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Post-fire assessment and reinstatement of steel structures

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Abstract
It is widely accepted that many steel structures remain their integrity after fire while their reuse and reinstatement is a critical economical issue. Although significant quantitative research has been conducted the past years, in most cases the stability of the structure as a whole is not addressed, hence no specific guidelines and code provisions have been established for the proper appraisal and rehabilitation of fire damaged structures. This article presents technical aspects of the assessment method and evaluation of fire damaged steel structures, from which useful conclusions are drawn for the safe reuse of the structural elements and connection components, while the reinstatement survey is also comprehensively described. To reliably evaluate the remaining strength, the understanding of the mechanical properties of damaged steel after a fire event is a requisite. Moreover, the current work focuses on the behavior of structural normal steel (hot rolled and cold formed) as well as high strength bolts after exposure to elevated temperatures. Information on stainless steel, cast iron and wrought iron is also presented. Due to the complexity of the issue, an elaborate presentation of the mechanical properties' influencing factors is followed. Subsequently, a wide range of experimental studies is extensively investigated in the literature while simplified equations for determining post-fire mechanical properties are proposed, following appropriate categorization. According to the parametric investigation of the aforementioned data, it can be safely concluded that the most common scenario of buildings after fire events, i.e. apart from excessively distorted structures,

implies considerable remaining capacity of the structure, highlighting that subsequent demolish should not be the case, especially regarding buildings of major importance.

Keywords: post-fire material; structural steel; high-strength bolts; fire-damage assessment; reinstatement; steel structures

1. Introduction

The last decades, the post-fire performance of structural steel elements has attracted many researchers. Although the fire safety of a structure is of paramount importance, the reinstatement of fire damaged structures is in the center of interest nowadays. Since 1960's, the research is focused on the mechanical properties of the material as well as the holistic behavior of the structure, taking into consideration both low strength [1-7] and high strength steels [8-11], while cold-formed [12] and stainless steel [13] have gained considerable attention as well. In particular for cold-formed steel, distinguish from hot-rolled sections is deemed mandatory, taking into consideration the manufacturing process and the sensitivity to stability phenomena.

Despite the recent interest in the post-fire performance of steel structures, an important study published by Kirby et al. [4] in 1986 contributed to the onset of several specifications. Apart from steel features, elevated temperature properties of wrought iron have been documented therein; furthermore, an extensive investigation of the residual properties of cast iron was conducted recently by Maraveas et al. [14].

The mechanical behavior of connections also plays a substantial role in the heating or cooling phase of an axially restrained member. For this purpose, many experimental studies deal with high strength bolt failure after exposure to high temperatures and subsequent cooling down [15-20], to identify both the range and the causes of deterioration. In general, although the mechanical behavior of both structural steel and bolts depends on various factors (such as the steel type, manufacturing process, heating temperature and duration, cooling rate, etc.), the majority of studies indicate that insignificant strength reduction was observed after heating to temperatures up to 500^{o}C. Also, valuable results were observed via experimental fire development on full-scale steel structures. The Swinden Technology Centre conducted a major research project [21], which applies to an eight storey steel framed building, while a cold-formed steel portal frame was tested by Johnston et al. [22]. Both of the studies above, which can be observed in **Fig. 1**, adequately represent the true behavior under fire conditions, aiming to the rational guidance establishment.

Despite the importance of fire design of steel structures, specific guidelines have not been established by the current design codes for the determination of the remaining capacity of steel members after the fire event, with the exception of some recommendations proposed by the British Standards [23], the updating of which is essential since it regards limited steel types and specific fire temperatures. In addition, it is worh to consider that steel members perform differently when as part of a structure, owing to certain force and stress redistribution or materials over-strength, compared to the one of individual members; an important detail which is not taken into account by the present regulations. A characteristic example, which has been verified in the literature through both experimental and analytical studies, is the beneficial effect of secondary structural elements on the overall resistance of the structure, even for cold-formed structural systems.

In most cases, fire damaged structures can be successfully repaired to fulfill their original functions, provided that a reliable appraisal is ensured. It is a common mistake for one to judge insufficiently, influenced by the visual impact, before a proper investigation is followed. Even large distortions can be reversible by special techniques that have been developed hitherto, and they are frequently conducted to members that are partially loaded.

The main aim of this work is to highlight the contribution to the assessment of fire damaged steel structures and their subsequent reuse. Encouraging the engineer to correlate the in-site inspection with the literature review allows a more efficient and comprehensive appraisal.

a) 

b) 

Figure 1. Fire tests in progress, conducted by a) Kirby et al. [21] and b) Johnston et al. [22].

2. Reinstatement of structural behavior after fire

The uncertainties encountered in conducting a fire damage assessment, mainly during the procedure of the in-site investigation, usually lead to conservative decisions, concerning no severely affected structural elements mostly. Moreover, significant redistribution of forces through undamaged parts of the structure from the fire affects the appraisal, the reliability of which depends largely on the experience of the inspector. For such reasons, a well-established guidance accompanying the site visit is considered mandatory.

2.1. Appraisal process

The step-by-step process of the fire damage appraisal is dissimilar to the fire resistant design of structures, which can be followed by prescriptive approaches. **Fig. 2** depicts the reinstatement survey flow chart of steel structures which illustrates the basic steps.

The first crucial point of the study is to collect information about the fire severity. An initial in-site inspection is required to examine the physical evidence, which is described in detail below (section 2.2). Specific measurements are carried out including destructive and non-destructive techniques (section 2.3). Subsequently, the post-fire mechanical properties are evaluated in accordance with results found in the literature (for which a more elaborated study is presented in section 3), while the overall capacity of the structure can be examined by conducting structural analyses (section 2.4). For instance, the excessive resulting displacements can be explained via the proper fire loading simulation. The procedure is completed with the suggestion of the strengthening or the replacement of critical members; some insight information is given in section 4 of the present work.

