A Summary of Ten Years of Research on HPFRC Coupling Beams

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Abstract. The design of coupling or "link" beams connecting structural walls in earthquake-resistant construction requires the use of intricate diagonal and transverse reinforcement detailing to ensure adequate strength, stiffness and energy dissipation during an earthquake event. The tensile strain-hardening behavior exhibited by high-performance fiber reinforced concretes (HPFRCs), along with their compression behavior that resembles that of well-confined concrete, led the senior writers to consider their use as a means to simplify the required reinforcement detailing in coupling beams, while leading to comparable or even enhanced seismic performance. Short coupling beams with a span-to-depth ratio (ℓ_n/h) of 1.0 were first investigated. Test results showed that HPFRC provides confinement to the diagonal reinforcement and increases coupling beam shear strength and drift capacity. This allows for a substantial reduction in both diagonal and confinement reinforcement without compromising deformation capacity. A follow-up study on coupling beams with $\ell_n/h = 1.75$ showed that a ductile flexural mechanism with high damage tolerance can be achieved through the use of HPFRC. A precast scheme with a short embedment length was shown to effectively anchor the beam into the wall without interfering with the wall reinforcement. Also, an HPFRC mixture with high-strength (2300 MPa) hooked steel fibers in a 1.5% volume fraction was found to be the most promising in terms of structural performance, economy and ease of construction. In order to cover the range of ℓ_n/h ratios common in practice, additional studies were conducted on more slender coupling beams, with $\ell_n/h = 2.75$ and 3.3. It was shown that slender precast HPFRC coupling beams can develop a high drift capacity and damage tolerance, even when diagonal reinforcement is eliminated. The results from this work thus provide structural engineers and contractors a viable design alternative for use in earthquake-resistant coupled wall construction.

1. Introduction

Structural walls are commonly used for lateral strength and stiffness in earthquake-resistant construction. Due to the need for window and/or door openings, these walls are typically “pierced”, which leads an otherwise solid wall to be “split” in two or more walls connected by relatively short beams referred to as “coupling” or “link” beams. Because of their low span-to-depth ratio, typically between 1 and 4, these beams require special detailing requirements to ensure adequate deformation capacity during earthquakes.

Current design practice for coupling beams is based on findings from research conducted in the early 1970s [1] and consists of the use of diagonal bars designed to resist the entire shear demand, combined with heavy amounts of confinement reinforcement (Fig. 1). While this reinforcement detailing has been shown to lead to adequate stiffness, strength, and deformation capacity under displacement reversals [2], it is labor intensive and often controls the construction schedule. There has thus been a need for simpler yet structurally efficient coupling beam designs that can be constructed more quickly and with less material and labor.

Fig. 1. Reinforcement detailing in diagonally reinforced coupling beam

Because of the strain-hardening behavior of HPFRC materials when subjected to direct tension, as well as their compression stress-strain response that resembles that of well-confined concrete, it was hypothesized that the use of HPFRC materials in coupling beams would allow a substantial reduction in both diagonal and transverse reinforcement without compromising strength, stiffness and deformation capacity. This hypothesis was confirmed through research conducted over the past ten years at the University of Michigan. A summary of the main findings from this research is presented herein.

2. HPFRC Materials Investigated

Three different HPFRC mixtures were used during the various experimental phases to evaluate their ability to increase shear strength and ductility, as well as to serve as partial replacement for diagonal and transverse reinforcement. The properties of the three types of fibers used are summarized in Table 1 and the HPFRC mixture proportions are summarized in Table 2. All three mixtures exhibited the desired strain-hardening response in tension and led to adequate structural performance in terms of shear strength, stiffness and deformation capacity. However, both ultra-high molecular weight (Spectra) and high-strength twisted steel (Torex) fibers had drawbacks that led to the adoption of a high-strength hooked steel fiber mixture for the majority of the coupling beam tests. Specifically, the mixture with Spectra fibers was expensive and difficult to mix, and the high-strength Torex fibers, although easier to mix, are not commercially available. As a result, the highly workable hooked steel fiber mixture design developed by Liao et al. [5] was adopted. Additional data regarding the mechanical properties of these mixtures can be found in References [3, 4].

