POST-FIRE MECHANICAL PROPERTIES OF STRUCTURAL STEEL

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1. SUMMARY

This paper presents a review of the mechanical properties of structural steel exposed to fire and cooled down. The existing design codes do not provide satisfactory recommendations concerning the post-fire properties of steel or the post-fire performance of a steel member, which shows the need for further research on the topic. Experimental results from laboratory tests, including samples taken from real fire damaged steelwork, are collected herein. The available data are analyzed in order to evaluate the residual capacity of fire damaged steel, i.e. the elastic modulus, the yield and ultimate strength and the remaining ductility, which are related to its reuse. For this purpose, simplified formulas are proposed for the estimation of the post-fire mechanical properties of structural steel according to its type.

2. INTRODUCTION

The last decades, post-fire performance of structural elements has gained considerable attention. Apart from the fire safety of a structure, the reinstatement of fire damaged structures is in the centre of interest nowadays. The research is focused on the mechanical properties of the material [1] and on the total behaviour of the structure [2-10], taking into consideration both low strength [2-6] and high strength steels [7-10].
Despite the significance of fire design of steel structures, no specific guidelines have been established by the current design codes for the determination of the remaining capacity of steel members after fire, with the exception of some recommendations by the British Standard [11], which is no longer in use. This paper contributes to the assessment of fire damaged steel and its subsequent reuse.

3. INFLUENCING FACTORS

Initially, it is necessary to examine some relevant information about the metallurgical properties of steel. The following analysis is based on a Monograph by Digges et al. [1].
The majority of microstructures of steel are formed through the austenite transformation during the cooling phase. Knowing how austenite decomposes to other microstructures

(e.g. pearlite, bainite, martensite, ferrite) is necessary for the clear understanding of the heat treatment of steel. The end product or final structure is greatly influenced by the temperature at which transformation occurs, which, in turn, is influenced by the cooling rate. In addition, the chemical composition of steel (especially the carbon content) is particularly crucial for the thermodynamic and kinetic of the transformation.

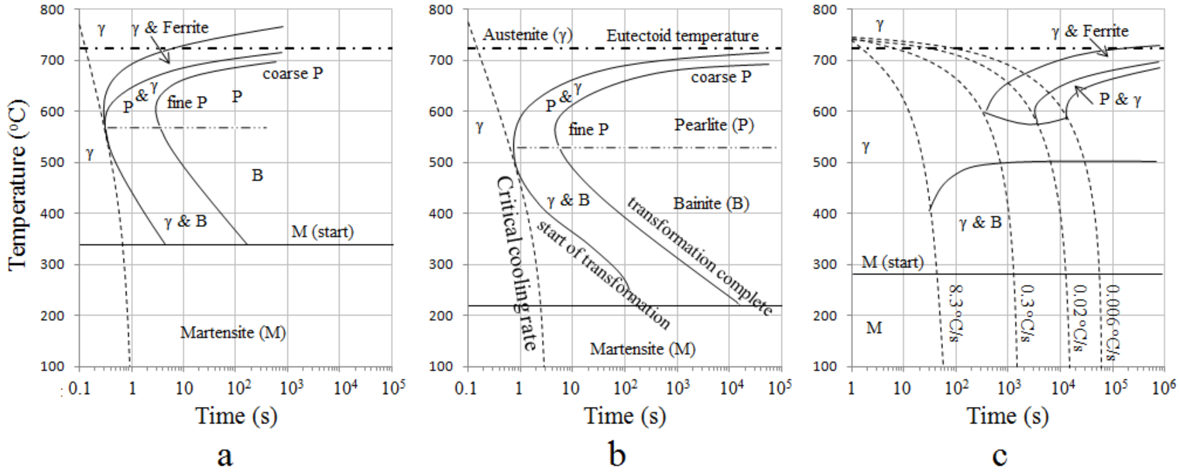

Fig. 1: Schematic diagrams illustrating isothermal curves (IT), critical cooling curves and resulting microstructures for (a) hypoeutectoid, (b) eutectoid and (c) alloy steel [12]

