10^{th} International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-X
G. Pijaudier-Cabot, P. Grassl and C. La Borderie (Eds)
https://doi.org/10.21012/FC10.243583

HIGH STRAIN-RATE RESPONSE OF UHPFRC IN SUPPORT OF IMPACT RESISTANT STRUCTURAL DESIGN

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Key words: High Strain Rate, UHPFRC, Modified Hopkinson Bar

Abstract. Understanding the dynamic response of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) is one of the most critical issue in the design of protective structures and critical infrastructures which need to withstand explosion or impact actions. These dynamic phenomena cause a different response of the cementitious materials which must be carefully evaluated at the design stage. In the frame of a research aimed to design special shields to protect buildings or critical infrastructures from the effect of IEDs (Improvised Explosive Devices) a comprehensive study on UHPFRCs' dynamic response has been developed. In this paper are described the different testing set-ups used to analyse the dynamic behaviour of the UHPFRC materials in different failure modes (tension, compression, shear) at high strain-rate.

1 INTRODUCTION

Critical infrastructures (such as particular buildings, tunnels and bridges) have a fairly high vulnerability to the effects of the Improvised Explosive Devices (IED). To protect infrastructure elements from the effects of IED protective structures, such as reinforced concrete shields, are often used. These elements are able to withstand overloads caused by stress waves generated by blast and dissipate the huge amount of energy in deformation preventing no-desired effects such as spalling. As consequence, the wave propagation provokes, in the inner part, tension waves that usually can exceed the material strength. Thus some concrete fragments can be ejected and projected at high velocities causing lethal threats to people and serious damage to internal equipment. When a critical structure has been designed without any blast protection, it is necessary to improve its resistance capacity by means of a retrofitting. Usually, it consists of an additional structural member attached to the existent structure.

Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) is an advanced cementitious composite material combining cement-based matrix with a low water-to-binder ratio and reinforcing fibres (usually $\geq$2% in volume). The introduction of fibres leads to obtain a ductile behaviour with large dissipation of energy together with outstanding strength. Thanks to these characteristics UHPFRC is a promising material for construction of protective structures. Indeed, several researcher groups developed solutions for protective element based on UHPFRC against fast transient loads such as impact, blast, or contact charges. Despite the considerable interest aroused, many aspects in the mechanical response of these materials must be still deeply investigated, in particular in the high-strain rate regime. In order to properly design a protective structure fast transient loading events, caused by impact or blast, need to be understood. In particular the knowledge of the material response at these loading regimes is fundamental.

This paper focuses on mechanical characterisation at high strain rate of the UHPFRC materials and presents the experimental techniques used. These results were obtained in the frame of a research aimed to protect buildings or critical infrastructures from the effect of IEDs (Improvised Explosive Devices) by means of a series of sandwich systems, combining reinforced concrete and UHPFRC layers. This research conducted in Switzerland and supported by the Federal Department of Defence, Civil Protection and Sport – armasuisse Science and Technology involved the DynaMat Laboratory of the University of Applied Sciences of Southern Switzerland (Lugano) for the study of the dynamic behaviour of several UHPFRCs in tension, compression, shear.

2 MATERIALS

The UHPFRCs investigated are commercial products characterised by outstanding strength and durability. They are cementitious material mixes composed of micro silica, cement, quartz sand, water, and super plasticisers. As result the matrixes obtained are extremely durable and highly resistant (equivalent water/binder ratio = 0.17). By adding a high percentage of steel micro-fibres reinforcement (generally $\geq$3% in volume) excellent mechanical properties such as very high compression (180-210 MPa), flexural (40-50 MPa), and tensile strength (8-12 MPa) can be reached. The elastic modulus is usually around 50 GPa. Other relevant characteristics are: high ductility, high water and gas impermeability, very high resistance to chloride penetration, carbonation, acid attack and abrasion. In this research three UHPFRCs mixes, having 3%, 4% and 5% fibre content, were investigated. High carbon straight fibres 10 mm and 13 mm long with a 0.16 mm diameter (aspect ratio l_f/d_f equal to 62.50 and 81.25) were used. To study the direct tension behaviour cylindrical specimens with a diameter of 20 mm and diameter/height ratio equal to 1 were used. This specimen size can be considered large enough to reasonably represent the behaviour of composite materials containing fibres (at least 70 fibres per sample). All specimens were pre-notched (notch/radius = 0.15) in order to prevent multiple fractures.
The quasi-static tests were carried out by means of a standard Zwick/Roell machine having maximum load capacity of 50kN. Stroke was considered as feedback parameter during the tests. The displacement rate imposed during the tests was equal to $5\cdot10^{-5}$ mm/s. The average tensile strength of UHPFRC with 5% fibre content was 9.7$\pm$1.9 MPa, while the correspondent tensile strength of the matrix (UHPC) was 8.0 ± 0.5 MPa. The number of fibres in the cross–section was 114$\pm$28. In the quasi-static compression test the strength was 167$\pm$25MPa. The results of the UHPFRC with 3% and 4% fibre content can be found in [1].