Table 1. Fiber properties (specified by manufacturer)

Fiber Type	Length (in./mm)		Diameter (in./mm)		L/d	Tensile Strength (ksi/MPa)		Elastic Modulus (ksi/GPa)	
Spectra (Mixture 1)	0.5	13	0.0015	0.038	340	375	2570	17000	117
Torex (twisted steel) (Mixture 2)	1.2	30	0.012	0.3	100	360	2470	29000	200
Hooked Steel (Mixture 3)	1.2	30	0.015	0.38	80	333	2300	29000	200

Table 2. HPFRC mixture proportions by weight of cement

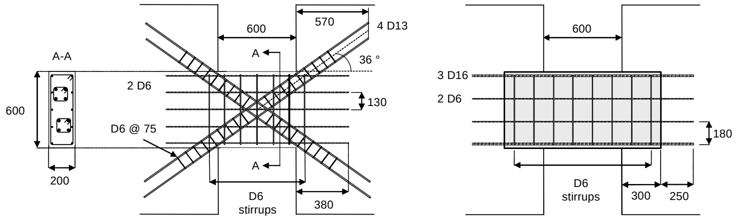
	Cement	Fly Ash	Sand	Agg.	Water	SP[1]	VMA[2]
Mixture 1 Spectra ($V_f = 2\%$)	1	0.15	1	0	0.4	0.02	0
Mixture 2 Torex ($V_f = 1.5\%$)	1	0.15	1	0	0.4	0.02	0
Mixture 3 Hooked ($V_f = 1.5\%$)	1	0.875	2.2	1.2*	0.8	0.005	0.038

[1] Super-plasticizer (Glenium 3200HES); [2] Viscosity Modifying Agent (Rheomac VMA 362)

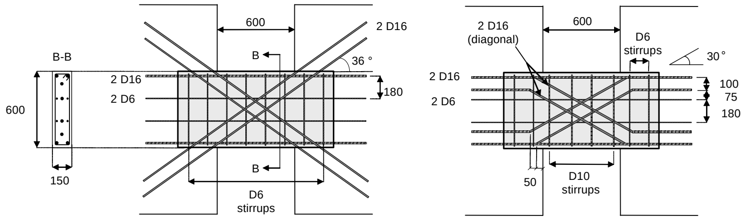
* 13 mm (1/2 in.) maximum size

3. Coupling Beam Detailing

The first four coupling beam specimens tested had an aspect (span-to-depth) ratio of 1.0. The reinforcement of these specimens is shown in Fig. 2. Specimen 1 was constructed with conventional reinforced concrete and reinforced according to the requirements of the ACI Building Code [5]. Specimens 2 and 3 were constructed with HPFRC Mixture 1 (Table 2), and modified reinforcement detailing.



a) Specimen 1 **b) Specimen 2**



c) Specimen 3 **d) Specimen 4**

Fig. 2. Reinforcement of specimens with $\ell_n/h = 1.0$ [3]

Results of these tests [3] demonstrated that HPFRC can replace the confinement reinforcement around the diagonal bars, and showed that the HPFRC coupling beam can be precast and embedded into the adjacent walls. The test results of Specimen 4, which was constructed with HPFRC Mixture 2 (Table 2), showed that the diagonal reinforcement can be bent within the precast HPFRC section and exit the beam horizontally. This detail significantly simplifies placement of the precast section on the jobsite. Comparing the shear stress versus drift response of Specimens 1 and 4 (see Fig. 3), a significant improvement in shear strength is evident with the use of HPFRC, even though the area of diagonal reinforcement used in Specimen 4 was approximately 80% of that used in Specimen 1. For two vertical walls rotating the same amount when subjected to lateral displacements, drift is defined as the angle between a tangent passing through the beam end and the horizontal (beam chord).

Based on the results from the tests of coupling beams with an aspect ratio of 1.0, eight more coupling beam specimens with aspect ratios of 1.75, 2.75 and 3.3 were tested [6]. The reinforcement layouts proposed on the basis of these tests for coupling beams with aspect ratios between 1.5 and 2.5, and greater than 2.5, are shown in Figs. 4a and 4b, respectively. Special column-type transverse reinforcement is only provided at the beam ends because fiber reinforcement is sufficient to confine the remaining coupling beam span. The shear stress versus drift response of these specimens is shown in Fig. 5. The specimens were shown to develop a stable flexural response with energy dissipation and stiffness retention capacities comparable to those of well detailed diagonally-reinforced concrete coupling beams. This performance was achieved with a 70% and 100% reduction in digon-

