Concrete is strong in compression but weak in tension with brittle fracture characteristics. To increase its ductility and post-cracking load-carrying capability, intensive researches have been reported to add various types of fibres into concrete mixture. A new type of steel fibre with spiral shape has been recently proposed. Laboratory tests demonstrated that compared to other fibre types such as hooked-end, deformed and corrugated fibres, this new fibre has larger displacement capacity and provides better bonding into the concrete matrix. However, the dynamic properties, especially tensile properties, of concrete reinforced with spiral-shaped steel fibres need be further investigated for a better understanding of this material and potential application in critical engineering buildings/infrastructures against blast and impact loads. This study carries out split Hopkinson pressure bar (SHPB) tests and numerical simulations to study the behaviour of spiral fibre reinforced concrete (SFRC) under dynamic splitting tension. In SHPB tests, tapered striker bar was used to generate stress wave with half-sine shape so that stress wave oscillation and dispersion were eliminated. The simulations are implemented using commercial software LS-DYNA as a plane-stress problem. The SFRC specimens are modelled in mesoscale with distinctive consideration of mortar matrix, coarse aggregates and spiral fibres. The numerical simulation results are compared with SHPB test data. The validity and feasibility of the mesoscale numerical model in analysing behaviours and properties of SFRC under dynamic splitting tension are demonstrated. The influence of fibre contents on the dynamic splitting tensile strengths of SFRC material is parametrically studied.

KEYWORDS

Spiral fibre, fibre reinforced concrete, mesoscale model, splitting tension, high strain rate, aggregate shape, polygonal.

INTRODUCTION

The use of fibre reinforced concrete (FRC) in constructions of long-span or high-rise structures, heavy-duty pavements, tunnel lining or critical engineering buildings has been more and more frequent due to improved ductility and energy absorption capability from fibre addition compared to plain concrete. Fig. 1 gives some examples of engineering projects using FRC. It was observed that with the increase in fibre strength, ductility, strength and post-crack behaviour of FRC were improved because of the prevention of rupture from high-strength fibres, and the primary mode of damage was debonding of the fibres from the matrix (Holschemacher et al. 2010). Laboratory tests with consideration of three types of fibres made of polymer and steel also observed that under quasi-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 (Bindiganavile and Banthia 2001a, 2001b). Although it was indicated that added fibres significantly improve the resistance capacity of concrete subjected to dynamic loadings by many studies, Li et al. (2008) observed that the added fibres had limited effect on the impact resistance of FRCs. The possible reason is that rather short fibres with lengths of about 10 to 15 mm were used by Li et al. (2008), which made the fibres vulnerable to debonding under impact loading, and the debonded fibres became ineffective to resist impact loads. The test results reported by Gao et al. (1997) indicated that with the increase of steel fibre volume dosage and fibre length, the fracture toughness and tensile strength of FRC increased because more and longer fibres are more efficient in arresting cracks. Swamy and Jojagha (1982) conducted repeated drop-weight tests considering...
steel fibres with various geometries and reported that with a fibre volume fraction of 1%, impact strength and energy absorption capabilities of FRCs were substantially increased over those of plain concrete.

![Image](image1.png)

(a) Heavy-duty pavement

![Image](image2.png)

(b) CCTV headquarters

![Image](image3.png)

