Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 47 (2023) 348–353

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

27th International Conference on Fracture and Structural Integrity (IGF27)

High and Very-High Strength Steels under harsh conditions of temperature and loading

Daniele Forni[a,*], Deborah Briccola[a], Matteo Dotta[a], Nicoletta Tesio[a], Ezio Cadoni[a]

[a] *University of Applied Sciences and Arts of Southern Switzerland - DynaMat SUPSI Laboratory, Mendrisio 6850, Switzerland*

Abstract

A comprehensive understanding of the plastic deformation of material at high strain rates and elevated temperature is required in steel structure design, particularly in special cases (e.g. off-shore, large span bridges, high-rise buildings). High Strength Steel (HSS) and Very High Strength Steel (VHSS) are being used in increasingly modern and advanced structures. When compared to traditional grade steel, they have superior mechanical properties, which result in weight savings and a lower life cycle cost (minor costs for construction and maintenance). To produce these steels, they have to be quenched and tempered. It produces differentiation between materials with martensitic microstructures on the outside and bainitic-ferritic microstructures on the inside. Due to their differentiated microstructures, these steels behave as functional graded materials. Therefore, understanding the mechanical response of homogeneous parts at various strain rates and temperatures is fundamental. The deformation mechanisms of these steels under mentioned combined harsh conditions are complex and depend on the micro-structural features of the material. At high strain rates and elevated temperatures, plastic deformation can occur through mechanisms such as dislocation slip, dynamic plasticity, and dynamic strain ageing. The competition between these deformation mechanisms can lead to a significant change in the mechanical behaviour of these advanced steels, particularly in the strain rate and temperature regimes where these mechanisms are active. In this paper, we will review the recent state of knowledge developed at DynaMat Laboratory on the mechanical behaviour of HSS and VHSS under combined conditions of elevated temperature and high strain rate, including its macro-structural features, deformation mechanisms, and constitutive modelling. The tests were carried out in a wide range of temperature (20÷900°C) and strain rate (10^{-3}÷10^{3} 1/s) by means of a Split Hopkinson Tensile Bar equipped with a water-cooled induction heating system on round specimens having a diameter of 3 mm and gauge length of 5 mm. Both the core and the peripheral parts of the section of two slabs 40 mm thick of S690QL and S960QL steels were investigated.

© 2023 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the IGF27 chairpersons

Keywords: Tensile test; Split Hopkinson Tensile Bar; VHSS; High-strain rates; elevated temperatures.

---

[*] Corresponding author. Tel.: +41-58-666-6396.
E-mail address: daniele.forni@supsi.ch

2452-3216 © 2023 The Authors. Published by ELSEVIER B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the IGF27 chairpersons
10.1016/j.prostr.2023.07.090

1. Introduction

The increased strength properties of high-strength steel and very high-strength steel have led to their growing use in civil, ship, and mechanical engineering over the past decades. Despite their advantages, these steel grades are not so widely adopted due to their high costs, the lack of detailed design codes, and proper experimental data.

Many researchers (Kodur and Banthia (2015); Forni et al. (2016); Forni et al. (2017)) have concentrated their attention in the last few years on constructions in urban habitats subjected to both natural and man-made strong accidents. A few examples include catastrophic earthquakes (such as the Tohoku earthquake in 2011), severe fire loadings (such as the Deepwater Horizon disaster in 2010), gas explosions (such as the BASF headquarters incident in Ludwigshafen in 2016), wind storms, accidental or malicious impacts on critical infrastructures, and, last but not least, terrorist attacks (such as the 2001 World Trade Center terrorist attacks).

Among these extreme acts, terrorism has increased dramatically in recent decades. As a result, structural systems' ability to withstand these loads has gained considerable attention. Consequently, many researchers have studied how to avoid the spreading of an initial local failure caused by extreme loadings. This failure results in the collapse of a disproportionately large part of a structure (HMSO (2011); Ellingwood et al. (2007)). This topic, commonly known as progressive or disproportionate collapse, has gained increasing attention since the early 1970s (Ronan Point building collapse). However, a remarkable increase in knowledge has occurred in this field only since the 9/11 World Trade Center tragedy. As a result, scientists have begun to explore ways to make buildings stronger and safer when they are subjected to extreme conditions, such as fires and explosions.

