Strain-rate effects on S690QL high strength steel under tensile loading

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ARTICLE INFO

Article history:
Received 21 May 2020
Received in revised form 5 September 2020
Accepted 7 September 2020
Available online xxxx

Keywords:
High strain-rates
Tensile tests
SHTB
High strength steel (S690QL)
Material constitutive laws

ABSTRACT

High Strength Steels are increasingly demanded in building constructions, shipbuilding and other industries. Hard impact and explosion are possible hazards for steel structures as high-rise buildings, bridges, ships, offshore. Present lack of data sets under high strain-rates might be generate uncertainty in structural assessment under severe dynamic events. In this work a comprehensive experimental investigation of the S690QL structural steel under dynamic tensile loading is presented. Round specimens (extracted from inner and outer zone of plate 40 mm thick) 3 mm in diameter and a having gauge length of 5 mm were tested in order to obtain the stress-strain flow data under three different loading regimes, i.e. quasi-static (10−3 s−1), medium (3–30 s−1) and high strain-rates (250–950 s−1). The results indicate that both core and peripheral parts are moderately strain-rate sensitive. High strain-rate results were compared with those of S355 and S960QL steels in similar conditions. Finally, the stress-strain data of both zones were analysed to determine the material parameters of existing widely used constitutive models.

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1. Introduction

Currently, the development of new high-performing materials (high and very high strength steels) and the needs to enhancing the design of particular steel structures require more accurate numerical modelling especially for dynamic loads such as those caused by blasts and impact loadings. Even though in most civil engineering constructions mild steel is used, there is an increasing demand in using high-grade steels such as high (HSS) and very high (VHSS) strength steels, e.g. in high rise buildings, mobile cranes, offshore structures as well as long-span bridges. Replacing mild structural steels by HSS and VHSS results in unchanged load capacities with a simultaneous reduction in material thickness offering a substantial weight saving [1–3] and leading to numerous advantages such for example longer or lighter spans, reduced lifting and transport costs, greater load-carrying capacities as well as reduced welding needs. Moreover, these materials offer higher strengths in comparison to mild steels, keeping the uniformity of properties with time, the ability to be fastened together by simple connection devices, the adaptation to prefabrication and the ability to be rolled into a wide variety of shapes and sizes. On the contrary, it is worth noting that the use of VHSS and/or HSS is generally limited as a result of the deficiency of design guidelines as well as long term experience [3], which are added to other drawbacks such as particular difficulties in assembling (e.g. galvanising) and higher costs. Moreover, while comprehensive studies exist on both numerical analyses and experimental investigations for high strength steel columns [4–10], seismic performances [11–16], structural performances [17,18], fatigue and ductility behaviour [19,20] as well as welding properties [21,22], the strain-rate effects have been poorly investigated [23–27].

Shi et al. [4] modelled a series of S690 steel column and experimentally analysed the overall buckling behaviour of S690 and S960 steel column [5]. Wang et al. [6,7] performed a parametric analysis based on their results on the overall buckling behaviour of high strength (460 MPa) steel box- and H-columns. An experimental investigation on the overall buckling behaviour of S960 steel columns was performed by Ban et al. [8]. Li et al. [9] studied the overall buckling behaviour of high strength steel welded box- and H-columns with nominal yield strength of 690 MPa. Based on their experimental results, the same authors [10] elaborated a numerical analysis for simulating the compressive column behaviour. In order to understand the plasticity development of cross-section under severe seismic actions several cyclic experiments, parametric studies and numerical investigations have already been conducted on H-section beam-columns and box-section beam-columns made of Q460 steel [11], Q460D [12], Q690 [13–16]. Wang et al. [17] carried out a deep experimental investigation into the structural performance of compressed high strength steel hollow sections. Different structural hollow sections were examined. In addition, quasi-static tensile tests were performed on samples machined from the hollow sections and the basic stress-strain properties were determined. Shi et al. [18] collected and statistically analysed an extensive range of test data of the HSS produced by steel manufacturer in China. Statistical parameters of the material properties were obtained. De Jesus et al. [19] compared the fatigue behaviour between the S355 mild steel and
the S690 high strength steel grades. In comparison to the S355 mild steel, the S690 HSS showed a higher resistance to fatigue crack initiation but a lower resistance to crack propagation. 

