Post-fire behaviour of structural stainless steel

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Abstract

Stainless steel offers excellent mechanical properties as well as corrosion resistance and performs better in a fire compared to carbon steel in that it retains its strength and stiffness for a longer duration. The current paper is focussed on the post-fire condition, which has only received limited attention to date from the research community. The motivation for the work is to show that stainless steel elements which have been exposed to fire can be re-instated with minimal additional costs in a short time frame. The paper proceeds with a description of recent material tests into the residual properties of grade 1.4301 austenitic stainless steel, following exposure to elevated temperature. Two different types of test are added to this available data. Firstly, a series of tensile tests are completed on coupons taken from a loaded stainless steel beam previously examined under fire conditions. Secondly, a set of virgin coupons (i.e. which have not been previously heated or tested) are exposed to different levels of elevated temperature and cooling procedures. This is with a view to understanding the ability of structural elements made from this material to survive a fire and continue in service. The results are then employed along with other data obtained from the literature to conduct a detailed study into the design considerations.

Keywords

Stainless steel, cellular beams, post-fire, load history, loaded coupons, virgin coupons, cooling method, reinstatement

1 Introduction and background

Stainless steel is becoming increasingly popular as a construction material in response to demands for more sustainable, durable and resilient structures. As such, the many advantages of stainless steel as a construction material relative to other more traditional metals such as carbon steel are being readily acknowledged by researchers and practitioners. These include the excellent mechanical strength and ductility characteristics and exceptional corrosion resistance, as recognized in the latest version of the Eurocode [1] and stainless steel design manual [2]. The following characteristics of stainless steel are particularly noteworthy and relevant at the current time:

- Ready availability of a large number of grades with different properties, to satisfy various applications;
- High strengths with considerable strain-hardening and excellent ductility;
- Good to excellent uniform corrosion resistance, without the need for any other additional protection; and
- Relatively low thermal conductivity properties and excellent behaviour (strength retention) at high temperatures.

While carbon steels are mostly subdivided into a number of grades depending on their nominal yield strength (e.g. S235, 275, S355, etc.), different stainless steel grades are typically classified based on their chemical composition and metallurgical structure. The most common grades in structural engineering are the austenitic, duplex

and ferritic groups; these families are covered by the product standard for stainless steel [3].

The current paper is concerned with the behaviour of structural stainless steel following exposure to elevated temperatures and subsequent cooling. This is critically important for the rehabilitation and salvage plans for a real structure and is an increasingly important topic in the current age of sustainability and re-use of materials. In this context, new post-fire data is presented and combined with other experimental results to draw some conclusions. There are two fundamental research questions which are considered:

- How does stainless steel behave following exposure to fire conditions and how does it compare to carbon steel?
- Are the post-fire mechanical properties influenced by the load history? The considered beam is loaded, heated then cooled down as in a real fire situation: does this have an influence on the mechanical properties, post-fire?

As the probability of a local fire is estimated as being 14 times greater than a fully developed fire [4], the importance of this research is to be found in assessing critical components or parts of structures which are not easy to replace. The influence of the cooling process seems to be small according to the data available in the literature (e.g. references Table 3). Nevertheless, a key question is whether or not it is economically viable to locally take advantage of the better material properties of stainless steel during fire? This can perhaps be extended to complete parts of structures (such as

frames), in situations where reinstatement works at a lower level would cause the temporary closing of upper levels for example.

Two different test programmes are discussed in this paper, intending to study the influence of heating and then cooling of stainless steel as well as the influence of load history on the post-fire material behaviour. The relevant scenarios are schematically represented in Figure 1. In the first series, coupon tests are conducted on samples taken from a previously tested stainless steel structural member which was subjected to elevated temperature [5]. These are denoted as the 'loaded test' scenario in Figure 1 and are depicted by the dashed line. Secondly, the 'virgin' samples (solid line in in Figure 1) refer to tests done on coupons after a heat treatment, i.e. the coupons are heated to a specified temperature, cooled down and then mechanically tested. In a real situation however, the component is loaded, heated, cooled down due, for example, to the intervention of the fire brigade, perhaps partially unloaded (for reinstatement works), to get back in service again. This is named 'real behaviour' (Figure 1) and is depicted by the centre line in the figure.

Figure 1 Load history versus time for several regimes. The temperature is provided by varying the colour of the line.

To assess the performance of stainless steel components in their post-fire condition, uncertainties in the material properties must be reflected based on a probabilistic theory [6]. For that reason, a large number of tests were collated from the literature and are included in the following discussions. Based on this analysis, through the partial factor method, characteristic values are proposed. The current paper proceeds with a brief description of the fire test which was conducted prior to extracting these 'loaded test' samples, and this is following by the analysis of the 'virgin' post-fire mechanical properties.

