Effects of Matrix Ductility on the Shear Performance of Precast Reinforced HPFRCC Coupling Beams

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ABSTRACT

This paper investigates the effect of ductile deformation behavior of high performance hybrid fiber-reinforced cement composites (HPHFRCCs) on the shear behavior of coupling beams to lateral load reversals. The matrix ductility and the reinforcement layout were the main variables of the tests. Three short coupling beams with two different reinforcement arrangements and matrixes were tested. They were subjected to cyclic loading by a suitable experimental setup. All specimens were characterized by a shear span-depth ratio of 1.0. The reinforcement layouts consisted of a classical scheme and diagonal scheme without confining ties. The effects of matrix ductility on deflections, strains, crack widths, crack patterns, failure modes, and ultimate shear load of coupling beams have been examined. The combination of a ductile cementitious matrix and steel reinforcement is found to result in improved energy dissipation capacity, simplification of reinforcement details, and damage-tolerant inelastic deformation behavior. Test results showed that the HPFRCC coupling beams behaved better than normal reinforced concrete control beams. These results were produced by HPHFRCC's tensile deformation capacity, damage tolerance and tensile strength.

1. Introduction

To improve the ductility of coupling beams and to suppress particularly the shear mode of failure, several types of coupling beams have been investigated through last decades. These include diagonally reinforced concrete coupling beams (Paulay and Binney 1974, Barney et al 1977, and Galano and Vignoli 2000), RC coupling beam with rhombic reinforcement layout (Tegos and Penelis 1988), RC beams with plate reinforcement (Subedi 1989, Su et al 2005, and Su and Zhu 2005), steel I-beams (Shahrooz et al 1993, Harries et al 1995, and Park and Yun 2005), and composite beams with structural steel beams embedded in nominally reinforced concrete (Gong and Shahrooz 2001) and concrete filled steel tubes (Teng et al 1999). In experimental studies, these types of coupling beams performed better than those with conventional reinforcement. Nevertheless, these coupling beams complicate the construction and consequently the cost of the building. These drawbacks have led to the evaluation of other reinforcement alternatives and the construction method.

In common earthquake-resistant design, the reinforcement detailing of coupling beams includes the use of diagonal reinforcement. These reinforcement details, although efficient for assuring adequate behavior under large load reversals, are difficult to construct and lead to reinforcement congestion problems. Therefore, the use of HPFRCCs in coupling beams in order to eliminate steel reinforcement detailing, simplify current reinforcement requirements in coupling beams and improve structural behavior is needed. And the use of precast coupling beams can be considered in order to avoid casting problems associated with the use of regular concrete and HPFRCCs.

The objective of this study is to explore the use of HPFRCC materials as a new design alternative in

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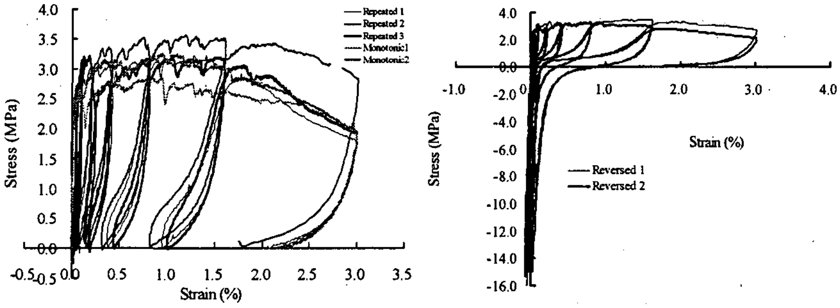
본 연구는 한국과학재단 연구비(특정기초:R01-2005-000-10546-0과 국제공동연구:F01-2005-000-10203-0)지원에 의한 연구의 일부임

coupling beams and to investigate the influence of cement composite properties, particularly strain hardening and multiple cracking, on seismic performance of coupling beams with low shear span-to-depth ratios when subjected to large displacement reversals. The investigation focuses mainly on the comparative behaviors of RC and precast HPFRCC coupling beams in terms of failure mechanism, ultimate strength, and hysteretic capabilities.



(a) Monotonic and repeated tensile response of HPHFRCC (b) Cyclic tension compression response of HPHFRCC

Fig. 1 Uniaxial tensile and compressive response of HPHFRCC

2. HPFRCC characteristics

For high performance cement composites, high performance has taken on meanings of high strength, high workability, and high durability. For HPFRCC, the qualification for high performance was first described by Naaman and Reinhardt. In this paper, a high performance fiber-reinforced cement composites was distinguished from an ordinary fiber-reinforced concrete by the unique uniaxial tensile stress strain curve. For a HPFRCC, a strain-hardening branch after first cracking must exist. The presence of this branch, and especially with a large tensile strain capacity, makes an HPFRCC different from an FRC. From this definition, high performance in HPFRCC means high tensile ductility.

