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Influence of steel fiber content on the rate-dependent flexural performance of ultra-high performance concrete with coarse aggregates

Shaohua Li\textsuperscript{a,b}, Ole Mejhede Jensen\textsuperscript{c}, Qingliang Yu\textsuperscript{a,b,*}

\textsuperscript{a} School of Civil Engineering, Wuhan University, 430072 Wuhan, PR China
\textsuperscript{b} Department of the Built Environment, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, the Netherlands
\textsuperscript{c} Department of Civil Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

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\textbf{A B S T R A C T}

Steel fiber is widely used to improve the flexural performance of ultra-high performance concrete (UHPC), yet the synergistic effect of steel fiber and coarse aggregates in UHPC containing coarse aggregates (UHPC-CA) has not been elucidated. Here, the influence of fiber content on the rate-dependent flexural performance of UHPC-CA is investigated from the view of the synergistic effect of steel fiber and coarse aggregates. Results reveal that the increasing pull-out force due to the increase of the crack mouth opening speed at a higher loading rate is responsible for the flexural curve type transition of UHPC-CA. The first crack stress is insensitive to the fiber content. However, the dynamic increase factors (DIFs) of the flexural strength and energy absorption capability of UHPC-CA decrease with increasing fiber content, which is attributed to a lower crack propagation speed of UHPC-CA with a higher fiber content. A model concerning the crack propagation speed and the critical angle for the fracture of coarse aggregates is proposed.

\section{1. Introduction}

Ultra-high performance concrete (UHPC) is considered as a promising new cementitious material, which is particularly characterized by its superior flexural strength and excellent post-cracking ductility performance \cite{1,2}. The excellent mechanical performance makes it potentially competitive for structures which may be subjected to extreme load conditions with different loading rates, e.g. earthquakes \cite{3–5}. The ultra-high performance is generally achieved by eliminating coarse aggregates to decrease the size of microcracks, resulting in a dense and homogeneous microstructure \cite{6,7}. But, it also leads to a high production cost and severe autogenous shrinkage \cite{8,9}. To deal with the above problems, recently, we introduced coarse aggregates into UHPC, while guaranteeing the high mechanical performance of UHPC \cite{10}. The experimental results have proven that the incorporation of coarse aggregates does not bring impairment to the strength, instead, it even results in a higher impact resistance \cite{11,12}. Hence, UHPC with coarse aggregates (UHPC-CA) can be made suitable for specialized structures exposed to extreme loading rates.

The superior flexural performance of UHPC, including strength and post-cracking ductility, is mainly affected by the incorporation of fibers \cite{13,14}. The incorporation of fibers into the matrix of UHPC can solve the problem of brittleness, and result in a high energy absorption capability and ductility via the fiber bridging effect once cracks appear \cite{15}. Among the available fibers, steel fiber is the most widely used one \cite{9}. Since steel fiber is a very costly raw material used in UHPC, characterization of the influence of steel fiber content on the flexural performance of UHPC under different loading rates is vital to the design and production of UHPC \cite{16,17}. The influence of steel fiber content on the flexural performance of UHPC under different loading rates has been comprehensively \cite{18–20}. Under quasi-static loading condition, the flexural strength of UHPC increases pseudo-linearly with the increase of fiber content, whereas the first cracking is insignificantly affected by the fiber content \cite{21,22}. Increasing the content of hybrid fibers can result in the increase of post-crack strength \cite{23}. Meanwhile, under rate-dependent loading condition, the addition of steel fiber resulted in a lower dynamic increase factor (DIF) compared with the normal concrete without steel fiber \cite{15}. The increase in steel fiber content led to the enhancement in residual flexural performance after impact damage \cite{9}. Yet, the influencing mechanism of steel fiber content on the rate-dependent flexural performance of UHPC-CA has not been clarified.

From the view of meso-mechanics, the macroscopic flexural failure of UHPC-CA can be assigned to the fractures of coarse aggregates, matrix and ITZ and the pull-out or fracture of steel fiber from matrix \cite{24–26}.

\textsuperscript{*} Corresponding author at: School of Civil Engineering, Wuhan University, 430072 Wuhan, PR China.
E-mail address: q.yu@bwk.tue.nl (Q. Yu).