(c) Rock tunnel lining

Figure 1 Examples of engineering projects with the application of FRC

From review of the above studies, it can be noticed that the key factors for effective enhancement in strength, deformability and energy absorption capacity of concrete materials include the fibre strength, geometry and deformability. Xu et al. (2012) recently performed drop-weight tests on concrete specimens reinforced with 7 types of fibres. It was demonstrated by the test results that FRC reinforced with spiral-shaped steel fibres outperformed other 6 fibre types in terms of impact loading resistance, compressive strength, post-cracking resistance and energy absorption capability, 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. Impact tests on steel fibre reinforced concrete beams also indicated the superiority of spiral fibre in enhancing the energy dissipation ability (Hao et al. 2014). To further study the dynamic tensile properties of spiral fibre reinforced concrete (SFRC), in the present study, splitting tensile tests were conducted using split Hopkinson pressure bar (SHPB) system. The full length of spiral fibres ranges from 30 to 40 mm with the nominal spiralled length 15 mm, and the diameter is 0.56 mm. The fibre volume fraction of 1.0% is considered in preparing the SFRC specimens. Numerical model is also developed using commercial software LS-DYNA to simulate the SHPB tests. The SFRC specimens were modelled in mesoscale with distinctive consideration of mortar matrix, coarse aggregates and spiral fibres. The numerical simulation results are compared with SHPB test data. The validity and feasibility of the mesoscale numerical model in analysing the behaviours and properties of SFRC under dynamic splitting tension are demonstrated. Reliable numerical simulations can thus be carried out to perform intensive simulations to study the influences of fibre properties (length, dosage, random distributions and orientation, etc.) on the SFRC properties, instead of the performing physical tests. This not only results in significantly savings for conducting laboratory tests, but also allows detailed observations of the specimen failure process under high-speed impact loadings.
EXPERIMENTAL STUDY

Mixture of Specimens and Quasi-static Properties

The dimension of all tested cylindrical specimens is Ø75-37.5 mm. The diameter and full length of the spiral fibre are 0.56 mm and 35 mm, respectively. The spiral fibres have a nominal length of 15 mm. The specifications of the spiral fibre and details of the SFRC mixture are given in Table 1, and Table 2, respectively. To obtain the quasi-static properties of SFRC, uniaxial compressive and splitting tensile tests were conducted using hydraulic testing machine. The average mechanical properties of the SFRC material under compression and splitting tension of 6 specimens are summarised in Table 3.

Table 1 Specification of spiral fibres

<table>
<thead>
<tr>
<th>Strength</th>
<th>Nominal length</th>
<th>Diameter</th>
<th>Aspect ratio</th>
<th>Coil diameter</th>
<th>Coil pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300 MPa</td>
<td>15 mm</td>
<td>0.56 mm</td>
<td>27</td>
<td>5 mm</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

Table 2 Mixture proportions

<table>
<thead>
<tr>
<th>Water to cement ratio</th>
<th>Fibre volume fraction</th>
<th>Mix proportion (kg/m³)</th>
<th>Water</th>
<th>Cement</th>
<th>10 mm aggregates</th>
<th>7 mm aggregates</th>
<th>Minus 4 mm aggregates</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48</td>
<td>1.0%</td>
<td></td>
<td>205</td>
<td>426</td>
<td>444</td>
<td>306</td>
<td>130</td>
<td>843</td>
</tr>
</tbody>
</table>

Table 3 Material properties under quasi-static loading

<table>
<thead>
<tr>
<th>Density</th>
<th>Compressive strength</th>
<th>Tensile strength</th>
<th>Young's modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>2247 kg/m³</td>
<td>43.25 MPa</td>
<td>2.87 MPa</td>
<td>29.76 GPa</td>
</tr>
</tbody>
</table>

SHPB Test Setup

The dynamic splitting tensile tests were conducted using SHPB test system. The schematic view of the SHPB apparatus is shown in Fig. 2. The incident and transmitted pressure bars have the same dimension of Ø75-2000 mm. Strain gauges are attached at midpoints of pressure bars. The bars are made of stainless steel with elastic modulus 200 GPa, density 7800 kg/m³, and Poisson’s ratio 0.3. A tapered impact ram was used to impact and generate half-sine loading wave form so that the violent wave oscillation and dispersion in SHPB tests can be eliminated (Lok et al. 2002). The specimen was diametrically sandwiched between pressure bars.

In SHPB tests with the assumption that the peak dynamic stress \( f_{td} \) of the splitting cylinder is proportional to the peak transmitted stress \( \sigma_T \), it has (Tedesco et al. 1993)

\[
f_{td} = \frac{2P_T}{\pi LD}
\]

in which
\[ P_t = \pi R^2 \sigma_r \]  

is the transmitted force, and \( R \) is the radius of the SHPB pressure bar.

