Analysis of the Materials Behaviour at High Strain-Rate in Support of Impact Resistant Structural Design

Ezio Cadoni[1], Matteo Dotta[1], Daniele Forni[1]

[1] DynaMat Laboratory, University of Applied Sciences of Southern Switzerland
Campus SUPSI – Trevano, 6952 Canobbio, Switzerland
ezio.cadoni@supsi.ch
matteo.dotta@supsi.ch
daniele.forni@supsi.ch

Abstract. Nowadays one of the most important challenge for structural engineering is the mitigation of the disastrous consequences, in terms of loss of life and economic impact, caused by extreme loading coming from accidents (explosion, fire), natural disasters (earthquakes, hurricanes, floods) and terroristic attacks (impact and blast). This new scenario imposes to the research community the need to enhance the knowledge of the effects of dynamic loads on structures, analysing as first priority the materials behaviour under such extreme conditions. In this direction, the utilisation of laboratory experimentation with innovative techniques can provide a strong base for the validation of existing computational models, or the implementation of new ones, towards the prediction of the structural responses under these extreme loading conditions. At a second step, it will be possible to develop better strategies for the mitigation of their effects (new technologies and materials). In this paper are described several advanced experimental techniques aimed to understand the dynamic behavior of the materials (metals, UHPC) in different failure modes (tension, compression, shear) at high strain-rate and in combination with high temperature.

Keywords: High strain-rate, Hopkinson bar, Impact, Material characterization, UHPC, Steel.

1. INTRODUCTION

Nowadays one of the most important challenge for structural engineering is the mitigation of the disastrous consequences, in terms of loss of life and economic impact, caused by extreme loading coming from accidents (explosion, fire), natural disasters (earthquakes, hurricanes, floods) and terroristic attacks (impact and blast). This new scenario imposes to the research community the need to enhance the knowledge of the effects of dynamic loads on structures, analysing as first priority the materials behaviour under such extreme conditions. Such type of loadings cause stress and strain wave propagation in the structures and consequently strain-rate in the materials. The strain-rate level can varies from 10^{-1} s^{-1} in case of earthquake to $10^2 - 10^3$ s^{-1} in case of blast. It can be stated that for low level of strain-rate ($\dot{\varepsilon}<10^{-1}$ s^{-1}) the variation of the mechanical properties is not so important and can be neglected. This can be assumed for earthquake but the anomalous failures and unpredicted collapses observed in near-source earthquakes (for example in Kobe) have put in doubt this affirmation. When the ground velocities reach peak over 1.5 m/s [as those recorded during the Northridge (1.77 m/s) or for Kobe (1.76 m/s) earthquakes] the strain-rate in the material can be higher than 10 s^{-1} [Peroni *et al.*, 2013]. Decidedly more elevated are the strain-rates caused by an impact or an explosion. Another important aspect that must be taking into account is the multi-hazard scenary, where multiple extreme loadings are contemporary (for example impact and low/high temperature). This can be very dangerous for the structural safety because coupled phenomena can trigger catastrophic event such as progressive collapses [Forni *et al.*, 2016] or brittle failures.

With this premise can be recognised how the mechanical behaviour of the materials studied in a wide range of strain-rate is fundamental for the comprehension of the structural behaviour under extreme loadings. Furthermore is evident that such behaviour has to be analysed by means of reliable tools that permit to highlight variation of their mechanical properties.

In this direction, the utilization of laboratory experimentation with innovative techniques can provide a strong base for the validation of existing computational models, or the implementation of new ones, towards the prediction of the structural responses under these extreme loading conditions. Consequently, it will be possible to develop better strategies for the mitigation of their effects (new technologies and materials).

In the paper are described several advanced experimental techniques aimed to understand the dynamic behavior of the materials (metals, UHPC) in different failure modes (tension, compression, shear) at high strain-rate and in combination with high temperature.

The results have been obtained in several researches such as those addressed to understand the dynamic response of various sandwich systems against Improvised Explosive Devices, using a combination of reinforced concrete and UHPFRC layers, that is the object of multi-year on-going research conducted in Switzerland and supported by the Federal Department of Defence, Civil Protection and Sport – armasuisse Science and Technology of the Swiss Confederation; or those aimed to understand the dynamic behaviour of the new structural steels in presence of high strain-rate and high temperature, in the frame of the COST Action TU0904 "Integrated Fire Engineering and Response".

