

# PERFORMANCE OF SPIRAL-SHAPED STEEL FIBRE REINFORCED CONCRETE STRUCTURE UNDER STATIC AND DYNAMIC LOADS

Hong Hao\* and Yifei Hao

Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering,  
Curtin University, Kent Street, Bentley, WA 6102, Australia. \*Email: hong.hao@curtin.edu.au

## ABSTRACT

Concrete is the most widely used construction material due to its impressive resistance to compressive load. The major weaknesses of concrete are its brittleness and poor resistance to tensile forces. Intensive number of studies has been conducted to add various types of short discrete fibres into concrete mix to enhance its ductility and post-peak load-bearing capacity. A spiral-shaped steel fibre was recently proposed for reinforcing concrete material with 3D bond components. A series of laboratory tests have been conducted for a comprehensive investigation of the performances of spiral-shaped steel fibre reinforced concrete materials and structures. A fundamental understanding of the bond-slip behaviour of spiral fibres and its mechanism of reinforcing the matrix was achieved by conducting pull-out tests. Compressive and direct tensile tests on  $\text{\O}100\text{-}200$  mm concrete specimens with spiral fibres of different geometries were conducted for properly determining fibre geometries to reinforce concrete materials. Split Hopkinson pressure bar (SHPB) tests were carried out to study the dynamic behaviour of spiral steel fibre reinforced concrete (SFRC) with various volume fractions under compression and splitting tension. The corresponding relations of dynamic increase factor (DIF) vs. strain rate were proposed based on test data. Repeated drop-weight impact tests on SFRC beams reinforced with the commonly-used hook-end fibres and spiral fibres were performed. Test results demonstrated the superiority of spiral fibres in bonding and enhancing concrete structural elements in resisting impact loads. The even distributions of spiral fibres in comparison with crimped fibres in concrete matrix were justified by physical examinations. Mesoscale simulations with distinctive consideration of mortar matrix, coarse aggregates and spiral fibres were conducted for statistical derivation of dynamic properties of spiral SFRC. While having demonstrated the promising performances of concrete reinforced with spiral fibres, further studies are also suggested based on the observations and results obtained.

## KEYWORDS

Spiral fibre, steel fibre reinforced concrete, pull-out, distribution, dynamic properties, structural responses, blast and impact.

## INTRODUCTION

Throughout the ages, concrete has always been and continues to be one of the most impressive construction materials. Concrete exhibits excellent resistance to compressive loads, corrosion, and heat etc. The wide availability of materials used to manufacture concrete and the price at which these materials can be obtained make it even more appealing for using concrete as the primary source of construction. Despite the beneficial properties of concrete there is a major flaw in the capacity of concrete, i.e., the brittleness due to low resistance to tensile loading. Tension crack development and propagation is one of the major issues of application of concrete in construction. Moreover, the increased possibility of being subjected to blast and impact loads requires the concrete material possessing increased ductility and energy dissipation capability. Besides the reinforcing bars entrenched within the concrete matrix, the addition of discrete fibres to brittle materials to increase their strength and ductility has been used since ancient times, with mud huts manufactured with baked clay reinforced with straw and masonry mortar reinforced with animal hair. The most common of these small fibres in today's ready-mix concrete industry include glass, steel, natural and synthetic fibres, each with their own special ability to enhance the properties of concrete in one way or another. Unfortunately, the ideal fibre for reinforcement has not yet been industrialised, with the properties for this "perfect" fibre requiring high strength and modulus of elasticity, ease of dosing and distribution, and high bonding strength and frictional resistance that do not exceed the strength of fibres (Johnston 2001).

Among all types of fibres commercially available in industry, those made of steel have occupied the majority of the industrial market to be used for reinforcing concrete material. For analysis of behaviours of steel fibre

reinforced cementitious or concrete (SFRC) material and structural elements subjected to different loading conditions, it is critical to characterise the bonding strength and pull-out behaviour of steel fibres from cementitious matrix. The past four decades have seen several researchers making predictions and developing models for the pull-out behaviour of steel fibres with various geometries in SFRC (Brandt 2008). It is generally acknowledged that the geometry of steel fibres influences the combined action of bond components such as adhesion between fibre and matrix, frictional bond component, and the mechanical characteristics of concrete reinforced with steel fibres (Naaman and Najm 1991). Various attempts have been made to improve the bond-slip characteristics of steel fibres, with the most effective method utilising mechanical deformation such as hook-end fibres, crimped fibres, undulated fibres, twisted fibres and flat end fibres etc. which have become available in construction industries (Hsueh 1990). It has been noted that anchorage bond and frictional bond are only able to be provided by these commercial steel fibres in a two-dimensional plane along one or two directions. Steel fibre that is able to provide bond components tri-dimensionally is believed to more effectively improve the mechanical properties of SFRC materials. In a pilot study conducted by Xu et al. (2012b), 6 types of fibres, namely hook-end fibres, flattened fibres, cold rolled fibres, undulated fibres, synthetic fibres, and spiral fibres were considered to reinforce concrete specimens and their effectiveness of reinforcement was evaluated by conducting compressive tests under static and drop-weight impact loads. Two types of spiral fibres, one with relatively small coil pitch (spiral I) and the other with relatively large coil pitch (spiral II) allowing coarse aggregates to fit in laterally, were considered as shown in Figure 1. Ø100-100 mm specimens were impacted by the impactor weighing 96.7 kg dropping from heights of 2 m and 3.8 m, respectively. In the study it was found that spiral II fibres outperformed the other types of fibres in reinforcing concrete matrix in terms of compressive strength, toughness and sensitivity to strain rate as illustrated by Figure 2.