Figure 1 shows the isothermal time-temperature-transformation (TTT) diagrams for three different types of steel: a) hypoeutectoid steel (less than 0.80% of carbon), b) eutectoid steel (0.8% of carbon) and c) alloy steel. Firstly, the steel is held at elevated temperatures, greater than the eutectoid temperature (A_1=727 ^{o}C), where the transformation to austenite begins. The temperature A_3 is associated with the completion of the transformation of ferrite to austenite. It must be noted that for hypoeutectoid steel, A_3 varies linearly, inversely related to the carbon composition (maxA_3=910^{o}C).
The course of transformation can be completed in either an isothermal or a continuously cooling way. If the austenite is cooled unchanged to a relatively low temperature (M_s), partial transformation takes place instantaneously, producing martensite. This formation attribute to the maximum hardness that can be obtained, while the transformation can be resulted by cooling in water (CIW) or in ice. The critical cooling rate for each steel type is clearly illustrated in Fig. 1.
In contrast, if austenite decomposes in higher temperatures than M_s, the final product can be bainite, pearlite, or ferrite - with high, medium and low hardness, respectively. This can also be formulated via slower cooling methods, such as cooling in air (CIA) or cooling in furnace (CIF). In most plain carbon steels bainite will not form on continuous cooling due to the fact that austenite has already transformed to ferrite and pearlite. CIF is usually applied to produce softening (annealing).
Apart from the identification of the phase transformation, the microstructure characteristics lead to an understanding of the possible conditions during and after fire, such as the spheroidizing of the iron carbide, or the change in grain size or morphology.
Moreover, with the aid of tensile tests, the shape of the stress-strain curve for heated steel coupons after cooling in air or in furnace is similar to that obtained from the unheated steel and there is no significant change in elongation. For the steel cooled in water, the yield plateau disappears (decrease of ductility) and a dramatic increase in strength is found. This behaviour is clearly illustrated in Fig. 2 (Lee et al. [6]).

Concerning the heating duration, for long heating time the temperature inside the steel sample is evenly distributed. Consequently, with the increase of fire exposure time, the mechanical properties of structural steel are hardly influenced.
The manufacturing process does have an effect on the residual yield and tensile strength, with the "cold worked" steels presenting a greatly reduced strength with increasing heating temperature compared with the "hot rolled" steels. Cold-worked and heat-treated structural steel loses its strength more rapidly above 450 ^{o}C [5].
Concluding, for any steel alloy at a given composition, different heat treatment pathways will result in different microstructures, which in turn can change the steel's mechanical properties by almost an order of magnitude.

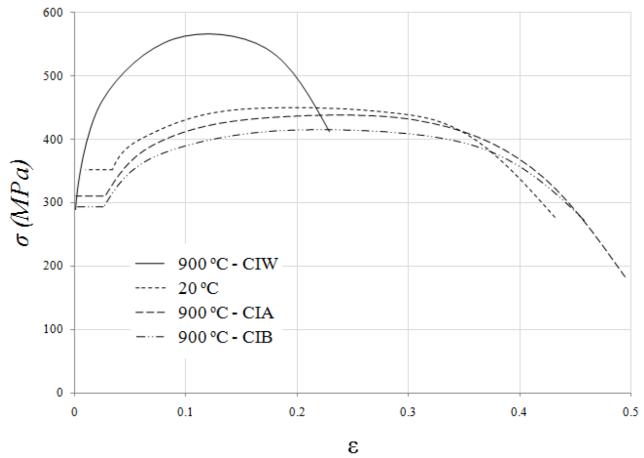

Fig. 2: Influence of different cooling methods on stress-strain curves [6]

4. PROPOSED EQUATIONS FOR POST-FIRE PROPERTIES

Considering the above, it is obvious that there are many uncertainties in evaluating the residual mechanical properties of damaged steelwork on the basis of microstructures. Another way of determining the post-fire properties could be through fire simulation. Many tests have been conducted on steel coupons after heating, via electric furnaces, and cooling treatment.
A total of 128 test results from six studies [4-9] (some of which were derived from real fire damage [4]) were collected for structural steel, whereas 56 full-range stress-strain curves are available. The initial yield strength f_y at ambient temperature and the values of T are in the range of 231 to 1045 MPa and 100 to 1000 ^{o}C, respectively. The residual properties were obtained from tension tests on steel specimens after heating and cooling to room temperature via different cooling methods. In addition, there is a variety of structural steel types. For these reasons, a significant difference between test results is expected. The details of the tests are summarized in Table 1.
The experimental ratios of f_{yT}/f_y, f_{uT}/f_u and E_{sT}/E_s are plotted in Fig. 3, where f_y, f_u and E_S are the reference yield strength, ultimate strength and elastic modulus (i.e. before the fire exposure) and those with the subscript T are the corresponding temperature dependent values. The different behaviour of steel coupons can be clearly observed, depending on the cooling rate (CIW, CIA, CIF), the steel type (alloy or carbon-based), and the manufacturing process (hot-rolled or heat-treated).