As a result, materials knowledge under extreme loading conditions, e.g. blasts and fires, has become a relevant problem, but some aspects require further investigation. For example, it is impossible to construct definite empirical equations for structural assessment. In addition, full-scale tests are almost prohibitively expensive, hardly reproducible, and require a great deal of time as well. Depending on the level of risk assessment, numerical analyses of increasing complexity are usually performed to study structural behaviour under extreme loading conditions. Nevertheless, a complex numerical simulation is highly dependent on how well the material behaviour is implemented along with the appropriate computational algorithms. As a matter of fact, when considering blast effects, it is important not to ignore the material's performance at elevated temperatures as well. High temperatures and high strain rates have not been studied much, except in the case of marine structural steels, but under limited temperatures ($-100 \div 200$°C) (Choung et al. (2013); Simon et al. (2018)).

In this paper, a review of recent findings is presented on how S690QL (HSS) (Cadoni and Forni (2019); Cadoni et al. (2022)) and S960QL (VHSS) (Cadoni and Forni (2019)) steel perform under combined conditions of elevated temperatures ($20 \div 900$°C) in a wide range of strain rates ($10^{-3} \div 10^{3}$ 1/s).

Nomenclature

ϵ_I	incident pulse (-)
ϵ_R	reflected pulse (-)
ϵ_T	transmitted pulse(-)
C_0	elastic wave speed in the bar (m/s)
A_0	cross section of the input and output bars (mm^2)
A	cross section of the specimen (mm^2)
L	specimen gauge length (mm^2)
$\dot{\epsilon}$	strain-rate (s^{-1})
$f_{y,dyn}$	dynamic true yield stress (MPa)
$f_{y,sta}$	static true yield stress (MPa)
D, q	Cowper-Symonds constitutive parameters.
ϵ_0	true plastic strain (-)
$\dot{\epsilon}_0$	Johnson-Cook reference strain-rate (s^{-1})
T^*	Johnson-Cook homologous temperature (-)
A, B, n, c, m	Johnson-Cook constitutive parameters.

2. Sample geometry

Starting from the initial section geometry, e.g. plate thicknesses (Fig.1.2), small prismatic samples with 6 x 6 mm cross-sections were obtained from the peripheral and core samples area, respectively (Fig.1.1). The sample geometry, commonly adopted to perform tests at high strain-rates, was then obtained by turning the sample until the final geometry: 3 mm in diameter and having a gauge length of 5 mm (Fig.1.3).

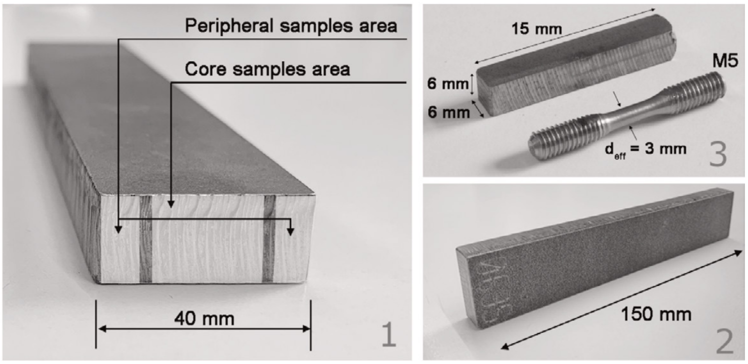

Fig. 1. Sample geometry. From Cadoni et al. (2022).

