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Dynamic Mechanical Behaviour of Ultra-high Performance Fiber Reinforced Concretes

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Abstract: Ultra-high performance fiber reinforced concretes (UHPFRC) were prepared by replacing 60% of cement with ultra-fine industrial waste powder. The dynamic mechanical behaviour of UHPFRC with different fiber volume fraction was researched on repeated compressive impact in four kinds of impact modes through split Hopkinson pressure bar (SHPB). The experimental results show that the peak stress and elastic modulus decrease and the strain rate and peak strain increase gradually with the increasing of impact times. The initial material damage increases and the peak stress of the specimen decreases from the second impact with the increasing of the initial incident wave. Standard strength on repeated impact is defined to compare the ability of resistance against repeated impact among different materials. The rate of reduction of standard strength is decreased by fiber reinforcement under repeated impact. The material damage is reduced and the ability of repeated impact resistance of UHPFRC is improved with the increasing of fiber volume fraction.

Key words: ultra-high performance fiber reinforced concretes; split Hopkinson pressure bar; dynamic; repeated impact

1 Introduction

Ultra-high performance fiber reinforced concrete (UHPFRC) is a new type of building material with very high compressive strength of more than 200 MPa. The high strength and ductility of UHPFRC make it an ultimate building material, *eg*, for bridge decks, thin-wall shell structures, highly loaded columns and military defense. Beside its improved strength properties, it has outstanding durability[1-5]. In this paper, ultra-high performance fiber reinforced concretes were prepared by replacing 60% of cement with ultra-fine industrial waste powder. The ground fine quartz sand with maximal diameter of 600 μm was totally replaced by natural sand with maximal diameter of 2.5 mm and basalt aggregates with maximal diameter of 10 mm. The advantages of granular packing and component complementing are achieved by the means of trinary composition of ultra-fine industrial waste powder.

The effect of the strain-rate on the strength of concrete is an important factor in the design of structures that may experience impact, penetration and blast. It is generally accepted that there is an apparent increase of the dynamic strength when the concrete is subjected to high strain-rate. European CEB recommends dynamic strength formulas for concrete which take bilinear relations between the dynamic strength and the logarithm of strain rate with a change in slope at the strain rate of 30/s. A great number of tests have been conducted to find the effect of strain rate on dynamic strength by using various test methods, *eg*, drop-hammer techniques, servo-hydraulic loading rigs, split Hopkinson pressure bar (SHPB) and explosive devices. SHPB is effective to obtain the dynamic stress-strain behaviour of materials. Grote investigated the behaviour of concrete and mortar by SHPB experiments with strain rates between 250 and 1700/s. Lok researched the dynamic characteristics of steel fiber reinforced concrete through 75 mm diameter SHPB. Ross tested several cylindrical concrete specimens with diameter from 19 to 51 mm by SHPB in direct tension, splitting tension, and direct compression[6-10].

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Previous dynamic researches were about concretes or fiber reinforced concretes with low or middle strength. Structures usually suffered more than one time impact but few researches dealt with repeated impact. The present paper studied the dynamic behaviour of UHPFRC under repeated impact in different impact modes through SHPB. The paper also discovered the effects of material composition, impact times and impact modes on the behaviour of UHPFRC under repeated impact.

2 Experimental

2.1 Materials preparation and static mechanical properties

Four cementitious materials were used in the preparation of UHPFRC including portland cement, silica fume, ultra-fine fly ash and ultra-fine slag. Their chemical composition and properties are listed in Table 1. Cement of PⅡ Grade-52.5 was used. The maximum particle size of natural sand is 2.5 mm with a fineness modulus of 2.6. The coarse aggregate is basalt with maximum particle size of 10 mm. The superplasticizer was produced by Grace Company in Shanghai China with a water-reducing ratio more than 40%. The equivalent diameter, length and tensile strength of the fine steel fibers are 0.2 mm, 13 mm and 1 800 MPa, respectively.

Six types of UHPFRC were prepared. The mix proportion is listed in Table 2. UFRC1 and UFRC2 are without and with coarse aggregates respectively. 60% cement was replaced by ultra-fine industrial waste powder by weight. Ground fine quartz sand was totally replaced by natural sand. The volume fraction of steel fiber was 0 to 4%. The cementitious materials and sand were put in a forced mortar mixer at the same time and mixed for 3 min. Then mixed the water and superplasticizer together and put the liquid into the mixer to mix for 6 min. Finally, dropped fibers and mixed for 3 min so that fibers were well distributed in the mortar. After mixing, the mixture of UHPFRC was cast into steel moulds and compacted using a standard vibrating table. The specimens were stored in the standard conditions (20±2 ℃, RH >90%) and demoulded after 24 h. Then the specimens were cured in the standard conditions for 60 d before test. The static uniaxial compressive results are shown in Table 3. Results show that the static strength, elastic modulus and toughness are improved with the increase of fiber volume fraction.