Hradil et al. [20] proposed a rational method for estimation of ductility requirements for selected steel details and particular design situations. Guo et al. [21] investigated the micro structural characteristics and the mechanical properties of HSS plates following their joining by multi pass ultra-narrow gas laser welding (NGLW) and gas metal arc welding (GMAW). Comparing the two welding processes, differences in tensile strength and elongation were found. In a previous study the same authors [22] investigated the same properties on S960 HSLA steel plates welded using a fibre laser system, finding that the tensile properties of the laser welded joint matched those obtained for the base material. Yang et al. [23] performed an experimental study on the dynamic behaviour of S690 steel at intermediate strain-rates (from 266 s\(^{-1}\) to 4109 s\(^{-1}\)) in compression using a Split Hopkinson Pressure Bar setup [25]. The mechanical behaviour in tension of a VHSS (S960QL) under extreme conditions (20–900 °C and 0.001–900 s\(^{-1}\)) was studied by Cadoni et al. [26]. Alabi et al. [27] performed tensile tests on S690QL and S960QL high strength steels at intermediate strain-rates (from 0.04 s\(^{-1}\) to 100 s\(^{-1}\)).

In conclusion, a scarcity of full stress-strain data sets for high strength steels (HSS) under dynamic conditions has been highlighted. As a consequence, further experimental researches are highly recommended [23]. This need is attempted to be remedied in this paper by studying the mechanical tensile properties of samples obtained from a S690QL high strength steel plate (\(t = 40\) mm) in a wide range of strain-rates: quasi static (0.001/ s), intermediate (3–30 s\(^{-1}\)) and high strain-rates (250–950 s\(^{-1}\)). Core and peripheral materials have been examined in order to study the relative sample position influence. A comparison between peripheral and core mechanical properties is reported. Moreover, also a comparison between the tensile property results on the S355 low-alloy structural steel [28] and on the S960QL very high strength steel [26] tested in the same dynamic conditions is reported as well. Finally, material parameters of the main constitutive material models are also determined.

2. S690QL structural steel

The S690QL structural steel [29] has been studied in this research. This steel is commonly adopted where higher strength is required, i.e. for long-span bridge components, bearing element in high-rise buildings, off-shore structures and cranes, in power plants, mining applications or LPG vessel, etc. In quasi-static conditions and 20 °C, the minimum nominal tensile yield strength is 690 N/mm\(^2\) while the ultimate tensile strength is 770 N/mm\(^2\) [30]. Samples were obtained from commercially available S690QL plate 40 mm thick by means of WEDM (Wire-Electrical Discharge Machining) as described in [26].

Hardness measurements of the whole section (\(t = 40\) mm) was performed to verify the material property uniformity. Hardness Vickers (HV30) measurements highlighted a limited difference between the external peripheral (~7 mm) and the internal core materials (Fig. 1). As a consequence the samples were worked out in the longitudinal direction from steel plates from two different positions as highlighted in Fig. 1. A detailed description of the samples preparation (Fig. 2) has been reported in Cadoni et al. [26], while a detailed description of the geometry is reported in Cadoni et al. [31]. The chemical composition [32] is the following: C (0.168%), Si (0.318%), Mn (1.35%), P (0.010%), S (0.0006%), N (0.0039%), Mo (0.220%), Ni (0.050%), Cr (0.277%), V (0.000%), Nb (0.023%), Ti (0.001%), B (0.0016%), Zr (0.002%), Al (0.038%) and Fe (balanced).

![Fig. 1. Hardness measurements HV30 within the whole section thickness.](image)

![Fig. 2. Samples preparation steps.](image)
The micrographs are shown in Fig. 3(a) and in Fig. 3(b), where the inner (core) part shows a bainitic structure (B) while the outer (peripheral) part shows a martensitic structure (M).

