Construction and Building Materials 173 (2018) 359–367

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental determination of crack-bridging constitutive relations of hybrid-fiber Strain-Hardening Cementitious Composites using digital image processing

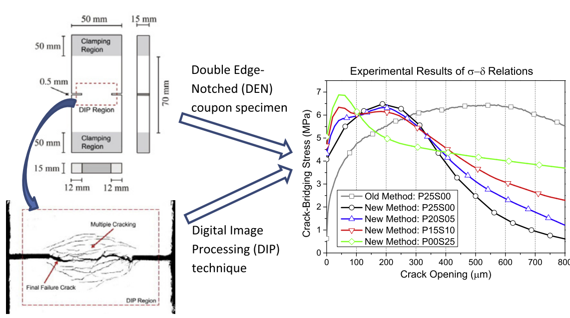
Jing Yu [a], Cong Lu [b,*], Yixin Chen [a], Christopher K.Y. Leung [a]

[a] Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong Special Administrative Region, China
[b] Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing 210096, China

HIGHLIGHTS

- Hybrid-fiber SHCCs with PVA/steel fibers at a fixed total fiber fraction are studied.
- Limitation of commonly-used methods for obtaining σ-δ relations of SHCCs is discussed.
- A new test method to obtain satisfactory σ-δ relations for SHCCs is proposed.
- Hybrid-fiber SHCCs have the potential to show smaller crack widths than PVA-SHCCs.
- Positive synergetic effect is observed between PVA and steel fibers in SHCCs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 December 2017
Received in revised form 14 March 2018
Accepted 21 March 2018
Available online 24 April 2018

Keywords:
Strain-Hardening Cementitious Composite
Hybrid fibers
Crack-bridging constitutive relation
Pseudo-strain-hardening index
Digital image processing
Crack detection

ABSTRACT

This study explored the potential benefits of employing hybrid polyvinyl alcohol (PVA)/steel fibers in Strain-Hardening Cementitious Composites (SHCCs) at the single-crack level. Due to the multiple-cracking nature of SHCCs with tight crack spacing, direct measurement of the crack-bridging constitutive relation for a single crack is challenging, as any reasonably sized physical gauge length would cover a number of subparallel cracks, therefore masks the true value of crack opening. In this study, a new test method using Digital Image Processing to capture the opening of a single crack in a double edge-notched specimen under tension was proposed. Compared to the commonly-used single-crack tension method, the proposed method obtained a more satisfactory crack-bridging relation for SHCCs. With the test results from the new method, it was found that hybrid-fiber SHCCs have the potential to show smaller crack widths than PVA-SHCCs, and the hybridization of PVA/steel fibers results in a positive synergetic effect at the single-crack level under uniaxial tension. In addition, the pseudo-strain-hardening indices were used to evaluate the potential of achieving tensile strain-hardening of hybrid-fiber SHCCs. The findings of this study can support future designs of SHCCs for the experimental determination and model calibration of the crack-bridging relations, and provide a better understanding of fiber hybridizations in SHCCs.

1. Introduction

Concrete is the most widely used construction material in the modern world, but plain concrete fails in a brittle manner with

* Corresponding author.
E-mail addresses: jyuad@connect.ust.hk (J. Yu), conglu@seu.edu.cn (C. Lu), ychenbu@connect.ust.hk (Y. Chen), ckleung@ust.hk (C.K.Y. Leung).

https://doi.org/10.1016/j.conbuildmat.2018.03.185
0950-0618/

little warning. Research on the fracture of composites has led to the development of Strain-Hardening Cementitious Composites (SHCCs) that exhibit high tensile train capacity and multiple cracking behaviors [1–3]. Typical tensile stress-strain curve and crack development under tension of such material are shown in Fig. 1. At the ultimate state under tension, the strain of SHCCs can reach 3–8%, with the crack width typically self-controlled to less than 100 μm before final failure [4–16]. With high ductility, excellent crack control ability as well as high toughness, SHCCs have clear advantages over normal concrete for many structural applications [17–20].

In common SHCCs, only polymer fibers such as high-modulus polyethylene (HMPE), polyvinyl alcohol (PVA) and high tenacity polypropylene (HTPP) have been employed, as high tensile train capacity can be achieved with a relative low fiber volume fraction (no more than 3%) [4]. To further enhance the mechanical performance of SHCCs, the utilization of hybrid polymer/steel fibers as reinforcements has been investigated by several researchers [21–29]. With a suitable combination of different fibers, the hybridization has the potential to improve the mechanical properties of hybrid-fiber SHCCs, compared to mono-fiber composites [21–29].