3. Mechanical tests under harsh combined conditions

To characterize the mechanical properties at high strain rates and elevated temperatures, a Split Hopkinson Tensile Bar was equipped with an Ambrell compact EASYHEAT induction water-cooled heating system with a maximum power of 2.4 kW able to locally heat the sample gauge length up to 900°C. A high-speed camera (*Photron FSTCAM NOVA S12*) was also used to record the whole deformation process. See Fig. 2

In Forni et al. (2016), an exhaustive description of SHTB equipped with a heating system is provided. It also provides the general assumptions to be met to obtain an accurate measurement of a material's mechanical properties under dynamic loading by using the following equations:

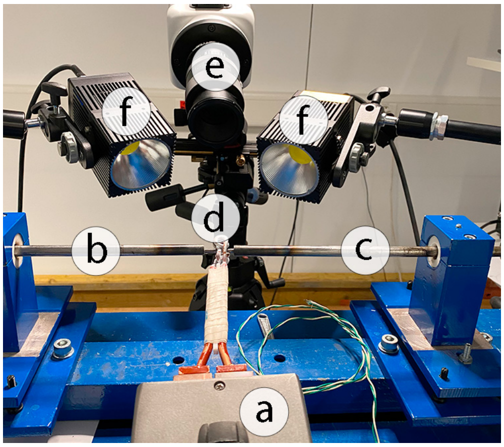

Fig. 2. Setup for high strain-rate tests at elevated temperature: heating system (a), input (c) and output (b) bars, sample to be tested (d) high-speed camera (e), and led lighting system (f).

Material		S690QL			S960QL		
Specimens worked out from	[-]	C, P$^{(1)}$	C$^{(1)}$	C, P$^{(1)}$	C, P$^{(1)}$	C$^{(1)}$	C, P$^{(1)}$
Testing conditions	[-]	v_1	v_2	v_3	v_1	v_2	v_3
Particle velocity	[m/s]	2.67	3.26	4.68	3.36	4.00	5.47
Target strain rate at 20 °C	[s^{-1}]	$\dot{\epsilon}_1^* = 250$	$\dot{\epsilon}_2^* = 450$	$\dot{\epsilon}_3^* = 950$	$\dot{\epsilon}_1^* = 250$	$\dot{\epsilon}_2^* = 500$	$\dot{\epsilon}_3^* = 950$

(1) C = Core, P= Peripheral.

Table 1. Dynamic tests programme carried out at the following target temperatures: 20 °C, 400 °C, 550 °C, 700 °C, and 900 °C.

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

$$\epsilon(t) = -\frac{2C_0}{L} \int_0^t \epsilon_R(t) \quad (2)$$

$$\dot{\epsilon}(t) = -\frac{2C_0}{L} \cdot \epsilon_R(t) \quad (3)$$

Detailed information on the dynamic testing plan under different conditions is provided in the following Table 1.

4. Results and discussion

This experimental investigation has demonstrated that peripheral and core materials are sensitive to high temperatures and strain-rates. Nevertheless, core and peripheral materials of S690 and S960 exhibit comparable flow stress data (e.g. $f_{p,0.2}$ and f_u). Fig. 3 illustrates the effect of temperature on the mechanical properties of peripheral materials (for brevity, only a specific loading condition and only peripheral materials are reported).

In terms of strain rate sensitivity, it has been observed that the core S690 material shows higher strain rate sensitivity than the peripheral part. On the other hand, the peripheral S960 part has slightly higher strain rate sensitivity than the core part.

The temperature effect is clearly visible in Fig. 3, where the flow stress of tests at increasing temperatures is reported. More specifically, an increase in temperature leads to a general decrease in mechanical properties. For example, Fig. 4 highlights the ultimate tensile strength decrease. The rate of decrease is slower up to 400°C than above 550°C, where the decrease rate is higher. Between 400°C and 500°C, a transition zone has been highlighted. Within this temperature range, the strength decrease is limited, and some occasional increases are noted. This phenomenon has been attributed to dynamic strain ageing.