Source	Number of specimens	Number of curves	Steel type	Average f_y (MPa)	T(°C)	Cooling method
Smith et al. (1981) [4]	54	-	Hot rolled	231-436	100-1000	CIA*
Outinen and Mäkeläinen (2004) [5]	14	-	Cold worked	566	464-538	CIF**
Zhou and Zhao (2008) [7]	7	3	Hot rolled	539	600-900	CIW***
Lee et al. (2012) [6]	9	9	Hot rolled	358	200-1000	CIA
	9	9	Hot rolled	359	200-1000	CIW
Qiang et al. (2012) [8]	11	11	Hot rolled	490	300-1000	CIA
	13	13	Heat treated	789	100-1000	CIA
Qiang et al. (2013) [9]	11	11	Heat treated	1045	100-1000	CIA

* Cooling in air ** Cooling in furnace *** Cooling in water

Table 1: Summary of Test Data for Structural Steel

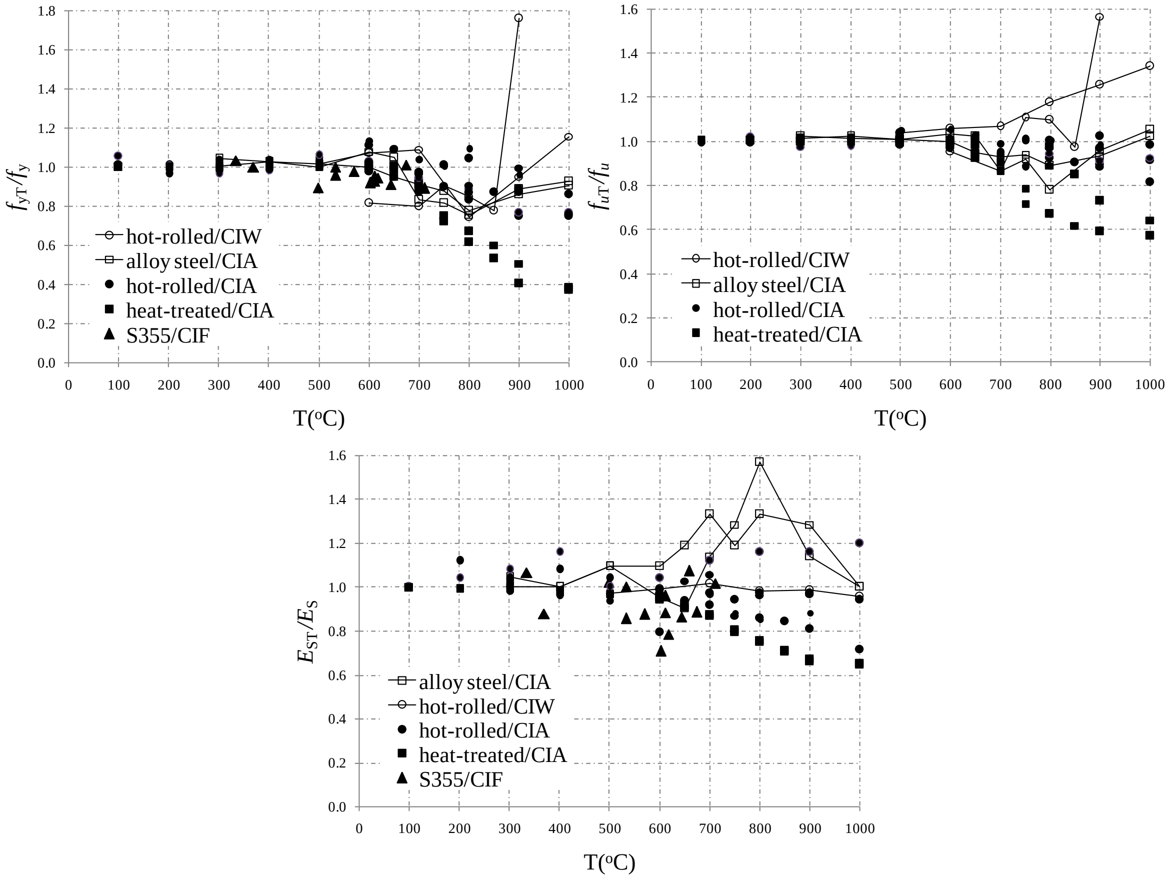

Fig. 3: Ratio of f_{yT}/f_y, f_{uT}/f_u and E_{sT}/E_s as a function of temperature for structural steel

Indeed, the increase of the capacity for low-alloy steels (mainly vanadium contained) is characteristic for temperatures above 800 °C (where austenitization is completed). This is also the case for cooling-in-water test results.