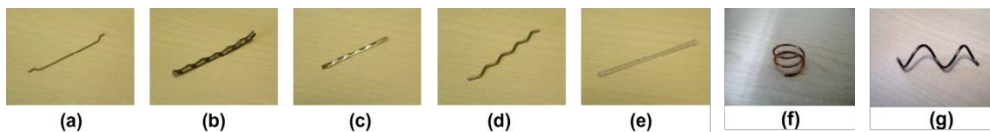
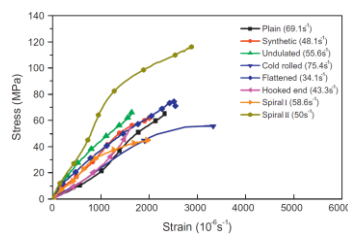
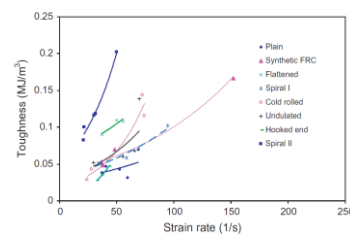


Figure 1 Fibres considered in (Xu et al. 2012b): a) hook-end, b) flattened, c) cold rolled, d) undulated, e) synthetic, f) spiral I and g) spiral II



(a) Stress-strain curves under 3.8 m impact



(b) Toughness vs. strain rate

Figure 2 Comparison of properties of concrete reinforced with different types of fibres (Xu et al. 2012b)

A follow-up study (Xu et al. 2012a) focused on comparing the splitting tensile properties of concrete reinforced with spiral II fibres and hook-end fibres. Notched cylindrical specimens with load adaptor (Figure 3) were prepared for static and drop-weight tests. It was found that spiral fibres performed better in terms of ductility, toughness, crack controllability and rate sensitivity as illustrated in Figs. 4 and 5. The authors attributed the superiority of spiral fibres to their three-dimensional bond components and confinement to concrete matrix.

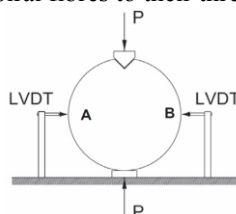


Figure 3 Schematic of notched specimen with load adaptor (Xu et al. 2012a)

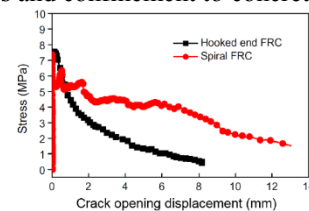


Figure 4 Comparison of splitting tensile stress-COD curves under quasi-static loading (Xu et al. 2012a)

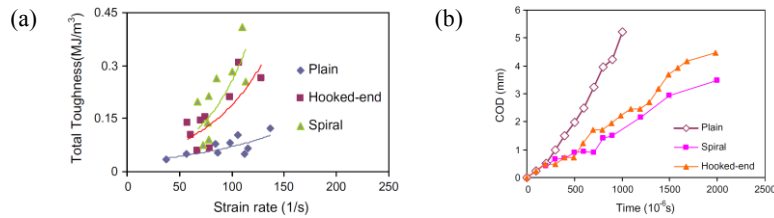


Figure 5 Comparison of a) toughness and b) COD histories of SFRC under impact loading (Xu et al. 2012a)

Based on the observations from (Xu et al. 2012a; Xu et al. 2012b), a series of experimental and numerical studies have been conducted for a more comprehensive understanding of properties of concrete reinforced with spiral-shaped steel fibres under static and dynamic loadings. To explore the reasons that explain the superiority of spiral fibres, pull-out tests on 2D fibres (straight and hook-end fibres) and 3D spiral fibres were carried out for distinct comparison and fundamental understanding of the mechanism of spiral fibres reinforcing the concrete matrix. Because changing the fibre geometry might result in different bond-slip performance of individual fibres, hence the mechanical properties of SFRC, parametric studies were conducted to systematically investigate the influences of spiral fibre geometries on performances of SFRC under compression and direct tension. Suggestion was given to select geometrical parameters according to the test results, followed by split Hopkinson pressure bar (SHPB) tests on specimens with different volume fractions of spiral fibres to investigate dynamic material properties of SFRC under compression and splitting tension. Based on the understanding of dynamic properties of spiral SFRC, drop-weight impact tests were performed to evaluate the effectiveness of spiral fibres in enhancing deformability and energy absorption capacity of concrete structural elements under impact loads. Mesoscale numerical models with distinctive consideration of mortar matrix, aggregates and spiral fibres were developed predict behaviours of spiral-fibre reinforced concrete specimens under impact loads. Finally, to investigate the distribution of spiral fibres in concrete structure prepared under normal mixing and vibrating procedure, beam specimens were prepared and internal examination of fibre distributions were conducted by cutting the specimens into pieces. These studies are summarised in the present paper. Discussions on the effectiveness of spiral fibres in reinforcing concrete matrix are made. Further studies are also suggested.

## GEOMETRICAL CHARACTERISTICS OF SPIRAL FIBRES

The three-dimensional characteristics of spiral fibres can be represented by nominal length, wire diameter, coil diameter and coil pitch as shown in Figure 6. In all tests reported in this study the wire diameter is 0.56 mm. The nominal aspect (length-to-diameter) ratio is determined by the nominal length and diameter of the wire. Complications arise with the number of different geometries a spiral can have, varying the coil pitch and coil diameter to create optimum toughness while maintaining a viable steel/concrete ratio. More importantly, as mentioned in the study by Xu *et al.* (2012b), the spiral fibre with relatively small coil pitch did not perform well. This is primarily because coarse aggregates were expelled from the volume inside the spiral fibres, making the specimens more heterogeneous with more defects such as micro cracks and air voids. Laboratory study of the influence of spiral fibre geometries on mechanical properties of SFRC is introduced in the following section.

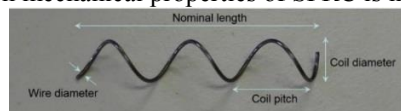


Figure 6 Parameters representing spiral fibre characteristics

## PULL-OUT TESTS

The study of steel fibre pull-out behaviour from concrete is fundamental to understand the behaviour of SFRC as a composite when it is incorporated in structures. Numerous attempts have been made to better understand the effects of geometry of hook-end fibres on the mechanical behaviour of pull-out in SFRC (Alwan et al. 1999; Laranjeira et al. 2010b; Naaman and Shah 1976; Zile and Zile 2013). Despite the valuable understanding gained from these models, there have been no investigations into spiral shaped steel fibres in SFRC and no attempts to model the pull-out behaviour of a spiral fibre. To bridge this gap, laboratory tests were conducted to study the pull-out behaviour of spiral fibres from concrete matrix. In addition, straight fibres and hook-end fibres were also tested for comparison. The embedment depths of all fibres were 30 mm. It should be noted that the mixing constituents and proportions of concrete matrix given in Table 1 are consistent throughout the laboratory tests presented in this paper. The test setup is schematically given in Figure 7 below. The compressive strength of concrete in pull-out tests is 44 MPa.