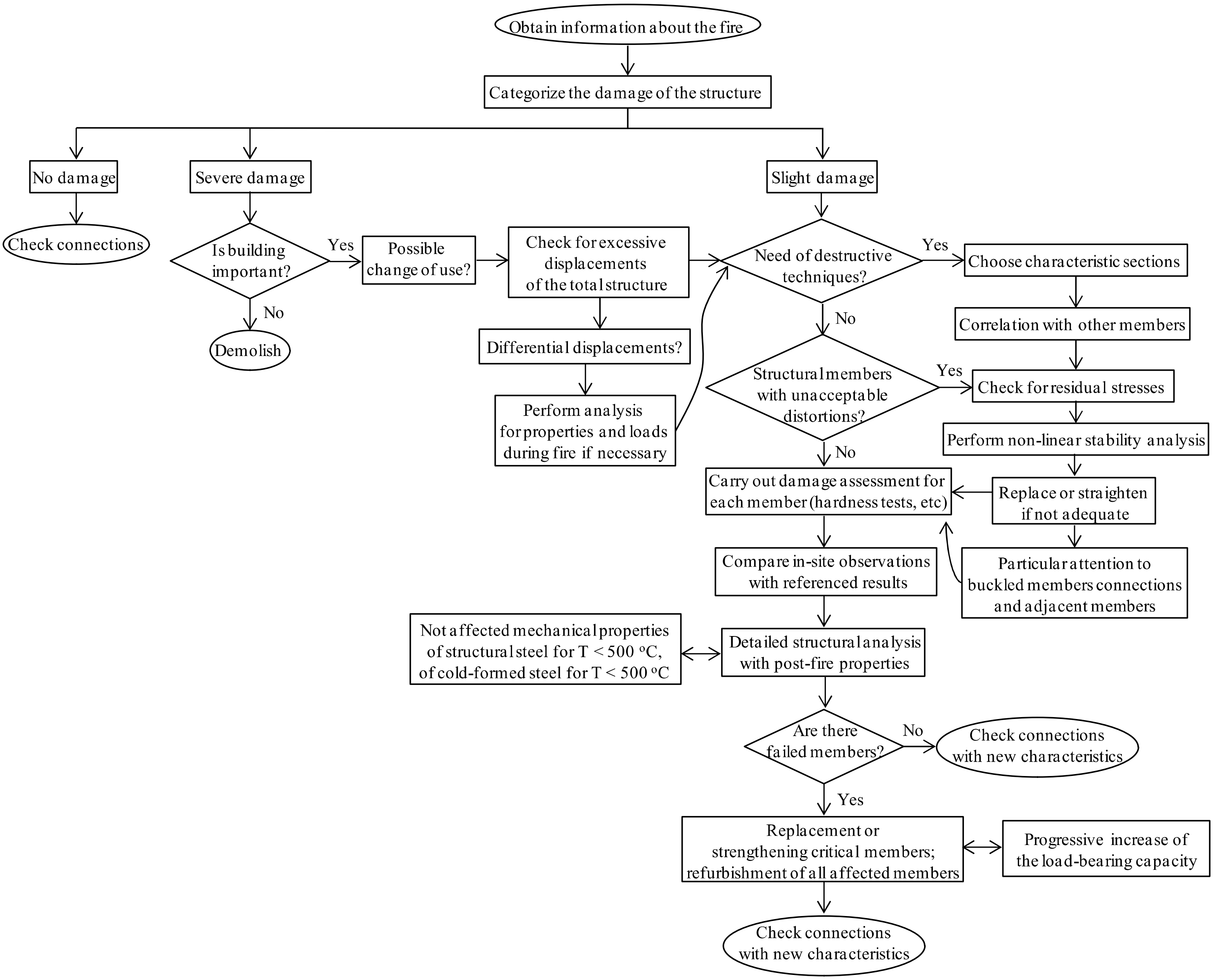


Figure 2. Reinstatement survey flow chart for fire damaged steel structures.

2.2. In-site inspection

As it was aforementioned, fire characteristics (i.e. load, temperature, cooling method, etc.) play a substantial role in the accurate determination of a fire assessment. In case there is no data available, the engineer is advised to identify physical effects that will be visible from the structural elements, such as the glass window first crack (about 150-200°C) or its break out point (over 300°C). An extended survey for several materials is presented in **Table 1** [24].

Table 1. Physical effects of temperatures on various materials [24].

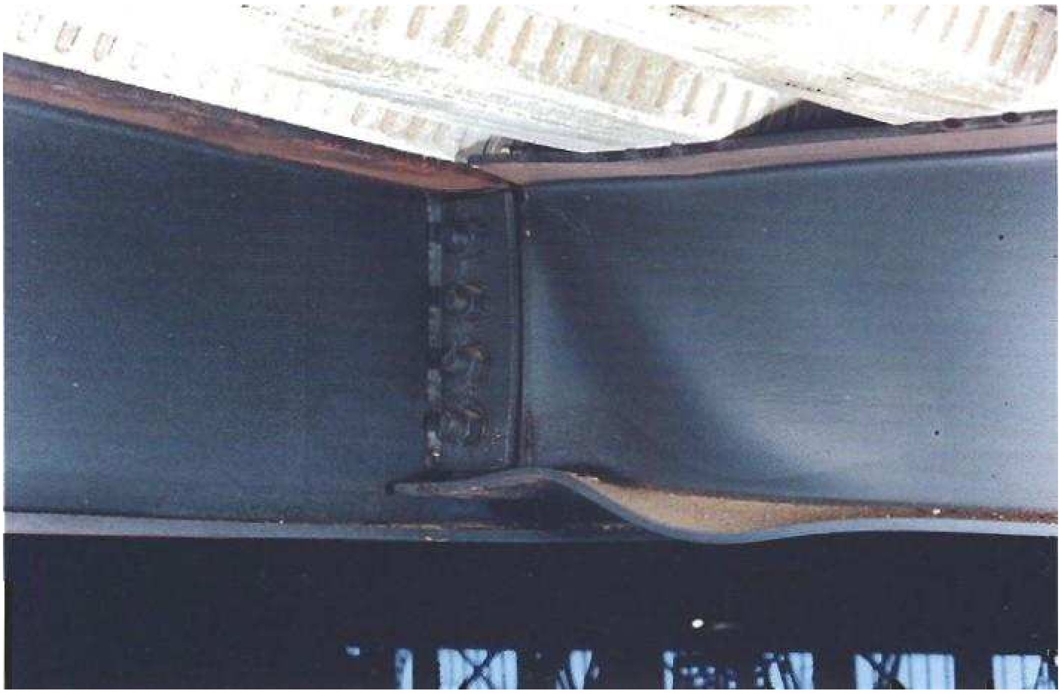
Material	Examples	Condition	Temperature (^oC)
Polystyrene	Foam insulation; light shades; handles	Softens	50-60
	Curtain hooks; radio containers	Melts and flows	120
Polyethylene	Bags; Film	Shrivels	49
	Bottles; buckets	Softens and melts	66
Vinyl-based paints	Structural steel paint	Melts, flows, bubbles, or burns	120
UHMW/HD Polyethylene pipe	Water and waste pipes	Melts, flows, bubbles, or burns	190
Concrete	Structures	Surface crazing; deep cracking	290-590
		Spalling; powdered; light colored	590-950
		Extensive spalling	950
Lead	Plumbing lead; flashing; storage batteries	Sharp edges rounded or drops formed	300-350
Zinc	Plumbing fixtures; flashing; galvanized surfaces	Drops formed	400
Structural steel	Structures	Coarse, eroded surface	560-660
Aluminium	Small machine parts; brackets; toilet fixtures; cooking utensils	Drops formed	650
Molded glass	Glass block; jars and bottles; tumblers; solid ornaments	Softened or adherent	700-750
		Rounded	750
		Thoroughly flowed	800
Sheet glass	Window glass; plate glass; reinforced glass	Softened or adherent	700-750
		Rounded	800
		Thoroughly flowed	850
Silver	Jewelry; tableware; coins	Drops formed	950
Brass	Door knobs; furniture knobs; locks; lamp fixtures; buckles	Sharp edges rounded or drops formed	900-1000
Bronze	Window frames; art objects	Sharp edges rounded or drops formed	1000

In particular for structural steel, as documented by Dill [1], color or surface change can be related to the attained temperature. At temperatures above 650^{o}C, the coarse eroded surface is found, different from the mill rolling appearance. Hence, the inspector should collect evidence before any removal from the elements' surface which can be considered of vital importance to draw conclusions [25].