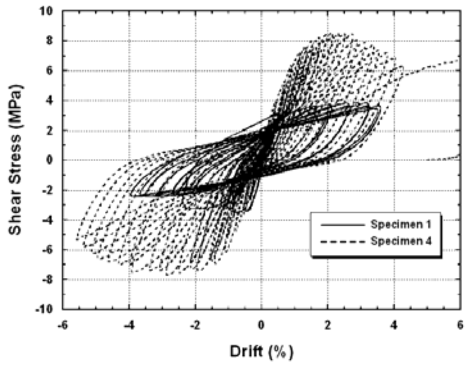
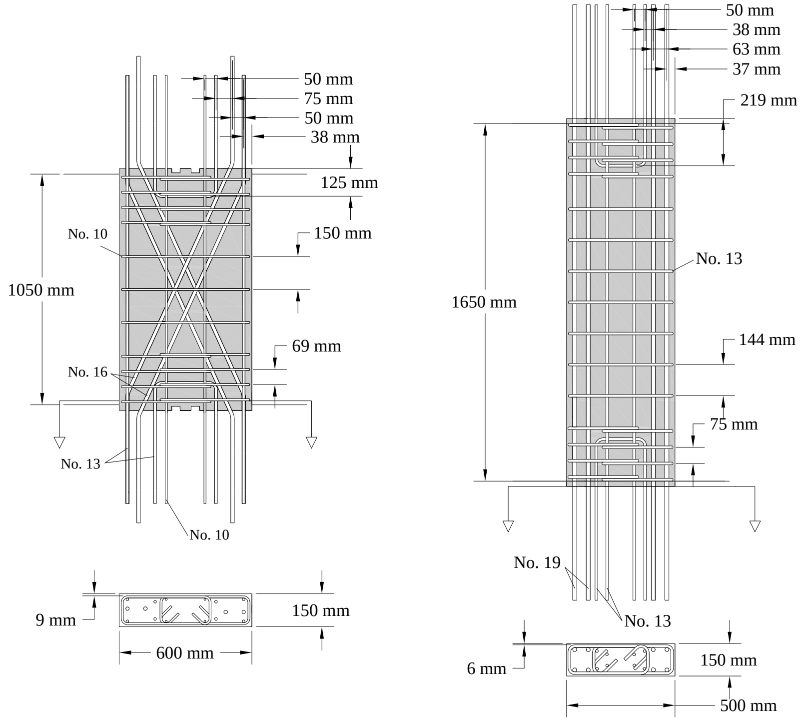


Fig. 3. Response of Specimens 1 (blue) and 4 (red) [3]

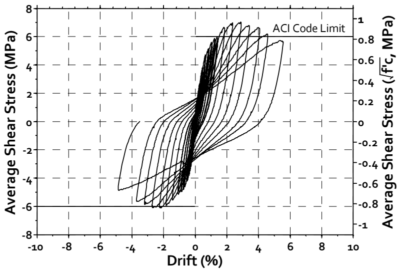
al reinforcement for moderate and slender coupling beams, respectively, when compared to a conventional reinforced concrete design. The shear force not resisted by diagonal reinforcement is assumed to be resisted by transverse reinforcement and the HPFRC material. A shear stress of $5\sqrt{f_c'}$, [psi] ($0.42\sqrt{f_c'}$, [MPa] was found to be a conservative limit for the contribution of the HPFRC material to shear strength.

A major advantage of the proposed HPFRC coupling beams is the ability to precast the HPFRC section (shaded grey in Fig. 4) and embed it into the walls without interfering with the wall reinforcement. This is achieved by embedding

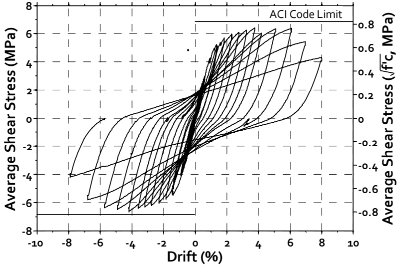


a)$l_n/d = 1.75$ b)$l_n/d = 3.3$

Fig. 4. Reinforcement detailing for “short” and “slender” HPFRC coupling beam specimens



a)l_n/d = 1.75



b)l_n/d = 3.3

Fig. 5. Shear stress versus drift response of “short” and “slender” coupling beam specimens

Fig. 6. Coupled wall specimen

the precast HPFRC section only as deeply as the wall cover. Also, the bending of the diagonal reinforcement allows for all of the coupling beam reinforcement to exit the beam horizontally for anchorage in the wall. This limits the potential for interference with the dense wall boundary element reinforcement. In order to prevent damage localization at the precast beam-wall interface, and thus a premature sliding shear failure, U-shaped or straight dowel bar reinforcement crossing the cold joint was found to be adequate to force most of the beam inelastic deformations to occur away from the cold joint. The ease with which these precast HPFRC coupling beams can be placed on the jobsite is a major improvement over the construction methods currently used for diagonally reinforced concrete and steel coupling beams.

