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Post-fire mechanical properties of carbon steel and safety factors for the reinstatement of steel structures.

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Abstract

This paper provides guidance on the post-fire material properties and associated safety factors for structural carbon steel which are required for the assessment and retrofitting of existing steel buildings which have suffered and survived a fire. Nowadays, there is a discrepancy between the methodology which is used in the design stage of a building (mostly based on the partial factor method) and the verification methods used after a fire. In the past decade, a number of researchers have published test data and there is more information available on the mechanical properties of steel following a fire. Nevertheless, a statistical evaluation of these results has yet to be conducted although design codes generally adopt a reliability-based approach for the analysis and assessment of buildings. To fill this gap of knowledge, the current article includes a statistical evaluation of the mechanical data from 718 tests collected from 19 peer-reviewed articles and doctoral theses. The study is done for hot-rolled steel, cold-formed steel as well as wrought or cast iron. By focusing on the effect of a fire on the mechanical properties after cooling, which is mostly related to how the coefficient of variation of their distribution increases, adjusted safety factors are proposed together with a reduced reliability index based on economic and social considerations. It is contended that by following this method, possible misunderstandings can be avoided and decisions on the salvage and rehabilitation of structures can be based on performance data and technical analysis, thus reducing the need for individual judgement.

Keywords:

Carbon steel, post-fire, retention factor, existing buildings, statistical approach, safety factor, reliability

1. Introduction

This paper is concerned with the mechanical behaviour of structural carbon steel following exposure to elevated temperature and subsequent cooling. For the majority of structures that survive a fire and can be reinstated afterwards, it is necessary to ensure that they have sufficient strength and stability to survive for the rest of their projected lifetime. The influence of fire on the mechanical material characteristics of the structural elements depends on the material itself, the maximum temperature reached during the fire, the soak time at high temperature and the cooling regime. In the past, there has been considerable research effort devoted to the behaviour of structural materials following a fire, and many researchers have published performance data and even predictive formulae. However, the available data has never been assessed using a reliability-based approach. This means that the data have typically been presented in a deterministic manner, without any statistical analysis. Even the most recent publications [1], [2], [3] which provide very useful information and are based on extensive literature surveys, do not include statistical data analysis.

In this context, the current paper aims to fill this gap by using the available information from the literature and conducting a reliability-based assessment which can then be used in the analysis of structures following a fire to make informed decisions on their future service life. A comprehensive literature review is conducted to collect all available data for different types of steel, from several peer-reviewed papers and doctoral theses. Probabilistic-based codes require that, by preference, uncertainties should be presented based on an array of available, measured, data. Herein, a meta-analysis is used to generate more general applicable retention factors R_θ and to identify and quantify the most salient influential factors. The study comprises carbon steels of various strengths (Table 1), cold-worked or cold-formed steel and cast or wrought irons. Currently, steel grades with a yield strength of up to 2020 MPa are available but the very high strength grades are mainly limited in application to the automotive and aerospace sectors. This investigation is limited to grades ranging from normal strength steels to the highest steel grades used in structural applications, i.e. grades with a yield strength of up to a maximum value of 1200 MPa.

Table 1. Names of steel grades used in this article

Name of subsets	Abbreviation	Yield strength (MPa)	European reference standards
Normal structural steel	NSS	≤ 420	EN 10025-2 to 5 EN 1993-1-1 Table 6.2
High strength structural steel	HSS	> 420 and ≤ 700	EN 10025-6 EN 1993-1-1 and -1-12
Very high strength structural steel	VHSS	> 700 and ≤ 960	EN 10025-6
Ultra high strength structural steel	UHSS	> 960 and ≤ 1200	VDA239-100:2016
Cold-formed steel	CFS	300 up to 550	EN 10049-2
Cast and wrought iron	Cast	≤ 385	EN 10293

For the mechanical properties, the main focus is given to the yield (f_y) and tensile strength (f_u), the ultimate strain (ε_u) and Young's modulus (E). In the design of most new buildings, the yield strength and Youngs modulus are of most significance as these are used in the strength and stability checks, as well as in the determination of deformations. The tensile strength and ultimate strain are included more implicitly in the ductility requirements which is why they are included also in the current analysis.

In this context, the current paper proceeds with a brief description of the state-of-the-art, followed by a detailed description of the methodology which is employed for the statistical analyses. Then, the available test data is presented together with the statistical analyses to assess the post-fire mechanical properties. The whole data set is categorised into six different groups of carbon steel, as given as given in Table 1, which includes the names of the subsets, the strength categories for each group and the relevant European standards.

2. State-of-the-art

The first scientific-based approach relating to the reinstatement of steel structures after a fire was published by Smith et al., in 1981 and this remains one of the most cited and used documents in this field [4]. This article was then updated into an SCI publication [5] and its data was included in Annex B of the former British Standard 5950 Part 8 [6]. However, the data is not included in the current version of Eurocode 3 Part 1-2 and was most likely omitted owing to space restrictions [7]. Nevertheless, the background performance and test data remain relevant and valid and are used in the current paper.

Part 8 of BS 5950 [6] recommends that for the assessment of structural elements following exposure to temperatures greater than 600°C and subsequent cooling, the mechanical properties of structural steel should be limited to a maximum of 90% of the nominal strength values for mild steels S235 and S275 and to 75% for S355. A later erratum recommends that for cold-formed steels up to Z35, the mechanical properties should be limited to 70% of the nominal strength values once they are exposed to temperatures of 300°C or more, followed by cooling [5]. It is generally accepted that steel which has not suffered significant distortions during a fire can be re-used [8] and also that if the steel temperature reaches 650°C, it is likely that the structure has collapsed in any case. When BS 5950-8 was replaced by Eurocode 3 Part 1-2 [7], those rules were removed and the interest of the scientific community in this research area rapidly decreased. It is noteworthy that some of the former British standard clauses can still be found in the Chinese standard CECS252:2009 [9].

Aside from the design standards, other significant works in this field were published by Franssen in 1991 [10], Tide in 1998 [8] and Outinen and Mäkeläinen in 2002 [11]. In the last decade, interest and activity from the scientific community has noticeably increased again, most likely due to the rising importance of sustainability and the re-use of materials, and a number of experimental studies have been published. Most recently, an extensive study of 353 tests was published [1]. Furthermore, another noteworthy contribution [12] includes a framework for the assessment of a structure following exposure to fire, involving 3 distinct stages, as shown in Figure 1 which illustrates the importance of partial factors in the design and assessment of structural elements.

One of the key challenges in the consideration of the post-fire condition of a structure that did not fail and may be classified as reusable is that engineers are dealing with an existing structure, rather than a new design, which is more typical. This complicates the assessment, as illustrated in Figure 1, as all partial safety factors used in the usual semi-probabilistic design approaches have been optimized for new buildings (Stage 1 in Figure 1) rather than existing structures (as are required in Stage 3). It is noteworthy that a rigorous design basis is available [13] to lower the reliability level based on economic and societal aspects, following a fire, and this is investigated later in the current paper.

3. Methodology for the statistical evaluation of test data

A significant amount of test data has become available in the last decade on the mechanical behaviour of carbon steel in the post-fire condition, which provides an ideal basis for the current statistical evaluation. In this section, the procedures that are used in this article to determine the characteristic values of the mechanical properties are first discussed, followed by an overview of the experimental dataset which is used in the analysis. Then, the methodology to derive the post-fire characteristic values taking into account the variability that cannot be assigned to the post-fire situation are explained.

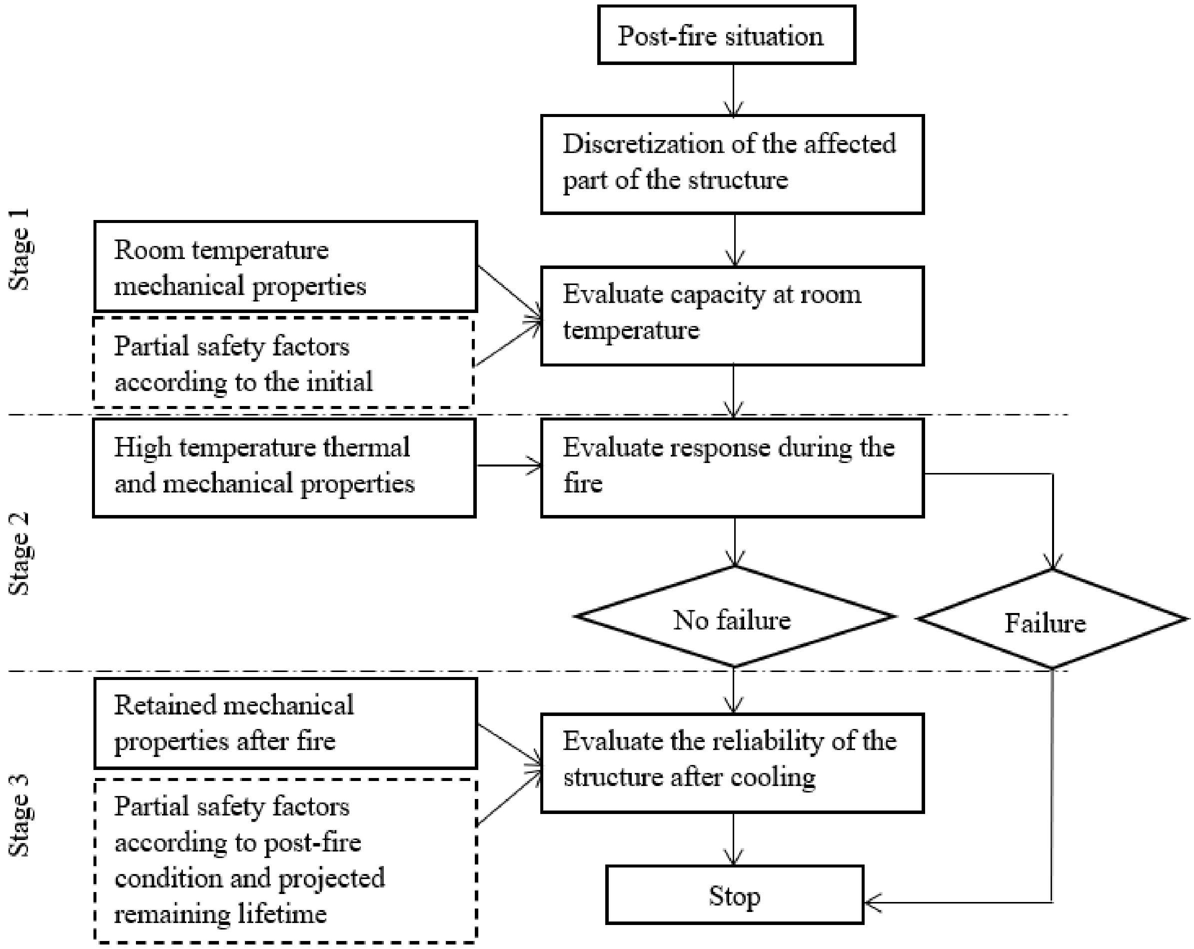


Figure 1 Flow chart illustrating the three stages of assessing the performance of a structure following a fire and subsequent cooling, adapted from [12].

3.1. Characteristic values

This section explains the procedure for obtaining a material property value from test data, in accordance with Eurocode 0 [14] and also elsewhere [15]. The characteristic value of a single property X_k is typically used in combination with an appropriate partial factor (γ_M) from the relevant material code, to determine the design value of the property (X_d).

In this paper, the collected data is processed in a statistical manner using the characteristic fractile factor (k_n) and based on the following assumptions:

- Generally, experimental datasets and their uncertainties can be represented by a chosen distribution combined with specified probability densities, giving the probability that the considered property falls within a specified range of values. The determination of the characteristic values of a single property X_k requires knowledge or selection of the distribution.
- In the current work, it is assumed that all variables follow either a normal (N) or a log-normal (LN) distribution, following the Joint Committee of Structural Safety (JCSS) recommendations (2000). Therefore, the mean value (μ), standard deviation (σ) and coefficients of variation (V) are used to characterize the yield strength (f_y), ultimate strength (f_u), strain at ultimate strength (ε_u) and Young's modulus (E).
- There is no prior knowledge of the value of the mean of the data.
- The use of a conservative upper limiting value of the coefficient of variation is acceptable, in accordance with Eurocode 0 [14]. This value is taken from the JCSS document [16].

