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Dynamic compressive behaviour of spiral steel fibre reinforced concrete in split Hopkinson pressure bar tests

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HIGHLIGHTS

- We used spiral-shaped steel fibres in fibre reinforced concrete mix.
- Static material properties are improved by increasing the content of spiral fibres.
- SHPB tests are conducted to test the material property for higher strain rate range.
- Increasing fibre content increases the crack control and energy absorption abilities.
- Increasing fibre content increases rate sensitivity of strength and Young's modulus.

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ABSTRACT

It has been well demonstrated that adding fibres into concrete increases the impact loading resistance capacity of the concrete material. Recent studies proved that using spiral-shaped steel fibres further increases the post-failure, energy absorption and crack stopping capacities of concrete as compared to other conventional steel fibres because spiral-shaped fibre better bonds in the concrete matrix and has larger deformation ability. This research further investigates the dynamic compressive properties of spiral fibre reinforced concrete (SFRC) by conducting high rate impact tests using split Hopkinson pressure bar (SHPB). SFRC specimens with different volume fractions of spiral fibres ranging from zero to 1.5% are prepared and tested. The concrete matrix for all SFRC specimens is mixed to obtain a compressive strength of 35 MPa. The influences of different volume fractions of fibres on strength, Young's modulus, stress–strain relationand energy absorption of SFRC specimens under quasi-static and dynamic loadings are studied. In dynamic compression tests, the strain rate achieved ranges from 50 s^{-1} to 200 s^{-1}. The failure processes and failure modes of SFRC specimens with different fibre volume fractions are captured by the high speed camera during the tests and compared. Dynamic stress–strain curves under different strain rates are derived. The energy absorption capacities of the tested specimens are obtained and compared. Rate effects on the compressive strength and Young's modulus are also discussed. The corresponding empirical DIF (dynamic increase factor) relations for spiral SFRC are proposed.

1. Introduction

Fibre reinforced concrete (FRC) has been more and more commonly used in constructions of high-rise buildings or critical protective structures because adding fibres into concrete matrix effectively increases the ductility and the impact energy absorption capability. Since steel fibres were first proposed as dispersed reinforcement for concrete in 1963 [1], a considerable number of researches have been conducted to investigate the improvement of FRC under various loading conditions compared to conventional concrete. Many types of fibres including high modulus steel, glass, carbon and asbestos fibres of different shapes, low modulus synthetic polymer fibres and natural fibres have been studied [2]. Generally fibre addition in the concrete mixture improves tensile strength, impact resistance and toughness, proportionally with fibre volume, but insignificantlyimproves the material compressive strength [3,4]. Using low modulus polymer fibres may even reduce the compressive strength [5,6]. On the other hand, some studies have found that steel fibre addition does increase the compressive strength. For instance, Song and Hwang reported their experimental study on steel fibre reinforced concrete (SFRC) with hooked end mild carbon steel fibres of volume fractions varying from 0.5% to 2.0% and concluded that the compressive strength increased with the fibre content [7]. In another experimental study carried out by Holschemacher et al. it was found that increasing

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zfibre strength increased the strength, ductility and post-cracking behaviour of SFRC because high-strength fibres prevented the rupture and the damage mode was primarily debonding of the fibres from the cementmatrix [8]. The finding was consistent with the observations from laboratory tests that considered three types of polymer fibres and straight flat-ended steel fibres [9,10], in which authors found that under both static and low-rate impact load, the predominant failure mode was the steel fibre pull-out, resulting in poor post-cracking and energy absorption capability. These studies revealed that the full capacity of steel fibres to reinforce concrete matrix can be achieved only if debonding failure of fibres does not occur, and it is important to use high-strength fibres with strong bonding to cement matrix.

Due to the relatively low deformation capability, although high-modulus and high-strength steel fibres provide strength to FRC, their improvement in ductility and post-cracking capacity of the material is limited. On the other hand, polymer fibres enhance the ductility and post-cracking capacity of the FRC owing to the large deformation capability, but could result in reduction in compressive strength because of the low modulus and low strength. To overcome the defects and take advantage of the beneficial properties of the two types of fibres, researches on concrete reinforced with hybrid fibres, i.e., steel and polymer fibres, have been conducted. In experimental studies of static and dynamic material properties (in the strain rate range from $2 \times 10^{-6}\,\mathrm{s}^{-1}$ to $0.2\,\mathrm{s}^{-1}$) of FRC with inclusion of hybrid fibres (0.5% steel fibres and 1.5% polyethylene fibres), it was found that FRC mixed with hybrid fibres achieved significant improvement in tensile strength, tensile strain hardening behaviour, and energy absorption capacity, and the tensile strength increased with the strain rate [11,12]. Another study used instrumented drop-weight apparatus to test the efficiency of hooked-end steel fibre (0.5% Ø0.5–40 mm) and hybrid fibre (steel fibres plus 0.1% Ø0.018–12 mm polypropylene fibres) reinforced concrete and found that adding 0.1% polypropylene fibres improved the impact loading resistance of FRC because of the large deformation capacity of the polypropylene fibres [13].