Table 1 Chemical compositions and properties of cementicious materials

Items	Chemical composition/%						Specific surface	Density
	SO_3	SiO_2	Fe_2O_3	MgO	Al_2O_3	CaO	/(m^2/kg)	/(10^3kg/m^3)
Cement	2.24	20.60	4.38	0.55	5.03	65.06	346	3.02
Silica fume	0.80	94.50	0.83	0.97	0.27	0.54	20 000	2.20
Fly ash	1.45	54.98	5.93	1.27	31.34	3.90	720	2.33
Slag	1.00	34.20	0.43	6.70	14.20	41.70	800	2.82

Table 2 Mix proportions of UHPFRC/%

Materials	Cement	Silica fume	Fly ash	Slag	V_f	Sp/Binder	Sand/Binder	Sand/Cag	Water/Binder
UFRC1V_0	40	10	25	0	0	0.02	1.2	—	0.15
UFRC1V_3	40	10	25	3	3	0.02	1.2	—	0.16
UFRC1V_4	40	10	25	4	4	0.02	1.2	—	0.16
UFRC2V_0	40	10	25	0	0	0.02	1.2	1	0.16
UFRC2V_2	40	10	25	2	2	0.02	1.2	1	0.17
UFRC2V_3	40	10	25	3	3	0.02	1.2	1	0.17

Note: V_f—fiber volume fraction, Sp—superplasticizer, Cag—coarse aggregate

Table 3 Uniaxial compression results

Materials	Uniaxial compressive strength/MPa	Peak strain /($\times 10^{-3}$)	Elastic modulus /GPa	Toughness index		
				η_{c5}	η_{c10}	η_{c30}
UFRC1V_0	143	2.817	54.7	2.43	2.43	2.43
UFRC1V_3	186	3.857	57.3	3.59	5.08	5.57
UFRC1V_4	204	4.165	57.9	4.57	6.32	7.39
UFRC2V_0	151	3.138	56.3	2.23	2.23	2.23
UFRC2V_2	190	3.593	57.1	3.56	4.04	4.42
UFRC2V_3	211	4.163	58.4	4.39	6.14	6.20

2.2 Test method of repeated impact

The cylinder specimen for SHPB test was 70 mm in diameter and 35 mm in length. A typical SHPB set-up is outlined in Fig.1. It is composed of elastic input and output bar with a short specimen placed between them. The impact of the projectile at the free end of the input bar develops a compressive longitudinal incident wave $\varepsilon_i(t)$. Once this wave reaches the bar specimen interface, a part of it $\varepsilon_r(t)$, is reflected, whereas another part goes through the specimen and transmits to the output bar $\varepsilon_t(t)$. Those three basic waves are recorded by the gauges pasted on the input and output bars. Three kinds of technology including gimbal device, wave shaping and direct strain measure were used to increase the experiment accuracy. According to the wave propagation theory, the average stress, strain and strain rate of specimens can be calculated by the following equations:

$$\sigma = E_0 \varepsilon_t(t) \frac{A_0}{A_s}$$

$$\dot{\varepsilon} = \frac{2C_0}{L_s}[\varepsilon_i(t) - \varepsilon_t(t)]$$

$$\varepsilon = \int_0^t \dot{\varepsilon}(t)\,dt \qquad (1)$$

where, E_0 and C_0 are the Young's modulus and the elastic wave speed of the bar respectively, A_0 and A_s the cross section areas of the bar and the specimen respectively, and L_s the length of the specimen.

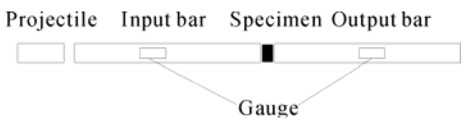


Fig.1 SHPB test set-up

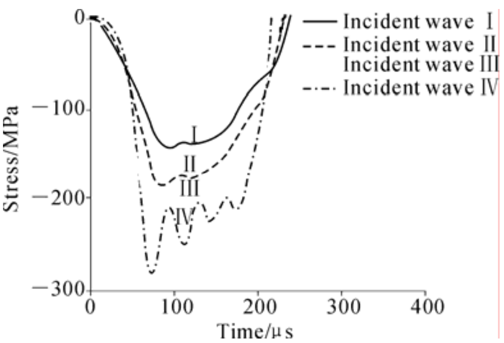


Fig.2 Incident waves on repeated impact

Materials and structures in use usually suffered more than one time impact so it is important to research the decrease of the dynamic strength and the development of materials damage under repeated impact. The strain rates of concretes are usually within 10^2/s on impact through SHPB. Repeated impact on UHPFRC by four kinds of loading modes of different incident waves (Fig.2) is as follows: mode A: the first impact is from incident wave Ⅰ, others are from incident wave Ⅱ; mode B: the first impact is from incident wave Ⅱ, others are from incident wave Ⅱ; mode C: the first impact is from incident wave Ⅲ, others are from incident wave Ⅱ; mode D: the first impact is from incident wave Ⅳ, others are from incident wave Ⅱ.

