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# UTILIZATION OF STEEL FIBERS IN DIAGONALLY REINFORCED CONCRETE COUPLING BEAMS AS ADDITIONAL TRANSVERSE REINFORCEMENTS

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The purpose of this study is to investigate the feasibility of using hooked-end steel fibers as additional transverse reinforcements such as cross ties and leg bars for diagonally reinforced concrete (DRC) coupling beams aligned vertically over coupled special structural walls. Three 1/3-scale short beams were made and tested under cyclic shear in a double curvature condition. All specimens have the same reinforcement configuration except for transverse reinforcing details and the clear span length-to-section depth ratio ($l_n/h$) of 2.0. Reinforced concrete (RC) coupling beam (RC-CB) was designed with full confinement of diagonally reinforced concrete beam section based on the seismic design provisions of the ACI 318-14 Code. To improve the constructability without sacrificing strength and ductility, the fiber contents in the FRC0.75-CB and FRC1.50-CB specimens replacing additional transverse bars with steel fibers were 0.75% and 1.50% at volume fraction, respectively. Test results revealed that additional transverse reinforcement in the diagonally reinforced coupling beams have a significant effect on the cracking and structural behaviors. For diagonally reinforced coupling beams with only hoops and without crossties and legs of hoop, the addition of steel fiber at volume fraction of more than 0.75% to concrete provides equal cracking and structural behaviors as compared to those of diagonally reinforced coupling beam with full confinement details.

*Keywords*: Reinforced concrete, Steel fibers, Transverse reinforcement, Confinement, Constructability, Ductility.

## 1 INTRODUCTION

Reinforced concrete coupled shear walls have long been used as the main lateral-load resisting elements in the medium- and high-rise buildings. These walls under earthquake attacks should retain high shear strength, high stiffness, high ductility and high-energy dissipation capacity without collapsing. The design philosophy for coupled shear walls is that the input energy during a strong seismic event should be dissipated over height of the building in the coupling beams rather than being concentrated in the base of each wall (Paulay and Santhakumar 1976).

After the 1964 Alaska earthquake, it was noted that short coupling beams should be reinforced with diagonal bar groups to satisfy the energy dissipation capacity and ductility required in the reinforced concrete (RC) coupling beams of coupled shear wall systems (Tassios *et al*. 1996). In 1999, the details of diagonal reinforcements for short coupling beams were first introduced into the America Concrete Institute (ACI) Building code requirements for structural concrete. The diagonal reinforcement detail for coupling beams in ACI 318-99 (ACI 1999) led to the difficulties of placing diagonal bar group and transverse reinforcement along diagonal bar group. In 2008, ACI 318 committee (ACI 2008) proposed an alternative detailing option confining the full beam cross section with transverse reinforcement without hoops along diagonal bar group to improve the constructability. However, diagonal reinforcement detail with full confinement also has not solved a practical difficulty of placing reinforcement bars.

Chaallal *et al.* (1996) examined the performance of steel fiber reinforced concrete (SFRC) wall/coupling beam joint under cyclic loadings. The steel fibers in the study were used to replace the hoop reinforcement in the conventionally reinforced coupling beams and the boundary element of walls. Kuang and Baczkowski (2009) investigated the effect of steel fibers on the shear behavior of conventionally reinforced coupling beams with span-to-depth ratios of 1.0, 1.5 and 2.0 under monotonic loading. Jang *et al.* (2015) studied the feasibility of replacing hoops in the DRC coupling beams under cyclic loading with hooked-end steel fibers. Kim *et al*. (2015) investigated the effect of transverse reinforcing method including the use of steel fibers on the seismic performance of DRC coupling beams. Cai *et al.* (2016) also evaluated the seismic performance of conventionally reinforced concrete coupling beams under high shear reversals. These research results indicated that the utilization of steel fibers is feasible to replace transverse reinforcement in the conventionally and diagonally reinforced concrete coupling beams under moderate chord rotation cycles. The study experimentally investigates the feasibility of replacing additional transverse reinforcement in DRC coupling beams with steel fibers.

