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Structural behavior prediction of SFRC beams by a novel integrated approach of X-ray imaging and finite element method

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HIGHLIGHTS

- Variability in fiber dispersions causes different flexural responses of SFRC beams.
- Flexural prediction of SFRC beams via an FE method and X-ray imaging is proposed.
- Post-cracking tensile strengths are deduced by a calibration method via FE analysis.
- Variability in fiber dispersions are considered in the FE model using X-ray images.
- Proposed method provides good agreement with experimental results.

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ABSTRACT

Several studies have revealed that the fiber distribution is usually not uniform since many parameters during the fabrication process cause different fiber distributions and orientations within individual steel fiber-reinforced concrete (SFRC) members. This phenomenon results in large scattering in the post-cracking flexural responses among the material characterization specimens. Consequently, when estimating the flexural behavior of SFRC beams, conflicting results are often obtained using only a single constitutive stress-crack opening laws to characterize the material behavior in tension without considering the different fiber distributions and orientations. In this paper, a novel integrated approach is established to estimate the flexural behavior of SFRC beams using both a finite element (FE) method and X-ray imaging. In the prediction approach, a parameter that can be determined using the measured fiber distribution properties from an X-ray image is proposed to consider the variability of the fiber dispersion in each SFRC member. A method is presented for deducing the constitutive stress-crack opening laws using an FE analysis and the proposed parameter from X-ray images. In the numerical FE method, the variability of the fiber dispersion of the individual SFRC beams is determined by identifying the stress-strain relation in each mesh based on the proposed parameter from the X-ray images. The FE method provides better prediction results of the loading capacity for the SFRC beams.

1. Introduction

Concrete is the most popular construction material in the world. However, although the most recent type of concrete, high-performance concrete, provides better performance in terms of strength and durability, it is inherently brittle and thus prone to cracking due to its relatively weak tensile strength. To overcome the shortcomings of this cementitious material, steel fibers are added to modify its mechanical behavior [1,2]. The addition of fibers into concrete up to a volume fraction of 1.5% only marginally improves its compressive strength [3–5]. The potential effects of fiber reinforcement are more pronounced in the post-cracking regime where, unlike plain concrete whose stress diminishes suddenly to zero, steel fiber-reinforced concrete (SFRC) is capable of maintaining proportional stress due to the crack-bridging stresses of the random fibers. Among other improvements, e.g., increasing the shear strength [6–9] and impact resistance [10–12], limiting the drying shrinkage cracking [13,14], and enhancing the water tightness [15,16], the primary advantage of using discrete steel fibers is to render the concrete with an enhanced residual post-cracking tensile strength and energy absorption capacity [17–27].

Due to the increased knowledge fueled by design guidelines and structural codes [28–33] and the experience gained from pilot tests

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Nomenclature

A_{Ave}	area under the computed P-δ curve by FE model using average tension-softening curve
$A_{Ave(X)}$	area under the average computed P-δ curves by FE model using X-ray image
A_{Com}	area under the computational P-δ curve of the prism
A_{Exp}	area under the experimental test P-δ curve of the prism
b	width of the prism
CMOD	crack mouth opening displacement
COV	coefficients of variation
f_t	tensile strength
F_1	load corresponding to $CMOD_1$ = 0.5 mm on the P-CMOD curve
F_3	load corresponding to $CMOD_3$ = 2.5 mm on the P-CMOD curve
f'_c	compressive strength
G_f^I	mode I fracture energy
h_{sp}	height of the prism at the notch section
l_{cs}	characteristic length
Le_i	embedded length of the i^{th} fiber
Lo_i	location of the i^{th} fiber
L_f	fiber length
MA_{Ave}	average ratio of the areas under the experimental test curves to those of the FE_{Ave} curves
$MA_{Ave(X)}$	average ratio of the areas under the experimental test curves to those of the $FE_{Ave(X\text{-}ray)}$ curves
MP_{Ave}	average ratio of the maximum loads in the post-peak region of the experimental test curves to those of the FE_{Ave} curves
$MP_{Ave(X)}$	average ratio of the maximum loads in the post-peak region of the experimental test curves to those of the $FE_{Ave(X\text{-}ray)}$ curves
N_f	number of fibers
P	load
P_{Ave}	maximum load in the post-peak region of the computed P-δ curve by FE model using average tension-softening curve
$P_{Ave(X)}$	maximum load in the post-peak region of the average computed P-δ curves by FE model using X-ray image
P_{Exp}	maximum load in the post-peak region of the experimental test P-δ curve
RNF	representative number of fibers
R^2	coefficient of correlation
SLe_i	score for the embedded length of the i^{th} fiber
$S\alpha_i$	score for the orientation of the i^{th} fiber
TN_f	total number of fibers
w	crack width or crack opening
α_i	orientation of the i^{th} fiber
α_{ave}	average orientation of fibers per cross-section
δ	deflection
ε	strain
σ	stress
ΔA	Difference between the areas under the experimental and computational P-δ curves