The strain rates of UHPFRC are from 10 s to 10^2 s by the four kinds of impact modes. The incident wave on the first impact increases from Mode A to Mode D so as to make specimens have different initial damage. Then the incident wave Ⅱ is used for other impact and the changes of dynamic properties of UHPFRC are researched.

3 Results and Discussion

3.1 Stress waves on repeated impact

Fig.3 shows the stress waves transmitted through the same material under repeated impact in different impact modes. With the increase of the projectile speed of the first impact from mode A to mode D, the incident and transmitted waves under the first impact are strengthened and the damage of specimens on the first impact increases at the same time. The same projectile speed results in the similar incident waves on the second and the third impact but the transmitted wave is weakened with the increase of material damage. Fig.3 shows that the more the material damage is on the first impact the faster the weakening rate of the transmitted wave is and the more the reflective wave is strengthened.

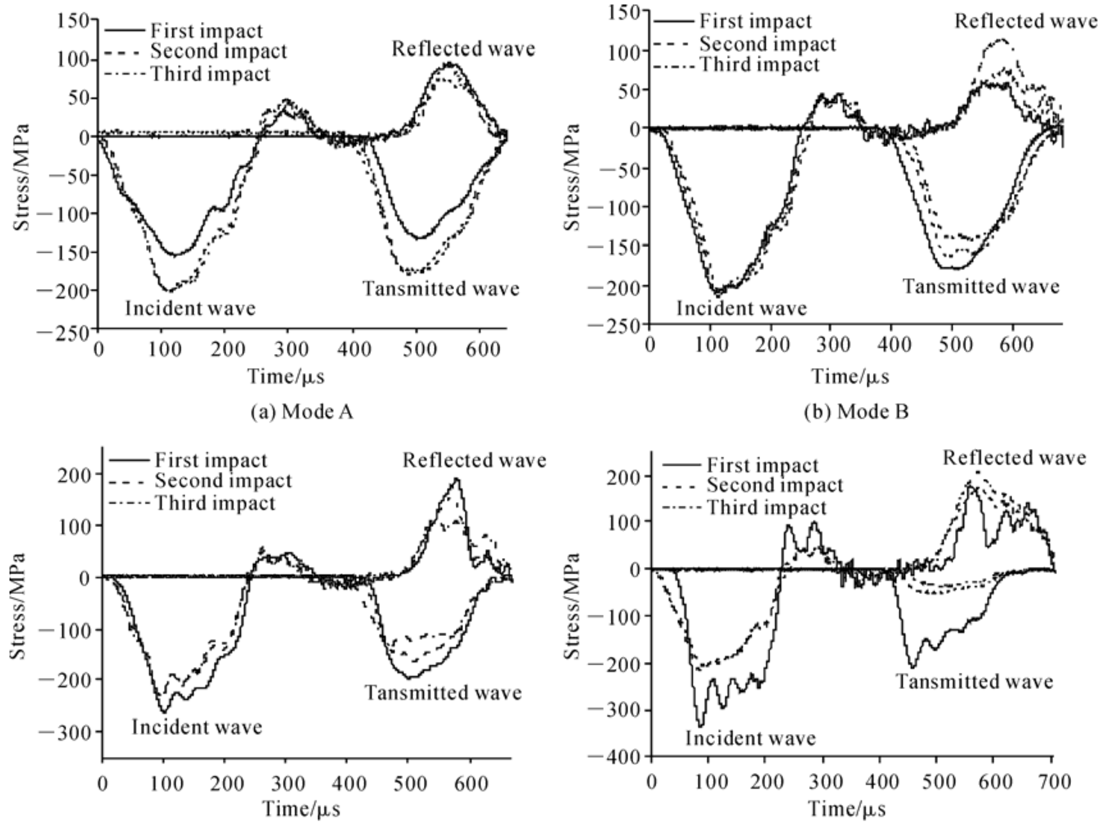
3.2 Dynamic properties of UHPFRC under repeated impact