All the results have been obtained at the DynaMat Laboratory of the University of Applied Sciences of Southern Switzerland (Lugano). This laboratory (see Figure 1) is fully equipped for the dynamic analysis of the materials and consists in four modified Hopkinson bars, one 3D-Modified Hokinson bar, and two Hydro-Pneumatic Machines and all the equipment for recording (transient recorders, high speed camera, optical displacements fast transducers etc.). The laboratory has been recently included in the list of the Research Infrastructures of national relevance for the Confederation.

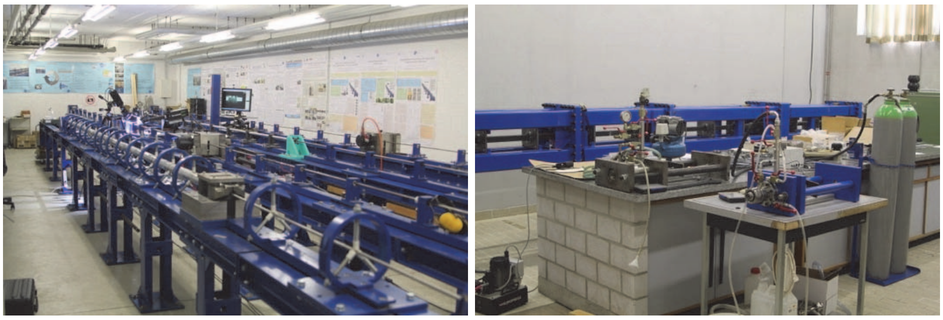

Figure 1. DynaMat Laboratory

2. STRAIN-RATE IN MATERIALS

The mechanical properties of the materials can be influenced by the strain-rate. Its effect can be positive, negative or null. This means that there are materials in which the increase of the strain-rate led to an increase of material properties, other materials behave in the opposite direction i.e. the properties decrease with increasing the strain-rate, finally other materials are insensitive or in a negligible manner to any variation of strain-rate. The causes of such dependence are originated in the material microstructure: in metals the defects and the dislocation mechanic play an important role as well as in quasi-brittle materials plays the fracture phenomenon. In concrete, for example, under low strain-rate tensile loading the fracture process starts from existing micro-cracks and macro-cracks and has the time to choose and develop along the path of least energy requirements, i.e., around aggregate particles and through the weakest zones of the matrix. Due to low overall stress level and relaxation of the material, the extension of micro-cracks in other areas of higher strength is rather limited. Under impact tensile loading conditions much energy is introduced into the structure in a short time, and cracks as concentration points are forced to develop also along a shorter path of higher resistance – through stronger matrix zones and some aggregate particles. The very rapidly increasing overall tensile stress causes extensive micro-cracking in other areas, since relaxation cannot occur in the extremely short time of fracture.

2.1 MATERIAL CONSTITUTIVE RELATIONSHIPS

The material constitutive relationship is a formulation that describe the flow stress as a function of strain, strain-rate and temperature. There are two families of functions. The first is directly obtained by best fitting of experimental values and often expressed as a product of different member each describing only one effect $\sigma(\varepsilon, \dot{\varepsilon}, T) = f(\varepsilon) \cdot g(\dot{\varepsilon}) \cdot h(T)$. The most famous model was proposed by Johnson and Cook [1983]. The second one the flow stress is obtained as addition of different members representing respectively strain hardening, strain-rate and thermal softening. The most popular expression was proposed by Zerilli and Armstrong [1987] in the form $\sigma(\varepsilon, \dot{\varepsilon}, T) = f(\varepsilon) + g(\dot{\varepsilon}) + h(T)$ and is physical based and are consistent with micromechanics of material behaviour (dislocation density etc). These equations need a certain number of experiments at different strain-rate, different temperature, in order to calibrate the model on the material. Higher is the precision of the results higher is the accurateness of the numerical provision obtained.

3. EXPERIMENTAL TECHNIQUES AT HIGH STRAIN-RATE

Dynamic tests are generally more complicated than static tests. In particular in the high strain-rate regime inherent difficulties are present due to inertia effects, specimen geometry, and stress-wave propagation phenomena. Each regime of strain-rate is governed by some certain phenomena as reported in Table 1.