Table 1 Mixing constituents and proportions of concrete matrix

| Water                 | Cement                | Sand                  | <4mm aggregates       | 4-7mm aggregates      | 7-10mm aggregates     |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 205 kg/m <sup>3</sup> | 426 kg/m <sup>3</sup> | 843 kg/m <sup>3</sup> | 130 kg/m <sup>3</sup> | 306 kg/m <sup>3</sup> | 444 kg/m <sup>3</sup> |

The general shapes of the force-slip curves observed in pull-out tests are given in Figure 8. It can be seen that straight fibre gave the least bonding strength among all types of fibres. Hooking the ends was able to effectively enhance the bonding strength and frictional bond component. Unlike the behaviours of 2D steel fibres, the pull-out force on spiral fibres from concrete matrix increased with a series of peaks before a final maximum peak force followed by the complete drop marking the end of the test. As the pull-out process progressed, an increasing force was needed for debonding. This may be attributed to the pull-out procedure applied whereby the fibre was pulled out from the central axis of the spiral rather than pulling in a circular manner following the coil diameter of the spiral as schematically illustrated in Figure 9. As the pull-out process progressed deeper into the concrete, the fibre was progressively pulled out at a decreasing angle,  $\theta$ , to the central axis. An increasing force was needed to pull out fibre deeper in the concrete matrix because the fibre needed to overcome an increasingly larger volume of concrete. This is in agreement with previous experimental works by Laranjeira et al. (2010) who showed that the load at which fibres failed decreases at increasing inclination angles. Although the latter paper was addressing the condition of an inclined hook-end fibre, the results may be applied to the spiral fibres since spiral fibres can be viewed as a fibre that is inclined at every point.

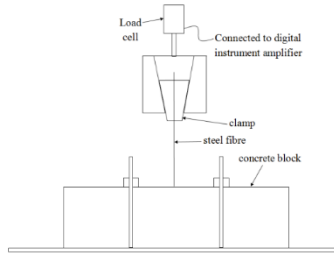


Figure 7 Schematic diagram of pull-out test setup

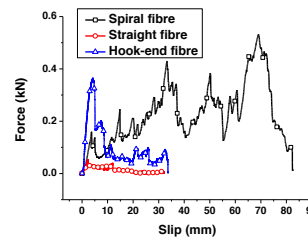


Figure 8 Typical force-slip curve in pull-out tests

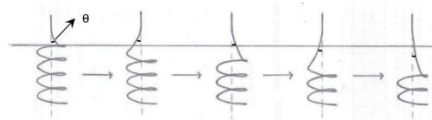


Figure 9 Spiral fibre pull-out process

From the pull-out curve, peaks were observed between the starting point of the pull-out process and the final peak. The peaks may be indicative of the bond strengths at various depths of the fibre as the fibre was pulled out. It was also observed that concrete spalling occurred at intervals corresponding to the peaks. For each peak, the pull-out force increased gradually until the force exceeds the matrix strength at that point. Once the pull-out force reached this value, a fragment of the concrete was spalled off and the pull-out force drops. This increase-decrease trend of the pull-out force continued throughout the pull-out process, resulting in the numerous peaks observed in Figure 8. Research by Leung and Li (1992) showed that spalling-compressive strength is higher than the conventional compressive strength of concrete which is due to the very small region of concrete that is involved in bearing the locally induced stresses. Concrete spalling occurs when that region of the concrete reaches a pressure equal to concrete compressive strength. The final peak (which was the maximum peak in most cases) is indicative of the ultimate bond strength after which a complete drop was observed which marked the end of the test where the fibre was pulled out completely. From the comparison in Figure 8, with the same embedment depth, spiral fibres had the highest slip capacity, and more importantly the highest energy dissipation (area under force-slip curves) per single fibre's complete pull-out. As the integration of pull-out behaviour of individual fibres is the dominant factor that determines the mechanical properties of SFRC, the observations in Figure 8 clearly demonstrated why spiral fibres outperformed other types of fibres in terms of enhancing ductility, toughness and energy absorption capability of the concrete matrix.

## SENSITIVITY OF MECHANICAL PROPERTIES TO FIBRE GEOMETRIES

As is mentioned above, the geometry of spiral fibres has important influences on the workability, homogeneity and mechanical properties of SFRC materials. Laboratory tests were carried out to investigate the influences of fibre geometries on compressive and tensile properties of SFRC materials reinforced with 1% fibres by volume. The wire diameter was 0.56 mm. Spiral fibres with different nominal lengths (17mm, 25mm and 34mm) (equivalent to nominal aspect ratios of 30, 45 and 60), coil pitches (5mm, 10mm and 15mm), and coil diameters (3mm, 6mm and 9mm) were considered, as shown in Figure 10 and summarised in Table 2. Compressive and

direct tensile tests were conducted on Ø100-200mm specimens. 6 samples from each batch were tested with 3 samples under compression and 3 under tension. Individual fibres were carefully dosed into concrete mix to prevent from getting balled.

