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Flaw characterization and correlation with cracking strength in Engineered Cementitious Composites (ECC)

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ABSTRACT

Engineered Cementitious Composite (ECC) is a class of fiber reinforced composites showing strain hardening behavior. The variation of cracking strength among various sections of a tensile specimen is a key factor governing the cracking behaviors of ECC. This study employs X-ray computed tomography method to investigate the correlation between cracking strength and flaw distribution in ECC, and identifies the dimensions of pre-existing flaws to be the main influencing parameters. Specifically, the largest cross-sectional area of a flaw perpendicular to stress can be well correlated with cracking strength. To validate the observation, the classic model on first crack strength is modified in this study by adopting a refined fiber bridging relation and employing iterated crack profile. The simulated cracking strength vs flaw size relation is in good agreement with test results. This study provides an improved understanding of the multiple cracking mechanism in ECC, which is useful for material design.

1. Introduction

In view of the quasi-brittle nature of conventional cementitious composites, fibers are incorporated to increase material toughness and to provide ductility. Engineered Cementitious Composite (ECC) is a class of fiber reinforced composites that can reach high tensile strain of several percent while carrying increasing tensile load [1–4]. With the formation of multiple cracks, the crack width in ECC materials can be controlled to under 80 μm [5]. Unlike much wider cracks in conventional concrete, such fine cracks have little effect on the material's resistance to water/chemical transport and they may even exhibit self-healing [6,7]. Compared to concrete members, the durability of ECC members is significantly enhanced [8–10]. With these outstanding properties, various applications of ECC to provide seismic loading carrying capacity, deformability and durability of full scale structures have been proposed and implemented [11–16].

The tensile ductility of ECC have been observed to have higher variability than other properties. High ductility is associated with saturated cracking, where fine cracks at close spacing are formed uniformly along the tensile specimen. However, unsaturated cracking, with clusters of cracks interspaced by un-cracked specimen segments, is commonly observed. This phenomenon is mainly due to the large variation of cracking strength among different parts of the tensile member, as segments with higher cracking strength may not undergo cracking before ultimate failure occurs in sections with lower strength. The full deformation capacity of ECC may not be realized. The variation in cracking strength can be attributed to: 1) distribution of matrix inherent flaws and 2) variation of fiber reinforcement content [17]. Between the two factors, it is considered by many researchers that the flaw distribution dominates [1,17]. This will also be supported by the modeling results in the present study.

Among the methods to investigate the distribution of flaw size [18,19], prior experimental study [20] examined the flaw size distribution by cutting a tested specimen into a number of sections. As shown in Fig. 1 [20], each section was photographed, after which the images were subjected to thresholding in the Image-J software to distinguish the flaws from matrix. The maximum flaw size at each section was then determined. However, as cutting with a saw causes a loss of several millimeters in specimen thickness, the size of the same flaw measured from the sections on the two sides of the cut is usually different. This generates considerable error in determining the flaw size. Moreover, only a limited number of sections can be practically cut so the section with the largest flaw may not be truly located. The section cutting method is therefore not sufficiently accurate for the quantitative correlation of composite cracking strength to flaw distribution. A better method needs to be introduced.

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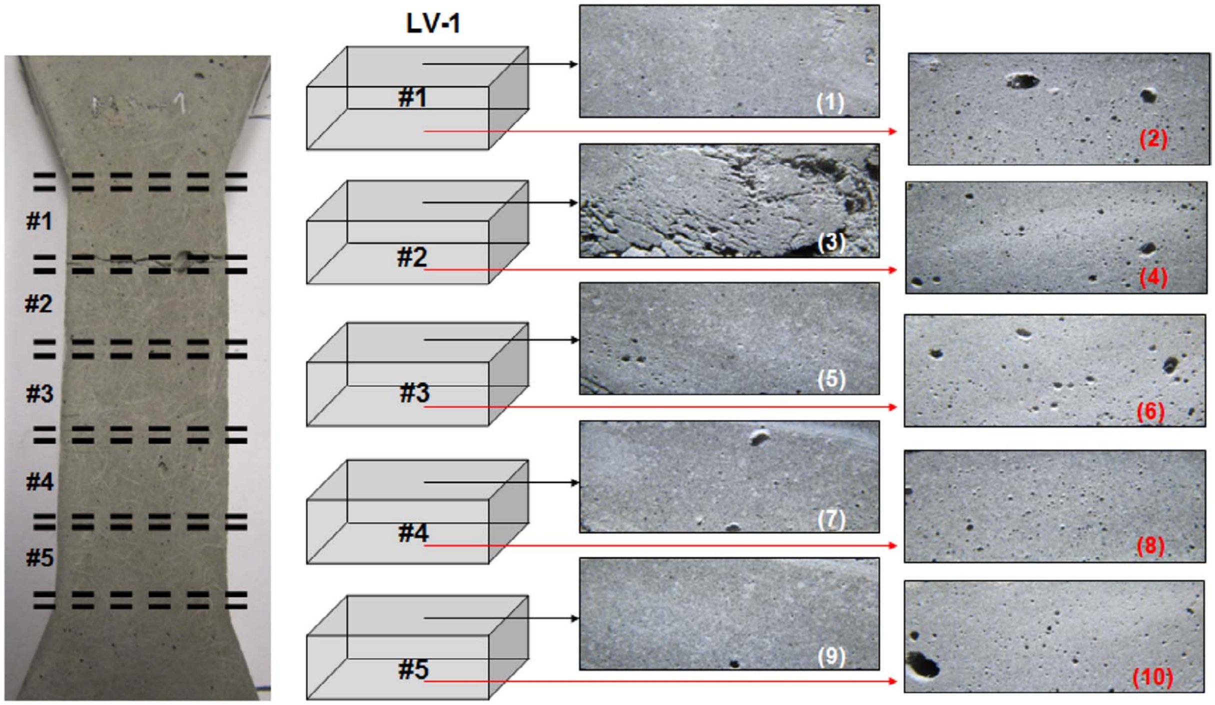