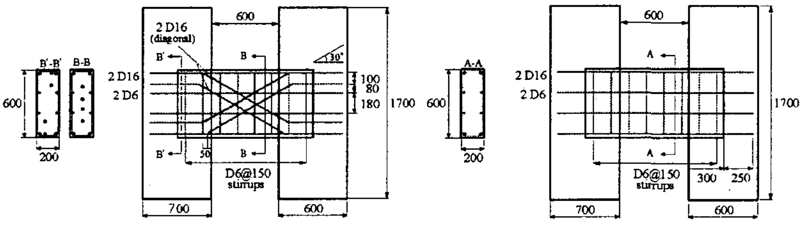
The comparison between reinforced HPFRCC and RC is based on the material properties of both cement matrices. HPFRCCs and concrete have similar ranges of tensile and compressive strength (3.25 to 3.56MPa and 44 to 57MPa, respectively).

Fig. 1 shows a typical response of composite reinforced with hybrid fibers under three loading schemes. The unloading curve softens gradually while stress is decreasing and the stiffness of the unloading curve is smaller for large displacements. The unloading curve crosses again after reaching a certain level of compressive stress because the cracks close. The reloading curve are the initial elastic unloading, crack opening with low stiffness, and increasing tensile stiffness with increasing crack opening. The tensile strain capacity shown in Fig. 1(a) and (b) is similar to the uniaxial tension test results for three schemes. Cyclic loading does not limit the tensile strain capacity of the hybrid fiber-reinforced cementitious composite used in this study.

3. Experimental program for HPFRCC coupling beams

3.1 Specimen configuration

Three large-scale coupling beams were constructed. All the specimens were of identical dimensions as shown in Fig. 2. The seismic behavior of reinforced HPHFRCC coupling beams was experimentally investigated



(a) CB1 and CB2 specimens (b) CB3 specimen

Fig. 2 Specimen geometries and reinforcement details (Unit : mm) and compared to RC using an approximately 3/4-scale coupling beam. In this investigation, the variables that were the object of the study were the type of cementitious material used in the coupling beam and the main reinforcement layout. Two coupling beam specimens with diagonal reinforcements have the same dimensions and reinforcement details but different cement composites (normal concrete and HPHFRCC). The inclination of the diagonal reinforcement is given by the angle.

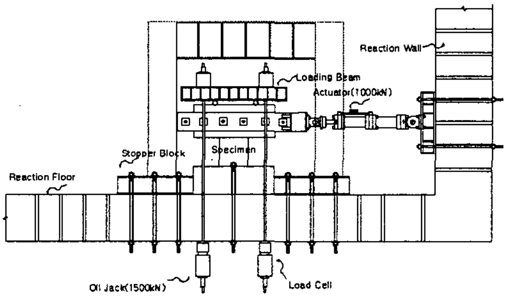


Fig. 3 Test set-up and loading application

3.2 Tets setup

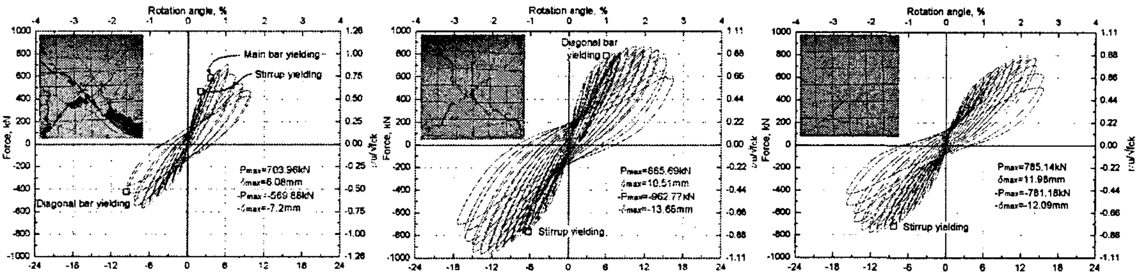
Each test specimen models a single coupling beam and the connected portions of the two stiff RC members representing structural walls. Two members were attached at the bottom and the top ends of each 90-rotated specimen, so that the specimen could be fixed onto the loading frame and reaction floor by crewing bolts into the embedded anchors in the two members. The test specimens were horizontally cast, then rotated and placed into the test setup with one of the members fixed to the reaction floor (Fig. 3). As shown in Fig. 3, in horizontal position, displacement cycles were applied to the upper wall portion through a horizontal 1,000kN actuator with its line of action passing through the beam center. To reduce rotation of the top wall segment during loading, a steel support beam was placed on roller supports above the top wall segment, and was connected to the strong floor with four 35-mm-diameter Dywidag bars. The upper wall portion of the test specimens was braced by two sets of ball jigs that were bolted to reaction frame to prevent out-of-plane movements.