3. Experimental techniques

With the aim to investigate the dynamic behaviour of this steel three different regimes have been selected, i.e. low, medium and high strain-rates. For each regime different machines have been adopted three different experimental techniques by keeping the same specimen shape and size. The specimen elongation have been contactlessly measured by the displacement of two black-and-white edges (targets) on it by means of an electro-optical Extensometer H.-D. Rudolph GmbH (Model 200XR) having measurement frequency range of 0–250 kHz (Fig. 4). For the tests at medium (3 s$^{-1}$, 30 s$^{-1}$) and high strain-rates (250 s$^{-1}$, 450 s$^{-1}$ and 950 s$^{-1}$) the data have been acquired with a HBM Gen2-Genesis HighSpeed Transient Recorder & Data Acquisition System with maximum sample rate of 1 MHz. During the dynamic tests a fast cameras IDT- MotionPro Y4-S3 with 50kfps has been used.

3.1. Mechanical testing at low strain-rates

The quasi-static tests have been carried out by means of an electro-mechanical universal machine Zwick/Roell - Z50 (Fig. 4(a)). The precision of load cell used is 0.01. The mechanical extensometer used is of 0.3 μm resolution and the software used to monitor the experimental data is TestXpert.

3.2. Mechanical testing at medium strain-rate

The medium strain-rate regime has been investigated by using a Hydro-pneumatic Machine (HPM) (Fig. 4(b)) designed for the determination of the mechanical characteristics in strain-rate range between $10^{-1}$ and $5 \cdot 10^1$ s$^{-1}$ [33–35]. It consists of a sealed piston that divide a cylindrical tank in two chambers: one chamber is filled with gas at high pressure (e.g. 150–180 bars), the other one is filled with water. The test starts by activating a fast-electro-valve, as a consequence the second chamber discharges the water through a calibrated orifice. The end of the piston shaft is connected to the specimen that is fixed to...
the supporting structure through an instrumented bar. Depending on the velocity of the gas expelling from the chamber regulated by the choice of a fixed calibrated orifice, a specific constant strain rate is applied to the tested sample. Two different calibrated orifices having diameter of 1 and 3 m were used in order to obtain two target strain-rates of about 3 and 30 s$^{-1}$, respectively.

### Table 1
High strain-rate test plan for the S690QL structural steel.

| Test condition | Bar speed (m/s) | Imposed load (kN) | Target strain-rate (s$^{-1}$) |
|----------------|----------------|-------------------|-----------------------------|
| S690QL Core & Peripheral | 2.67 | 16.6 | $\varepsilon = 250$ |
| Core | 3.26 | 20.3 | $\varepsilon = 450$ |
| Core & Peripheral | 4.68 | 29.1 | $\varepsilon = 950$ |

#### 3.3. Mechanical testing at high strain-rate

A Split Hopkinson Tensile Bar (SHTB) [36,37] has been used to study the dynamic behaviour at high strain-rates. A SHTB consists of two circular straight high strength steel bars, having a diameter of 10 mm, with a length of 9 and 6 m, respectively (Fig. 4(c)). The first 6 m of the longer bar is used as a pretensioned bar and the other 3 m as input bar. The second bar is entirely used as output bar. The cylindrical sample is screwed between the input and output bars. The testing velocity is governed by the amplitude of the stress of the pretensioned bar obtained by pulling it with a hydraulic actuator. The pretension load is beared by a blocking system. The test starts when the a fragile bolt in the blocking system breaks, so it is suddenly released. In this way a very long loading pulse with 2.4 ms duration with linear loading rate during the rise time (30 $\mu$s) is generated causing dynamic tensile loading on the sample. A detailed description of the SHTB functioning as well as the basic assumptions to be fulfilled in order to obtain an accurate measurement of the mechanical properties of a material under dynamic loading has been reported in [28,31]. As a consequence it is possible to apply the one-dimensional elastic plane stress wave propagation theory. The stress (1), the strain (2) as well as the strain-rate (3) versus time can be then evaluated:

$$\sigma(t) = E_0 \frac{A_0}{A} \varepsilon_T(t) \quad (1)$$

$$\varepsilon(t) = -\frac{2C_0}{L} \int_0^t \varepsilon_R(t) \, dt \quad (2)$$

$$\dot{\varepsilon}(t) = -\frac{2C_0}{L} \varepsilon_R(t) \quad (3)$$

where $E_0$ is the modulus of elasticity of the bars, $A_0$ is input and output bars cross-section, $A$ is specimen cross-section within the gauge length $L$, $C_0$ is the elastic wave speed in the bar, $\varepsilon_T$ and $\varepsilon_R$ are the transmitted and reflected pulses, respectively.

