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An analytical approach to predict shear capacity of steel fiber reinforced concrete coupling beams with small span-depth ratio

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ABSTRACT

Coupling beams with span-depth ratio no more than 2.5 tend to fail in shear-dominant rather than in flexure. The use of steel fiber in reinforced concrete coupling beams is considered as an available method to improve the shear strength and seismic behavior of coupling beams. This paper proposed a theoretical approach based on strut-and-tie model to predict the shear capacity of steel fiber reinforced concrete (SFRC) coupling beams with small span-depth ratio. To develop the model, the shear transfer mechanism was studied based on the test results of steel fiber reinforced concrete coupling beams with span-depth ratio no more than 2.5. The proposed model considered the effect of span-depth ratio, steel fiber with different type and volume fraction and concrete compressive strength on shear capacity. The shear predictions of the coupling beams were compared with the experimental values, and results indicated good accuracy of the proposed model.

1. Introduction

Coupling beams with small span-depth ratio no more than 2.5 are usually used in structural design of coupled walls or core walls in order to meet the requirements of lateral stiffness and seismic performance. The most common reinforcement forms in coupling beams are conventional reinforcement with longitudinal and transverse bars, or diagonal reinforcement. A number of experimental investigations of coupling beams have been completed to study the shear behavior and seismic performance of reinforced concrete coupling beams with conventional reinforcement and diagonal reinforcement [1,2]. It is believed that the coupling beams with diagonally distributed reinforcement can resist higher shear loads and dissipate more earthquake energy than those using conventional reinforcements. However, the diagonal reinforced coupling beams are usually configured with a large amount of steel bars which brings new problems, such as construction inconvenience, especially used in the coupling beams with small span-depth ratio. The addition of the reinforcement also causes cast difficulty of concrete in beam-adjacent wall joint region [3].

Some experimental works focusing on high performance concrete coupling beams have been performed to solve this problem, such as using steel fibers to replace partially reinforcement in reinforced concrete coupling beams without diagonal reinforcements. Canbolat et al. [4] demonstrated that the use of high performance fiber reinforced cement composites could be an alternative design method for reinforced concrete coupling beams to simplify the diagonally reinforcement requirements. In his research study, ultra-high molecular weight polyethylene (PE) fibers with volume fraction 2.0% was used in short coupling beams to replace the diagonal reinforcement. It is shown that the use of HPFRCC allow a simplification of diagonal reinforcement detailing in RC coupling beams while ensuring a stable seismic behavior. Chaallal et al. [5] have conducted an experiment to study the seismic behavior of steel fiber reinforced concrete coupling beams under reversed cyclic loading for the first time. The first specimen was designed in conventional reinforcement with longitudinal and transverse bars according to standard for design of concrete structures in Canada. The transverse reinforcements used in the second specimen were reduced and replaced with steel fibers with volume fraction of 0.76%. The test results showed that the hysteresis curve of the second specimen was more plump and stable, and its energy dissipation capacity was 32% more than that of the first specimen, and it also had the higher shear capacity compared with the first one. Zhang [6] experimentally investigated steel fiber reinforced high-strength concrete coupling beams with small span-depth ratio to study the effect of span-depth ratio (from 1.0 to 2.5) and volume fraction of steel fibers (from 0.5% to 1.5%) on ductility and energy dissipation capacity. The concrete used in these specimens was C60 with end-hooked steel fiber. He stated that conventional reinforced high-strength concrete coupling beams with moderate volume fraction of steel fibers performed better in ductility and energy dissipate than those without steel fibers. Cai et al.

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[7] stated that the addition of crimped steel fibers could increase the energy dissipation and deformation capacity of reinforced concrete coupling beams when the concrete grade was C50. In his study, the pinched hysteretic response of conventional reinforced concrete coupling beams with small span-depth ratio were improved significantly when volume fraction of steel fibers increased to more than 2.0%.

Some studies considered the possibility of using steel fibers as shear reinforcement in concrete elements. The research presented by Dinh et al. [8] was aimed at experimentally investigating the behavior and shear strength of SFRC beams. Test results showed that the use of hooked steel fibers in a volume fraction greater than or equal to 0.75% could be used in place of the minimum stirrup reinforcement required by ACI Committee 318. A series of panel tests were performed to assess the effectiveness of steel fibers as a possible replacement for conventional transverse reinforcement [9]. The test results indicated that the fiber volume fraction of approximately 1.0% was required to achieve satisfactory performance in terms of shear strength. An experimental study on steel fiber reinforced concrete (SFRC) beams was presented to investigate the effect of steel fibers on shear behavior without conventional shear reinforcement, and results show that a relatively low amount of fibers could significantly improve the shear strength of concrete beams [10].

