Title no. 102-S68

High-Performance Fiber-Reinforced Cement Composites: An Alternative for Seismic Design of Structures

by Gustavo J. Parra-Montesinos

An overview of recent applications of tensile strain-hardening, high-performance fiber-reinforced cement composites (HPFRCCs) in earthquake-resistant structures is presented. Applications discussed include members with shear-dominated response such as beam-column connections, low-rise walls, and coupling beams, as well as flexural members subjected to large displacement reversals. The results presented in this paper show that HPFRCC materials are effective in increasing shear strength, displacement capacity, and damage tolerance in members subjected to large inelastic deformations. The use of HPFRCCs in beam-column connections allowed total elimination of joint transverse reinforcement while leading to outstanding damage tolerance. Similarly, HPFRCC low-rise walls exhibited drift capacities larger than 2.0% with only minor damage at drifts ranging between 1.0 to 1.5%. One of the most encouraging results was observed in HPFRCC flexural members unreinforced in shear, which sustained reversed cyclic shear stresses as high as 2.7 MPa up to 6.0% plastic hinge rotation.

Keywords: beams; fibers; joints; shear; walls.

INTRODUCTION

The use of fiber-reinforced concrete or cement composites (FRCCs) to enhance the performance of structural elements has been the subject of many research projects during the past few decades (refer to Balaguru and Shah 1992; Naaman et al. 1996; Adebar et al. 1997; Krstulovic-Opara 1999; Parra-Montesinos 2003). Typically, FRCCs have been shown to be effective in improving structural performance in members under gravity loads, as well as in increasing shear strength, ductility, energy dissipation, and damage tolerance in members subjected to reversed cyclic loading (Henager 1977; Jiuru et al. 1992; Filiatrault, Pineau, and Houde 1995; Vasconez, Naaman, and Wight 1998; Parra-Montesinos and Wight 2000a,b; Bayasi and Gebman 2002). Numerous types of FRCCs reinforced with steel, polymeric, glass, and carbon fibers have been evaluated for structural applications. As one might suspect, not all FRCCs behave in a similar manner, and thus proper material selection is critical to achieve the desired structural performance.

To categorize FRCCs based on their tensile performance, Naaman (1987) proposed a new class of FRCCs, referred to as high-performance fiber-reinforced cement composites (HPFRCCs) (refer also to Naaman and Reinhardt 1996). The idea behind this new classification of FRCCs was to distinguish between the typical tensile performance obtained with traditional FRCCs, characterized by a softened response after first cracking, and the tensile strain-hardening response with multiple cracking exhibited by selected types of fiber cement composites. Figure 1 shows a qualitative comparison between typical tensile stress-strain curves corresponding to high-performance and regular FRCCs. As can be seen, HPFRCCs exhibit substantially larger strain capacity and toughness compared with traditional FRCCs, which makes them ideal for use in members subjected to large inelastic deformation demands.

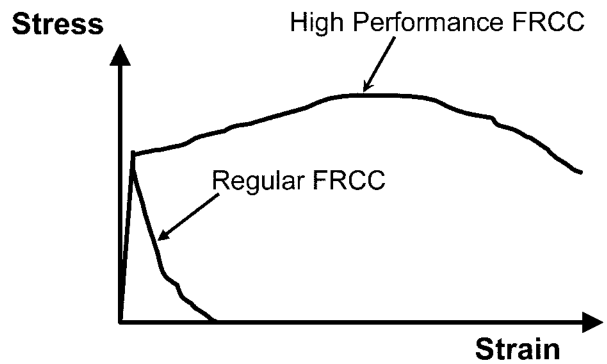


Fig. 1—Tensile stress-strain response of regular and high-performance FRCCs.

While the use of regular FRCCs in earthquake-resistant structures has led to encouraging results, far more possibilities open with HPFRCC materials, should a low volume fraction be sufficient to ensure a tensile strain-hardening response. The application of HPFRCC materials to earthquake-resistant structures has been one of the major research thrusts at the Department of Civil and Environmental Engineering in the University of Michigan during the last few years. Research areas in this topic range from fiber and material development (Li 1993; Naaman 1999) to large-scale structural applications (Vasconez, Naaman, and Wight 1998; Parra-Montesinos and Wight 2000a,b; Xia and Naaman 2002; Kim and Parra-Montesinos 2003; Canbolat, Parra-Montesinos, and Wight 2005; Parra-Montesinos, Peterfreund, and Chao 2005). Parallel to the work conducted at the University of Michigan, researchers from other research institutions have also looked at seismic applications of HPFRCCs, such as precast bridge piers (Yoon and Billington 2002) and seismic upgrading of deficient structures (Dogan and Krstulovic-Opara 2003; Kesner and Billington 2003). In this paper, results from selected research projects on the subject are presented with the intention of increasing awareness in the structural engineering community of the potential of these materials for use in earthquake-resistant structures. As it will be shown, excellent seismic performance can be obtained in shear-critical members constructed with HPFRCC materials, such as beam-column joints, squat

ACI Structural Journal, V. 102, No. 5, September-October 2005.
MS No. 04-091 received February 19, 2004, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published in the July-August 2006 *ACI Structural Journal* if the discussion is received by March 1, 2006.