In most of the experimental programmes from which results are employed in the current work, tests on the virgin material (i.e. without heating and cooling) are also reported. These results are used as the reference value at 20°C, namely $X_{i,amb}$. However, in some specific cases, this information is not available in the literature and then the relation between the nominal (or code specified) yield strength ($f_{y,n}$) and the mean value of the yield strength according to EN 10025, is determined in accordance with the expression given in Eq. (1) which is taken from the JCSS code of practice (2000):

$$\mu = f_{y,n} \cdot \alpha' \cdot exp(-u \cdot V_{amb}) - C \tag{1}$$

where $f_{y,n}$ is the specified (or nominal) yield strength, α' is the spatial position factor, exp is the natural exponential function and u is a factor related to the fractile of the distribution used to describe the distance between the nominal and mean value, typically found to be in the range of -1.5 to -2.0 for EN 10025 steels. V_{amb} is the coefficient of variation at ambient conditions and C is a constant which reduces the yield strength as given in mill certificate to the static yield strength; a value of C = 20 MPa is recommended [16]. Generally, α' is taken as equal to 1.05 for webs and 1.0 otherwise, to include the additional effect of the rolling direction. A value of 1.05 may be used for plates with a thickness which is less than 10 mm. For specimens taken from a welded hollow section profile, the ratio of f_{ya}/f_{yb} is used for α' in which f_{ya} is the average yield strength including any cold-working effects, and f_{yb} is the yield strength of the base material. In accordance with Eurocode 3 Part 1-3 [17], f_{ya} can be obtained using Eq. (2), in which k has a value of 7 for a rolled section, n_c is equal to 4 for a hollow section with four 90° angles, t is the thickness of the base material, A_g is the gross sectional area of the hollow section and $f_{u,n}$ is the tensile strength of the base material:

$$f_{ya} = f_{yb} + (f_{u,n} - f_{yb}) \cdot \frac{k \cdot n_c \cdot t^2}{A_g} \leq \frac{f_{u,n} + f_{yb}}{2} \tag{2}$$

It is noteworthy that these values are only valid for low-alloy carbon steels which adhere to the requirements of EN 10025 and a specified (or nominal) yield strength ($f_{y,n}$) of the base material up to 380 MPa. In the USA and Canada, 50% higher coefficients of variation on the resistance models are typically used [16].

With the use of a LN distribution for the steel properties, Eqs. (3) to (5) are valid for a coefficient of variation V_{test} between 0.0 up to 0.20. In the following equations $X_{test,i}$ represents the property that is being considered with the subscripts y, u, ε_u and E indicating when f_y, f_u, ε_u or E, respectively, is being discussed.

$$\mu_x = exp\left(\frac{\sum_{i=0}^{n} \ln\left(X_{test,i}\right)}{n}\right) = exp\left(\mu_y\right) \tag{3}$$

$$\sigma_y = \sqrt{ln(V_{test}^2 + 1)} \approx V_{test} = \frac{\sigma_x}{\mu_x} = \frac{1}{\mu_x(n-1)} \sum \left(X_{test,i} - \mu_x\right)^2 \tag{4}$$

$$X_k = exp\left(\mu_y \pm k_n \sigma_y\right) \approx \mu_x \cdot exp\left(k_n \sqrt{ln(V_{test}^2 + 1)}\right) \approx \mu_x exp(k_n V_{test}) \tag{5}$$

In these expressions, $X_{test,i}$ is an individual test result from test i, n is the number of tests which have been conducted and μ_x is the mean.

The value of the characteristic fractile factor k_n is determined in accordance with Eurocode 0 [14] and its value with respect to the number of tests n is illustrated in Figure 2 for a distribution where V_{test} is known a priori. A minimum conservative value of 1.645 as proposed by other researchers [15] is employed herein.

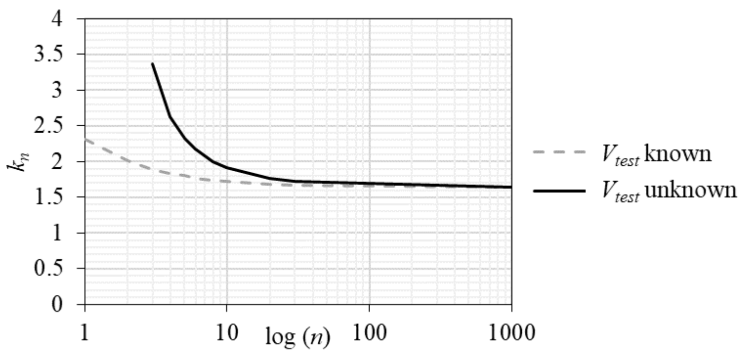


Figure 2. Characteristic fractile factor according to EN 1990 annex D [14].

An upper estimate for the coefficient of variation V_{test} cannot be derived based on mathematical considerations and therefore some engineering judgement and professional expertise are usually needed [15]. Some guidance is provided by the JCSS code of practice [16] and a series of coefficients of variation based on tests executed under ambient conditions (V_{amb}) are proposed, as given in Table 2. However, as previously mentioned, these mean values and coefficients of variation are only valid for low alloy structural steel without heat treatment and which adhere to the product standard EN 10025 [18]. The values are relevant for the nominal material properties given in Table 2, where B is a factor equal to 1.5 for structural carbon steel, 1.4 for low alloy steel and 1.1 for quenched and tempered steels. In general, the coefficient of variation at ambient temperature (V_{amb}) is relatively low and therefore the difference between a normal (N) and lognormal (LN) distribution is hence negligible.

Table 2. Mean values and coefficients of variation for the main material properties according to JCSS [16]

Property	Mean value μ	V_{amb}
f_y	$f_{y,n} \cdot \alpha' \cdot exp(-u \cdot V_{amb}) - C$	0.07
f_u	$B \cdot f_{u,n}$	0.04
ε_u	$\varepsilon_{u,n}$	0.06
E	E_n=210 GPa	0.03

According to the classification procedures for carbon steels, when a particular structural steel does not meet all of the specified mechanical conditions for a particular grade, it is downgraded to the next classification which can result in remarkable overstrength for some materials. The codified nominal values are therefore the minimum values, and many carbon steel grades exhibit considerable overstrength. That has been extensively demonstrated through a number of testing programmes (e.g. [19, 20, 21, 22].

To illustrate the conservatism of the values of V_{amb} in Table 2, they are compared to the values from one of these test programmes [21], and the results are given in Table 3. Clearly, as this test programme included a large number of experiments, very low scatter is achieved. Also, it is worth noting that V_{amb} decreases for higher grades of structural steel.

Table 3. Mean values and coefficients of variation for the main material properties according to [21]

Property	Grade	Mean value μ	V_{amb}
f_y	S235	$1.25 \cdot f_{u,n}$	0.055
	S355	$1.2 \cdot f_{u,n}$	0.05
	S460	$1.15 \cdot f_{u,n}$	0.045
f_u	S235	$1.2 \cdot f_{u,n}$	0.045
ε_u	S355	$1.125 \cdot f_{u,n}$	0.0325
E	S460	$1.1 \cdot f_{u,n}$	0.0325

3.2. Reduction of mechanical properties during fire and recovery following subsequent cooling

Overview of all available data

A large data set comprising the results in 19 peer-reviewed journal papers and doctoral theses are included in the current study, and these are summarized in Table 4. This includes a total of 718 individual tests on with different grades of carbon steel, mostly used in structural applications, including materials from Europe (S grades), Australia (also known as S grades), China (Q grades) and North America (A grades). Cold-formed galvanized sections are also included (G grades in the table). Some experiments on new or historical cast and wrought iron sections are also included to extend the application domain to existing old structures or those containing cast elements (mostly connections). It is noteworthy that a similar analysis has also been conducted on structural stainless steel and this information is available elsewhere [23].

In Table 4, each reference is characterised by a set number, its year of publication, a subset number, the corresponding steel grade, soak time during which the specimen is kept at elevated temperature and the cooling regime. A number of different cooling regimes are employed including specimens that are cooled in air (CIA), cooled in the furnace (CIF), cooled in blanket (CIB) and cooled in water (CIW). The labels LPG and Elec indicate if the specimens were heated in a liquefied petroleum gas furnace or an electrical furnace, respectively, where this information is available. The reality and influence of cooling patterns following a real fire is usually unknown and parts of the structure may cool differently (actively or passively) to others.

Table 4. Details of the test data

Authors	Set number	Year	Subset reference	Corresponding steel grade	Soak time	Cooling regime
				(MPa)	(h)	
Smith et al. [4]	1	1981	0	Wrought		CIA
			1	S235-355JR		CIA
			2	S235-355JR	1.00	CIA
			3	S235-355JR	4.00	CIA
Outinen, [24]	2	2007	4a	S355J2H		CIF
			4b	G350Z		CIF
J. Lee, [25]	3	2012	5	A992 = S345	1.00	CIA
			6	A992 = S345	1.00	CIB
			7	A992 = S345	1.00	CIW
Qiang et al. [26]	4	2012	8	S460NL	0.17	CIA
			9	S690QL	0.17	CIA
Qiang et al. [27]	5	2013	10	S960QL	0.17	CIA
S.P. Chiew et al. [28]	6	2014	11	S690RQT	0.17	CIA
Gunalan et al. [29]	7	2014	12	G300	1.00	CIA
			13	G500-550	1.00	CIA
W. Wang et al. [30]	8	2018	14	Q460	0.33	CIA
			15	Q460	0.33	CIW
Lu et al. [31]	9	2019	16	Q235-420	0.50	CIA
			17	Q235-420	0.50	CIW

H.T. Li, B. Young's [32]	10	2019	18	S690	0.33	CIF
			19	S960	0.33	CIF
H Zhou et al. [33]	11	2019	20	Q690	0.50	CIA
			21	Q690	0.50	CIW
Y. Cai, B. Young's [3]	12	2019	22	G450-550	0.25	LPG/CIF
			23	G450-550	0.25	Elec/CIF
X-Q Wang et al. [2]	13	2020	24	S690QT	0.5 -4	CIA
			25	S1070QT	0.5 -4	CIA
			26	S690QT	0.5 -4	CIF
			27	S1070QT	0.5 -4	CIF
			28	S690QT	0.5 -4	CIW
			29	S1070QT	0.5 -4	CIW
F. Azhare et al. [34]	14	2017	30	S1200		CIA
F. Azhare et al. [35]	15	2018	31	S1200		CIW
C. Siwei et al. [36]	16	2017	32	Q690		CIA
Z. Chen et al. [37]	17	2016	33	Q460-650	0.33	CIA
			34	Q835	0.33	CIA
			35	Q460-650	0.33	CIW
			36	Q835	0.33	CIW
J. Lu et al. [38]	18	2017	37	G20Mn5N	0.33	CIA
			38	G20Mn5QT	0.33	CIW
C. Maraveas et al. [39]	19	2015	39	Cast		CIA
			40	Cast		CIW

Figure 3 presents the post-fire experimental results together with the reduction factors for the yield strength $k_{y,\theta}$ and elastic modulus $k_{E,\theta}$ as given in Eurocode 3 Part 1-2 [7]. Each colour in the figures represents the results from a different test programme.

The temperature reached during the fire and the soak time have important implications on the mechanical properties. The reference temperature is the maximum temperature kept constant for at least 10 minutes (if recorded, as shown in Table 4). The data is rounded down to the 20°C increment, so a heating temperature of 505 °C, for example, belongs to the 500°C dataset. Although there is a large data set with 718 test results, the number of data per heating temperature and per group remains limited (< 22 for each case considered and a minimum of 2). In addition, metallurgical transitions can take place in the steel with important implications on the mechanical properties. It is noticed that, on some occasions, a higher heating temperature results in a better post-fire property for example, the ductility of tie rods [37] or cold-formed profiles [32] which increases.

The dashed lines are employed for the reduction of the material properties when the temperature rises whereas the dots represent the recovery of these properties after cooling. The values are plotted versus the maximum temperature achieved and maintained during each experiment. It is noteworthy that reduction factors for the ultimate strength and ultimate strain are not provided for carbon steel in Eurocode 3 [7]. All of the test data $X_{test,i}$ are normalized by the corresponding property value at ambient temperature (20°C) $X_{i,amb}$. The elastic modulus values are normalised to a nominal ambient value of E_n = 210 GPa.

