# *High-Performance Fiber Reinforced Concrete in Earthquake-Resistant Construction*

## *What Can We Gain?*

*By Gustavo J. Parra-Montesinos*

The benefits of using strain-hardening, high-performance fiber reinforced concrete (HPFRC) in critical regions of earthquake-resistant structures are increasingly recognized. Because of their ductile behavior, HPFRCs are particularly attractive for use in regions where large inelastic deformation capacity is required in order to withstand the demands induced by a severe earthquake. Test results have shown that HPFRCs act as a replacement to special seismic reinforcement detailing by providing additional shear resistance and confinement, which could lead to major simplifications in construction of earthquake-resistant structures.

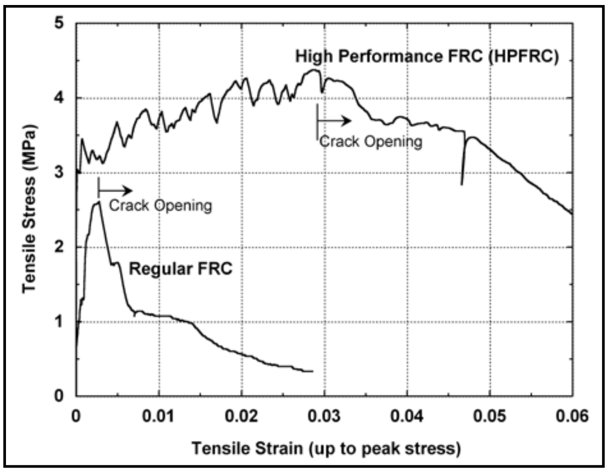



*Figure 1: Tensile stress versus strain response for high-performance and regular fiber reinforced concretes*

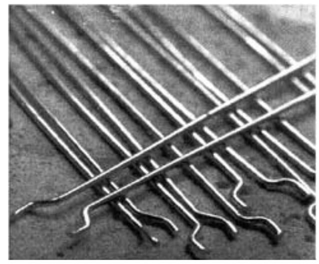
### Introduction to HPFRC

In 1987, Naaman proposed to categorize fiber reinforced concrete based on its tensile behavior after first cracking (*Figure 1*). When strain-hardening behavior is observed, the mixture is categorized as High-Performance Fiber Reinforced Concrete (HPFRC). When strain-softening behavior is observed, the mixture is categorized simply as Fiber Reinforced Concrete (FRC).

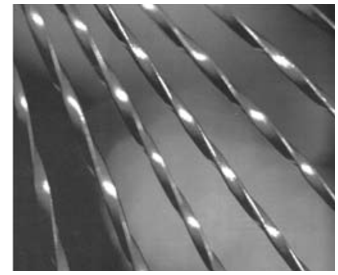
Once first cracking occurs in HPFRC subjected to direct tension, the fibers that bridge the crack carry an increasing amount of load, leading to additional cracking in the composite. This cracking process, which will ultimately result in a dense array of fine cracks, continues until damage localizes (considerable fiber pullout) at one or a few cracks, typically at a tensile strain between 0.5 and 3%. In regular FRC, on the other hand, because the fibers cannot carry additional load after cracking, damage localization begins as soon as first structural cracking occurs.

Fibers also enhance the compression behavior of concrete, primarily by increasing its strain capacity. HPFRCs have been shown to exhibit a behavior similar to that of well confined concrete, with strain capacities in excess of 1%. This suggests that relaxations in confinement reinforcement are possible when using HPFRCs versus normal concrete.

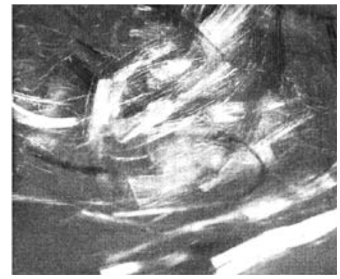
Tensile strain-hardening behavior has been obtained through the use of various types of fibers, such as hooked or twisted steel fibers (*Figures 2a and b, respectively*), straight ultra-high molecular weight polyethylene (PE) fibers (Figure 2c), and PVA fibers in 1.5 to 2.0% volume fractions. However, most recently investigated structural applications have focused on the use of steel fibers. Steel fibers (either hooked or twisted) are generally 30 to 50 mm long and 0.38 to 0.55 mm in diameter (or equivalent diameter).