ACI member **Gustavo J. Parra-Montesinos** *is an assistant professor of civil engineering at the University of Michigan, Ann Arbor, Mich. He is Secretary of ACI Committee 335, Composite and Hybrid Structures, and is a member of ACI Committees 318-F, New Materials, Products, and Ideas; 544, Fiber Reinforced Concrete; and Joint ACI-ASCE Committee 352, Joints and Connections in Monolithic Concrete Structures. His research interests include the seismic behavior and design of reinforced concrete, hybrid steel-concrete, and fiber-reinforced concrete structures.*

walls, and coupling beams, as well as in flexural members subjected to high shear stress reversals, even when little or no transverse steel reinforcement is used.

RESEARCH SIGNIFICANCE

This paper discusses the potential of HPFRCCs for use in earthquake-resistant structures. Emphasis is placed on members with shear-dominated response or flexural members subjected to high shear, for which extensive transverse reinforcement detailing is required to ensure adequate seismic behavior. It is shown that substantial reductions or even elimination of transverse steel reinforcement can be achieved through the use of HPFRCCs, simplifying the construction of critical regions of earthquake-resistant structures. Further, research results indicate that the use of HPFRCC materials leads to an increase in displacement capacity and outstanding damage tolerance, which make these composites attractive for reducing the need for costly post-earthquake repairs.

HPFRCC MATERIALS FOR SEISMIC APPLICATIONS

Several HPFRCC materials have been evaluated for use in earthquake-resistant structures during the past two decades. Until the 1990s, the achievement of high-performance properties or strain-hardening response in tension was possible only by using large amounts of fibers (typically in volume fractions $V_f \geq 6\%$), as was the case of slurry-infiltrated fiber concrete (SIFCON) or slurry-infiltrated mat concrete (SIMCON) (Krstulovic-Opara and Malak 1997). The application of materials with large fiber volume fractions, however, was very limited due to the tremendous difficulty in material mixing and casting, and thus the structural engineering community has been basically restricted to using regular FRCCs with a tensile softening response, similar to that shown in Fig. 1. During the last few years, several researchers have devoted significant effort in developing new fiber cementitious composites that exhibit a tensile strain-hardening response after first cracking while requiring low fiber volume fractions, typically below 2.0% (Li 1993; Naaman 1999). Among these materials, those reinforced with either steel or ultra-high-molecular-weight polyethylene (PE) fibers have been more extensively evaluated for seismic applications. Typical matrix constituents consist of cement, fly ash, flint sand 30-70, water, and a high-range water-reducing admixture to enhance composite workability. In strain-hardening FRCCs with low volume fractions, coarse aggregate is generally eliminated because it adversely affects the tensile performance of the composite.

Two types of steel fibers have been successfully used in earthquake-resistant elements: hooked fibers (Fig. 2(a)) and twisted fibers (Fig. 2(b)) (Naaman 1999). Strain-hardening response in tension with hooked steel fibers has been obtained when added to a mortar matrix in a 2.0% volume fraction (Kim and Parra-Montesinos 2003; Chompreda and Parra-Montesinos 2005). In these particular cases, 30 mm long and 0.5 mm diameter fibers were used. With regard to twisted steel fibers, high-performance tensile response can be achieved with a 1.5 to 2.0% volume fraction. These fibers come in a variety of cross sections (that is, triangular, square) and have a length of 15 to 50 mm and an equivalent diameter of 0.2 to 0.7 mm. Figure 3 shows a typical tensile stress-strain response obtained from direct tensile tests of dog-bone specimens containing hooked and twisted steel fibers. As can be observed, even though both materials exhibit a tensile strain-hardening response, the composite with twisted steel fibers exhibits superior tensile performance with larger strength, strain, and toughness capacity compared with that with hooked steel fibers.

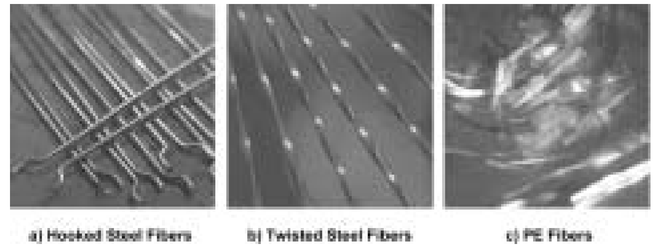


Fig. 2—Typical fibers used for seismic applications (courtesy of Antonine E. Naaman).