2 Stainless steel members at elevated temperature

There has recently been considerable research into the behaviour of stainless steel structural elements during a fire, although many of the studies are either numerical (when looking at large-scale behaviour) or smaller-scale material tests. In 2018, for the first time in the public domain, a fire test was conducted on a full-scale stainless steel cellular beam which was exposed to uniform static loading and a standard fire, as shown in Figure 2 [5].

With a load ratio of 30% of the design load, the beam was tested in a furnace in accordance with the EN1363-1 [7] and EN1365-3 [8] up until failure (without fracture). The beam was installed in a furnace chamber at Tampere University. The total length of the beam exposed to fire was 4000 mm and it was made from austenitic grade 1.4301 stainless steel. It had an overall depth of 290 mm and the width of the flanges was 300 mm. The beam flange and web thicknesses were 14 mm and 8 mm, respectively. The specimen also included 8 mm thick web stiffeners located at the beam supports and at the load application points on both sides of the web. The diameter

of the circular openings was 200 mm and they were located at 300 mm centres. A series of 250 mm thick aerated concrete blocks were placed on top of the beam during testing, in order to simulate the floor slab and provide three-sided heating.

Figure 2 Cellular beam during installation above the furnace [5]

During the test, the temperatures were recorded by a range of thermocouples. The average maximum temperature measured in the cross-section during the test was 759 °C and the maximum temperature in the web was recorded at 785 °C. The difference between bottom and top flange temperatures was about 250 °C, mainly owing to the presence of the concrete blocks on the top flange. Similar temperature development was recorded in across all of the beam sections. The failure mechanism was initiated by web post buckling between the loading point and the beam support [5]. It was also demonstrated numerically that high failure temperatures can be achieved thanks to the higher strength retention inherent to stainless steel, compared with carbon steel [9].

For austenitic grade 1.4301, the nominal reduction factors for the proof strength ($f_{0.2}$) and Young's modulus (E), which are denoted as $k_{0.2,\theta,SS}$ and $k_{E,\theta,SS}$ respectively, are shown in Figure 3 [10], together with the equivalent values for carbon steel ($k_{Y,\theta,CS}$ and $k_{E,\theta,CS}$). It is clear that stainless steel retains its strength up to 500°C after which, between 500 and 600°C, the reductions of the yield (or proof) strength and Young's modulus (E) begin to drop quite rapidly.

Figure 3 Reduction of yield strength and Young's modulus for carbon and grade 1.4301 austenitic stainless steel according to Eurocode 3 Part 1-2 [10].

As mentioned previously, a load ratio of 30% was applied to the tested cellular beam. The theoretical critical temperature using the guidance given in Eurocode 3 Part 1-2 [10] for this beam is 777°C (compared with 759°C during the experiment) whilst an identical beam made from carbon steel can theoretically last until 664°C. Both theoretical critical temperatures are illustrated in Figure 3 by, respectively, a dashed and centre vertical grey line. In summary, the research conducted into this stainless steel cellular beam showed that the member performed better than a carbon steel equivalent beam, and survived for a longer period. The focus in the current paper is investigating whether this improved fire performance extends to the post-fire behaviour, and if stainless steel beams consequently require less effort and cost for rehabilitation.

3 Experimental programme

In the following subsection, the details of the two test programmes on previously loaded and virgin test samples, respectively, are described. Before presenting this data, it is worth noting some of the key characteristic values that are significant for stainless steel which demonstrates non-linear stress-strain behaviour with large degrees of strain hardening. The benefits of this characteristic on the strength of cross-section is extensively taken into account in the continuous strength method (CSM) [2] which will be employed later in this paper. Stainless steel material properties are typically defined using 4 key parameters: 0.2% proof strength ($f_{0.2}$), ultimate strength (f_u), total strain corresponding to the ultimate strength (ϵ_u) and the Young's modulus (E). This is in contrast to carbon steel which is usually described using an elastic-perfectly plastic constitutive response, requiring only the yield strength and Young's modulus.

3.1 Loaded specimens

In section 2 of this paper, an elevated temperature test programme on a welded stainless steel cellular beam was described. After testing, this beam was allowed to cool naturally, in the furnace (CIF), and then a series of coupons were cut from the tested beam, in order to facilitate the current study. A total of 18 tensile test coupons were cut and tested representing the areas of maximum bending moment and shear force in the beam, as shown in Figure 4, together with the load arrangement. Three coupons were taken from each location. The beam was tested under two point-loading which produced constant bending moment in the portion of the specimen between the loads (A, C and E) and constant shear outside the loading points (B, D and F). The test was terminated when the web posts buckled between the load application point F2 and the beam support.