3.2.1 Effect of impact times on the dynamic mechanical properties of UHPFRC

Fig.4, Fig.5 and Table 4 show the strain-stress curves and the test results of UHPFRC under repeated impact in mode A. The weak resistance of UHPFRC matrix against repeated impact results in complete crack of the matrix specimen after the second impact so it cannot tolerate any more impact. The resistance of UHPFRC against repeated impact is strengthened largely by fiber reinforcement. The speed of projectile at the second impact is higher than that at the first impact in mode A, so the peak stress of the specimen on the second impact is greater than that on the first impact. But it decreases gradually from the third impact because of the increasing damage of the material. The decreasing rate of peak stress is reduced by increasing fiber volume fraction. Especially UFRC1V$_4$ with the fiber volume fraction of 4%, the peak stress of it remains almost the same on the second and third impact and is above 100 MPa on the forth and fifth impact, which shows its excellence in the resistance against repeated impact. Fig.4 and Fig.5 show that the damage of the specimen is weak and the stress-strain curve bends back under the first impact, and that the rising slope of the stress-strain curves decreases and a flat stage appears with the increase of impact time.

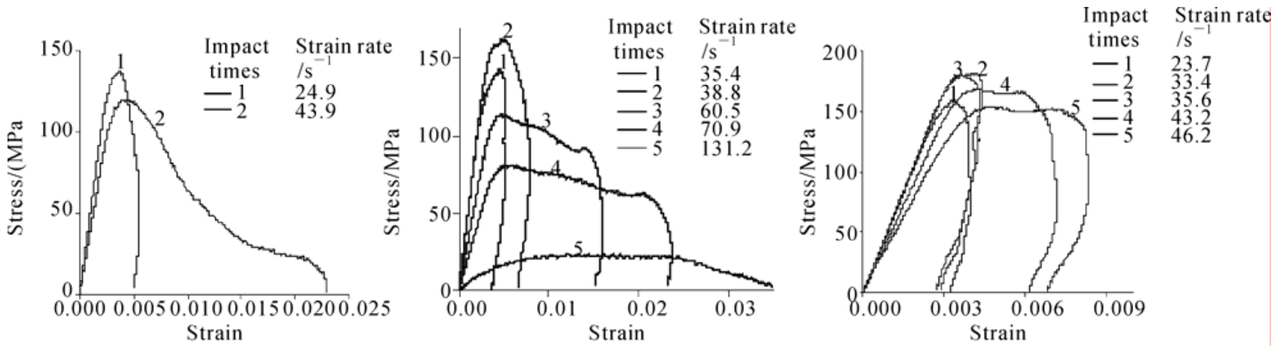
Stress-strain curves show that the peak stress decreases largely with the increase of impact times when the specimen strain is over 0.01 and the strain rate is over 60 s. The strain of UFRC1V_4 is below 0.01 and its strain rate is below 50 s after successively five times of impact, and the decline of its peak stress is no more than 15%. Table 4 shows that the strain rate and peak strain increase while the peak stress and elastic modulus decrease gradually with the increase of impact times, and illustrates the accumulation of material damage under repeated impact.

The peak stress of strain rate sensitive homogeneous material increases and its peak strain decreases with the increasing of strain rate which is called strain rate hardness. Cementitious material with much micro-crack shows different results at high strain rates for its inhomogeneity and its dynamic behaviour is influenced by the results of strain rate hardness and damage toughness. As the material damage is slight on the first impact, the effect of strain rate hardness is dominant and the rising stage of the stress-strain curve is approximately linear and the initial elastic modulus increases with the increase of strain rate. With the increase of impact times the material damage increases and the damage zones are formed because of the formation and development of much micro-crack which increases energy dissipation and delays the unstable extension of crack so as to improve the material toughness.



(a) Mode A (b) Mode B (c)Mode C (d) Mode D

Fig.3 Different stress waves transmitted through UFRC1V_4 in different impact modes