Table 2 List of geometries of spiral fibres corresponding to the batches

| Batch                | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|----------------------|----|----|----|----|----|----|----|
| Nominal length       | 17 | 34 | 25 | 25 | 25 | 25 | 25 |
| Nominal aspect ratio | 30 | 60 | 45 | 45 | 45 | 45 | 45 |
| Coil diameter (mm)   | 6  | 6  | 6  | 6  | 3  | 9  | 6  |
| Coil pitch (mm)      | 10 | 10 | 5  | 15 | 10 | 10 | 10 |

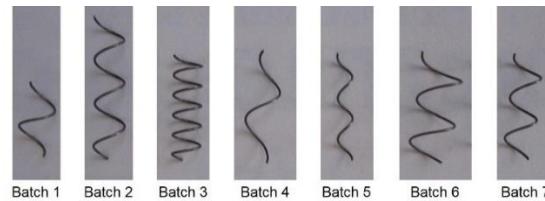


Figure 10 Spiral fibres with different geometries mixed in different batches

Due to the difficulty of testing concrete in direct tension, steel caps with dimensions illustrated in Figure 11 were fabricated for direct tensile testing. The inside of the steel caps and the ends of concrete samples were blast cleaned for better adhering concrete to the caps using Sikadur epoxy. Steel rods were screwed into each end of the samples and then assembled into the hydraulic testing machine. An angle meter with magnetic base was used to ensure that all samples were tested as vertical, concentric to the direction of the tensile force applied, as can be seen in Figure 12. Concentrically loading the samples under tensile loading ensures that the failure mechanism occurs horizontally through the middle half of the sample. A tensile load was continuously applied to the steel rods until the sample had been completely pulled apart into two pieces and no fibres were still bridging the gap between the two halves of the sample.

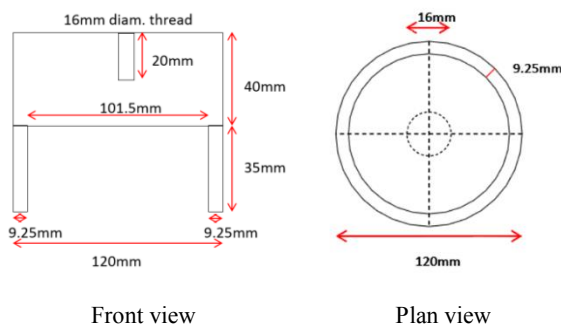


Figure 11 Schematic of steel cap design for direct tensile testing (not to scale)



Figure 12 A sample in direct tensile test

From the compressive and direct tensile tests, specimens from Batches 2 and 3 were found to have quite inconsistent mechanical properties. For Batch 2 specimens, the large aspect ratio of 60 significantly reduced the workability and the even distribution of spiral fibres in the concrete matrix. Moreover, the fibres were more likely to get balled. Examinations before and after tests confirmed large air voids existed both on surface and inside the specimens. On the other hand, the inconsistent behaviours of Batch 3 specimens were expected as the coil pitch of spiral fibres was only 5 mm, which is smaller than most of the coarse aggregates as indicated in Table 1. As discussed above, the small coil pitch expels coarse aggregates from the volume occupied by spirals, making the specimens more heterogeneous with more defects during casting and curing. Due to the significant inconsistencies of specimens from Batches 2 and 3, their stress-strain curves are not used. Typical stress-strain curves of specimens from other batches, i.e., Batches 1 and 4-7, under compression and direct tension are compared in Figure 13. As can be seen, the stress-strain curves in Figure 13 do not show significant differences within limited strain range. Specimens reinforced with spiral fibres of longer full length had higher deformability as the fibre pull-out process is dependent on its full length embedded in the matrix. However, as the post-peak resistance is relatively low and this range is of less interest, the data are not shown in this paper. The observations from Figure 13 demonstrate that as long as the nominal aspect ratio and coil pitch are properly determined to prevent from fibre balling and inconsistency, selection of other geometrical parameters can be relatively flexible.

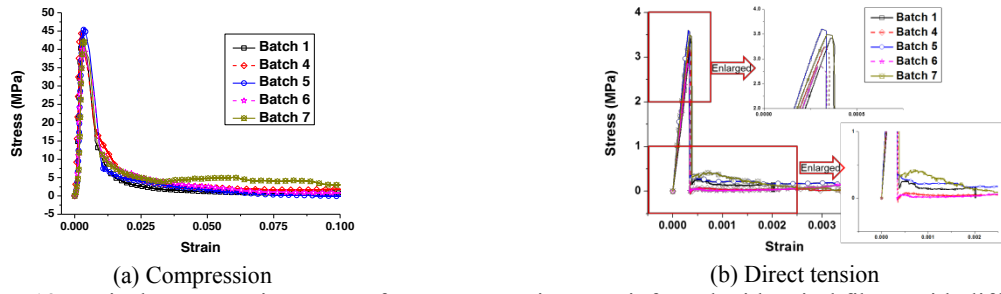


Figure 13 Typical stress-strain curves of concrete specimens reinforced with spiral fibres with different geometries

### SHPB TESTING OF DYNAMIC COMPRESSIVE AND SPLITTING TENSILE PROPERTIES

Split Hopkinson pressure bar (SHPB) tests were conducted to understand the dynamic behaviours and properties of SFRC with spiral fibres under compression and splitting tension.  $\varnothing 75$ -37.5mm SFRC specimens containing different volume fractions of spiral fibres from 0% (plain concrete) to 1.5% with interval of 0.5% were prepared for SHPB tests. The nominal length, wire diameter, aspect ratio, coil diameter and coil pitch are 15mm, 0.5mm, 30, 5mm and 10mm, respectively. The SHPB test setup is illustrated in Figure 14 while examples of recorded incident and transmitted stress histories from compressive and splitting tensile tests are given in Figure 15. Formulae to calculate stress, strain and strain rate of tested specimens, and verification of stress equilibrium are presented in (Hao and Hao 2013).