Simultaneously, the deformation of the entire structure should be monitored in order to categorize the holistic damage, beyond the aesthetic aspects linked to the fire visual impact. In case the damage is indicated as critical, for instance when excessive permanent deflections or stability issues appear, while the building is of low importance, the demolition approval is remained. In all cases, an elaborate damage classification survey should take place. Furthermore, possible change of the building's use, thus the serviceability approval level, can be also proposed. On the other hand, it is expected that horizontal movements are not observed after fire events unless the structural system of the building was not adequately designed in advance. In this case, a structural analysis is highly suggested, also considering the pre-fire condition of the structure. The removal of useless elements can be favorable to the overall capacity, if necessary.

In addition to visual observations, a detailed report is usually followed, where the members are distinguished in three categories of deformation, which is convenient according to Tide [3]: a) straight members that appear unaffected, b) noticeably deformed members and c) severely deformed members.

The observation of fire damaged elements provides to the engineers great insight into the ability of structures to withstand in the fire. For this reason, structural deformations of special interest, created during or after fire events are attached in **Figs. 3-4**. In particular, local buckling of the bottom flange and web folding occurred at a secondary beam (**Fig. 3a**) during the heating and cooling phases of the Cardington multi-storey steel frame test, respectively [21]. Such failure is attributed to the axial rigidity of the adjacent connection, the bolts of which do not seem to be affected. In this case, it is highly recommended for the inspector to check for any possible twisting of the primary beam, as it is observed for the corresponding one in **Fig. 3b**. Another failure that highlights the stress development during the cooling phase is attributed to the shear fracture of the bolts at the fin-plate joints. These facts reinforce the statement that localized damages of key elements may be more critical for the overall stability. Another type of distortion, regarding cold-formed steel frames, is observed in **Fig. 4** [12]. The column under investigation is regarded noticeably deformed (category b); the restoration through heat-straightening works is preferable as opposed to its replacement.

a) 

b) 

Figure 3. Fin-plate connections of secondary beams showing local buckling [21].

Figure 4. Cold-formed steel frame after fire [12].

2.3. Testing methods

Following the preliminary checks, one should examine case-by-case the affected members. Through this step, several techniques can be utilized, containing both destructive and non-destructive operations such as: measurements, hardness tests, liquid-penetrant examination - detecting discontinuities on welds, metallographic observations and tensile tests by removing samples - although it is not considered as preferable. To avoid multi-testing, the depicted results could be correlated with members of the same characteristics.

Special attention should be given to bolted connections nearby distorted members, since it is evident that the members have suffered axial forces beyond the yield strength, most likely during both the heating and the cooling phase. It is worth to mention that bolted moment connections are not designed to carry high axial forces transferred by the beams. Therefore, the stiffer is the connection resisting the axial forces, the more vulnerable the connection can be, as indicated in the previous paragraph.

A hardness test is confirmed as a reliable method by measurements given by Kirby et al. [4]. The same observation is considered for the bolts' behavior assessment, as it has been investigated by Yu [15]. Meanwhile, another important parameter to consider is the hardness measurement, since when it is found high, it implies a warning for the material deterioration [1].

2.4. Desk study

The next phase of the appraisal process is to analyze the results. It is aforementioned that stability analyses are essential for extreme global or local deformations. However, the key role for the steel integrity reinstatement is attributed to the accurate correlation of the results with the corresponding literature. The engineer, taking into consideration the available information of the damaged structure, should be able to establish the residual capacities in the desirable approximation, by adopting the proposed formulas presented in the following section of the current research study.

3. Post-fire properties

To effectively obtain the post-fire properties of structural steel elements, an investigation on the factors that affect the remaining member's capacity should be carried out. The proper distinction of structural steel properties will follow based on the experimental results.

3.1. Influencing factors

Although the interaction of the most influencing factors is obvious, each one of these factors should be examined in isolation to establish a reliable data analysis of fire exposed structural elements. Consequently, a straight forward overview can be adopted for the material exposed and fire characteristics.

3.1.1. Microstructure formulation

It is essential to examine the metallurgical properties of steel. The following analysis is based on Digges et al. [2]. The majority of steel microstructures are formed through the austenite transformation during the cooling phase. The way that austenite decomposes to other microstructures (eg. pearlite, bainite, martensite, ferrite, etc.) is deemed necessary for the complete understanding of the heat treatment of steel. The end product, or the final structure, is greatly influenced by the temperature at which transformation occurs, which in turn is influenced by the cooling rate. Moreover, material science implies that the chemical composition of steel (especially the carbon content) is particularly crucial for the thermodynamics and kinetics of the phase transformations.

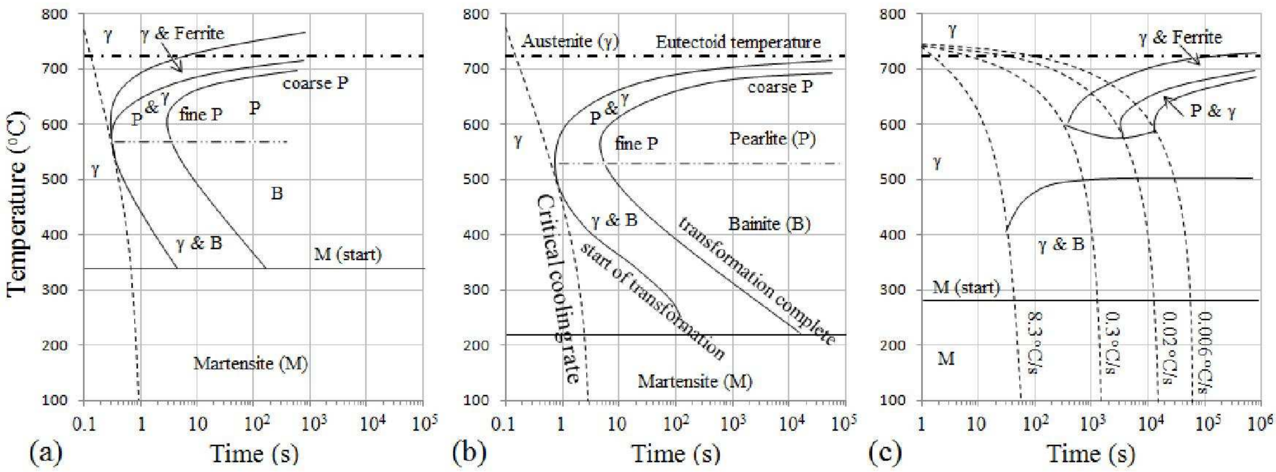


Figure 5. Schematic diagrams illustrating isothermal curves (IT), critical cooling curves and resulting microstructures for a) hypoeutectoid, b) eutectoid and c) alloy steel [26].