(a)UFRC1V_0 (b)UFRC1V_3 (c)UFRC1V_4

Fig.4 Stress-strain curves of UFRC1 at different impact times in mode A

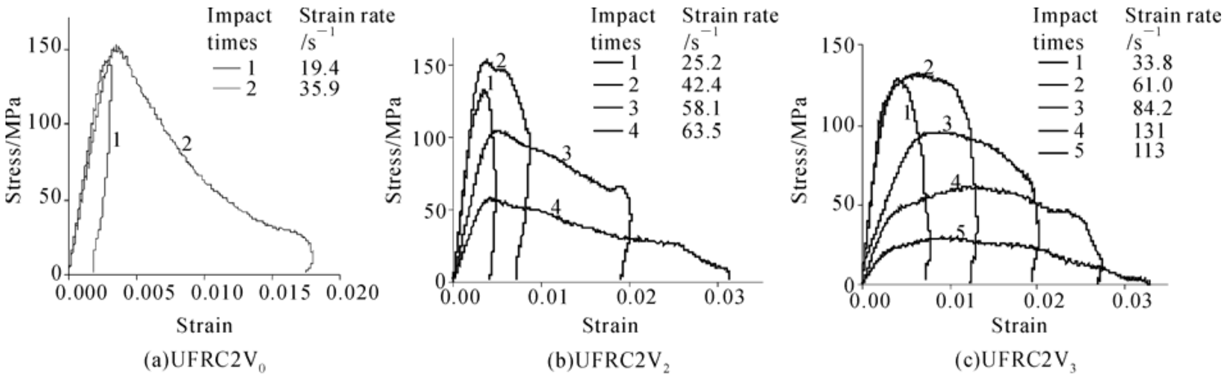


Fig.5 Stress-strain curves of UFRC2 at different impact times in mode A

Table 4 Experimental results of UHPFRC at different impact times in mode A

Materials	Impact times	Stain rate /s^{-1}	Elastic modulus /GPa	Peak strain (×10^{-6})	Peak stress /MPa
UFRC1 V_0	1	24.9	50.1	3 588	138
	2	43.9	39.2	4 051	120
UFRC1 V_3	1	35.4	48.7	4 518	143
	2	38.8	49.2	4 956	162
	3	60.5	31.2	5 629	114
	4	70.9	20.5	6 087	81
	5	131.2	4.6	12 197	24
UFRC1 V_4	1	23.7	55.3	3 270	160
	2	33.4	56.7	4 094	182
	3	35.6	56.1	3 629	181
	4	43.2	46.7	4 272	169
	5	46.2	40.9	4 579	154
UFRC2 V_0	1	19.4	56.5	2 768	142
	2	35.9	51.5	3 538	152
UFRC2 V_2	1	25.2	51.9	3 427	133
	2	42.4	55.6	3 833	155
	3	58.1	27.6	4 842	106
	4	63.5	17.6	4 143	58
UFRC2 V_3	1	33.8	51.5	4 070	129
	2	61.0	48.9	6 169	133
	3	84.2	15.0	7 760	96
	4	131	15.6	11 662	62
	5	113	8.2	9 299	29

3.2.2 Effect of impact mode on the mechanical properties of UHPFRC

Fig.6 and Table 5 show the different strain-stress curves and the test results of UHPFRC in different impact modes. Results show that the strain rate, elastic modulus, peak stress and peak strain increase gradually under the first impact from mode A to mode D in that the amplitude of incident wave increases gradually with the changing of impact modes while the material damage also increases. With the same amplitude of incident wave on the second impact but different material damage for each mode, the stress-strain curves on the second impact change in the pattern contrary to that on the first impact, namely, the elastic modulus and peak stress on the second impact decrease from mode A to mode D. In the same impact mode the elastic modulus and peak stress decrease while the strain rate and peak strain increase with the increase of impact times. In mode B and mode C, the reduction of elastic modulus and peak stress decreases with the increase of fiber volume fraction. In mode D the strain rates of different materials are all over 90/s and the strain is over 0.02 on the first impact while the elastic modulus and peak stress decrease significantly on the second impact. It can be concluded that the serious damage at the high strain rate on the first impact leads to the similar dynamic properties of different materials on the second impact or the effects of different material composition on the ability of resistance against repeated impact are insignificant.

3.2.3 The standard strength of UHPFRC on repeated impact

The standard strength of materials on repeated impact is defined as:

$$I_n = F_n / F_0$$

where, I_n is the standard strength of the specimen after *n* times of impact, F_0 and F_n the peak loads of the specimen on the first and *n*th impact respectively.

Fig.7 shows the changing process of the standard strength of UHPFRC under repeated impact in different impact modes. The matrix of UHPFRC usually cracks completely on the first impact, but only in mode A can it be impacted twice. The second standard strength I_2 of UFRC1V_0 and UFRC2V_0 decrease to 86% and 96% respectively while the increase of I_2 of UFRC1 and UFPC2 reinforced by fibers range from 11.6% to 22.5% and from 2.6% to 9.8% compared with I_1 and then I_n decreases with the increase of impact times. The reduction of I_n falls more slowly with the increase of the fiber volume fraction. The standard strength of UFRC1V_4 reduces only by 10% after 5 times of impact in mode A which justifies its excellence in repeated impact resistance. As the material damage caused by the first impact increases from mode A to mode D, the reduction rate of standard strength increases gradually from mode A to mode D. In mode B, the reduction of I_2 of UFRC1V_3 and