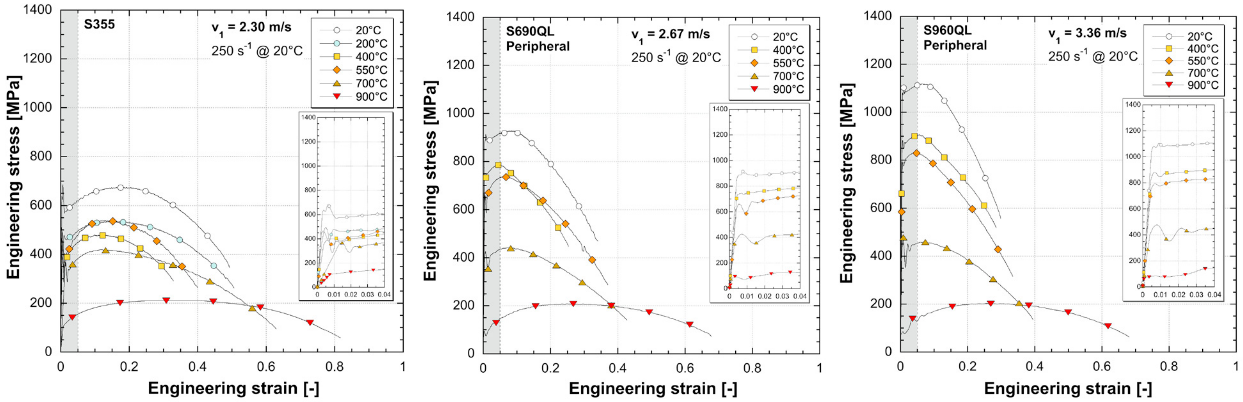

Fig. 3. Engineering stress vs strain diagrams: comparison between S355 (Forni et al. (2016)), S690QL (Cadoni et al. (2022)) and S960QL (Cadoni and Forni (2019)) peripheral materials.