3 DYNAMIC TESTING SET-UPS

The mechanical characterisation of material is of critical importance to correctly design any structures. In fact, only giving true information on the material behaviour in different loading modes and in a wide range of strain rate, the material constitutive models can be properly calibrated [2]. A brief description of the experimental set-ups used in the research is given in the following.

3.1 Direct tensile test

In order to study the behaviour in tension of UHPFRC a Modified Hopkinson Bar [3–8] has been used (Figure 1). It consists of two circular aluminium bars, having a diameter of 20 mm, with a length of 3 and 6 m for input and output bar, respectively. The UHPFRC specimen was glued to the input and output bars by an epoxy resin. The pretensioned bar was a high strength steel (6m length) connected to the input bar. By pulling one end (the other is connected with a blocking system) of the pretensioned bar is possible to store elastic energy in it. The pretensioned bar is connected with the incident bar and has the same acoustical impedance so the spurious reflections in this interface is avoided. By releasing this energy (rupturing the brittle intermediate piece), a rectangular shape wave (with 2.4ms duration) with small rise-time (about 60μs) is generated and transmitted along the input bar loading the specimen to failure. This is a uniaxial elastic plane stress wave, as the wave-length of the pulse is long compared to the bar transverse dimensions, and the pulse amplitude does not exceed the yield strength of the bar.

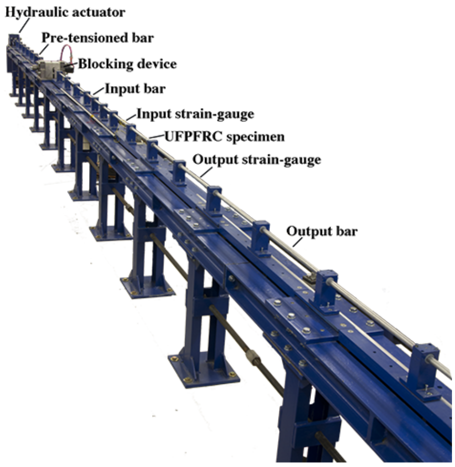

Figure 1: Modified Hopkinson Bar device.

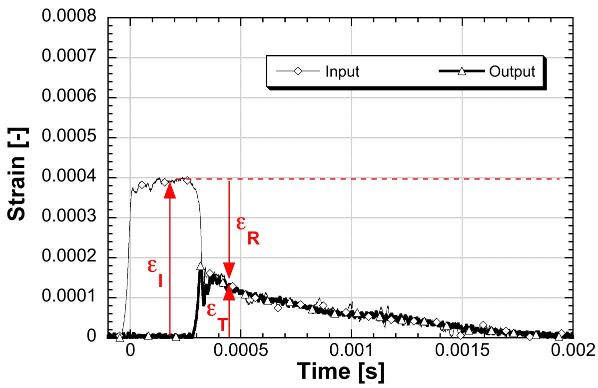

Figure 2: Raw signals of direct tensile test with MHB.

The pulse propagates along the input bar with the velocity C_0 of the elastic wave with its shape remaining constant. When the incident pulse (ϵ_I) reaches the UHPFRC specimen, part of it (ϵ_R) is reflected by the specimen whereas another part (ϵ_T) passes through the specimen propagating into the output bar as shown in Figure 2. It can be observed that the length of the pulse is needed to permit the specimen the pull-out all fibres in the fracture section [9].