Fig. 1. Sections of a specimen cut and analyzed [20].

X-ray computed tomography (μCT) is a modern technique most widely used in medical science. It can reconstruct the 3D model of a sample without destroying the original, by collecting 2D projections at different angles around an axis of rotation [21]. When an X-ray beam illuminates and transmits through the sample, the beam intensity will be attenuated after absorption by the different phases and components of the material [6]. Generally, a unit with higher density will absorb more X-ray. The intensity of the transmitted X-ray beam is recorded by a digital detector and the value of the attenuation coefficient for each voxel is transformed into CT numbers according to the Hounsfield scale [22]. After the collection of raw data, a set of gray-scale 2D cross sections that depicts the density distribution within the sample can be constructed. These 2D images can then be used to reconstruct the 3D model of the internal structure. There have been several studies using this technique to map the internal flaw structure or cracking in composites. In [23], X-ray micro-tomography was used to characterize the internal geometry of flaws and micro-cracks in fiber-reinforced polymer laminates. In [6], X-ray computed micro-tomography is adopted to derive three-dimensional morphological data on micro-cracks in ECC before and after self-healing. In this study, this technique will be employed to study the correlation between flaw distribution and cracking strength in ECC composites for the first time.

The present study involves both experimental and theoretical investigations. For the experimental part, with the use of X-ray computed tomography method, the internal structure of the composites will be revealed and the size and shape of flaws are then assessed. Meanwhile, the formation time for each crack will be recorded by taking photos during the tensile test and the cracking strength of them can then be determined by locating the time points in the stress-strain curve. The flaw distribution will then be correlated with the corresponding cracking strength. For the theoretical part, a refined model for ECC cracking strength based on the classic model in [1] will be proposed. Modeling and experimental results will then be compared and discussed.

2. Experimental procedures

2.1. Materials and mix proportions

This study is aimed at evaluating the influence of flaw distribution on the cracking behavior of ECC. Specimen is therefore prepared for uniaxial tensile test. The ECC mixture used for this study was developed by the Advanced Civil Engineering-Materials Research Lab (ACE-MRL), at the University of Michigan. The mix proportion is tabulated in Table 1.

The mixing of the ECC material was conducted according to a standard procedure [24]. The fresh ECC was cast into a dogbone-shaped mould (Fig. 2) which is designed to prevent failure at the ends caused by stress concentration. The specimen was demoulded after 24 h and then cured for 7 days in a curing room with temperature of 23 ± 2 °C.

2.2. Testing with simultaneous image recording

The uniaxial tensile test was performed on a Material Testing Machine and the tensile loading was applied at a displacement rate of 0.5 mm/min. During loading, photographs of the specimen surface were taken to capture the formation of cracks. Since the cracks in ECC are very fine, especially at their initiation stage, it is desirable to achieve the highest possible resolution in the captured image. With this objective, a macro lens with magnification of 1:1 was used on a full-frame camera (model: Nikon D610) with the resolution of 6016 × 4016. Mounted on a tripod, the camera was placed in front of the MTS machine (Fig. 3). After the focus was placed manually on the sample surface, a remote timer was used to take one photograph every second, so the formation time of each crack can be captured with sufficient precision.

Table 1
Mix proportion for ECC (by weight ratio).

Cement	Fly ash	Sand	Water	Superplasticizer	Fiber
0.3	0.7	0.36	0.25	0.4%	2%