The strain has been evaluated by means of Eq. (2) and verified by means of the electro-optical direct measure as well. Three different target strain-rates were imposed at 250 s$^{-1}$, 450 s$^{-1}$ and 950 s$^{-1}$ (Table 1). The imposed load in the pretensioned bar was evaluated in order to obtain the target strain rate. In fact, the strain rate of the plastic zone is a function of the reflected pulse (Eq. (3)) that is obtained by subtracting the transmitted pulse (related to the material response also considering the dynamic increment) from the incident pulse (which remain constant for the whole duration of the test) [33]. At least three satisfactory

![Fig. 5. Quasi-static representative results.](image)

![Fig. 6. Representative engineering stress-strain diagrams.](image)
tests for each testing condition were performed. The results obtained from the S690QL high strength steel have been compared with those obtained from a similar mechanical characterisation on the S355 [28] and S960 [26] steels.

4. Results and discussion

In order to make a comparison between the main mechanical properties at room temperature obtained from the S690QL high strength steel with those obtained from the S355 [28] and the S960QL [26] structural steels the same tensile properties evaluated in these researches were determined. For the sake of clarity all the mechanical tensile property data are reported in Tables 3–4. The quasi-static test results are shown in Fig. 5. The S690QL structural steel shows slightly higher peripheral values of the flow stress data than the core material. On the contrary, the S960QL structural steel has an opposite behaviour: lower peripheral flow stress data than the core material. This consideration lead to the conclusion that the hardenability of specific steels may be governed by the quenching and tempering processes as well as the alloy design. [26,32,33,38].

Because of the high test repeatability at the same testing condition, only representative engineering curves at specific strain-rate are depicted (Fig. 6). The strain-rate sensitivity is highlighted in Fig. 6. At increasing strain rates both the materials (core and peripheral) keep their strain hardening abilities. In addition, at the higher speed testing condition (ε ~ 950s\(^{-1}\)) an instability is present (upper and lower yield strengths) in both materials.

The dynamic increase factor (DIF) such as the ratio between the dynamic to the quasi-static strength can be used as an important parameter to measure the rate sensitivity of a specific mechanical property. DIFs for the proof (\(f_{0.2\%}\)) and the ultimate (\(f_u\)) tensile strengths have been calculated. In Fig. 7 the average values have been reported. From this Figure it is possible to point out that the higher strain rate sensitivity

| Table 2 | Dynamic increase factor (DIF) fitting coefficients. |
|---------|-------------------------------------------------------|
|         | Core                  | Peripheral                  |
|         | A        | n        | A        | n        |
| Proof strength | 1.0288   | 0.025718 | 1.0013   | 0.015239 |
| Ultimate tensile strength | 1.0384   | 0.013942 | 0.9968   | 0.017083 |

Fig. 7. Dynamic Increase Factors for: proof tensile strength (a), ultimate tensile strength (b) and comparison (c,d) with available data in literature [23,27].
is highlighted up to 400 - 450 s\(^{-1}\). Then, in the range between 400 s\(^{-1}\) and 950 s\(^{-1}\) the DIFs trend reach a slightly horizontal plateau, meaning that in this strain-rate range the material is less strain-rate sensitive. Fig. 7 shows how the experimental data (up to 950 s\(^{-1}\)) can be well approximated by a power law. From a designing point of view, one can predict the dynamic proof tensile and ultimate tensile strengths starting from the quasi-static tensile values. The proposed equations is:

\[
f_d = f_s \cdot A \cdot \varepsilon^n\]  

(4)

where, \(A\) and \(n\) are fitting coefficient reported in Table 2, while \(f_d\) and \(f_s\) are the dynamic and the quasi-static tensile strengths, respectively.