*a) Hooked Steel Fibers*



*b) Twisted Steel Fibers*



*c) PE Fibers*

*Figure 2: Typical fibers used in HPFRC's (courtesy of Antoine E. Naaman)*

### Applications of HPFRC in Earthquake-Resistant Construction

Closely spaced and properly detailed transverse reinforcement provides a stable mechanism for shear resistance and confinement of concrete and longitudinal bars during displacement reversals. Confinement, in turn, increases concrete ductility, controls crack growth and helps maintain member integrity. The use of adequate transverse reinforcement detailing becomes particularly critical in structural members, or regions subjected to moderate to high shear stress levels, and/or large inelastic rotations. Examples include coupling beams, beam-column connections, and plastic hinge regions of flexural members. Observations from experimental research, as well as from post-earthquake evaluations have shown that the use of extensive, carefully detailed transverse reinforcement is indeed effective in ensuring adequate structural behavior during a major earthquake.

For members designed as part of the lateral-force-resisting system in regions of high seismicity, ACI 318 requires a significant amount of transverse reinforcement for shear strength and confinement purposes. The use of HPFRC in these members increases shear strength and provides confinement, and so has the potential for substantially reducing the amount of transverse reinforcement.

Consider the case of reinforced concrete (RC) coupling beams in earthquake-resistant coupled-wall systems. To ensure adequate shear resistance and deformation capacity in the coupling beams, intersecting, heavily confined diagonal reinforcement cages are required by code, as shown in *Figure 3*. By using HPFRC, major simplifications in transverse reinforcement detailing of critical members in earthquake-resistant structures can be achieved, without compromising structural performance.

*Figure 3: Typical diagonal reinforcement detailing in RC coupling beams (courtesy of Jack P. Moehle)*

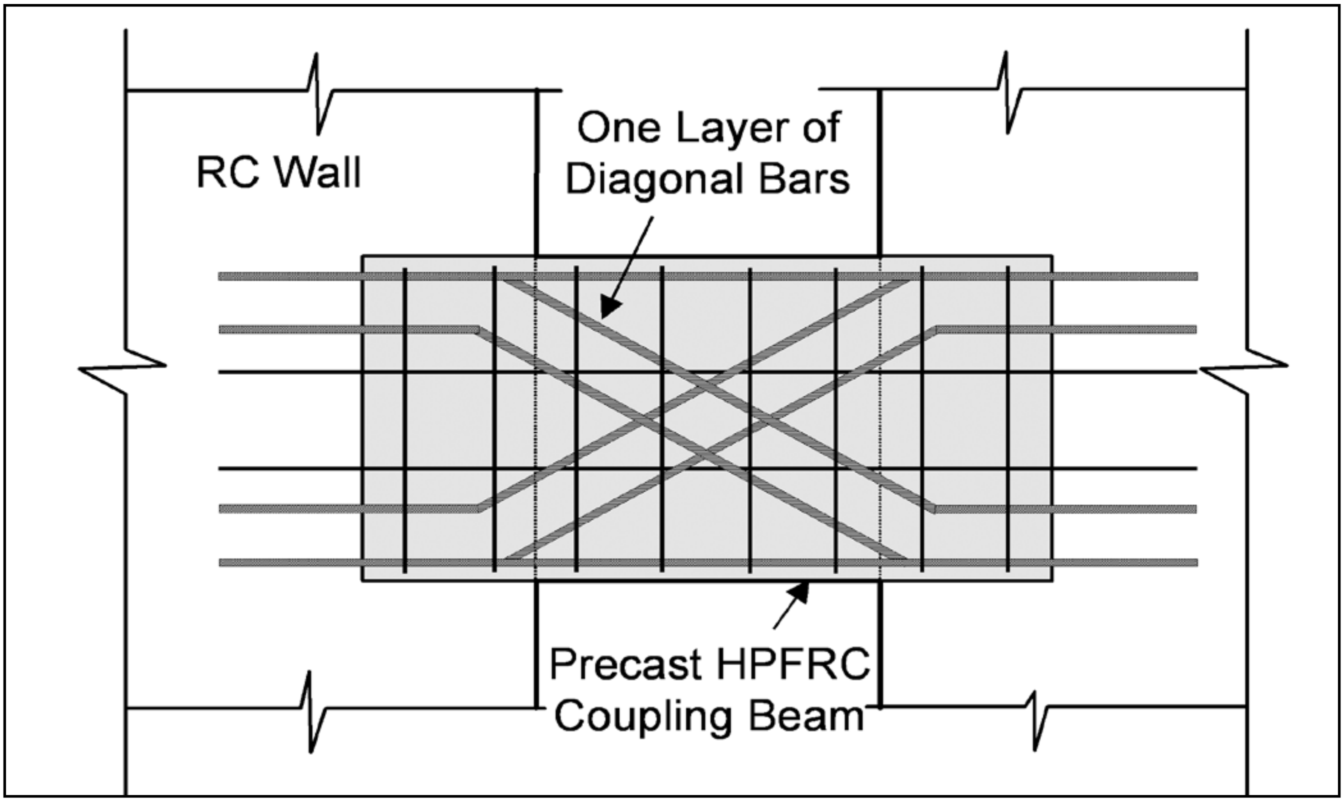



*Figure 4: HPFRC coupling beam design proposed by Canbolat et al (2005)*

### *Coupling Beams*

Coupling beams in structural wall systems play a major role in system behavior during earthquakes. These beams undergo very large rotation and shear stress demands during a severe earthquake, which requires intricate diagonal and transverse reinforcement detailing to satisfy the anticipated seismic demands (*Figure 3*).