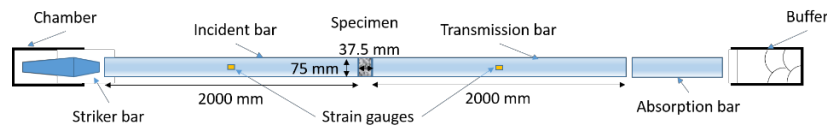


Figure 14 Schematic of SHPB test setup

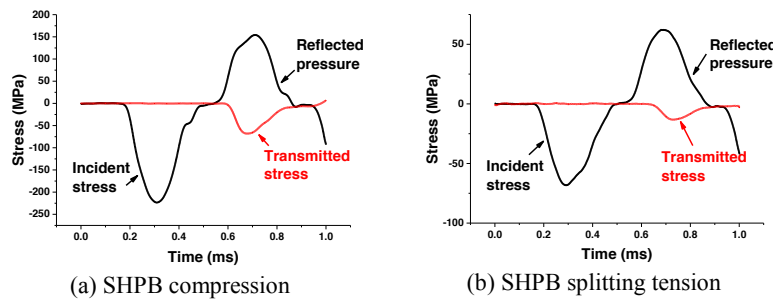


Figure 15 Typical stress waves recorded in SHPB tests

In SHPB compressive tests, besides the observations that the number of cracks and fragments was markedly reduced with the increase of fibre additions (Figure 16), it was also indicated by the test results that when the strain rate is below  $100 \text{ s}^{-1}$ , 1.0% seemed to be the optimal volume fraction of spiral fibres in terms of ductility and energy dissipation capability. Under higher strain rate, the energy absorption capability of spiral SFRC can be further improved by adding more fibres in the matrix as shown in Figure 17.



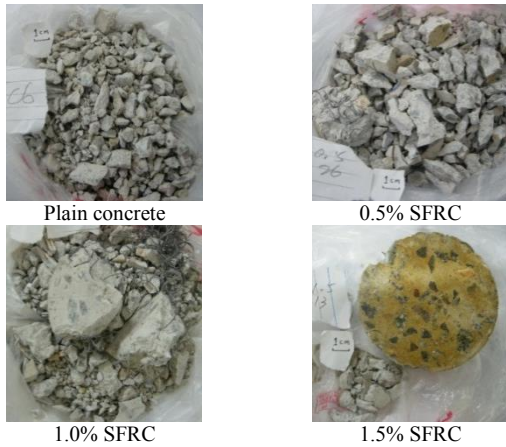


Figure 16 Comparison of failure patterns under the same impact

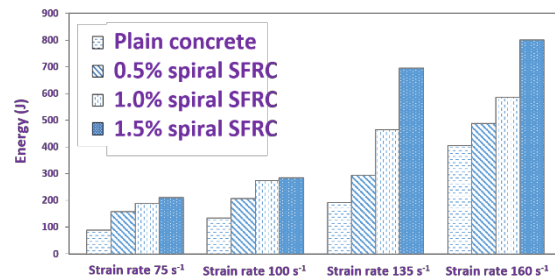


Figure 17 Comparison of energy absorption (Hao and Hao 2013)

In SHPB splitting tension tests, the dynamic splitting tensile strength, deformability, crack controllability and energy absorption capability of spiral SFRC were found to increase with the fibre content. Failure processes were recorded by high speed camera for detailed investigation and image analysis of splitting crack widths. It should be noted that for reaching higher rate of framing, the resolution of photos was sacrificed, and the crack widths could only be estimated as 0.5 mm (size of one pixel) multiplied with integers. The crack widths of SFRC specimens with different volume fractions of spiral fibres with respect to time under stress rate of 150 GPa/s are given and compared in Figure 18 where the time instant corresponding to the first appearance of crack is set to zero.

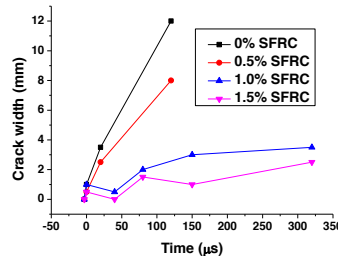


Figure 18 Comparison of crack widths under stress rate of 150 GPa/s

Figure 18 shows significant differences among specimens reinforced with different dosages of spiral fibres. Compared to plain concrete specimen, termed as 0% SFRC in the figure, the width and opening velocity of crack in the specimen with 0.5% spiral fibre reinforcement are effectively reduced. It is very interesting to note that at 40 μs, the crack widths in both 1.0% and 1.5% SFRC specimens were reduced as compared to those at 0 μs, indicating the cracks in the two specimens were recovered, or in other words, pulled back by spiral fibres. Another reduction in crack width can be observed at 150 μs in 1.5% SFRC specimen. Overall the crack widths of 1.0% and 1.5% spiral SFRC specimens developed with much slower rates, demonstrating the excellent crack controllability is further enhanced by adding more fibres.

Both compressive and splitting tensile strengths of the tested specimens were found to be sensitive to strain rate as shown in Figure 19 where the dynamic increase factor (DIF), the ratio of dynamic to static strengths, are used to represent the strength increment. Plain concrete is the least sensitive to strain rate among all materials. The sensitivity increases with the volume fraction of spiral fibres, and the 1.5% SFRC material exhibits the most significant rate sensitivity. This is consistent with the findings by Banthia et al. (1994) that SFRC specimens with higher dosage of fibres were stronger and tougher under impact. The curves in Figure 19 are best-fit relations according to scattered data of specimens containing different dosages of spiral fibres. The fitted DIF versus strain rate relations are formulated by equations below where the subscripts C, 0.5%, 1.0% and 1.5% denote materials of concrete, 0.5%, 1.0%, and 1.5% spiral SFRC, respectively. They can be used to model spiral SFRC materials in numerical prediction of SFRC structural responses to high-rate loadings.

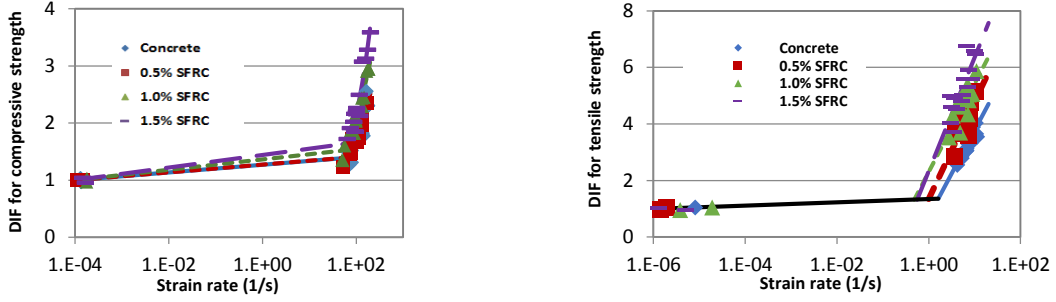


Figure 19 DIFs of spiral SFRC for compressive and tensile strengths

$$CDIF_c = \begin{cases} 0.0672(\log \dot{\epsilon}) + 1.2688 & \text{for } 10^{-4} s^{-1} \leq \dot{\epsilon} \leq 64.8 s^{-1} \\ 2.6418(\log \dot{\epsilon})^2 - 8.575(\log \dot{\epsilon}) + 8.2551 & \text{for } 64.8 s^{-1} \leq \dot{\epsilon} \leq 200 s^{-1} \end{cases} \quad (1)$$