Fig. 5 demonstrates the isothermal time-temperature-transformation (TTT) diagrams for three different types of steel: a) hypoeutectoid steel (less than 0.8% 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°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 ($A_{3,max}$=910°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 attributes to the maximum hardness that can be obtained while the transformation can take place by cooling in water (CIW) or in ice. The critical cooling rate for each steel type is illustrated in **Fig. 5**.

In contrast, if austenite decomposes at 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 the air (CIA) or cooling in the furnace (CIF). In most plain carbon steels, bainite will not form on continuous cooling because austenite has already transformed into ferrite and pearlite. CIF is usually applied to produce softening (eg. annealing).

Apart from the identification of the phase transformation, the microstructure characteristics lead to the understanding of the possible conditions during and after the fire event, such as the spheroidizing of the iron carbide, or the change in grain size or morphology.

3.1.2. Cooling method

Heating and cooling effects are considered similar to tempering and annealing techniques during steel fabrication [18]. Therefore, an instant cooling method, for example, cooling in water (which could be a natural fire condition), in conjunction with the aforementioned microstructure alterations, can significantly increase the post-fire properties of steel.

With the aid of tensile tests, it is found that the shape of the stress-strain curve for heated steel coupons after cooling in air or furnace is similar to that obtained from the unheated steel as long as there is no significant change in elongation. For the steel cooled in water, the yield plateau disappears (i.e. lower ductility), while a dramatic increase in strength is obtained. Such behaviors are presented in graphical forms by tests conducted in the literature [7].

3.1.3. Heating duration and maximum temperature

With regards to the heating duration, for a long heating time the temperature inside the steel sample is evenly distributed. Consequently, with the increase of the fire exposure time, the mechanical properties of structural steel are hardly influenced. This observation is confirmed by several experimental results [13,14].

On the other hand, the maximum temperature reached during heating, strongly affected the post-fire behavior. For instance, bolts' tempering temperature is highlighted as a key variable, over which the residual strength reduction begins [15]. Nevertheless, the exceedance of austenising temperature (approximately 700^{o}C) with subsequent quenching, demonstrates enhanced material strength with the simultaneous breaking strain reduction, according to Renner et al. [16]. Finally, the repeated heating, as observed by Chiew et al. [11], demonstrated insignificant effects on the post-fire properties, when same heating and cooling procedures were followed.

3.1.4. Simultaneous loading

It is well known that axially restrained members generate even larger axial forces during thermal loading. This could affect both the structural member and the bolted connection significantly, leading to reducing certain mechanical properties at elevated temperatures. However, this factor is not examined for structural steel by the present work.

The bolt pre-tension loss is considered as a characteristic example [19]. Heating to temperatures lower than 300^{o}C produces a reversible thermal expansion so that the bolt regains its lost pre-tension force. In contrary, heating to temperatures above 300^{o}C, the rapid decrease of mechanical properties in combination with the pre-tension force cause permanent plastic deformations. In the latter scenario, the pre-tension force will be eliminated after such a fire event.

3.1.5. Manufacturing process

The manufacturing process impacts on the residual yield and tensile strength, with the "cold worked" steels showing a great reduction in strength while increasing heat temperature compared to the "hot rolled" steels. Cold-worked and heat-treated structural steel loses its strength more rapidly above 450^{o}C [5]. This may also be the case during welding of cold-formed sections; the strength enhancing martensite phase, which is gained from large plastic deformation and high strain rate at low temperatures (cold-forming), reverts to the lower strength austenitic phase.

To synopsize, 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 significantly.

3.2. *Proposed equations for post-fire properties of structural steel*

Considering the above, it is obvious that there are various 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 177 test results from eight studies [5-9, 11-13], some of which were derived from real fire damages [5], were collected for structural steel, whereas 109 full-range stress-strain curves are available. The initial yield strength, f_y, at ambient temperature and the values of temperatures, T, are in the range of 231MPa to 1045MPa and 100 to 1000°C, respectively. The residual properties were obtained from tension tests on steel specimens after heating and cooling to room temperature via different cooling methods. Furthermore, there is a variety of structural steel types. Hence, a significant difference between test results is expected. The details of the tests are summarized in **Table 2**.

Table 2. Summary of Test Data for Structural Steel.

Source	Number of specimens	Number of curves	Steel type	Average f_y (MPa)	T (°C)	Cooling method
Smith et al. (1981) [5]	54	-	Hot rolled	231-436	100-1000	CIA*
Outinen and Mäkeläinen (2004) [6]	14	-	Cold worked	566	464-538	CIF**
Lee et al. (2012) [7]	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
Chiew et al. (2014) [11]	6	6	Heat treated	773	100-1000	CIA
Gunalan et al. (2014) [12]	30	30	Cold-formed	352-664	300-800	CIA

