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High strain rate response of UHP(FR)C in compression

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Abstract. The objective of this study was to investigate the compression behaviour of the UHPFRC and its matrix (UHPC) under high strain rate. Two experimental set-ups were used for compression testing: a traditional Split Hopkinson Pressure Bars and a compression version of the Modified Hopkinson Bar. The tests were conducted, in the range of 100–500 s^{-1} on cylindrical specimens with both diameter and height of 20 mm. Results show significant increases in peak strength and dissipated energy.

1. Introduction

Nowadays Ultra-High Performance (Fibre-Reinforced) Concretes – UHP(FR)Cs are principally used for rehabilitation and strengthening of structures. While many authors have examined the quasi-static behaviour (for example [1–6]), there is still a lack of knowledge about the material behaviour of UHP(FR)C under high strain rates above 100 s^{-1}. Recently, a few works about the tensile behaviour have been published as [7–11].

The objective of this study was to investigate the compression behaviour of the UHPFRC and its matrix under high strain rate. Two experimental set-ups were used for compression testing: a traditional Split Hopkinson Pressure Bars [12] and a compression version of the Modified Hopkinson Bar. The tests were conducted in the range of 100–600 s^{-1} on cylindrical specimens with both diameter and height of 20 mm.

2. Materials

The materials here analysed were commercial products characterized by high strength and durability, thanks to the exceptional properties of the matrix (UHPC). UHPFRC was obtained adding to the UHPC an elevate percentage of high strength steel fibres reinforcement (3% in volume) having a diameter of 0.16 mm and a length of 13 mm. The UHP(FR)C specimens had a cylindrical shape with diameter and height of 20 mm. All specimens were drilled out from standard cube (150 mm side). The results of the quasi-static compressive tests were $f_C = 104 \pm 22$ MPa for UHPC and $f_C = 127 \pm 21$ MPa for UHPFRC.

The Young's modulus was 51 GPa. Moreover UH-PFRC had high durability guaranteed by high water and low gas permeability, very high resistance to chloride penetration, carbonation, acid attack and abrasion.

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3. Experimental set-ups

The high strain rate compressive behaviour was examined by means of two set-ups.

3.1. Split Hopkinson Pressure Bar

The dynamic compression tests were performed using a Split Hopkinson Pressure Bar (SHPB), installed at the Dynamic Testing of Materials Laboratory of the Research Institute of Mechanics – Lobachevsky State University of Nizhny Novgorod (Russia), which consists of an input (2) and an output (5) bars with the specimen (4) sandwiched between them as schematically shown in Fig. 1. When the strike bar (1) impacts onto the input bar a compressive incident wave $\varepsilon_I(t)$ travels along the input bar. Once it reaches the specimen, a reflected wave ε_R (t) and a transmitted wave $\varepsilon_T(t)$ are generated, propagating along the input and output bar respectively. According to the one-dimension wave propagation theory the forces and particle velocities/displacements at the two faces of specimen can be determined by those three waves recorded. In Fig. 1a is also shown the Lagrangian graph describing the strain history of the two bars.

In Fig. 2 the incident, reflected and transmitted pulses measured on input and output bars in a dynamic compression test of UHPC specimen are shown. It can be observed as at high strain rate the specimen failure is reached just in the first cycle of loading. The time necessary to bring the specimen at failure in compression is about 100 μs.

With this set-up were carried out the test with higher strain rates.

3.2. Modified Hopkinson Bar in Compression

The Modified Hopkinson Bar for compression test installed at the DynaMat Laboratory (Fig. 3) consists of a hydraulic actuator (1) that put in tension a pre-stressed loading bar (2) thanks to a blocking ring (3) placed at the other extremity of this bar (see Fig. 4a). The pre-stressed

