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Application of the strut-and-tie method for steel fiber reinforced concrete deep beams

M. Moradi, M. Reza Esfahani [*]

Department of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

HIGHLIGHTS

- Simple method for designing SFRC deep beams with opening is proposed.
- The proposed method is based on behavioral modeling of SFRC beams under tension in the context of STM.
- Influence of SFRC in behavior of deep beams with opening is investigated.
- Results experimentally validate the proposed method.

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ABSTRACT

Using steel fiber reinforced concrete (SFRC) causes significant improvement in the behavior of deep beams with openings. This paper proposed a method for designing SFRC deep beams with opening, which was derived from previous studies on the behavior modeling of SFRC beams under tension and design principles of strut and tie method. To evaluate the proposed method, four large-scale specimens were used, which included two SFRC and two reinforced concrete deep beams with opening. Results of the test series illustrated the applicability of the proposed method.

1. Introduction

Deep beams serve many applications in buildings and other structures. In some cases, openings through structural members are frequently required. Deep beams, due to nonlinear strain and complex stress distributions, are classified as D-regions. Bernoulli's hypothesis cannot be applied to these members. In other words, shear deformations against bending deformations cannot be ignored in such a member.

Strut and tie method could be considered as a powerful method for the direct design of these members. STM design idealizes a deep member with concrete compressive struts connected with steel tensile ties at nodes as frictionless pins. In other words, STM reduces the complex states of stress in a simple truss, comprised of uniaxial stress paths. Those members deigned based on STM generally have limited post-peak ductility [1,2]. Choosing inappropriate truss models may result in unacceptable cracks under service loads [1]. The resulting reinforcement layouts based on this method are usually extremely complicated [3].

There are several experimental studies on using SFRC in deep beams with and without opening [3–8]. Using SFRC in such members provides a better crack control and increases first crack strength [3–8]. SFRC might cause more widespread cracks in deep beams [3]. This behavior leads to a more complete plastic mechanism upon failure, which increases the ultimate load-carrying capacity and ductility [3]. Naik and Kute [5] represent a new method based on artificial neural network to evaluate the shear strength of SFRC deep beams without web reinforcement bars, which is clearly inappropriate for SFRC deep beams with opening. There is no sufficient theoretical designing method for SFRC deep beams with opening. Using finite element methods has been the only solution to design these members in some recent studies [3,4]. Previous studies have demonstrated that the ultimate load of most deep beams designed by STM is much higher than that of the design load [1–4]. Therefore, this designing method ensures

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[*] Corresponding author at: Department of Civil Engineering, Ferdowsi University of Mashhad, P.O. Box 91775-1111, Mashhad, Iran.

E-mail addresses: mehdimoradi@live.com (M. Moradi), esfahani@um.ac.ir (M.R. Esfahani).

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the safety of structures. However, in SFRC deep beams with openings designed by try and error based on finite element analysis, the reported experimental ultimate load has been much lower than the similar RC specimens with an equal design load [3,4]. It may affect the safety of structures.

In this research, a new method is proposed to design D-regions, especially SFRC deep beams with openings. To evaluate this method, four large-scale reinforced concrete deep beams with openings were manufactured and tested. The results of the tests are compared with the valves predicted by the method.

2. Proposed method

Before explaining the proposed method, it is necessary to introduce the modeling and behavior of SFRC beams under tension.

In typical fiber volume contents, SFRC exhibits a strain softening behavior. However, degradation in load-carrying capacity is slower than plain concrete. Fibers can bridge cracks; therefore, SFRC can carry significant tensile forces across cracks (Fig. 1a). Owing to the bridging effect, SFRC has greater ductility and energy absorption than plain concrete [9]. For typical strain softening SFRC, only one crack can be formed and all further deformations are localized at this crack (Fig. 1a). In the case of the presence of steel reinforcement in SFRC beam under tension, strain-hardening as well as strain-softening behaviors is observed and multiple cracks occur in the beam (Fig. 1b). In post-cracking, SFRC beams with reinforcing bars have greater tensile stress. Accordingly, energy dissipation and ductility increase [9].

The tensile behavior models of SFRC, with and without reinforcing bars, will be reviewed in the following sections.

