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The variation of flow-dependent tensile behavior in radial flow dominant placing of Ultra High Performance Fiber Reinforced Cementitious Composites (UHPFRCC)

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A B S T R A C T

The present research is chiefly concerned with the flow-dependent tensile behavior of Ultra High Performance Fiber Reinforced Cementitious Composites (UHPFRCC). The situation of fabricating a thin square-sectioned UHPFRCC plate with radial flow was considered. Both experimental and analytical study was performed to verify the validity of the analytical approach for prediction of the tensile behavior. In analytical work, the variation of the fiber orientation distribution according to the flow was first explored, and the consequent variation of the tensile behavior was estimated. The combination of the resistance by the fibers and the matrix, considering a probability density distribution for the fiber orientation distribution across crack surface, was considered in the analysis. The rotational movement of fiber in the fluid cementitious matrix was also taken into account. The comparison between the experimental and analytical results demonstrated the effectiveness of the proposed analytical approach.

1. Introduction

Even though direct tensile tests are increasingly adopted to unveil the strain hardening behaviors of some brand-new fiber reinforced cementitious composites [1], the tensile properties of fiber reinforced concrete are generally estimated by means of flexural tensile tests because of several difficulties in direct tensile tests. The design criteria for the tensile behavior of fiber reinforced concrete are normally determined based on flexural test results with analytical approach, such as inverse analysis, or with empirical formulae. However, as noted in several early studies, fiber reinforced concrete, especially with high strength, shows a large variation of tensile strength and behavior [2], which is considered to be mainly due to the large variation in the fiber orientation distribution according to the filling method [3–7]. Moreover, it was already demonstrated that the fiber orientation distribution is dependent on the flow characteristics and distance, especially for steel fiber reinforced cementitious composites [8–10]. Therefore, it is not reasonable to consider the tensile behavior obtained from flexural tests with small size specimens as representative behavior for application to structures.

Typical fiber reinforced concrete contains coarse aggregates, which restrain free rotational movement of fibers in fresh condition to some degree. Low fluidity also disturbs the rotational movement. The variation of fiber orientation distribution is therefore a little limited along the flow of fresh concrete. However, ultra high performance fiber reinforced cementitious composites (UHPFRCC), which does not have coarse aggregates and is composed of very fine particles (less than 0.5 mm in diameter) with 2 vol.% of steel fibers (length 13 mm and diameter 0.2 mm), exhibits homogeneity and high fluidity. Given these properties, the rotational movement of fibers and the variation of the fiber orientation distribution according to the flow of the fresh composites should be deeply considered. The fiber orientation distribution inevitably have a significant influence on the tensile behavior of the composites.

It can be also said that structural design based on the tensile behavior obtained from laboratory experiment can lead to serious risks in safety or economical disadvantage. Considering these problems, UHPFRCC structural design has thus been performed with consideration of real tensile characteristics via two major approaches. The first is to establish a design on the basis of the tensile properties which are determined after testing numerous specimens cored on different locations in a prototype structure. The second is to apply a sufficiently high safety factor on the results obtained from the laboratory test if there is no investigation

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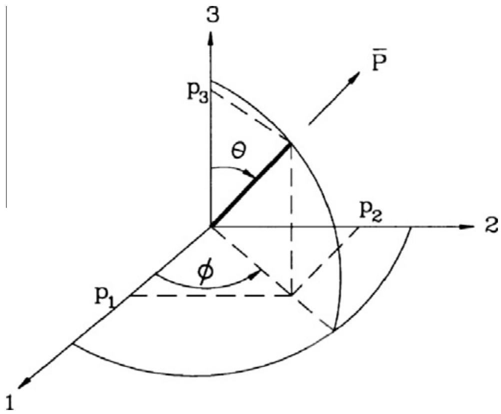

Fig. 1. Coordinate system to define the fiber orientation.

Table 1
Mix proportion of UHPFRCC.

