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Responses and post-impact properties of ultra-high performance fibre reinforced concrete under pendulum impact

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ABSTRACT

The present research aims to understand the response and post-impact properties of ultra-high performance fibre reinforced concrete (UHPFRC) under low-velocity impact. An UHPFRC applying coarse basalt aggregate is developed by using the optimized particle packing theory and considering the mineral oxide engineering and steel fibre utilization. A reliable low-velocity impact method employing pendulum impact test set-up is designed and applied. The results show that the residual strength of UHPFRC beams after impact follows ‘ $-e^x$ ’ law with the number of impact, while the residual rigidity, toughness and impact resistance tend to linearly decrease. The rigidity and toughness are more appropriate indicators than ultimate bearing capacity based on the analysis on damage index. An analytical model is proposed to predict the residual impact resistance of UHPFRC beams with the static property of flexural toughness and validated against the experimental data.

1. Introduction

Ultra-high Performance Fibre Reinforced Concrete (UHPFRC) is a relatively new building composite material, which has superior mechanical strength, impact resistance, fatigue resistance and durability [1–6]. Those excellent characters and properties make it suitable to be used in impact resistant components and structures, such as protective elements in military and municipal engineering.

The excellent impact resistance of UHPFRC is greatly dependent on raw materials and mix design methods, such as water-to-binder ratio, mineral admixture condition, powder content, and aggregate size and content. Currently, most UHPFRCs are designed by using only fine aggregates or refined aggregates [2,3,7,8], in order to avoid the limit of intrinsic strength of coarse aggregate, overcome the inherent weakness of interfacial transition zone, increase the homogeneity and eliminate stress concentration at the contact points between aggregates. However, concrete containing appropriate type and content of coarse aggregate can possess certain advantages, such as reduced autogenous shrinkage [3], improved elastic modulus and workability [9], enhanced stress-strain behaviour of confined concrete [10]. A slightly higher strength of concrete in presence of coarse aggregate has also been observed [11,12]. Our previous research further proved that the incorporation of coarse basalt aggregate to UHPFRC induces rather limited decrease on the mechanical strength, while greatly reduces the powder amount, consequently cost of UHPFRC [13]. Nevertheless,

investigation on the effect of coarse aggregate on properties of UHPFRC under impact loading is still very limited. In addition, basalt aggregate exhibits a better intrinsic strength than ordinary rock [14], which is potentially more suitable to match the high strength of paste matrix of UHPFRC. Hence, the properties of UHPFRC with coarse basalt aggregate under impact loading need to be investigated.

In recent years, numerous experimental and analytical studies have focused on responses and properties of UHPFRC under high-velocity impact loading, such as bullet or projectile impact test, blast test and split-Hopkinson bar test [15–17]. Nevertheless, the impact responses and post-impact properties of UHPFRC under low-velocity impact loading are also of great significance and can provide insights on specific practical problems, such as vehicle impact on concrete infrastructure during traffic accident, ship collision on bridges’ pillars or offshore structures, falling object impact on concrete slab, wheel-rail interaction on concrete sleeper [18,19], etc. However, it is noticed that no standard low-velocity impact testing methods for UHPFRC are available currently. Drop-weight test and modified Charpy system recommended by ACI Committee 544 are widely used [20–24]. However, these low-velocity impact testing methods are not appropriate for evaluating UHPFRC because of certain drawbacks. A high standard deviation and coefficient of variation from ACI repeated drop-weight impact test are usually observed, even more than 50% of coefficients of variation [21]. The number of impact is too large for fibre reinforced concrete, sometimes as high as 1000 blows [22]. The Charpy type

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impact test can only measure small geometrical size of specimen with short fibres [24]. The drop-weight impact test usually has a rebounded and secondary impact effect, when the specimens do not completely damage [25]. Hence, it is necessary to develop a new low-velocity impact experimental method for UHPFRC.