Table 1. Strain-rate for different cases of loading

Case of loading	Strain-rate	Governing phenomena	Machine
Quasi-static.	$10^{-6} \div 10^{-5}$ s^{-1}	Frame rigidity, isothermal, inertia force neglected	Universal hydraulic or electro-mechanic machine.
Gas explosion, earthquake.	$10^{-3} \div 10^{-1}$ s^{-1}	Vibration and resonance	
Soft impact, pile driving, aircraft landing.	$10^{-1} \div 10^{1}$ s^{-1}	Vibration and resonance, inertia forces	Drop weigth machine, Swinging pendulum, Hydro-Pneumatic machine.
Hard impact, blast.	$10^{2} \div 10^{3}$ s^{-1}	Wave propagation, adiabatic	Hopkinson bar, SHPB, Taylor test.
High velocity impact.	$10^{4} \div 10^{5}$ s^{-1}	Shock-wave propagation, plane strain.	Gas gun, explosive driven plate impact.

The experimental techniques in different regimes have to allow a precise characterization of material taking into account the variables that influences the material behaviour.

3.1 SPLIT HOPKINSON PRESSURE BAR

The most suitable tool and commonly accepted test method for studying the material behaviour undergoing impact loadings is the split Hopkinson bar. This technique was developed firstly for compression test [Davies, 1948; Kolsky, 1953]. It consists of applying a pressure stress wave by shooting a projectile normally to the transversal cross-section of a first bar, called input bar, giving rise to a stress wave propagating along the input bar, then acting on a specimen inserted between the input bar and another bar called output bar (see Figure 2).

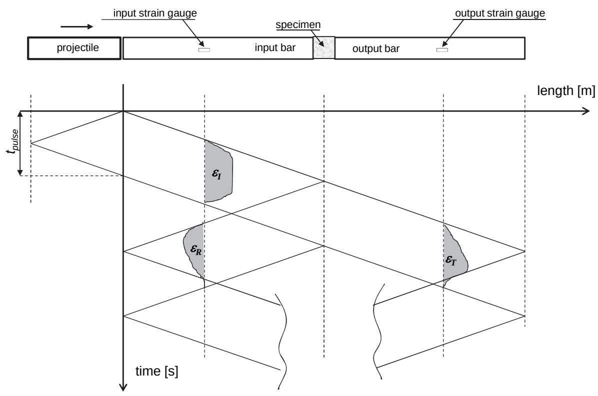

Figure 2. Split Hopkinson Pressure Bar scheme and Lagrangian diagram.

The input and output bars are equipped by strain gauges which measure the incident (ε_I), reflected (ε_R) and transmitted (ε_T) pulses acting on the cross section of the specimen.

The application of the elastic one-dimensional stress wave propagation theory to the split Hopkinson bar system of Figure 2 allows to calculate the forces F_1 and F_2 and the displacements δ_1 and δ_2 acting on the two faces of the specimen in contact with the input and output bars by means of the following relationships which are mainly based on the recorded deformations (ε_I), (ε_R) and (ε_T) of the elastic input and output bars:

$$F_1(t) = EA[\varepsilon_I(t) + \varepsilon_R(t)] \tag{1}$$

$$F_2(t) = EA[\varepsilon_T(t)] \tag{2}$$

$$\delta_1(t) = C_0 \int_0^t [\varepsilon_I(t) - \varepsilon_R(t)]\,dt \tag{3}$$

$$\delta_2(t) = C_0 \int_0^t [\varepsilon_T(t)]\,dt \tag{4}$$

Having realised the condition of the specimen deformation in a homogeneous stress state (that means having kept the specimen gauge length sufficiently short in a way that the wave reflections inside the gauge length provide the stress homogenization), the average stress σ, strain ε and strain-rate $\dot{\varepsilon}$ in the specimen material can be determined with the following relationships:

$$\sigma(t) = \frac{F_1(t)+F_2(t)}{2A_0} = \frac{1}{2}\,E\frac{A}{A_0}[\varepsilon_I(t)+\varepsilon_R(t)+\varepsilon_T(t)] \cong E\cdot\frac{A}{A_0}\cdot\varepsilon_T(t) \tag{5}$$

$$\varepsilon(t) = \frac{\delta_1(t)+\delta_2(t)}{L} = \frac{C_0}{L}\int_0^t [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)]dt \cong -\frac{2\cdot C_0}{L}\int_0^t \varepsilon_R(t)\,dt \tag{6}$$

$$\dot{\varepsilon}(t) = \frac{C_0}{L}[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)] \cong -\frac{2\cdot C_0}{L}\cdot\varepsilon_R(t) \tag{7}$$

where: L = gauge length of the specimen, A_0 = cross-sectional area of the specimen, t = test time, E = elastic modulus of the bar, A = cross-sectional area of the bar and C_0 = the elastic wave speed in the bars.