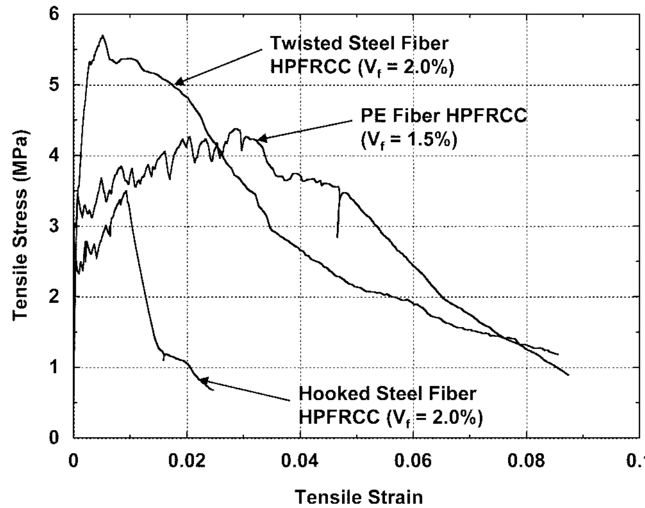


Fig. 3—Tensile stress-strain response of steel and PE fiber HPFRCCs.

Polymeric fibers have also been extensively used in HPFRCC earthquake-resistant members. In particular, ultra-high molecular-weight polyethylene (PE) fibers (Fig. 2(c)) in volume fractions ranging between 1.5 and 2.0% have been shown to lead to excellent tensile response with multiple cracking patterns (Kim and Parra-Montesinos 2003; Parra-Montesinos, Peterfreund, and Chao 2005; Chompreda and Parra-Montesinos 2005). These fibers have a tensile strength of 2590 MPa and an elastic modulus of 117 GPa, and are commonly used in lengths ranging between 15 and 38 mm with a diameter of 0.038 mm. A typical tensile stress-strain response obtained with an HPFRCC mortar containing PE fibers in a 1.5% volume fraction is shown in Fig. 3. Compared to steel fiber HPFRCCs, PE fiber HPFRCCs generally exhibit a larger strain capacity before damage localization (peak post-cracking strength). However, they also exhibit a softer postcracking ascending branch with a

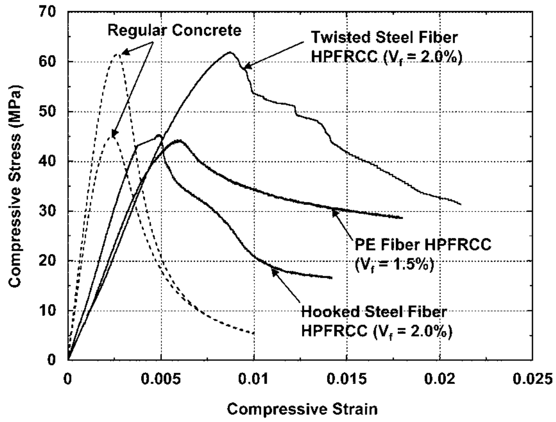


Fig. 4—Compressive stress-strain response of steel and PE fiber HPFRCCs.

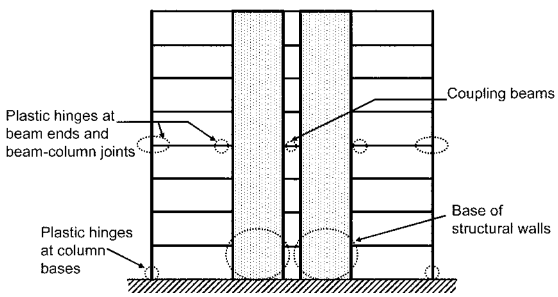


Fig. 5—Potential applications of HPFRCCs in earthquake-resistant structures (Parra-Montesinos 2003).

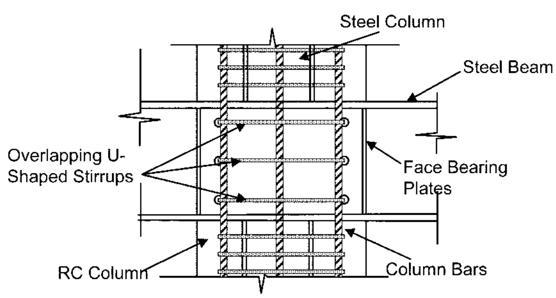


Fig. 6—Standard details in hybrid RCS connections.

descending tail similar to that of HPFRCCs with twisted steel fibers.

With regard to the response of HPFRCCs in compression, they also exhibit superior behavior with large strain capacity compared to regular concrete. Figure 4 shows compressive stress-strain curves obtained from PE fiber and hooked and twisted steel fiber HPFRCC cylinders. Also shown in Fig. 4 are idealized stress-strain curves for regular concrete with the same compressive strength (Ahmad 1981). Clearly, the ascending branch of HPFRCCs is softer compared to that of typical concretes due to the lack of coarse aggregate. The post-peak response, however, resembles that of a well-confined concrete and, as shown in Fig. 4, compression strain capacities larger than 1.0% in an unconfined state are possible with these materials. Thus, HPFRCC materials are not only attractive to increase shear strength and distortion capacity in structural members, but also to relax confinement reinforcement requirements in critical regions of earthquake-resistant structures while providing an adequate level of ductility (Campione, Mindess, and Zingone 1999; Parra-Montesinos, Peterfreund, and Chao 2005; Chompreda and Parra-Montesinos 2005).

