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Effect of fiber content variation on the strength of the weakest section in Strain Hardening Cementitious Composites (SHCC)

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HIGHLIGHTS

- A numerical approach is proposed which distributes fibers randomly.
- The bridging law in a section is correlated with all nearby fibers and thus changes continuously.
- A size effect on the fiber content variation between sections is revealed.

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ABSTRACT

Fiber dispersion, especially the variation of fiber content among different sections of a member, is a major factor that influences the mechanical properties of fiber composites. In this study which focuses on Strain Hardening Cementitious Composites (SHCC), a numerical approach is proposed to compute the bridging laws in various sections of a specimen with varying content of randomly distributed fibers. Through the analysis, the weakest plane which governs the ultimate strength and saturated crack spacing is determined. This weakest plane is then investigated for members of different sizes, and a size effect is revealed.

1. Introduction

Strain Hardening Cementitious Composites (SHCC) is a kind of material featured by strain hardening behavior associated with multiple cracking up to high tensile strain [1–4]. For strain hardening and multiple cracking to occur, the fibers in a cracked section need to have a load carrying capacity well beyond that at first cracking, so cracking can occur in other sections when loading is increased [5–7]. The fiber dispersion in SHCC, which affects the strength at various sections, is hence a crucial factor to achieve the desired mechanical performance. In existing theories, integration over all fibers is performed to obtain the crack bridging behavior from the debonding/pull-out behavior of single fibers, and uniform distribution of fibers is normally assumed [1,8]. However in reality, due to the difficulty in dispersing fibers uniformly in the cement paste during mixing [9–12], inevitable inhomogeneity in fiber distribution will cause the fiber number to change from one section to another.

Research has recently been conducted to study the dispersion of fibers within a single section [13–16]. A fiber dispersion coefficient was proposed to evaluate the non-uniformity of fiber distribution within an individual section. However, the difference of fiber numbers between different sections, which determines the variation of bridging laws in different sections and governs the multiple cracking behavior, has not been investigated. To enhance ductility and durability, saturated multiple cracking with small crack spacing and opening is desirable. However, if the peak bridging strength of the weakest section is lower than the cracking strength of most sections, these sections cannot crack so saturated multiple cracking cannot be achieved. The strength of the weakest section is therefore a governing factor that determines the mechanical properties of SHCC, and it is strongly affected by the variation of fiber content between sections. It should be noted that the bridging law of the weakest section is dependent on all nearby fibers crossing it that are centered at neighboring sections, which actually correlates with the fiber content in a longitudinal zone extending by half the fiber length on each side of the weakest section.

In this study, a dumbbell shaped specimen is divided into a number of sections and the fibers are distributed into the specimen

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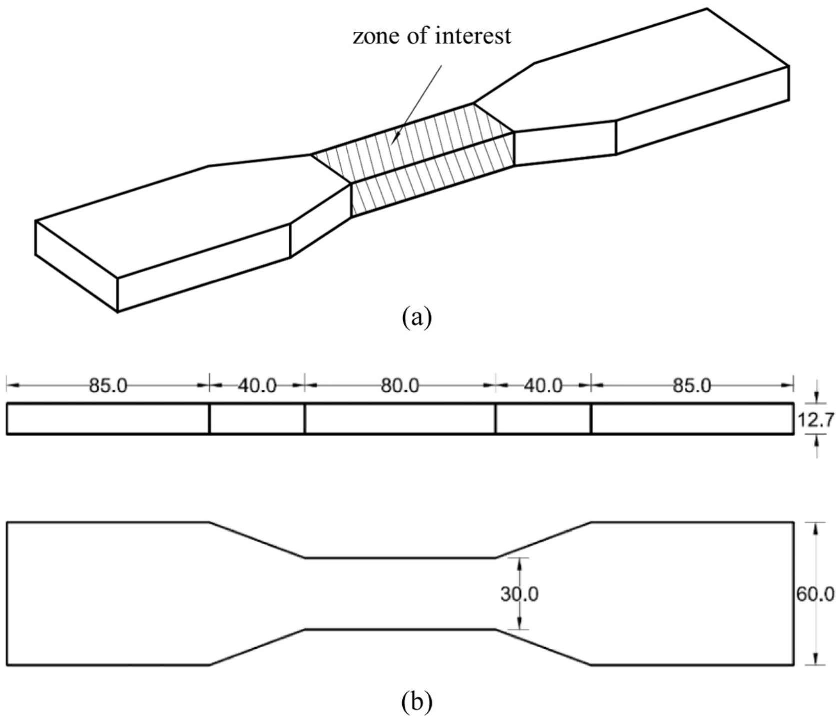