Besides, the majority of current studies only place emphasis on investigating the total impact number and energy absorption under repeated low-velocity impact loading. Researches concerning impact responses and post-impact properties assessment are rather scarce. Both crack propagation and damage pattern are critical factors to interpret impact response and resistant mechanism of UHPFRC. Furthermore, residual property (e.g. compressive strength after impact) is one of the most crucial parameters for damaged composite materials [26], which is widely used to evaluate the damage degree and health status of structures and components under extreme conditions, such as residual strength after fatigue loading, freeze–thaw cycles or high temperature exposure [27–29]. The investigation on post-impact properties (e.g. residual strength, stiffness, toughness, impact resistance) can provide key parameters and bases for the design of protective elements and components. Nevertheless, impact resistance (energy absorption capacity) of UHPFRC is much more difficult to be determined than other static properties, due to the complexity of impact test. For these reasons, necessity to investigate the impact responses and post-impact properties of UHPFRC under repeated low-velocity impact loading, and to propose a reliable analytical model to predict the impact resistance by several key variables based on simple static tests is evident.

The objective of this paper is to design a reliable repeated low-velocity impact testing device and method, investigate the impact responses and post-impact properties of UHPFRC with coarse basalt aggregate, and classify the damage levels by analysing the damage index. Furthermore, an analytical model is proposed to predict the residual impact resistance of UHPFRC beams with the static property of flexural toughness and validated against the experimental data.

2. Experimental program

2.1. Materials

The raw materials used in this study are Portland cement CEM I 52.5 R (PC), micro-silica (mS), limestone powder (LP), silica sand (S), coarse basalt aggregate (BA), tap water (W), PCE-type superplasticizer (SP) and steel fibre (SF). The specific densities of those ingredients were measured by a gas pycnometer (AccuPyc 1340 II Pycnometer®), shown in Table 1. The particle size distributions (PSD) of the used materials were measured by the sieve and laser diffraction analyses (Malvern Mastersizer 2000®), respectively, shown in Fig. 1. The chemical compositions of the used powders were tested by X-ray Fluorescence (XRF), shown in Table 2. Table 3 exhibits the characteristics of utilized steel fibre.

2.2. Mix design

The recipe of UHPFRC in this study is illustrated in Table 4. A PCE-type superplasticizer is utilized to achieve a desired fluidity with a dosage of 1.6% by the weight of total powder, based on the previous study [30]. The optimal proportion of powders is 5% of micro-silica and 20% of limestone powder by mass of the total powder, by considering the flow ability, mechanical strength and drying shrinkage of UHPFRC

Table 1
Specific densities of raw materials.

Materials	CEM	mS	LP	S	BA 2–5	BA 2–5	W	SP
Specific density (g/cm ³)	3.15	2.32	2.71	2.72	3.05	2.89	1.00	1.07

Fig. 1. The PSD of raw materials and designed UHPFRC matrix.

pastes [13]. The dosage of steel fibre is 2% vol. of the UHPFRC, which is proven to be an appropriate dosage for UHPFRC [4,31]. The fractions of aggregates are determined by applying the Brouwers method [32–36],

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \quad (1)$$

where D is the particle size (μm), D_{min} and D_{max} represent the minimum and maximum particle size, respectively (μm). $P(D)$ is the cumulative fraction of the total solids being smaller than size D . q is the distribution modulus, which is greatly dependent on the type of concrete [37,38]. A relatively low q value of 0.19 in our previous study is proposed and suggested for UHPFRC containing coarse aggregate and relatively low powder content [13]. The PSDs of the target and designed curve of UHPFRC matrix are shown in Fig. 1. The casting and curing of the concrete follow the same procedure as presented in the previous study [13].

2.3. Testing methods

2.3.1. Fresh behaviour

The spread flow of UHPFRC was measured by using a truncated conical mould (Abrams cone: height 300 mm, top diameter 100 mm, base diameter 200 mm), in accordance with EN 12350-8: 2007 [39]. Fresh concrete was filled in the mould and the cone was lifted straight upwards to allow the concrete flow freely without jolting. The spread flow was calculated by the average value of two perpendicular diameters. The flow test was conducted at room temperature of about $20 \pm 1^\circ\text{C}$. The fresh concrete was filled in a cylindrical container of known volume, and then its mass was determined to calculate the fresh density.