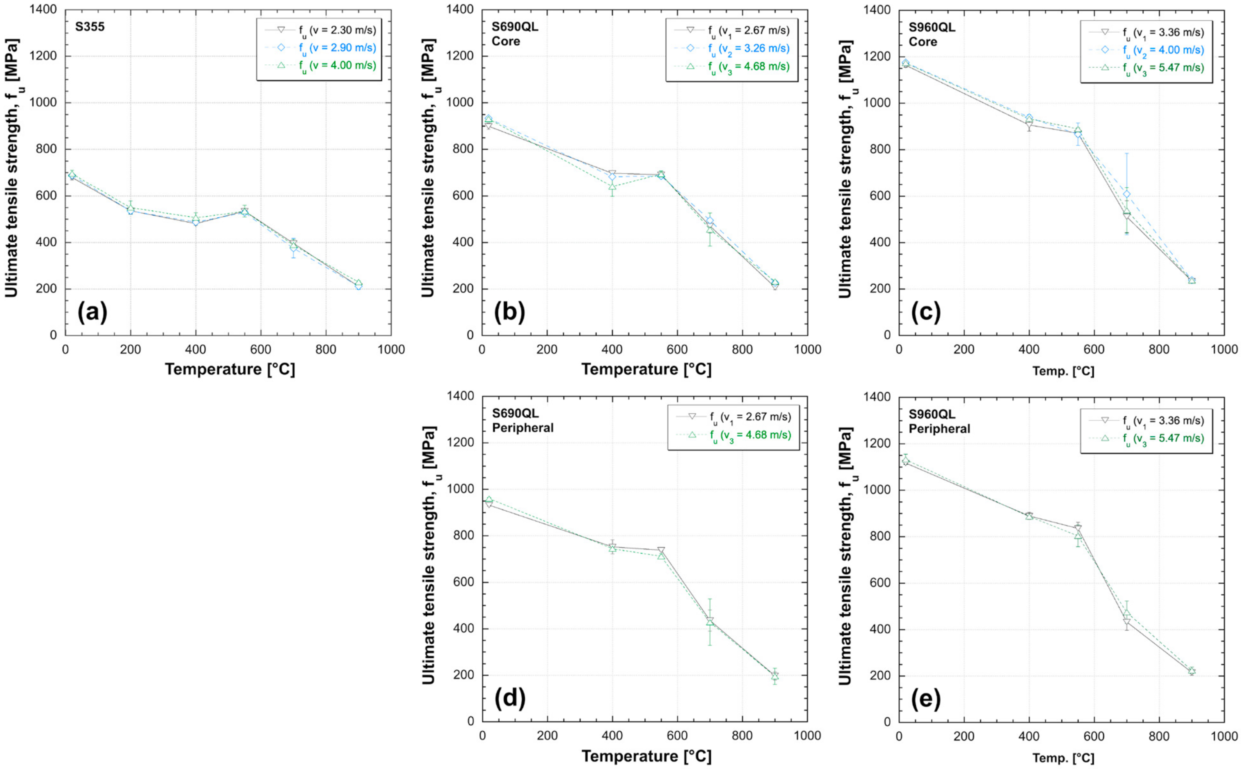

Fig. 4. Ultimate tensile strength reduction trends. Comparison between S355 (Forni et al. (2016)), S690QL (Cadoni et al. (2022)) and S960QL (Cadoni and Forni (2019)) structural steels.

4.1. Material constitutive models

Following the recommendation suggested by Eurocode 3 (EN 1993-1-2), at elevated temperatures, a linear-elliptic-perfectly plastic model followed by a linear descending branch should be adopted. Therefore, the approach of the linear-elliptic-perfectly plastic model has been adopted, and the corresponding stress-strain diagrams have been calibrated from experimental data collected at high strain rates and temperatures. In Fig. 5 a comparison among diagrams calibrated for the S355, S690L and S960QL structural steels has been reported. The main hypotheses and assumptions have been reported in Cadoni et al. (2022).

The experimental data also allowed the calibration of two material constitutive models widely adopted in the numerical simulation of dynamic events. The first represents the dynamic to quasi-static yield stress ratio (eq. 4). It was proposed by Cowper and Symonds. The second is a material constitutive strength model proposed by Johnson and Cook able to represent the whole true plastic behaviour (eq. 5). The constitutive parameters of both models and the specific conditions to be used within numerical simulations were reported in Cadoni and Forni (2019), Cadoni and Forni (2019); Cadoni et al. (2022).

$$\frac{f_{y,dyn}}{f_{y,sta}} = 1 + \left(\frac{\dot{\epsilon}}{D}\right)^{(1/q)} \quad (4) \qquad \sigma_{eq} = (A + B \cdot \epsilon_p^n) \cdot (1 + c \cdot ln\frac{\dot{\epsilon}}{\dot{\epsilon}_0}) \cdot (1 - (T^*)^m) \quad (5)$$

5. Conclusions

The use of modern quenching techniques makes it possible to produce high-strength steel that performs better while being lighter and less expensive. For these reasons, cranes, trucks, dumpers, temporary bridges, and other products are