Figure 4 Cellular stainless steel beam and the locations of the tensile coupon specimens

Tensile coupon tests for the specimens were prepared and conducted at ambient temperature in accordance with EN 10002 [11]. An extensometer of 25 mm gauge length was used to measure longitudinal tensile strain of the coupon specimens. The loading machine (MTS 810 Material Test System) was driven by displacement control and the crosshead separation rate was 5 mm/min. The parallel length of the coupons was 120 mm. Tensile loading was applied to the specimens until fracture. The extensometer was used to measure the extension of the test pieces up to 7% strain. Above this deformation level only the force and crosshead separation were monitored. The percentage elongation after fracture was then determined after the tests.

The stress-strain curves from these the tensile tests are presented in Figure 5 and the data is given in Table 1, including the maximum temperature that was measured at that location, during the fire test (θ_{exp}). The data that is presented in italic text is from samples taken from the web of the beam. Tests on the flange coupons show that

there are no significant differences between the post-fire strength values determined at different beam locations. With reference to Figure 5, it is clear that the samples taken from similar locations (e.g. D1, D2 and D3 which are in the web, in the high shear zone) are very similar to each other, as expected. Generally, the samples in the high moment (mid-span) regions (i.e. the A, C and E samples from the bottom flange, web and top flange, respectively) retained less of their strength after heating, compared with the equivalent samples taken from the shear zone. The difference is as high as 90 N/mm² in some cases in the web regions. However, the difference in the web ultimate strength values was much lower, around 15 N/mm². It is noteworthy that the coefficient of variation was less than 0.02 for the strength values and therefore the response of sample F2 can be assessed as an outlier compared to F1 and F3.

Figure 5 Stress-strain response for the previously loaded and heated samples.

Table 1 Test results of coupons out of heated beam (*italic values = web*)

Coupon	θ_{exp} (°C)	$f_{0.2}$ (N/mm ²)	f_u (N/mm ²)	E (kN/mm ²)
A1	838	262	616	209.2
A2	832	256	613	183.4
A3	838	261	615	189.5
B1	784	259	613	191.7
B2	775	278	621	194.5
B3	784	258	605	185.6
E1	642	263	607	191.4
E2	636	275	611	197.3
E3	642	285	613	195.1
F1	580	287	613	194.2
F2	559	338	637	202.9
F3	580	287	612	196.0
C1	834	282	641	189.6
C2	834	282	638	182.1
C3	823	281	642	189.0
D1	794	368	657	182.4
D2	794	370	656	183.4
D3	779	376	662	206.7

3.2 Unloaded specimens

In the previous section, the details of material tests taken from coupons that were extracted from a previously loaded and heated stainless steel cellular beam were described. In the current section, similar coupon tests are described although in this case, the material was not taken from the tested beam, but from virgin material which was taken from the plates that the cellular beam was made from.

A total of 30 tests were conducted on both 8 mm and 14 mm thick

samples (i.e. from the flange and web plates used in the beam), and the details are given in Table 2. Each coupon was initially heated to the target temperature (θ) in an oven at a rate of 10 °C/min and then allowed to soak at the target temperature for 20 minutes, accordance with the details given elsewhere [12]. After this, the coupons were generally quenched in cold water (CIW) to cool them, representative of what might happen in a real fire. To study the effect that cooling type has on the post-fire mechanical properties, additional tests were done at 750°C for both the 8 mm and 14 mm thicknesses, where the coupons were removed from the oven and allowed to cool naturally in air (CIA). Once the coupons were at room temperature, a standard tensile test was completed, in accordance with the procedure proposed by Huang and Young [12].

Table 2 Test results of coupons out of virgin specimens (italic values = web)

t (mm)	θ (°C)	Cooling method	E (kN/mm ²)	$f_{0.2}$ (N/mm ²)	f_u (N/mm ²)	ϵ_u (%)	f_{fr} (N/mm ²)	ϵ_{fr} (%)
8	20	CIW	178.8	269.1	625.7	59.0	366.6	67.2
8	250	CIW	200.9	272.1	632.3	59.1	457.7	66.1
8	500	CIW	210.4	269.3	632.1	59.6	441.7	67.1
8	750	CIW	184.1	255.3	639.3	55.9	497.2	62.6
8	750	CIA	203.7	237.7	613.6	57.5	454.4	64.3
14	20	CIW	188.9	264.3	679.9	63.7	523.9	72.4
14	250	CIW	198.9	287.8	684.7	48.9	532.8	57.1
14	500	CIW	188.9	281.8	697.0	63.9	548.3	72.8
14	750	CIW	186.6	263.8	705.8	61.3	582.1	69.5
14	750	CIA	218.2	257.8	693.7	63.2	542.5	71.7

The results from the post-fire virgin (unloaded) coupon tests are given in Table 2, where f_u and ϵ_u are the ultimate stress and strain, respectively, and f_{fr} and ϵ_{fr} are the stress and strain at fracture, respectively. In addition, the stress-strain curves are presented in Figure 6. As stated before, 3 repeats were completed for each test, and the average value are presented in the table and figure.