TARGET APPLICATIONS FOR HPFRCC MATERIALS IN EARTHQUAKE-RESISTANT STRUCTURES

Because of the increase in construction costs associated with the addition of fibers to the cementitious matrix, HPFRCCs are generally intended for use only in critical regions where inelastic deformation demands may be large and substantial reinforcement detailing is required to ensure satisfactory behavior during an earthquake. In particular, the excellent tensile behavior exhibited by HPFRCC materials makes them attractive for members with shear-dominated response, such as beam-column connections, squat walls, and coupling beams, as well as in regions of flexural members subjected to large inelastic deformations combined with high shear, such as column and structural wall bases, and selected beam plastic hinge regions in frame structures (Fig. 5).

In the following, results from recent studies on the application of HPFRCCs in members subjected to large displacement reversals are discussed to illustrate their potential for improving structural performance while allowing for significant reductions to, or even elimination of, transverse reinforcement requirements.

Members with shear-dominated response

Because of the large tensile strength and strain capacity exhibited by HPFRCC materials, their use in members with a low aspect ratio offers an alternative to increase distortion capacity, shear strength, and damage tolerance. Several applications have been investigated at the University of Michigan—in particular, beam-column connections, low-rise walls, and coupling beams.

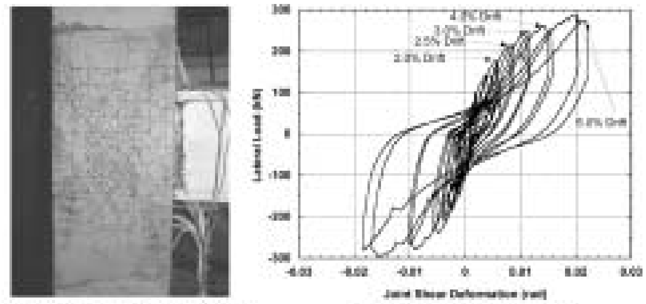
Beam-column connections—Beam-column connections of reinforced concrete frame structures are often subjected to large shear stress demands during earthquakes. To ensure adequate performance under load reversals, Joint ACI-ASCE Committee 352 recommendations (Joint ACI-ASCE Committee 352 2002) include special provisions for seismic detailing of beam-column connections. These provisions include substantial transverse reinforcement to provide confinement to the connection region, upper limits for joint shear stress, as well as minimum anchorage lengths for longitudinal beam and column bars. Traditionally, reinforced concrete beam-column connections have been designed following a strength-based approach. Recently, with the increasing attention paid to structural performance and damage estimation during earthquakes, several researchers have focused on studying not only the strength, but also the deformation capacity of reinforced concrete beam-column connections (Pantazopoulou and Bonacci 1992; Bonacci and Wight 1996; and Parra-Montesinos and Wight 2002). If damage is to be controlled in reinforced concrete connections, then joint shear distortions should be kept low, roughly below 0.5% for only minor to moderate damage, and below 1.0% to prevent severe damage. An alternate philosophy that could be followed in connection design consists of the use of highly damage-tolerant materials, such as HPFRCCs, to allow larger joint deformations yet with little damage, and thus relieving other structural members from large inelastic deformation demands during earthquakes.

The potential of HPFRCC materials for use in hybrid reinforced concrete column-steel beam (RCS) connections, and, more recently, in connections of reinforced concrete framed structures, was investigated by Parra-Montesinos and Wight (2000a,b), and Parra-Montesinos, Peterfreund, and Chao (2005), respectively. Figure 6 shows the details used in a standard RCS connection. In these RCS connections, the steel beam passes continuously through the reinforced concrete column. Connection confinement is commonly provided through overlapping U-shaped stirrups passing through holes drilled in the web of the steel beam. In addition, closely spaced stirrups are required just above and below the steel beam flanges to increase concrete bearing strength as well as to transfer shear to the regions of the connection outside the width of the beam flanges.