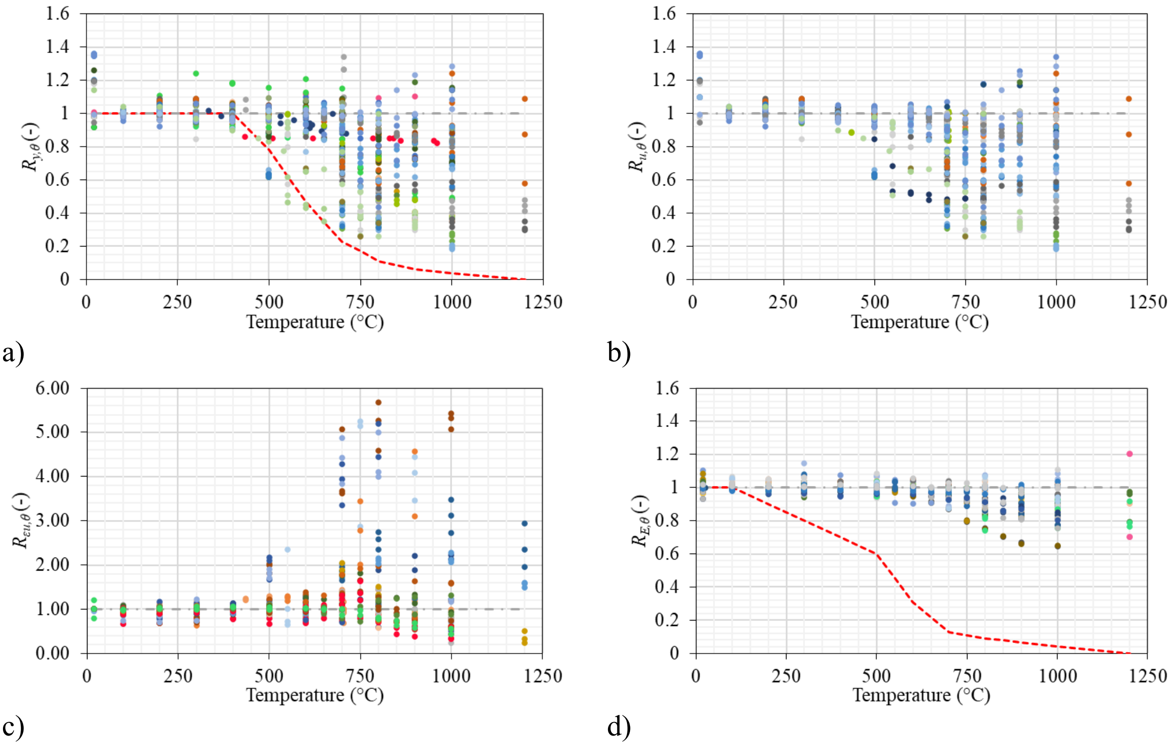


Figure 3 Summary of all test results: a) yield strength, b) ultimate tensile strength, c) ultimate strain and d) Young's modulus after cooling down (dots). Each colour represents one reference. The reduction factors $k_{y,\theta}$ and $k_{E,\theta}$ during heating following [7] are the dashed line.

Reference tests under ambient conditions

As previously discussed, steel samples are sometimes downgraded if they do not completely comply with specific requirements in the material standards. This can have a significant impact on the population homogeneity and hence cause problems with the consistency of statistical distributions. To evaluate this effect i.e. to see if higher coefficients of variation are observed for a series of steel samples, all test results in ambient conditions are collated and verified against the yield strength mean values. The mean value for each data set is estimated using Eq. (1), based on the nominal yield strength.

In accordance with the Probabilistic Model Code [16], some studies propose that a fixed value of the standard deviation is employed rather than the coefficient of variation V_{amb}. In the current work, Eq. (1) may be employed for yield strengths up to 380 MPa, using the values given Table 2 of rolled steel sections are employed (i.e. V_{amb} = 0.07). Since other estimation methods are not available, this value is also applied to all other grades under consideration, as it provides a conservative representation for higher grades of steel. Figure 4 presents the ratio of the measured yield stress $f_{y,test,amb}$ to either the mean value (if several samples were tested in ambient conditions) or the previously described estimation of the mean yield stress versus the nominal yield strength $f_{y,n}$, for the ambient data included in the references listed in Table 3.

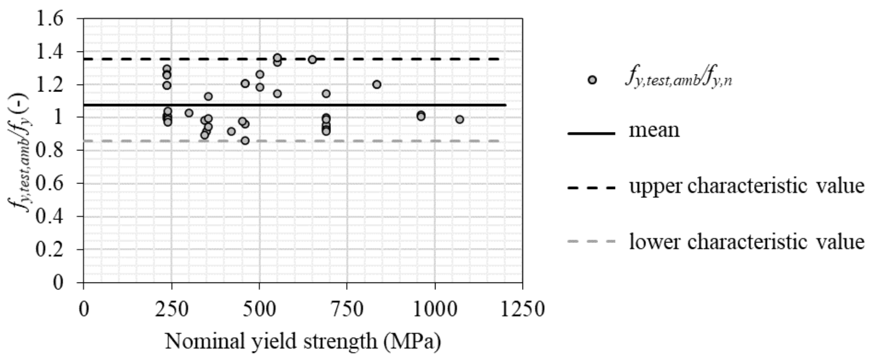


Figure 4. Ratio of test result to mean value versus nominal yield strengths.

Based on these test results, the coefficient of variation for the whole dataset at ambient temperature V_{amb} is found to equal 0.14, with a value of 0.12 for grades of carbon steel with a yield strength of below 420 MPa and up to 0.15 for higher strength grades. This is clearly quite high compared to the proposed value of 0.07 for rolled sections and even in contradiction with the data previously described in Table 3. However, this data is based only on European steel grades [21], whereas the data given in Figure 4 considers a wider set of results. This point is addressed in more detail later in this paper when all grades are discussed. Therefore, in the current work, dividing the single property $X_{test,i}$ by its corresponding measured value at ambient temperature is the preferred methodology, if this information is available.

Reference post-fire tests

With reference to Figure 3, a number of interesting post-fire particularities are observed:

- As highlighted previously, considerable overstrength can sometimes be observed in Figure 3(a) where the normalised yield strength without heating is also provided.
- Carbon steels recover most of their properties after cooling down, as long as there was no initial heat treatment involved in their production processes (as it is the case for ultra high strength carbon steels) or changes in their microstructure. Figure 3 shows that after a fire where the steel temperatures reach 500°C, the materials seem to regain most of their mechanical properties, and this is valid for all of the considered grades. For Young's modulus (E) however, the recovery is complete until around 600°C as shown in Figure 3(d).
- The scatter in the results appears to increase significantly at temperatures above 500°C. Uncertainty in the results are reflected not only in the characteristic values but also in an increasing safety factor.
- The normalised tensile strength (f_u) after cooling down as shown in Figure 3(b), shows a more uniform distribution than the corresponding results for the yield strength. This is largely attributed to the fact that f_u is much less affected by strain hardening at high temperature compared with f_y.
- The normalised ultimate strain (ε_u) after cooling down as presented in Figure 3(c) is quite constant until a temperature of about 800 °C. This is discussed in more detail elsewhere in this paper.

The graphs presented in Figure 3 represent the retention factors $R_{y,\theta}$, $R_{u,\theta}$, $R_{\varepsilon u,\theta}$ or $R_{E,\theta}$ for yield strength, ultimate strength, ultimate strain and Young's modulus, respectively, at a temperature θ (°C), given as the value of the considered property after a full cycle including heating to a temperature θ (°C) and then cooling down, normalized by its value at ambient temperature before the cycle. R_θ is the product of the reduction factor $k_{y,\theta}$ (or $k_{E,\theta}$) and a new factor named herein as the recovery factor $r_{y,\theta}$ (or $r_{E,\theta}$) (i.e. $r_\theta = R_\theta/k_\theta$). The recovery factor r_θ may achieve values higher than 1.0 when the properties are fully recovered after cooling down, as shown in Figure 5.

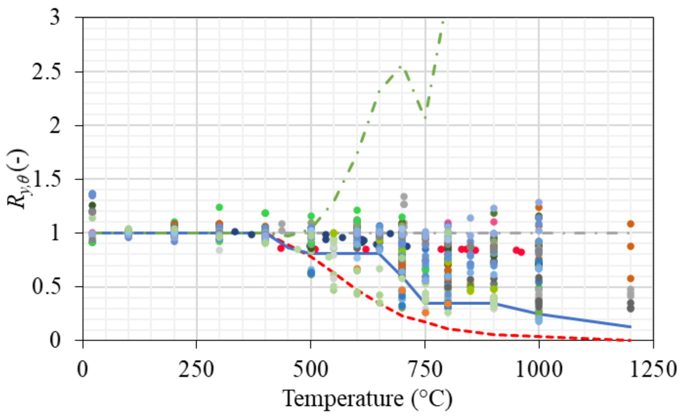


Figure 5. Illustration of reduction, recovery and retention factors for the yield strength for all of the structural steels.

Figure 4 illustrates that the coefficient of variation V_{amb} of the virgin material without having yet been subjected to heating and cooling is not negligible. To evaluate the modification of this coefficient after being exposed to fire, namely $V_{post,\theta}$, it is assumed that both V_{amb} and $V_{post,\theta}$ are related as expressed in Eq. (6). This leads to an expression for the characteristic value of the considered property, as given in Eq. (7). Clearly, $V_{post,\theta}$ cannot be lower than zero and V_{amb} is limited (cannot be lower than) to the previously chosen value of Table 2 from the JCSS code [16].

$$V_{test,\theta}^2 = V_{amb}^2 + V_{post,\theta}^2 \tag{6}$$

$$X_{k,post,\theta} = X_{k,\theta} = exp\left(\mu_{post,\theta} \pm k_n\sqrt{\left(V_{test,\theta}^2 - V_{amb}^2\right)}\right) \tag{7}$$

However, a very limited number of tests and/or a high standard deviation can lead to unrepresentative deviations. To avoid this, the proposed retention factor R_θ is adjusted by an operator in accordance with Eq. (8) where *θ-1* and *θ+1* are the preceding and following temperature intervals which has the effect of (i) forcing a decrease in the retention factor and (ii) removing the influence of outlying values, by comparing it to the averaged value of its neighbouring intervals. The maximum of both is retained. This process is illustrated in Figure 6. The method, as described above, is purely analytical and unbiased by some engineering judgement.

$$R_{\theta,i} = min\left(R_{k,\theta-1,i}; MAX\left(R_{\theta,k,i}; \frac{R_{k,\theta-1,i} + R_{k,\theta+1,i}}{2}\right)\right) \tag{8}$$

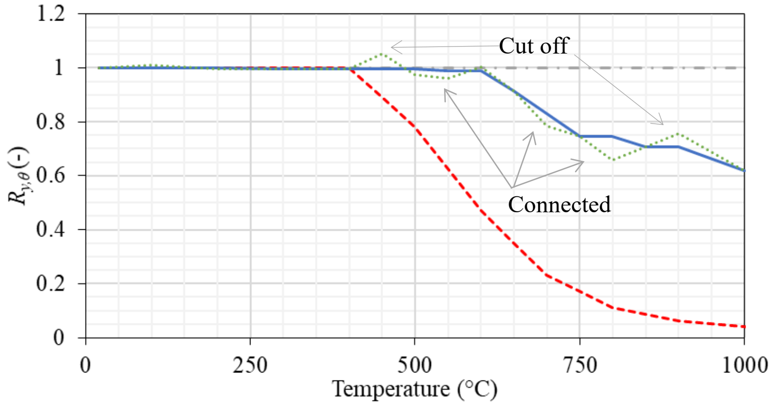


Figure 6 Illustration of the operator effect to obtain the proposed retention factors for the yield strength $R_{y,\theta}$ using calculated raw data (before correction) as well as processed data.

The harmonizing or flattening effect of this operator is illustrated in Figure 7, depicting all collated results for f_y with the calculated characteristic values based on Eq. (7) (dotted line) as well as the corrected characteristic value (solid line).

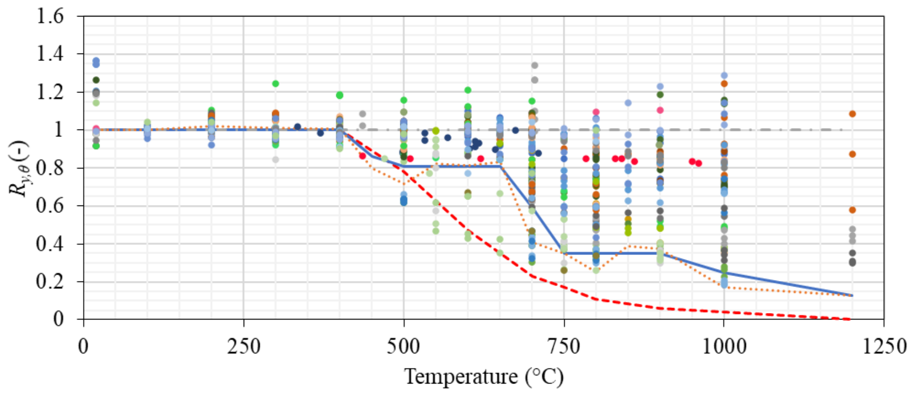


Figure 7 All structural steel test results for the yield strength. Illustration of the operator effect to obtain the proposed retention factors $R_{y,\theta}$.