Accordingly, the loading rate \( \dot{\sigma} \) and the strain rate \( \dot{\varepsilon} \) in the specimen can be estimated from the equations

\[ \dot{\sigma} = \frac{f_d}{t} \]  

(3)

and

\[ \dot{\varepsilon} = \frac{\dot{\sigma}}{E} \]  

(4)

where \( t \) is the time lag between the start of the transmitted stress wave and the maximum transmitted stress, and \( E \) is the Young’s modulus of the specimen.

**Test results**

13 SFRC specimens with 1% spiral fibres were tested under dynamic loads with strain rate ranges from 2.75 to 11 \( 1/s \). Fig. 3 gives typical stress histories recorded in SHPB test and damaged specimen after test. Fig. 4 summarises the obtained dynamic increase factors (DIF) which is defined as ratio of dynamic to static strength.

(a) Typical stress histories in SHPB tests

(b) Damaged specimen

Figure 3 Typical stress histories and damage patterns in SHPB tests

Figure 4 DIFs obtained from SHPB tests
NUMERICAL STUDY

Material Model

The plasticity concrete model developed by Malvar et al (1997) is used to model mortar matrix in the simulation. This model uses three shear failure surfaces with the consideration of damage and strain rate effects. The strain rate effect on the material strength is described by the DIF. In the simulation, the compressive DIF relations for mortar matrix are adopted from (Hao and Hao 2011). The tensile DIFs for mortar matrix are adopted from (Malvar and Crawford 1998). The compressive and tensile DIFs of mortar matrix are given below.

\[ CDIF = 0.0419 \left( \log \dot{\varepsilon}_d \right) + 1.2165 \quad \text{for} \quad \dot{\varepsilon}_d \leq 30 \text{s}^{-1} \quad (5) \]

\[ CDIF = 0.8988 \left( \log \dot{\varepsilon}_d \right)^2 - 2.8255 \left( \log \dot{\varepsilon}_d \right) + 3.4907 \quad \text{for} \quad 30 \text{s}^{-1} \leq \dot{\varepsilon}_d \leq 1000 \text{s}^{-1} \quad (6) \]

\[ TDIF = \left( \frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_n} \right)^0 \quad \text{for} \quad \dot{\varepsilon}_d \leq 1 \text{s}^{-1} \quad (7) \]

\[ TDIF = \beta \left( \frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_n} \right)^{1/3} \quad \text{for} \quad \dot{\varepsilon}_d > 1 \text{s}^{-1} \quad (8) \]

where \( \delta = \frac{1}{1 + 8\sigma_{cs}/f_{c0}} \), \( \log \beta = 6\delta - 2 \), \( f_{cs} \) is the static compressive strength and \( f_{c0} = 10 \text{MPa} \), \( \dot{\varepsilon}_n = 10^{-6} \text{ s}^{-1} \).

The coarse aggregates in the present study are modelled by PSEUDO_TENSOR model (Mat_16). The DIFs of coarse aggregates used in the present study are obtained from (Hao and Hao 2013) and given below.

\[ CDIF = 0.0187 \left( \log \dot{\varepsilon}_d \right) + 1.2919 \quad \text{for} \quad 1 \text{s}^{-1} \leq \dot{\varepsilon}_d \leq 220 \text{s}^{-1} \quad (9) \]

\[ CDIF = 1.8547 \left( \log \dot{\varepsilon}_d \right)^2 - 7.9014 \left( \log \dot{\varepsilon}_d \right) + 9.6674 \quad \text{for} \quad 220 \text{s}^{-1} \leq \dot{\varepsilon}_d \leq 1000 \text{s}^{-1} \quad (10) \]

\[ TDIF = 0.0598 \left( \log \dot{\varepsilon}_d \right) + 1.3588 \quad \text{for} \quad 10^{-6} \text{s}^{-1} \leq \dot{\varepsilon}_d \leq 0.1 \text{s}^{-1} \quad (11) \]

\[ TDIF = 0.5605 \left( \log \dot{\varepsilon}_d \right)^2 + 1.3871 \left( \log \dot{\varepsilon}_d \right) + 2.1256 \quad \text{for} \quad 0.1 \text{s}^{-1} \leq \dot{\varepsilon}_d \leq 50 \text{s}^{-1} \quad (12) \]

Because there are only very limited test data available, the tensile DIF is set to have a constant value when strain rate exceeds 50 \text{l/s} to avoid overestimation of aggregate strength.