To eliminate the need for hoops over the beam depth, as well as to increase bearing damage tolerance, an HPFRCC material (referred to as engineered cementitious composite [ECC] [Li 1993]) was proposed for use in RCS connections by Parra-Montesinos and Wight (2000a,b). This ECC material contained PE fibers in a 1.5% volume fraction. One approximately 3/4-scale exterior beam-column subassembly was tested under large displacement reversals to evaluate the potential of HPFRCC materials as a replacement of joint transverse reinforcement. Figure 7(a) and (b) show the joint condition at the end of the test and the shear force versus shear deformation response of the ECC connection, respectively. As can be observed in Fig. 7(a), the specimen with ECC material exhibited a large number of hairline diagonal cracks with little damage at the end of the test (5.0% drift). In terms of shear distortion response (Fig. 7(b)), it is clear that the ECC connection exhibited excellent performance during the test, even though no transverse steel reinforcement was used in the connection region. The fact that the ECC connection sustained a peak shear distortion of approximately 2.0% with only little damage gives an indication of its outstanding damage tolerance. In addition, this HPFRCC connection was 50% stronger than a companion standard RCS connection constructed with overlapping U-shaped stirrups and regular concrete.

Figure 8(a) and (b) show a close look at the cracking pattern exhibited by a regular concrete RCS connection similar to that shown in Fig. 6 and the ECC connection, respectively. As can be seen, the regular concrete connection sustained severe damage with diagonal crack widths exceeding 5 mm. The ECC connection, on the other hand, exhibited a substantially larger number of cracks of much smaller widths compared to the regular concrete joint. While the cracks in the ECC connection were difficult to notice even at a few centimeters from the column face, the cracks in the regular concrete connection could easily be identified several meters away from the specimen. It is worth mentioning that only limited damage due to bearing of the steel beam on the surrounding concrete was observed in the ECC connection, contrary to the wide vertical cracks that formed in the front and back column faces of the regular concrete connection.

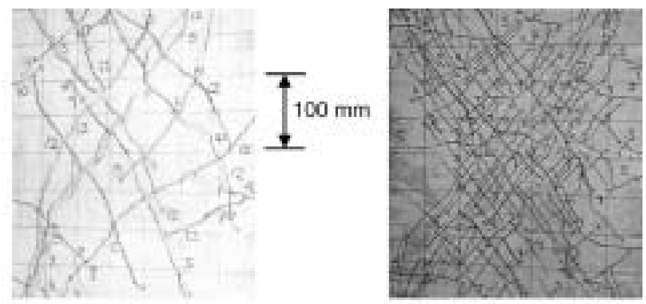
Similar results were obtained from the tests of two reinforced concrete beam-column connections in which confinement reinforcement was fully eliminated by using an HPFRCC material containing PE fibers in a 1.5% volume fraction (Parra-Montesinos, Peterfreund, and Chao 2005). These connections were able to sustain shear stress demands comparable to the maximum limit allowed in Chapter 21 of the ACI 318-02 (ACI Committee 318 2002) with only minor damage.



a) Cracking Pattern at 5.0% Drift

b) Shear Force versus Shear Distortion Response

Fig. 7—Behavior of hybrid RCS connection constructed with ECC material (Parra-Montesinos and Wight 2000a).



a) Regular Concrete Connection

b) ECC Connection

Fig. 8—Comparison of crack density and width in regular concrete and ECC RCS connections.

HPFRCC materials were also found to be effective in reducing slip of reinforcing bars passing through beam-column connections. In the tests of RCS and reinforced concrete beam-column connections, the bond between the steel reinforcing bars and the surrounding HPFRCC material remained almost intact even after bar yielding, preventing the occurrence of large concentrated rotations at the joint faces with the associated reduction in stiffness and energy dissipation capacity. For the case of reinforced concrete connections, a peak average bond stress of 10 MPa was calculated at bar tensile strains in excess of 1.0%.

Low-rise walls—HPFRCCs have been successfully used in lightly reinforced low-rise walls (Kim and Parra-Montesinos 2003) to increase their displacement capacity when subjected to large displacement reversals. Reinforced concrete squat walls exhibit limited drift capacities, typically below 1.0%. In addition, proper steel reinforcement detailing is required to avoid premature diagonal tension or compression failures, sliding shear failure, and crushing of the wall boundary regions. To evaluate the feasibility of increasing drift capacity in squat walls through the use of advanced cementitious materials, two low-rise walls with a shear span-to-depth ratio of 1.5 were recently tested by Kim and Parra-Montesinos (2003). One wall was constructed with an HPFRCC containing PE fibers in a 1.5% volume fraction, while the HPFRCC in the other specimen contained a 2.0% volume fraction of hooked steel fibers. Also, both wall specimens were designed to exhibit a diagonal tension failure with limited flexural yielding to better evaluate wall shear distortion capacity and contribution of fibers to shear strength. Vertical and horizontal reinforcement ratios of 0.21 and 0.13% were provided in each wall, which are lower than the minimum specified in the ACI Building Code (ACI Committee 318 2002). In addition, no confinement rein-

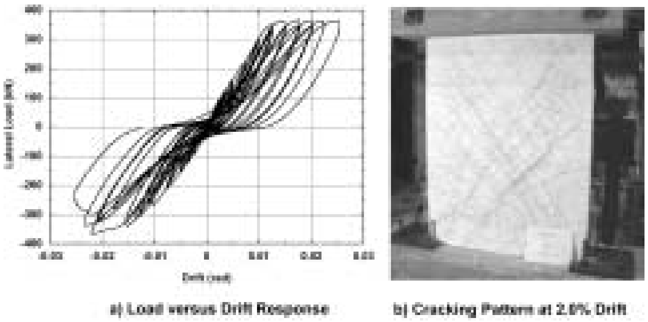


Fig. 9—Seismic behavior of HPFRCC low-rise walls (Kim and Parra-Montesinos 2003).