4. Retention factors

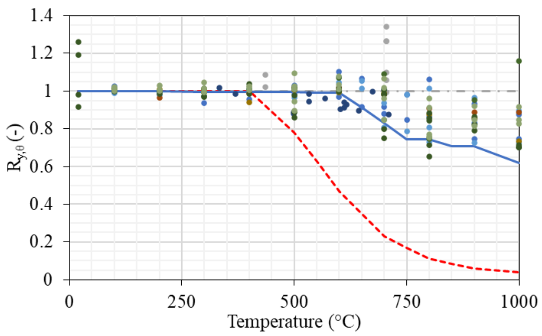
In this section, each classification of carbon steel is discussed in terms of its recovery of strength and stiffness following exposure to elevated temperature and subsequent cooling. In the following figures, the retention factor R_θ is presented as a solid line (with an additional subscript denoting the considered mechanical property). Additionally, the reduction factors of the base material for the yield strength $k_{y,\theta}$ and elastic modulus $k_{E,\theta}$ in accordance with Eurocode 3 Part 1-2 [7] are also presented as a dashed line. For easy identification of outliers, some subset numbers (and their corresponding colours) are highlighted directly on the appropriate graphs.

4.1. Normal strength structural steel

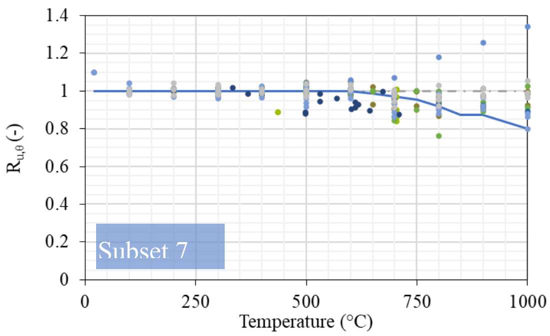
Normal strength structural steel (NSS) is defined as steel with a yield strength between 235 and 420 MPa, as defined in Eurocode 3 Part 1-1 [40]. The set of available data is limited to 184 tests in total, from which 11 tests in ambient conditions are available, as shown in Table 5. Also included in the table are V_{test} and V_{amb} which are the measured and lower bound values of the coefficient of variation of the virgin material, respectively, without having yet been subjected to heating and cooling. For the lower bound terms, the values given in Table 2 will always be used, which are the basis of the actual safety factors at ambient temperature in European codes. A significant degree of scatter is observed and therefore it is concluded that not all steels included in these test programmes satisfy the EN 10025 product standard. This is attributed to the practice of under-grading carbon steel if it does not meet the requirements for a higher grade as discussed previously. Of course, this has the effect of significantly increasing the corresponding coefficient of variation. The retention factors for the yield strength, ultimate tensile strength, ultimate strain and Young's modulus are presented in Figure 8.

Table 5. Normalized properties of normal structural steel in ambient conditions.

	$f_{y,test}/f_{y,n}$	$f_{u,test}/f_{u,n}$	ε_u	E_{test}/210 MPa
	(-)	(-)	(%)	(-)
Number of tests	11	11	10	6
Mean	1.05	1.10	1.00	0.98
V_{test}	0.12	0.01	0.04	0.01
V_{amb}	0.07	0.04	0.06	0.03



a)



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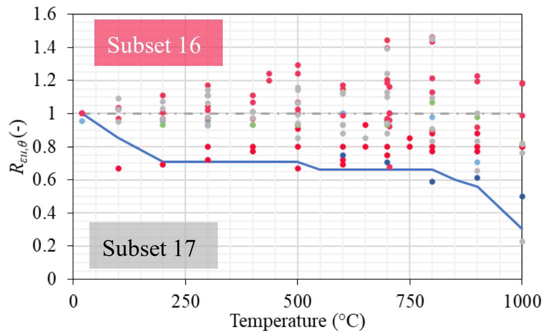

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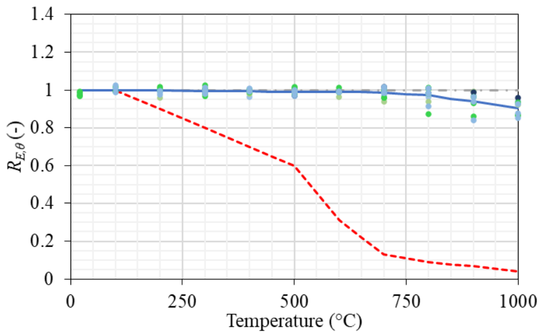


d)

Figure 8 Summary of normal strength structural steel test results including a) yield strength, b) tensile strength, c) ultimate strain and d) Young's modulus after cooling down (dots).

With reference to the data presented in Figure 8, the following observations and conclusions are deduced:

Yield strength:
The yield strength retention factor $R_{y,\theta}$ as shown in Figure 8(a) shows a clear descending trend from approximately 600°C to 0.75 at 750°C. All of the subsets show similar general behaviour including a stepwise function which can be approximated by a linear function starting from 600°C, with a retention factor of unity, reducing to a value of 0.62 at 1000°C.

Ultimate strength:
It is observed in Figure 8(b) that the influence of exposure to elevated temperature on the post-fire ultimate tensile strength is rather limited. The retention factor for the tensile strength $R_{u,\theta}$ remains equal to unity until about 700°C and then slightly decreases to a minimum value of 0.82 at 1000°C. The values belonging to subset 7 however give an opposite trend. These are the ASTM A99 specimens which were cooled in water (CIW) and the different behaviour is most likely due to a change in the microstructure during the heating and cooling cycle.

Ultimate strain:
One of the ductility requirements in Eurocode 3 Part 1-1 [40] stipulates that the ratio of f_u/f_y should be greater than 10%. As stated before, the influence of heating and cooling is quite limited on the ultimate strength and therefore it is generally concluded that if the Eurocode 3 ductility criteria are fulfilled in the virgin material before the fire, these will be maintained even after fire and subsequent cooling. For the ultimate strain as shown in Figure 8(c), excellent performances are observed for the samples included in subsets 16 (sheets cooled in air) and 17 (square hollow sections cooled in water). It is shown that for the average value there is no loss in ultimate strain following the heating and cooling cycle. Although, due to the increased scatter, the characteristic value decreases significantly to 0.71 at 200°C, then further to 0.66 at 800°C in a gentler way, and then drops more sharply to 0.31 at 1000°C.

Young's modulus:
The influence of the fire on Young's modulus is very limited. The retention factor $R_{E,\theta}$ has a value of unity until a temperature of 700°C and then decreases linearly to a value of 0.90 at 1000°C.

As a general conclusion to this section on normal strength carbon steels, it can be stated that for a post-fire assessment, the verification of the resistance criteria is likely to be the most important factor. Therefore, with reference to the steps in Figure 1, if all criteria in stage 1 are satisfied and if a structure survives a fire (i.e. stage 2 is also satisfied), it is only necessary to re-check the ultimate limit states before a structure can return to service life.

4.2. High strength steel

High strength steels (HSS) can be produced in a number of different ways, typically involving either heat treatment or cold-working, and therefore the influence of the temperature that is reached during a fire as well as the soak time and cooling regime are likely to be important to the post-fire mechanical properties. In the last decade, there has been a reasonable body of research published on this material including a total of 259 test results. A summary of the main parameters under ambient conditions is given in Table 6, to obtain an overview of the homogeneity of the test series. The retention factors for the yield strength, ultimate tensile strength, ultimate strain and Young's modulus are presented in Figure 9 and are discussed hereafter.

Table 6. Normalized properties of high strength structural steel in ambient conditions.

	$f_{y,test}/f_{y,n}$	$f_{u,test}/f_{u,n}$	ε_u	E_{test}/210 MPa
	(-)	(-)	(%)	(-)
Number of tests	14	14	12	14
Mean	1.09	1.10	1.00	0.99
V_{test}	0.16	0.00*	0.00*	0.03
V_{amb}	0.07	0.04	0.06	0.03

*Due to a lack of available data, standardised values [16] are adopted resulting in a coefficient of variation equal to 0.00.

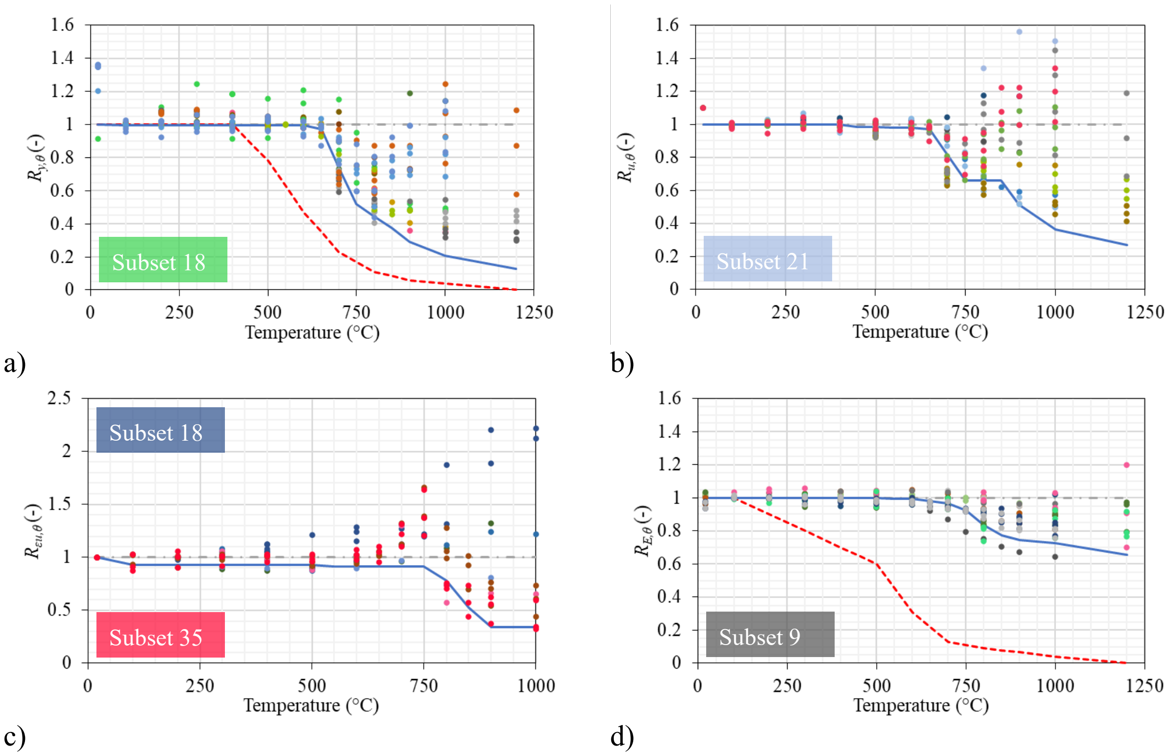


Figure 9 Summary of high strength steel test results including a) yield strength, b) tensile strength, c) ultimate strain and d) Young's modulus after cooling.

Yield strength:

As for the normal strength steels previously discussed, there is a degree of scatter for the yield strength, as shown in Figure 9(a), which is mostly as a result of the Bisalloy® samples in subsets 24, 26 and 28. These were cooled in air, furnace and in water, respectively. The yield strength retention factor $R_{y,\theta}$ follows the same trend as the reduction factor ($k_{y,\theta}$) but with a change which is noticeably from around 650°C. Accordingly, between ambient and 650°C, $R_{y,\theta}$ has a value of unity, between 650°C and 750°C $R_{y,\theta}$ reduces linearly to 0.52 and at higher temperatures, up until 1200°C, $R_{y,\theta}$ reduces further linearly to 0.13.

Ultimate strength:

For the ultimate strength, between ambient and 650°C, $R_{u,\theta}$ has a value of 1.0, between 650°C and 750°C $R_{u,\theta}$ reduces linearly to 0.66 and then remains at this value until around 850°C after which it again decreases to a value of 0.27 at 1200°C. Therefore, the reductions in tensile strength are less extreme than those observed for yield strength. It is noteworthy that the coupons from subset 21, which performed very well until about 1000°C, are cut out of 20 mm steel plate and quenched in water, which increases the ultimate strength.

Ultimate strain:

With reference to Figure 9(c), it is observed that the retention factor for ultimate strain $R\varepsilon_{u,\theta}$ slowly decreases to 0.91 at around 750°C, and then drops to around 0.34 at 900°C, and remains almost constant at this value as the temperature increases (0.30 at 1200°C). Subset 18 (Optim 700™ steel) also shows increased ultimate strains in terms of the retained values. It is interesting to note that, for subset 35 i.e. rods cooled in water, this beneficial effect disappears at 800°C. The fluctuations in values (increasing (Subset 18) and decreasing results (Subset 35)), cause again a sharp decrease in the coefficient of variation and therefore in the characteristic value.

Young's modulus:

While for normal strength steel the effect of heating and subsequent cooling on the Young's modulus was very limited, a more significant reduction is observed for higher strength steels. Between ambient and 700°C, $R_{E,\theta}$ has a value of 1.0 then followed by a linear reduction to 0.66 at 1200°C. The values of subset 9 always time below the characteristic value.