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As a non-negligible part of UHPC-CA [12], coarse aggregates play a crucial role during the failure of UHPC-CA under flexural loading. Thus, characterization of the fracture of coarse aggregates is helpful to explore the failure mechanism of UHPC-CA under different loading rates. Different from the failure of normal concrete, the crack in UHPC-CA has been proven to propagate through the coarse aggregate due to the enhancement of ITZ [27]. Moreover, previous studies on normal concrete and high performance concrete (HPC) suggest that the fracture of coarse aggregates is influenced by fiber content and loading rate [28,29]. Higher fiber content resulted in a fewer fracture across coarse aggregates, while higher loading rates led to more fractures across coarse aggregates. It is therefore hypothesized that the coarse aggregates would play different roles in the flexural failure of UHPC-CA with the variation of fiber content and loading rate. However, the synergistic effect of steel fiber and coarse aggregates on the rate-dependent flexural performance of UHPC-CA has not been well understood.

Here, the objective of this paper is to investigate the influence mechanism of steel fiber content on the rate-dependent flexural performance of UHPC-CA, especially, the synergistic effect of steel fiber and coarse aggregates in UHPC-CA with different fiber contents. Firstly, the influence of steel fiber content on the flexural stress-deflection curve, first crack stress and flexural strength of UHPC-CA under different loading rates are measured by three points bending test method, and the fracture of coarse aggregates is quantitatively characterized. Further, the influence of steel fiber content on the fracture process of UHPC-CA is investigated by a digital image correlation (DIC) technique to reveal the influencing mechanism of steel fiber content on the rate-dependent flexural performance of UHPC-CA. The results from this research shed light on the influencing mechanism of steel fiber content on the rate-dependent flexural performance of UHPC-CA and will be helpful to the design and production of UHPC with good flexural performance and economic efficiency.

2. Experimental program

2.1. Mix proportions and sample preparation

The raw materials used in this study were Portland cement CEM I 52.5 R (PC), silica fume (SF), limestone powder (LP), sand 0–2 mm (S), coarse basalt aggregate (BA), tap water (W), PCE-type superplasticizer (SP) and steel fiber. BA with a size 2–5 mm were used in this study, see Fig. 1. The chemical and physical properties of the powders are shown in Table 1. The straight steel fibers with a diameter of 0.2 mm and a length of 13 mm was adopted in this study. To investigate the influence of steel fiber content on the rate-dependent flexural performance of UHPC-CA, three different steel fiber contents (1%, 1.5% and 2%) were chosen. Owing to the excellent flowability of the recipe used in this study, no fiber ball phenomenon in the fresh UHPC with high volume content of steel fibers was observed in this study. The mix proportions for UHPC-CA investigated in this study are summarized in Table 2.

The mixing procedure of UHPC-CA is as follow: all the powders and sand were firstly dry mixed, then, 75% water, mixed solution of 25% water and superplasticizer, steel fiber and basalt aggregate were sequentially added. After that, the UHPC-CA mixture was poured into molds with the dimensions of 50 × 50 × 50 mm³ for compressive test and 40 × 40 × 160 mm³ for three points bending test [3]. All the samples were covered by polyethylene film and stored at room temperature (20 °C) for 24 h. Afterward, they were demoulded and cured in water at room temperature (20 °C) until the designed age.

2.2. Flexural test setup and testing

As shown in Fig. 2, three-point bending test was employed to measure the flexural performance of UHPC-CA. The span is 100 mm. To investigate the rate-dependent flexural performance of UHPC-CA, five different loading rates were set as 0.2, 2, 20, 100 and 200 mm/min. The loading rate of 0.2 mm/min represents the quasi-static loading condition [30], while the loading rate of 2, 20, 100 and 200 mm/min represent the rate-dependent loading conditions. The force of loading is measured by a load cell with the capacity of 25 kN. The deflection at the centre of the specimens is recorded by a displacement sensor. The load force and the deflection at the centre of the specimen were recorded simultaneously. Given that the time for the force balance is less than 1 ms, which is far less than the whole loading time. Hence, the inertial force due to the acceleration and the mass was not considered. Five specimens in each loading rate were tested.

2.3. Identification of the fracture process of UHPC-CA

The digital image correlation technique (DIC) was used to characterize the fracture process of UHPC-CA under different loading rates. A high-speed camera and a high intensity flashlight were installed in front of the specimen with a safety distance of 0.5 m. The recording rate was set as 2000 frames per second (0.0005 s inter-frame time).

