Effect of steel fiber on the shear transfer strength across a crack in reactive powder concrete

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Abstract
In structural concrete members that have geometrical discontinuities, the type of failure is called direct shear failure when there is no; the same member may change its response when the load arrangement is changed. This kind of failure is related to the cracks along the plane where the loaded member slides along the stationary support system and cracks are perpendicular to the axis of the member. Numerical analysis on push-off specimens were conducted in this study to investigate the shear strength in reactive powder concrete, which has cementitious compositions. The validation of the material and geometrical model to check the efficiency of the constitutive model to simulate the behavior of shear strength of RPC was achieved through comparison with the experimental result of previous work. The effects of volume fraction, aspect ratio, shape of steel fibers on the shear strength were considered to be the variables of the study. The data analyzed showed that the increase in volume fraction of steel fiber from 0% to 0.5% resulted in an increase in the shear strength of RPC by 40.3%, while, an increase in the volume fraction of steel fiber from 0% to 1.5% increased the shear strength of RPC by 140.3%. Using hook ended steel fiber increased the shear strength of RPC by 62.5%. Furthermore, the shear strength of RPC increased by 49.8% when the aspect ratio increased from 75 to 100. The stiffness and ductility of RPC members increased when the volume fraction, aspect ratio increased and provided shape of steel fiber.

Keywords
Shear strength, reactive powder concrete, and numerical analysis.

1. Introduction
Reactive powder concrete (RPC) is a cementitious material that has higher axially tensile and compressive strength in comparison with the normal strength concrete (NSC). The density of RPC is higher than that of NSC and it does not have coarse aggregate. However, the cementitious compositions of RPC cause brittle failure in tension or compression, therefore steel fibers were added [1].

Direct shear strength of concrete between interfaces of two parts needs to be included in the design consideration. The type of failure as not in direct shear represented by sliding one part with respect to the other. An example of the direct shear strength is concrete corbel, beam-column joint,…etc. Many researchers made efforts to study the shear strength mechanism. They believed that the shear strength of normal concrete was based on the contribution of friction and aggregate interlock [1,2,3]. In 1966 Birkeland and Birkeland [4] studied the aggregate interlock mechanism as the dominate variable that
affects the shear strength of concrete. They proposed shear resistance model for uncracked normal strength concrete. The basic of this model was considered in the provision of ACI 318-2014. Cement paste-aggregate adhesion and dowel action were the parameters considered in shear resistance of NSC [5]. Dilation of shear that considered to contribute to shear strength was studied by Wang et.al [6]. Numerous investigations have been made to understand the shear strength behavior with various empirical formulas for calculating the shear strength capacity [7,8,9]. Al-Quraishi [10] investigated experimentally direct shear strength of fiber reinforced normal concrete and reactive powder concrete. The influence of volume fraction of steel fiber, concrete compressive strength, shear reinforcement ratio on direct shear strength were studied. Furthermore, shear-slip behavior, shear capacity and modes of failure were also investigated. The results showed that the shear strength increased when using RPC instead of NSC in constructing the specimen.

According to the knowledge of the author, the research has been conducted experimentally to present the behavior of direct shear strength of RPC. This study provides numerical study to the effect of steel fiber on the direct shear capacity in RPC.

2. Objective of this study
The main goal of this study was to investigate the effect of several parameters as: volume fraction, aspect ratio, shape of steel fiber on the shear strength of RPC.

3. Push-Off Test Specimens
The push-off specimen used in this numerical analysis consists of two blocks connected together in inverted position. The concentrated load at the top and bottom of the specimen is applied directly on the contact area between two blocks to produce pure shear stresses. These specimens were tested experimentally by Al-Quraishi et al [10]. A detailed dimension of push-off specimen is shown in figure 1. To avoid any unwanted modes of failure and to produce a pure shear failure, the tested specimens had reinforced the two blocks with longitudinal and lateral rebar as indicated in figure 1.

4. Mix proportions of RPC
A mix proportions of RPC proposed by Hirschi and Wombacher, 2012 [ as listed in table 1] was adopted in this study and the target compressive strength of cubes was 105 MPa.

| Table 1. Mix proportion of RPC. |
|-------------------------------|
| Material | Weight (kg/m³) |
|---------|---------------|
| Cement  | 810           |
| Silica fume | 186.3        |
Figure 2 shows the steel fiber types that were used in this study. The first type is the hook end steel fiber having a length of 80 mm and diameter of 0.35 mm. The second type (straight fiber) has a length of 15 mm, diameter of 0.15 mm and aspect ratio of 100. The third type (straight fiber) has a length of 20 mm, diameter of 0.25 mm and aspect ratio of 75.