$$CDIF_{0.5\%} = \begin{cases} 0.0679(\log \dot{\epsilon}) + 1.2716 & \text{for } 10^{-4} s^{-1} \leq \dot{\epsilon} \leq 63.6 s^{-1} \\ 1.2421(\log \dot{\epsilon})^2 - 2.8505(\log \dot{\epsilon}) + 2.4951 & \text{for } 63.6 s^{-1} \leq \dot{\epsilon} \leq 200 s^{-1} \end{cases} \quad (2)$$

$$CDIF_{1.0\%} = \begin{cases} 0.0907(\log \dot{\epsilon}) + 1.3628 & \text{for } 10^{-4} s^{-1} \leq \dot{\epsilon} \leq 58 s^{-1} \\ 1.8921(\log \dot{\epsilon})^2 - 4.7911(\log \dot{\epsilon}) + 4.0877 & \text{for } 58 s^{-1} \leq \dot{\epsilon} \leq 200 s^{-1} \end{cases} \quad (3)$$

$$CDIF_{1.5\%} = \begin{cases} 0.1101(\log \dot{\epsilon}) + 1.4404 & \text{for } 10^{-4} s^{-1} \leq \dot{\epsilon} \leq 50.7 s^{-1} \\ 5.5039(\log \dot{\epsilon})^2 - 18.587(\log \dot{\epsilon}) + 17.319 & \text{for } 50.7 s^{-1} \leq \dot{\epsilon} \leq 200 s^{-1} \end{cases} \quad (4)$$

$$TDIF_c = \begin{cases} 0.0569 \log \dot{\epsilon} + 1.3414 & \text{for } 10^{-6} s^{-1} \leq \dot{\epsilon} \leq 1.622 s^{-1} \\ 3.0701 \log \dot{\epsilon} + 0.7085 & \text{for } 1.622 s^{-1} \leq \dot{\epsilon} \leq 20 s^{-1} \end{cases} \quad (5)$$

$$TDIF_{0.5\%} = \begin{cases} 0.0569 \log \dot{\epsilon} + 1.3414 & \text{for } 10^{-6} s^{-1} \leq \dot{\epsilon} \leq 0.9946 s^{-1} \\ 3.4471 \log \dot{\epsilon} + 1.3493 & \text{for } 0.9946 s^{-1} \leq \dot{\epsilon} \leq 20 s^{-1} \end{cases} \quad (6)$$

$$TDIF_{1.0\%} = \begin{cases} 0.0569 \log \dot{\epsilon} + 1.3414 & \text{for } 10^{-6} s^{-1} \leq \dot{\epsilon} \leq 0.4877 s^{-1} \\ 3.1296 \log \dot{\epsilon} + 2.2996 & \text{for } 0.4877 s^{-1} \leq \dot{\epsilon} \leq 20 s^{-1} \end{cases} \quad (7)$$

$$TDIF_{1.5\%} = \begin{cases} 0.0569 \log \dot{\epsilon} + 1.3414 & \text{for } 10^{-6} s^{-1} \leq \dot{\epsilon} \leq 0.5561 s^{-1} \\ 4.0106 \log \dot{\epsilon} + 2.3491 & \text{for } 0.5561 s^{-1} \leq \dot{\epsilon} \leq 20 s^{-1} \end{cases} \quad (8)$$

## DROP-WEIGHT IMPACT TESTS ON SFRC BEAMS

To study the structural responses of spiral SFRC beams under impact loads, laboratory impact tests were conducted. Concrete beams reinforced with hook-end fibres were also prepared and tested for comparison. Both spiral and hook-end fibres had the same nominal aspect ratio of 50.  $100 \times 100 \times 350$  mm SFRC beam specimens with 0.5% and 1.0% fibre fractions by volume were prepared for impact tests using instrumented drop-weight system. Repeated impact tests with impactor weighing 15.2 kg were carried out with 0.5 m and 1.0 m drop heights. The boundary conditions, test setup and measurement of load and deflection are illustrated in Figure 20.

0.5% SFRC beams with spiral fibres and hook-end fibres exhibited similar performances under impact loads, therefore the related results are not given in this paper. When the volume fraction was increased to 1%, spiral SFRC beams significantly outperformed hook-end SFRC beams in terms of deformability and energy dissipation capability as illustrated in Figure 21. This is consistent with the findings from SHPB tests where the change of spiral fibre volume fraction from 0.5% to 1% resulted in significant improvement in strength, crack controllability and energy absorption capability under impact loads.

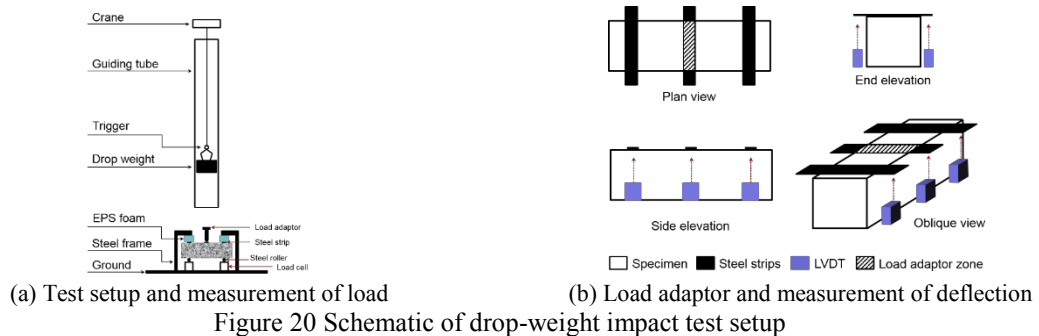
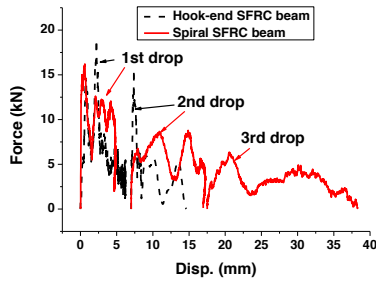
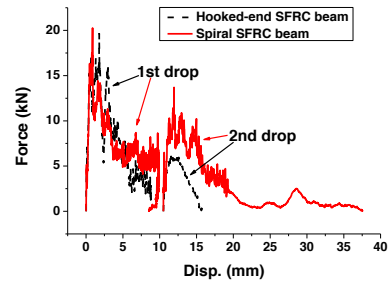