As shown in Fig. 3, before the three-point bending test, the front surface of the beam was first coated with a thin layer of paint, then some small black spots were sprayed on the white surface to form a speckle pattern, which is used for DIC calculation. The range used for DIC analysis is 40 × 40 mm², with corresponding pixels of 256 × 256.

| Table 1 Chemical and physical properties of powders. |
|-----------------------------------------------------|
| Substituent (%) | PC | SF | LP |
| CaO | 67.97 | 0.90 | 55.10 |
| SiO₂ | 16.19 | 93.06 | 0.49 |
| Al₂O₃ | 3.79 | – | 0.09 |
| Fe₂O₃ | 3.59 | 2.06 | 0.07 |
| K₂O | 0.53 | 1.15 | – |
| Na₂O | 0.27 | 0.63 | – |
| SO₃ | 3.13 | 1.28 | 0.06 |
| MgO | 1.71 | 0.70 | 0.1 |
| TiO₂ | 0.28 | – | 0.01 |
| MnO | 0.09 | 0.07 | 0.01 |
| LOI | 0.51 | 0.88 | 43.3 |
| Specific density (g/cm³) | 3.15 | 2.20 | 2.71 |
| BET surfaces area (m²/kg) | 1420 | 18,400 | 1080 |

Fig. 1. Coarse basalt aggregates with size of 2–5 mm.
acquired images were subsequently processed by Ncorr, which is an open-source 2D DIC MATLAB software [31]. Detailed information about the basic principle of DIC is provided elsewhere [32]. Finally, the surface strain and the displacement of crack mouth were used to analyse the crack propagation speed and the crack mouth opening speed of the UHPC-CA beam under flexure loading.

2.4. Characterization of the fracture of coarse aggregates

To quantitatively characterize the fracture of coarse aggregates, an image process method was proposed to analyse the fracture surface of UHPC-CA. The procedure of this method includes image acquisition, marking coarse aggregates, identification of coarse aggregates and quantitatively characterization of fracture surface. More detailed information can be found in our previous studies [33–35]. It is noted that a coarse aggregate particle is recognized to be fractured when a “mirrored” aggregate particle can be found in the same position on the fracture surface. With the aid of an image processing software called ImageJ, the percentage of fracture across coarse aggregate was calculated as follow:

\[ P_{fr} = \frac{A_{cr}/2}{A_{cr}/2 + A_{ar}} \times 100\% \]  

(1)

where \( P_{fr} \) is the percentage of fracture across coarse aggregates under different loading rates; \( A_{cr} \) is the total area of green colour; \( A_{ar} \) is the total area of grey colour.

2.5. Characterization of the surface characteristics of the pull-out steel fiber

The scratches and attachments on the surface of steel fibers can be used to indirectly reflect the pull-out behavior of steel fiber [25]. To qualitatively analyse the pull-out behavior of steel fiber under different loading rates, the surface characteristics of the pull-out steel fiber were observed by scanning electron microscope (SEM). A FEI Quanta 200F SEM was used. The magnifications were set as 350X and 1000X.

3. Results

3.1. Influence of steel fiber content on the compressive strength

The ultra-high compressive strength is the basic property of UHPC.

| No. | PC  | SF   | LP  | S   | BA  | W   | SP   | Steel fiber volume content (%) |
|-----|-----|------|-----|-----|-----|-----|------|------------------------------|
| 1   | 637.5 | 42.5 | 170 | 988 | 488 | 174.3 | 8.5 | 1 |
| 2   | 637.5 | 42.5 | 170 | 988 | 488 | 174.3 | 8.5 | 1.5 |
| 3   | 637.5 | 42.5 | 170 | 988 | 488 | 174.3 | 8.5 | 2 |

Fig. 2. Schematic of the testing system for three-point flexural test.

Fig. 3. Schematic of identification of the fracture process with DIC technique.
The compressive strength of UHPC-CA with different steel fiber contents is shown in Fig. 4. The corresponding static compressive strengths of the UHPC-CA at 28 days are 151, 156 and 161 MPa for fiber content of 1.0%, 1.5% and 2.0%, respectively, which meets the strength requirement of UHPC [7,36]. It is further indicated that the ultra-high mechanical performance of UHPC can be guaranteed while introducing coarse aggregates. Meanwhile, even though the improvement is not considerable, it can be concluded that increasing the steel fiber content shows a positive effect on the compressive strength of UHPC-CA, which is in line with the previous studies on UHPC without coarse aggregates [30]. This is attributed to that the increasing steel fiber content would lead to more steel fibers sustaining the cracking simultaneously, resulting in the delay of the formation and propagation of cracks, thus, contributing to the increase of compressive strength [37].