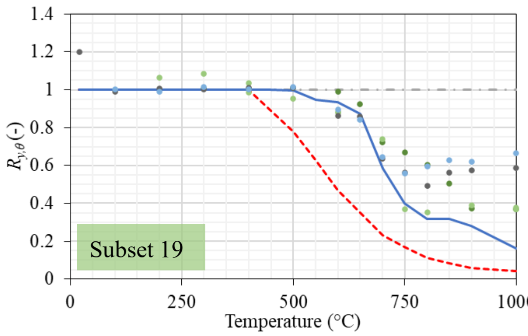
4.3. Very high strength steel

This range of very high strength structural steel (VHSS) is covered by Eurocode 3 Part 1-12 [41] and EN 10025-6 [42]. Very high strength steels cover grades with a yield strength between 700 MPa and 960 MPa. These are generally still quite novel in the construction sector but are growing in popularity as the attraction to lighter and more bespoke designs increases. Of the database given in Table 3, only 4 research papers include tests on these grades resulting in a total of 54 experiments, with 4 in ambient conditions; these are outlined in Table 7. Figure 10 presents the retention factors for yield strength, tensile strength, ultimate strain and Young's modulus, based on these data. As with the high strength steels, it is noteworthy that the production route for these grades can influence their behaviour under both elevated temperature, and post-fire conditions.

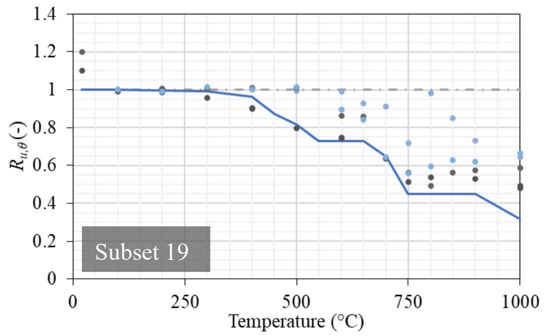
Table 7. Normalized properties of very high strength structural steel in ambient conditions.

	$f_{y,test}/f_{y,n}$	$f_{u,test}/f_{u,n}$	ε_u	E_{test}/210 MPa
	(-)	(-)	(%)	(-)
Number of tests	4	4	3	4
Mean	1.10	1.10	1.00	1.00
V_{test}	0.09	0.00*	0.00*	0.01
V_{amb}	0.07	0.04	0.06	0.03

*Due to a lack of available data, standardised values [16] are adopted resulting in a coefficient of variation equal to 0.00.



a)



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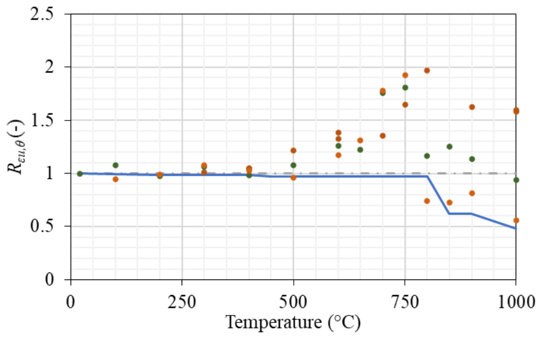

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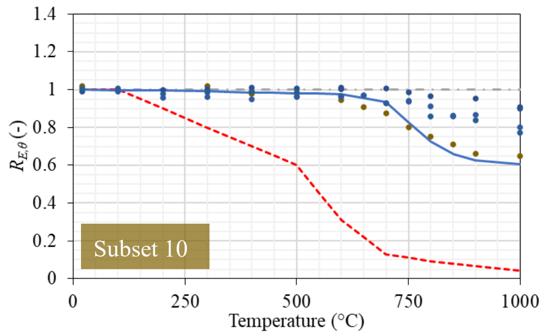


d)

Figure 10 Summary of very high strength steel test results including a) yield strength, b) tensile strength, c) ultimate strain and d) Young's modulus after cooling.

The shape of all curves is, in general, almost the same as for the high strength steel grades. The following observations are made from the data presented in Figure 10.

Yield strength:

The yield strength follows, again, almost the same trend as the reduction factor ($k_{y,\theta}$). The retention factor is 1.0 between ambient temperature and 500°C, and this is followed by a linear reduction to a value of 0.84 at 650°C and then a further linear reduction to a value of 0.32 at 850°C and 0.16 at 1000°C. The lowest values are found for subset 19 which were tests on coupons taken from a square hollow section which was 120×120×4 in size and made from Optim 900™ steel, which is very similar to S960. Note that in the previous subset of HSS with Optim 700™, this steel performed better as the average, for this grade it is reversed.

Ultimate strength:

For the ultimate strength $R_{u,\theta}$, a lower scatter is generally observed, as for the HSS-grade. After exposure to temperatures higher than 250°C, the retention factor decreases. Starting from about 400°C, an almost linear decrease is observed to 0.45 at 750°C and then up to a retention factor of 0.32 at 1000°C.

Ultimate strain:

With reference to Figure 10(c), for the ultimate strains, after heating up to 500°C and then cooling, all tests deliver higher ultimate strains, the steel is relaxed and regains its initial ductility. Starting from 800°C however, a higher scatter is found which leads to a quick drop of the retention factor to 0.62 at 850°C, then descending to 0.48 at 1000°C.

Young's modulus:

The retention factor for Young's modulus exhibits a significant reduction (almost linear) from 600°C and has a value of 0.66 at 850°C, as shown in Figure 10(d). It then shows a less significant decrease to 0.61 at 1000°C. It is noteworthy that subset 10 is largely responsible for the lower values in the higher temperature range.

4.4. Ultra high strength steel

Ultra high strength steel (UHSS) is carbon steel with a yield strength of greater than 960 MPa, as defined by [34]. These grades are relatively unusual still in structural applications but are quite common in aerospace applications, some parts of cranes and also in the profiles of dumper trucks which must withstand high stresses. Of the data included in this study, and given in Table 3, only one reference includes information on the behaviour of these grades [2], under ambient conditions. Therefore, it is not possible to complete a statistical evaluation. In total, test results from 61 experiments are available after heating and then cooling down.

Table 8. Normalized properties of ultra high strength structural steel in ambient conditions.

	$f_{y,test}/f_{y,n}$	$f_{u,test}/f_{u,n}$	ε_u	E_{test}/210 MPa

	(-)	(-)	(%)	(-)
Number of tests	1	1	1	1
Mean	0.99	1.10	1.00	1.02
V_{test}	-	-	-	-
V_{amb}	0.07	0.04	0.06	0.03

Figure 11 presents the retention factors for yield strength, tensile strength, ultimate strain and Young's modulus, based on these data. Again, the shape of the curves is very similar as for the high and very high strength steels, although there is a slight decrease in the level of temperature exposure required to observe changes in the retention values, as outlined hereafter.

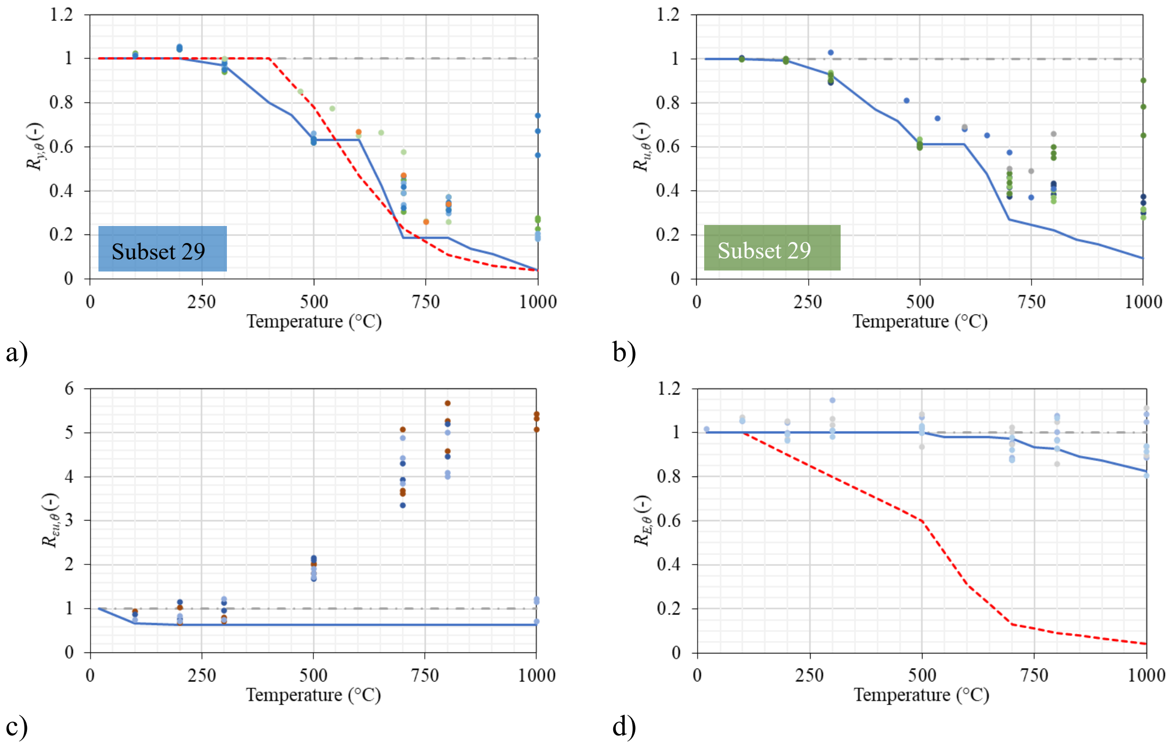


Figure 11 Summary of ultra high strength steel test results including a) yield strength, b) tensile strength, c) ultimate strain and d) Young's modulus after cooling.

Yield strength:

The retention factor is unity between ambient temperature and 250°C, and this is followed by a linear reduction to a value of 0.65 at 500°C. The retention factor remains at this value until 600°C after which is decreases linearly to a value of 0.19 at 700°C and 0.04 at 1000°C. Subset 29 shows a substantial improvement at 1000°C after a temporary loss of yield strength for 5 mm thick sheet made of Bisalloy® 400 steel grade (S1070) and cooled in water. This single grade obviously has a negative impact on the coefficient of variation.

Ultimate strength:

For $R_{u,\theta}$, less scatter is observed in the data. Subset 29 reacts similarly for the ultimate strength as observed previously for the yield strength, which has a negative impact on the coefficient of variation. The retention factor $R_{u,\theta}$ is unity between ambient temperature and 200°C, and drops over 0.61 at 500°C to a value of 0.10 at 1000°C.

Ultimate strain:

After heating up to 300°C, all tests deliver higher ultimate strains, just as for high strength steels (up to 6 times higher than the one of the virgin material) however even more pronounced. The factor $R_{\varepsilon u,\theta}$

however starts to decrease immediately from a value of 0.67 at 100°C and then stays almost constant (it is 0.64 at 1000°C).

Young's modulus:

Again, some influence on Young's modulus can be noticed from 700°C. The factor $R_{E,\theta}$ decreases rather smoothly to 0.82 at 1000°C, a factor slightly higher than for the high and very high strength steels.

4.5. Cold-formed steel (CFS)

Cold-formed steel members are commonly used as load bearing studs and joists in light gauge steel frame construction. They offer significant advantages in terms of high strength-to-weight ratios and the profiled cross-sections can be optimised by improving the second moment of area and to ease their fabrication. Structures built with such profiles are popular for low-rise and temporary structures. The results in the current analysis comprise 71 tests in total of which 8 are virgin specimens as given in Table 9.

Table 9. Normalized properties of CFS in ambient conditions.

	$f_{y,test}/f_{y,n}$	$f_{u,test}/f_{u,n}$	ε_u	$E_{test}/210$
	(-)	(-)	(%)	(-)
Number of tests	8	8	2	7
Mean	1.12	1.10	1.00	1.05
V_{test}	0.12	0.00*	0.00*	0.04
V_{amb}	0.07	0.04	0.06	0.03

*Due to a lack of available data, standardised values [16] are adopted resulting in a coefficient of variation equal to 0.00.