Consequently, a distinct analysis on the basis of the above criteria proves necessary, in order to establish appropriate relationships between the residual mechanical properties. For sake of simplicity, linear relationships are suggested for temperatures between 600 ^{o}C and 1000 ^{o}C, taking into consideration cooling-in-air test results.
Eqs. (1)-(2) are more accurate, according to all test data of mild steel, but sometimes not conservative for high strength steel. Eqs. (4)-(5) are recommended for practical use in order to determine the residual yield and ultimate strength of high strength and alloy steel after cooling down from fire temperatures up to 1000 °C. The predictions of Eqs. (1)-(5) are compared with the test data in Fig. 4.

$$\frac{f_{yT}}{f_y} = \begin{cases} 1 \\ 1.504 - T/1200 \\ 0.748 \end{cases}, \quad \frac{f_{uT}}{f_u} = \begin{cases} 1 & T \le 600^o C \\ 1.208 - T/2900 & 600^o C < T < 900^o C \\ 0.896 & T \ge 900^o C \end{cases} \tag{1)-(2}$$

$$\frac{E_{sT}}{E_s} = \begin{cases} 1 & T \le 600^o C \\ 1.431 - T/1400 & T > 600^o C \end{cases} \tag{3}$$

$$\frac{f_{yT}}{f_y} = \begin{cases} 1 \\ 1.756 - T/800 \\ 0.748 \end{cases}, \quad \frac{f_{uT}}{f_u} = \begin{cases} 1 & T \le 600^o C \\ 1.655 - T/920 & 600^o C < T < 800^o C \\ 0.782 & T \ge 800^o C \end{cases} \tag{4)-(5}$$