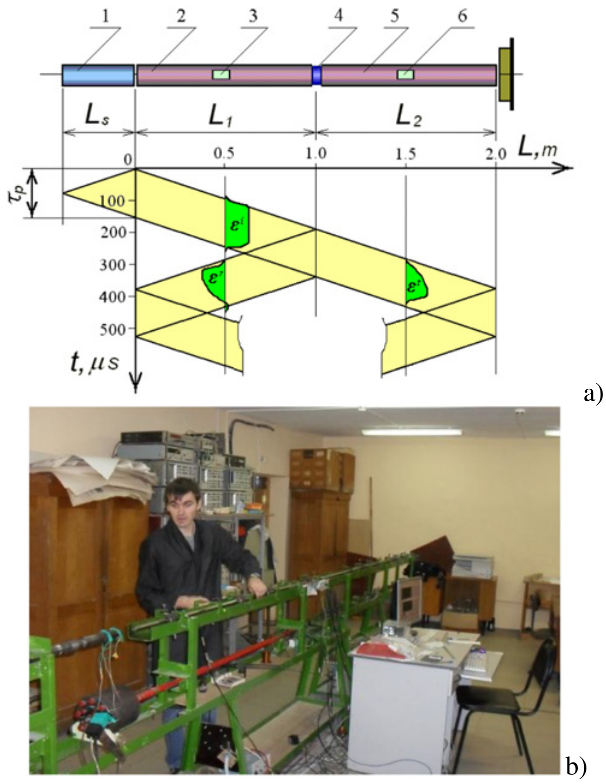

Figure 1. Dynamic compression testing set-up: a) scheme and Lagrangian graph; b) view.

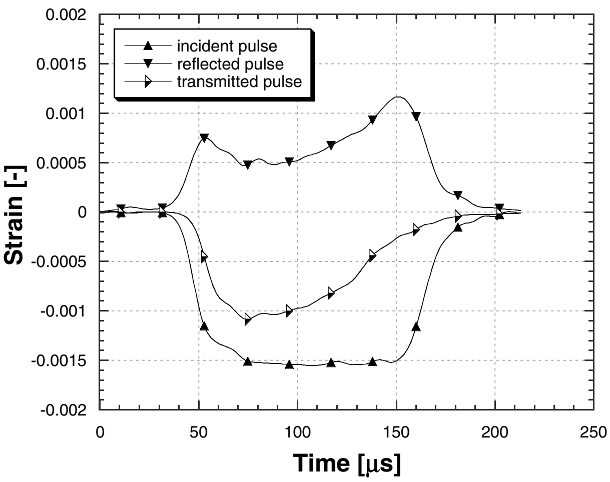

Figure 2. Signals measured on the input and output of UHPC.

bar was a high strength steel bar having a diameter of 12 mm and a length of 6 m. This pre-stressed bar is directly connected to an aluminium bar with a diameter of 30 mm and a length of 3 m working as input bar (4). The specimen (5) was sandwiched between the input bar and another identical bar used as output bar (6). Pulling the pre-stressed bar it is possible to drive the test by the energy stored in it. The test starts when a fragile bolt (see Fig. 4b) positioned between the pre-stressed bar and the hydraulic actuator (1) by suddenly breaks. Consequently a rectangular stress wave pulse is generated and propagates through the input bar, the specimen (5) and the output bar (6), causing a

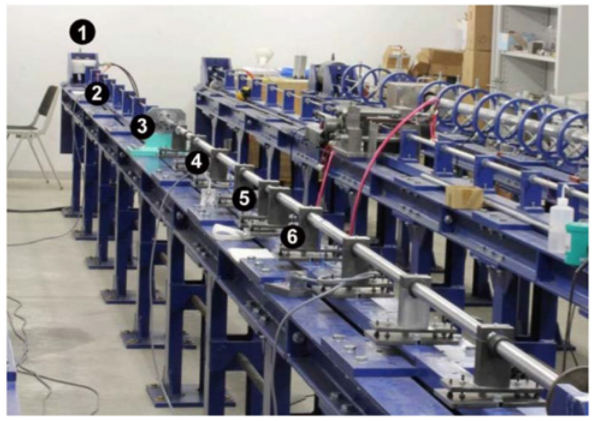

Figure 3. Modified Hokinson Bar set-up in compression.