3.2 TENSION TEST USING SPLIT HOPKINSON BAR

The dynamic tensile strength can be measured using the split Hopkinson bar and its modification. The traditional Split Hopkinson Pressure Bar (SHPB) is normally used to study the indirect tensile strength by splitting test (Figure 3a). With the same configuration, the tensile strength is measured in bending by semi-circular bend test (Figure 3b). Removing the output bar and using a longer specimen is possible to investigate the tensile behaviour of materials under high loading rates by spalling test (Figure 3c). Finally, the direct tensile strength can be measured by the split Hopkinson bar essentially by using a set-up in which the projectile hit the flange of the one bar (Figure 3d).

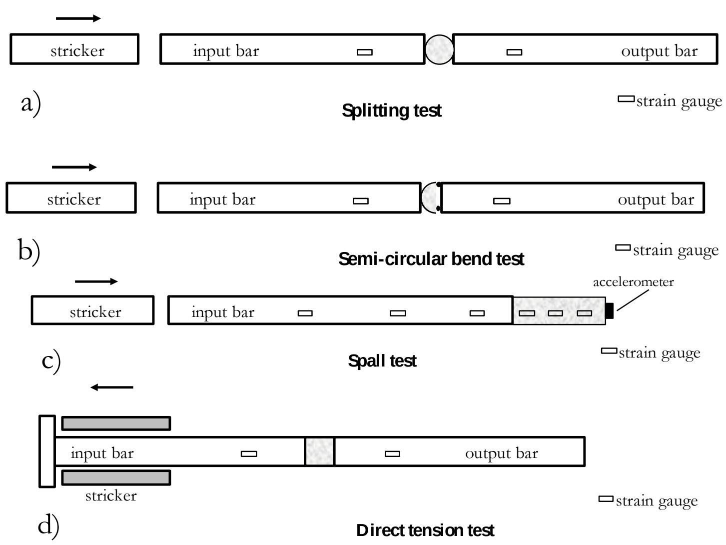

Figure 3. Experimental set-ups for tension test.

3.3 UNIVERSAL JRC-MODIFIED SPLIT HOPKINSON BAR

An innovative version of the split Hopkinson bar, which can be used for performing tension, compression and shear tests, in the strain-rate range 10^2 to 10^3 s^{-1} (10^4 s^{-1} in shear), was developed and patented at the Joint Research Centre in the seventies in the frame of nuclear reactor safety studies [Albertini and Montagnani, 1974; Albertini and Montagnani, 1976] of severe accidents and of automotive crashworthiness. In the last decades has been used also for concrete and rocks.

The development of the JRC-Modified split Hopkinson bar was particularly needed in order to dispose of a unique versatile equipment capable of working in tension, compression and shear, generating the long duration pulses. Using the classic SHPB dynamic testing equipment it would have been necessary to launch long projectile in order to obtain such pulse duration of few milliseconds, what is a very difficult task, in particular for the realisation of a plane impact of the projectile on the input bar, an absolute necessary condition for the generation of the elastic stress plane wave pulse needed for a correct analysis of the SHPB by means of the one-dimensional elastic plane stress wave propagation theory.

The main modification to the classical Hopkinson bar introduced consists in the substitution of the projectile, normally used to generate the impact loading pulse, with a statically elastic pre-tensioned bar which is the physical continuation of the input bar as shown in Figure 4 where different configurations are shown for testing materials in tension, compression and shear.

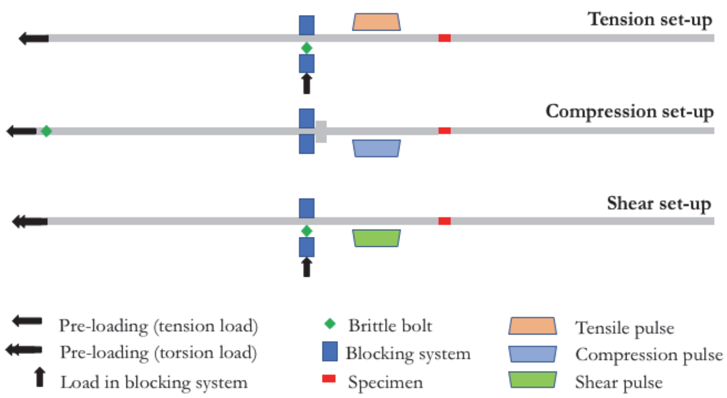

Figure 4. Different set-ups of JRC-Modified split Hokinson Bar for tension/compression/shear test.