2.3.2. Compressive and tensile splitting strength

The fresh UHPFRC was casted into steel moulds ($100 \times 100 \times 100 \text{ mm}^3$) for compressive and tensile splitting strength test. All samples were covered with polyethylene film to prevent the moisture loss. They were demoulded approximately 24 h after casting and then cured in water under room temperature of $20 \pm 1^\circ\text{C}$. The compressive and tensile splitting strength of UHPFRC samples were measured following the specifications set in the standards EN 12390-3: 2009 [40] and EN 12390-6: 2009 [41], respectively, at different curing ages.

2.3.3. Pendulum impact test

As discussed above, a novel and reliable testing set-up and method for repeated low-velocity impact needs to be designed to research the

Table 2
Chemical composition of powders.

Substance (%)	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	Na ₂ O	SO ₃	MgO	TiO ₂	MnO
CEM	67.02	16.80	4.14	3.48	0.23	–	4.14	1.67	0.27	0.09
mS	0.90	93.06	–	2.06	1.15	0.63	1.28	0.70	–	0.07
LP	97.21	0.87	0.17	0.13	–	–	0.11	1.17	0.01	0.01

impact responses and post-impact properties of UHPFRC. Impact tests can be divided into three categories (qualitative, semi quantitative and quantitative), depending on the property measured by which the impact test is conducted. But quantitative interpretation of impact testing results to derive inherent physical material parameters has shown to be still quite difficult. Furthermore, impact tests should follow some primary criterion and achieve goals as: (1) simple to handle; (2) energy sufficient to fracture the specimen; and (3) number of blows to achieve a specified distress level [42].

In this study, the repeated low-velocity impact test was carried out by using a pendulum set-up (length 12 m, width 4 m, height 6 m), shown in Fig. 2. The impact height can be adjusted from 0 up to 4 m, while the impact mass can be changed from about 22 kg to 40 kg. The point-contact hammer, released from a certain height, impacts the hanging concrete specimen perpendicularly at the lowest position. The velocities of hammer and specimen, before and after impact, are measured by the high-speed camera by recording movement during short period of time. The frame rate of high-speed camera is set at 5000 frames per second, and the displacement of movement is measured around 5 cm based on a white board background with centimetre grids drawn on it. The impact resistance of UHPFRC can be described by the energy absorbed by the specimen. The absorbed energy during a single impact can be calculated by using,

$$E = 1/2M_h V_0^2 - 1/2M_h V_r^2 - 1/2M_s V_s^2 \quad (2)$$

where the E is the absorbed energy by specimen during a single impact (J); M_h and M_s are the masses of hammer and specimen (kg), which are 30.3 kg and 31.7 kg, respectively; V_0 and V_r are the velocities of hammer before and after impact (m/s), the hammer is released from the height of 1.4 m and the initial impact velocity V_0 for each impact is approximately 4.78 m/s; V_s is the velocity of concrete beam after impact (m/s) and assumed as a constant, because inertia induced self-vibration is very limited compared to the kinetic velocity and very short (usually 1 or 2 ms) compared to measuring period (tens of milliseconds in this study) [43,44]. The mass and initial velocity of hamper is chosen after preliminary trials in order to acquire a moderate impact number. The impact is repeated several times till a pre-designed impact number or complete failure of specimen.

Standard notched beam has been recommended by various organizations such as RILEM TC 162 [45] and EN 14651 [46] to test the impact resistance of concrete [47]. The notch is made on the rear surface of beam. It has been reported that the variations of conventional drop-weight impact results are often very high, attributed to the shape of specimen [48,49]. This is also observed in the preliminary experiments during this study. Notched specimens tend to reduce the variations of testing results, attributed to certain fracture path along the notch plane [50]. Furthermore, it is also convenient to evaluate the post-impact properties of this kind of specimen, which will be discussed in following sections.

To sum up, this proposed impact testing method has several advantages in comparison with conventional drop-weight test. Firstly, the

Table 3
Characteristics of steel fibre.