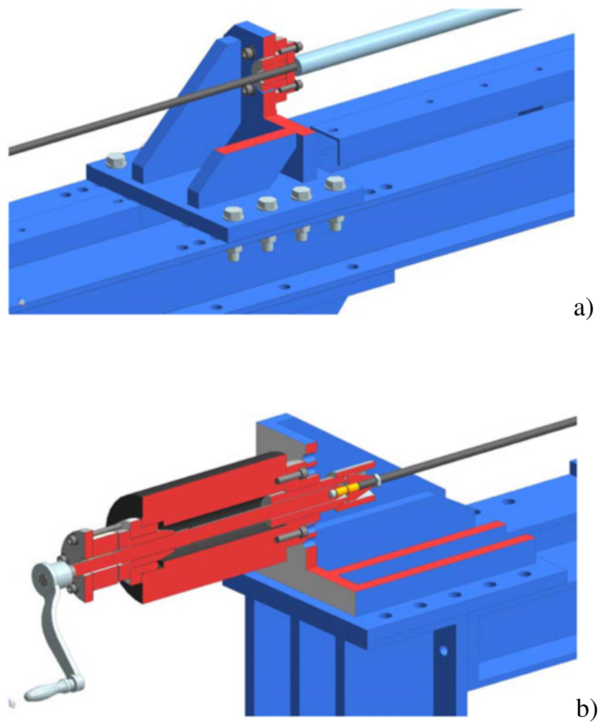

Figure 4. Details of the MHB in compression: a) blocking ring; b) fragile bolt.

state of compression stress in the specimen. By the strain gauges placed on the input and output bars the test signals were obtained and in Fig. 5 the input and output signals (Fig. 5a) as well as the incident, reflected and transmitted signals (Fig. 5b) are shown.

4. Results

The tests performed by means of SHPB were carried out using two (aluminium and steel) strikers having a diameter of 20 mm and a length of 300 mm. To obtain the strain rates three different pressure values were used (1, 3 and 6 bars). In the MHB only one velocity were used in order to compare the UHPFRC and UHPC (the preload was 50 kN).

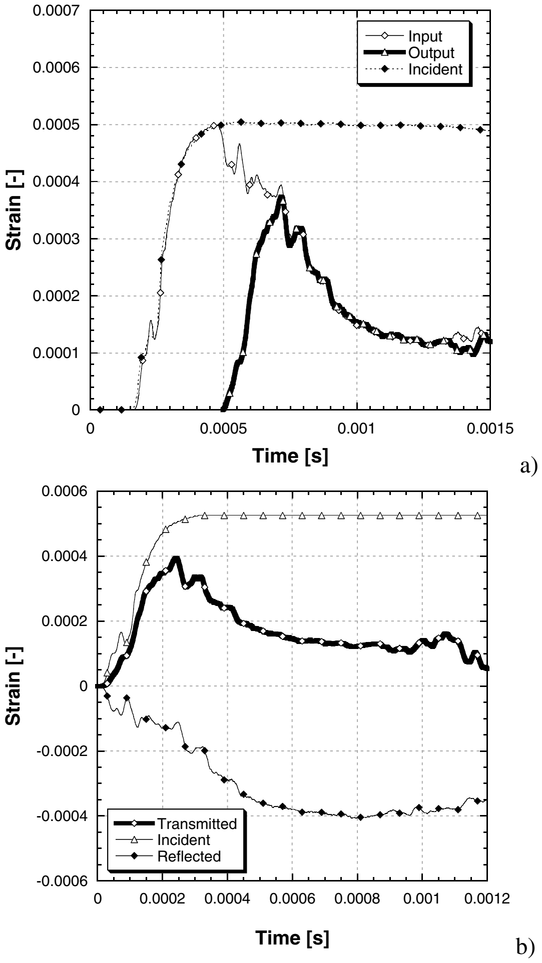

Figure 5. Compression test: a) input and output signals; b) incident, reflected and transmitted signals.

4.1. Ultra High Performance Concrete

4.1.1. SHPB results

The tests on UHPC specimen were performed using the aluminium striker at 1 and 3 bars as pressure in the gas gun obtaining an impact velocity equal to 15.4 and 27.2 m/s respectively. The strain rate obtained was in average 181 and 462 s^{-1}. As well known also in this case it can be observed as the compressive strength increases with increasing strain rate.

In Tables 1 and 2 are collected the results at the two strain rates while in Figs. 6 and 7 the stress versus time curves are shown.