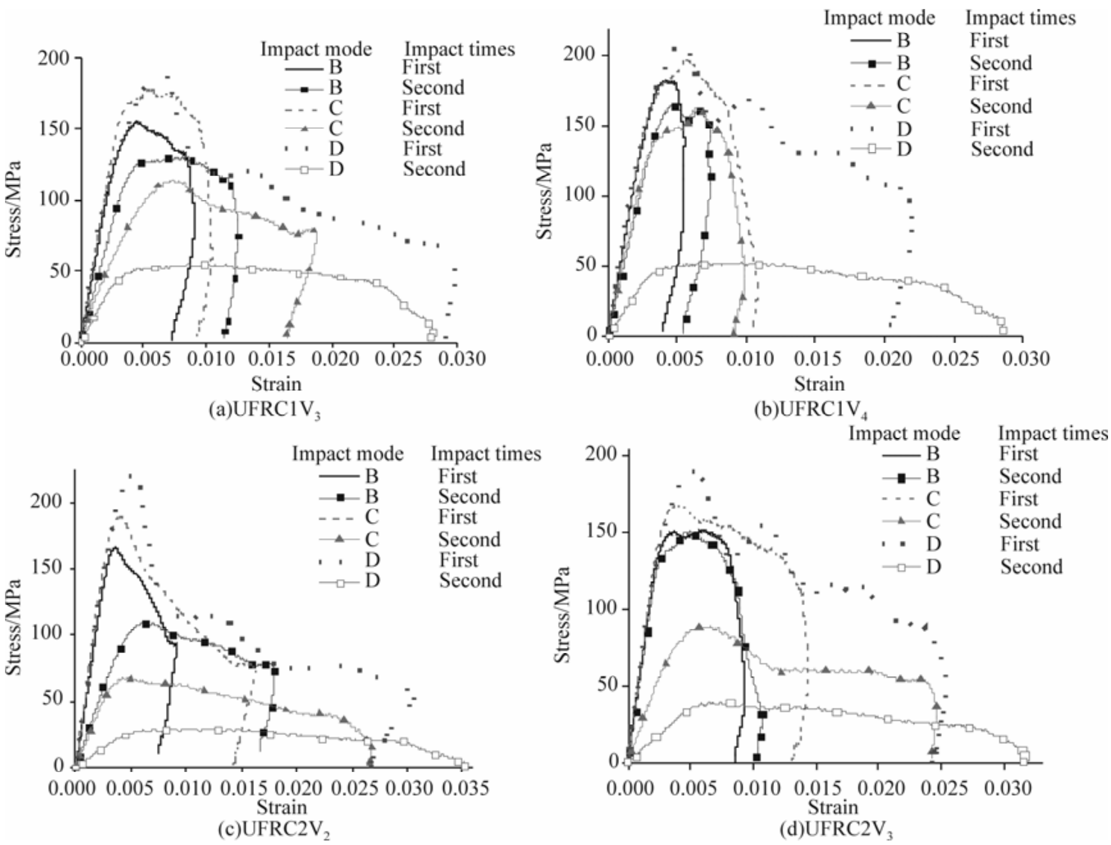


Fig.6 Effect of different impact modes on the stress-strain curves of UHPFRC

Table 5 Experimental results of UHPFRC in different impact modes

Materials	Impact mode	Impact times	Stain rate /s^{-1}	Elastic modulus /GPa	Peak strain /($\times 10^{-6}$)	Peak stress /MPa
		1	38.8	49.6	4 421	155
	B	2	59.9	33.1	7 607	130
		3	87.6	16.0	9 057	78
		1	66.8	53.7	5 575	178
UFRC1V$_3$	C	2	82.1	27.2	7 304	115
		3	88.4	13.7	5 764	56
		1	99.2	57.4	6 308	192
	D	2	98.9	16.2	9 969	55
		3	131.8	8.5	8 854	34
		1	35.5	57.3	4 418	183
	B	2	39.9	43.7	4 769	165
		3	66.2	36.4	8 708	144
		1	67.1	57.2	5 570	199
UFRC1V$_4$	C	2	69.8	47.5	6 337	164
		3	57.3	36.8	4 798	134
		1	90.3	65.1	5 399	207
	D	2	102.9	15.0	9 650	52
		3	139.5	9.4	10 991	38
		1	34.7	56.2	3 539	166
	B	2	63.6	24.3	6 444	110
		3	102.6	14.0	9 563	51
UFRC2V$_2$		1	42.7	62.9	3 966	189
	C	2	60.4	20.6	4 734	67
		3	81.8	10.7	5 474	21.3
	D	1	91.3	61.9	4 948	220
		2	112.5	5.8	9 791	30
		1	38.7	59.5	3 672	151
		2	43.5	57.1	4 936	152
	B	3	56.1	50.1	6 872	136
UFRC2V$_3$	C	1	52.4	62.1	3 807	168
		2	72.2	22.6	5 892	89
	D	3	97.8	11.8	5 592	35
		1	96.3	64.9	5 566	192
		2	90.6	7.3	6 559	39