## 2 REINFORCEMENT DETAILS FOR DRC COUPLING BEAMS

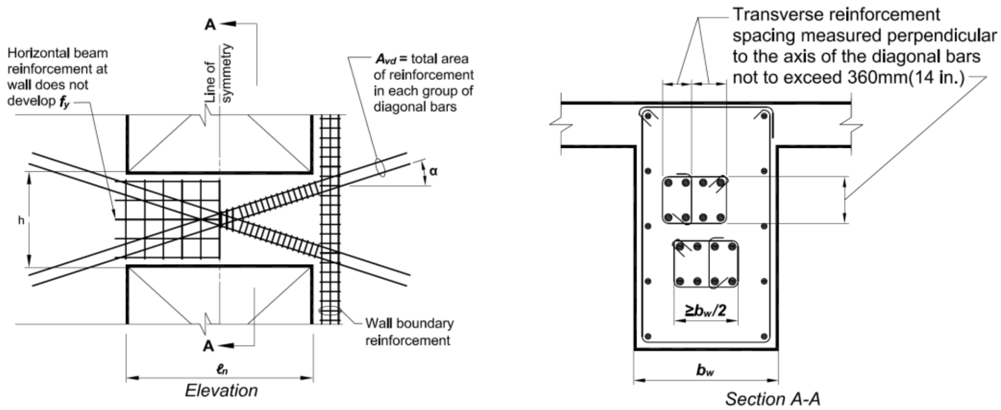
As shown in Figure 1(a), ACI 318-99 first adopted provisions for diagonal reinforcement in short coupling beams. Placing the extensive transverse reinforcement required by the code was causing construction difficulties for contractors and engineers. ACI Committee 318 has adopted simplified alternative detailing provisions for coupling beams in 2008 that permit confinement of the whole section rather than only the diagonal reinforcement shown in Figure 1(b), in an effort to simplify both design and construction.

## 3 MATERIALS AND TESTING METHODS FOR DRC COUPLING BEAMS

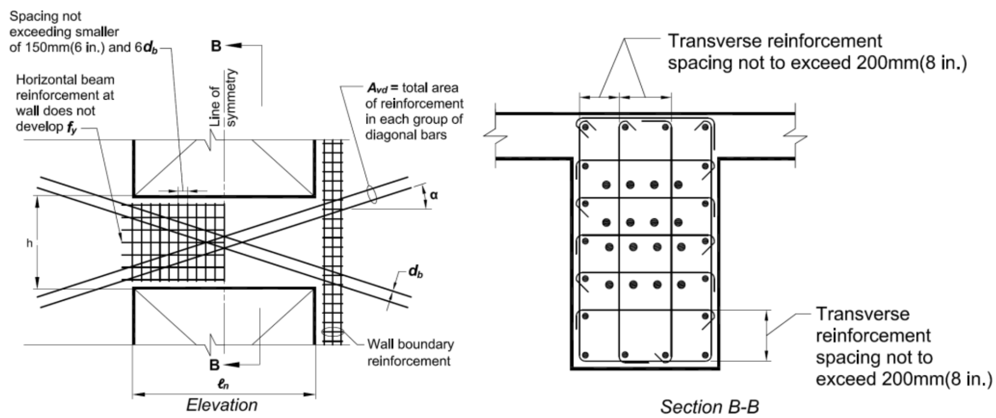
### 3.1 Materials

The steel reinforcement used for all specimens consisted of hot-rolled deformed bars for 10 mm diameter bars and cold-rolled deformed bars for 6mm diameter bars. Average values of 10 mm diameter bars obtained by coupon tests were yield strength ($f_y$) equal to 495 MPa and ultimate strength ($f_t$) of 597 MPa. 6 mm diameter bars had average yield and tensile strengths of 349 MPa and 462 MPa, respectively. No significant differences in modulus of elasticity of steel bars were shown and the average measured value was 206 GPa.

The conventional and steel fiber reinforced concrete was specified to have a maximum aggregate size of 13 mm with complete grain size distribution and water-to-cement ratio (W/C) = 0.30 were used. A conventional concrete with specified compressive strength of 70MPa was used to produce the RC-CB. Adding hooked-end steel fiber at volume fraction of 0.75 and 1.50% and cast for the two coupling beams, FRC0.75-CB and FRC1.50-CB, respectively, mixed the steel fiber reinforced concrete. The hooked-end steel fibers have widely been used and are readily available for purchase in Korea. The 0.5mm diameter fibers had a length of 30 mm resulting in an aspect ratio (*l/d*) of 60. The tensile strength of the fibers was 1,100 MPa. Compressive strengths of normal concrete, FRC0.75 and FRC1.50 mixtures are 66.5, 60.5 and 59.7 MPa, respectively.




(a) Confinement of individual diagonals.

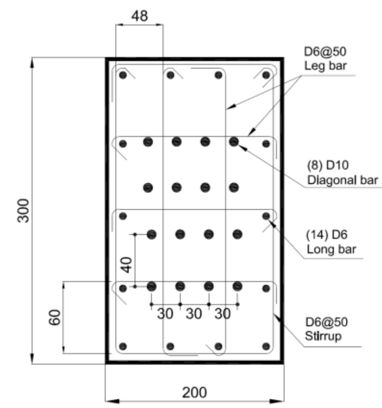



(b) Full confinement of diagonally reinforced concrete beam section.