The tensile crack-bridging (σ-δ) constitutive relation shows the dependence between the tensile crack-bridging stress σ transferred across a crack and the corresponding crack opening δ. It should be pointed out that the difference between the crack-bridging (σ-δ) relation and the fiber-bridging relation (Fig. 2) is the bridging effect provided by the matrix, which should be quite small as very fine particles are used in making SHCCs. For SHCCs, the σ-δ constitutive relation is of elementary importance, since it links the material microstructure (micro-scale) to the composite tensile strain-hardening behavior (macro-scale) [30]. Therefore, the σ-δ constitutive relation is the result of a delicate balance of multiple factors, including the matrix properties, characteristics of the fiber/matrix interface, as well as fiber properties, orientation, distribution and interaction. The experimental study of the individual effects of these factors is very complex, as they interact in a highly coupled manner. Micromechanical modeling of the σ-δ relation of SHCCs was first carried out by Li and Leung [1], then modified by Maalej et al. [31] as well as Lin et al. [32], and recently updated by Yang et al. [33]. For model verification, a reliable testing method to determine the σ-δ relation is required. Various researchers have explored the σ-δ relation of SHCCs, but the accuracy of the testing methods (in terms of the measured tensile stress or crack opening) is debatable. This aspect is further discussed in Section 2.

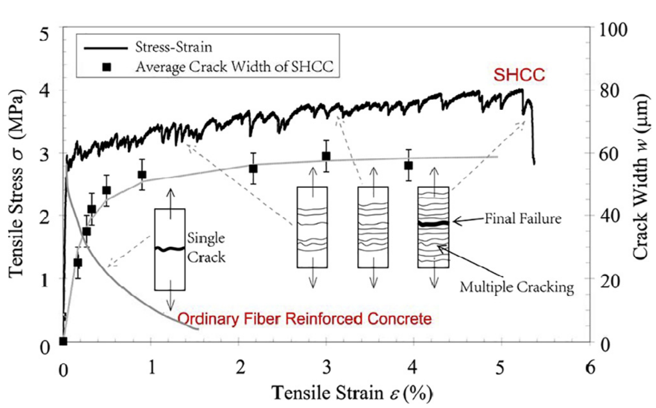


Fig. 1. Typical tensile stress-strain curve and crack width development of SHCCs (Modified from Li [4]).

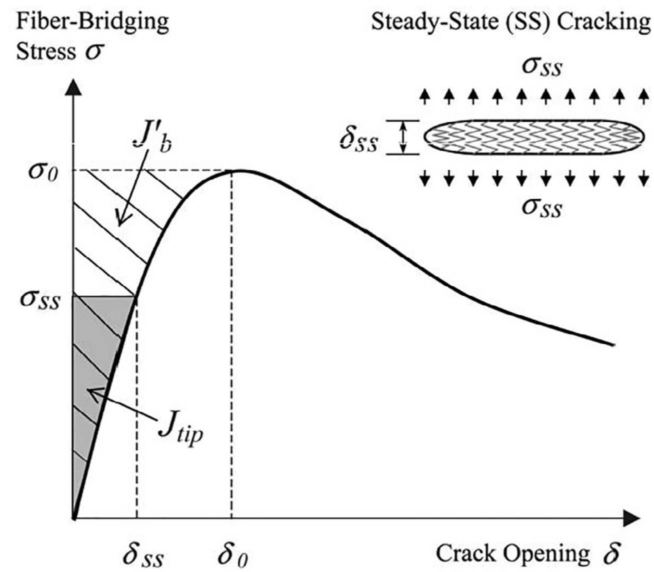


Fig. 2. Typical fiber-bridging constitutive relation of SHCCs (modified from Li [4]).

The objective of this study is to experimentally explore the mechanical properties at the single-crack level of SHCCs with a fixed total volume fraction (2.5%) of hybrid polyvinyl alcohol (PVA) and steel fibers. To obtain satisfactory single crack-bridging curves of SHCCs, a new test method to determine the σ-δ relation is firstly proposed, and the results are compared to the results from the commonly-used test method. With the test results from the new method, the synergetic effect of hybrid PVA/steel fibers and the potential of the hybrid-fiber system to achieve tensile strain-hardening were evaluated.

2. Limitations of commonly-used methods on determining crack-bridging relation for SHCCs

2.1. Direct test method

To initiate and maintain a single crack, the stress fields have to be locally intensified by using geometrical constrictions. This approach is commonly adopted for detecting the σ-δ constitutive relation of tension-softening fiber reinforced concrete, using different test methods in direct tension (e.g., [34,35]). For direct measurement of the σ-δ relation for SHCCs, the single-crack tension (SCT) method was first proposed by Yang and Fischer [36] and further explored by Pereira et al. [37], where a thin round notch was inserted in the middle of the specimen to reduce the cross-section and force the specimen to fail in that particular section (Fig. 3). As reported by several researchers [12,38–40], using extensometers or linear variable differential transformers (LVDTs), a crack width of over 500 μm was experimentally recorded at peak stress for PVA-SHCCs. However, investigation of un-notched SHCC specimens under uniaxial tension discloses that the width of the localized crack before final failure is much smaller than 500 μm [4]. Since SHCCs undergo tensile strain-hardening after cracking occurs at the notch, the transferred tensile stress by the fibers to the region adjacent to the notch can result in additional cracking, as experimentally observed [40,41]. These additional cracks can contribute to the measured crack opening, as any reasonably sized physical gauge length (from an extensometer or LVDT) is often much larger than the crack spacing of SHCCs, which can be as small as 1–2 mm [4]. For SHCCs, the SCT method can therefore properly capture the development of σ, but not the δ. The comparison of the