Wang et al. (2014) [13]	20	20	Stainless	305-623	200-1000	CIF

*cooling in air; **cooling in furnace; ***cooling in water

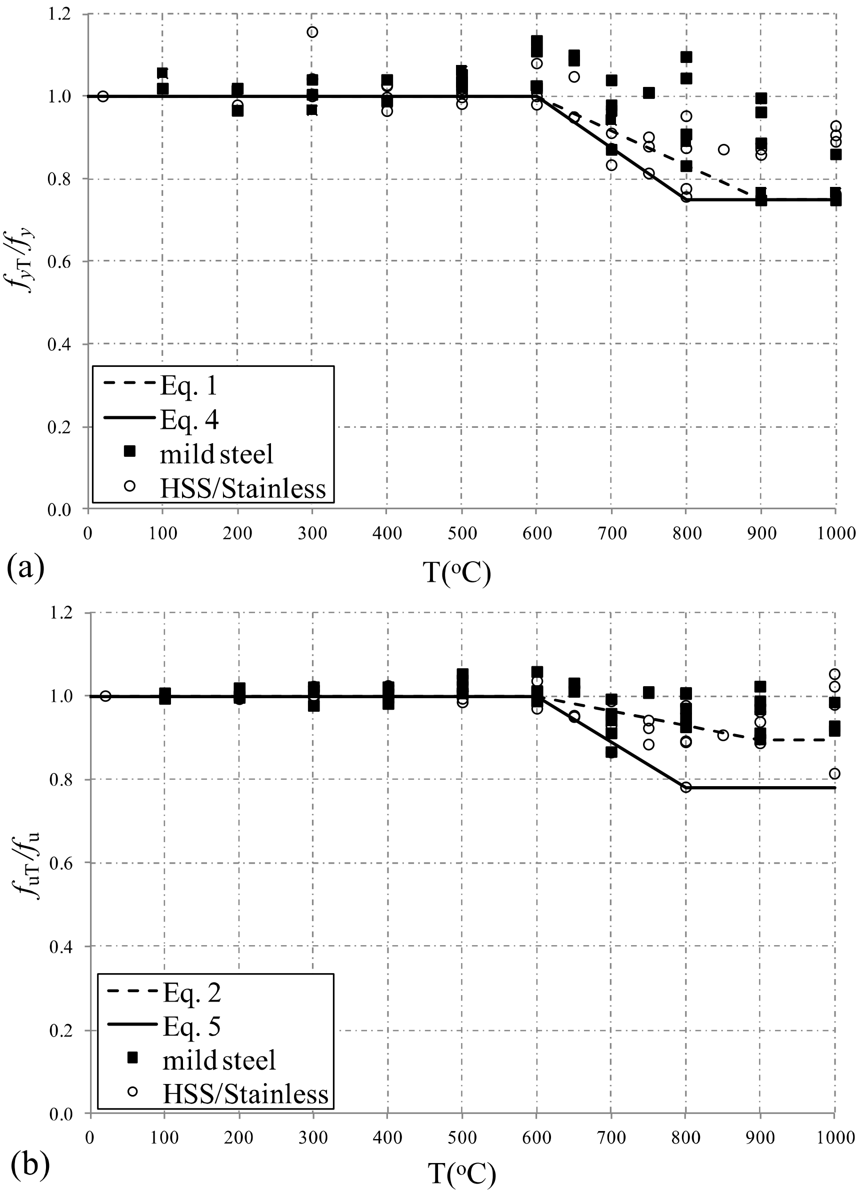
Three major types of structural steel are defined herein, in order to evaluate effectively the post-fire mechanical properties, while considering the manufacturing process: a) hot-rolled steel, b) heat-treated steel, and c) cold-formed steel. Particularly for hot-rolled steel, a minor variation between mild and high strength steel (HSS) is observed.

For instance, the increase of the capacity of low-alloy steels (i.e. mainly vanadium contained) is characteristic for temperatures above 800°C, where austenitization is completed. This also applies to cooling-in-water test results. Consequently, a parametric analysis on the basis of the criteria above deems necessary. For simplicity, linear relationships are suggested for temperatures between 600°C and 1000°C, taking into consideration cooling-in-air test results.

In general, the proposed expressions herein are based on observations according to the graphical representation of the available test data. On that basis, it was preferred to take into account conservative results, without any statistical elaboration. In this way, the designer will be based on computations that will incorporate safety criteria for the remaining capacity of the fire-damaged structural elements. The main factors which lie behind the variation of the test results, making the post-fire properties especially sensitive, are regarded such as: the environmental conditions during each test, the material properties of the coupons, the cooling method, the preload history and the area of the cross-section that the coupons are selected from (eg. flange or the web, corner or flat, etc.). Consequently, to avoid further difficulty and uncertainty in practice, a major categorization for the easier implementation is adopted by the authors.

The experimental ratios of f_{yT}/f_y, f_{uT}/f_u and E_{sT}/E_s for hot-rolled steel are plotted in **Fig. 6**, where f_y, f_u and E_S are the reference yield strength, ultimate strength and elastic modulus (i.e. before the fire exposure), while those with the subscript T are the corresponding temperature dependent values.

Eqs. (1)-(5) define the potential predictions and are compared with the test data. Eqs. (1)-(2) are the most accurate ones according to all test data with mild steel, but sometimes overestimate the strength of high strength steel. Eqs. (4)-(5) are recommended for practical use to determine the residual yield and ultimate strength of high strength, alloy and stainless steel after cooling down from fire temperatures up to 1000°C.



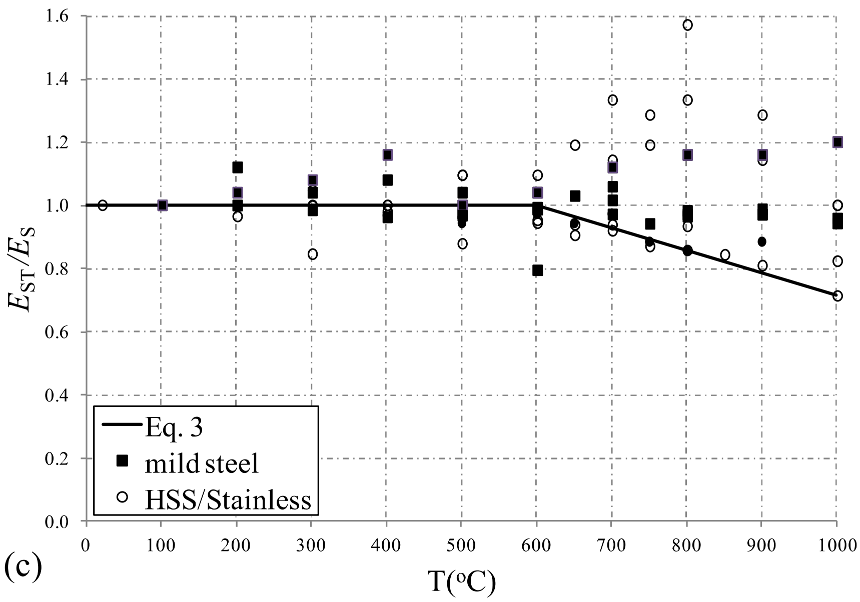


Figure 6. The ratio of a) f_{yT}/f_y, b) f_{uT}/f_u and c) E_{sT}/E_s as a function of temperature for hot-rolled steel.

Residual factors of mild steel:

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

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

Residual yield and ultimate strength of high strength, alloy and stainless steel:

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

Post-fire mechanical properties for heat-treated steel are defined by Eqs. (6)-(8). An obvious difference between cold-formed and heat-treated steel is apparent in terms of yield and ultimate strength [6,12,13]. Therefore, the residual capacities for cold-worked steel and the sudden decrease of which is clearly illustrated in **Fig. 7**, are established by Eqs. (9)-(10), respectively. The comparison of the corresponding equations with the test data is also presented.