The relative amplitudes of the incident, reflected and transmitted pulses, depend on the mechanical properties of the specimen. Strain-gauges, glued on the input and output bars of the device, are used for the measurement of the elastic deformation (as a function of time) created on both half-bars by the incident/reflected and transmitted pulses, respectively. The application of the elastic, uniaxial stress wave propagation theory to the Hopkinson bar system and by using equations (1) to (4) allow calculation of the forces F_I and F_O and the displacements δ_I and δ_O acting on the two faces of the specimen in contact with the input and output bars, respectively [10].

$$F_{\mathrm{I}}(t) = A_{bar} \cdot E_{bar} \cdot [\epsilon_{\mathrm{I}}(t) + \epsilon_{\mathrm{R}}(t)] \quad (1)$$

$$F_{\mathrm{O}}(t) = A_{bar} \cdot E_{bar} \cdot \epsilon_{\mathrm{T}}(t) \quad (2)$$

where A_{bar} and E_{bar} are the area of the bar cross-section and the elastic modulus of the bar, respectively while t is the time.
The displacements of the input and output bar-specimen interfaces are given by:

$$\delta_{\mathrm{I}}(t) = C_0 \int_0^t [\epsilon_{\mathrm{I}}(t) - \epsilon_{\mathrm{R}}(t)]\, dt \quad (3)$$

$$\delta_{\mathrm{O}}(t) = C_0 \int_0^t [\epsilon_{\mathrm{T}}(t)]\, dt \quad (4)$$

Therefore the average values of stress $\sigma_{\text{spec.}}$, strain $\epsilon_{\text{spec.}}$ and strain-rate $\dot{\epsilon}_{\text{spec.}}$ in the specimen are:

$$\sigma_{spec.}(t) = \frac{F_{\mathrm{I}}(t) + F_{\mathrm{O}}(t)}{2A_{\text{spec.}}} \quad (5)$$

$$\sigma_{spec.}(t) = \frac{E_{bar} \cdot A_{\text{bar}}}{2A_{\text{spec.}}} \cdot [\epsilon_{\mathrm{I}}(t) + \epsilon_{\mathrm{R}}(t) + \epsilon_{\mathrm{T}}(t)] \quad (6)$$

where $A_{\text{spec.}}$ is the area of specimen gauge length cross-section.

$$\epsilon_{spec.}(t) = \frac{\delta_{\text{I}}(t) - \delta_{\text{O}}(t)}{L_{\text{spec.}}} \quad (7)$$

$$\epsilon_{spec.}(t) = \frac{C_0}{L_{\text{spec.}}} \int_0^t [\epsilon_I(t) - \epsilon_R(t) - \epsilon_T(t)]\, dt \quad (8)$$

where $L_{spec.}$ is the length of specimen gauge-length.

$$\dot{\epsilon}_{spec.}(t) = \frac{C_0}{L_{spec.}}[\epsilon_I(t) - \epsilon_R(t) - \epsilon_T(t)] \quad (9)$$

where $L_{spec.}$ is the length of specimen gauge-length.

In the case of the short specimens, the travel time of the wave through the specimen is small in comparison to the duration of the test. Thus, the specimen can be considered as being in load equilibrium at its ends and in a uniform stress state created by the many wave reflections taking place at the ends of the specimen. The condition of force equilibrium at both ends of the specimens is expressed by:

$$F_{\text{I}}(t) = F_{\text{O}}(t) \quad (10)$$

or

$$\epsilon_{\text{I}}(t) + \epsilon_{\text{R}}(t) = \epsilon_{\text{T}}(t) \quad (11)$$

Leading to the following simplified relationships for the stress, strain and strain-rate in the specimen:

$$\sigma_{spec.}(t)_{eng.} = E_{bar} \cdot \frac{A_{bar}}{A_{spec.}} \epsilon_T(t) \quad (12)$$

$$\epsilon_{spec.}(t)_{eng.} = -\frac{2 \cdot C_0}{L_{spec.}} \int_0^t \epsilon_R(t)\, dt \quad (13)$$

$$\dot{\epsilon}_{spec.}(t)_{eng.} = -\frac{2 \cdot C_0}{L_{spec.}} \epsilon_R(t) \quad (14)$$

The simplified relationships (12), (13), (14) can be used for the determination of the stress-strain-strain rate curves after verification of the condition (10) of force equilibrium at the ends of the specimen; such verification can be done by checking that at each time t of the test the algebraic sum of the incident pulse $\epsilon_I(t)$, of the reflected pulse $\epsilon_R(t)$, and of transmitted pulse $\epsilon_T(t)$, is equal to zero as requested by the relationship (11).