The regions that do not satisfy Bernoulli's hypothesis are referred to as Discontinuity regions (D-regions), which commonly occur at members with abrupt changes in cross section or the presence of concentrated loads. In such regions, the shear resistance is no longer uniform over the depth of the regions and cannot be modeled based on the classical beam theory. Strut-and-tie model could be considered as a useful method to design and analyze D-region members under complicated flows of loads. The main force flow in D-regions is mainly through a major compression diagonal and the failure is usually governed by crushing the diagonal compressive strut [11]. The coupling beam with small span-depth ratio is a typical example of D-region due to the complex stress distributions and nonlinear strain inside them. Such deep beam undertakes higher shear stress than normal beam and the strength is usually controlled by shear rather than flexure if the longitudinal reinforcement is used in a normal amount [12,13]. It is essential to understand the shear behavior of coupling beams with small span-depth ratio.

Strut-and-tie model design reduces the complex stress and idealizes D-regions with concrete compressive struts representing the flow of compressive stress and tensile ties consisting of reinforcing bars and the tension members, and these struts and ties are joined at nodes to represent an idealized truss [12]. Lee et al. [14] applied strut-and-tie model to coupling beams design of Burj Khalifa based on the STM procedure in Appendix A of the American Building Code Requirements for Structural Concrete 318-14 [15]. Khalifa [16] developed strut-and-tie model to account for the contribution of fiber composite in shear resistance of short coupling beams based on the experimental results. Wight et al. [17] used strut-and-tie model to analysis and design deep beams and proposed detailed design steps. Erwin et al. [18] revealed that a simple strut-and-tie model that merely satisfies force equilibrium can give similar accuracy if structural parameters are properly considered. Margherita et al. [19] proposed a strut-and-tie model to determine the shear strength of exterior reinforced concrete beam-column joints. Based on the strut-and-tie model, Perera et al. [20] developed a simple automatic procedure for predicting the shear capacity of RC beams shear strengthened with FRP, and the optimal configuration of strut-and-tie mechanism was also resolved. A strut-and-tie model was proposed by Wael [21] to estimate the shear strength of squat walls, which was more accurate and reliable than other seven sets of shear strength predictive formulas that based on the procedures provided in American code ACI 318-14 [15], the European code EC8 [22], Barda et al. [23], Hwang et al. [24], Wood [25], Sánchez-Alejandre et al. [26] and Gulec et al. [27]. The softened strut-and-tie model developed by Shyh-Jiann Hwang and Hung-Jen Lee was used in estimating the shear strength of beam column joints, deep beams, corbels and squat wall [11]. This model was derived to satisfied equilibrium, compatibility and constitutive laws of cracked reinforced concrete and emphasized the importance of the compression softening phenomenon [28].

This paper aims at proposing an analytical method for the prediction of shear capacity in steel fiber reinforced concrete (SFRC) coupling beams with small span-depth ratio no more than 2.5 based on the softened strut-and-tie model. In order to develop the model, the previous experimental results of SFRC coupling beams with small span-depth ratio are reviewed to understand the shear mechanism of such short coupling beams better. In addition, the proposed model considers the effect of span-depth ratio, steel fiber with different type and volume fraction, compressive strength of fiber concrete and horizontal and vertical reinforcement on shear strength. Then the validity and accuracy of the model are assessed by comparing predictions with experimental results.

2. Review of previous experimental results

A number of SFRC coupling beams with small span-depth ratio no more than 2.5 have been tested under lateral reverse cyclic load [7,29] according to Chinese test standard. These coupling beams were designed in conventional reinforcement form with longitudinal and transverse bars. A list of the test used is presented in Table 1. The list summarizes the main parameters and test results of specimens, and also includes the references they from. The geometry of the specimen as well as the reinforcement details are shown in Figs. 1 and 2. The key test variables were span-depth ratio (from 1.0 to 2.5), compressive strength of fiber concrete (from 40.5 Mpa to 80.7 MPa) and volume fraction of steel fibers (from 0.5% to 2.5%).

One feature of these specimens can be concluded from the test results summarized in Table 1 that most of SFRC coupling beams with small span-depth ratio tend to behave shear dominant failure as diagonal tension mode and diagonal compression mode. The shear diagonal compression failure was characterized by crushing of the concrete at diagonal section. This failure mode occurred when the specimen was provided with sufficient transverse reinforcement to suppress shear failure along the diagonal crack, otherwise shear diagonal tension failure will take place if the fiber concrete in diagonal section could resist more compressive stress.

Regarding specimens CCB2-3, CCB2-4 and CCB2-5, it is notable that high-strength concrete was used in these specimens. The experimental results showed that the failure modes of the specimens were changed from shear failure to flexure-shear failure when the volume fraction of steel fiber increased from 0.5% to 1.0%. As the volume fraction of steel fiber continued to increase to 1.5%, the failure mode of the specimen was changed to flexure failure. The results indicated that the brittle failure behavior of short coupling beams was significantly improved with the increase of volume fraction of steel fiber, and steel fibers could effectively restrain the shear cracking development and made a significant contribution in shear resist mechanism of short coupling beams. In addition, the use of high-strength concrete, on the one hand, can avoid premature failure of concrete. On the other hand, some research conducted by Naaman [30,31] and Banthia [32] showed that the