Figure 20 Schematic of drop-weight impact test setup





(a) 1.0% SFRC beams under 0.5 m drop height



(b) 1.0% SFRC beams under 1.0 m drop height

Figure 21 Comparison of load-deflection curves

From the comparison of load-deflection curves given in Figure 21a, it can be observed that although the hook-end SFRC beam was able to sustain higher impact loads for the 1<sup>st</sup> and 2<sup>nd</sup> drops from 0.5 m height, implying its relatively higher stiffness, it was more vulnerable to fibre debonding, and fractured after the 2<sup>nd</sup> impact with total displacement of about 15 mm. In comparison, the deformability of the beam with spiral fibre reinforcement was significantly higher with a total displacement of more than 35 mm. Moreover, while hook-end SFRC beam completely lost its load carrying capacity after the 2<sup>nd</sup> impact, spiral SFRC beam was still able to sustain a third impact. For impact tests with drop height of 1.0 m, although severe damage was found in both beams after the 2<sup>nd</sup> impact, the load-carrying capacity and the deformability of spiral SFRC beam were higher compared to those of the hook-end SFRC beam as shown in Figure 21b. The observations in Figure 21 clearly demonstrate the better bonding of spiral fibres to the concrete matrix compared to hook-end fibres, leading to a much higher energy absorption capability.

### MESOSCALE MODELLING OF SPIRAL SFRC

The above experimental programs tested specimens prepared under well controlled laboratory environment with high-quality batching. As the mechanical properties, especially tensile properties, of the SFRC composite are highly dependent on the dosages and distributions of fibres and aggregates, conducting the statistical analysis accounting for these factors is believed to give less biased parameters for material modelling. Mesoscale modelling of spiral SFRC material under splitting tension as plane-stress problems has been conducted using LS-DYNA. Information about material models and parameters for mortar matrix, coarse aggregates, steel fibres and pressure bars, and mesh size convergence are given by Xu et al. (2012c). An example of the developed mesoscale model containing 1% spiral fibres is shown in Figure 22 while the model validation is given in Figure 23 below.

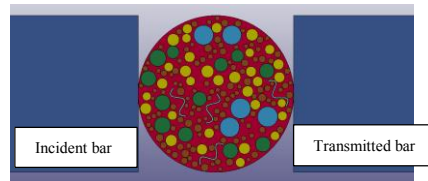


Figure 22 An example of SHPB simulation using mesoscale model

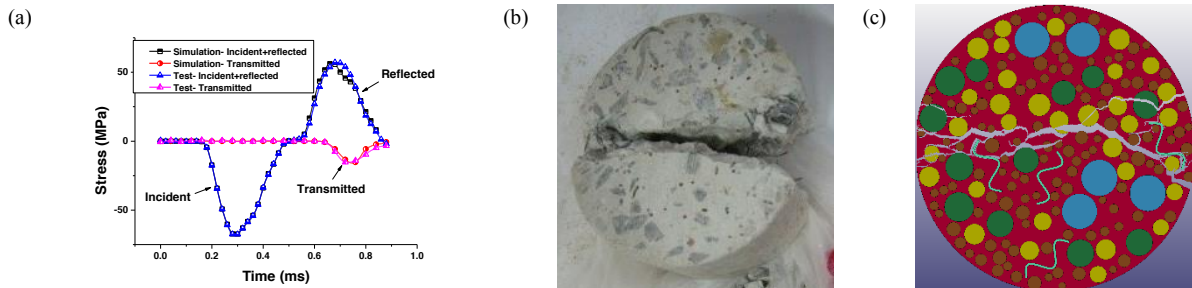


Figure 23 Comparison of numerical simulation and test results a) stress histories, b) damaged specimen from tests, and c) damaged specimen from numerical simulation

Intensive numerical simulations considering different volume fractions of spiral fibres and random distributions of coarse aggregates and fibres are underway for generating statistical distributions of SFRC material properties

accounting for the random distributions of aggregates and fibres, based on which further study will be conducted to develop the material model of spiral SFRC for predicting the dynamic responses of spiral SFRC structures subjected to blast and impact loads.

## INVESTIGATION OF FIBRE DISTRIBUTIONS IN SFRC

Proper distribution of steel fibres in concrete mix is always a challenge and requires proper construction quality control to prevent fibre balling. Besides investigating the mechanical performances of spiral SFRC materials and structures, the distributions of discrete fibres in SFRC are also examined in this study. Laboratory tests were performed with SFRC beams cast with industrially utilised crimped fibres and spiral fibres, respectively. Steel fibres with volume fraction of 1% were dosed into concrete mix. The fresh SFRC was placed into formworks and internally vibrated using concrete vibrator. In total 16 beams were prepared. After being cured for 28 days, SFRC beams were segregated into five pieces using an angle grinder fitted with a diamond blade, which allowed internal examinations of fibre distributions along four cross-sections as shown in Figure 24 where the upper surface (cast face) is on the left hand side of each image.