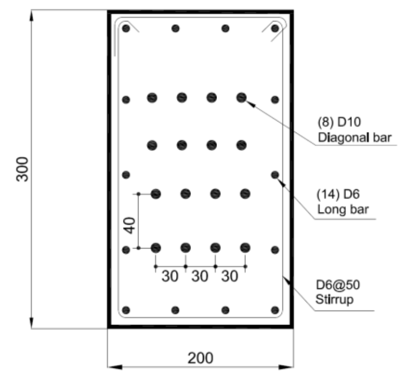
Figure 1. Coupling beams with diagonally oriented reinforcement in ACI 318-11 (ACI 2011).

## 3.2 Test Specimens

A total of three specimens were manufactured and tested up to failure to evaluate the hysteretic and cracking behaviors of DRC coupling beams replacing additional transverse reinforcements with hooked-end steel fibers. Each specimen consisted of two stiff concrete blocks simulating pier walls and a coupling beam connected to approximate mid-height of each concrete block. Figure 2 shows the reinforcement details of RC-CB and FRC0.75-CB specimens. Aspect ratio, span length to depth ratio ($l_n/h$) is 2.0. All coupling beams had a 200 mm wide by 300 mm deep cross-sections. A 6 mm diameter longitudinal deformed bar was placed on the surface of section at spacing of about 55 mm. Each specimen was reinforced with two bundles of eight 10 mm diameter deformed bars. Control RC-CB specimen was detailed in accordance with full confinement of diagonally reinforced concrete beam section specified for coupling beams in ACI318-11. FRC0.75-CB and FRC1.50-CB specimens had similar reinforcement details to RC-CB specimen except that steel fibers were replaced with additional transverse reinforcement such as cross ties and leg bars.




(a) RC-CB.




(b) FRC0.75-CB.

Figure 2. Reinforcement details of RC-CB and FRC075-CB specimens (unit: mm).

### 3.3 Testing Method and Procedure

The DRC coupling beams were placed and tested in vertical position under cyclic shear displacement using steel loading frame as shown in Figure 3. The rectangular steel frame was connected with hinge joint between lower or upper beam and vertical columns to deform the frame freely. Lateral displacement was introduced to the top beam of loading frame via a horizontal actuator with the capacity of 1,000 kN. To prevent the out-of-plane of coupling beam, guide ball jig system was supported on the top concrete block of specimen. Displacement-controlled cycles of increasing amplitude were subsequently applied at increments equal to 0.5% chord rotation up to 85% of maximum strength.

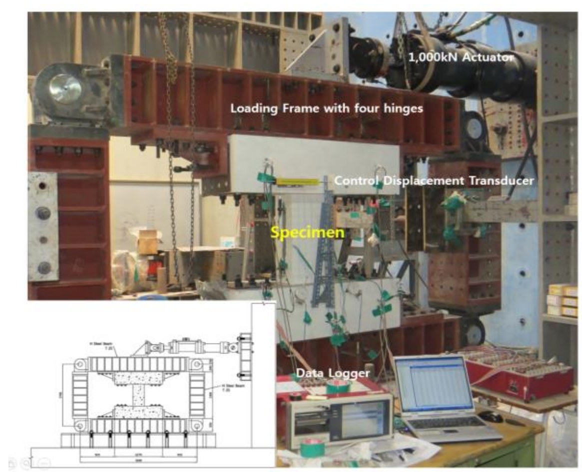
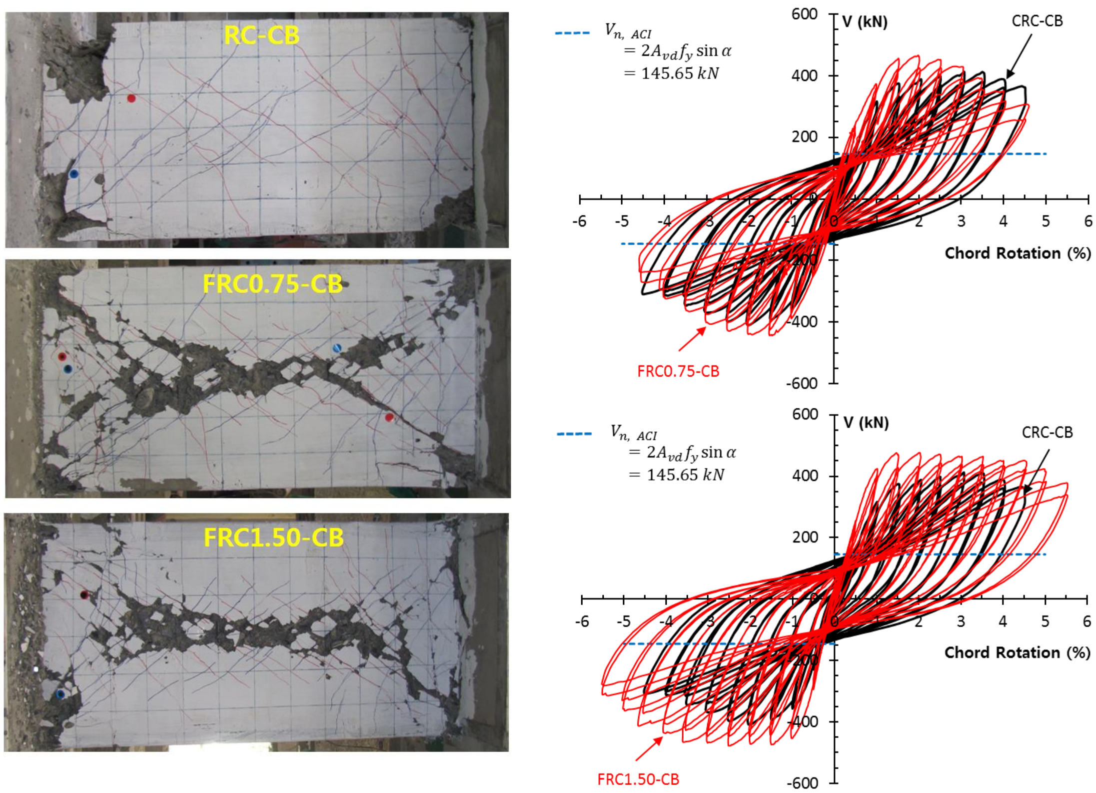