With reference first to the curves presented in Figure 6, it is clear that the general form of the stress-strain curves remains unchanged after exposure to elevated temperature, including the nonlinearity and degree of strain hardening that occurs. The various observations from the data in the table are outlined hereafter.

Young's modulus: For both the 8 mm and 14 mm coupons, there was an increase in E when the coupons were exposed to temperatures up to 500°C. After exposure to 500°C, E increased by 17.7% for the 8 mm thick sample compared with the equivalent ambient value. However, after exposure to 750°C, the E value was actually 3% and 4% lower for the 8 mm and 14 mm coupons, respectively, compared with the corresponding values at ambient temperature. Generally, the effect on Young's modulus after a coupon has been exposed to elevated temperature was more noticeable for the 8 mm coupons than the 14 mm samples. With reference to the cooling method, for both 8 and 14 mm coupons, the increases in Young's modulus after exposure to 750°C was noticeably greater for the air-cooled coupons, most likely owing to the slower cooling method.

Figure 6 Post-fire stress-strain curves on grade 1.4301 stainless steel

0.2% proof stress: For the 8 mm coupons, the 0.2% proof stress generally remained the same until 500°C. After this point, there was a 5% decrease in the value at 750°C. On the other hand, for the 14 mm coupons, there was an increase in $f_{0.2}$ after exposure to 250°C and 500°C of 9% and 7%, respectively. After higher temperatures, there was a very marginal decrease in $f_{0.2}$. Converse to the earlier observations for E, for both the 8 mm and 14 mm coupons, there was a greater decrease in $f_{0.2}$ for the samples that were air cooled after being heated to 750°C compared to those that were quenched in water. So, whilst the Young's modulus actually increased when the samples were cooled slowly (in air), the strength reduced in this same scenario. This is due to the metallurgical changes that occur with these changes in temperature conditions.

Ultimate strength: The ultimate strength remained more or less the same across all temperature ranges examined for both the 8 mm and 14 mm coupons. The samples that were air cooled after being heated to 750°C demonstrated marginally lower ultimate strengths than those that were water cooled – this is similar to the observations that were made for $f_{0.2}$.

Ultimate strain: It is clear from the data presented in Table 2 that the ultimate strain of the stainless steel material remains relatively unchanged from its ambient value even after exposure to 250°C or 500°C. After it has been heated to 750°C, there is a slight decrease in the ultimate strain of around 5% of the ambient value, for the samples that were cooled in water. This decrease is even less for those coupons that were cooled in air.

Fracture point: In terms of the eventual fracture of the coupon, the strength at which this occurred was generally greater for coupons that had been heated to higher degrees of elevated temperature. This increase was quite notable for both the 8 mm and 14 mm samples, reaching 23% and 11% respectively of the corresponding ambient values. This observation was less pronounced for the coupons that were air-cooled, similar to $f_{0.2}$ and f_u . Conversely, the coupons that were exposed to relatively higher temperatures experienced earlier fracture in terms of the ϵ_{fr} value. In this instance, the fracture strain for the coupons that were air cooled was closer to the ambient value compared with the samples that were quenched in water.

In conclusion to this section, it is generally observed that the thickness of the sample, and the method of cooling is quite impactful to the residual properties of the materials after exposure to temperature. For the samples considered in this study, it is shown that quenching the coupons in water rather than allowing the samples to cool naturally in air resulted in greater retention of the strength terms ($f_{0.2}$, f_u and f_{fr}) but the corresponding strain values were somewhat reduced. However, this was not observed by others [13, 14, 15]

4 Discussion: behaviour of stainless steel following exposure to fire conditions

A comprehensive literature study was conducted in which around 270 post-fire tests of stainless steels were presented from 8 peer reviewed articles ([16]- [15]), including the data presented earlier in this paper. Table 3 gives an overview of the articles and defines set numbers which will be used to discuss the results.