Length (L) (mm)	Fibre shape	Bundling	Diameter (d) (mm)	Aspect ratio (L/d)	Density (kg/m ³)	Tensile Strength (MPa)	Elastic Modulus (GPa)
13	Straight	Loose	0.2	65	7850	2750	200

Table 4
Recipe of designed UHPFRC.

Materials	PC (kg/ m ³)	mS (kg/ m ³)	LP (kg/ m ³)	S 0–2 (kg/ m ³)	BA 2–5 (kg/ m ³)	BA 5–8 (kg/ m ³)	W (kg/ m ³)	SP (kg/ m ³)	SF Vol. %
Quantity	588	39.2	156.8	839.9	413.2	232.3	187.8	12.6	2%

different swing movements between hammer and specimen can eliminate rebound and secondary impact during each full impact. Secondly, the acquired impact resistance (absorbed energy) should be more accurate based on kinetic energy difference, because the absorbed energy is normally calculated by impact number and gravitational potential energy [23,24,28]. However, the specimen cannot absorb all potential energy, which leads to an overestimated impact resistance. Thirdly, the variation of results should be lower based on notched specimens. Lastly, the pendulum set-up is easily compatible with most low-velocity impact tests of UHPFRC and a moderate impact number is sufficient, due to the flexible change of specimen (e.g. shape and size) and hammer (e.g. shape, mass and height).

2.3.4. Central point bending test

During the repeated pendulum impact test, impact responses of UHPFRC can be collected, such as crack propagation, damage pattern and energy dissipation. Meanwhile, partially and completely damaged beams will be collected. To analyse the post-impact properties and research correlations between impact resistance and basic key static parameters, the flexural behaviours of both original and partially damaged beams after a certain impact number are subsequently measured, based on RILEM TC 162-TDF [45]. Some UHPFRC beams and central point bending set-up are shown in Fig. 3. Based on the load–deflection curve, the corresponding post-impact properties can be deduced, such as residual strength, rigidity and toughness, as well as damage index and levels.

3. Results and discussion

3.1. Fresh and static behaviours

The fresh properties and static strengths of the designed UHPFRC are presented in Table 5. The slump flow and fresh density of the designed UHPFRC are approximately 560 mm (class of SF2 according to SCC guideline [51]) and 2562 kg/m³, respectively. The excellent slump flow can be explained by the used PCE-type superplasticizer, high limestone powder content, utilization of coarse aggregate, as well as the achieved optimal packing of the solid ingredients. The PCE molecules are adsorbed onto particles and separated by opposing their attractive forces with steric and/or electrostatic forces, which then disperse the particles, release the free water and increase fluidity [30]. The

Fig. 2. Pendulum impact set-up: scheme (a), before (b) and after (c) impact.

limestone powder increases the workability because of its low water demand and electrostatic repulsion effect by localizing the Ca^{2+} surface with the groups of OH^- [52]. Compared to finer aggregates, coarse aggregate has lower surface area, which contributes to improved workability [9]. The optimal packing ensures more water available to lubricate the system and provide better workability [53].

The compressive strengths are 141.1 MPa and 153.4 MPa after the curing age of 28 d and 91 d, respectively. The tensile splitting strengths are 16.3 MPa and 18.1 MPa at 28 d and 91 d, respectively, which is greatly attributed to the reinforcement of steel fibre by comparing the results with our previous research [13]. The development of compressive strength demonstrates that most hydration and strength development occur within the first 2 weeks and further increase relatively mildly. To further demonstrate the advantages of the designed UHPFRC, the concept of the binder efficiency is utilized,

$$X_{\text{binder}} = \sigma_c / m_{\text{binder}} \quad (3)$$

where X_{binder} is the binder efficiency, σ_c is the compressive strength of concrete (MPa) and m_{binder} is the total mass of the binders (kg) including Portland cement and micro-silica in this study, the limestone powder is regarded as filler. The binder efficiencies of the designed UHPFRC in this study can reach up to 0.225 and 0.245 after 28 and 91 days, respectively, which is much higher than the values of previously reported UHPFRCs under similar curing conditions and dosage of steel fibre [4,7,38,54–58], as illustrated in Fig. 4. The high binder efficiency of the designed UHPFRC is attributed to the following reasons: (1) low powder content because of the applied coarse basalt aggregate; (2) dense and homogeneous skeleton with utilization of the modified packing model and optimum distribution modulus; (3) optimal mineral condition by considering positive synergic effect.

