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Experimental study on shear properties of aligned steel fiber reinforced cement-based composites

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HIGHLIGHTS

- The shear reinforcement of aligned steel fibers is higher than random steel fibers.
- The shear strain obtained by the method of DIC has both advantages and disadvantages.
- Shear load-displacement and stress-strain curves are obtained.

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ABSTRACT

Shear behavior is one aspect of the fundamental mechanical performance of steel fiber reinforced cement-based composites. In order to investigate the influence of fiber orientation on the shear properties of steel fiber reinforced cement-based composites, the shear behavior of aligned steel fiber reinforced cement-based composites (ASFRC) and conventional steel fiber reinforced cement-based composites with random distribution of steel fibers inside (SFRC) was experimentally compared using modified double-plane direct shear tests. In the tests, the shear displacement was recorded by LVDT and shear strain was determined by digital image correlation analysis (DIC). Then the shear load-displacement and stress-stain curves of the two series specimen were obtained. The results show that when the volume fraction of steel fiber in the range of 0.8–2.0%, the alignment of steel fibers causes the increase in shear strength, modulus and toughness up to 40%, 30% and 50%, respectively. A major reason is that when the steel fibers are aligned the number of the fibers bridging the cracked shear section is increased and the fiber spacing is reduced.

1. Introduction

The shear strength is one of the fundamental mechanical properties of concrete. Some structural elements, e.g., beam-column joints and shear walls, are prone to shear failure. There is necessity for concrete to have better shear resistance. However, as a brittle material, the capacity of deformation of concrete is poor and the shear failure is always sudden [1]. Incorporating steel fiber is one of the solutions to improve the weakness of brittle of concrete [2–6]. The properties of steel fiber reinforced concrete have been investigated extensively in the past decades and it is well recognized that incorporating of steel fiber into concrete can greatly improve the tensile (flexural, splitting) strength, toughness, cracking resistance, durability, energy absorption, etc. [7–12]. It is also found that the addition of steel fibers can partially replace the transverse reinforcement [13–15].

In steel fiber reinforced concrete, steel fibers are randomly distributed in both location and orientation. When subjected to shear load, some of fibers don't take effect due to the detrimental orientation. If all or most of the steel fibers in concrete have the orientation favorable to resist shear load, the shear performance of the steel fiber reinforced concrete will be improved significantly. Mu, etc. [16] have successfully prepared an ASFRC with orientation effective coefficient of steel fibers in concrete more than 0.90. The higher orientation effective coefficient leads to the higher probability of a single fiber intersecting a section and hence reinforces the matrix more effectively [17]. It is proved that ASFRC has advantage in uniaxial tension and bending strength compared with SFRC [16,18]. It is expected that the shear properties of the cement-based composites with the same aligned steel fibers should be better than those of the random steel fibers.

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In this paper, the main objective is to disclose the advantage of steel fiber reinforced cement-based composites in shear performance. The shear strength and shear load-deformation curves of ASFRC and SFRC were experimentally tested by modified double-plane direct shear tests. To record the shear displacement and strain accurately, both LVDT monitoring and digital image correlation analysis were employed. Then the shear stress-strain relationship and shear toughness are determined. The reinforcing mechanism of aligned steel fibers on the shear resistance of cement-based composites was analyzed as well.

2. Test methods

2.1. Specimen preparation

The cement used in the test was an ordinary Portland cement P•O42.5. The sand was natural river sand with fineness modulus of 2.6. The steel fiber was a round straight steel fiber with equivalent diameter of 0.5 mm and aspect ratio of 60. The prism specimens with size of 100 mm × 100 mm × 300 mm were prepared for shear tests. A basic cement-based composite mix with water to cement ratio (W/C) 0.36, cement to sand ratio 1:2 was designed. In the specimen preparation, the steel fiber was incorporated with volume fraction (V_f) of 0.8%, 1.2% and 2.0%, respectively (Table 1). The specimens of ASFRC with aligned steel fibers and SFRC with random steel fibers were prepared at the same time. In the preparation of ASFRC specimens, exactly the same procedures as described in [16] were followed by applying uniform electromagnetic field to fresh mixture. The specimens were demolded after 24 h indoor condition and then cured in fog room with temperature of 20 ± 2 °C and RH 95% or above to the age of 28 d for tests.