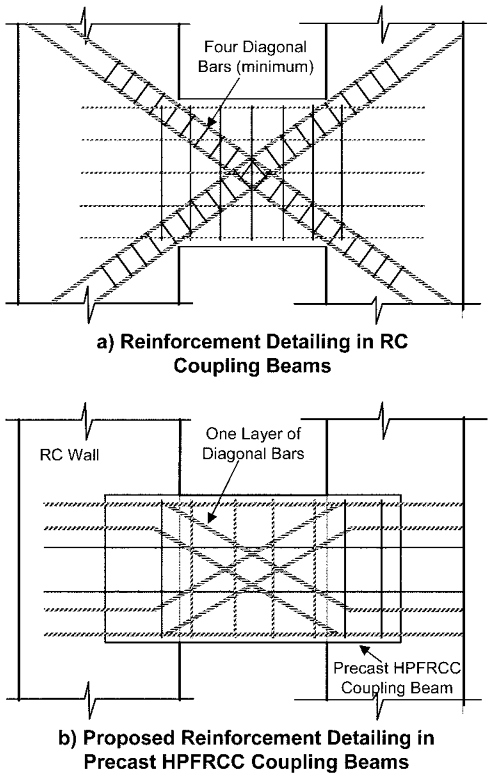


Fig. 10—Reinforcement detailing in RC and HPFRCC coupling beams (Canbolat, Parra-Montesinos, and Wight 2005).

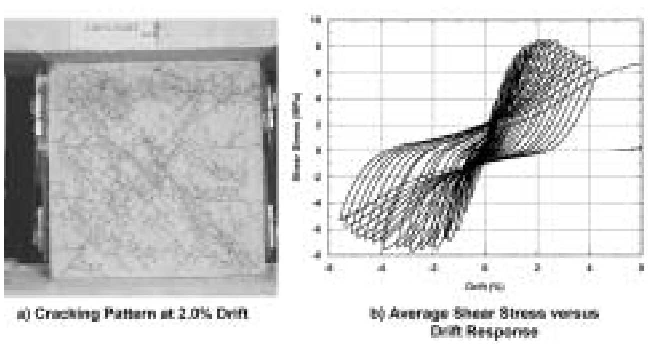


Fig. 11—Seismic behavior of HPFRCC coupling beams (Canbolat, Parra-Montesinos, and Wight 2005).

forcement was used in the wall boundary zones to evaluate the compression strain capacity of unconfined HPFRCC materials and their ability to provide lateral support to the main longitudinal bars.

Figure 9(a) and (b) show the lateral load versus drift response and the cracking pattern at 2.0% drift for the wall with PE fibers, which were similar to those in the steel fiber HPFRCC wall. As can be seen, this wall exhibited a drift capacity of 2.5% with only moderate damage at 2.0% drift. Ultimately, the fibers pulled out, leading to a diagonal tension failure. Even though a 2.5% drift could be considered well above any reasonable drift demand for a low-rise wall, larger drift capacities could have been obtained if the specimens were designed to sustain more significant flexural inelastic deformations. Besides increasing wall displacement capacity, the fibers in the concrete matrix contributed significantly to wall shear strength (estimated at approximately 80%). With regard to the behavior of the wall boundary zones, no significant distress was observed throughout the tests, even though no confinement reinforcement was provided and compression strains as large as 1.0% were attained at the extreme wall fibers. It is worth mentioning that even though the hysteretic behavior of both wall specimens was nearly identical, the HPFRCC wall with PE fibers exhibited a larger number of cracks of smaller width and larger damage tolerance compared to the wall with hooked steel fibers.

Coupling beams—Beams coupling structural walls have long represented a challenge for structural engineers due to the high shear demands imposed during earthquakes. During the 1970s, extensive research work was performed, primarily at the University of Canterbury by Paulay and collaborators (Paulay 1971; Paulay and Binney 1974), to develop reinforcement details that would ensure satisfactory behavior at large distortion demands. From these investigations, a new reinforcement detail for coupling beams that consists of diagonal reinforcement cages resembling a truss was developed (Fig. 10(a)). However, the stringent transverse reinforcement requirements for these diagonal cages often lead to severe reinforcement congestion with the associated construction difficulties. In addition, the diagonal reinforcement cages must lie on different planes, requiring an increase in coupling beam width.