The way of functioning the modified Hopkinson bar, for example in compression (Figure 5), consists of the following phases:

i. elastic energy is stored in the pre-tensioned loading bar (2) by statically tensioning the length of this bar comprised between a blocking ring placed at the extremity (3) of the pre-tensioned bar continuous to the input bar (4) and a brittle intermediate piece placed at the other extremity connected to the hydraulic actuator (1).
ii. a rectangular stress wave pulse is generated by suddenly breaking the brittle intermediate piece and propagates through the input bar, the specimen (5) and the output bar (6), provoking a state of compression stress in the specimen because the particles move from the left to the right.
iii. records are taken by the strain-gauge stations glued on the input and output bars of the elastic deformation.

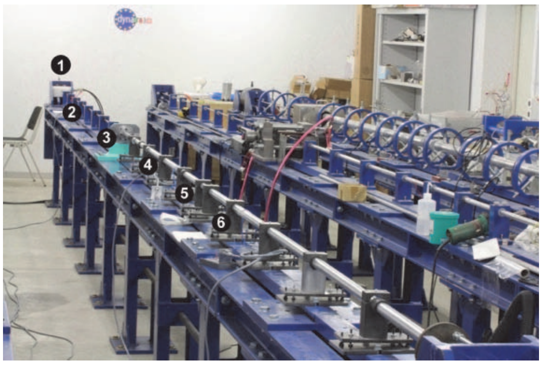

Figure 5. JRC-Modified split Hopkinson Bar for test in compression.

3.4 ADVANCE IN NEW TESTING APPARATUS: THE 3D-MODIFIED HOPKINSON BAR

The 3D-MHB is a Hopkinson bar apparatus able to apply a tri-axial stress before the dynamic test. The basic concept is shown in Figure 6. It consists of one hydraulic actuator (1) connected to the pre-tensioned bar (2), and of five other hydraulic actuators (3) installed at the end of the five output bars (5). Finally the input bar (4) is connected directly to the pre-tensioned bar in one end and in the other end is in contact with the specimen (6).

A quasi-static tri-axial stress state is introduced in the specimen by the hydraulic actuators (3) of the output-confinement bars (5). The rupture of the brittle bolt (between (1) and (2)) gives rise to a rectangular square pulse propagating into the system and loading dynamically the specimen until fracture. The strain gauges on the input (4) and output-confinement bars (5) record the incident, reflected and transmitted pulses allowing the reconstruction of the equivalent stress-strain curves.

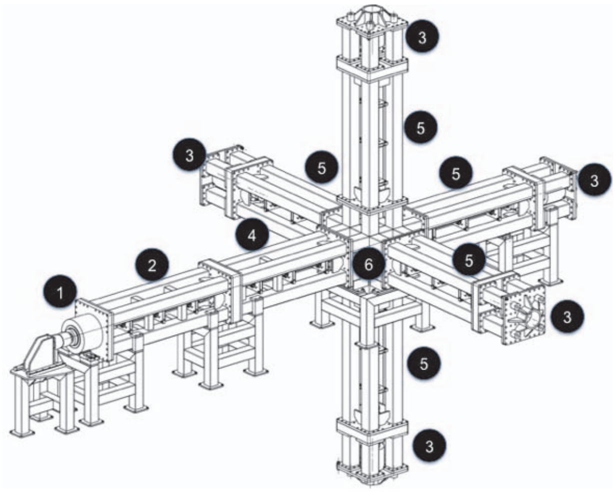

Figure 6. The 3D-Modified Hopkinson Bar apparatus scheme.

It is important to realise that the measurement on all the output bars also provide information on wave/energy transmission and transformation at material failure. This allows to study energy/wave released during material fracturing.

The construction of the 3D-MHB apparatus started [Cadoni *et al,* 2015] with the uniaxial set-up. The new equipment was built and installed in the DynaMat Laboratory. In this configuration it represents a Modified Hopkinson Bar in compression adding a hydraulic actuator at the end of the output bar. It consists of a pre-tensioned bar (cylindrical bar), input and output bars (with square cross-section). The dimensions of the three bars are reported in Table 2. The total length of the 3D-MHB apparatus along the impact axis is of 7.82m. The length becomes 8.80m when the bumper system is installed.

Table 2. Dimension of the 3D-MHB.