4.1.2. MHB results

The compression test using the MHB was performed imposing a 50 kN of preload that produce an equivalent impact of 11.3 m/s. In Table 3 and Fig. 8 the results are shown.

Table 1. Results on UHPC_pressure 1 bar. $v_{impact} = 15.44$ m/s.

Specimen	Stress Rate [GPa/s]	Max Stress [MPa]	Fract. strain [‰]	Fract. time μs]	Strain rate [s^{-1}]	Total energy [kJ/m^2]
UHPC_29	5'311	96.22	9	65	200	37.51
UHPC_30	5'509	100.28	11	62	214	39.13
UHPC_31	5'995	91.22	5	40	148	27.08
UHPC_34	6'820	105.95	6	40	160	29.57
Average	5'909 (672)	98.42 (6.24)	*7.97 (2.84)*	*52 (14)*	*181 (32)*	*33.32 (5.89)*

Table 2. Results on UHPC_pressure 3 bar. $v_{impact} = 27.2$ m/s.

Specimen	Stress Rate [GPa/s]	Max Stress [MPa]	Fract. strain [‰]	Fract. time μs]	Strain rate [s^{-1}]	Total energy [kJ/m^2]
UHPC_35	12'990	167.6	6.28	24	465	65.21
UHPC_36	9'364	126.7	7.83	23	588	67.17
UHPC_37	14'783	197.9	6.17	22	409	73.33
UHPC_38	17'010	198.7	6.16	19	385	63.32
Average	*13'537 (3'232)*	*172.7 (33.9)*	*6.61 (0.81)*	*22 (2)*	*462 (91)*	*67.26 (4.34)*

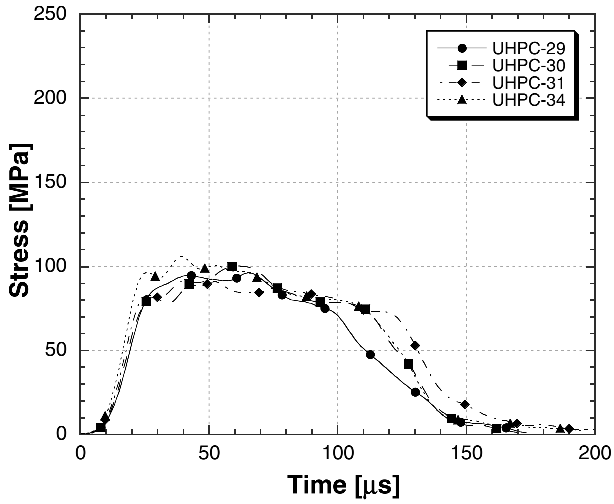

Figure 6. Results on UHPC at 181 s^{-1}.

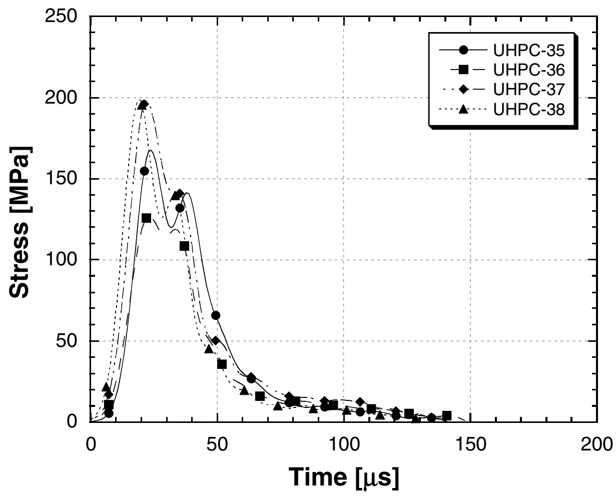

Figure 7. Results on UHPC at 462 s^{-1}.