It is well known \cite{1} that the steel strengthening mechanisms used to develop high strength steels lead to a yield strength increase but have much less influence in the subsequent strain hardening behaviour. This means that high strength steels (\(f_y > 500\) MPa) show reduced capacity for strain hardening after yielding and reduced elongation than lower strength steels (\(f_y < 500\) MPa). This is also specified on EN 1993-1-12 \cite{30} which recommend minimum requirements for the \(f_u/f_y\) ratio (\(\geq 1.05\)), elongation at failure higher than 10% and uniform strain not less than 15\(f_y/E\). These parameters have been evaluated at the imposed strain-rates for the S690QL steel. A comparison with the same parameters evaluated for the S355 \cite{28} and S960QL \cite{26} structural steels is reported as well (Figs. 8 and 9). From Fig. 8 it is possible to observe that in quasi-static conditions the above mentioned structural steels comply with the limit value of \(f_u/f_y \geq 1.05\). At high strain rates the limit value is not reached, as shown in Fig. 8. It is worth noting that this should not be intended as a norm violation, but it express only the ductility reduction (or embrittlement) of the material at high strain rate. This ratio is referred to the dynamic values of \(f_u\) and \(f_s\), it decrease with increasing the strain rate because the DIF of yield is higher than those of ultimate strengths (see Fig. 7). A different behaviour is observed for the uniform strain (Fig. 9(a)) which should not be less than 15\(f_y/E\). In fact, only in quasi-static conditions the S960QL structural steel fully meets the specific standards, while at high strain-rate both the materials comply the limit values. With regard to the elongation at failure (Fig. 9(b)), which should not be less than 10%, the evaluated parameters meet the specified standard limit.

Another parameter used to highlight the different behaviour between the high strength steels and steels of lower grade is the so called yield ratio (YR). This parameter is defined as the ratio of yield to ultimate tensile strength and generally increases as the strength of the steel increases. This is highlighted in Fig. 10(a) in quasi-static conditions. A different behaviour is observed at high strain-rates (Fig. 10(b), (c) and (d)), where a limited increase is noted.

Thanks to a post-mortem measurement at the reduced sample section (diameter and the meridional radius of curvature), it has been possible to evaluate the last two points of the true stress-strain curves by using the Bridgman \cite{39} formulae (see eqs. 7 and 8).

The strain energies have been evaluated as the integral of true stress-strain curves \cite{26} till fixed strain values. The modulus of resilience, \(U_y(\varepsilon = \varepsilon_y)\), the modulus of toughness \(U_f(\varepsilon = \varepsilon_f\), true\), and the strain energy up to the true uniform strain, \(U_u(\varepsilon = \varepsilon_f)\) were then assessed.

5. Constitutive material models

5.1. True stress and true strain

The engineering stress-strain curves are normally used in order to obtain elastic and plastic material properties (i.e. proof strength, ultimate tensile strength, uniform strain, plastic hardening exponent,
etc.). These provide satisfactory information for structural design. Namely, for most engineers the interest is still limited to a solely engineering stress vs. strain curve, or in a more simple load-elongation curve from the tensile test. In case of extreme loadings (impact, blast), finite element codes require constitutive relationships that describe the material behaviour including large plastic deformations. The true stress and true strain curve can be obtained by the engineering stress and strain values as follows:

\[
\varepsilon_{\text{true}} = \ln \left(1 + \varepsilon_{\text{eng}}\right)
\]

\[
\sigma_{\text{true}} = \sigma_{\text{eng}} \cdot \left(1 + \varepsilon_{\text{eng}}\right) / C_0 / C_1
\]

These relations are valid only up to the uniform strain. Beyond this point, where the necking starts, the flow curve is governed by a stress triaxial state in the specimen. The triaxial state of stress in the necking zone is alike to those created in the notch of a circumferentially notched round specimen. The correction factor is given by the widely used Bridgman equation [39]. It requires diameter reduction and radius

\[R = 2a\]

Fig. 10. Yield Ratio (YR) for different strain-rate ranges and different structural steels.

Fig. 11. Reduced sections obtained form high speed camera records.