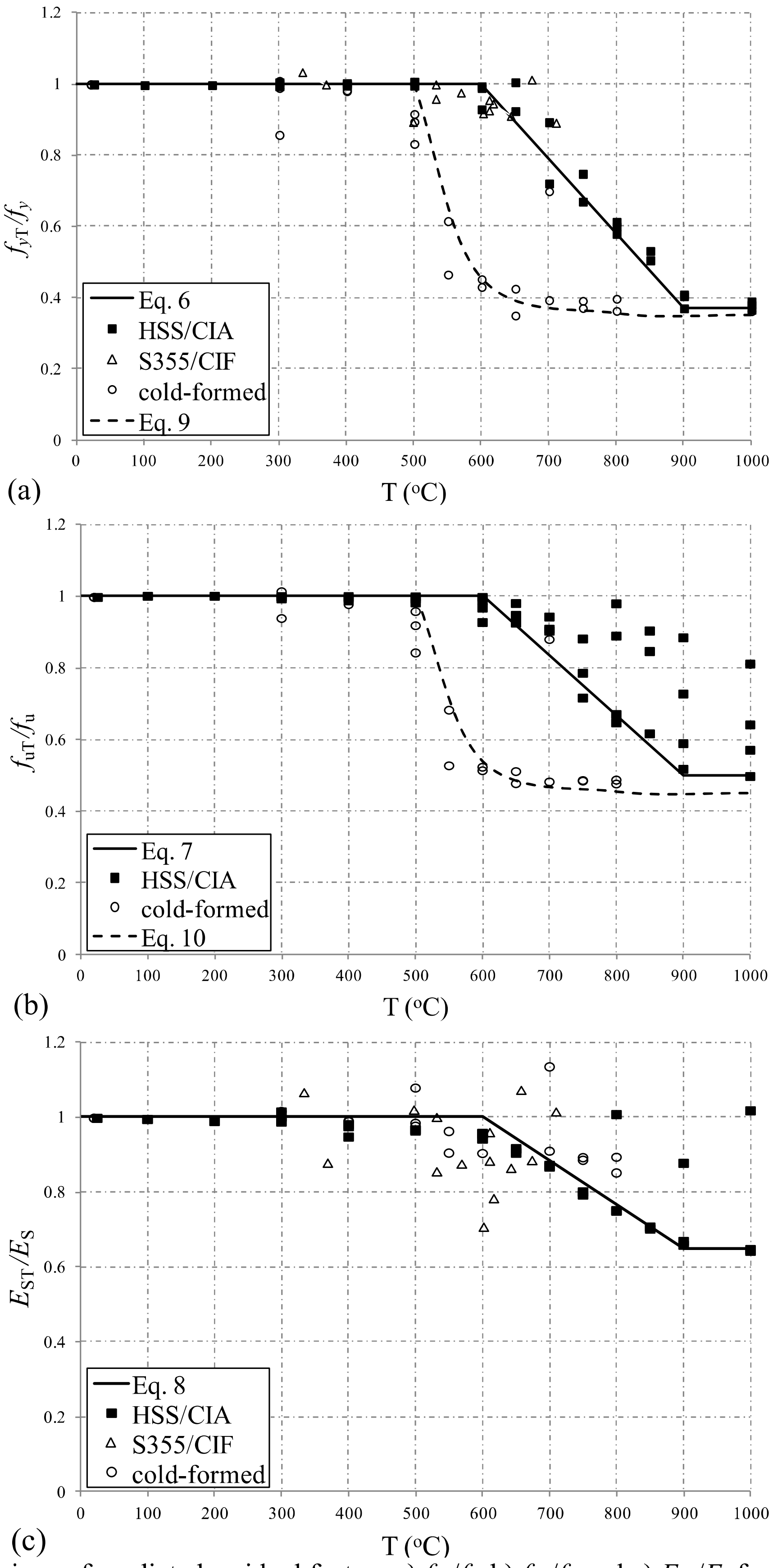


Figure 7. Comparison of predicted residual factors a) f_{yT}/f_y, b) f_{uT}/f_u and c) E_{sT}/E_s for heat-treated and cold-formed steel.

Residual factors of heat-treated steel:

$$\frac{f_{yT}}{f_y}=\begin{cases}1\\2.258-T/480\\0.371\end{cases},\ \frac{f_{uT}}{f_u}=\begin{cases}1\\2.0-T/600\\0.500\end{cases},\ \frac{E_{sT}}{E_s}=\begin{cases}1 & T\le 600^oC\\1.702-T/850 & 600^oC<T<900^oC\\0.649 & T\ge 900^oC\end{cases} \tag{(6)-(8)}$$

Residual factors of cold-worked steel:

$$\frac{f_{yT}}{f_y}=\begin{cases}1\\0.65\cdot(500/T)^{10}+0.35\end{cases},\ \frac{f_{uT}}{f_u}=\begin{cases}1\\0.55\cdot(500/T)^{10}+0.45\end{cases},\ \begin{matrix}T\le 500^oC\\T>500^oC\end{matrix} \tag{(9)-(10)}$$

It is concluded that the post-fire behavior of structural steel is hardly influenced after exposure to temperatures up to 500^{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 25%. The distinction between mild steel and HSS is also stated in Appendix B of British Standards 5950-8 [23], which recommends the reuse of steel grade S235 and S275, following a 10% reduction in the initial strength. On the other hand, for steel grade 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 [5,7,8] (**Fig. 6**). On the other hand it is worth to note that these suggestions are considered as non-conservative for heat-treated [8,9] and cold-worked steel, as the deterioration of the capacity is more significant (**Fig. 7**; residual factors over 35%).

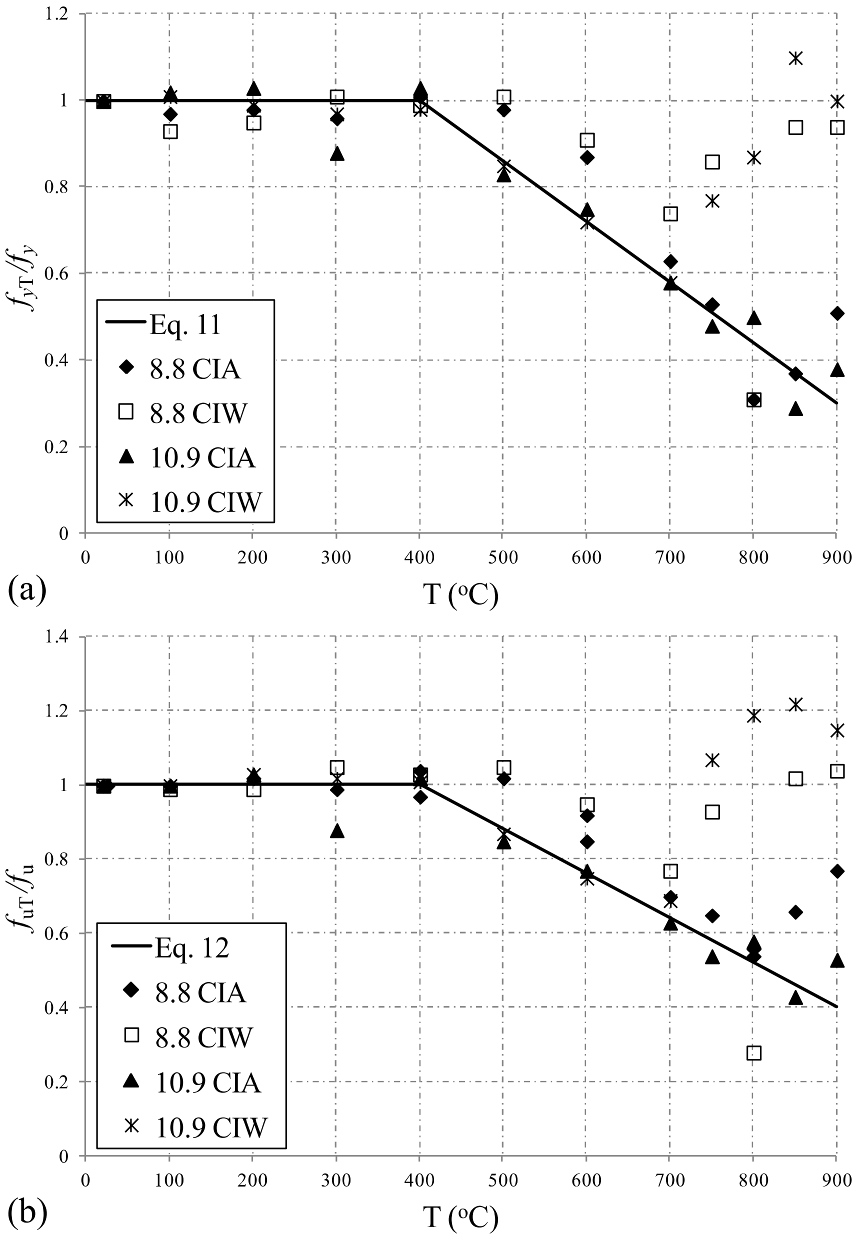
3.3. Proposed equations for post-fire properties of high strength bolts