Fig. 1. a) Interest zone and; b) dimensions of a dumbbell shaped specimen.

with their midpoints randomly located in the sections. The bridging effect of randomly distributed fibers centered at a section on neighboring sections is then investigated. In a subsequent step, the bridging law of each section is computed by summing the bridging effect of fibers in all neighboring sections and the weakest section can be determined. The effect of member size on the ratio between the bridging strength of the weakest section and strongest section is then studied.

2. Variation of fiber numbers between sections

A mathematical approach to estimate the effect of fiber content variation in different sections is employed in this study. As the dumbbell shaped specimen is commonly used for assessing the tensile performance of SHCC [17], the zone of interest (Fig. 1a) in a dumbbell shaped specimen is investigated. The cross-section is 30 mm × 12.7 mm and the zone length is 80 mm as shown in Fig. 1b. For a section near the ends of the zone, the bridging behavior is also affected by fibers with midpoints lying outside the zone, as long as the fiber can intersect with the section. In other words, fibers with centers within half of the fiber length beyond each end of the zone should be considered in the analysis. In the case where 12 mm long fibers are employed, a zone with length of 92 mm (6 mm + 80 mm + 6 mm) is therefore investigated.

In PVA-SHCCs, normally 2% volume fraction of PVA fibers are added and the diameter for the fibers d_f is 39 μm. The number of fibers with midpoints that fall into the zone is thus calculated as:

$$N_{total} = \frac{30\text{ mm} \times 12.7\text{ mm} \times 92\text{ mm} \times 2\%}{\pi(39\ \mu\text{m}/2)^2 \times 12\text{ mm}} = 48904 \quad (1)$$

The 92 mm long zone is cut into 1840 sections along its longitudinal direction (with a spacing of 0.05 mm between sections). When each individual fiber is mixed into the specimen, the position of its midpoint can be taken to follow a random distribution, where a random number from −119 to 1720 (1840 in total) is generated to assign a section for the fiber midpoint to be located. The number of fibers with their midpoints lying in every one of the 1840 cross-sections can then be determined and the result is shown in Fig. 2. It can be seen that the number is changing discontinuously from one section to the next as there is no correlation between the numbers of fibers that fall into adjacent sections. However, the bridging stress at a crack is affected by all nearby fibers whose midpoints are 'close enough' to that particular section and will hence vary continuously along the specimen. This aspect will be demonstrated in the following section.

3. Variation of bridging laws between sections

Assuming there are n_A fibers with midpoints at a Section A, their bridging effect on an opened crack at Section B, which is at a distance of z (smaller than half fiber length) from Section A, is investigated. A schematic diagram is drawn in Fig. 3. At this crack, the embedded length of a fiber with its midpoint at Section A is given by:

$$l_e = \begin{cases} l_f/2 - z/\cos\theta, & \text{when } z < (l_f/2)\cos\theta \\ 0, & \text{when } z < (l_f/2)\cos\theta \end{cases} \quad (2)$$

where l_f is the fiber length and θ denotes the fiber inclination angle. At a crack opening of δ, the contribution of these fibers to the crack bridging stress at Section B is obtained by integration over inclination angle:

$$\sigma_{B-A} = n_A \int_0^{\arccos\left(\frac{2z}{l_f}\right)} P_b(\delta, \theta, l_e) \sin\theta d\theta \quad (3)$$

The upper limit acrcos($2z/l_f$) is the critical angle beyond which the fibers cannot reach section B. sin θ is the probability for fibers in 3D random orientation to lie at inclination θ [5]. $P_b(\delta,\theta,l_e)$ stands for the bridging force in a single fiber when the crack opening is δ. To compute this, the stress-crack opening relation from [18] is adopted. For a fiber perpendicular to the cracked plane, the