![Type 1](image1)
![Type 2](image2)
![Type 3](image3)

**Figure 2. Steel fiber used in this investigation**

5. **Stress-Strain curve of RPC**

The stress-strain curves of RPC in tension and in compression are needed to simulate the behavior of RPC numerically by Finite Element Method (FEM). The shape of steel, aspect ratio and volume fraction of steel fiber are considered in cube and cylinder samples to draw the stress-strain curves. Cubes of 15 x 15 x 15 cm were used to measure the compressive strength and draw compressive stress-strain concrete. Cylinders of 100 x 200 mm were used to measure the tensile strength and draw the tensile stress-strain curve of concrete. The compressive strength of concrete was tested according to BS1881-116 and the tensile strength of concrete was tested according to ASTM C496. The vertical displacement in cubes and horizontal displacement in cylinders were measured through dial gauges to draw the stress-strain curves in both tension and compression. Figure 3 shows the specimens under tests and figure 4 shows the stress-strain curves for each type of specimen.
Variables Consideration

A total of five push-off specimens were considered in this numerical analysis. The influence of steel fiber content on the shear strength was studied on three specimens (S1-fib0%, S2-fib0.5% and S3-fib1.5%). The shape of steel fiber was investigated by comparisons of two specimens (S2-fib0.5% and S4-hook0.5%). Finally, the influence of aspect ratio of steel fiber was studied on two specimens (S2-fib0.5% and S5-aspect0.5%). The characteristics of the analyzed specimens are summarized in Table (2).

Table 2. Characteristics of Analyzed Specimen.

| Specimens  | Volume fraction of steel fiber (%) | shape of steel fiber | Aspect ratio of steel fiber | $f'_c$ (MPa) | $f_t$ (MPa) |
|------------|-----------------------------------|----------------------|----------------------------|--------------|-------------|
| S1-fib0%   | 0                                 | Straight             | 75                         | 95           | 2.6         |
| S2-fib0.5% | 0.5                               | Straight             | 75                         | 98           | 3.5         |
| S3-fib1.5% | 1.5                               | Straight             | 75                         | 105          | 8           |

Figure 4. Stress-Strain curve of concrete in tension and in compression for each variable
7. Finite Elements Analysis
In FEA, the non-linear analysis including both material and geometric equations is adopted here. ABAQUS software program were used in this investigation.

7.1 Material Model
Concrete damage plasticity is the material model used in this investigation. Concrete behaves as a brittle material and the dominate type of failure is the crushing in compression and cracking in tension zone. By increasing the confining pressure on concrete, the dominate type of failure transfers to quasi-brittle material which is controlled by the fracture energy required to generate micro-cracks.

The bilinear stress-strain relationship with hardening as shown in figure 5 is used to model the steel reinforcement.

In the nonlinear analysis of reinforced concrete tested specimens, the smeared crack approach for modeling of the cracks is adopted with fixed crack model. In this model, the crack is formed when the principal stress exceeds the tensile strength. It is assumed that the cracks are uniformly distributed within the material volume.

![Stress-strain curve of reinforcement](image)

Figure 5. Stress-strain curve of reinforcement

7.2 Geometrical Modeling
In ABAQUS, a 3D isoperimetric brick element with 16 nodded elements was used to represent the concrete in push-off specimen. Deformation increments of 0.01mm was used to apply the load on the specimen. Figure 6 represents the geometric model of the specimen used.

![Geometric model of the specimen](image)
Figure 6. Geometrical model of the specimen

8. Calibration of Numerical Model
To check the validity of the material and geometrical model adopted in the present study, ABAQUS results were calibrated with the stress-slip relation presented in reference [10] for RPC. Figure 7 shows a good agreement between the numerical and experimental result. Through the ultimate shear capacity, the ratio of numerical to the experimental result was 0.91. Also, the shear stress-slip curve followed the experimental results.

Figure 7. Experimental and numerical shear stress-slip curve of RPC

9. Numerical Analysis
A very good prediction of numerical model to the experimental shear strength and to the behavior of shear stress-slip behavior leads to study the variables mentioned above.

In the numerical analysis, the maximum axial compression force applied at the top and bottom of the specimen is divided by the area of shear plane to produce shear stress of RPC as follows:

\[ \tau = \frac{P}{b \times h} \]  

Where; \( P \): maximum axial compressive force, \( b \): width of shear plane, and \( h \): height of shear plane.

