RC bond-slip specimens complying with RILEM test method. Dependence of the heating and cooling rate on mechanical properties of S275 type smooth reinforcing steel was identified by either destructive or non-destructive testing methods. Two different techniques including their pros&cons and difficulties in implementing the tests were therefore closely compared. Moreover, major parameters characterizing the behavior of the steel samples exposed to the aggressive fire were compared with the control ones. It is found that not only the ductility in the fire-exposed specimens was essentially different from the ones at ambient temperature but also the deterioration in yield and ultimate strength was considerably affected.

Keywords: Fire, destructive, non-destructive, elevated temperature, tensile test

1. INTRODUCTION

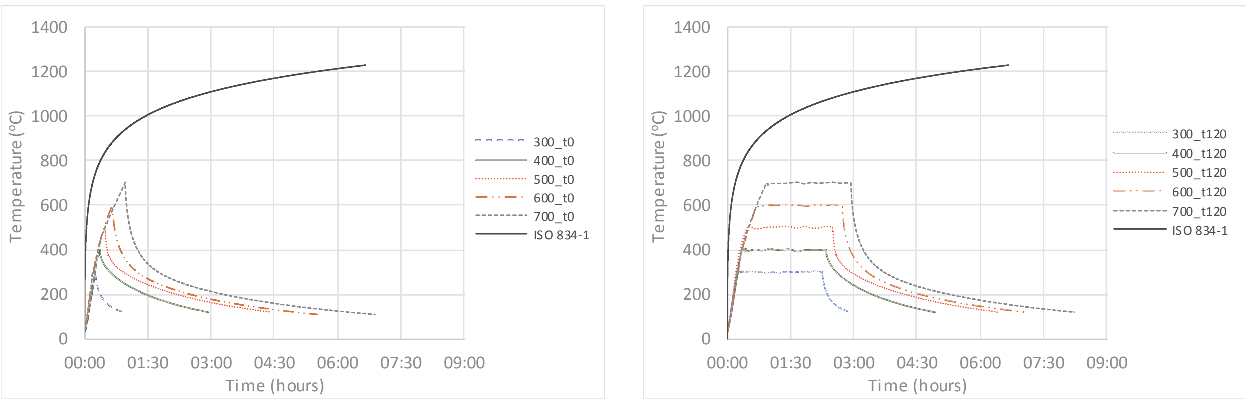
A considerable amount of existing substandard RC structures are vulnerable to high or even moderate thermal effects. Those can simply actuate the global failure mechanism, which brings the requirement to examine the performance of substandard members in the fire. A special attention should therefore be given to the substandard RC members exposed to aggressive fire. Moreover, the dependence of the heating and cooling rate on material mechanical properties should be identified by the available testing methods. There are several literatures investigating the global response of the reinforced concrete members under thermal effects [1-5]. Studies are also available regarding the behavior of steel after temper treatment [6-9].

Studies on the performance of buildings in fire reveal that further developments are still needed due to the inherent complexity in the behaviour of composite materials at elevated temperatures. Therefore, the effect of passive fire at material level should be revealed. In this paper, the mechanical properties of hot rolled structural steel (i.e. S275 type smooth reinforcing bar) under thermal effect were examined. For this reason, the reinforced concrete bond-slip test specimens constructed according to EN 10080:2005 [10] were firstly heated up to a certain level of temperature (i.e. in a range of 300-700 °C). Then, samples for destructive and non-destructive testing were taken from the reinforcing bar. After that, steel samples were machined to the desired shape and dimension for both tensile and non-destructive tests. Finally, major parameters characterizing the response of the test samples exposed to the aggressive fire were compared with the control ones.

Within the framework of this study, basic premises can be summarized as follows (i) investigating the behaviour of S275 type smooth reinforcing bar under aggressive fire by destructive and non-destructive methods (ii) comparing two different testing methods with their advantages & disadvantages and also the difficulties in implementing the tests (iii) investigating the effect of elevated temperature and cooling regime on strength and ductility parameters.