Table 3 List of articles, authors, set number and date of publication

Article	Authors [reference]	Set No.	Year
Residual behaviour of steel re-bars and R/C sections after fire	Felicetti et al. [16]	1,2	2009
Stress-strain model of austenitic stainless steel after exposure to	Wang et al. [17]	3,4,5	2014

elevated temperatures			
Post-fire behaviour of ferritic stainless steel materials	Huang et al. [18]	6	2017
Residual mechanical properties of stainless steels S30408 and S31608 after fire exposure	Gao et al. [14]	7	2018
Behaviour of three types of stainless steel after exposure to elevated temperatures	Tao et al. [19]	8,9,10	2018
Mechanical properties of lean duplex stainless steel at post-fire condition	Huang et al. [13]	11	2018
Behaviour of stainless steel bolts after exposure to elevated temperatures	Hu et al. [15]	12,13	2019
Performance of stainless steel structures following a fire	Current paper	14, 15, 16, 17	2020

This data includes samples taken from reinforcement, sheets, plates and cold-formed welded hollow sections (in the corners and opposite to the welded face) and bolts. It is subdivided into 17 sets mainly depending on the material types involved in the research. Comparison will be made with a set of data concerned with carbon steel specimens containing 718 tests, but, more specifically, against results of 187 tests on low alloy steel with yield strengths up to S420 grade. The details of the carbon steel references can be found in a paper soon to be published by the same authors. A brief summary can be found in section 4.3.

4.1 Definition of symbols and graphical presentation

The retention factor R_θ at a temperature θ (°C) is the characteristic 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. Normalized values x_i are calculated by dividing the considered property by its mean initial value i.e. for an unheated specimen $= x_{i,0}/x_{i,20}$. Using normalized values eases the analysis by erasing the effect of a possible over-strength compared to the nominal value of the property.

The full set of all these normalized data is presented in Figure 7. Different symbols are used in the figure as will be throughout the paper: circular dots for austenitic (●), squares for duplex (■) and plain triangles for ferritic (▲) stainless steels. Bigger dots are used for the test results described in section 3.2 (unloaded, CIW); and non-filled circular symbols (○) are for the 'loaded test' data presented in section 3.1 (CIF). R_θ is the product of the reduction factor k_θ and a recovery factor r_θ ($= R_\theta/k_\theta$). Stainless and carbon steels both 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 7 Overview of all recorded normalized properties

An example of the reduction, recovering and retention for grade 1.4301 stainless steel is presented in Figure 8 plotted on a logarithmic scale, for the 0.2% proof strength where the initial factor $k_{0.2,0}$ is taken from [2]. It is seen that, up to 900°C, this grade almost completely recovers its proof strength and that at 1200°C the loss only reaches 28% ($r_\theta = 0.72$).

Figure 8 Reduction, recovery and retention factor for $f_{0.2}$ of EN1.4301 stainless steel

4.2 Statistical processing of the data series

The derivation of the design values based on tests should be carried out by appropriate statistical techniques [20]. In general, for a single property evaluation, the characteristic value is used [21]. Out of a defined number of samples, the characteristic value of a property X_k can be calculated following Eq. (1) where 'exp' denotes the natural exponential function. Note that the use of a lognormal distribution is recommended by [22] and the use of fractile factors k_n as provided in Table 4 for a known coefficient of deviation V_x . Presently, an upper value of V_x is used, taken as equal to unity for the carbon steel specimens listed in [22], as shown in Table 5.

$$X_k = \exp(m_y - k_n s_y) \quad (1)$$

The mean value m_y , standard deviation s_y and coefficient of variation V_x are given by equations (2) to (4). As the work is conducted with normalized values, V_x is finally equal to s_x .

$$m_y = \frac{1}{n} \sum \ln(x_i) \quad (2)$$

$$s_x = \sqrt{\frac{1}{n-1} \sum (x_i - m_x)^2} \quad (3)$$

$$s_y = \sqrt{\ln(V_x^2 + 1)} \approx V_x = s_x/m_x \quad (4)$$

Table 4 Fractile factors based on V_x known (without $\infty/1,64$) [21]

n	1	2	3	4	5	6	8	10	20	30
k_n	2.31	2.01	1.89	1.83	1.80	1.77	1.74	1.72	1.68	1.67

Table 5 Coefficient of variation for low-alloy carbon steel [22]

Property	$V_x = V_{amb}$
f_y	0.07
f_u	0.04
ϵ_u	0.06
E	0.03

Even with the total number of collated data being equal to 260, the number of data per heating temperature and per group remains limited (< 30 each). In addition, it was noticed that on some occasions, a higher heating temperature resulted in a better post-fire property probably due to a change in metallurgical properties, as discussed

previously. This is the reason for separating some of the data sets in the current analysis. A roundoff of 20°C is however used, so that a heating temperature of 505 °C, for example, belongs to the dataset of 500°C. Therefore, the notation θ means an interval ranging from $\theta-20$ to $\theta+20$ °C.