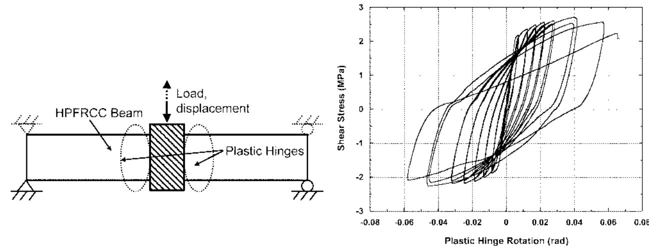
As an alternative to the traditional diagonally reinforced concrete coupling beams, the use of HPFRCCs was studied by Canbolat, Parra-Montesinos, and Wight (2005) to eliminate the need for transverse reinforcement around the main diagonal bars. Two HPFRCC materials were investigated: one with PE fibers in a 2.0% volume fraction, and the other with twisted steel fibers in a 1.5% volume fraction. Even though reinforcement requirements are simplified, the use of cast-in-place HPFRCC coupling beams would impose additional challenges from a construction viewpoint. Therefore, the use of precast HPFRCC beams, in combination with regular reinforced concrete structural walls, was proposed to facilitate construction and ensure adequate material quality control. Figure 10(b) shows the reinforcement details used in the HPFRCC coupling beam with twisted steel fibers. As can be observed, only one layer of diagonal reinforcement with no transverse reinforcement around it was used in the coupling beam. It should be mentioned that a reduction in diagonal reinforcement of HPFRCC coupling beams can be achieved without compromising shear strength due to the additional contribution of fibers to diagonal tension strength.

Figure 11(a) and (b) show the cracking pattern at 2.0% drift and the average shear stress versus drift response for the coupling beam with twisted steel fibers, respectively (Canbolat, Parra-Montesinos, and Wight 2005). As expected, an extensive number of diagonal cracks of small widths formed in the specimen during the early loading cycles, as opposed to the formation of a few wide diagonal cracks, which is typical of reinforced concrete coupling beams. This HPFRCC specimen sustained a peak shear stress demand of approximately 8.6 MPa ($1.1\sqrt{f_c'}$ MPa) up to 3.0% and 4.0% drift for the positive and negative loading directions, respectively. At larger drifts, a strength decay process began as the steel fibers pulled out. This strength decay was gradual, however, because the loss of diagonal tension capacity of the fiber cementitious material was partially compensated by an increase in the contribution from the diagonal bars, which by those drift levels were behaving in the strain-hardening range. The steel fiber HPFRCC coupling beam was cycled up to 6.0% drift, and then loaded monotonically up to 8.0% drift, the displacement at which fracture of the diagonal bars occurred. With regard to shear distortion capacity, this coupling beam sustained a distortion of 3.0% during the reversed loading cycles, and slightly larger than 6.0% during the final pushover. It should be mentioned that the HPFRCC material was effective in preventing buckling of the diagonal bars, even after damage localization occurred.

Flexural members under large shear reversals

In end regions of beams and columns of earthquake-resistant frame structures, a large number of closely spaced hoops are required to provide concrete confinement, shear resistance, and lateral support to longitudinal bars. Because of the degradation of shear-resisting mechanisms in flexural members under displacement reversals (Wight and Sozen 1975; Aschheim and Moehle 1992; Martín-Pérez and Pantazopoulou 1998), the ACI Building Code (ACI Committee 318 2002) requires the use of sufficient transverse steel reinforcement so that the shear strength developed through a truss mechanism is larger than the shear demand when plastic hinges form at beam ends. With regard to reinforced concrete columns, although some concrete contribution to shear strength may be assumed, stringent transverse reinforcement requirements are also specified in design codes. Thus, a research program was recently conducted at the University of Michigan (Chompreda and Parra-Montesinos 2005) to study the potential use of HPFRCCs to relax transverse reinforcement requirements in plastic hinge regions of flexural members.

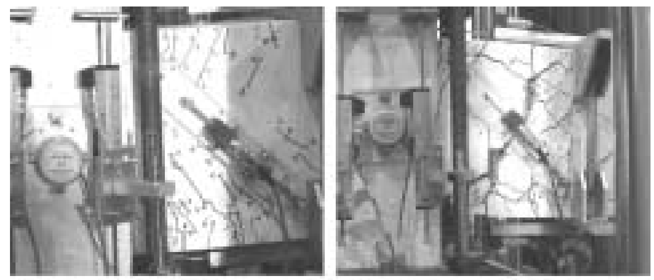
From reversed cyclic load tests of five HPFRCC flexural members with no axial load conducted by Chompreda and Parra-Montesinos (2005), as well as from test results reported by other researchers (Mishra and Li 1995; Fischer and Li 2002), it has become clear that HPFRCCs represent a viable alternative to reduce or even eliminate transverse reinforcement in plastic hinge regions. Figure 12 shows the test setup and a plot of average shear stress versus plastic hinge rotation response for a flexural member with no transverse reinforcement tested by Chompreda and Parra-Montesinos (2005). This member was constructed with an HPFRCC material reinforced with a 2.0% volume fraction of PE fibers and contained only longitudinal bars representing a 1.1% reinforcement ratio. As can be observed, this HPFRCC flexural member exhibited an excellent response with a peak shear stress of 2.7 MPa ($0.40\sqrt{f_c'}$, MPa) at plastic hinge rotations of up to 6.0%. With regard to damage tolerance, Fig. 13 shows the condition of the plastic hinge region in the HPFRCC member and in a reinforced concrete member designed according to Chapter 21 of