3.2 Compression test

To study the compressive behaviour of UHPFRC the used set-up (Figure 3) is a compression version of the MHB and based on the same loading principle used for tension test [11, 12]. The input (4) and output (5) bars are in aluminium and had a diameter of 30mm and a length of 3m. The pretensioned bar (2) is in high strength steel. Detailed information on the functioning can be found in [11]. Differently from tension version in this MHB the blocking system (3) is a physical block between the pretensioned and the input bar (see Figure 4). The system is released by rupturing a bolt near the hydraulic actuator (1) as depicted in Figure 5.

Figure 3: Set up for compression test.

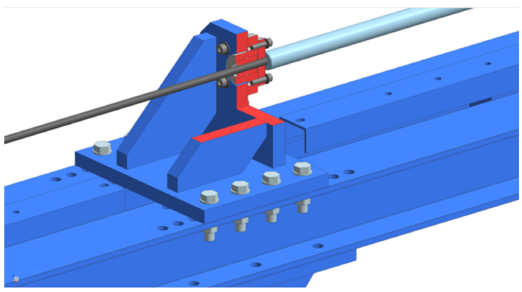

Figure 4: Blocking system in the MHB compression.

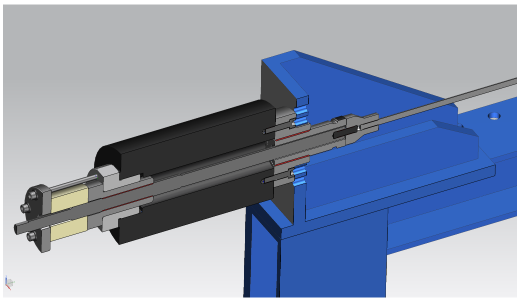

Figure 5: Brittle bolt in the MHB compression.

3.3 Shear test

The experimental set-up used for shear test at high strain rate is based on the compression set-up. The unique modification is at the specimen level, as shown in Figure 6.

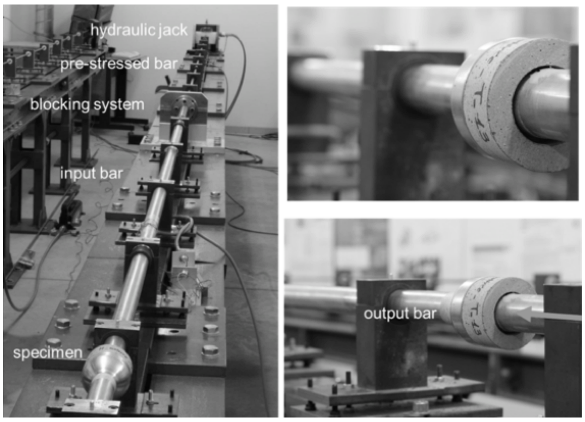

Figure 6: Set up for shear test.

The shear specimen has been designed following an optimisation study. It consists in two coaxial cylindrical parts jointed at the basis through a thin circular crown which represents the gauge part with length between 5 and 15mm. It permits to achieve homogeneous stress distribution in the gauge part also in case of testing at high strain rate by means of stress wave propagation and reflections inside the gauge length. All the conditions for the application of the one-dimensional elastic stress wave propagation theory are fulfilled also in the here described dynamic shear MHB experiment; therefore it is possible to apply the following relationships in order to calculate the shear stress, shear strain and shear strain rate of the specimen material. In Figure 7 is shown the specimen after a shear test.

Figure 7: Specimen after shear test.