2. EXPERIMENTAL PROGRAM

The bond-slip test specimens were exposed to passive fire in a furnace. The influence of different temperature levels such as 300, 400, 500, 600 and 700 °C was investigated at material level by four steel samples taken from reinforcing steel of RC specimens. The heating and cooling regime were different than the available heat treatment techniques. The application of fire was intended to be in agreement with ISO 834-1 [11], which considers a rapid increase in the temperature with time and then, a rather slow increment was assumed after a specific value. However, the furnace was not capable of heating so rapidly. Hence, the target temperature value was reached later than the expected time. Moreover, unlike the proposed heating regime in the corresponding standard, the temperature was kept constant for 2 hours in some test series after reaching the peak value. Thus, the duration effect was taken into account. The temperature of 1049 °C that will be reached in 2 hours is given as a maximum value in ISO 834-1 [11]. However, the concrete specimens could not keep their integrity after 700 °C. It is due to use of very low strength concrete, which results in rapid strength deterioration at high temperature. Therefore, the temperature of 700 °C was selected as a maximum target value during heating. The heating and the cooling regime are visually presented in **Figures 1a, b**.

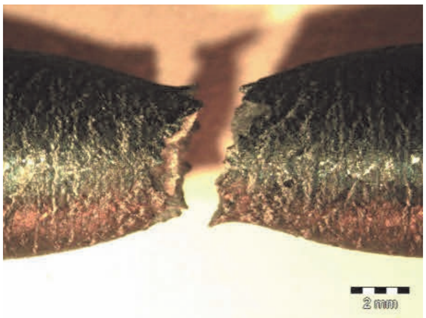


(a) (b)

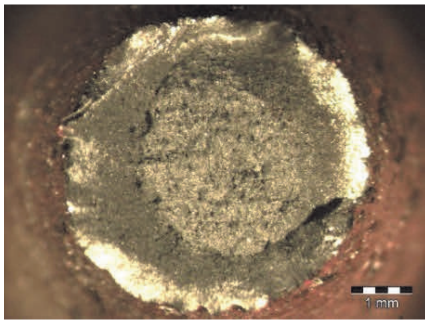
Figure 1 Heating and cooling regime (a) fire exposure time 0 mins (b) fire exposure time 120 mins

The samples for destructive and non-destructive tests were taken from reinforcing bar of RC specimen as mentioned earlier. Four tensile test samples, after which they were machined to dog-bone shape, were tested for each temperature level. The tensile tests were performed in accordance with ASTM E8/E8M-13a [12]. Note that, samples were machined to the desired shape according to the corresponding standard. The speed of the tests was selected as 0.5 mm / min, which is in the given range of ASTM E8/E8M-13a [12].

Metallographic analysis of the tested steel was performed on pieces which has 4 mm thickness and cut from the cross-section of bars. Pieces for metallography were prepared by standard metallographic techniques such as, moulding, grinding, polishing and etching (5 % Nital). After revealing the microstructure of each temper treated sample, the hardness tests were performed on the same samples. The hardness test was conducted according to Vickers Hardness test method [13]. The Vickers indenter has pyramidal geometry. This indenter was applied to the surface about 49 N (HV5) for 10 seconds. After completion of loading, the HV number is determined by the ratio of F/A, where F is the force applied to the indenter and A is the surface area of the resulting indentation in square millimeters. Moreover, the photographs of the crack surface were taken in the damaged samples to provide more detailed information (**Figure 2**).

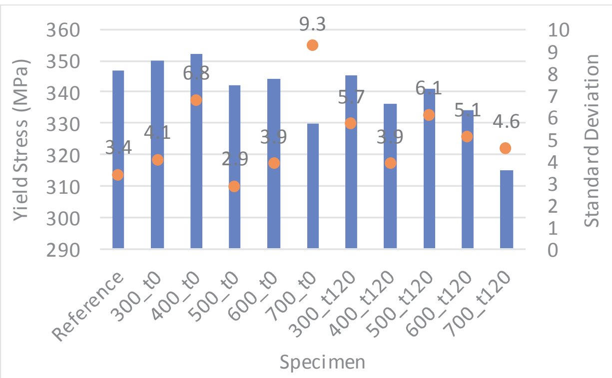


(a)



(b)

Figure 2 Fracture surface (a) top view (legend 1mm) (b) side view (legend 3mm)



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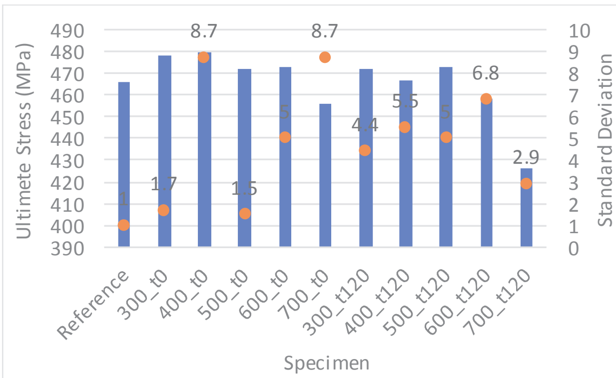