### 3.2. Influence of steel fiber content on the flexural performance under quasi-static loading

#### 3.2.1. Flexural curve

To analyse the influence of steel fiber content on the flexural behaviour of UHPC-CA under quasi-static loading, the flexural curves of UHPC-CA containing different steel fiber contents are presented. As shown in Fig. 5, the pre-crack part of the flexural curve is almost insensitive to the fiber content, which is consistent with the previous studies [22,30]. It has been postulated that there is no microcrack initiated during the pre-crack part [38], thus the variation of steel fiber content shows insignificant influence on the pre-crack performance. However, after the appearance of the first crack, some differences can be found in the flexural curves with the increase of the steel fiber content. In the case of the sample with the fiber content of 1.0%, there is a sudden flexural stress drop of flexural stress with the appearance of first crack. After that, the flexural curve shows strain hardening behaviour although the flexural stress is still less than the first crack stress. In the case of fiber content of 1.5%, the flexural stress drop is less than that of sample with fiber content of 1.0%. Further, the flexural curve shows strain hardening behaviour leading to a higher flexural stress than the first crack stress. As the fiber content increases to 2.0%, the flexural stress drop is almost indistinguishable, suggesting an obvious strain hardening behavior. Moreover, all the flexural curves show good post-crack performance of UHPC-CA, confirming the positive effect of steel fiber on the good ductility of UHPC-CA. In addition, a higher fiber content results in a higher load sustainability, which can be attributed to that a higher fiber content leads to a lower stress concentration between fiber and matrix, consequently, the delay of initiation and propagation of cracks [37].

![Fig. 4. Influence of steel fiber content on the compressive strength.](image)

Based on the experimental results and the previous studies [22], the typical flexural stress–deflection curves of UHPC-CA can be divided into two categories, which are shown in Fig. 6. Both types show elastic stage and deflection softening stage. The type I curve shows obvious strain hardening behaviour, while the type II curve shows a sudden stress drop with the appearance of first crack. After the points of crack localization, the flexural curves show strain softening behaviour. Here, the flexural stress corresponding to the first crack is defined as the first crack stress, whereas the highest flexural stress is defined as the flexural strength. Thus, for type I curve, the flexural stress is higher than the first crack stress, in contrast, for type II curve, the flexural strength equals to the first crack stress.

#### 3.2.2. First crack stress and flexural strength

Based on the definition of the typical curves, the influences of steel fiber content on the first crack stress and the flexural strength of UHPC-CA are shown in Fig. 7. The first crack stresses at the steel fiber content of 1.0%, 1.5% and 2.0% are 21.8, 21.9 and 21.6 MPa, respectively, whereas the flexural strengths are 21.8, 23.3 and 26.9 MPa, respectively. It means that the first crack stress is insensitive to the increase of steel fiber content, while the flexural strength is positively related to the increase of steel fiber content. This is consistent with the results in refs. [22,30], which studied the influence of steel fiber content on the flexural performance of UHPC without coarse aggregates. The differences between the influence of steel fiber content on the first crack stress and the flexural strength should be due to that the first crack stress is related to the fracture of coarse aggregates, matrix and ITZ, while the flexural strength is related to the combination of the fractures of coarse aggregates, matrix and ITZ and the pull-out of steel fiber from the matrix [30].