Table 5
Fresh properties and strengths of UHPFRC.

Spread flow (mm)	Fresh density (kg/m ³)	28 d σ_c (MPa)	91 d σ_c (MPa)	28 d σ_t (MPa)	91 d σ_t (MPa)
560 mm	2562	141.1	153.4	16.3	18.1

Fig. 4. Binder efficiency of the designed UHPFRC.

3.2. Impact response

3.2.1. Crack propagation

Fig. 5 shows the crack propagation on the top surface. After the first

Fig. 3. Specimens and set-up of central point bending test.

Fig. 5. Crack propagation after impact number of 0 (a), 1 (b), 2 (c) and 3 (d).

Fig. 6. Crack values vs. number of impact.

impact, a long and thin crack can be observed, and it develops further after the second impact. An obvious macro crack can be seen after the third impact. It should be pointed out that the UHPFRC beams are complete failed (broke into two parts) after repeated impact of 4 times.

The comparative analysis on the values of crack length and width is shown in Fig. 6. The crack depth and width of UHPFRC beam are not propagated simultaneously, which can be classified into three stages. At the first stage, the crack resistance is mainly depending on the brittle matrix of UHPFRC. Crack depth is developed more quickly at the initial impact, while the crack width only increases slightly. At the second stage, fibre bridge effect begins to work and the crack resistance is highly dependent on the bonding force between fibre and matrix. Both crack length and depth have a further increase and macro crack occurs with the further impact. At the third stage, the crack propagates rapidly till the complete damage, due to the pull-out of steel fibre and simultaneously drastic degeneration of crack resistance. The value saltation of crack width during the third impact can be regarded as a threshold point and a good indicator to the coming complete damage.

3.2.2. Damage pattern

The fracture pattern of completely damaged beam was evaluated, as shown in Fig. 7, to further understand the fracture mechanism of UHPFRC under low-velocity impact loading. The UHPFRC beams show a flexural-like fracture, only one dominant macro crack occurs along the notch. There is almost no front face-crater and rear face-scabbing, punching fracture or delamination, which can be probably observed in other composite materials under impact, based on the different impact velocity and energy, size of specimen and impactor. The fracture pattern of UHPFRC beam indicates that the crack always initiates and propagates along the notch, eventually decreasing variations of testing results, which is in line with Ref. [50]. Therefore, notched beam is proposed and suggested for impact test, attributed to certain fracture

Fig. 7. Fracture pattern of completed damaged beams.

path along the notch plane. It can be concluded that the fracture of UHPFRC beam only generates in a limited local area, nearby the position of maximum moment under impact loading.

To explain the effect of steel fibre on impact resistance of UHPFRC, a qualitative comparison of steel fibres surface under static flexural and impact loading is performed, shown in Fig. 8. It should be noted that fibres are pulled out from the matrix. Although the fibre–matrix bonding surface of this thin steel fibre is large enough, no cut-off is identified because of high instinct strength of the steel fibre (see Table 3), which proves that this type of high-strength thin fibre is suitable to design impact resistant UHPFRC. In addition, longitudinal scratches can be observed on the steel fibre surfaces, attributed to the abrasion caused by the particles during the pull-out process.

The scratches subjected to impact loading are more extensive and severer than those under static loading, which can be attributed to the loading rate effect. Because the matrix is normally sensitive and enhanced under high loading rate, leading to the increase of the friction between the fibre surface and UHPFRC matrix [59]. It means that the steel fibre works more efficient and indispensable for UHPFRC subjected to impact loading.