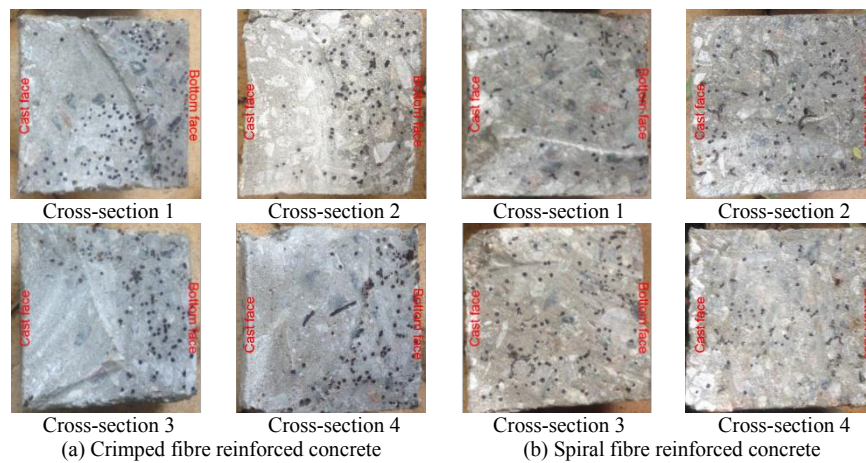


Figure 24 Comparison of fibre distributions along cross-sections

From Figure 24, it can be observed that the distribution of crimped fibres was dramatically affected between pouring and setting. The vibration caused them move away from the centre of the specimen and occupy the other regions, especially sink to the bottom of the formwork. On the other hand, the spiral fibre samples displayed a far more random or sporadic, less congregated, distribution. These results give reason to believe that the spiral fibres do, in fact, remain within the same vicinity of their original positions in the concrete matrix between pouring and setting. Once untangled, these fibres then become embedded within the concrete matrix, and do not significantly change positions between this time and the time at which setting of the sample is complete. Crimped fibre samples did not benefit from this internal vibration at all, with the increasing time of vibration forcing fibres further away from the centre of sample and towards the outer walls of the specimen, making it harder to sporadically distribute the crimped fibres throughout the concrete than it is to distribute spiral fibres, due to their ability to move after pouring has occurred.

## SUMMARY

The present paper reports a series of laboratory tests for comprehensive studies of the performances of spiral-shaped steel fibre reinforced concrete materials and structures under different loading conditions. Studies summarised in the paper include pull-out tests on straight, hook-end and spiral fibres from concrete matrix, sensitivity analysis of mechanical properties of spiral SFRC to fibres geometries, SHPB tests on the dynamic compressive and splitting tensile properties of spiral SFRC, repeated drop-weight impact tests on SFRC beams, numerical SHPB tests of spiral SFRC considering different fibre volume fractions and random distributions of coarse aggregates and fibres, and evaluation of fibre distributions in beam specimens from the construction perspective. Results from these investigations demonstrate the promising effects of spiral fibres which can be considered as a potentially superior discrete reinforcement in concrete technology.

One possible drawback of spiral fibre is its slightly lower resistance in the beginning stage of bond-slip curves as shown in Figure 8. Replacing a portion of spiral fibres by short 2D fibres, namely using hybrid fibres to reinforce concrete matrix, is believed to be an effective measure to overcome spiral fibres' shortcoming.

Experimental studies on SFRC materials and structures with 1% volume fraction of steel fibre reinforcement considering different blend ratios of short hook-end and spiral fibres are underway.

## ACKNOWLEDGMENTS

The authors acknowledge Australian Research Council (grant number DP130104332) and China National Natural Science Foundation (grant number 51227006) for financial support to carry out this study.

## REFERENCES

- Alwan, J.M., Naaman, A.E., Guerrero, P. (1999). "Effect of mechanical clamping on the pull-out response of hooked steel fibers embedded in cementitious matrices", *Concrete Science and Engineering* 1, 15-25.
- Banthia, N., Chokri, K., Ohama, Y., Mindess, S. (1994). "Fiber-reinforced cement based composites under tensile impact", *Advanced Cement Based Materials* 1, 131-141.
- Brandt, A.M. (2008). "Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering", *Composite structures* 86, 3-9.
- Hao, Y., Hao, H. (2013). "Dynamic compressive behaviour of spiral steel fibre reinforced concrete in split Hopkinson pressure bar tests", *Construction and Building Materials* 48, 521-532.
- Hao, Y., Hao, H., Chen, G. (2014). "Experimental investigation of the behaviour of spiral steel fibre reinforced concrete beams subjected to drop-weight impact loads", *Materials and Structures*, 1-18.
- Hsueh, C.-H. (1990). "Interfacial debonding and fiber pull-out stresses of fiber-reinforced composites", *Materials Science and Engineering: A* 123, 1-11.
- Johnston, C. (2001). "Fibre-reinforced cements and concretes", Taylor & Francis, New York.
- Laranjeira, F., Molins, C., Aguado, A. (2010). "Predicting the pullout response of inclined hooked steel fibers", *Cement and Concrete Research* 40, 1471-1487.
- Leung, C.K., Li, V.C. (1992). "Effect of fiber inclination on crack bridging stress in brittle fiber reinforced brittle matrix composites", *Journal of the Mechanics and Physics of Solids* 40, 1333-1362.
- Naaman, A.E., Najm, H. (1991). "Bond-slip mechanisms of steel fibers in concrete", *ACI Materials Journal* 88.
- Naaman, A.E., Shah, S.P. (1976). "Pull-out mechanism in steel fiber-reinforced concrete", *Journal of the Structural Division* 102, 1537-1548.
- Xu, Z., Hao, H., Li, H. (2012a). "Dynamic tensile behaviour of fibre reinforced concrete with spiral fibres", *Materials & Design* 42, 72-88.
- Xu, Z., Hao, H., Li, H. (2012b). "Experimental study of dynamic compressive properties of fibre reinforced concrete material with different fibres", *Materials & Design* 33, 42-55.
- Xu, Z., Hao, H., Li, H. (2012c). "Mesoscale modelling of dynamic tensile behaviour of fibre reinforced concrete with spiral fibres", *Cement and Concrete Research* 42, 1475-1493.
- Zile, E., Zile, O. (2013). "Effect of the fiber geometry on the pullout response of mechanically deformed steel fibers", *Cement and Concrete Research* 44, 18-24.