### 3.3. Influence of steel fiber content on the flexural performance under rate-dependent loading

#### 3.3.1. Flexural curve transition

To investigate the influence of steel fiber content on the rate-dependent flexural performance of UHPC-CA, the flexural curves of UHPC-CA under different loading rate are analysed. The strain hardening behaviour can overcome the brittle nature of concrete as the appearance of crack, which is benefit to the energy absorption of UHPC-CA during the engineering application [36]. As shown in the appendix, the flexural curves of UHPC-CA with 1.5% and 2% steel fiber contents show strain hardening stage after the first crack at any loading rate, whereas the flexural curve of UHPC-CA with 1% steel fiber content shows no strain hardening stage at the low loading rates, i.e. less than 20 mm/min. Here, as the analysis is focused on the transition of flexural curves, this part just presents the results of UHPC-CA with steel fiber content of 1%, because the flexural curve transition is not found in UHPC-CA with steel fiber contents of 1.5% and 2%. The flexural curves of UHPC-CA with steel fiber contents of 1.5% and 2% are shown in the appendix. As shown in Fig. 8, at low loading rates, i.e. 0.2 mm/min and 2 mm/min, the flexural curves of UHPC-CA with steel fiber content of 1% belong to the type II, with an obvious flexural stress drop after the appearance of the first crack. In contrast, as the loading rate increases to be higher than 20 mm/min, the flexural curves change from type II to type I. This might be related to the increase of pull-out force of single steel fiber with the increase of the loading rate. Meanwhile, the flexural strength of UHPC-CA with the fiber content of 1% increases with the increase of loading rate, which is in agreement with the previous studies [39,40]. Moreover, all the curves show good ductility after rupture, suggesting that the UHPC-CA with steel fiber is capable of absorbing considerable energy even after the appearance of rupture under different loading rates.

#### 3.3.2. First crack stress and flexural strength

To quantitatively analyse the influence of the steel fiber content on
the rate-dependent flexural performance of UHPC-CA, the first crack stress, the flexural strength and the corresponding dynamic increase factors (DIFs) are shown in Fig. 9. It is obvious that both the first crack stress and the flexural strength show significant sensitivity to the loading rate, which is analogously to the previous investigations on UHPC without coarse aggregates. However, the DIF of the first crack stress is insensitive to the steel fiber content, whereas the DIF of the flexural strength decreases with the increase of steel fiber content. It means that the first crack is mainly controlled by the fracture of UHPC-CA matrix rather than the steel fiber regardless of the loading rates. With the increase of the steel fiber content, the cracking resistance of UHPC-CA matrix shows a higher level, resulting in a lower fracture speed. Meanwhile, the DIF of the flexural strength is higher than that of the first crack stress, resulting in the flexural curve type transition of UHPC-CA with fiber content of 1% as the loading rate increases from 2 mm/min to 20 mm/min.

3.3.3. Energy absorption capability

Energy absorption capability is another key factor of the flexural performance of UHPC. To evaluate the influence of the steel fiber content on the rate-dependent energy absorption of UHPC-CA under flexural loading, the energy absorption and the corresponding DIF under different loading rates are analysed, as shown in Fig. 10. At the loading rate of 0.2 mm/min, the energy absorptions are 42, 49 and 58 J at the steel fiber content of 1%, 1.5% and 2%, respectively. It is indicated that increasing the steel fiber content shows a positive effect on the energy absorption capability of UHPC-CA, which is in agreement with the previous results [41]. With the increase of loading rate, all the energy absorptions of UHPC-CA with different fiber contents show the increase tendency. However, the DIF of the energy absorption of UHPC-CA shows negative relationship with the steel fiber content, specifically, the DIFs are 2.2, 2.0 and 1.9 at the steel fiber content of 1%, 1.5% and 2%, respectively. It might be ascribed to that different steel fiber contents lead to different failure processes of UHPC-CA, i.e. the fracture of coarse aggregate and the pull out of steel fiber, which will be discussed in the following sections.

3.4. Fracture process of UHPC-CA under flexure

The fracture process is related to the fracture of coarse aggregates and the pull-out of steel fibers, therefore, the fracture process of UHPC-CA with different flexural curve types can be used to clarify the failure mechanism. As shown in Fig. 11, the fracture process zones can be found at the bottom of sample as the flexural curve departs from a linear style.
It can be recognized as the appearance of the first crack [42]. After the appearance of the first crack, there is a sudden stress drop in the type II flexural curve, whereas the strain hardening appears in the type I flexural curve. Previous studies suggest that the strain hardening performance is resulted from the bridging effect of steel fibers distributed in the matrix of UHPC [43]. Given that the crack positions are similar at different fiber contents, the different bridging performance might be related to the steel fiber number per unit area and the bridging force of single steel fiber. It is easily understood that the steel fiber number per unit area increases with the steel fiber content, consequently, the strain hardening can be found in the UHPC-C with fiber contents of 1.5% and 2%. Some studies concerning the pull-out of steel fiber suggest that the

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**Fig. 8.** Flexural curves of UHPC-CA with 1% steel fiber content at different loading rates: (a) 0.2 mm/min; (b) 2 mm/min; (c) 20 mm/min; (d) 100 mm/min; (e) 200 mm/min; The points of the first crack are marked by blue arrows. Corresponding curves for 1.5% and 2% steel fiber content are shown in the appendix. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Fig. 9. Influence of steel fiber content on the first crack stress and the flexural strength of UHPC-CA under different loading rates. (a) first crack stress; (b) DIF of first crack stress; (c) flexural strength; (d) DIF of flexural strength.