The base material property is, by nature, also characterized by a certain coefficient of variation at ambient temperature. It is assumed that the measured coefficient of variation from the test V_{test} can be expressed by Eq. (5) where V_{amb} is given in Table 5 and V_{post} is the coefficient of variation due to the post-fire situation (logically ≥ 0):

$$V_{\text{test}}^2 = V_{\text{amb}}^2 + V_{\text{post}}^2 \quad (5)$$

However, a very limited number of tests lead to unrepresentative deviations. To avoid this, the proposed retention factor R_θ is adjusted in accordance with Eq. (6) where $\theta-1$ and $\theta+1$ are the preceding and following temperature intervals. This operator makes that the retention factor will never rise and that for a point k the maximum value of k itself or the mean value of the previous and value is taken. This process is illustrated in Figure 9.

$$R_{k,\theta,\text{proposal}} = \min\left(R_{k,\theta-1}; \max\left(R_{k,\theta}; \frac{R_{k,\theta-1} + R_{k,\theta+1}}{2}\right)\right) \quad (6)$$

Figure 9 Calculated raw and processed data for the proof strength of grade 1.4301

Where $k_{y,\text{SCI-A}}$ stand for the reduction according to [2], $r_{y,\theta}$ the retention values before applying the operator out of Eq. (6) and $R_{y,\theta}$ after applying the operator. The method, as described above, is purely analytical and unbiased by some engineering judgement. For this reason, the factors resulting from this assessment are ideally suited to the assessment of post-fire properties.

4.3 Reference values for carbon steel

Although carbon steel is not the focus of the current paper, a brief summary of a similar analysis for carbon steel is presented herein to highlight the differences with stainless steel. Besides the clear ductility requirements (expressed as $f_u/f_y \geq 1.1$, $\epsilon_u \geq 15\%$ and $\epsilon_u \geq 15\epsilon_y$ [23]), the main important parameters for low alloy carbon steel are the yield strength basically characterizing its resistance and Young's modulus E governing displacements and instabilities. The post-fire verifications are only done for structures or components which still meets the requirements for serviceability limit states (deformations).

As those are covered by the different buckling curves prescribed in the Eurocode [23], all the results (184 points) for low alloy steels up to S420 without cold forming or heat treatment are given in Figure 10. A full yield strength recovery is obtained until a temperature of about 600°C, followed by a linear decrease of the property up to a loss (of the yield strength) of roughly 20% at 750°C. After this, it is observed that there is a plateau up to 900°C when carbon steels start to again lose strength (35% loss at 1000°C). The dashed curve

is the strength reduction factor ($k_{y,\theta}$) during heating according to Eurocode 3 Part 1-2 [10] and the solid line indicates the retention factors ($R_{y,\theta}$). It is notable that there is a relatively large overstrength at ambient temperature shown by some samples.

Figure 10 Yield strength reduction factor ($k_{y,\theta}$) and retention factor ($R_{y,\theta}$) for low-alloy carbon steel up to S420

For the Young's modulus (Figure 11), the scatter of the results is much smaller and full recovery can even be seen until about 700°C. With reference to the values given Table 5, this was an expected conclusion. The retention factor ($R_{E,\theta}$) decreases linearly hereafter until it reaches around 0.85 at 1000 °C.

Figure 11 Retention factor valid for E and low-alloy carbon steel out of 106 tests

For carbon steel, the risk of failure due to instability or excessive deformations will be predominant during the fire. In the post-fire conditions however, the opposite is true, and the resistance will become the main concern. In addition, it is also reported in the literature that for normal [24] and high strength [25] grades the soak time (time exposed to higher temperatures) and the cooling procedure can largely influence the post-fire behaviour.

5 Design considerations

Based on the test results presented in Section 3, it appears that the ability of grade 1.4301 stainless steel to recover its mechanical properties is almost complete after exposure to fire. The post-fire ultimate strength (f_u) however seems to decrease even for temperature of only 250°C. This reduction stays constant until the highest test temperature of 834°C. The design models most commonly used for stainless steel structures, such as the CSM [2], require knowledge of the ultimate strength of stainless steel. The following sections present a more detailed discussion on the post-fire properties of the different stainless steel families typically used in construction, including all of the available data.

5.1 Austenitic stainless steels

The majority of the information available in the literature pertaining to the post-fire behaviour of stainless steel is relating to the austenitic grades, including the data from 151 individual tests (see Table 3). These tests include specimens that were heated and then cooled either in air, in the furnace or in water. Different soaking periods have also been used across the various programmes. In this analysis each grade (e.g. Grade 1.4301) is followed by a forward slash symbol (/) which is then followed by the set number, as given in Table 3. The test specimens which were subjected to a cold working process were excluded from this analysis, which included some samples from set 1 and set 4. In fact, it was noticed that cold working (induced during fabrication) has a negative impact on the post-fire behaviour and should be treated separately which is beyond the scope of the current work.