of large-scale SFRC structures, SFRC applications have extended from being used as partially load-bearing structures to serving as components of load-carrying structural members that are characterized by a high redundancy in which substantial redistributions in the stress can occur (e.g., shell roofs [34], suspended elevated slabs [35], and precast roof elements [36,37]). However, the application of SFRC in full load-carrying structural members with a clearly defined stress distribution (e.g., SFRC structural beams) has not been fully developed.

The well-known challenges that hinder the application of steel fibers in full load-carrying structures include the difficulties in deriving their post-cracking tensile strengths for characterizing the material behavior in tension and in incorporating them into existing prediction methods to estimate the flexural behavior of large-scale members [38–41]. Several experimental studies (e.g., [42,43]) have revealed that the post-cracking tensile strength is a material property that is significantly affected by the distribution and orientation of the embedded fibers. During the fabrication process, many parameters (e.g., the casting and vibration methods [44], boundary formwork [45], viscosity and flowability of the SFRC composites [46,47], and types and properties of the fiber [48]) cause different fiber distributions and orientations within the individual concrete members. This phenomenon results in a large scattering response in the post-cracking tensile strengths among the specimens during material characterization [27,49]. Consequently, when estimating the flexural behavior of SFRC structures, deriving unique constitutive stress-crack opening laws from material test specimens to represent the tensile behavior of structural members without considering the differences between their fiber distributions and orientations leads to discrepancies [38–41]. SFRC is an anisotropic and inhomogeneous material, and its behavior primarily depends on its unique fiber dispersion; therefore, it is necessary to consider the variability of the fiber dispersions to reliably predict the flexural behavior of SFRC members [40,41].

Recently, efforts have been made to more reliably predict the flexural behavior of SFRC beams by incorporating the effects of the fiber distribution and orientation into the analytical method and computational models. Cuha et al. [50] and Soetens and Matthys [51] modeled SFRC as a two-phased material using the 3D finite element (FE) method. The concrete was treated as a homogenous phase, while the fibers were treated as discrete entities that were randomly dispersed in the solid mesh via a Monte Carlo sampling algorithm. Although the effects of the fiber location and orientation were directly accounted for, the concrete/matrix interface was modeled using an analytical method based on experimental data of the pullout test of a single fiber (e.g., [52,53]). Consequently, the model could not account for the mutual interactions of the collective fibers, and unsatisfactory prediction results were obtained for the samples with fiber densities of 40 kg/m^3 [51]. Other researchers have used X-ray technology to obtain data on the fiber distribution properties to help estimate the flexural behavior of SFRC more precisely. Robins et al. [54] developed a simple X-ray technique using 30-mm-thick SFRC elements that were sliced from SFRC beams to determine the probability density associated with the embedded fiber lengths and orientations at the cracked section. This statistical data together with the test data of the single-fiber pullout response in [55] were used to develop the tensile stress-profile that was incorporated in a cross-section analysis to estimate the flexural behavior of SFRC beams in other companion papers [56,57]. Jones et al. [56] concluded that the inaccurate flexural predictions of prisms with a larger fiber content was attributed to the test results of single-fiber pullout responses that may not accurately represent the behavior of multiple interacting fibers in concrete. More recently, Sarmiento et al. [58] used fiber distribution data from the 3D scanning tomography of segments of SFRC beams at critical regions to formulate and incorporate two fiber parameters (i.e. orientation and volume) into a numerical method to determine the constitutive stress-strain rela-