9.1 Influence of steel fiber content
The influence of steel fiber content on the direct shear strength was studied by changing the volume fraction of steel fiber from 0% in S1-fib0% specimen to 0.5% in specimen S2-fib0.5% and to 1.5% in specimen S3-fib1.5%. The analysis shows that an increase in volume fraction of steel fiber from 0% to 0.5% increased the shear strength of RPC by 40.3%, while, an increase in the volume fraction of steel fiber from 0% to 1.5% increased the shear strength of RPC by 140.3%, the results are shown in table 3. The reason for that is - the shear strength in the direction perpendicular to the applied load depends mainly on the tensile strength of concrete, which increased by increasing the volume fraction of steel fiber.

From figure 8, the behavior of all specimens till 0.5mm slippage was the same, after that, the stiffness of the specimens increased with increasing the steel fiber content.
Table 3. Effect of volume fraction of steel fiber on the shear strength of RPC.

| Specimen    | Steel fiber content (%) | Maximum load (KN) | Shear strength (MPa) | Percentage of increasing in shear strength (%) |
|-------------|-------------------------|-------------------|----------------------|-----------------------------------------------|
| S1-fib0%    | 0                       | 105.61            | 3.52                 | -                                             |
| S2-fib0.5%  | 0.5                     | 148.25            | 4.94                 | 40.3                                          |
| S3-fib1.5%  | 1.5                     | 253.89            | 8.46                 | 140.3                                         |

Figure 8. Shear stress-slip behavior of S1-fib0%, S2-fib0.5% and S3-fib1.5% specimens

9.2 Influence of Shape of Steel Fiber
The influence of end anchorage of steel fiber was studied by comparing the shear strength of push-off specimen constructed with end anchorage steel fiber (S4-hook0.5%) with the shear strength of push-off specimen of straight steel fiber (S2-fib0.5%). The results showed that using hook ended steel fiber increased the shear strength of RPC by 62.5%, as shown in Table 4.

From figure 9, before cracking, the end anchorage of steel fibers does not affect the behavior of shear stress-slip curve. Meanwhile, after cracking, the stiffness and ductility of the tested specimen increased, and the type of failure changed from brittle to ductile.

Table 4. Shape of steel fiber effect on shear strength of RPC.

| Specimen   | Steel fiber content (%) | End anchorage of steel Fiber | Maximum load (KN) | Shear strength | Percentage of increasing in shear strength (%) |
|------------|-------------------------|------------------------------|-------------------|----------------|-----------------------------------------------|
| S2-fib0.5% | 0.5                     | Straight                     | 148.25            | 4.94           | -                                             |
| S4-hook0.5%| 0.5                     | Hook                         | 240.91            | 8.03           | 62.5                                          |
Influence of Aspect Ratio of Steel Fiber

To investigate the effect of aspect ratio of steel fiber on shear strength of RPC, the comparison is made between the specimen S2-fib0.5% which has aspect ratio of 75 with the specimen S5-aspect 0.5% which has aspect ratio of 100. The results show that the shear strength of RPC increased by 49.8% when the aspect ratio increased from 75 to 100, as shown in table 5. These findings agree with the basic that an increase in the shear strength with increase in the tensile strength of concrete, which depends on the aspect ratio.

From figure 10, the pre-cracking behavior of the shear stress-slip curve was the same till 0.4 mm slippage, after that, the stiffness of the specimen increased with the increasing aspect ratio and the specimen shows more ductile behavior.

**Table 5.** Effect of aspect ratio of steel fiber on shear strength of RPC.

| Specimen       | Steel fiber content (%) | Aspect ratio | Maximum load (KN) | Shear strength (MPa) | Percentage of increasing in shear strength (%) |
|----------------|-------------------------|--------------|-------------------|----------------------|---------------------------------------------|
| S2-fib0.5%     | 0.5                     | 75           | 148.25            | 4.94                 | -                                           |
| S5-aspect0.5%  | 0.5                     | 100          | 222.16            | 7.40                 | 49.8                                        |

**Figure 9.** Shear stress-slip behavior of S2-fib0.5% and S4-hook0.5% specimens

**Figure 10.** Shear stress-slip behavior of S1-fib0.5% and S5-aspect0.5% of RPC.
10. Conclusion

- An increase in the volume fraction of steel fiber from 0% to 0.5% increased the shear strength of RPC by 40.3%, while, an increase in the steel fiber content from 0% to 1.5% increased the shear strength of RPC by 140.3%.
- Using hook ended steel fiber instead of straight steel fiber increased the shear strength of RPC by 62.5%.
- The shear strength of RPC increased by 49.8% when the aspect ratio increased from 75 to 100.
- Before the first crack, the shear stress-slip behavior is the same for all specimens because the steel fiber is not yet activated. After that when the first crack appeared at the post-cracking stage, the steel fiber is activated and stiffness and ductility is increased by aspect ratio, end anchorage and volume fraction of steel fiber.

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