The same procedure was followed for the high strength bolts' remaining capacity after heating and cooling conditions. Among the experimental results, residual shear strength is established by Yu [15]. The available test data is summarized in **Table 3**.

Table 3. Summary of Test Data for high strength bolts.

Source	Number of specimens	Number of curves	Steel type	Average f_y (MPa)	T (^{o}C)	Cooling method
Yu (2006) [15]	40	-	A325/A490	346*/433*	90-800	CIA
Lou et al. (2012) [18]	24	24	8.8/10.9	837/1130	100-900	CIA/CIW
Hanus et al. (2011) [20]	8	5	8.8	-	400-800	CIA/CIW

*average shear capacity



(a)
f_{yT}/f_y
T (°C)
Eq. 11
8.8 CIA
8.8 CIW
10.9 CIA
10.9 CIW
(b)
f_{uT}/f_u
T (°C)
Eq. 12
8.8 CIA
8.8 CIW
10.9 CIA
10.9 CIW

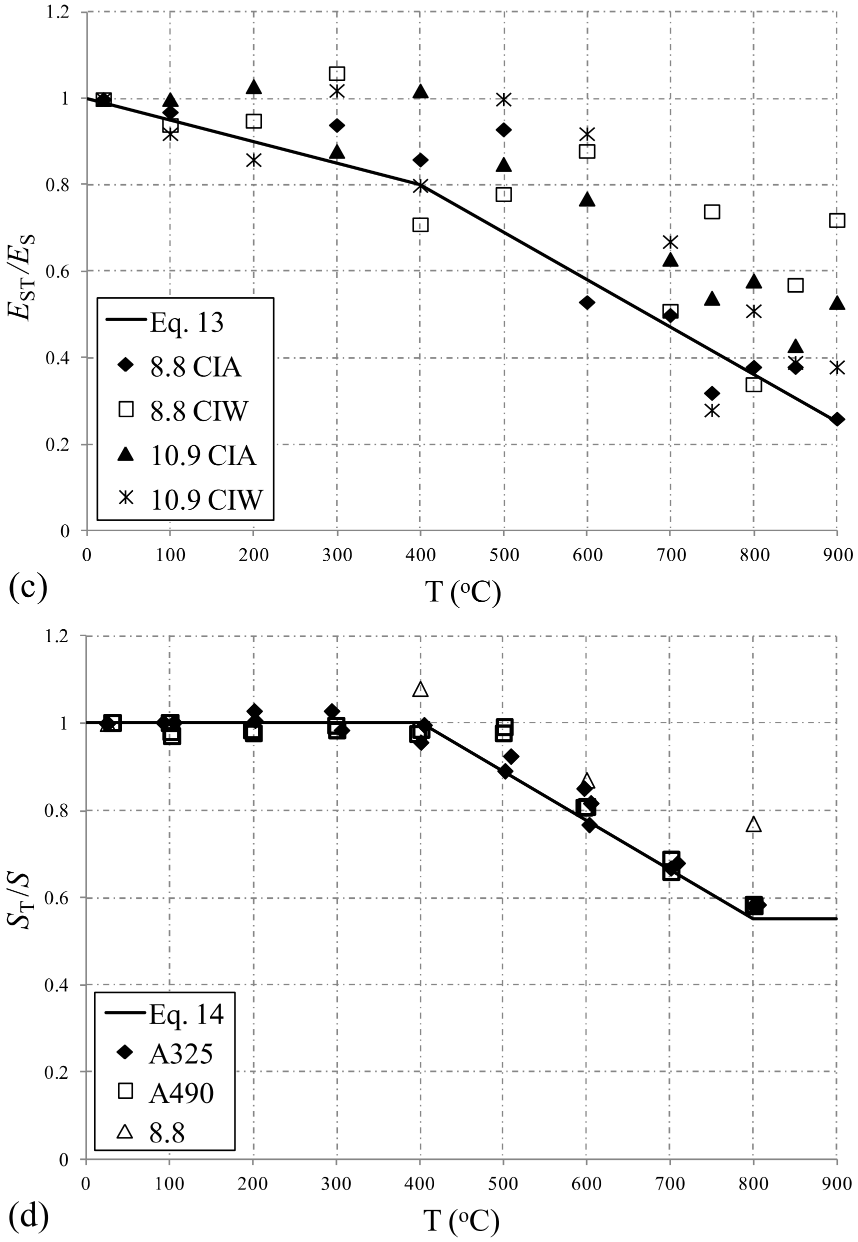


Figure 8. Comparison of predicted residual factors a) f_{yT}/f_y, b) f_{uT}/f_u, c) E_{sT}/E_s and d) S_T/S for high-strength bolts.

The residual factors of a) the yield strength, f_{yT}/f_y, b) the ultimate strength, f_{uT}/f_u, c) the elastic modulus, E_{sT}/E_s, and d) the shear strength, S_T/S, can be obtained from **Fig. 8**. Different bolt qualities (eg. class 8.8 and 10.9) demonstrate similar behavior after the fire event while the mechanical properties' enhancement for the water cooled specimens is easily noticed. The adopted formulas account for the air cooling experimental results, thus the worst case scenario. The proposed Eqs. (11)-(14), which are graphically compared with the test data in **Fig. 8**, indicate that the post-fire properties remain unaffected for temperatures up to 400^{o}C, whereas the mechanical properties deteriorate from 25-55% of the initial ones for temperatures up to 900^{o}C.