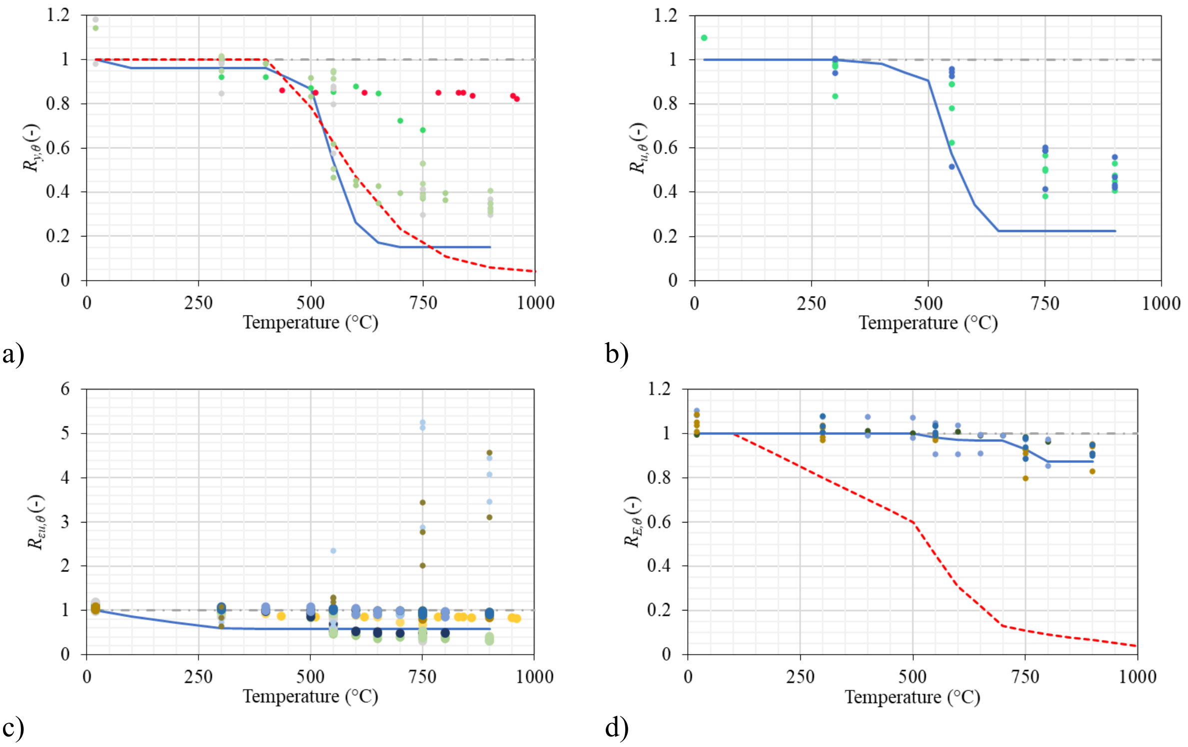


Figure 12 Summary of cold-worked steel test results including a) yield strength, b) tensile strength, c) ultimate strain and d) Young's modulus after cooling.

Cold-formed steel sections are subjected to strain hardening during fabrication which generally results in enhanced yield strength and reduced ductility, so the results after heating are completely different than in the previous sections for hot rolled steels. Previous research into this topic [29] and [3] has indicated that CFS grades have a transition temperature of around 500°C, above which the properties significantly change. The observations from the current analysis is outlined hereafter.

Yield strength:

For the yield strength, even after heating to only 100°C, a small reduction (0.96) is already be observed in the retention factor for yield strength. Then from 400°, $R_{y,\theta}$ reduces rapidly to 0.26 at 600°C after which is decreases gradually to a value of just 0.15 following exposure to 900°C.

Ultimate strength:

The ultimate strength behaviour is similar to the yield strength in that $R_{u,\theta}$ begins to decrease from 400°C at which stage it reduces rapidly to a value of 0.22 at 650°C and then stays constant at higher temperatures.

Ultimate strain:

The ultimate strains increase significantly by a factor of up to 10 for temperatures above 550°C, although this is not reflected in the retention factor shown in Figure 12(c) due to the effect of the operator described in Eq. (8). Starting from 20°C, a linear decrease is observed to 0.59 at 300°C. The retention factor then stays almost constant over the rest of the temperature range (0.58 at 900°C).

Young's modulus:

As for the other steel grades the Young's modulus stays more or less constant until 700°C but then $R_{E,\theta}$ decreases to a value of 0.87 at 900°C.

4.6. Cast and wrought iron

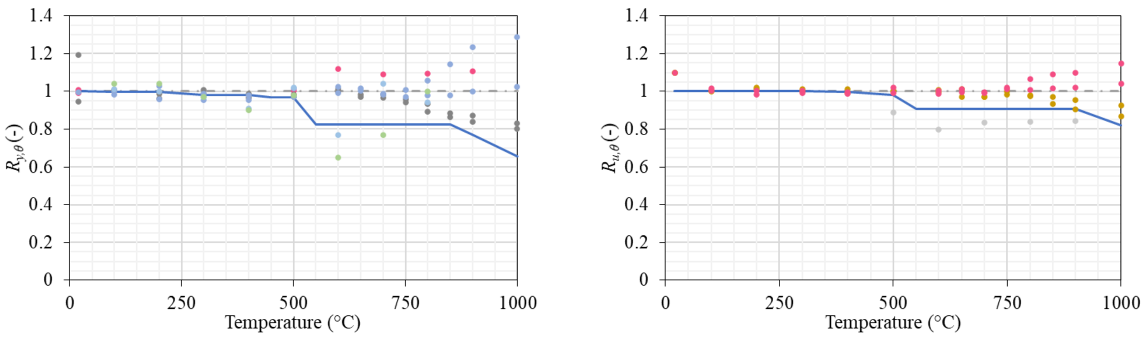
This section includes data on a combination of wrought and cast iron samples from new (mostly used in complex joints) or historical steel products. The information is gathered from three references [4], [39] and [38], which include the results of 77 tests including 6 at ambient conditions. The results presented in Table 10 are very similar to the observations made for normal steel strength (see Table 5).

Table 10. Normalized properties of cast and wrought iron in ambient conditions.

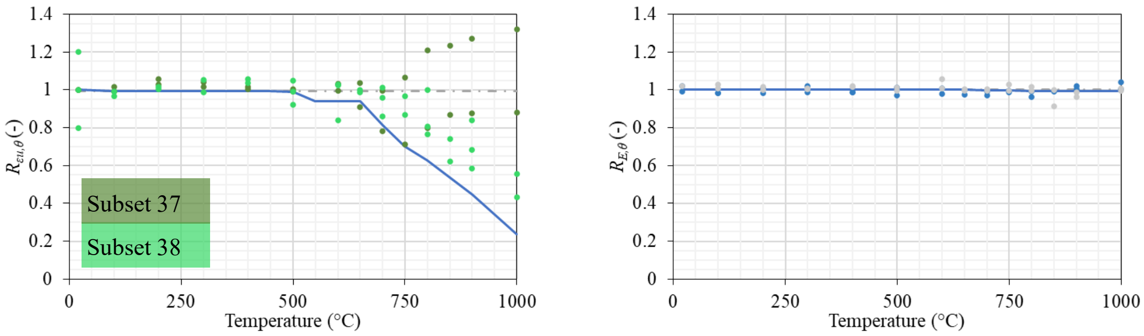
	$f_{y,test}/f_{y,n}$	$f_{u,test}/f_{u,n}$	ε_u	E_{test}/210 MPa
	(-)	(-)	(%)	(-)
Number of tests	6	6	6	1
Mean	1.06	1.10	0.99	1.01
V_{test}	0.11	0.00*	0.13	0.01
V_{amb}	0.07	0.04	0.06	0.03

*Due to a lack of available data, standardised values [16] are adopted resulting in a coefficient of variation equal to 0.00.

With reference to Figure 13, the influence of cooling regime, hot working, and other treatments is unclear, but the results are relatively homogeneous, as outlined hereafter. After heating in fire conditions and then cooling, these materials perform quite well compared with the other steels considered in this study.



a) b)



c) d)

Figure 13 Summary of cast and wrought iron test results: a) yield strength, b) tensile strength, c) ultimate strain and d) Young's modulus after cooling down (dots). The solid line is the retention factor R_θ.

0.2% proof stress:

The impact of the heating and cooling procedure starts at 500°C but the reduction stays limited for the 0.2% proof stress. $R_{y,\theta}$ equals 0.82 at 550°C and stay constant until 850°C after which a linear decrease is observed until $R_{y,\theta}$ reaches a value of 0.66 at 1000°C.

Ultimate strength:

For the ultimate strength, the retention performance generally is excellent. Between ambient and 500°C, all of the original ultimate strength is retained, reducing to 0.90 at 600°C and 0.82 at 1000°C.

Ultimate strain:

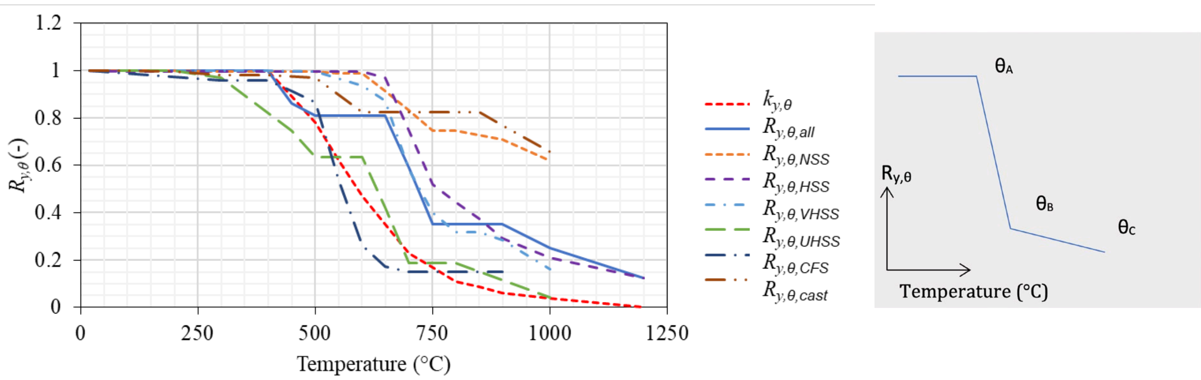
The ultimate strain retention factor is almost 1.00 at 500°C but subsequently decreases linearly from 650°C (0.95) to reach a low value of 0.24 at 1000°C. It is worth mentioning that 2 subsets from the same reference [38] show remarkable differences in their behaviour depending on the cooling method; subset 37 is air-cooled where subset 38 is water-cooled.

Young's modulus:

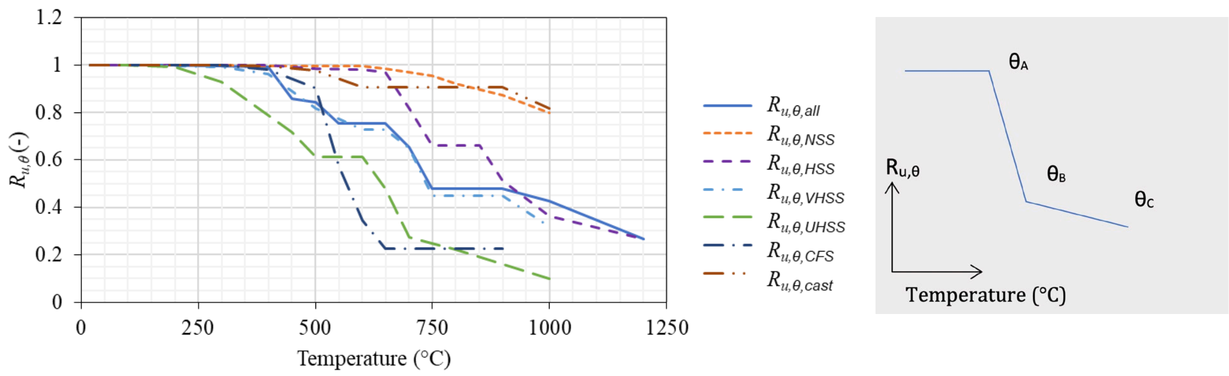
As evidences in Figure 13(d), there is no significant effect at all on Young's modulus following exposure to elevated temperature and subsequent cooling, in stark contrast to the other materials examined in this study.

4.7. Summary of all the results

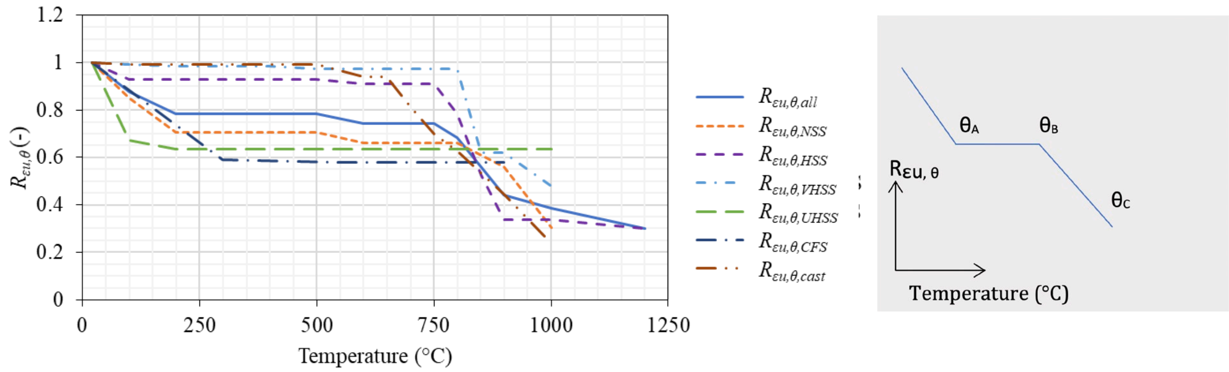
In this section, the results presented previously for each category of structural steel are summarised and comparisons are drawn between the different steel types. Figure 14 presents the retention curves for the yield strength, tensile strength, ultimate strain and Youngs modulus, respectively, for each of the different material categories considered in this study. This includes normal strength steel (NSS), high strength steel (HSS), very high strength steel (VHSS), ultra high strength steel (UHSS), cold-formed steel (CFS) and cast/wrought iron.