Relative weight ratios to cement						Steel fiber (V_f^a, %)
Cement	Water	Silica fume	Fine aggregates	Filler	Superplasticizer	
1.00	0.25	0.25	1.10	0.30	0.018	2%

[a] Fiber volume expressed as a volumetric ratio to the whole volume.

on a prototype structure [11,12]. However, the former requires investigation every time whenever a new structural shape or placing method is applied, and thus imposes a considerable burden of time and efforts, whereas the latter is undesirable in terms of economic efficiency.

In order to realize economic as well as healthy production of UHPFRCC, it is helpful to induce flow direction so as to obtain the required fiber orientation distribution according to the purpose of the structure at placement, and to exactly predict the tensile behavior considering the fiber orientation distribution.

The authors have proposed an analytical model to predict the tensile behavior considering fiber orientation distribution in UHPFRCC [13]; and performed numerical simulation for the variation of fiber orientation during flow molding as well [14]. We are herein trying to extend our investigation to verify the proposed methodology and show the usefulness in an actual manufacturing of structure with flow molding process. In this paper, the scenario of fabricating a thin square-sectioned UHPFRCC plate with radial flow from the center was considered.

2. Methodology for analytical approach

2.1. Fiber orientation vs. tensile behavior

The tensile behavior can be predicted separately in two stages: pre-cracking and post-cracking tensile behavior. Pre-cracking tensile behavior is expressed using the mechanism of elastic shear transfer between the matrix and the fiber in the composites and the rule of mixture is normally applied to estimate the mechanical properties of the composite materials. Taking into account the effect of fiber orientation and length, the tensile stress of the composites based on the rule of mixture can be written in the equation

$$\sigma_c(\varepsilon_c) = \sigma_m(\varepsilon_c)V_m + \eta_l\eta_\theta\sigma_f(\varepsilon_c)V_f \quad (1)$$

where ε_c is the tensile strain in the composites; $\sigma_f(\varepsilon_c)$ represents the tensile stress at a strain ε_c in the fiber and $\sigma_m(\varepsilon_c)$ is for the matrix; V_m and V_f indicate the volume fraction of the matrix and the fiber, respectively; η_l represents the length efficiency coefficient and η_θ means the fiber orientation coefficient.

η_l is determined with the consideration of fiber packing, fiber length and volume fraction, and the material properties of both matrix and fiber [15,16]; η_θ can be expressed by Eq. (2) if the geometrical arrangement of fiber is only considered for simplicity [17].

$$\eta_\theta = \int_{\theta_{\min}}^{\theta_{\max}} p(\theta)\cos^2\theta d\theta \quad (2)$$

In Eq. (2), $p(\theta)$ is a probability density function for the fiber orientation and θ represents the angle between each fiber axis and the tensile stress direction.

Even though higher value of fiber orientation coefficient leads to slightly improved pre-cracking tensile performance, the difference is very difficult to be distinguished in experiments with the cementitious composites.

As well known, in fiber reinforced composites, the major role played by fibers is in the post-cracking domain. Post-cracking tensile behavior is expressed as the combined behavior of the resistance by the fibers and the matrix, considering a probability density distribution for the fiber orientation across crack surface and the pullout behavior of steel fiber. The resistance by the fibers can be calculated by integrating the pullout resistance of the individual fiber at the crack plane, when if assuming that all fibers are pulled out without breakage. When the pullout resistant force of a single fiber at the cracked plane is given as a function of the inclined angle of the fiber (θ), the embedded length of the fiber (l_e) and the crack opening displacement (δ), which is denoted as $P(\theta, l_e, \delta)$, the fiber bridging stress of the composites at a given crack opening displacement can be obtained from Eq. (3) [18].

$$\sigma_b(\delta) = \frac{4V_f}{\pi d_f^2}\int_0^{\frac{\pi}{2}}\int_0^{\frac{l_f}{2}} P(\theta, l_e, \delta)p(l_e)p(\theta)\cos\theta dl_e d\theta \quad (3)$$

where $p(l_e)$ is probability density functions for l_e and $p(\theta)$ is for θ as mentioned earlier. For three-dimensional random distribution of fibers, $p(\theta)$ is equal to $\sin\theta$ and $p(l_e)$ is given as $2/l_f$. l_f denotes the fiber length.

Fig. 2. UHPFRCC placing and flow directions.