Since the introduction of coupling beam diagonal reinforcement in the ACI Code contractors have noted difficulties in con-struction. To address a demand for less congested coupling beam designs, Canbolat et al. (2005) investigated the use of HPFRC as a means to significantly reduce transverse reinforcement around diagonal reinforcement while increasing shear capacity. The result was a new HPFRC precast coupling beam design (*Figure 4*) that reduces the amount of diagonal reinforcement and, more importantly, eliminates transverse reinforcement required to support the diagonal bars and confine the concrete. This design allows the placement of diagonal reinforcement in one layer, which also reduces coupling beam width.

The HPFRC coupling beam design was evaluated through large-scale tests under displacement reversals at the University of Michigan (Canbolat et al., 2005). Compared to the typical reinforced concrete design shown in Figure 3, the new HPFRC coupling beam design (*Figure 4*) provided substantially higher shear strength with large drift capacity (*Figure 5*). It is worth mentioning that the peak shear stress demand sustained by the coupling beam was approximately 35% higher than the upper shear stress limit specified in the ACI Code (ACI 2002) (i.e. 1.13 , in MPa). The use of an HPFRC in the coupling beam led to a more uniform and dense crack distribution compared to a few wide diagonal cracks observed in the RC coupling beam tested. Before damage localization, diagonal cracks in the HPFRC coupling beam exhibited negligible width upon unloading, indicating no need for repairs. In the case that deformation demands in the coupling beams are large enough to cause damage localization in the HPFRC, the material was shown to still be capable of providing confinement to the diagonal reinforcement, which ensured adequate coupling beam behavior after considerable fiber pullout.

### *Structural Walls*

The seismic design of structural walls includes the evaluation of wall displacement capacity to meet the expected earthquake-induced demands. Assuming sufficient transverse reinforcement is provided to prevent a shear failure during inelastic displacement reversals, wall flexural rotation capacity will likely be limited by the compression strain capacity of concrete. Where concrete strains produced by wall rotation may exceed the crushing strain of the concrete at the edges of the wall, heavy amounts of confinement reinforcement in the wall boundary regions are provided to enhance concrete ductility and thus, increase wall rotation capacity (Wallace, 1994).

As an alternative to providing extensive transverse reinforcement detailing to ensure adequate wall deformation capacity, a structural designer can increase the number of walls in the building to reduce displacement demands to levels that can be accommodated without the need for special reinforcement detailing. This solution was proven effective during the 1985 Chilean Earthquake, where buildings containing large percentages of wall area behaved well despite the lack of special seismic reinforcement detailing (Wight et al., 1996).

A third option is to use an HPFRC material that behaves like confined concrete. This option was experimentally investigated by Parra et al. (2006), in which regular concrete was replaced by HPFRC in the wall plastic hinge region. The investigation was to evaluate if, in addition to ensuring adequate plastic hinge rotation capacity, the use of HPFRC would enhance wall shear resistance and damage tolerance.

*Figures 6a and 6b* show the reinforcement detailing at the wall base (plastic hinge region) for a reinforced concrete (RC) wall test specimen, designed based on the 2002 ACI Code, versus that in an HPFRC wall specimen. In the RC wall specimen, hoops in the wall boundary were provided, spaced at one fourth of the wall thickness, while the transverse reinforcement spacing in the HPFRC wall was six times that in the RC wall. It should be mentioned that hoops in the HPFRC wall were only provided on one boundary region, while the other wall edge transverse reinforcement was only the extension of the wall horizontal reinforcement.