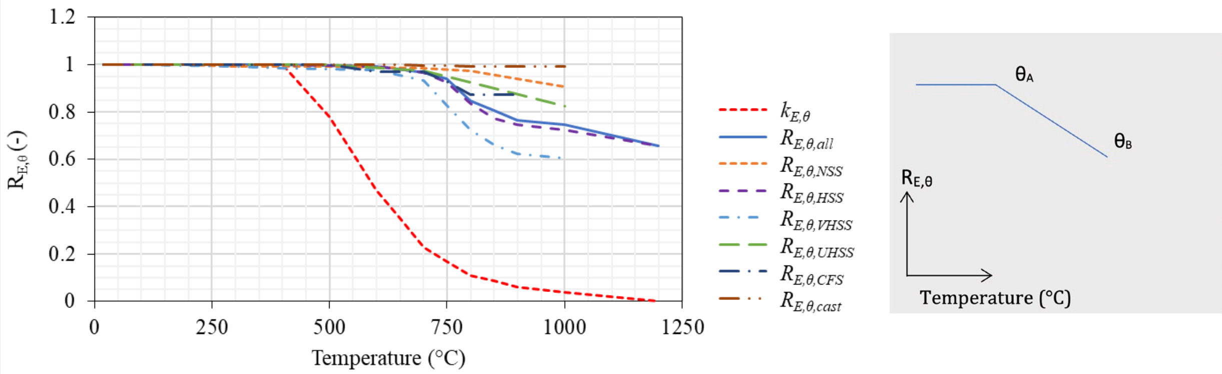
a)



b)



c)



d)

Figure 14 Comparative figure with the different materials retention factors of all grades and at the right simplified versions.

In general, the trends are very similar across all of the steel types. For comparatively higher strength steels, the starting point of the reduction in each property value occurs at a lower temperature. Structural steel and cast or wrought iron exhibit similar behaviour in terms of retention of their properties after a fire. On the other hand, cold-formed steel retains less of its yield and ultimate strength ($R_{y,\theta}$ and $R_{u,\theta}$) even after exposure to temperatures of around 500°C.

The information in the graphs given in Figure 14 is also presented in tabular form in Table 11. The retention factors for the yield strength and Young's modulus for each of the steel grades included in this study is presented; the subscript for each term indicates the material under consideration. It is evident that the evolution of the retention factors can be simplified into either a bi- or tri-linear curve, as shown for each property in Figure 14. The characteristic temperatures θ and accompanying retention factors R_θ can be found in Table 12 for each material group and individual mechanical property. In the table, for each data set, the temperature/retention factor (θ (°C)/R_θ) is provided.

Molkens, T., Cashell, K.A., Rossi, B. Post-fire mechanical properties of carbon steel and safety factors for the reinstatement of steel structures. Engineering Structures 234 (2021) 111975.
https://www.sciencedirect.com/science/article/abs/pii/S0141029621001255

Table 11 Retention factors for different grades of carbon steel after exposure to elevated temperature θ (steel temperature)

Exposed steel temperature θ	Retention factor after exposure to a temperature θ relative to the value of $f_{y,n}$ or E_n at 20°C													
	All grades		**Normal strength steel**		**High strength steel**		**Very high strength steel**		**Ultra high strength steel**		**Cold formed steel**		**Cast and wrought iron**	
	Retention factor for yield strength $R_{y,\theta,all}$	Retention factor for Young's modulus $R_{E,\theta,all}$	Retention factor for yield strength $R_{y,\theta,NSS}$	Retention factor for Young's modulus $R_{E,\theta,NSS}$	Retention factor for yield strength $R_{y,\theta,HSS}$	Retention factor for Young's modulus $R_{E,\theta,HSS}$	Retention factor for yield strength $R_{y,\theta,VHSS}$	Retention factor for Young's modulus $R_{E,\theta,VHSS}$	Retention factor for yield strength $R_{y,\theta,UHSS}$	Retention factor for Young's modulus $R_{E,\theta,UHSS}$	Retention factor for yield strength $R_{y,\theta,CFS}$	Retention factor for Young's modulus $R_{E,\theta,CFS}$	Retention factor for yield strength $R_{y,\theta,cast}$	Retention factor for Young's modulus $R_{E,\theta,cast}$
20°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.998	1.000	1.000	1.000	1.000	1.000	1.000
200°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	1.000	1.000	1.000	1.000	1.000	1.000
300°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.991	0.968	1.000	0.960	1.000	0.979	1.000
400°C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.986	0.000	1.000	0.960	1.000	0.979	1.000
500°C	0.809	1.000	1.000	1.000	1.000	0.998	1.000	0.980	0.633	1.000	0.867	1.000	0.970	1.000
600°C	0.809	1.000	1.000	1.000	1.000	0.994	0.935	0.976	0.633	0.986	0.263	0.971	0.824	1.000
700°C	0.591	0.966	0.830	0.986	0.745	0.968	0.583	0.933	0.187	0.973	0.150	0.970	0.824	0.997
800°C	0.351	0.846	0.746	0.973	0.446	0.835	0.317	0.725	0.187	0.926	0.150	0.874	0.824	0.992
900°C	0.351	0.767	0.708	0.939	0.290	0.746	0.283	0.624	0.114	0.000	0.150	0.874	0.769	0.992
1000°C	0.250	0.746	0.618	0.905	0.208	0.725	0.162	0.606	0.041	0.823			0.656	0.992
1200°C	0.126	0.655			0.126	0.655		0.000						
NOTE: For intermediate values of the steel temperature linear interpolation may be used. Values ≥ 0.990 are set equal to 1.000														

Table 12. Proposed simplified retention factors suitable for design

Property	$R_{y,\theta}$			$R_{u,\theta}$			$R_{\varepsilon u,\theta}$			$R_{E,\theta}$	
θ (°C)/ R_θ	θ_A	θ_B	θ_C	θ_A	θ_B	θ_C	θ_A	θ_B	θ_C	θ_A	θ_B
All	400/ 1.00	750/ 0.40	1200/ 0.13	400/ 1.00	750/ 0.48	1200/ 0.27	200/ 0.78	750/ 0.70	1200/ 0.30	700/ 1.00	1200/ 0.65
NSS	600/ 1.00	750/ 0.75	1000/ 0.62	650/ 1.00	1000/ 0.82	-	200/ 0.71	800/ 0.66	1000/ 0.31	800/ 1.00	1000/ 0.90
HSS	650/ 1.00	750/ 0.52	1200/ 0.13	650/ 1.00	750/ 0.66	1200/ 0.27	750/ 0.91	900/ 0.34	1200/ 0.30	700/ 1.00	1200/ 0.66
VHSS	600/ 1.00	800/ 0.32	1000/ 0.16	400/ 1.00	750/ 0.45	1000/ 0.32	800/ 1.00	850/ 0.62	1000/ 0.48	600/ 1.00	1000/ 0.61
UHSS	250/ 1.00	700/ 0.19	1000/ 0.04	200/ 1.00	500/ 0.61	1000/ 0.10	100/ 0.67	1000/ 0.64	-	700/ 1.00	1000/ 0.82
CFS	400/ 1.00	600/ 0.26	900/ 0.15	400/ 1.00	650/ 0.22	900/ 0.22	300/ 0.59	900/ 0.58	-	700/ 1.00	900/ 0.87
Cast	500/ 1.00	550/ 0.82	1000/ 0.66	500/ 1.00	600/ 0.90	1000/ 0.82	500/ 1.00	650/ 0.95	1000/ 0.24	1000/ 1.00	-

5. Uncertainty aspects

The recommended material safety factor $\gamma_{M0,amb}$ for carbon steel equals 1.0, which corresponds to a very high certainty of the material characteristics (V_{amb} = 0.0). This was extensively demonstrated in a recent European project [21] and is out of the scope of this article. An increasing uncertainty has an impact on the design values used in the assessment procedure. Consequently, in this section, a different approach is needed to determine the fractile factor k_n (Eq. (5)), to remain in accordance with the codes. On the contrary, when the standard deviation of the mechanical properties' distribution function increases after the fire, the safety factors must then be adjusted. But, since this article deals with existing structures for which the remaining lifetime might be reduced, adjustments of the reliability level are also considered. An optimized target reliability considering economic and social aspects for existing structures can compensate the adverse impact of the increasing uncertainties.

5.1. Safety factor

A simple method to obtain the relevant partial factor is to divide the design value of a resistance variable by its characteristic value, as described in annexes C and D of Eurocode 0 [14]. The derivation of a material property contributing to the resistance of a material should be carried out by (i) assessing a characteristic value which is divided by a partial factor or (ii) direct determination of the design value. Once the probability distribution function is known (LN, see [16]), Eq. (9) gives the design value ($X_{d,\theta}$) of the property (X) under consideration [15], using method (ii) as described above:

$$X_{d,\theta} = \frac{\mu_{post,\theta}}{\sqrt{V_{test,\theta}^{\ 2} + 1}} exp\left(-\alpha\beta\sqrt{ln\left(V_{test,\theta}^{\ 2} + 1\right)}\right) \tag{9}$$

In this expression, the variables depend on the exposure temperature θ, and therefore the subscript θ is included in Eq. (9). In the current work, $\mu_{post,\theta}$ is defined as the mean of the property X_θ at the exposure temperature θ and $V_{test,\theta}$ is the coefficient of variation of the same property. The same notation as in Eq. (4) to (6) are otherwise employed. Method (i) with a characteristic value corresponding to a 5% fractile leads to Eq. (10). Regarding the different material subsets considered in this study, the steel type with the least number of available tests is the ultra high strength steels which has 64 test results available. With reference to Figure 2, it was already shown that a constant fractile factor of unity leads to an error in the coefficient of variation of less than 2%.

$$X_{k,\theta} = \frac{\mu_{post,\theta}}{\sqrt{{V_{test,\theta}}^2 + 1}} exp\left(-1.645\sqrt{ln\left({V_{test,\theta}}^2 + 1\right)}\right) \tag{10}$$

It is noteworthy that for post-fire situations, the coefficient of variation can become higher than 0.20 and so the term $\sqrt{ln\left({V_{test,\theta}}^2 + 1\right)}$ in Eq. (10) can no longer be approximated by $V_{test,\theta}$, which was previously the case in Eq. (5). Thus, the appropriate safety factor will be equal to the ratio of the characteristic to the design value, as given in Eq. (11). The sensitivity factor α_R for resistance effects has a value of 0.8 in accordance with Eurocode 0 [14] and the reliability factor β for new structures in Consequence Class 2 (CC2), is equal to 3.8 [14]. A CC2 refers to medium consequence for loss of human life, while economic, social or environmental consequences are considerable. Examples of CC2 are residential and office buildings, as well as public buildings with a medium consequence of failure.

$$\gamma_{M0,\theta} = \frac{X_{k,\theta}}{X_{d,\theta}} = \frac{\exp\left(-1.645\sqrt{\ln\left({V_{test,\theta}}^2 + 1\right)}\right)}{\exp\left(-\alpha\beta\sqrt{\ln\left({V_{test,\theta}}^2 + 1\right)}\right)} \tag{11}$$

In the previous section, Eqs. (6) and (7) gave the coefficient of variation resulting from a test $V_{test,\theta}$ as a combination of the coefficient of variation from the virgin material ($V_{amb} = 0.07$) and the corresponding post-fire value ($V_{post,\theta}$) depending on the temperature exposure. Regarding safety factors however, the final assessment in the post-fire condition should use the product of both safety factors i.e. one factor linked to the material properties in ambient conditions ($\gamma_{M0,amb}$) and another related to the post-fire conditions ($\gamma_{M0,post,\theta}$). All of these safety factors can be derived based on Eqs. (6) and (11) and their dependency to the temperature is depicted in Figure 15.