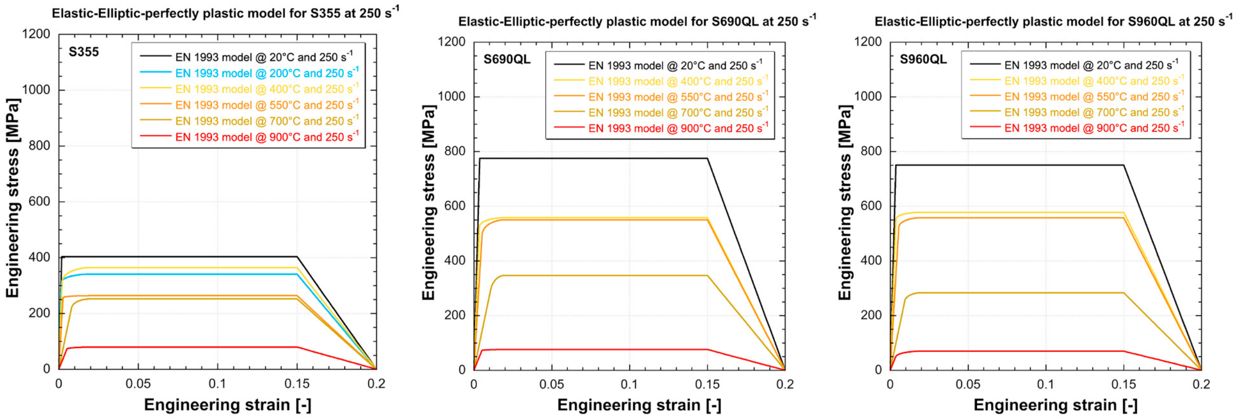

Fig. 5. Modified EN 1993 elastic-elliptic-perfectly plastic model at 250s^{-1} for S355 (Forni et al. (2016)), S690QL (Cadoni et al. (2022)) and S960QL (Cadoni and Forni (2019)) structural steels.

made of HSS and VHSS. However, despite the benefits of using high-strength steel, further experimental research is more than necessary. Exploiting its full potential will require experimental investigations. The behaviour of HSS and VHSS at high temperatures and high strain rates is important when it comes to their application in civil engineering, and data are therefore required. S690QL and S960QL are being investigated as part of this investigation campaign in order to reveal more information and facilitate their widespread use, which is currently hampered by the lack of suitable constitutive mechanical models.

It is also important to consider the ability of the material to dissipate the blast's energy through plastic deformation and its strength characteristics. Therefore, further research in this area is required. Moreover, in view of a correlation between fracture strength and the overall behaviour of HSS after yield and before failure, taking a closer look at the phenomena that occur in the microstructure during testing should be of particular interest.

References

Cadoni, E., Forni, D., 2019, Mechanical behaviour of a very-high strength steel (S960QL) under extreme conditions of high strain rates and elevated temperatures. Fire Safety Journal, 109.

Cadoni, E., Forni, D., 2020, Strain-rate effects on S690QL high strength steel under tensile loading. Journal of Constructional Steel Research, 175.

Cadoni, E., Briccola, D., Dotta, M., Forni, D., 2022, Combined effect of elevated temperature and high strain rates on S690QL high strength steel. Journal of Constructional Steel Research, 199.

Forni, D., Chiaia, B. and Cadoni, E. (2016), Strain rate behaviour in tension of S355 steel: Base for progressive collapse analysis, Engineering Structures 119, 164-173.

Forni, D., Chiaia, B. and Cadoni, E. (2017), Blast effects on steel columns under fire conditions, Journal of Constructional Steel Research 136, 1-10.

Kodur, V., Banthia, N., 2015, Response of Structures Under Extreme Loading, PROTECT 2015, ISBN: 978-1-60595-227-7.

Queen's Printer and Controller of Her Majesty's Stationery Office, 2011, Review of international research on structural robustness and disproportionate collapse. Building regulations: research and Building regulation, ISBN 978-1-40983-007-8.

Ellingwood, B.R., Smilowitz, R., Dusenberry, D.O., Duthinh, D., Lew, H.S., Carino, N.J., 2007, Best Practices for Reducing the Potential for Progressive Collapse in Buildings, NIST Interagency/Internal Report (NISTIR), 7396.

Choung, J., Nam, W., Lee, J.-Y., Lee, 2013, Dynamic hardening behaviors of various marine structural steels considering dependencies on strain rate and temperature, Marine Structures, 32.

Simon, P., Demarty, Y., Rusinek, A., Voyiadjis, G.Z., 2013, Material behavior description for a large range of strain rates from low to high temperatures: Application to high strength steel, Metals, 10.

Forni, D., Chiaia, B., Cadoni, E., 2016, High strain rate response of S355 at high temperatures. Material and Design, 94.

Cowper, G., Symonds, P., 1957, Strain-Hardening and Strain-Rate Effects in the Impact Loading of Cantilever Beams, Division of Applied Mathematics, Brown University.

Johnson, G., Cook, W., 1983, A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures, Proceedings of the 7th International Symposium on Ballistics.