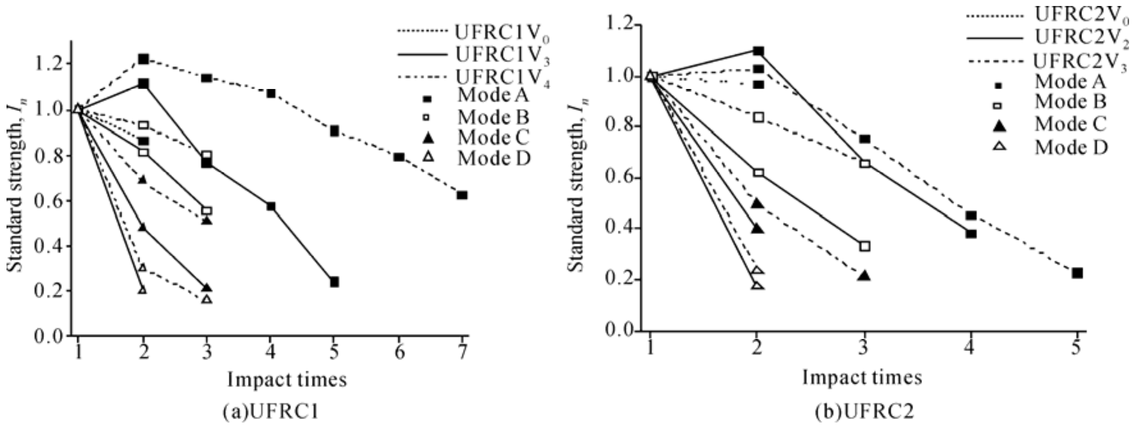


Fig.7 Effect of steel fiber fraction on the standard strength of UHPFRC

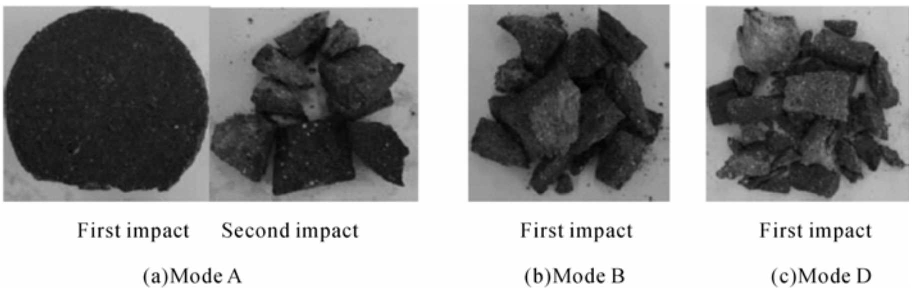


Fig.8 Fracture patterns of UFRC1V_0 on repeated impact

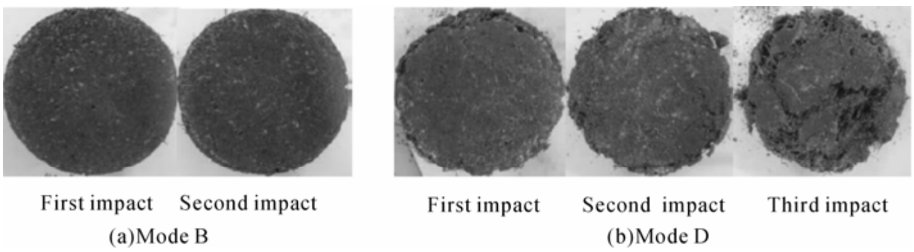


Fig.9 Fracture patterns of UFRC1V_3 on repeated impact

UFRC2V_3 and I_3 of UFRC1V_4 is no more than 20% compared with I_1. This shows their high ability of repeated impact resistance. In mode C, I_2 of UFRC1V_3, UFRC1V_4, UFRC2V_2 and UFRC2V_3 is about 48%, 68%, 40% and 50% respectively which shows the remaining ability of resistance against repeated impact. In mode D, I_2 of UHPFRC reduces to 20%-30% and I_3 to 15%. Thus it can be seen that the more the fiber volume fraction increases, the greater the ability of resistance against repeated impact UHPFRC has. The damage caused by the first impact has significant effect on the ability of resistance against repeated impact. Materials with less damage have higher ability of resistance against repeated impact.