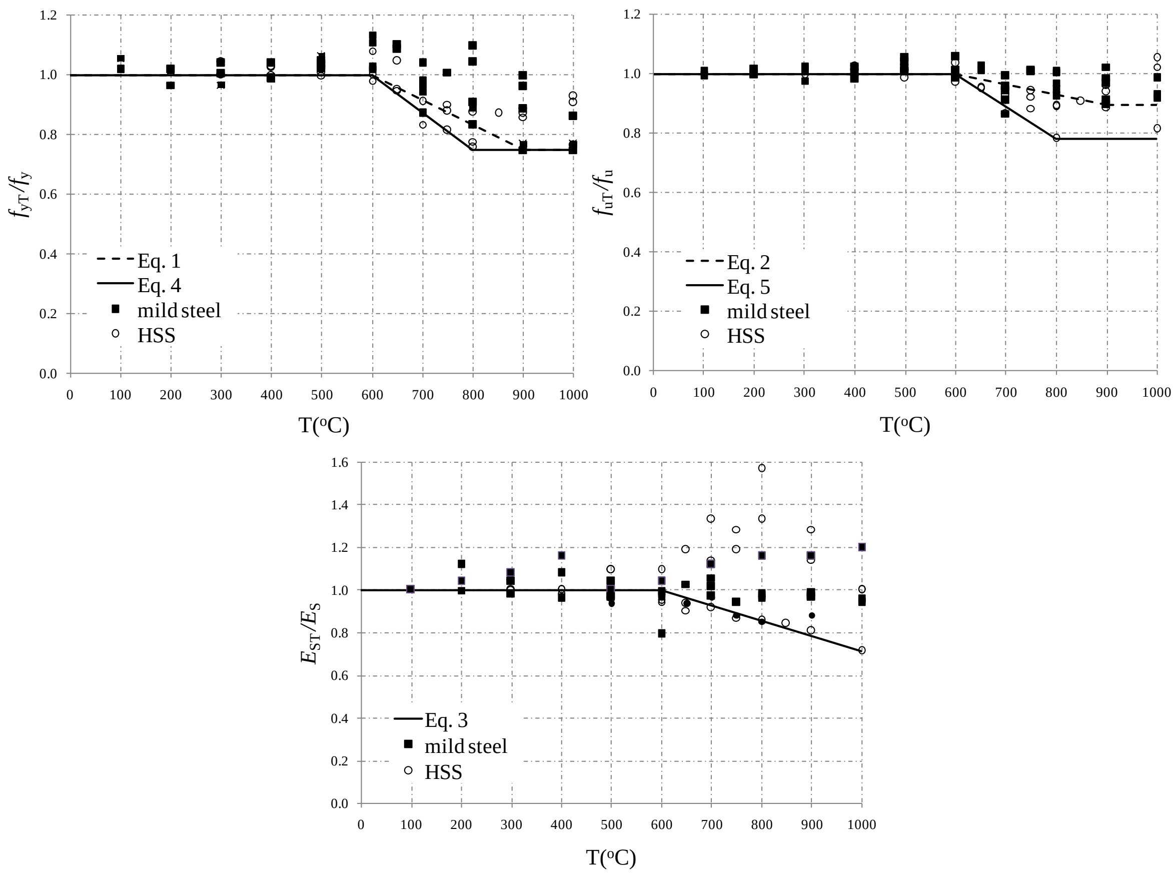

Fig. 4: Comparison of predicted residual factors f_{yT}/f_y, f_{uT}/f_u and E_{sT}/E_s for hot-rolled steel

Post-fire mechanical properties for heat-treated and cold-worked steel are determined via Eqs. (6)-(8). Meanwhile, according to Zhong et al. [10], there is no obvious difference between cold-worked and heat-treated steels in terms of the influence of heat exposure. Fig. 5 shows the corresponding linear expressions, compared with the respective test data.

$$\frac{f_{yT}}{f_y} = \begin{cases} 1 \\ 2.258 - T/480 \\ 0.371 \end{cases}, \quad \frac{f_{uT}}{f_u} = \begin{cases} 1 & T \le 600^o C \\ 1.816 - T/740 & 600^o C < T < 900^o C \\ 0.592 & T \ge 900^o C \end{cases} \tag{6)-(7}$$

$$\frac{E_{sT}}{E_s} = \begin{cases} 1 & T \le 600^o C \\ 1.702 - T/850 & 600^o C < T < 900^o C \\ 0.649 & T \ge 900^o C \end{cases} \tag{8}$$

It should be noted that the post-fire behaviour of structural steel is hardly influenced after exposure to temperatures up to 600 ^{o}C. In addition, the residual ultimate strength of mild steel is found greater than 90% of the initial one, whereas none of the properties of hot-rolled steel is reduced more than 75%. The distinguish between mild steel and high strength steel (HSS) is also stated in Appendix B of British Standard 5950-8 [11], which recommends the reuse of S235 and S275 reduced by 10% of the initial strength, whereas for S355 at least 75% of the strength is regained on cooling from temperatures above 600 ^{o}C, which is in agreement with the experimental results of [4,6-8] (Fig. 4). However, these suggestions are considered as not conservative enough for heat-treated steel [8,9], where the deterioration of the capacity is obviously more significant (Fig. 5, residual factors > 37%).

