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# Effectiveness of high performance fiber-reinforced cement composites in slender coupling beams

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## HIGHLIGHTS

- HPFRCC greatly contributed to reducing the cracking damage and shear distortion of coupling beams.
- The HPFRCC specimens showed lower percentages of stiffness degradations than the normal concrete.
- The conventionally reinforced specimen eventually suffered shear failure even with HPFRCC.
- The diagonally reinforced specimens achieved much higher shear stresses than the code limit.

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## ABSTRACT

This study aims at exploring the use of high performance fiber-reinforced cement composites (HPFRCCs) as an innovative method of improving the seismic performance of slender coupling beams. Also, the effect of diagonal reinforcement in slender coupling beams is evaluated in comparison to conventional reinforcement. Three 1/2-scale coupling beams having the length-to-depth ratio of 3.5 were tested under cyclic lateral loading up to about 10% drift. The key test variables were material type and reinforcement layout. For the material type, normal concrete and HPFRCC using PVA discrete fibers of 2% volumetric ratio were compared. The mix proportions of the HPFRCC were determined through detailed material tests. Two types of reinforcement layout were tested: conventional and diagonal layout. Furthermore, the strength and stiffness characteristics of reinforced concrete or HPFRCC coupling beams are examined by assembling a database of almost all coupling beam tests available in literature.

## 1. Introduction and background

Reinforced concrete (RC) coupling beams in coupled wall systems designed based on current codes [1–5] are expected to endure significant inelastic deformations, when subjected to design-level earthquakes. Suitably devised coupling beams may be able to not only survive over large displacement demands, but also serve as a primary source for energy dissipation [6].

In high-rise residential buildings of which the seismic force-resisting system consists of structural walls combined with RC slab–column frames, the depth of coupling beams is typically limited due to relatively small story heights [7]. Although this type of construction has been popularly used for many decades, the seismic design of slender coupling beams has not been investigated much. Most of the previous studies focused on deep coupling beams to invent proper methods of ensuring satisfactory ductility and relieving reinforcement congestion [8–11]. Some design codes (e.g. ACI 318-11 [2]) allow conventional reinforcement layout to be used for slender coupling beams having the length-to-depth ratio larger than 2, even in high seismic zones. This appears based on the presumption that diagonal reinforcement layout would neither much increase the shear strength nor improve the seismic performance. The possibility of sliding shear failure [6] that typically occurs in conventionally reinforced coupling beams is neglected in the case of slender coupling beams.

High performance fiber-reinforced cement composites (HPFRCCs) are characterized by strain-hardening response in direct (uniaxial) tension by developing numerous micro-cracks with assistance of engineered fibers [12–16]. HPFRCCs generally show

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**Nomenclature**

| | |
|---|---|
| $A_g$ | gross area of beam section |
| $A_s$ | area of longitudinal reinforcement |
| $A_v$ | area of transverse reinforcement |
| $A_{vd}$ | area of each group of diagonal reinforcement |
| $b$ | beam width |
| $d$ | effective depth of beam |
| $E_c$ | modulus of elasticity of concrete |
| $f_{cd}$ | design compressive strength of concrete |
| $f_{cm}$ | measured compressive strength of concrete |
| $f_u$ | measured ultimate strength of reinforcing steel |
| $f_y$ | measured yield strength of reinforcing steel |
| $f_{yl}$ | yield strength of longitudinal steel |
| $f_{yt}$ | yield strength of transverse steel |
| $G_c$ | shear modulus of concrete |
| $h$ | beam depth |
| $I_g$ | gross moment-of-inertia of beam section |
| $K_{0,cal}$ | theoretical initial stiffness |
| $K_{0,exp}$ | measured initial stiffness at the first loading cycle |
| $K_{y,exp}$ | measured yield stiffness |
| $l$ | beam length |
| $M_{n,0}$ | nominal moment strength computed ignoring effects of axial force |
| $M_{n,N}$ | nominal moment strength computed considering effects of axial force |
| $N_{p,max}$ | beam axial force imposed at the time of the maximum load $P_{max}$ |
| $P_u$ | ultimate beam shear assumed to be governed by nominal moment strength |
| $P_{max}$ | measured maximum lateral load |
| $P_{n,0}$ | lateral load corresponding to the nominal moment strength $M_{n,0}$, $P_{n,0} = 2M_{n,0}/l$ |
| $P_{n,N}$ | lateral load corresponding to the nominal moment strength $M_{n,N}$, $P_{n,N} = 2M_{n,N}/l$ |
| $s$ | spacing of transverse reinforcement |
| $V_n$ | nominal shear strength |
| $\alpha$ | angle between diagonal reinforcement and the longitudinal axis of beam |
| $\Delta_y$ | yield displacement |
| $\varepsilon_y$ | measured yield strain of reinforcing steel |
| $\Phi_0$ | factor accounting for the relative importance of shear to flexural deformation |
| $\gamma$ | shear distortion, $(\gamma_L + \gamma_R)/2$ |
| $\gamma_L$, $\gamma_R$ | angular changes in 90-degree angles at the side face of coupling beam |