4. Coupled Walls

In addition to tests of coupling beam components, two coupled wall specimens (approximately 1/3-scale) were tested. These specimens consisted of four beams ($\ell_n/h = 1.7$) linking two T-shaped structural walls (Fig. 6). In each specimen, three of the coupling beams were precast with HPFRC and reinforced similarly to the specimen shown in Fig. 4(a). The coupling beam at the second story was precast with regular concrete. Slabs were built at the second and fourth levels to facilitate application of lateral displacements. These slabs also

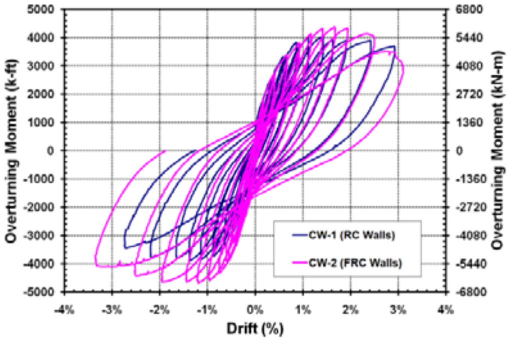


Fig. 7. Overturning moment versus drift response of coupled wall specimens

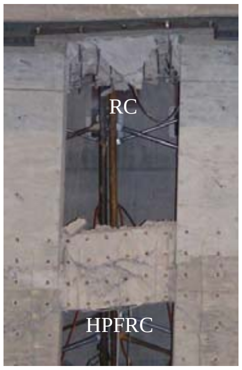


Fig. 8. Damage in coupling beams (RC on top, HPFRC on bottom)

allowed the evaluation of the precast beam-slab-wall interaction during earthquake-induced displacements.

The reinforcement of the first two stories of the wall specimens differed. The walls in the first specimen were designed and detailed to satisfy the requirements of the ACI Building Code [5], whereas HPFRC was used in the first two stories of the second specimen. In the HPFRC walls, the boundary element confinement reinforcement was reduced and a shear stress of $4\sqrt{f_c'}$ [psi] ($0.33\sqrt{f_c'}$ [MPa] was assumed to be resisted by the HPFRC, which is twice the value assumed for conventional reinforced concrete walls. Additional details on these tests are available in Reference [7].

Both specimens exhibited the high strength and stiffness characteristic of coupled walls, with excellent strength retention and energy dissipation up to a system drift of approximately 3.0% (Fig. 7). The HPFRC portions of the specimens exhibited narrower crack spacing and significantly improved damage tolerance (Fig. 8), despite simplified reinforcement detailing. These tests demonstrated that placement of the precast coupling beams, with the beam reinforcement threading through the adjacent wall reinforcement, was straight-forward. This proposed method is believed to be a viable alternative method for construction of coupled wall systems.

5. Summary and Conclusions

Experimental evidence indicates that the use of steel HPFRC materials in coupling beams is a viable alternative to simplify reinforcement detailing without compromising seismic performance. In coupling beams with span-to-depth ratios less than approximately 2.5, a nearly 70% reduction in diagonal reinforcement is possible, and elimination of diagonal reinforcement is possible in more slender coupling beams. In all cases, special column-type confinement reinforcement is only needed at the beam ends due to the confinement provided by the fiber reinforcement. For further construction simplification, the proposed HPFRC coupling beams can be precast, eliminating the need for cast-in-place HPFRC.

Results from two four-story coupled wall specimens subjected to lateral displacement reversals indicate that coupled wall systems with HPFRC coupling beams exhibit a stable seismic behavior with drift capacities on the order of 3%. The construction of the coupled walls with precast HPFRC coupling beams was shown to have potential for substantial reductions in construction labor and time.

Acknowledgments

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