A similar qualitative comparative analysis on coarse basalt aggregate fracture under static flexural and impact loading is presented in Fig. 9. A great difference between the fracture patterns of coarse basalt aggregate under different loadings is clearly seen. Under static flexural loading, more unbroken coarse basalt aggregates (bright) can be observed, while more broken ones (dark, splitting into two parts) exist after impact loading. It is hypothesized that cracks initiate at the relatively weaker interfacial transition zone (ITZ) between coarse aggregate and UHPFRC matrix under static loading [59,60]. It does not have sufficient time to seek the weak ITZ under impact loading, and directly develops through the aggregates as the shortest fracture path, which is in line with Ref. [59]. This forced fracture pattern under a higher loading rate contributes to enhanced fracture energy absorption and corresponding higher impact resistance of UHPFRC in presence of relatively stiffer and stronger coarse basalt aggregate.

Fig. 8. Fibre surface at static (a) and impact (b) loading.

3.2.3. Energy dissipation

The impact resistance of UHPFRC under pendulum impact can be defined as energy dissipation or energy absorption capacity. Fig. 10 shows the absorbed energy of UHPFRC beam during each impact, calculated by Eq. (2). Before the first three impacts, the UHPFRC beam can absorb approximately 160 J, which is about 46% of the total impact energy of hammer (346 J). After the first impact, the UHPFRC beam still has relatively high stiffness, which will be illustrated in the flowing analysis. The impact is more like an elastic collision, which leads more gravitational potential energy of hammer to transfer into kinetic energy of UHPFRC beam. During the second impact, the stiffness of the partially damaged beam degenerates, more energy is dissipated by the deformation energy and fracture energy of concrete itself, leading to a slight increase of absorbed energy. With the further increase of damage degree, more and more fibres are pulled out and cracks of the matrix develop deeper and wider. The potential deformation energy and fracture energy decrease, which result in the decrease of energy dissipation of the UHPFRC beam.

Fig. 10. Absorbed energy during each impact.

3.3. Post-impact properties

3.3.1. Residual load–deflection relationship

Residual properties are crucial parameters for damaged composite materials to evaluate the damage degree and structural health status. The load–deflection curves in Fig. 11 highlight the differences in behaviour between the original (reference) beam and those partially damaged beams.

The curve of the reference beam can be divided into two phases of behaviour: the first phase is elastic region, where linear behaviour is

shown and no constituent materials are damaged; the second phase is strain softening region, namely post-peak period. There is a very wide strain softening region after crack initiation and propagation, due to the pull-out process of steel fibre without identification of any cut-off. The behaviour of partially damaged beam can be divided into three phases. An extra short phase corresponds to strain hardening region, which can be observed between elastic and strain softening regions, from the end of the linear elastic region to the peak flexural load. This extra strain hardening region indicates that the damaged beam undergoes some certain elastic–plastic deformation during the fibre pull-out process

Fig. 9. Aggregate under static (a) and impact (b) loading.

Fig. 11. Load-deflection relationship after certain impact number (I: elastic region, II: strain hardening region, III: strain softening region).

under bending load. The residual load–deflection curves of beams under the first and second impact still show a very good remaining bearing capacity.

The envelopes (area covered by multiple curves) of the curves show the variation in results of repeated tests, which is likely due to local variations in fibre density and orientation [7,61]. It also should be noted that the strain hardening behaviour of the designed UHPFRC is not obvious, and a long load–deflection plateau does not occur. It is probably attributed to the utilized type and amount of steel fibre in this study [62]. In the future study, an appropriate length and dosage of steel fibre need to be further researched to enhance the ductility and impact resistance.

Based on the analysis on the load–deflection curves, it can be concluded that the designed UHPFRC beam has an excellent ductility and residual bearing capacity, which indicates that it is suitable to be used as impact resistant composite material.

3.3.2. Residual strength, rigidity, toughness, impact resistance

To further analyse and understand the post-impact properties, a number of key parameters are deduced based on the load–deflection curves, including residuals ultimate strength (ultimate flexural bearing capacity), rigidity, toughness and impact resistance.

The ultimate strength or ultimate bearing capacity (F_u) is the peak load on the load–deflection curve, which is a basic and crucial parameter of UHPFRC. The residual ultimate bearing capacity is presented in Fig. 12(a). An empirical relation is proposed by regression analysis, following ‘ $-e^x$ ’ law with the number of impact. The strength of UHPFRC beam decreases slightly after the 2nd impact, which means the UHPFRC can still remain a large percentage of its bearing capacity at

the initial several impact.