Fig. 12. True stress as a function of the true plastic strain: (a) at two distinct high strain-rates for core samples; (b) at the same strain-rate (250 1/s) for core and peripheral samples.
change in necked geometry. Then, after necking starts, the following equations have been used to evaluate the true stress-strain data:

\[ \sigma_{\text{true}} = \sigma_{\text{true},0} \left(1 + \frac{\varepsilon}{\varepsilon_0}\right)^n \]  

(7)

where, \( \varepsilon_0 \) is the initial strain while \( \sigma \) and \( R \) are the radius and the meridional profile curvature radius of the specimen at the reduced cross section (Fig. 11). The value depicted in Fig. 12 were calculated by Eqs. (7) and (8) from the measurement of \( \sigma \) and \( R \) obtained from high speed camera records (Fig. 11).

The true stress versus true plastic strain curves obtained monotoni-

ically increase and can be described by the well-known power expres-

sion due to Hollomon:

\[ \sigma = k \varepsilon^n \]  

(9)

where, \( K \) and \( n \) are the strength coefficient and the work hardening exponent, respectively.

5.2. Constitutive material models

The material behaviour to different mechanical and thermal loading conditions can be described by the stress-strain relations given by a con-

stitutive material model [40]. Due to their accuracy, their simple form and their easiness of implementation in the numerical simulations, widely used constitutive models are the strength models which relate the deviatoric stress to deviatoric strain. Two commonly used rate-

dependent models of this type are the Johnson-Cook [41] and the Cowper-Symonds [42] models. For their optimal calibration, both the models require a solid experimental dataset, which is the main reason

### Table 3

Experimental results (core samples).

| Target strain-rate, \( \varepsilon \) (s\(^{-1}\)) | Quasi-static | Medium strain-rate | High strain-rate |
|-----------------------------------------------|--------------|-------------------|-----------------|
| 0.001                                        | 0.001        | 3.6 ± 0.3         | 29 ± 8          |
| Reduction of area \( Z \) (%)             | 74.5 ± 2.3   | 72 ± 1            | 73 ± 1          |
| Up. yield strength, \( f_{\text{y,up}} \) (MPa) | n.r.         | n.r.              | n.r.            |
| Low. yield strength, \( f_{\text{y,low}} \) (MPa) | n.r.         | n.r.              | n.r.            |
| Proof strength, \( f_{\text{p,core}} \) (MPa) | 775 ± 5      | 870 ± 32          | 843 ± 42        |
| Effective yield strength, \( f_{\text{y,eff}} \) (MPa) | 778 ± 1      | 873 ± 30          | 833 ± 44        |
| Effective yield strength, \( f_{\text{y,core}} \) (MPa) | 774 ± 5      | 883 ± 54          | 859 ± 29        |
| Effective yield strength, \( f_{\text{y,core}} \) (MPa) | 786 ± 10     | 881 ± 57          | 868 ± 31        |
| Effective yield strength, \( f_{\text{y,core}} \) (MPa) | 917 ± 94     | 882 ± 55          | 869 ± 29        |
| Effective yield strength, \( f_{\text{y,core}} \) (MPa) | 808 ± 9      | 908 ± 51          | 876 ± 31        |
| Effective yield strength, \( f_{\text{y,core}} \) (MPa) | 808 ± 3      | 914 ± 63          | 874 ± 29        |
| Ult. tensile strength, \( f_{\text{u}} \) (MPa) | 817 ± 6      | 908 ± 37          | 890 ± 31        |
| Uniform strain, \( \varepsilon_0 \) (%) | 4.0 ± 0.4    | 6.6 ± 0.9         | 7.9 ± 0.6       |
| Eng. strain, \( \varepsilon_0 \) (MPa) | 434 ± 18     | 599 ± 62          | 646 ± 124       |
| Eng. strain, \( \varepsilon_0 \) (%) | 20.1 ± 1.1   | 27.3 ± 11         | 263 ± 5.9       |
| True strain, \( \varepsilon_0 \) (MPa) | 1410 ± 53    | 1758 ± 160        | 1931 ± 412      |
| True strain, \( \varepsilon_0 \) (%) | 1.37 ± 0.09  | 1.28 ± 0.04       | 1.30 ± 0.03     |
| Strain energy, \( U_f \) (MJ/m\(^3\)) | 1.43 ± 0.02  | 1.8 ± 0.1         | 1.70 ± 0.2      |
| Strain energy, \( U_f \) (MJ/m\(^3\)) | 31 ± 2       | 57 ± 10           | 68 ± 5          |
| Strain energy, \( U_f \) (MJ/m\(^3\)) | 139 ± 6      | 220 ± 9           | 209 ± 31        |