Although most studies indicated that fibre addition significantly improves the impact and dynamic loading resistance capacity of concrete, Li et al. found that fibre addition had limited effect on the impact resistance of the materials [14], which is inconsistent with the findings in [9–11]. The possible reason is that rather short fibres (about 10–15 mm long) were used in [14], which made the fibres vulnerable to debonding under impact loading, and the debonded fibres became ineffective to resist impact loads. A reduction in the energy absorption capacity of SFRC with 30 mm long straight fibres was also noticed under impact loading owing to fibre pull-out failure [10]. Moreover, the test results reportedin [3] indicated that the tensile strength and fracture toughness of SFRC increased with steel fibre volume and fibre length because more and longer fibres are more efficient in arresting cracking. These studies revealed that the fibre geometry and length affect the impact load resisting capacity of SFRC.

One of the most important properties of fibre-reinforced concrete is its considerably improved impact resistance. However, most previous studies are limited to static or low strain rate (usually less than $1\,\mathrm{s}^{-1}$) dynamic loadings. Only a limited number of studies performed high-speed impact tests to obtain FRC material compressive properties corresponding to relatively high strain rates [15–18]. It should be noted that usually strain rate is considered as quasi-static in the range between $10^{-8}\,\mathrm{s}^{-1}$ and $10^{-4}\,\mathrm{s}^{-1}$, low strain rate in the range between $10^{-4}\,\mathrm{s}^{-1}$ and $10^{0}\,\mathrm{s}^{-1}$, and high strain rate in the range between $10^{0}\,\mathrm{s}^{-1}$ and $10^{3}\,\mathrm{s}^{-1}$. In [15], Split Hopkinson pressure bar (SHPB) was used to perform uniaxial compressive impact tests of SFRC, in which concrete specimens with 0.6% hooked-end steel fibres (Ø0.54–35 mm) were tested under strain rate 20–100 s^{-1}. It was concluded that compressive strength of both plain concrete and SFRC increase with strain rate, SFRC does not exhibit a significant increase in uniaxial compressive strength although it possesses post-peak ductility than plain concrete, but the post-peak ductility is absent at strain rate higher than $50\,\mathrm{s}^{-1}$ because fragments of concrete can no longer bond onto the steel fibres. This observation is consistent with those reported in [10,14] that debonding failure makes the fibre reinforcement ineffective in resisting high-speed impact loads. These results demonstrate that strong bonding between fibres and cement matrix is crucial for using FRC material to resist high-rate impact and blast loads. Wang et al. prepared SFRC specimens containing 0, 3% and 6% ultra-short steel fibres to perform SHPB compressive tests up to strain rate $100\,\mathrm{s}^{-1}$ [16]. It was reported that SFRC showed strain rate sensitivity, and a high volume fraction of steel fibre resulted in higher strength. In a review paper, Suaris and Shah summarized the research outcomes on the strain rate effects on SFRC subjected to impact and impulsive loadings and concluded that the energy absorbed by SFRC under impact appeared to be 20–100 times that absorbed by plain concrete [17]. Considering steel fibres with various geometries, e.g. paddle, crimped andhooked, Swamy and Jojagha conducted repeated drop-weight tests with a 4.54 kg hammer dropping from a 457-mm height [18]. They found that with a fibre volume of 1.0%, substantial increases in impact strength and energy absorption of SFRC could be achieved over those of plain concrete. Unfortunately the number of studies of FRC material properties at high strain rate is very limited, and there is no systematic study of strain rate effect of FRC with different fibre contents on material properties, the dynamic increase factor (DIF) of FRC as a function of strain rate for different FRC is rarely available. In most design and analysis, DIF of plain concrete has to be used for FRC.

From the review of above studies, it can be noted that the fibre strength, geometry and deformability are key factors for effective improvement in strength, ductility and energy absorption capability of concrete material. In a recent study, Xu et al. carried out drop-weight experimental tests on concrete specimens reinforced with 7 different types of fibres. Their test results demonstrated that FRC with spiral-shaped steel fibres outperformed other 6 fibre types in terms of the impact loading resistance capacity, ultimate compressive strength, post-failure strength and energy absorption capability [19], because the spiral fibre has a three dimensional anchorage bond in the concrete matrix due to the fibre shape and better mechanical component of bond due to fibre deformation under impact as illustrated in Fig. 1 [20].

It should be noted that in the test reported in [19], SFRC specimens were impacted using drop-weight apparatus, which was only about to cover a relatively small range of strain rate. In addition, the volume fraction of spiral fibres considered in [19] was 1.0%. Therefore for a better understanding, further study of the dynamic properties of spiral SFRC material under a wider range of strain rates with different fibre volume fractions is deemed necessary. In the present study, a series of tests were conducted to study the mechanical properties of SFRC materials mixed with spiral fibres. Quasi-static compressive and splitting tensile tests and dynamic compressive tests were carried out using Baldwin Hydraulic Machine and split Hopkinson pressure bar (SHPB) system, respectively. All specimens tested are designed to have dimensions of Ø75 × 37.5 mm (L/D ratio equal to 0.5), which is suggested in [21] to eliminate the axial inertia effect in high-speed impact tests. Grease was evenly spread at both ends of all specimens in order to minimize the end friction confinement due to specimen-apparatus interaction. The length of spiral fibres ranges from 30 to 40 mm while the diameter is 0.5 mm. Different volume fractions of fibres, namely 0.0% (plain concrete), 0.5%, 1.0% and 1.5%, are considered. The influences of different volume fractions of fibres on strength, Young's modulus, stress–strain relation and energy absorption of