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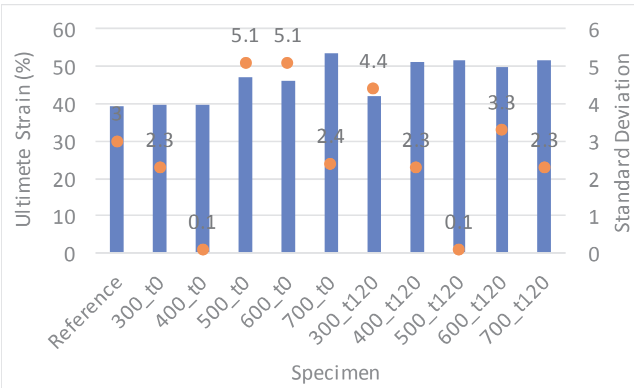

(c)

Figure 3 Change in the mechanical properties (a) yield stress (b) ultimate stress (c) ultimate strain (d) elastic modulus

3. RESULTS AND DISCUSSION

The consistent outcomes of the steel tensile tests are summarized in **Table 1** and **Figures 3a, c.** The strength deterioration was not very significant up to certain level of temperature. A significant drop in the ultimate stress was observed at 700 °C. As exposure time increases, the gap in the stress with respect to control ones increases even more at the same temperature levels. A similar trend was also observed for the yield stress at

700 °C, while no considerable deterioration in the yield strength was observed for the temperature levels lower than 700 °C. The response quantities related to elongation were dramatically increased especially after 500 °C. Those are approximately in the range of 20-30 % for different temperature levels. To conclude, heating/cooling regime affected the strain parameters intensely. The strength properties in the fire-exposed samples were rather different than the ones stored at ambient temperature.

The yield and the ultimate tensile strength of the tested steels can be estimated by using Vickers hardness values with the suitable relationship. Pavlina and Tyne [14] propose the following empirical formulas for estimation of yield and tensile strength.

$$\sigma_u = \left(\frac{H}{2.9}\right)\left(\frac{n}{0.217}\right)^n \qquad (1)$$

$$\sigma_y = \left(\frac{H}{3}\right)(0.1)^n \qquad (2)$$

where:

σ_u - the ultimate tensile strength (MPa)
σ_y - the yield strength (MPa)
H - the Vickers Hardness (kgf/mm^2)
n - the strain hardening exponent (-)

In these equations, the strain hardening exponent value, n, varies from 0.19 to 0.26 for structural low carbon steels [15] and n was chosen as 0.23.

Hardness is a measure of material resistance to localized plastic deformation. The hardness values generally decrease with increasing temperature. The reason for this behaviour is the stress relief annealing process. The temperature interval for annealing of ferrous alloys is valid especially in the specimens exposed to fire above 500 °C. If the specimens were held there for a sufficient period, the stress relaxation mechanism would be activated and result in increasing softness and ductility. The same hardness value as observed in the control one is obtained only for "500_t0" sample while the rest is dramatically different. The discrepancy in the results could be attributed to the heterogeneity of the tested specimen during production or internal inclusions. When the converted strength parameters obtained from hardness tests, results were closely compared with destructive testing, a good agreement especially in the ultimate strength was found for each temperature level. Those relevant to yield strength are always underestimated with respect to tensile test results which makes the prediction of the results challenging. Nevertheless, estimating the strength parameters with less error and without destructing the samples provides great benefits such as minimization of time, labour work and cost. All experimental results are summarized in **Table 1**.