Fig. 10. Influence of steel fiber content on the energy absorption of UHPC-CA under different loading rates. (a) energy absorption; (b) DIF of energy absorption.
The pull-out force of steel fiber increases with the loading rate [44], which might be responsible for the transition of the flexural curve of UHPC-CA with steel fiber content of 1%. With the propagation of macroscopic crack, the type II flexural curve shows a strain hardening stage after the appearance of the first crack, which might be attributed to the increasing number of the steel fibers bearing the flexural force with the increase of crack length. At the maximum flexural stress of the type II flexural curve and the maximum flexural stress of the type II flexural curve after the first crack, the fracture process zone reaches the top of the sample, indicating that the strain softening stage is controlled by the bridging effect of steel fibers.

To quantitatively analyse the fracture process of UHPC-CA, the crack propagation speed is calculated. Because the fracture process zone indicates the fracture of coarse aggregate and UHPC matrix, the upper end of the fracture process zone is selected to represent the movement trail of the crack. As shown in Fig. 3, the position of the upper end of the fracture process zone is marked, and the crack propagation speed is calculated by the average speed of the upper end of the fracture process zone.

The crack propagation speeds of UHPC-CA under different loading rates are shown in Fig. 12. Obviously, the crack propagation speed increases with the increase of loading rate. As the loading rate increases from 0.2 mm/min to 200 mm/min, the crack propagation speed increases by almost three orders of magnitude from less than 0.001 m/s to more than 0.1 m/s. This phenomenon is consistent with the fracture of other materials under different loading rates, which can be attributed to that a higher crack propagation speed means a higher energy consumption rate, which is used to balance the higher energy input rate at a higher loading rate [45,46]. However, regardless of the same loading rate, the crack propagation speed decreases with the increase of steel fiber content. This further confirms that the incorporation of steel fiber can restrict the fracture of UHPC-CA. The mechanism can be related to that a higher steel fiber content can further enhance the integrity and improve the interaction of the matrix of UHPC except the crack region, resulting in a larger region bearing the flexural load simultaneously [37]. Furthermore, a higher crack propagation speed means a higher crack open speed, consequently, a higher mechanical contribution from steel fiber to the flexural strength of UHPC-CA.

The percentage of the fracture across coarse aggregate of UHPC-CA with different steel fiber contents is shown in Fig. 13. At the quasi-static loading rate (0.2 mm/min), as shown in Fig. 13 (a) about 20% percentage of fracture across coarse aggregates appeared during the flexural test. This is significantly different from the result of normal concrete, in which the fracture of coarse aggregates is usually not observed in a flexural test [47,48]. However, the low percentage of fracture across coarse aggregates suggests that the coarse aggregate is much stronger than ITZ, although the quality of the ITZ in UHPC-CA is well improved. As seen, the percentage of the fracture across coarse aggregates increases with the increase of loading rate, which is in line with our previous study [33]. At the loading rate of 0.2 mm/min, the percentage of the fracture across coarse aggregates is less than 25%, whereas the percentage of fracture across coarse aggregates is more than 55% as the loading rate increases to 200 mm/min. The increasing trend is consistent with the results of normal concrete and high performance concrete [49–52]. On the other hand, at a given loading rate, the percentage of the fracture across coarse aggregates decreases with the increase of steel fiber content, although the difference is not obvious at the low loading rates (0.2, 2 and 20 mm/min). The difference becomes obvious as the loading rate is larger than 100 mm/min, which indicates that the fracture of coarse aggregates is the synergistic influence of loading rate and steel fiber content. Moreover, it can be seen from Fig. 13 (b) that, at any loading rate, the DIF of percentage of fracture across coarse aggregate shows a lower value in the case of a higher steel fiber content. Given that the coarse aggregate is the hardest component in UHPC-CA, higher flexural strength and higher energy absorption are expected at a higher percentage of the fracture across coarse aggregate.
4. Discussion

4.1. Transition of flexural curve type

As discussed in the Part 3.2, the flexural curve transition of UHP-CA with the fiber content of 1% might be attributed to the increased pull-out force with the increase of loading rate. Here, the crack mouth opening speed is quantitatively analysed by calculating the crack opening speed of the bottom of the sample from the displacement at the x-direction, as shown in Fig. 3. The crack mouth opening speed is calculated by the average opening speed of the crack before the appearance of the maximum flexural stress. It is noted that the time of the first crack is set as the starting point.