Figure 12 shows the results for all austenitic tests together with the reduction factor ($k_{0.2,\theta}$) for grade 1.4301 stainless steel [2] (dashed line) as well as the proposed values for $R_{0.2,\theta}$ obtained by statistical analysis (solid line) in the current work. The legend is not anymore repeated and data in these figures show the following:

- The 0.2% proof strength ($f_{0.2}$) starts to decrease from 800°C almost linearly to 70% of its initial value at 1200°C.
- No change can be observed for the ultimate strength (f_u).
- For the ultimate strain, a linear decrease from 1.0 to 0.93 is observed between 200 and 400°C. Afterwards this value remains constant until 1200°C.
- The Young's modulus starts to decrease immediately but this reduction halts at around 300 °C after which the value remains constant at around 90% of the unheated value.

(a)

(b)

(c)

(d)

Figure 12 Test results from austenitic stainless steel samples including (a) $f_{0.2}$, (b) f_u , (c) ϵ_u and (d) E

5.2 Duplex stainless steels

In comparison with the austenitic stainless steels, there is a notable dearth of data available on the duplex grades, in the literature (33 tests). Grades 1.4162/11; 1.4362/9; 1.4462/9 are included in these, the first set is from rectangular hollow sections and the others are cut from sheets. Figure 13 shows the results for all duplex tests together with the reduction factor $k_{y,\theta}$ for grade 1.4362 in the design guide [2] and the proposed values based on statistical analysis. It is seen that these results show the same tendency as the austenitic stainless steel family, previously discussed and the primary observations are given as:

- The 0.2% proof strength starts to decrease at 500°C almost linearly to 80% of its initial value at 600 °C and then remains constant until 1200°C.
- Almost no change can be observed for the ultimate strength in these tests. At 1000 °C a loss of only 4% is observed (based on only 3 tests, however).
- The ultimate strain is decreasing linearly from 1.0 to 0.8 between 20 and 700°C. From 700°C and above, very high ultimate elongations are reached on tested cooled down samples.
- The Young's modulus directly starts to decrease but starting from 300 °C it remains equal to 90% of the unheated value.

(a)

(b)

(c)

(d)

Figure 13 Test results from duplex stainless steel samples including (a) $f_{0.2}$, (b) f_u , (c) ϵ_u and (d) E

5.3 Ferritic stainless steels

An extensive study into the ferritic family on grade 1.4003 is found in sets 6 and 10 (Table 3). In total 75 tests are available which are also submitted to several cooling procedures in the set number 6 [18], including cooling in the furnace, air, forced air using a fan and in water. In general, it is concluded that this has negligible effects with exceptions for the ultimate strain. Coupons are taken out of hollow sections and sheets. Figure 14 shows the results for all ferritic tests together with the reduction factor $k_{0.2,\theta}$ for grade 1.4003 [2] and the proposed values based on statistical analysis.

The behaviour of the ferritic stainless steel grades is different to the austenitic and duplex grades due to a changing microstructure during the heating-cooling cycle. Between 850 and 1000 °C, the ferrite transforms to martensite [2]. Also, the grain size of the plated martensite increases with higher temperatures. It is the martensite which explains the increasing yield and ultimate strengths for the samples taken out of the hollow sections. The coupons out of the sheet however do not show this behaviour.

- The 0.2% proof strength $f_{0.2}$ shows a drop between 500 and 600 °C with a reduction reaching 65% of its initial value. Starting from 800°C, the samples start to re-gain their strengths which is however not taken into account in the proposed final value of

the retention factor. The re-gain of strength is sometimes remarkable above 850 °C.

- For the ultimate strength f_u , no reduction could be observed.
- For the ultimate strain, after heating up to 600°C and more, very high ultimate strains are reached after cooling. However the proposal does not take it into account, resulting in a step-wise decrease from 1.0 to 0.0 between 500 and 1100°C.
- The Young's modulus starts to decrease from 1100 °C onwards and reaches 80% of its initial value at 1200°C.

(a)

(b)

(c)

(d)

Figure 14 Test results from ferritic stainless steel samples including (a) $f_{0.2}$, (b) f_u , (c) ϵ_u and (d) E

5.4 Safety factor considerations

The coefficient of variation V_{post} has an impact on the characteristic

value but also on the safety factors i.e. the design value that should be used in the assessment of the building for reinstatement purposes. This can easily be demonstrated by Eq. (7) applied to the yield strength [20]:

$$f_{yd} = \frac{m_y}{\sqrt{1+V^2}} \exp\left(-\alpha\beta\sqrt{\ln(1+V^2)}\right) \quad (7)$$

where α is the sensitivity factor equal to 0.8 (resistance effect, recommended value for general cases [21]) and β is the reliability index which is, for new designed buildings, equal to 3.8. The coefficient of variation V equals V_{amb} in the case of a new building, as provided in Table 5. So, the characteristic value f_{yk} is obtained by replacing the product $\alpha\beta$ by 1.645 in Eq. (7) and the safety factor γ_{M0} is calculated through Eq. (8). For virgin material with $V_{amb} = 0.07$, the result equals to 1.10 i.e. exactly the value mentioned in the code [1] for stainless steel.