Element	Dimension [mm]	Cross-section area [mm^2]	Length [mm]
pre-tensioned bar	∅=56.5	2507	1750
input bar	L=50	2500	2200
output bar	L=50	2500	2100

All bars are made of aged maraging steel. This material has several advantages compared to other high strength steels. First, it is possible to reach the required strength, which is 1'600 MPa in the measurement cross-section and locally higher at connections and other discontinuities. Than, the ageing treatment requires moderate heating (around 500°C) and slow cooling minimizing thermal induced stress and thermal deformation of the pieces. It is possible to produce the bars with tiny details like threads without machining after ageing. It is also possible to treat the bars and the counter pieces to reach slightly different strength, minimizing the cost in case of damage. The drawbacks of the maraging steel are the cost and the limited choice of raw dimensions.

The 3D-MHB apparatus can generate a rectangular loading pulse of 2 MN amplitude and about 0.4ms duration which propagates through the input bar – specimen – output bar. It deforms the specimen at high strain-rate up to fracture.

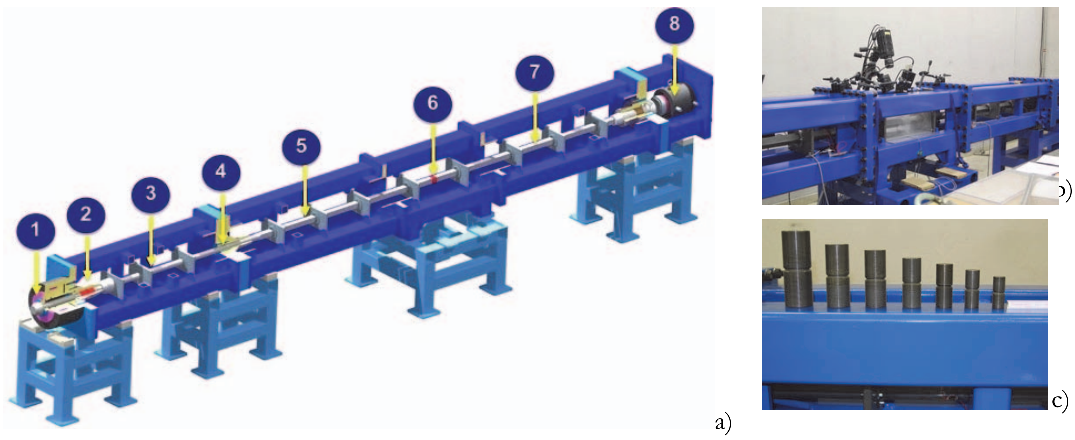

Figure 7. Experimental set-up for mono-axial testing.

The operative sequence in order to carry out a test using the 3D-MHB is as follows (refers to Figure 7):

i. A quasi-static stress state is introduced in the specimen by the hydraulic actuator placed at the end of the output bar (8).

ii. By the principal hydraulic actuator (1) the pre-tensioned bar (3) is pulled till the established preload value. At this moment, this load is withstood to the fragile bolt (2) (in Figure 7c are shown the series of bolts: from the larger (4MN) to the smaller(500kN)), the pre-tensioned bar and by the contrast ring (4). Because of the elastic movement of the entire system the pre-load on the specimen have to be checked and ruled by the actuator (8).

iii. A mechanical system permits to continue to load the bolt without any influence to the rest of the measurement apparatus. In the 3D-MHB, the rupture of the fragile bolt gives rise to a rectangular square pulse propagating to the input bar (5) and output bar (7) and dynamically loading the specimen (6) until fracture.

iv. The strain gages on the input and output-confinement bar record the incident, reflected and transmitted waves that allow the reconstruction of the equivalent stress-strain curves in the analytical way.

4. EXAMPLES OF MATERIALS RESPONSE TO HIGH STRAIN-RATE

4.1 APPLICATIONS OF UHPFRC FOR PROTECTIVE SHIELDS IN UHPFRC

The dynamic response of various sandwich systems, using a combination of reinforced concrete and UHPFRC layers, is the object of multi-year on-going research conducted in Switzerland and supported by the Federal Department of Defence, Civil Protection and Sport – armasuisse Science and Technology of the Swiss Confederation. These slabs were tested under blast by a series of near-contact charge tests carried out at the Detonics Laboratory of Hondrich (Switzerland). The tests were performed using C4 charges in contact and standoff distance of 3 and 6 cm, in Figure 8 the principal 5 set-ups are sketched. Plain concrete, UHPC and UHPFRCs were tested at high strain-rate in order to develop failure criteria for numerical assessment of structural reliability under blast or impact. In Figure 9 are shown the behaviour at high strain-rate of UHPC, UHPFRC in terms of stress versus displacement curves and the Dynamic Increase Factor of the strength in function of the stress-rate. It can be observed how the fibre increase the post-peak response of UHPFRC and how the Model Code fails in the predictions, but it is based on normal concrete.