Fig. 14 shows the width of the crack mouth and the crack opening speed. It can be seen from Fig. 14 (a) that the width of the crack mouth increases with the loading duration approximately linearly. However, the time for crack mouth reaching 3.0 mm decreases with the increase of loading rate. The results of crack opening speed under different loading rates is shown in Fig. 14 (b). As seen, the crack opening speeds are less than 0.1 mm/s at the loading rates of 0.2 mm/min and 2 mm/min, and the crack opening speeds increase to be higher than 1 mm/s as the loading rates increase to 20, 100 and 200 mm/min.

Previous studies concerning the influence of the loading rate on the pull-out of steel fibers have demonstrated that the pull-out force increases with the increase of pull-out rate [53–55]. Meanwhile, the surface morphology can be used to indirectly reflect the pull-out behavior [25], such as pull-out force, etc. To characterize the pull-out performance of steel fibers under different loading rates, their surface morphology after pull-out is presented.

As shown in Fig. 15, there are some longitudinal scratches on the surface of the pull-out steel fiber at the loading rate of 0.2 mm/min, indicating an interaction between the steel fiber and the matrix during the pull-out process. With the increase of loading rate, deeper longitudinal scratches and some small debris can be found on the surface of the steel fibers, which is consistent with previous study [33]. It is suggested that the bond stress increases with the increase of loading rate, resulting in a higher pull-out force, i.e. a better reinforcement quality of the steel fibers [56,57].

Hence, it can be deduced that the reinforcing effect of the steel fibers in UHP-CA matrix improves with the increase of the crack opening speed due to the increase of the loading rate. Meanwhile, a higher reinforcement force leads to a strain hardening behavior of UHPC-CA with the appearance of cracking. Consequently, the flexural curve changes from type II with a sudden stress drop to type I with strain hardening behavior as the loading rate increases to from 2 mm/min to 20 mm/min. It can be further deduced that there should be a turning point for the transition of the flexural curve type.

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Fig. 13. Fracture of coarse aggregate of UHPC-CA under flexure. (a) percentage of the fracture across coarse aggregate; (b) DIF of the fracture across coarse aggregate.

Fig. 14. Influence of loading rate on the crack opening of UHPC-CA. (a) width of crack mouth-loading duration; (b) crack opening speed.
Fig. 15. Surface morphology of steel fibers after pull-out under loading rate of 0.2 mm/min (a), 2 mm/min (b), 20 mm/min (c), 100 mm/min (d), 200 mm/min (e).
The fracture of coarse aggregates is influenced by the fracture propagation speed. Here, the relationship between the percentage of the fracture across coarse aggregates is help to understand the influence of steel fiber content on the fracture of coarse aggregates under different loading rates.

As discussed in the previous part, under the same loading rate, different fiber contents lead to different crack propagation speeds, along with different percentages of the fracture across coarse aggregates. Based on the previous research on heterogeneous materials, the meso-scale fracture of heterogeneous material is influenced by the fracture propagation speed [50,58]. Here, the relationship between the percentage of the fracture across coarse aggregates and the crack propagation speed is analysed. As shown in Fig. 16, although the results of UHPC-CA with different fiber contents are not in the same region, the percentage of the fracture across coarse aggregates is almost linearly proportional to the crack propagation speed. As the crack propagation speed is close to zero, the percentage of fracture across coarse aggregates is approximate 20%, whereas the percentage of the fracture across coarse aggregates increases to 70% at a crack propagation speed of 0.4 m/s. This can be attributed to that the cracks would select the weakest path to propagate at a lower fracture rate, while the cracks do not have sufficient time to establish the propagation path with least resistance due to the increase of whole energy release rate under a higher fracture rate [6,59]. It can be concluded that a higher crack propagation speed at a lower fiber content results in the increase of the percentage of the fracture across coarse aggregates under the same loading rate.