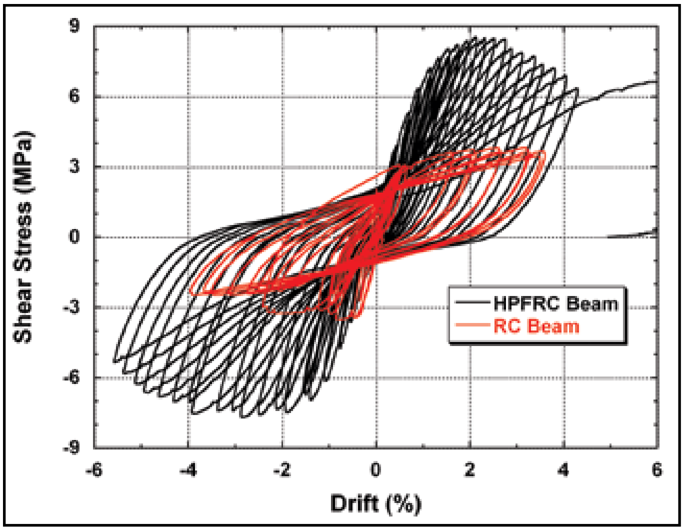
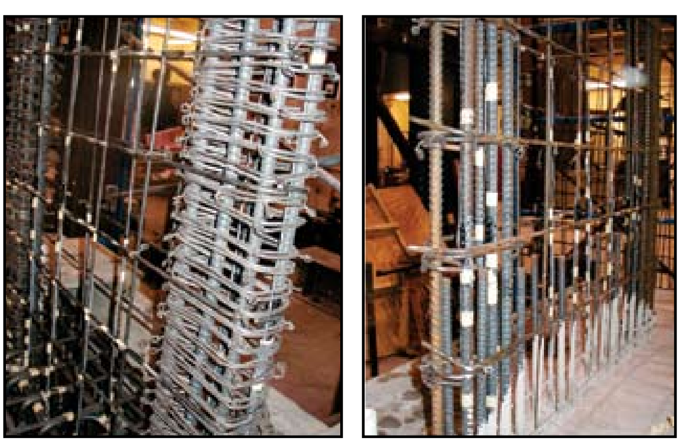



*Figure 5: Behavior of RC versus HPFRC coupling beams (Canbolat et al. 2005)*

The lateral load versus drift response for the two wall specimens is shown in *Figure 7*. Drift is defined as the ratio between the lateral displacement at the top of the wall and the wall height. As can be seen, the behavior of the two specimens was very similar, despite the differences in reinforcement detailing. While the RC wall exhibited significant shear-related damage after flexural yielding, the behavior of the HPFRC wall was dominated by flexural deformations with negligible compression-related damage in the wall boundary regions, even at 3% drift. Both walls were cycled up to 3.5% drift. Failure of the HPFRC wall occurred at this drift level due to fracture of the main longitudinal reinforcement. Although no clear indication of failure was observed in the RC wall, severe shear-related damage was observed at the end of the test.

## Conclusions

Strain-hardening, high-performance fiber reinforced concrete (HPFRC) offers structural engineers a new option for the design of critical regions in earthquake-resistant structures. By using a concrete material that is ductile in tension and compression, adequate shear resistance, deformation capacity and damage tolerance can be achieved without special seismic reinforcement detailing. Work is required, however, to get fiber reinforced concrete accepted as a structural material by building officials. ACI has taken a leadership role in this regard through the recent approval by Committee 318 (Structural Building Code) of design provisions that allow the use of steel fiber reinforced concrete as minimum shear reinforcement in beams.▪



*a) RC Wall* *b) HPFRC Wall*

*Figure 6: Boundary reinforcement detailing in reinforced concrete and HPFRC wall specimens (Parra et al. 2006)*

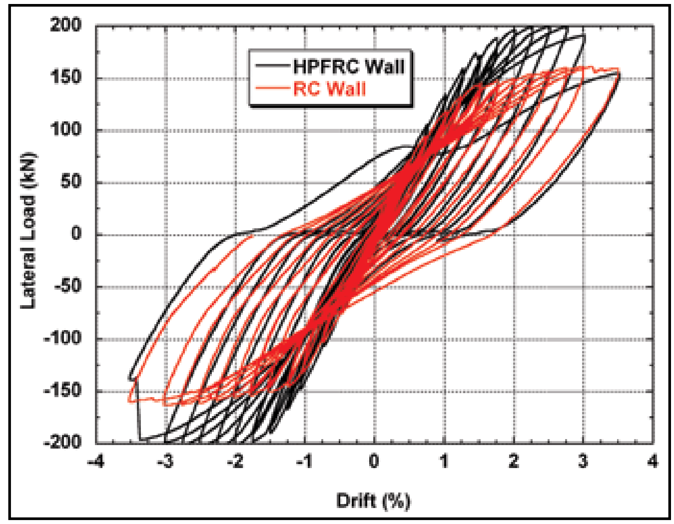



*Figure 7: Load versus displacement response for RC and HPFRC wall specimens (Parra et al. 2006)*

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***Additional information about HPFRC in earthquake-resistant structures can be found elsewhere (Parra, 2005; http://www-personal.umich.edu/~gjpm/)***

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