4. **Results and discussion**

The overall beam average shear stress versus drift response for all three specimens is shown in Fig. 4. The beam drift is defined as the ratio of the relative displacement between the two RC ends of the test specimens that simulated coupled structural walls to the beam clear span. The shear force applied to the coupling beam represents the load cell reading from the actuator.

From the shear stress-versus-drift hysteresis response obtained for three specimens, it can be seen that three coupling beams exhibited a stable behavior up to displacement levels of 1.0% drift for normal concrete coupling beam with diagonal reinforcement, CB1, and 2.4% drift for HPHFRCC coupling beam with and without diagonal reinforcement, CB2 and CB3.

In specimen CB1 (RC, with diagonal reinforcement), the shear to cause first flexural cracking was estimated to be 136 kN during the cycles to 0.1% drift. Diagonal cracks were first observed during the cycles to 0.2% drift at a lateral load of 335 kN. The main diagonal cracks developed during the cycles to



(a) CB1 (b) CB2 (c) CB3

Fig. 4 Shear stress versus drift hysteresis response

0.6% drift at a lateral load of 601 kN. These cracks started from the upper tensile corner of the beam and extended at approximately 45° almost half-way through the lower compressive corner of the coupling beam. At 1.0% drift, the maximum observed diagonal crack width increased to 2.0mm. At drift levels larger than 1.2%, damage became severe with diagonal cracks 4.0mm wide and some crushing of diagonal compression struts was observed at the bottom right corner.

Specimen CB2 (HPHFRCC, with diagonal reinforcement) showed a very different cracking pattern and damage process compared to specimen CB1. In this specimen, the formation of diagonal cracks was delayed. The formation of diagonal cracks started to occur during the cycles to 0.6% corresponding to a lateral load of 667 kN. Contrary to only a few diagonal cracks in CB1 with regular concrete, several short diagonal cracks propagated throughout the beam in CB2 as the load increased. This crack formation continued up to 1.2% drift. Crack widths at this loading stage ranged from 0.2mm at the center of beam to 0.05mm at the corner of beam. The formation of multiple cracks was seen in the diagonal direction up to 1.8% drift. At 2.0% drift, the formation of the localized cracks was observed diagonal cross the beam. At higher drift levels, the localized cracks continued grow larger until the testing was stopped.

In specimen CB3 (HPHFRCC, without diagonal reinforcement), a damage progress similar to CB2 was observed. The first flexural-shear cracks appeared at the middle of beam during the first negative cycle to 0.4% drift (at a lateral load of 383 kN). Short diagonal cracking began during the cycles to 0.8% drift. At 1.2 drift level, only minor damage, characterized by a large number of hairline cracks with widths ranging 0.05mm to 0.2mm, was observed. At 1.8% drift, first signs of damage localization in the HPHFRCC material were noticed at a few diagonal cracks that spanned opposite corners in the coupling beam. For the cycles performed at 2.0 and 2.2% drift, damage localization concentrated primarily at the diagonal crack in the positive loading direction and the other region exhibited only minor damage. As the specimen was pushed to larger drifts, another diagonal crack, perpendicular to the previously damaged crack, opened widely with a maximum width of 5.0mm and resulted in a complete failure of the coupling beam.

The great number of individual cracks was observed in the coupling beams made with the HPHFRCCs (CB2 and CB3). These coupling beams also achieved the higher drift capacities before localization of a crack. The greater number of individual cracks in reinforced HPHFRCC coupling beams, CB2 and CB3 specimen, compared to reinforced concrete coupling beam can be seen in a comparison of Fig. 4.

5. Conclusions

Coupling beams constructed with an HPFRCC material which is mixed with 0.75% of polyethylene fiber and 0.75% of steel cord in fiber volume fraction exhibited excellent strength, deformation capacity, and damage tolerance.

The structural performance of these new precast HPHFRCC coupling beams under reversal cyclic loading demonstrated that a more convenient reinforcement detailing can be used in coupling beams and still maintain adequate seismic behavior. The use of advanced fiber cement materials allowed the elimination and simplification of reinforcement bar, thus simplifying the beam construction process. The test results showed that HPFRCC coupling beams with simplified diagonal reinforcement exhibited higher shear strength and stiffness retention. HPFRCC beams reached a drift of at least 2.6% while maintaining approximately 80% of their shear-carrying capacity.

References

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