Residual factors of high strength bolts:

$$\frac{f_{yT}}{f_y}=\begin{cases}1\\1.56-T/710\\0.30\end{cases},\ \frac{f_{uT}}{f_u}=\begin{cases}1\\1.48-T/830\\0.40\end{cases},\ \frac{E_{sT}}{E_s}=\begin{cases}1-T/2000 & T\leq 400^oC\\1.24-T/910 & 400^oC<T<900^oC\\0.25 & T\geq 900^oC\end{cases} \quad (11)\text{-}(13)$$

$$\frac{S_T}{S}=\begin{cases}1 & T\leq 400^oC\\1.45-T/890 & 400^oC<T<800^oC\\0.55 & T\geq 800^oC\end{cases} \quad (14)$$

According to the literature [15,18] it has been proved that the high strength bolts are more sensitive to elevated temperatures (i.e. greater than 320^{o}C) than the structural steel, as the bearing failure mode changes to bolt shear failure. Interestingly, Lou et al. [19] addressed the issue of slip resistant bolted connections. The results indicated that the increase of the slip factor offsets the pre-load reduction in a way that the bolts exposed to temperatures lower than 300^{o}C, can be reused. More analytically, due to the increase of surface roughness, the slip factor after fire is obtained to increase up to 25% and 70% of the initial value depending on whether or not the blast-cleaning connections are inorganic zincs paint coated, respectively.

Regarding reuse issues, it is suggested that high strength bolts are likely to be replaced when temperatures higher than 400^{o}C are exhibited during the fire event, while hardness tests are recommended for cases of uncertainty. According to the British Standards [23], the bolts' replacement at the main connections is recommended in a conservative manner, when the paintwork has been burnt off, while HS bolts should be replaced "after heating to temperatures in excess of 500^{o}C". Finally, design calculations can be performed for the connection as a whole, taking into account the residual factors proposed herein. In the case that the attained temperatures cannot be observed, important information is also regarded by the deformation of the joint. In general, it is recognized [4] that in most cases the distortion of the member rather than the distortion of the connection is observed, especially for lightweight steelwork such as roof trusses. On the contrary, the effects of both the expansion and contraction of stiffer members induce large normal forces, making the connection more vulnerable.

3.4. Residual strength of cast and wrought iron

Wrought and cast iron materials have been widely used in historical structures [14], the preservation of which should be taken into account after fire events. Their post-fire behavior was observed by Kirby et al. [4]. Nevertheless no experimental data is available nowadays, except the recent results conducted by Maraveas et al. [14]. The work conducted in this paper demonstrates the mechanical behavior of cast iron under high temperatures as well as after cooling to ambient temperature. The results indicate deterioration in capacity only for temperatures between 600°C and 700°C. Oppositely, wrought iron demonstrates the same mechanical behavior after cooling from elevated temperatures [4]. The observations above are graphically displayed in **Fig. 9**.

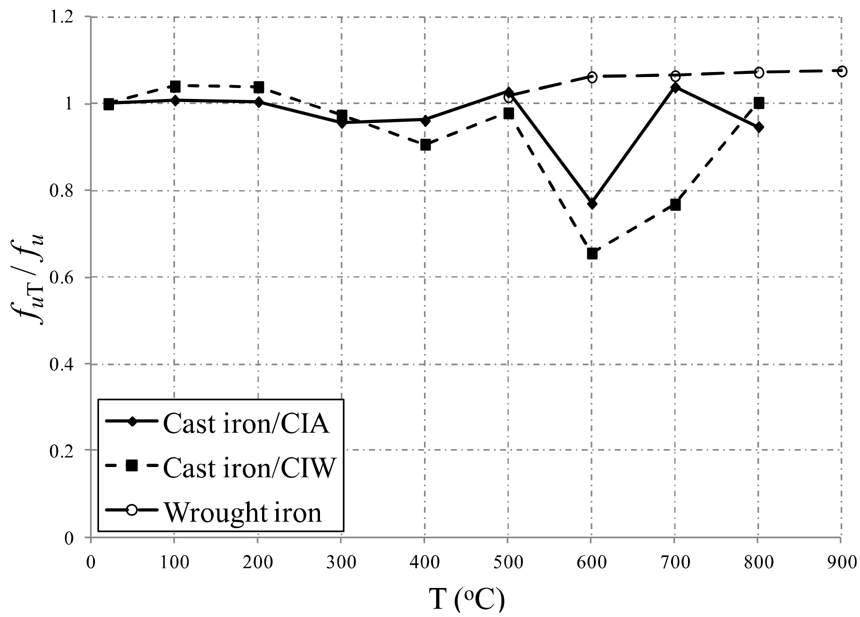


Figure 9. Residual factors f_{uT}/f_u for a) cast iron [14] and b) wrought iron [4].

4. Distorted members

Distorted members may have an effect on either the aesthetic or the structural aspect. Non-linear stability analyses are required, satisfying straightness criteria per the corresponding specifications.

For example, British Standards specify the straightness limitations as 1mm/m of length while the flanges should not exceed the squareness over 5mm [4]. In general, fire damaged steel members should be assessed on the basis of the design codes (Eurocode 3, British Standards, etc.), given that the structure must comply with the existing regulations.

On the other hand, reversibility criteria indicate that in the case that the resultant deformations allow the restoration of the structural element, then the deterioration of the properties is considered insignificant. As Dill [1] has stated in 1960: "*Steel which has been through a fire but which can be made dimensionally re-usable by straightening with the methods that are available may be continued in use with full expectance of performance in accordance with its specified mechanical properties*". To exemplify this, given that the member endures hot working without any damage (eg. fracture), it can be reused. If this is not the case, the replacement is the final alternative.

At final, checking for residual stresses in the adjacent members to the replaced ones is recommended. The repair is completed with the refurbishment of the slightly affected members or bolts and certainly the renewing of any intumescing paint systems.

5. Conclusions

This paper investigates the assessment of the post-fire properties for a large range of structural steel and high strength bolts as well as their subsequent reuse after a fire event. A review of the reinstatement of structural use is unfolded. The engineer is advised to investigate the fire-damaged steel structure via a flow chart while several issues are highlighted for the suitable restoration guidance, the lack of which is noticeable in the existing specifications.

The analysis of the influencing factors indicates the complexity of the problem; for this purpose the micro-structural alterations during elevated temperatures as well as following the cooling down period are thoroughly illustrated. Subsequently, the post-fire properties of the material can be developed using the suggested equations for each type of steel. An extended collection of experimental results is taken into account for various cases of structural steel and bolts that can be encountered in steel building and structures.

In conclusion, it is verified that the residual capacity is not strongly affected until the steel is exposed to certain fire temperatures and then cooled down. In particular, mild, high-strength and stainless 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. Regarding high strength bolts, the capacity reduces only when the temperature exceeds 400^{o}C, before cooling to ambient temperature while the influence of the cooling method is obvious for all cases. The last observation also regards cast iron steel; a brief review of the mechanical behavior is illustrated in a graphical form for the ease of understanding. The reuse of distorted members is documented, in some cases by using repairing methods, provided that the material strength is not deteriorated. The results and recommendations are presented in both graphical and tabular forms, aiming to a better insight of steel behavior after the fire event.

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