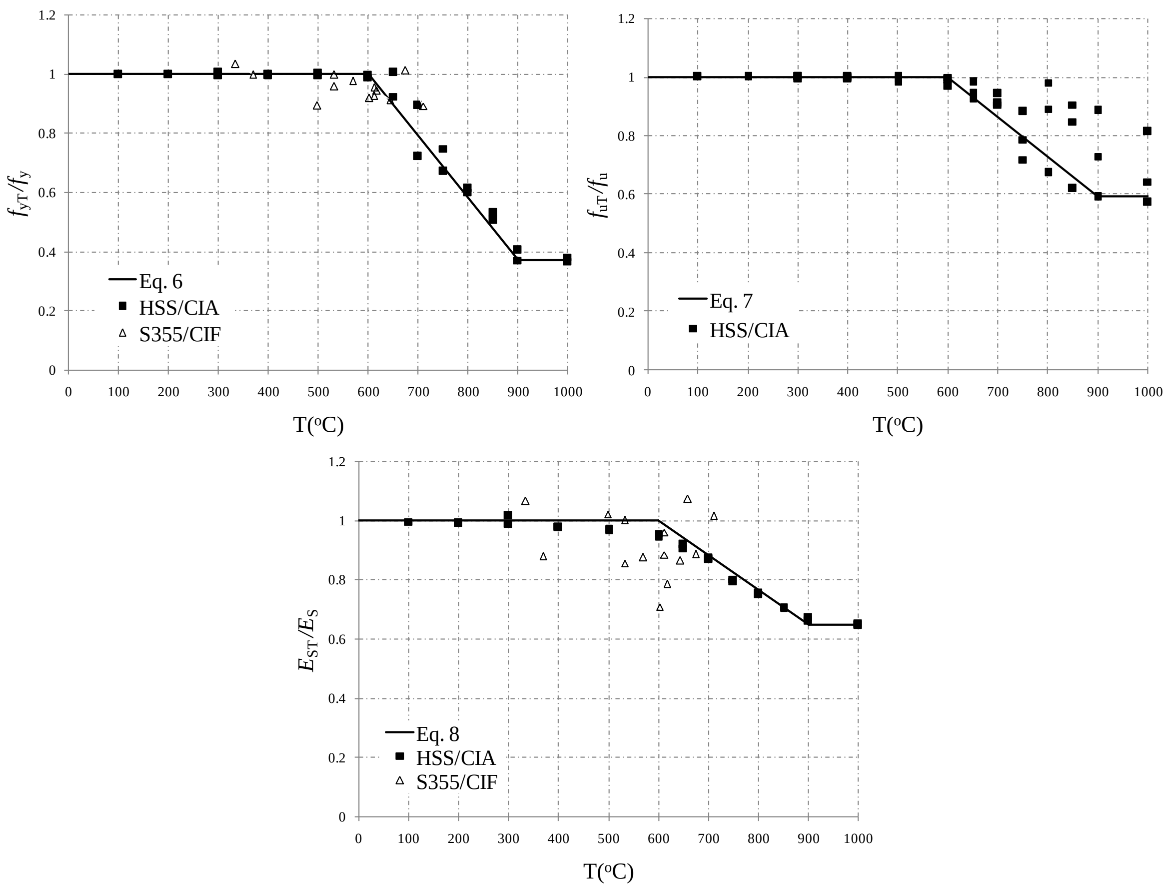

Fig. 5: Comparison of predicted residual factors for heat-treated steel

5. CONCLUSIONS

The data presented in this paper contribute to the assessment of the post-fire properties of a wide range of structural steel and consequently the reuse of a fire-damaged member. It can be stated that the post-fire behaviour, according to the available in the literature experimental results, is not strongly affected until the steel is exposed to fire temperature above 600 ^{o}C and then cooled down. More specifically, mild steels and high strength steels are able to regain at least 75% of their mechanical properties, for temperatures above 600 ^{o}C, whereas the yield strength for heat-treated or cold-worked steels reduces to 40% for temperatures up to 1000^{o}C. Moreover, an increase of the capacity has been obtained in many cases, which is attributed to the microstructural refinement. Finally, one can easily evaluate the post-fire properties of the material by means of the suggested equations according to the steel type.

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ΜΗΧΑΝΙΚΕΣ ΙΔΙΟΤΗΤΕΣ ΤΟΥ ΔΟΜΙΚΟΥ ΧΑΛΥΒΑ ΜΕΤΑ ΑΠΟ ΠΥΡΚΑΪΑ

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ΠΕΡΙΛΗΨΗ

Η εργασία παρουσιάζει μία βιβλιογραφική ανασκόπηση των απομενουσών μηχανικών ιδιοτήτων των δομικών χαλύβων όταν εκτεθούν σε υψηλές θερμοκρασίες και στη συνέχεια κρυώσουν. Το γεγονός ότι οι υπάρχοντες κανονισμοί δεν παρέχουν οδηγίες για τις απομένουσες ιδιότητες του χάλυβα υποδεικνύει την ανάγκη για περαιτέρω διερεύνηση. Αρχικά, αναλύονται οι παράγοντες που τις επηρεάζουν και στη συνέχεια παρουσιάζονται συγκεντρωμένα αποτελέσματα από πειράματα σε εργαστηριακά δοκίμια καθώς και σε δοκίμια προερχόμενα από πραγματικές πυρκαγιές. Με βάση αυτά τα πειραματικά αποτελέσματα προτείνονται εξισώσεις για την εκτίμηση των απομενουσών μηχανικών ιδιοτήτων (μέτρο ελαστικότητας, τάση διαρροής και τάση θραύσης), οι οποίες μπορούν να φανούν χρήσιμες για την αξιολόγηση και άρα την επαναχρησιμοποίηση των δομικών στοιχείων και μετά την πυρκαγιά.