To analyse the fracture of coarse aggregates theoretically, as shown in Fig. 17, the coarse aggregates are simplified as two-dimensional polygon, which is around by a weak interface, i.e. ITZ. It is noted that $\beta$ can be assumed to be uniformly distributed from 0° to 90° since the coarse aggregates are randomly distributed in UHPC-CA. Therefore, there is a critical angle ($0 \leq \beta_{cr} \leq 90$°), beyond which the fracture across the coarse aggregate will commence. The relationship between the percentage of the fracture across coarse aggregate and the critical angle ($\beta_{cr}$) of fracture across coarse aggregate is thus given by:

$$\beta_{cr} = 90(1 - P_{cr})$$

(3)

where $\beta_{cr}$ is the critical angle for the fracture across coarse aggregate.

As the percentage of fracture across coarse aggregates increases with the increase of crack propagation speed, it is suggested that the critical angle shows a variable value with the increase of the crack propagation speed. To analyse the critical angle under different crack propagation speeds, the critical angle is deduced from the experimental result.

As shown in Fig. 18, the critical angle decreases with the increase of crack propagation speed, which means that more coarse aggregates will crack. The relationship between the critical angle and the crack propagation speed can be approximated by:

$$\beta_{cr} = -123S_c + 67. R^2 = 0.9$$

(4)

where $S_c$ is the crack propagation speed.

It can be deduced that the ratio of the energy release rate of ITZ and coarse aggregate will change with the increase of the crack propagation speed, which is related to the energy input rate. At a lower crack propagation speed, the energy input rate is low, which can be easily balanced by the facture of ITZ and coarse aggregate. Hence, the crack will preferentially propagate along the weakest part of UHPC-CA, i.e. ITZ. With the increase of the crack propagation speed, the crack may not have sufficient time to establish a propagation path along the weakest part of UHPC-CA as it can’t balance the energy input rate. Here, the incorporation of different steel fibers leads to different crack propagation speeds, consequently, different proportions of the fracture across coarse aggregate.

Based on the above analysis, it can be concluded that a higher steel fiber content will lead to a lower fracture propagation speed, consequently, a lower percentage of the fracture across coarse aggregate. Given that the coarse aggregate is the hardest part of UHPC-CA, more fracture across coarse aggregate means a higher energy absorption. Meanwhile, it should be noted that, at the lower loading rates (0.2 and 2 mm/min), the difference between the fracture propagation speeds is modest, thus there is only a minor difference between the percentages of the fracture across coarse aggregate. As the loading rate increases to higher levels (20, 100 and 200 mm/min), the difference between the fracture propagation speed becomes more and more obvious, leading to clear differences between the percentages of the fracture across coarse aggregate at different fiber contents. Consequently, the influence of steel fiber content on the DIFs of the flexural strength and the energy absorption becomes more and more obvious with the increasing loading rate.

5. Conclusions

This work presents the influence of steel fiber content on the rate-dependent flexural performance of UHPC-CA. The influence of steel fiber content on the rate sensitivities of first crack stress, flexural strength, fracture of coarse aggregate and crack propagation are analyzed. The investigation leads to the following conclusions:

- The flexural curves of UHPC-CA with 1.5% and 2% steel fiber contents display a strain hardening stage following the first crack at any loading rate, whereas the flexural curve of UHPC-CA with 1% steel fiber content shows no strain hardening stage at the low loading rate, i.e. less than 20 mm/min, which can be attributed to a lower total bridging force of the steel fibers in UHPC-CA.

- With the increase of the loading rate, the flexural curve of UHPC-CA with 1% steel fiber content transforms from type II (without strain hardening stage) to type I (with a strain hardening stage), which is attributed to the increase of the pull-out force due to the increase of the crack mouth opening speed. The turning point appears between 2 mm/min and 20 mm/min.
At any given loading rate, the flexural strength and energy absorption capability of UHPC-CA increase with the increase of the steel fiber content, whereas the first crack stress is insensitive to the steel fiber content. However, the DIFs of the flexural strength and energy absorption capability of UHPC-CA decrease with the increase of steel fiber content.

The lower DIFs of the flexural strength and energy absorption of UHPC-CA with high steel fiber content is ascribed to a lower crack propagation speed due to a higher fiber content. A model concerning the crack propagation speed and the critical angle for the fracture of coarse aggregates is proposed.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

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### CRediT authorship contribution statement

**Shaohua Li**: Methodology, Investigation, Data curation, Formal analysis, Validation, Writing – original draft. **Ole Melhede Jensen**: Funding acquisition, Writing – review & editing. **Qingliang Yu**: Conceptualization, Supervision, Funding acquisition, Project administration, Writing – review & editing.