$$\gamma_{M0} = \frac{f_{k,\theta}}{f_{d,\theta}} = \frac{\exp\left(-1.645\sqrt{\ln(1+V^2)}\right)}{\exp\left(-\alpha\beta\sqrt{\ln(1+V^2)}\right)} \quad (8)$$

However, with increasing uncertainties with respect to temperature (see sections 5.1 to 5.3), this value will not remain constant but will depend on the maximum exposed temperature θ , as is $V_{test,\theta}$. For reason of easiness of the mathematical expressions, we will work with the product of $\gamma_{M0,amb}$ [1] by an additional safety factor $\gamma_{M0,post}$, see Eq. (9).

$$\gamma_{M0} = \gamma_{M0,amb} \cdot \gamma_{M0,post} \quad (9)$$

Substituting respectively V_{test} , V_{amb} and V_{post} in Eq. (8) delivers values for γ_{M0} , $\gamma_{M0,amb}$ and $\gamma_{M0,post}$.

Using this approach however, the final safety factor γ_{M0} is overestimated. As proposed in [26] for non-dominant variables, some adjustment of the sensitivity factor is required to have a less conservative approach. Based on all the test data collated in this paper (for all grades), the coefficient of variation V_{post} can be calculated for each temperature as well as the corresponding safety factor $\gamma_{M0,post}$. The evolution of all 3 coefficients of variation as well as all 3 safety factors is shown in Figure 15. Comparison is made between the safety factor γ_{M0} based on the tests (using V_{test} and Eq. (8)) and the one obtained using Eq. (9) (indicated as 'product' in Figure 15).

Figure 15 Coefficients of variation V_{post} and safety factors γ_{M0} valid for the post-fire scenario with $\beta = 3.8$.

The reliability index β of 3.8 (corresponding to a failure probability of $7.2 \cdot 10^{-5}$) is valid for new buildings. It is based on economic considerations since human safety issues are already ensured through much lower reliability indices [27]. For that reason, it is proposed to presently base our calculations on a reliability index of 3.3 which is

consistent with ISO 2394 [28] or even 3.1 as in [27]. The effect of this decreased index will compensate partially for the effect of increasing V_{post} . If heating goes up to above 550°C where V_{post} has a value of 0.07, the use of Eq. (8) together with a β of 3.1 leads to a safety factor γ_{M0} lower than 1.10, see Figure 16. At 550°C, it starts to increase but remains limited until a temperature of about 800°C. In practice, this means that a more refined study to assess the structure's reliability would only be needed when the temperature becomes higher than 800°C. It is important to note that, based on the study completed to date, for the Young's modulus, the post-fire effect is negligible.

Figure 16 Coefficients of variation V_{post} and safety factors γ_{M0} valid for the post-fire scenario with $\beta = 3.1$.

6 Conclusions

Today, re-using and / or rehabilitating structures following an extreme event should always be the preferred option compared to dismantling it, for economic as well as obvious environmental reasons.

In this paper, first, the influence of the load history on the mechanical behaviour of stainless steel dog-bone coupon was investigated as well as the effect of the cooling method on specimens from the same batch. It follows that both effects have no impact on the mechanical behaviour and that that strain hardening is occurring in the highly loaded shear areas.

Secondly, a quite extensive literature review is conducted on test results from either full parts of structures or on coupons submitted to high temperature and then cooled down in a controlled environment. The material characteristics such as proof and ultimate strengths as well as Young's modulus after exposure to high temperature are then extracted from all references and graphically analysed. One first demonstrates that the most commonly used grades of stainless steel retain most of their strength and stiffness after exposure to very high temperatures. The results also show that the heating level, cooling method and sample thickness are all influential to the retention of strength and stiffness after fire.

Thirdly, the coefficient of variation on the material properties V_{post} due to post-fire situation is evaluated for a range of temperatures, based on the collated experimental data. Assuming a reliability index β of 3.1 according to ISO 2394 and a higher measured coefficient of variation from the test V_{test} as provided in Eq. (5), the calculated post-fire safety factor γ_{M0} (for the reinstatement of stainless steel structures following exposure to fire and subsequently cooled), which varies depending on the maximum reached temperature, reaches acceptable values (lower than 1.10 or 1.20 until, respectively, 550°C or 800°C).

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