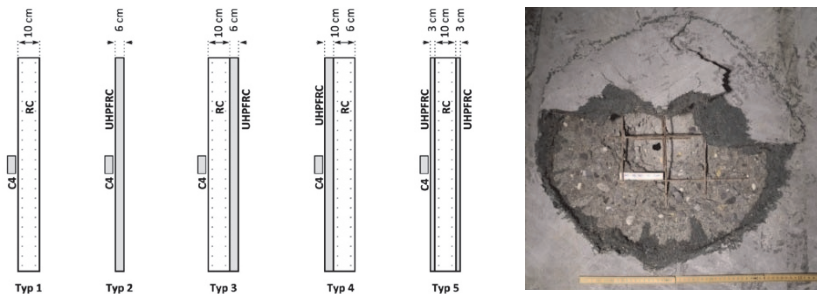

Figure 8. Scheme of the set-ups used to study the retrofitting by near-contact charge tests.

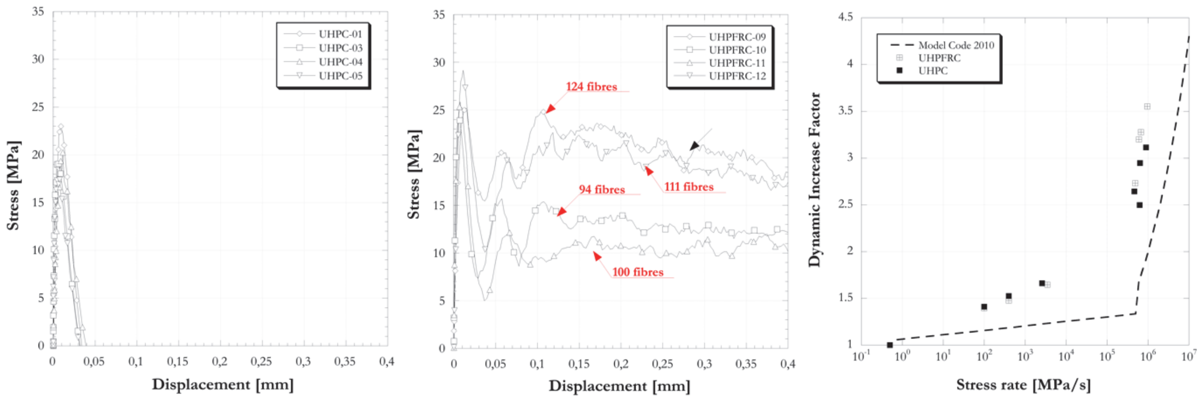

Figure 9. Experimental results on UHP(FR)C in tension [Cadoni and Forni, 2016].

4.2 APPLICATION ON REINFORCING STEELS SUBJECT TO FIRE AND BLAST

The study of combined effects of fire and blast was one of the aims of the research named "Behaviour of structural steels under fire in a wide range of strain-rates" developed in the frame of the COST Action TU0904 – "Integrated Fire Engineering and Response" by the DynaMat Laboratory (SUPSI) and the Institute of Structural Engineering (ETH Zürich).

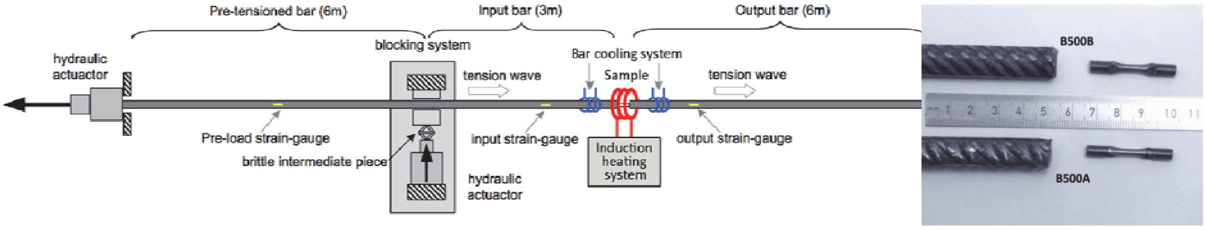

Figure 10. Experimental set-up for high strain-rate in combination of high temperatures.