The steel fibres are modelled by PIECEWISE_LINEAR_PLASTICITY material model (Mat_24) from the LS-DYNA database.

The pressure bars remain elastic in SHPB tests. Therefore they are modelled by the isotropic ELASTIC MATERIAL (Mat_1) in LS-DYNA. The parameters of the materials are listed in Table 4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Model in LS-DYNA</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar matrix</td>
<td>MAT_72R3</td>
<td>Density</td>
<td>2200 \text{kg/m}^3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unconfined compressive strength</td>
<td>35 \text{MPa}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poisson’s ratio</td>
<td>0.18</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>MAT_16</td>
<td>Density</td>
<td>2750 \text{kg/m}^3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unconfined compressive strength</td>
<td>160 \text{MPa}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poisson’s ratio</td>
<td>0.20</td>
</tr>
<tr>
<td>Steel fibre</td>
<td>MAT_24</td>
<td>Density</td>
<td>7800 \text{kg/m}^3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Young’s modulus</td>
<td>200 \text{GPa}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yield stress</td>
<td>1300 \text{MPa}</td>
</tr>
<tr>
<td>Pressure bar</td>
<td>MAT_1</td>
<td>Density</td>
<td>7800 \text{kg/m}^3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Young’s modulus</td>
<td>200 \text{GPa}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The components, i.e. coarse aggregates, spiral fibres and mortar matrix, are assumed to have perfect bonding in the mesoscale model. Erosion technique is adopted in the numerical simulation. An erosion criteria depending on the maximum principle strain of 0.2 is used for mortar matrix, aggregates and spiral fibres.
Mesoscale Numerical Model for SFRC

In the present study, mortar matrix, coarse aggregates and spiral fibres in the mesoscale model of SFRC specimen are distinctively simulated with the respective material properties. To simplify the model, coarse aggregates are assumed to have circular shape with random size and distribution. SFRC specimen is modelled with a 2D plane stress assumption (Hao et al. 2008). It is assumed that the fibre quantity and distribution are the same in every unit length along the specimen. The aggregate particle size distribution is assumed to follow the modified Fuller’s curve proposed by Walraven (1981) for 2D modelling as below.

\[
P(D < D_0) = P_t \left( 1.065D_0^{0.5} D_{\text{max}}^{0.5} - 0.053D_0^4 D_{\text{max}}^{-4} - 0.012D_0^6 D_{\text{max}}^{-6} - 0.0045D_0^8 D_{\text{max}}^{-8} - 0.0025D_0^{10} D_{\text{max}}^{-10} \right)
\]

where \( P \) is the cumulative percentage of aggregates passing a sieve with aperture diameter \( D \), \( D_{\text{max}} \) is the maximum size of aggregate particle. The maximum diameter of aggregate particle is set to be 10 mm, then the aggregates are divided into four ranges with diameters of 2-4, 4-6, 6-8 and 8-10 mm, respectively.

Shell elements are used in the numerical model. The SFRC specimen in simulation has diameter of 75 mm with a unit thickness of 1 mm. The lengths of pressure bars are both 2000 mm. The striker bar and absorption bar are neglected in the numerical model. Instead, time-dependent nodal force is adopted as the boundary condition input at the end of the incident bar. The spiral fibres and coarse aggregates of different diameter ranges are generated with random location and orientation, with the avoidance of overlapping among fibres, aggregates and specimen boundaries (Chen et al. 2015). Fig. 5 gives an example of the developed SFRC specimen.