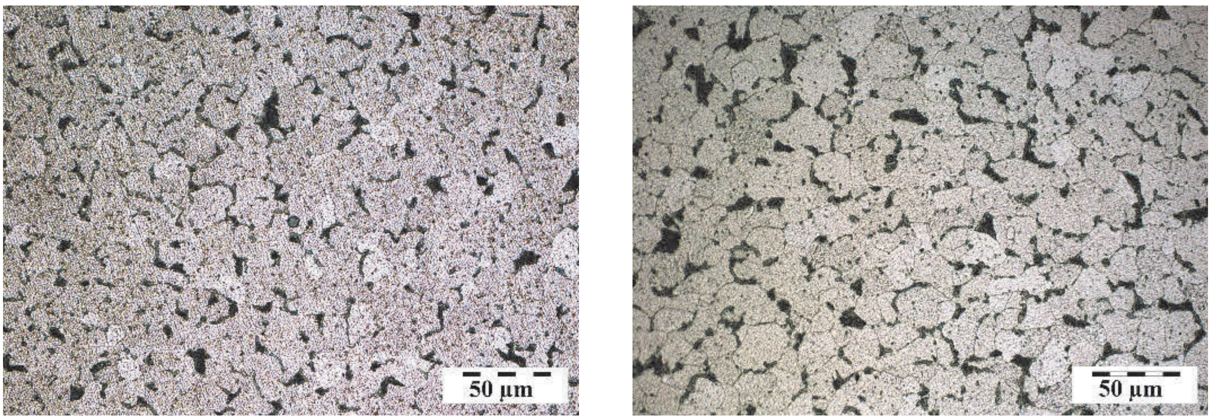

Figure 4 Microstructure at (a) room temperature (b) 600 °C

Table 1 Summary of experiment results

Sample	Description		Hardness			Tensile Test				
				Converted Strength*			Strength		Strain	
	Heating (°C)	Fire Exposure Time (mins)	HV5	σ_y (MPa)	σ_u (MPa)	E (GPa)	σ_y (MPa)	σ_u (MPa)	ε_o (%)	ε_u (%)
Control	N/A		137.7	265	472	202	347	466	19.7	39.3
300_t0	300	0	133.6	257	458	208	350	478	20.6	39.8
400_t0	400	0	134.4	259	461	207	352	480	20.5	39.9
500_t0	500	0	138.2	266	474	207	342	472	20.9	46.9
600_t0	600	0	133.0	256	456	201	344	473	20.4	46.2
700_t0	700	0	126.3	243	433	204	330	456	22.1	53.4
300_t120	300	120	134.3	259	460	199	345	472	20.0	41.9
400_t120	400	120	133.2	256	457	198	336	467	21.8	51.4
500_t120	500	120	127.5	246	437	201	341	473	21.4	51.8
600_t120	600	120	128.8	248	442	205	334	458	21.3	49.9
700_t120	700	120	122.7	236	421	211	315	426	21.1	51.6

* Yield and Ultimate values were obtained in a relation between hardness test and strength as presented by Pavlina and Tyne [14]
σ_y: Yield stress
σ_u: Ultimate stress
E: Elastic modulus
ε_o: Strain corresponding to ultimate stress
ε_u: Ultimate strain

The microstructures of each tested steels were captured, however, no significant change in the microstructure of the samples was observed since all samples were cooled at a slow cooling rate. **Figures 4a**, **b** show representative microstructure of S275 steel for temperature level 600 °C. As it can be visually seen in the corresponding figure, microstructure consists from typical ferrite and pearlite.

Macro photos of fracture surfaces in all tested samples were also taken for both top and side views. All of the tested specimens displayed a ductile response which positively affected the fracture characteristics. The taken photos of the representative cracked surface were presented in **Figures 2a, b** in the loading direction and the perpendicular direction to the loading direction (side view of the samples), respectively. The surface of the damaged sample had a moderate amount of necking and it was almost represented by cup and cone fracture characteristics. In the central region, which has an irregular and fibrous appearance, plastic deformation is clearly apparent. In outer side of the fracture surface, shear lips with an angle of 45° can be seen in **Figures 2a, b.** This angle represents the direction of maximum shear stress that causes shear lip in the final stage.

4. CONCLUSION

This study sets out an investigation of change in the mechanical properties of S275 type reinforcing steel after the aggressive fire. The steel samples, which were taken from the existing reinforced concrete specimen, were heated up to certain levels of temperature (i.e. 300-700 °C). Mechanical properties of reinforcing steel were determined by either destructive or non-destructive testing methods. After testing the steel samples, it is found that the strength parameters such as yield and ultimate strength were adversely affected by the increasing temperature. A considerable amount of strength deterioration was therefore observed. The deterioration was not only observed in the tensile test, but also a similar trend in the strength deterioration was found by the non-destructive method. Note that, the strength parameters were calculated through an empirical formula which converts hardness test results to yield and ultimate strength. Moreover, the elevated temperature resulted in an enhancement of the ductility properties. To conclude both the ductility and strength in terms of yield and ultimate strength in the fire-exposed specimens were essentially different from the ones stored at ambient temperature.

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