3.4 3D-MHB apparatus

A new equipment 3D-MHB (Figure 8) is installed in the DynaMat Laboratory and consists of a Modified Hopkinson Bar in compression adding a hydraulic actuator at the end of each output bar [13, 14]. In other words, the device permits to obtain a predetermined triaxial state before the addition of dynamic pulses. As result the five output bars and the input bar will permit to obtain the mechanical response of the materials in this particular condition. The device was designed to analyse the dynamic behaviour of damaged rocks in triaxial state to understand the massive rock when subject to a wave caused by blast for tunnel excavation or earthquake. At the present, only the first axis has been built and the system acts as a Modified Hopkinson Bar, having pretensioned cylindrical bar, input and output bars of equal length of 2 m and equal square cross-section of 50mm side length. At the end of the output bar is installed the hydraulic actuator to apply the pre-straining in the sample. The machine can generate a rectangular loading pulse of 2 MN amplitude and 800 μs duration which propagates through the input bar –specimen – output bar deforming the specimen up to fracture.

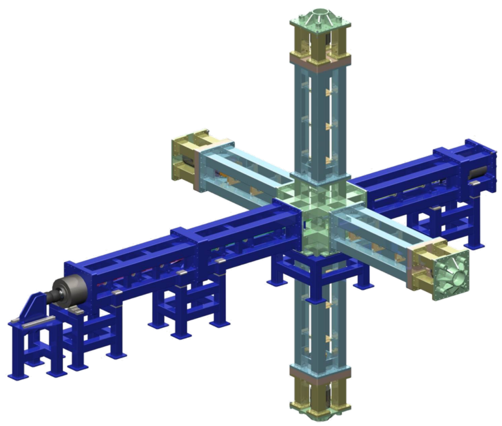

Figure 8: 3D-MHB set-up.

To investigate this effect, this UHPFRC was studied in parallel and orthogonal directions to the casting direction, taking constant the loading rate of 1.4 TPa/s. In Tables 1 , the experimental results are reported. The stress versus COD curves are depicted in Figures 10 and 11. In parallel direction the average number of the fibres in the fracture cross-section is lower than in the orthogonal direction. Considering the results in [1] it can be state that increasing the fibre content increases the peak-stress as well as the post-peak stress. When the orientation of the fibres is distributed along the load direction, the behaviour tends to be pseudo-elasto-plastic.

In Figure 9 is shown the scheme of the uniaxial version of the 3D-MHB. It consists of a pretensioned bar (cylindrical bar: ∅=56.5, L=1750mm)), input and output bars (with square cross-section: 50mm side; 2200 and 2100mm in length, respectively). 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. All bars are made of thermally aged maraging steel.

Table 1: Direct tensile strength results

vol. frac.	peak-stress	fract.time	n. fibres
	MPa	μs	-
0%	20.09 (2.16)	32 (3)	-
5%$\parallel$	27.03 (3.29)	50 (4)	126 (20)
5%$\perp$	27.61 (3.95)	43 (5)	137 (21)

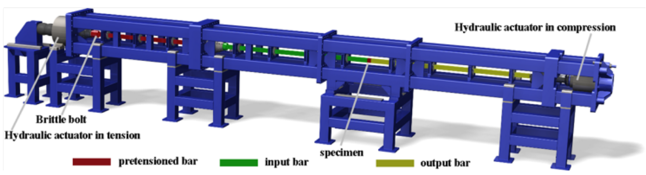

Figure 9: 3D-MHB, uniaxial set-up.

4 Results

For the sake of brevity only some results are presented (other results can be found in [1, 12–14]). In particular the results of direct tension results of UHPFRC with 5% fibre content are presented with the intention to highlight the effects of the fibre reinforcement as well as the fibre orientation and distribution. Being UHPFRC mouldable material in fresh condition, its rheology has a capital role in the fibres' distribution and orientation because they are governed by the casting flow.

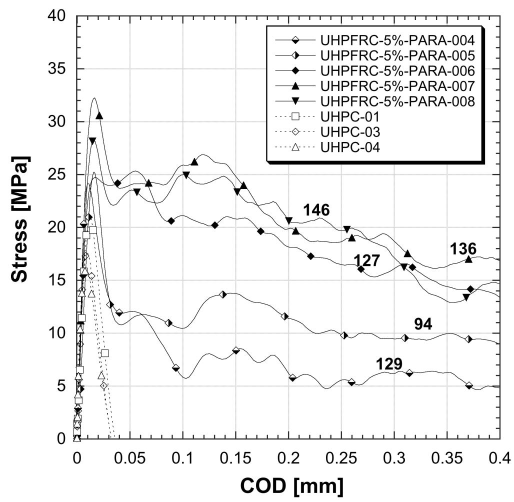

Figure 10: Stress vs. COD curves, parallel direction.