The flexural rigidity (EI) is defined as the force couple to bend a non-rigid structure or component in one unit of curvature, which can be deduced from the moment–curvature relation,

$$\frac{1}{\rho} = \frac{M(x)}{EI} \quad (4)$$

where ρ is the radius of curvature, $M(x)$ is the bending moment at the position of x along the length, E is the Young’s modulus, and I is the second moment of area. The parameters in this paper are all used in SI units. Considering the Bernoulli hypothesis (plane cross-section assumption), the small deformation theory and the boundary condition in this study [63,64], the flexural rigidity can be determined by interpretation of the test results from calculation of the concentrated load and corresponding deflection,

$$EI = \frac{FL^3}{48\delta} \quad (5)$$

where F is the concentrated load at the elastic region from central point bending test, L is the length of the beam, δ is the bending flexural deflection. A linear relation is obtained with the number of impact, as shown in Fig. 12(b). Unlike the residual strength, the residual flexural rigidity tends to linearly decrease.

The flexural toughness (T_f), representing energy absorption capacity, can be determined from the area under the load–deflection curve form flexural test,

$$T_f = \int_0^{\delta_u} F(\delta) d\delta \quad (6)$$

Fig. 12. Residual strength (a), rigidity (b), toughness (c) and impact resistance (d).

where δ_u is the maximum deflection, $\delta_u = 15$ mm in this study. The residual flexural toughness can be expressed by a regressed linear relation, as illustrated in Fig. 12(c). It is obvious that the residual toughness shares a similar decrease tendency to residual flexural rigidity, which indicates the residual toughness is more relevant to the rigidity rather than strength under low-velocity impact loading.

The residual impact resistance (E_r) can be represented by remaining energy dissipation capacity, which is calculated as follows,

$$E_r = \sum_n^{n_u} E(n) \quad (7)$$

where $E(n)$ is the absorbed energy during the impact number of n , based on Eq. (2); n_u is the total impact number till to complete damage. The regressed relation shows an ideal linear decrease, as shown in Fig. 12(d). The similar linear decrease indicates that it is possible to associate residual impact resistance with residual flexural rigidity and residual toughness.

3.4. Damage index and levels

It is of great significance to evaluate the damage degree and health status of protective concrete structures or components after impact events. For instance, residual ultimate bearing load and impact resistance can provide insights on assessment of the service ability subjected to both static and impact loading. Hence, it is important to propose a damage index to describe the damage degrees and levels of UHPFRC under repeated low-velocity impact loading.

In order to analyse the damage degree development, regression analysis is used to develop empirical relations, based on the collected experimental database. Empirical models are proposed to predict the post-impact properties with the number of impact (n) except for the last impact, including residual strength, flexural rigidity, flexural

toughness, and impact resistance,

$$F_u(n) = 61.7 - 9.8e^{n/1.68} \quad (8)$$

$$EI(n) = 130.9 - 40.1n \quad (9)$$

$$T_f(n) = 250 - 75.5n \quad (10)$$

$$E_r(n) = 511 - 160.6n \quad (11)$$

A function of damage index is suggested to describe the damage degree in this study [65,66],

$$D(n) = 1 - \frac{A(n)}{A(0)} \quad (12)$$

where $A(n)$ represents a certain property of UHPFRC, such as ultimate bending load, flexural rigidity, flexural toughness or impact resistance. $A(0)$ is the initial property without impact. According to Eqs. (8)–(12), the damage indexes of different post-impact properties can be written as,

$$D(n)|_{F_u} = 0.189(e^{n/1.68} - 1) \quad (13)$$

$$D(n)|_{EI} = 0.306n \quad (14)$$

$$D(n)|_{T_f} = 0.302n \quad (15)$$

$$D(n)|_{E_r} = 0.314n \quad (16)$$

Based on the damage indexes, the impact damage degree can be classified mainly into three levels [67]. The first level is light damage with a damage index of 0–0.5, corresponding to the first impact in this study. Only micro crack occurs in the UHPFRC beam at this stage. The UHPFRC beam can still be usable, due to the large residual bearing capacity and impact resistance. The second level is medium damage with a damage index of 0.5–0.75, corresponding to the second impact