3.2.4 The fracture pattern of UHPFRC on repeated impact

Fig.8 to Fig.11 show the fracture pattern of UHPFRC on repeated impact. The matrix of UHPFRC cracks severely after the first two times of impact and with the increasing of first impact load the damage increases from pieces dropping at the edge to total cracking into small parts. The fiber reinforcement improved greatly UHPFRC's ability of resistance against repeated impact. In mode A, UFRC2V_3, UFRC1V_3 and UFRC1V_4 suffer significant damage for 4, 5 and 10 times of impact respectively. Under repeated impact, slight crack appears on the side of fiber reinforced specimens before the crack extends to the center of the specimens at a low speed with the help of the fiber reinforcement. The specimens still remain intact although cracks across the middle of them appeare after several times of impacts. Materials damage on the second and third impact becomes more severe with the increase of damage on the first impact. In mode D, obvious cracks appear on the side of specimens UFRC1V_3 and UFRC1V_4 on the second impact and cracks exist in the middle of specimens on the third impact. It is on the first and second impact respectively that the same thing happens to UFRC2V_3. The damage of UFRC1V_4 is less severe than that of UFRC1V_3 and UFRC2V_3 after the same times of impact. The fracture pattern of UHPFRC is influenced by fibers strengthening and toughening. On the other hand, the fracture pattern can be explained by the point of stress wave. The tension strength of concrete is much lower than its compression strength. In the SHPB test, the stress wave is reflected as tension at the lateral of the specimen, which causes the tension damage of concrete. But for UHPFRC with fiber reinforcement, the randomly distributed fine fibers form networks to prevent tension damage. As a result, the destruction of fiber reinforced specimens is much slighter than that of matrix specimens on the same impact times.

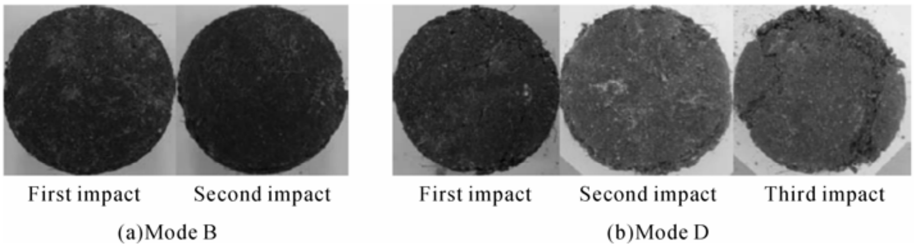


Fig.10 Fracture patterns of UFRC1V_4 on repeated impact

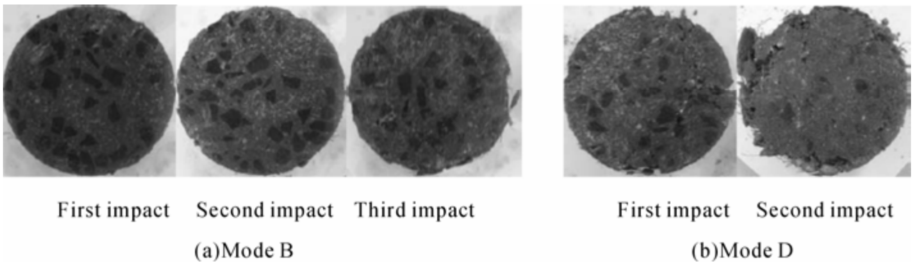


Fig.11 Fracture patterns of UFRC2V_3 on repeated impact

4 Conclusions

a) Ultra-high performance fiber reinforced concretes with 200 MPa compressive strength were prepared by replacing 60% of cement with ultra-fine industrial waste powder and replacing ground fine quartz sand totally with natural sand and basalt aggregates with maximal diameter of 10 mm.

b) The dynamic behaviour of UHPFRC with different steel fiber volume fractions was researched under repeated impact in four kinds of impact modes through SHPB. The ability of repeated impact resistance of UHPFRC is improved with the increase of fiber volume fraction. The peak stress and dynamic elastic modulus of UHPFRC decrease while the strain rate and peak strain increase with the increase of impact times. The rate of the reduction of standard strength decreases under repeated impact by fiber reinforcement.

c) The dynamic damage is controlled by fiber reinforcement under repeated impact. Fiber reinforced UHPFRC offers better integrity on repeated impact as compared with the matrix of UHPFRC. Only by the composition of high strength fine fibers can the excellent dynamic ability of UHPFRC be fully displayed.

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