### Table 4

Experimental results (peripheral samples).

| Target strain-rate, \( \varepsilon \) (s\(^{-1}\)) | Quasi-static | Medium strain-rate | High strain-rate |
|-----------------------------------------------|--------------|-------------------|-----------------|
| 0.001                                        | 0.001        | 2.8 ± 0.1         | 38 ± 2          |
| Reduction of area \( Z \) (%)             | 74.8 ± 1.3   | 71.7 ± 1.4        | 72.0 ± 0.1      |
| Up. yield strength, \( f_{\text{y,up}} \) (MPa) | n.r.         | n.r.              | n.r.            |
| Low. yield strength, \( f_{\text{y,low}} \) (MPa) | n.r.         | n.r.              | n.r.            |
| Proof strength, \( f_{\text{p,core}} \) (MPa) | 808 ± 4      | 839 ± 11          | 870 ± 6         |
| Effective yield strength, \( f_{\text{y,eff}} \) (MPa) | 774 ± 33     | 837 ± 12          | 868 ± 12        |
| Effective yield strength, \( f_{\text{y,eff}} \) (MPa) | 808 ± 5      | 830 ± 9           | 854 ± 4         |
| Effective yield strength, \( f_{\text{y,eff}} \) (MPa) | 814 ± 7      | 832 ± 10          | 859 ± 6         |
| Effective yield strength, \( f_{\text{y,eff}} \) (MPa) | 821 ± 6      | 834 ± 9           | 865 ± 7         |
| Effective yield strength, \( f_{\text{y,eff}} \) (MPa) | 854 ± 6      | 864 ± 7           | 892 ± 8         |
| Effective yield strength, \( f_{\text{y,eff}} \) (MPa) | 840 ± 6      | 859 ± 9           | 894 ± 5         |
| Ult. tensile strength, \( f_{\text{u}} \) (MPa) | 857 ± 5      | 870 ± 8           | 901 ± 2         |
| Uniform strain, \( \varepsilon_0 \) (%) | 6.6 ± 0.3    | 6.9 ± 0.2         | 7.7 ± 1.5       |
| Eng. strain, \( \varepsilon_0 \) (MPa) | 435 ± 8      | 572 ± 3           | 615 ± 53        |
| Eng. strain, \( \varepsilon_0 \) (%) | 41.3 ± 0.8   | 30.2 ± 0.1        | 33.8 ± 10.0     |
| True fract. Strain, \( \varepsilon_{\text{true},\text{up}} \) (MPa) | 1397 ± 56    | 1604 ± 98         | 1721 ± 142      |
| True fract. Strain, \( \varepsilon_{\text{true},\text{up}} \) (MPa) | 1.38 ± 0.05  | 1.26 ± 0.05       | 1.27 ± 0.00     |
| Strain energy, \( U_f \) (MJ/m\(^3\)) | 1.55 ± 0.02  | 1.7 ± 0.0         | 1.8 ± 0.0       |
| Strain energy, \( U_f \) (MJ/m\(^3\)) | 53 ± 1       | 58.5 ± 5          | 67.5 ± 13.5     |
| Strain energy, \( U_f \) (MJ/m\(^3\)) | 293 ± 5      | 234.3 ± 21        | 277.3 ± 82.1    |

\[ \sigma_{\text{true}} = K (\varepsilon_{\text{true}})^n \]
why in this paper it has been chosen their constitutive parameters evaluation.

The Johnson–Cook [41] strength model is a phenomenological model which is based on three effects: isotropic and strain rate hardening as well as thermal softening. In this paper the thermal softening parameter is evaluated by using the quasi-static results obtained on the core and peripheral materials by Neuenschwander [32].

The flow stress at room temperature can be written as:

$$\sigma_{eq} = \left(A + B \varepsilon_{p}^{n}\right) \left(1 + c \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}\right) \left(1-(T^{*})^{m}\right)$$

(10)

where, \(A\), \(B\), \(n\), \(c\) and \(m\) are fitting parameters to be calibrated, \(\varepsilon_{p}\) is the true plastic strain, \(\dot{\varepsilon}\) is strain-rate taken into account, \(\dot{\varepsilon}_{0}\) is the reference strain rate (assumed as 1 \(s^{-1}\)) while \(T^{*}\) is the so called homologous temperature.