At high strain-rate the effect of the increase of the temperature leads to a decrease of the strength capacity and to an increment of the strain capacity. The stress versus strain of B500A, B500B and AISI304 reinforcing steel are depicted in Figure 11. Considering they have the same grade, from these first results seems that the AISI304 steel behaves more uniformly in dynamics and high temperature (strain hardening). This fact, together with its intrinsic properties of durability, makes this steel an ideal material for rebar in case of dynamic load in presence of fire.

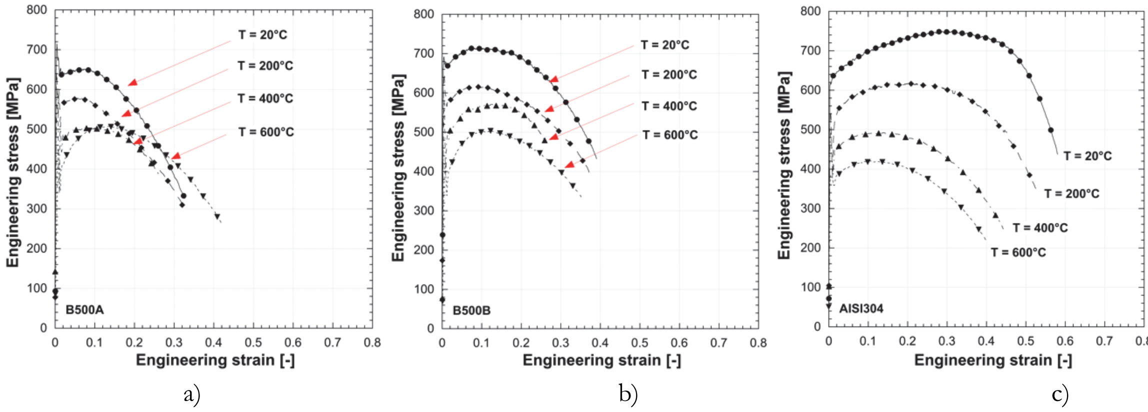

Figure 11. Engineering stress versus strain curves at 500 s-1 and different temperatures [Cadoni et al., 2016].

REFERENCES

Albertini, C. and Montagnani, M., [1974] "Testing techniques based on the Split Hopkinson bar", Inst. of Physics, Conf. Ser. No 21, London, 1974, pp. 22–32.

Albertini, C., Montagnani, M. [1976], "Waves Propagation Effects on Dynamic Loading", *Journal of Nuclear Engineering and Design*, Vol. 37, pp. 115-124.

Cadoni, E., Dotta, M., Forni, D., Riganti, G., Albertini, C. [2015], "First application of the 3D-MHB on dynamic compressive behavior of UHPC", *European Physical Journal WoC*, Vol. 94, pp. 01031.

Cadoni, E., Forni, D. [2016], "Experimental analysis of the UHPFRCs behavior under tension at high stress rate", *The European Physical Journal - Special Topics* Vol. 225, No. 2, pp. 253-264.

Cadoni, E., Dotta, M., Forni, D. [2016], "Tensile behaviour of reinforcing steels at high strain-rate and high temperature", *Key Engineering Materials*, Vol. 711, pp. 791-798.

Davis, R. M., A critical study of the Hopkinson bar, Cambridge University Press 240, pp 375-457, 1948.

Forni, D., Chiaia, B., Cadoni, E. [2016], "Strain rate behaviour in tension of S355 steel: Base for progressive collapse analysis", *Engineering Structures*, Vol. 119, pp. 164-173.

Kolsky, H., An investigation of the mechanical properties of materials at very high rates of loading, Proc. Phys. Soc. sect. B62, pp. 676-700, 1949.

Johnson, G. R., Cook, W. H. [1985] "Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures", *Engineering Fracture Mechanics*, Vol. 21, No. 1, pp. 31-48.

Peroni, M., Negro, P., Solomos, G. [2013] "Strain-rate sensitivity of steel members in seismic resistant buildings", *Proceedings of International Workshop "Application of High Strength Steel in Seismic Resistant Structures"*, Naples, Italy.

Zerilli, F. J., Armstrong, R. W. [1987], "Dislocation mechanics based constitutive relations for material dynamics calculations", *Journal of Applied Physics*, Vol. 61, No. 5, pp. 1816-1825.