2.1. Tensile behavior of SFRC beam without conventional steel reinforcing bars [10]

Voo and Foster [10] proposed a method to evaluate the tensile stress of steel fibers. In this model, tensile behavior is determined by integrating the behavior of one randomly oriented fiber over a three-dimensional space. In addition, both fiber pullout and fiber fracture are considered. Based on this method, tensile stress of steel fiber in a concrete section is obtained by Eq. (1):

$$\sigma_f = K_f \alpha_f V_f \tau_b \tag{1}$$

In Eq. (1), σ_f, K_f, α_f, V_f, and τ_b denote the portion of the stress carried by the fibers, global orientation factor, aspect ratio of the fibers (length to diameter ratio of fibers), fiber volume fraction (the percentage of the fiber volume in the entire volume of SFRC), and mean fiber matrix bond stress, respectively.

With a random distribution of fibers with equal probability, any given fiber crossing a crack has a shorter embedded length between zero and $lf/2$ (lf is length of the fibers). The average value of the local orientation factor for all the engaged fibers is given in Eq. (2):

$$K_f \approx K_{ave} = \frac{1}{2} - \frac{w}{l_f} \tag{2}$$

where w is crack width. If there are no available data regarding the interfacial fiber-matrix bond stress, Voo and Foster [10] recommended using Eq. (3). In this equation, f_{ct} is tensile strength of the concrete or mortar matrix, which could be calculated according to the compressive strength of concrete (Eq. (4)).

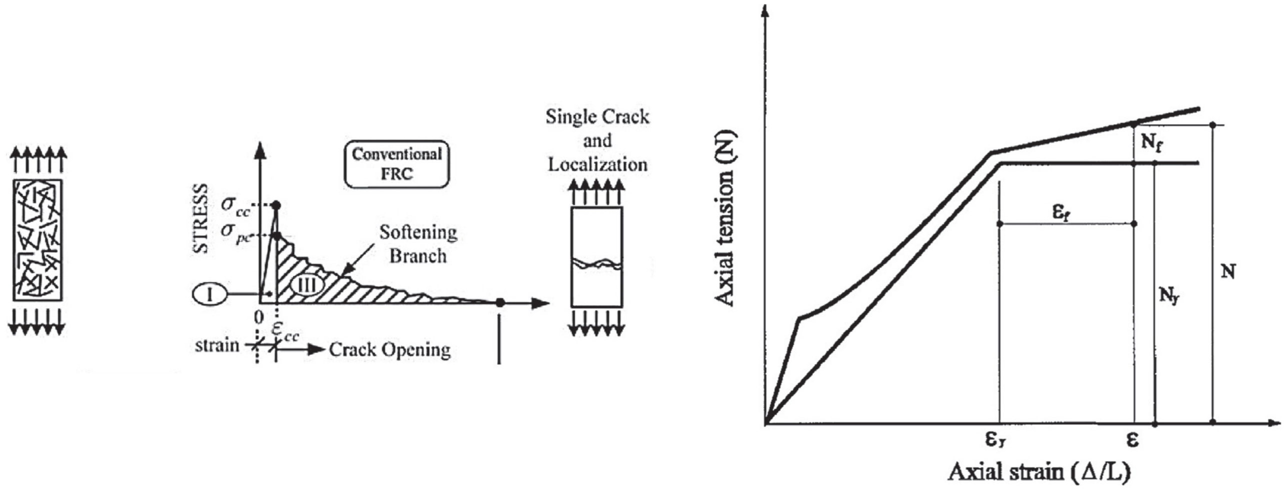
$$\tau_b = \begin{cases} 2.5 \times f_{ct} & \text{For hooked ended fibers in concrete} \\ 2.0 \times f_{ct} & \text{For straight fibers in concrete} \\ 1.2 \times f_{ct} & \text{For hooked ended fibers in mortar} \\ 1.0 \times f_{ct} & \text{For straight fibers in mortar} \end{cases} \tag{3}$$

$$f_{ct} = 0.33\sqrt{f_{cm}} \tag{4}$$

In the above equation, f_{cm} is nominal concrete compressive strength.

2.2. Tensile behavior of SFRC beam with conventional steel reinforcing bars [11]

Abrishami and Mitchell [11] proposed a model to calculate the effect of fibers on the tension stiffening behavior of the SFRC beams including conventional steel reinforcing bars. They assumed that the effect of steel fibers on tension stiffening was negligible until the reinforcing bar yielding occurred. The fibers were assumed to be effective only after the reinforcement yielding. They derived a model for SFRC in tension; the tension resisted by the fibers can be expressed by Eq. (5):



(a) Stress-strain curves of conventional SFRC [9]

(b) Typical response of SFRC with and without reinforcing bars [11].

Fig. 1. Behavior of SFRC beams under tension.