2.2. Test method

To ensure the shear failure of the specimen occurs at a certain section, instead of at a random section, and also to avoid the local compression failure in the loading area of the specimen, a thin slit with 10 mm deep and 2 mm wide was sawed along the perimeter at the shear section of the specimens. To measure the relative displacement, two linear variable differential transformers (LVDTs) were installed on the two opposite side surfaces of the specimen (Fig. 1). The test was performed on a 1000kN universal test machine. In the tests, the loading speed was set to be 0.1 mm/min. The shear load was recorded by a load transducer. The shear strength was calculated using Eq. (1),

$$\tau = F_{max}/\,2b_{eff}h_{eff} \quad (1)$$

where τ is the shear strength, MPa; F_{max} is the average peak shear load, N; b_{eff} is the effective width of the shear section, mm; h_{eff} is the effective height of the shear section, mm.

The shear load-displacement and stress-strain curve are important for the assessment shear properties. To obtain the shear load-displacement curves of the specimens, LVDT monitoring on was applied one side surface as shown in Fig. 1. To get the shear constitutive relationship, the shear strain was determined by digital image correlation method (DIC) on the other side surface of the specimen. In the DIC analysis on the other side surface of the specimen, the surface was painted to white as background; and then by spraying black paint onto the white background speckles were formed with high-contrast foreground. In the progress of double-plane direct shear test, a digital camera was used to record the deformation of the side surface by taking photos every second with resolution of 1.92 million pixels. After tests, the shear strain was computed by tracking the change of the speckle. As shown in Fig. 2, part of the speckles area on the shear surface was selected, where the speckles changed with the deformation of the shear section and the shear strain was calculated by analyzing the relative position of the speckles.

The shear strain can also be determined according to the deformation of a single speckle. The principle can be described using Fig. 3. For any shape, the change of its centroid is the embodiment of its overall change. So, for each speckle, the change of its centroid also reflects the deformation of the whole speckle. As shown in Fig. 3, when the speckle is divided into two parts with equal area, the variation of the centroid of the two regions also reflects the deformation of the respective region. Thus, before and after the deformation, the angular strain between the two centroids is the shear strain corresponding to the whole speckle. In Fig. 3, a speckle is divided into two parts with equal area by using a dashed line parallel to the y axis. Before deformation the centroids of the two parts are points A and B, respectively, and after deformation the centroids are points A' and B', respectively. The angular strain between AB and A'B' is the shear strain of the whole speckle.

This method is also applicable to the determination of shear strain according to the relative position of two or more speckles. In this investigation, based on the photos taken in the tests, the shear crack was identified, and then the shear strain of the specimen was calculated according to the deformation of speckles near the crack.

In the process of DIC analysis, the first order displacement gradient method [19] of digital image analysis is used, and the coordinates of point A and B after deformation are (Eq. (2)),

$$\begin{cases} x_A' = x_A + u_A \\ y_A' = y_A + v_A \\ x_B' = x_A' + \Delta x + u_x\Delta x + u_y\Delta y \\ y_B' = y_A' + \Delta y + v_x\Delta x + v_y\Delta y \end{cases} \quad (2)$$

where $\Delta x = x_B - x_A$; $\Delta y = y_B - y_A$; x_A and y_A are the coordinate of point A before deformation; $x_{A'}$ and $y_{A'}$ are the coordinate of point A after deformation; x_B and y_B are the coordinates of point B before deformation; $x_{B'}$ and $y_{B'}$ are the coordinates of point B after deformation; u_x, u_y, v_x, and v_y are the first-order displacement gradients of point A; u_A is the displacement of point A in x direction; v_A is the displacement of point A in y direction.

The shear strain of the speckle satisfies the Eq. (3),

$$\gamma = \frac{\Delta y}{\Delta x} - \frac{\Delta y'}{\Delta x'} \quad (3)$$

where γ is the shear strain of the speckle; $\Delta x' = x'_B - x'_A$; $\Delta y' = y'_B - y'_A$.

According to the shear strain of speckles in the shear section, the average value of the shear strain in the region is taken as the shear strain of the whole shear section.

Table 1
Mix proportion of steel fiber reinforced cement-based composites.

Water to cement ratio	Volume fraction of fibers (%)	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Steel fiber (kg/m^3)	Plasticizer (kg/m^3)
0.36	0.8%	237	659	1318	62.4	6.00
	1.2%	236	656	1312	93.6	6.67
	2.0%	234	651	1302	156	8.33