There are two challenges with this approach which need to be considered:

1. Given the chosen conservative upper value of the coefficient of variation (i.e. 0.07), the safety factor at ambient temperature V_{amb} based on the collated data is 1.10. Nevertheless, the more comprehensive recommendations of a recent European project [21] and implemented in Eurocode 3 Part 1-1 [43] recommend using a $\gamma_{M0,amb}$ factor of 1.0. Therefore, the product of $\gamma_{M0,amb}$ and $\gamma_{M0,post,\theta}$ gives $\gamma_{M0,post,\theta}$ or ($\gamma_{M0,\theta}$), where $\gamma_{M0,post,\theta}$ is the safety factor based on $V_{post,\theta}$ with a sensitivity factor α_R of 0.8, as shown in Figure 15.
2. Due to the variation of the coefficient of variation based on tests $V_{test,\theta}$, the calculated safety factor $\gamma_{M0,test,\theta}$ varies depending on the temperature (see Figure 15(a)). It is observed that the data sometimes leads to lower safety levels for steel exposed to higher temperatures which is perhaps counterintuitive. It is therefore necessary to include an operator which ensures that the safety factor does not decrease, and this is implemented using Eq. (12), which results in the data presented in Figure 15(b). The variables marked with an asterisk (*) symbol are those before the application of the operator.

$$V_{test,i,\theta} = MAX\left(V^*_{test,i,\theta-1}; V^*_{test,i,\theta}\right) \tag{12}$$

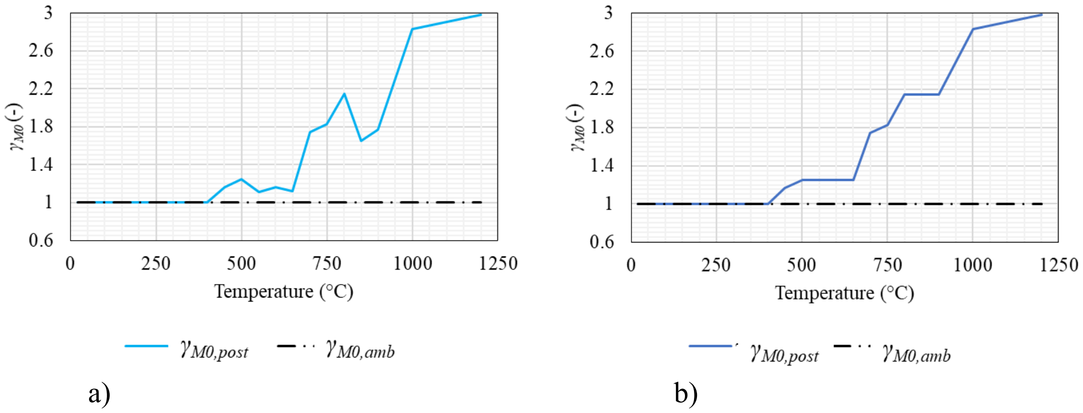


Figure 15. Safety factor based on all collected tests including (a) based on raw data (b) after correction has been applied.

In the ideal case, the product of both safety factors ($\gamma_{M0,amb}$ and $\gamma_{M0,post,\theta}$) should be equal to the value directly resulting from the previously mentioned coefficient of variation ($\gamma_{M0,test,\theta}$) which is however not presently the case. But it has been shown by other researchers [44] that, for the non-dominant variable, the sensitivity factor α should be taken as the product of 0.4 and 0.8 i.e. 0.32. Since $V_{post,\theta}$ depends on the temperature, it is non-dominant in the lower temperature regions and becomes more dominant when the steel is exposed to higher temperatures. The resulting safety factors for each studied subset ($\gamma_{M,\theta}$), taking this into account, are depicted in Figure 16, and further presented in Table 13.

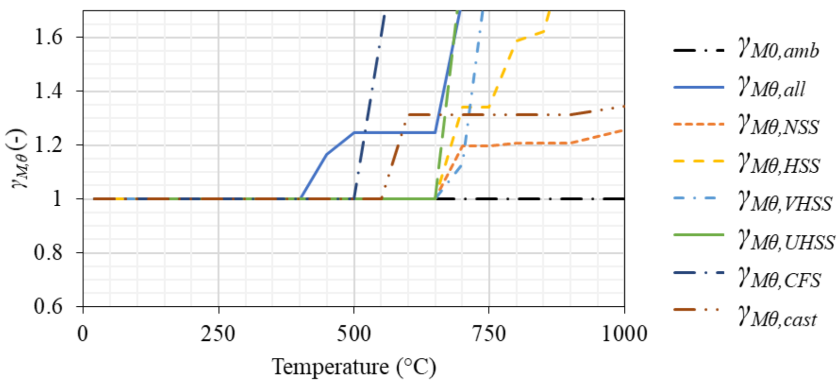


Figure 16 Summary of the safety factor with a reliability index β = 3.8 for all of the carbon steel grades examined in this study.

From Figure 16, it is observed that the impact of a fire on the properties of normal strength steel (NSS) is relatively low and only starts to increase after these materials have been exposed to temperatures above 650°C, and then a safety factor of 1.20 should be applied. For high strength steels (HSS) a double step is observed with a safety factor of 1.35 at 650°C increasing to 1.60 (and above) from 750°C. In the case of VHSS and UHSS, at 650°C the safety factor is higher than 1.60. For CFS, the level of temperature exposure that is required for the retention values to be affects changes from 650°C (valid for all other steel grades) to 500°C. For cast and wrought irons, the safety factor increases from 550°C but, even up to about 1000°C, its value remains limited to 1.30, which is important information for cultural heritage structures. All previously mentioned, all of this information is summarized in Table 13.

It is worth noting that the safety factor of 1.60 for HSS as discussed in the previous paragraph (i.e. $V_{test,\theta} \geq 0.34$) implies that steel structures can only be used for up to 62.5 % of its original design load following exposure to 750°C for HSS subsequent cooling. From the safety factors presented, it is concluded that the reinstatement of a structure is not possible in an economic manner once it has been exposed to this level of fire temperature. This is further exemplified by the corresponding temperature which is called the critical temperature: above this temperature reinstatement is not feasible. In fact, it follows from Figure 16 that for all types of steel apart from NSS, there exists a clear transition temperature θ_{lim} above which reinstatement becomes impractical and uneconomical; these values are also presented in Table 13.

Table 13. Critical temperatures and additional safety factors for different steel grades, with β=3.8

Name of subsets	Abbreviation	θ (°C)	Safety factor $\gamma_{M0,post,\theta}$
Normal strength structural steel	NSS	> 650 θ_{lim} > 1000	1.20
High strength structural steel	HSS	> 650 > 750 = θ_{lim}	1.35 >1.60
Very high strength structural steel	VHSS	> 650 > 700 = θ_{lim}	1.15 >1.60
Ultra high strength structural steel	UHSS	> 650 = θ_{lim}	>1.60
Cold-formed steel	CFS	> 500 = θ_{lim}	>1.60
Cast and wrought iron	Cast	> 550 θ_{lim} > 1000	1.30

5.2. Reliability factor

For buildings categorized in normal Consequence Class 2 [14], the reliability index β corresponding to a probability of failure of $7.23 \cdot 10^{-5}$ equals 3.8 [15]. It has previously been shown by a number of researchers [13], [45] that there should be a distinction between new, existing and even temporary structures regarding their reliability indexes. In accordance with ISO 2394 [46] it is proposed to limit β to a lower limit of 3.3 for an existing building in the post-fire condition, for which societal and human risks are still satisfactory [13]. Eq. (11) demonstrates that there is a direct impact of a lower β factor on the safety factor $\gamma_{M0,post,\theta}$, and this has been calculated and is depicted in Figure 17 and summarized in Table 14. The loss in material strength is still visible through the new safety factors but its effect is decreasing.

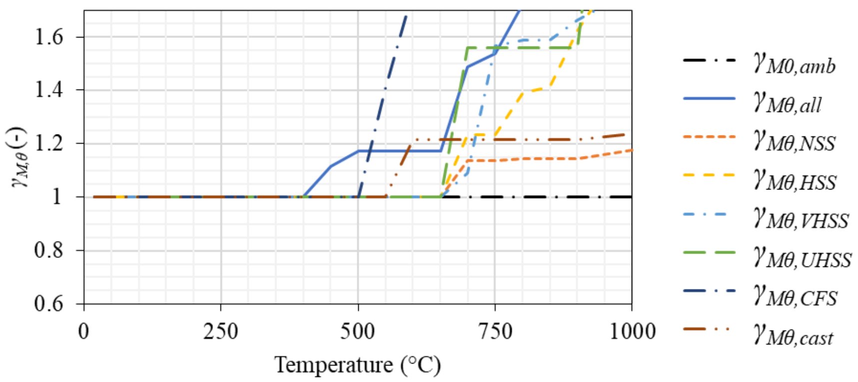


Figure 17 Summary of safety factor with a reliability index β = 3.3 for the different steel grades considered in this study.

Table 14. Critical temperatures and additional safety factors for steel grades discussed in this article, with β=3.3

Name of subsets	Abbreviation	θ (°C)	Safety factor $\gamma_{M0,post,\theta}$
Structural steel	NSS	> 650 θ_{lim} > 1000	1.15
High strength structural steel	HSS	> 650 > 750 > 850 = θ_{lim}	1.25 >1.40 >1.60
Very high strength structural steel	VHSS	> 650 > 700 = θ_{lim}	1.10 >1.60
Ultra high strength structural steel	UHSS	> 650	>1.55
Cold-formed steel	CFS	> 500 > 550 = θ_{lim}	>1.40 >1.60
Cast and wrought iron	Cast	> 550 θ_{lim} > 1000	1.20

6. Conclusions and perspectives

This paper deals with the determination of the post-fire steel material properties and safety factors used in the assessment and retrofitting of existing steel buildings which suffered and survived a fire. It is the first reliability-based approach for the reinstatement of structures based on the available information in the literature. The data is used to derive (i) retention factors for each of the significant and characteristic material properties i.e. directly providing an easy-to-use information on how a specific property changes in value when steel is subjected to a fire and subsequently cooled down and (ii) adjusted safety factors based on the details analysis reflecting the increase of variation in results after being heated and cooled down. Both factors depend on the maximum temperature to which the steel is exposed.

In total, 19 references and 718 test results are used to derive the evolution of four post-fire mechanical properties: yield strength, ultimate strength, ultimate strain and Young's modulus. Six different grades of steel are considered including cast and wrought iron. The key results are (i) the evaluation of the coefficient of variation for the characteristic mechanical properties at ambient temperature (i.e. compared to the corresponding nominal values) and a comparison with the codified values; (ii) the derivation of the characteristic values for the retention factors of each mechanical property following a fire and subsequent cooling; and (iii) due to the increasing uncertainty (i.e. increased coefficient of variation) on post-fire mechanical properties, the derivation of an additional safety factor is deemed necessary and also provided.

It is shown that, for normal strength steel and cast or wrought iron, the impact of fire on the post-fire properties remains reasonable until up to temperatures of 1000°C. It is proposed that the safety factor $\gamma_{M0,post,\theta}$ is increased to 1.15 for normal strength carbon steel and to 1.20 for cast and wrought iron. For other steel grades (high strength, ultra high strength or cold-formed steels), however, there exists a critical temperature above which reinstatement after the occurrence of a fire is economically unfeasible. In these cases, $\gamma_{M0,post,\theta}$ is greater than 1.60 when this critical temperature is reached during the fire. It is however worth noting that for cold-formed steel, this temperature is below 600°C and therefore it is less likely that these materials can be easily re-employed following a fire.

This paper gives a clear overview of the trends of the retention factors for the characteristic mechanical properties of the six steel grades considered, together with the post-fire safety factors that should be used in the eventuality of a reliability assessment for the reinstatement of a structure after the occurrence of a fire. Following this work, it is recommend that the following procedure is followed in the post-fire assessment of carbon steel structures: depending on the maximum temperature reached during the fire, the retention factor is taken from Table 12 and the additional safety factor taken from Table 14.

This paper deals only the material from which structural elements are usually made and does not consider interactions between different grades, such as might occur at connections for example. Due to the massivity of the surrounding components, the temperature of connections during a fire is usually lower than in the surrounding members and, after the fire, any damaged bolts can be readily replaced which makes their economic impact less detrimental. Nevertheless, it would be useful to conduct a similar study as that which is conducted here for components in steel connections such as bolts. For this, several publications exist however too few to conclude at the current time. It has been shown [47] that the retention behaviour of grade 4.6 bolts is comparable to that of normal strength structural steels, while grade 8.8 bolts seem to behave more similarly to high strength steels. This implies a reduction a reduction of the residual strength from 80% or 60% of its initial value after exposure above 600°C and 800°C, respectively [4] [6].

For high strength friction grip bolts (grades 10.9 or 12.9), it can be simply and conservatively assumed that these will have comparable behaviour to very high or even ultra high strength steel, as discussed in this paper. Recent research [48] on a series of carbon steel bolts (from M6 to M24, grades 8.8 and 10.9) made similar observations. In these experiments, bolts were heated to a fixed temperature, kept constant for 15 minutes and then cooled to ambient temperature. It was shown that there were no changes in the mechanical properties when the materials were exposed to a heating temperature of up to 250°C, insignificant losses occurred between 250°C and 400° but, at temperatures greater than 500°C, substantial changes in the properties were observed. Interestingly, the performance of the grade 10.9 bolts was relatively better than that of the grade 8.8 bolts. Specific scientific research on post-fire residual properties of welds is hard to find. One research group have studied butt welds [49] but there is a need for more research in this area.

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