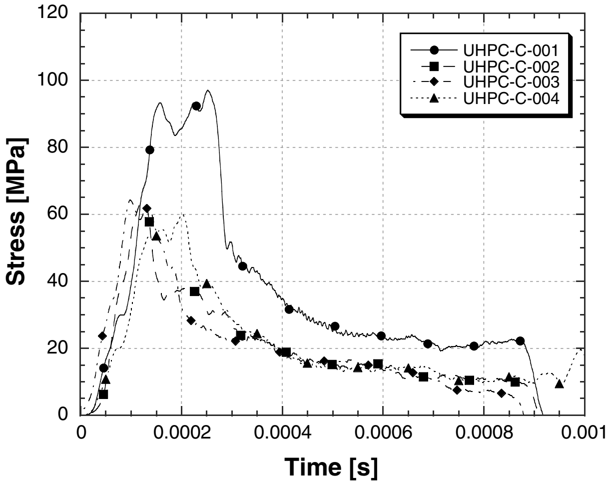

Figure 8. Results on UHPC at 136 s^{-1}.

Table 3. Results on UHPC with MHB.

Specimen	Stress Rate [GPa/s]	Stress [MPa]	Fract. strain [‰]	Fract. time [μs]	Strain rate [s^{-1}]	Tot. energy [kJ/m^2]
UHPC_01	1176	97.06	22.19	252	141	133.7
UHPC_02	934	64.1	8.51	121	153	61.65
UHPC_03	722	64.23	5.58	98	113	54.94
UHPC_04	340	60.15	13.18	201	137	70.87
Average	*793*	*71.39*	*12.37*	*168*	136	*80.30*
	(354)	*(17.22)*	*(7.26)*	*(71)*	(17)	*(36.22)*

Table 4. Results on UHPFRC_pressure 3 bar. $v_{impact} = 27.2$ m/s.

Specimen	Stress Rate [GPa/s]	Max Stress [MPa]	Fract. strain [‰]	Fract. time [μs]	Strain rate [s^{-1}]	Tot. energy [kJ/m^2]
UHPFRC_37	13'676	179.64	6.82	23	428	101.33
UHPFRC_38	14'463	183.45	13.04	36	392	117.17
UHPFRC_39	13'811	179.29	7.27	22	460	107.11
UHPFRC_40	11'258	153.96	16.89	36	585	119.65
Average	*13'302*	*174.09*	*11.00*	*29*	*466*	*111.32*
	(1'405)	*(13.55)*	*(4.84)*	*(8)*	*(84)*	*(8.58)*

4.2. Ultra High Performance Fibre Reinforced Concrete

4.2.1. SHPB results

For the tests on UHPFRC the pressure in the gas gun was incremented at 3 and 6 bars so impact velocities equal to 27.2 m/s (for aluminium striker) and 20.8 m/s (for steel striker) were obtained. The resulting strain rates were respectively. 466 and 688 s^{-1}.

The results on UHPFRC are resumed in Tables 4 and 5 and in Figs. 9 and 10.

4.2.2. MHB results

The tests performed by means of MHB had exactly the same condition used for UHPC.

The strain rate obtained was in average equal to 111s^{-1}.

Table 5. Results on UHPFRC_pressure 3 bar. $v_{impact} = 20.8$ m/s.

Specimen	Stress Rate [GPa/s]	Max Stress [MPa]	Fract. strain [‰]	Fract. time [μs]	Strain rate [s^{-1}]	Tot. energy [kJ/m^2]
UHPFRC_44	15'622	178.74	10.53	21	754	108.51
UHPFRC_45	15'589	176.10	8.83	19	777	107.38
UHPFRC_46	19'445	249.85	8.45	22	537	81.91
UHPFRC_47	19'641	229.10	9.83	21	684	95.64
	17'574	*208.45*	*9.41*	*21*	*688*	*98.36*
Average	*(2'275)*	*(36.83)*	*(0.94)*	*(1)*	*(108)*	*(12.41)*

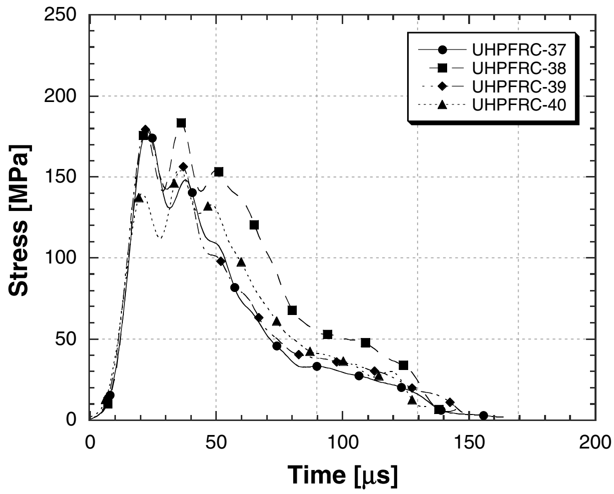

Figure 9. Results on UHPFRC at 466 s^{-1}.