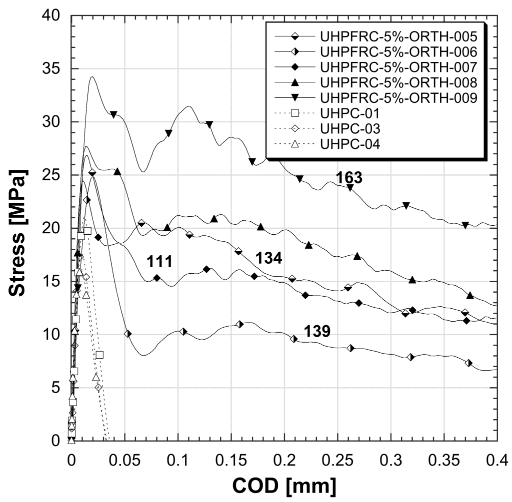

Figure 11: Stress vs. COD curves, orthogonal direction.

To study the shear response four different materials were tested: UHPC (matrix) and UHPFRC with 3%, 4% and 5% of fibers content. Every test has been performed with the same coring orientation, perpendicular to the specimen casting. The average results of dynamic shear tests are resumed in Table 2.

Table 2: Shear test results

UHPC	shear stress MPa	fract. time μs	fract. displ. mm
(0%)	15.9 (3.1)	222 (36)	0.27 (0.10)
(3%)	23.4 (5.9)	193 (37)	0.29 (0.05)
(4%)	26.6 (2.6)	244 (28)	0.34 (0.05)
(5%)	24.4 (1.0)	283 (19)	0.36 (0.10)

5 DISCUSSION

Each dynamic test has critical aspects that should be taking into account in the testing setup. These can be grouped in three categories: i) specimen characteristics (size and geometry); ii) specimen boundary conditions; iii) input wave characteristics. Each category affects the dynamic results. The first two contain parameters under user direct control, while the last one contains parameters only partially under user control. Tensile and shear tests are less sensitive to test conditions respect to compression test. In tension test the use of glue allows to practically get closer to the ideal uniform boundary loading conditions. Glue thickness governs, in conjunction with the bar stiffness and loading wave, the definition of the resulting loading rate over the specimen. Main boundary conditions variability is hidden into the specimen preparation (coring, grinding, notching). The notching process can induce geometrical non-uniformities and micro cracking leading to intrinsic material variability. The dynamic shear tests carried out are suitable to the high strain rate study thank to small gauge length and correspondent cross-section. The boundary conditions variability in the specimen-bar interfaces influences minimally the results if the specimen faces have acceptable flatness and parallelism. Compression test presents high variability in boundary conditions respect to previous tests, and the test results dispersion reflects this variability. This high variability is due to the combination effects of contact between the specimen face and the bar, specimen, eventual presence of copper or grease layers. Stress gradient at the boundaries is a critical factor to enucleate the cracking process that induces specimen failure. Compression test has to be considered a structural test with high sensitivity to boundary conditions.

6 CONCLUSION

The study of the dynamic behaviour of UHPFRCs requires a broad experimental campaign in order to obtain information on the material response to the different loading modes and in a wide range of strain rate. The experimental techniques used to determine the mechanical characteristics at high strain rate have been presented. The results in tension, compression and shear have demonstrated the influence of the fibres on the mechanical characteristics of the UHPFRC materials. In order to achieve a realistic structural assessment, in case of blast or impact, the use of numerical and analytical methods is needed. These methods must be supported by a comprehensive set of experimental testing results, preferably in shear or tension and successively in compression. The obtained experimental results are currently used to develop material failure criteria for structural reliability assessment of infrastructure elements against the effects of IEDs.

7 ACKNOWLEDGMENTS

This work has been supported by armasuisse-Science and Technology of the Swiss Federal Department of Defence, Civil Protection and Sport.

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