much higher ductility under both tension and compression than normal concrete [13,17–19]. Thus, confinement requirements may be relaxed in members of high reinforcement congestion by using HPFRCCs [18]. When subjected to seismic forces, in particular, HPFRCCs are deemed to improve energy dissipation through fiber bridging over micro-cracks and by providing excellent bond between reinforcing steel and cement composites [13].

During the last decade, several leading research groups played major roles in large-scale experimental investigations for the effectiveness of HPFRCCs in earthquake-resistant structures. Most of them tested shear-dominated building components such as deep coupling beams, beam–column joints, slab–column connections, and infill panels [20–27]. From the previous studies, it has been revealed that HPFRCC materials were effective in improving seismic performance such as ductility, energy dissipation, and damage control. However, the use of HPFRCCs in flexure-dominated members has not been investigated much.

Given the aforesaid concerns, this study explores the use of HPFRCCs as an innovative method of improving the seismic capacity of slender coupling beams through an experimental program. Detailed material tests were conducted to determine the mix proportions of the HPFRCC used for the construction of the coupling beam specimens. Also, the effectiveness of diagonal reinforcement layout in slender coupling beams is investigated in comparison with conventional reinforcement layout. Furthermore, the strength and stiffness characteristics of RC or HPFRCC coupling beams are examined by assembling a database of almost all coupling beam tests available in literature.

## 2. Descriptions for coupling beam tests

In this study, three approximately 1/2-scale coupling beam specimens were tested under cyclic lateral loading. Each specimen represented a slender coupling beam that is part of a coupled wall system combined with flat plates in a tall residential building. The significance of this study is that (1) a HPFRCC and/or (2) diagonal reinforcement were applied in the tested slender coupling beams for the purpose of improving the seismic performance.

### 2.1. Specimen details and test variables

Fig. 1 illustrates dimensions and reinforcing details of the three specimens: 1CF2Y, 1DF0Y, and 1DF2Y. In all specimens, the beam width ($b$) is 250 mm, the beam depth ($h$) is 300 mm, and the length ($l$) of the beam is 1050 mm, so that the length-to-depth ratio ($l/h$) is 3.5. Table 1 summarizes design details and test variables of the three specimens. The key test variables were (1) material type and (2) reinforcement layout. For the material type, a single type of HPFRCC using Polyvinyl Alcohol (PVA) fibers of 2% volumetric ratio was compared with normal concrete. Specimens 1CF2Y and 1DF2Y were made with the HPFRCC, while 1DF0Y was with normal concrete.

Two types of reinforcement layout were tested: conventional and diagonal layouts (Fig. 1). Specimen 1CF2Y was reinforced with the conventional layout, while the other two specimens were with the diagonal layout. In the conventional layout, longitudinal bars were arranged horizontally at the top and bottom of the beam, and transverse reinforcement was designed per ACI 318-11, §21.5. In the diagonal layout, four longitudinal bars were clustered as a diagonal group, and two mirror-opposite groups of diagonal bars passed through each other in the central region of the beam (see the elevation views in Fig. 1 and the section views in Fig. 10), according to ACI 318-11, §21.9.7. Transverse reinforcement were provided for the entire section of the beam as an alternative to enclosing each group of diagonal bars, and intermediate horizontal bars used to anchor transverse ties had a short embedded length (i.e., 150 mm) into the stubs in order not to develop yielding.

The amount of longitudinal bars (Table 1), which are diagonal in 1DF0Y and 1DF2Y or horizontal in 1CF2Y, was determined so that the ultimate shear stress ($P_u/bh$) expected in the beam is approximately equal to $0.5\sqrt{f_{cd}}$ (MPa) in all specimens, based on reaching the nominal moment strength at the beam ends. (This design method [38,39] is deemed reasonable because the shear stress level is considered one of the key factors affecting the performance of coupling beams.) Here, $P_u$ is the ultimate beam shear assumed to be governed by the nominal moment strength of the beam that was calculated using the design yield strength of reinforcing steel equal to 420 MPa. Also, $f_{cd}$ is the design compressive strength of