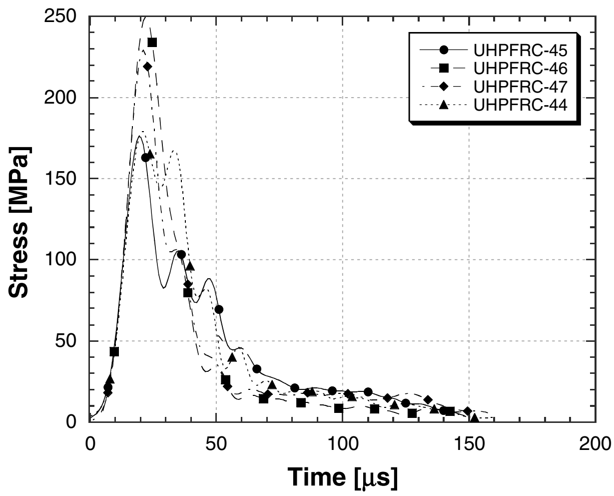

Figure 10. Results on UHPFRC at 688 s^{-1}.

5. Discussion

UHPC is a brittle material while UHPFRC can reduce the brittleness thanks to the addition of fibers in the mix. In particular the presence of the fibres enhances the post-peak behaviour. In Figs. 12 and 13 the stress versus displacement curves of UHPC and UHPFRC specimens tested in tension at about 450 and 700 s^{-1} are shown.

From these results it can be easily recognized the fibres role in the post-peak behaviour. The energy dissipation capacity is enhanced because of higher stress level for the same strain level. The peak strength seems not be

Table 6. Results on UHPFRC with MHB.

Specimen	Stress Rate [GPa/s]	Max Stress [MPa]	Fract. strain [‰]	Fract. time μs]	Strain rate [s^{-1}]	Tot. energy [kJ/m^2]
UHPFRC_002	677	100.5	16	279	78	93.70
UHPFRC_003	955	92.53	12	211	108	113.19
UHPFRC_004	716	88.92	24	255	135	109.70
UHPFRC_005	859	91.68	17	266	124	107.57
Average	*802* *(127)*	*93.41* *(4.9)*	*17* *(5)*	*255* *(29)*	111 (25)	*106.06* *(8.5)*

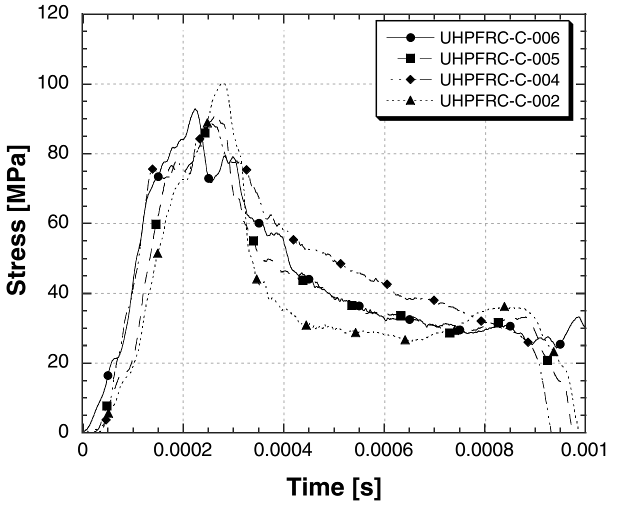

Figure 11. Results on UHPFRC at $110\,s^{-1}$.