Table 5 reports the five evaluated parameters. On the one hand, it can be noted that \(A\), \(B\) and \(n\) (hardening parameters) are similar for core and peripheral materials, with the exception of the \(A\) parameter which represents the quasi-static tensile true yield strength. This difference is due to the different quasi-static behaviour between the core and the peripheral material (see Fig. 5 and Tables 3–4). On the other hand, \(c\) (strain-rate sensitivity) is higher for the core material than for the peripheral material (see Fig. 13). In previous studies Yang et al. [23,25] proposed the fitting parameter evaluated after an experimental dynamic investigation on the same material. The isotropic hardening parameter \(A\) is in good agreement, while \(B\) and \(n\) are slightly different. The strain-rate hardening parameter \(c\) is, on average, in good agreement with the parameters evaluated in this research from the core and peripheral materials. The thermal softening parameter \((m)\) has been calibrated by using the effective yield strength data up to 2.0% of total strain. The obtained values are: \(m_{\text{core}} = 0.712\) and \(m_{\text{peri}} = 0.581\).

The results obtained applying the Johnson–Cook material strength model and the experimental data have been represented in Fig. 14 as a comparison.

The Cowper–Symonds constitutive model gives the quasi-static to dynamic yield strength ratio behaviour:

$$\frac{f_{y,\text{dyn}}}{f_{y,\text{sta}}} = 1 + \left(\frac{\varepsilon}{D}\right)^{1/q}$$

(11)

where, \(f_{y,\text{sta}}\) is the quasi-static yield strength while \(D\) and \(q\) are the coefficient to be determined through the experimental data at room temperature. The evaluated coefficient are reported in Table 6, while the comparison between the experimental and the Cowper–Symonds constitutive model is reported for the peripheral material in Fig. 6.

It is worth observing that the quasi-static yield strength values (\(A\) and \(f_{y,\text{sta}}\)) reported in Tables 5 and 6, are slightly different from the average values reported in Tables 3 and 4. This because, in order to have an improved data fit, the quasi-static yield strength values adopted for the constitutive model calibrations were evaluated neglecting the peak instability in the yield zone.

6. Concluding remarks

In this study the S690QL structural steel has been systematically investigated in a wide range of strain-rates \((10^{-3}-950 \text{ s}^{-1})\). According to the experimental results the following conclusions can be drawn:

- The S690QL steel is moderately strain-rate sensitive (Fig. 6). This is also highlighted by the strain-rate sensitivity coefficients \(c\) evaluated for the core \((c = 0.02572)\) and the peripheral materials \((c =\)
and peripheral parameters using the hardness profile as weight. In this way plate of 12 mm and other commercial available thickness can be easily simulated.

Supplementary researches are presently running with the following aims:

- to verify the mechanical characterisation of the single layers on samples of 12 mm thick (S690QL and S960QL) plates subjected to high strain rate with the project SUSHI (Steel Under Severe High Impact) in the frame of Open Access to JRC Research Infrastructures of the European Commission.
- to investigate the effects of the combination of high strain rates and elevated temperatures (fire followed by blast) on S690QL steel (core and peripheral parts).

Finally, these data will play a capital role in predicting the mechanical behaviour of S690QL in extreme condition of loading and temperature by finite element analysis.

### Declaration of competing interest
None.

### Acknowledgements
This work is part of research project *Behaviour of structural steels under fire in a wide range of strain-rate* founded by the State Secretariat for Education, Research and Innovation of the Swiss Confederation (project C12.0051), in the frame of COST ACTION TU9004 - Integrated Fire Engineering and Response (IFER). A special acknowledgement goes to Matteo Dotta for his precious collaboration in performing the tests, and to Prof. Dr. Mario Fontana and Dr. Markus Knobloch from Institute of Structural Engineering (ETH Zurich) for providing the raw material and for the inspiring discussions.

### Author statement
Ezio Cadoni and Daniele Forni equal contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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