Figure 3. Test setup for short coupling beams.

The horizontal loading procedure for the specimens consisted of force-controlled cycles and displacement-controlled cycles. Force-controlled cycles at 50 and 100 kN were first introduced to examine the crack formation, stiffness loss and displacement measurement. Instrumentation consisted of eight strain displacement transducers (SDTs) and three dial gauges to measure the horizontal displacement, shear displacement and vertical displacement. Ten wire strain gauges were post at selected locations on the diagonal reinforcement, transverse and longitudinal bars.

## 4 CRACKING AND HYSTERETIC BEHAVIORS OF DRC COUPLING BEAMS

Final failure patterns of DRC coupling beams with different types of additional transverse reinforcement were provided in Figure 4(a). As shown, RC-CB failed to the spalling of web concrete and buckling of diagonal reinforcement at 4.5% chord rotation. Both FRC series specimens showed flexure-compressive failure pattern due to diagonal shear cracks and buckling of diagonal reinforcement. At initial cycles, steel fibers limited the increase of crack's width and redistributed tensile stress in the web of DRC coupling beams. The spacing of cracks in the FRC series specimens was much closer than control RC-CB specimen because of the distribution of steel fibers. DRC coupling beam (FRC1.50-CB) using 1.50% steel fibers shows the superior cracking resistance to RC-CB and FRC0.75-CB specimens. However, as the chord rotation increased, the width of diagonal cracks increased gradually due to the pullout of steel fibers.




(a) Failure mode. (b) Hysteretic responses.

Figure 4. Failure mode and hysteretic responses of DRC coupling beams.

Figure 4(b) presents the hysteretic curves of DRC coupling beam specimens tested in this study. Both hysteretic responses of FRC series specimens were compared with that of control RC-CB specimen. Figure 4(b) indicated that FRC0.75-CB exhibited improved seismic performance but the FRC0.75-CB showed a little abrupt strength reduction and pinching after 3.5% chord rotation. These results presented that even though steel fibers were effective in controlling diagonal crack opening in FRC series specimens, there was a limit to provide appreciable resistance against crack closing, which occurred pinching in the hysteretic curves of the FRC series specimens.

All DRC coupling beams showed higher shear capacities than that determined by an equation for calculating nominal shear strength specified in ACI318-11. The utilization of hooked-end steel fibers replacing additional transverse reinforcement improved the initial stiffness and shear strength of diagonally reinforced coupling beams with aspect ratio of 2.0.

## 5 CONCLUSIONS

This paper provides experimental results on the DRC coupling beams to investigate the feasibility of replacing additional transverse reinforcements, such as cross ties and leg of hoop, with hooked-end steel fibers. Based on these test results, the following conclusions were drawn;

Diagonally reinforced concrete coupling beams with aspect ratio of 2.0 and full confinement of diagonally reinforced concrete beam section as specified in the ACI 318-11 exhibits a stable response up to 3.0% without strength deterioration. FRC0.75-CB and FRC1.50-CB specimens, which were used with concretes including 0.75 and 1.50% steel fibers without additional transverse reinforcements respectively, show similar performances to control RC-CB specimen.

The utilization of hooked-end steel fibers is feasible to simplify the complicate transverse reinforcement details in the diagonally reinforced concrete coupling beams with full confinement cross section. After 3.0% chord rotation, the DRC coupling beams replacing additional transverse reinforcement with steel fibers shows more remarkable crack-damage on the web than RC coupling beam.

**Acknowledgements**

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