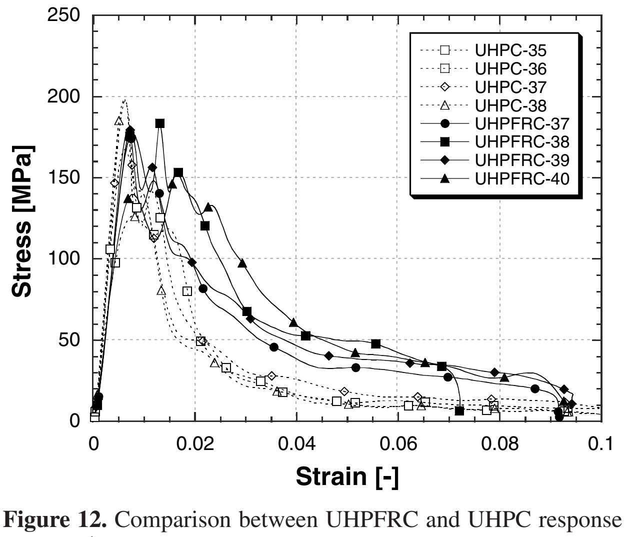

Figure 12. Comparison between UHPFRC and UHPC response at $466\,s^{-1}$.

influenced by the fibres presence. This can be reasonable because the principal role of the fibres is strictly related to the bridging effect.

The evolution of the strength in function of the stress rate (measured as the slope of the stress versus time curve) is shown in Fig. 14. The scattering of the results can be ascribed to several motivations. Firstly, the boundary

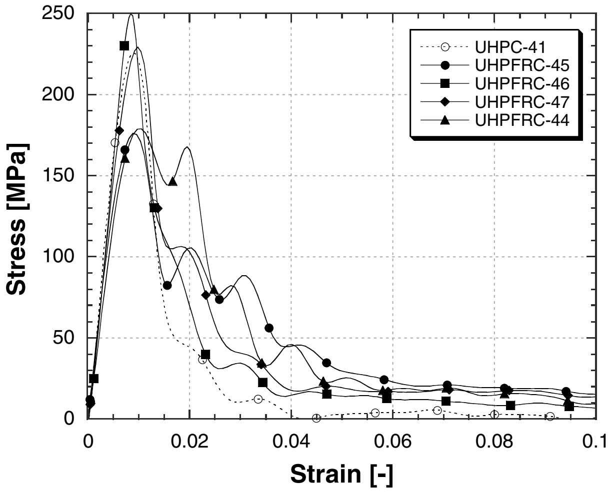

Figure 13. Comparison between UHPFRC and UHPC response at $688\,s^{-1}$.

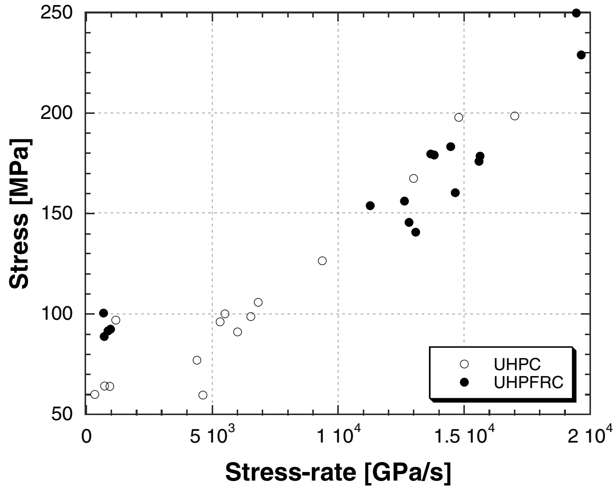

Figure 14. Strength versus stress-rate of UHPC and UHPFRC.

conditions of the specimens such as flatness, presence of grease or copper gasket. Secondly, the presence of the fibres can be considered a discontinuity in the materials causing the premature failure. Finally, the grade of dispersion of the fibres in the cross section is definitely different in each specimen.

6. Concluding remarks

The results of dynamic experimental investigations on ultra-high performance fibre reinforced concrete in compression have been described. The experiments were carried out using a Split Hopkinson Pressure Bar and a modified Hopkinson bar device.

UHPFRC shows an increase of the mechanical features as post-peak strength, failure time, and absorption energy respect to UHPC. The reason for this increase in the performance can be related to the contribution of the fibres distribution.

The results obtained at high strain rates are the basis to interpret the results acquired during blast experiments and to assess the goodness of the modelling.

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