Mesh Convergence

To find the optimal mesh size that gives accurate numerical simulation results with efficient use of computational time, mesh convergence tests are carried out. The mesh sizes of 0.14 mm, 0.28 mm and 0.56 mm are considered in the mesh convergence tests. The incident stress wave in mesh convergence tests has the same shape as that in Fig. 3a, but a slightly lower peak of 55 MPa. According to Eqs. 1 and 2, the dynamic splitting tensile strengths are directly related to the transmitted stress wave. Therefore the simulated transmitted stress waves are compared. Moreover, the crack opening velocity of the tested specimen in dynamic splitting tensile tests is an important parameter to evaluate the crack control capability of the material. In numerical simulation, the Y velocity histories of the nodes with the maximum absolute Y coordinates, Points A and B as indicated in Fig. 5, are recorded to track the crack opening velocity. The numerically simulated crack opening velocities with different mesh sizes are also compared in mesh sensitivity analysis. The comparison of transmitted stress wave and crack opening velocity with different mesh sizes are illustrated in Figs. 6a and 6b, respectively. As shown, numerical simulation using mesh size of 0.28 mm gives very similar results compared to that with 0.14 mm mesh whereas the analysis using mesh size of 0.56 mm gives apparently different prediction of transmitted stress and crack opening velocities. Considering the accuracy and the efficiency in simulation, the finite element model with mesh size of 0.28 mm is used in this study.
Comparison of Experimental and Numerical Results

The incident stress wave in Fig. 3a is used in the simulation to validate the developed numerical model. The comparison of stress histories from test and simulation is given in Fig. 7. It can be seen that the results from the test and numerical simulation match well. The numerical simulation gives reliable prediction of the responses, especially accurate peak transmitted stress as it is directly related to the splitting tensile strength, of SFRC specimen under dynamic splitting tension in SHPB tests.

Parametric Simulations

To investigate the influence of volume fraction of spiral steel fibres on the DIF of SFRC materials, specimens with 1%, 2% and 3% spiral fibres are developed as shown in Fig. 8, and parametric simulations are carried out. The input stress waves in parametric simulations have the same duration but different peak stresses so that the strengths of SFRC specimens with different volume fractions of spiral fibres under different strain rates can be obtained.
Fig. 9 gives the obtained DIFs from simulations considering different volume fractions of spiral fibres. It can be seen that the DIFs of spiral fibre reinforced concrete specimens are sensitive to strain rate. This is because 1) the strength of concrete matrix is dependent on strain rate (Hao et al. 2013), and 2) the loading rate influences the pull-behaviour of steel fibres from concrete matrix (Banthia and Trottier 1991, Kim et al. 2009). Moreover, it is found that DIFs are dependent on the volume fraction of spiral fibres. This is because of the contribution to the specimen strength from individual fibres. The more fibres in the concrete mixture, the higher splitting tensile strengths the specimen will gain.

**DISCUSSIONS AND CONCLUDING REMAKRS**

Previous studies have indicated the superiority of using spiral steel fibres to reinforce concrete material and improve the ductility, crack control capability, impact load resistance and energy absorption capacity. A series of dynamic splitting tensile tests by means of SHPB are described and results presented in this study. A mesoscale model with distinctive consideration of mortar matrix, coarse aggregates and spiral fibres is developed and numerical simulations are carried out using 2D plane stress model. Mesh sensitivity analysis indicated that 0.28 mm mesh is able to yield satisfactory simulation results while assuring efficient computational effort. The numerical model is demonstrated to be able to accurately predict the behaviour of SFRC specimen in SHPB splitting tensile tests. SFRC specimens with 1-3% spiral fibres are considered in the parametric simulations. It is found that the DIFs of SFRC material are dependent on both the strain rate and fibre content.

It should be noted that different distributions of coarse aggregates and spiral fibres inevitably influence the simulation results to a certain extent. Besides, simulations in the present study are carried out with 2D plane stress model. Future studies with intensive numerical simulations with 3D mesoscale model considering randomly distributed coarse aggregates and fibres will be carried out to study the influences of random fibre and aggregate distributions on the SFRC material properties.

**ACKNOWLEDGMENTS**

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**REFERENCES**