Fig. 13. Correlation between residual impact resistance and flexural toughness.

in this study. The crack propagates longer and wider to macro crack, and steel fibres slip from the matrix. The UHPFRC beam cannot be reused or maybe still reusable in some unimportant component, attributed to the degeneration of mechanical behaviour. The third level is severe damage with damage index of 0.75–1, corresponding to the third and last impact in this study. The crack grows rapidly till the complete damage and steel fibres are pulled out. The UHPFRC beam cannot non-reusable because of almost entire loss of mechanical properties.

3.5. Analytical modelling

It is widely accepted that it is much more difficult to determine dynamic properties (e.g. impact resistance or energy absorption capacity) of UHPFRC than its static properties, due to the complexity of the required test. Some researchers revealed that strength is associated with impact resistance (e.g. projectile penetration), while toughness is related to tension crack and scabbing [68]. The toughness reflecting the energy absorption capacity should have a relation with impact resistance. Another research tries to predict the initial impact behaviour (delamination damage) by economical static tests (e.g. shear stress) [69]. For these reasons, a reliable analytical model is proposed to predict impact resistance with several key static properties. The residual impact resistance in Eq. (16) shares a similar damage index equation with residual rigidity and toughness by comparing with Eqs. (13)–(15), as the degeneration rates are almost the same. Hence, the flexural rigidity and toughness are more appropriate as indicators than ultimate bearing capacity, which can be used to predict the residual impact resistance of UHPFRC beam. Considering the fact that both impact resistance and flexural toughness reflect the energy absorption capacity, it is more reasonable to predict the impact resistance by flexural toughness. Hence, an empirical model is proposed to predict the residual impact resistance, based on the acquired experimental database in this study,

$$E_r(n) = kT_f(n) \quad (17)$$

where k is a correlation coefficient. The correlation coefficient should show loading rate effect, which is mainly determined by the hammer (e.g. mass, velocity, texture) and specimen (e.g. shape, size, texture). In this study, the correlation coefficient is 1.996 ($R^2 = 0.99$). The proposed predicting model fits very well to the experimental results, as shown in Fig. 13. The proposed model is further validated by the relation between low-velocity impact resistance and flexural toughness of textile reinforced concrete [70], as shown in Fig. 13. Nevertheless, the

toughness varies at different impact conditions or loading rates [71], which probably affects the energy absorption and consequently the value of k . Hence, validation of the correlation coefficient k for a wider application needs further investigation with a larger experimental database and different impact loading rates.

4. Conclusions

The present research aims to understand the response and post-impact properties of ultra-high performance fibre reinforced concrete under low-velocity impact. A reliable low-velocity impact method employing pendulum impact test set-up is designed and applied in this study. Furthermore, an analytical model is proposed to describe the impact resistance of UHPFRC by its static properties and validated against the experimental data. Based on the obtained results, the following conclusions can be drawn:

- Coarse basalt aggregate can be successfully introduced into UHPFRC by applying an optimal particle packing model with a relatively low powder content and high binder efficiency. A reliable impact testing method for UHPFRC is proposed and designed with pendulum hammer and notched specimens.
- The crack depth and width of UHPFRC beam are not propagated simultaneously, crack depth is developed more quickly at the initial several impacts. The threshold point of crack width indicates the loss of major bearing capacity and impact resistance of UHPFRC beam.
- Damage of fibre and coarse aggregate under impact loading is severer than that under static loading. Most aggregates are broken at the fracture cross-section, which directly demonstrates that they work and improve the impact resistance under impact loading.
- Under the impact loading, the residual strength of UHPFRC beams follows ‘ $-e^x$ ’ law with the number of impact, while the residual rigidity, toughness and impact resistance follow linear law. The residual impact resistance has a similar damage index to the residual flexural rigidity and toughness instead of residual strength, and an analytical model to predict the residual impact resistance of UHPFRC beams with the flexural toughness is proposed and validated.

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