a) HPFRCC Beam Specimens

b) Average Shear Stress versus Plastic Hinge Rotation Response

Fig. 12—Behavior of HPFRCC flexural member with no transverse steel reinforcement (Chompreda and Parra-Montesinos 2005).



a) HPFRCC Member

b) RC Member

Fig. 13—Damage in HPFRCC and RC flexural members at 4.0% drift.

the ACI 318-02 (ACI Committee 318 2002) at 4.0% drift. As can be seen, even though a shear stress demand of 2.7 MPa was imposed to the HPFRCC specimen, only hairline diagonal cracks had formed in the plastic hinge region. On the other hand, the reinforced concrete specimen had sustained significant damage with wide flexural and diagonal cracks. It is worth mentioning that the HPFRCC material was effective in providing lateral support to the longitudinal beam bars up to a plastic hinge rotation of 4.0%. At large rotations, bar buckling initiated, which ultimately led to reinforcement fracture due to low-cycle fatigue. Therefore, depending on the expected rotation demands, the use of transverse reinforcement could be either discarded or provided in reduced amounts compared to that required by current building codes.

Seismic rehabilitation

Several investigations have been conducted to evaluate the feasibility of seismically upgrading structures through the use of FRCCs (Brunnhoeffer et al. 2000; Krstulovic-Opara et al. 2000; Griezic, Cook, and Mitchell 2001; Dogan and Krstulovic-Opara 2003). However, only a few studies have focused on the application of HPFRCC materials with low fiber volume fractions. Xia and Naaman (2002) evaluated the use of precast HPFRCC infill damper elements for seismic upgrading of steel structures. In that investigation, the middle region of the damper elements was designed with a reduced section, where most of the inelastic deformations were intended to occur. Figure 14 shows a picture of a specimen tested in that investigation. Research has also been conducted at Stanford University (Kesner and Billington 2004) on the use of HPFRCCs for seismic upgrading of deficient framed structures. In particular, the use of lightly reinforced precast HPFRCC infill panels to increase strength, stiffness, and energy dissipation capacity of existing steel framed structures was experimentally and analytically evaluated. Figure 15(a) shows a sketch of the

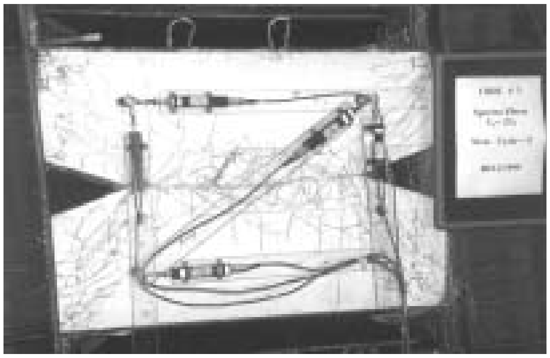


Fig. 14—HPFRCC damper element for seismic upgrading of steel structures (courtesy of Antoine E. Naaman).

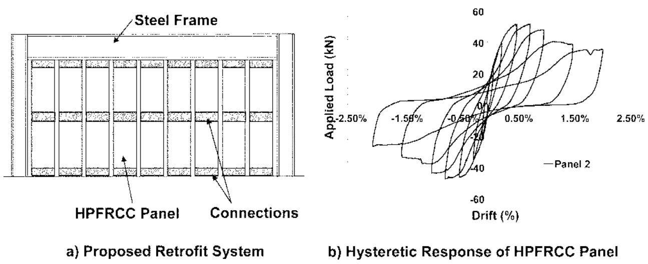


Fig. 15—HPFRCC precast panels for seismic upgrading of steel framed structures (Kesner and Billington 2004).

retrofit technique proposed by Kesner and Billington, which consists of the addition of light infill panels bolted to the beams of steel frames. The hysteretic behavior obtained from the test of an isolated HPFRCC infill panel is shown in Fig. 15(b). As can be seen, a stable response can be obtained in the precast panels with little reinforcement detailing up to a drift of approximately 1.5%, which, given the additional strength and stiffness added to the structure, should be sufficient to ensure adequate seismic behavior of the retrofitted framed structure.

CURRENT NEEDS

Although extensive work has been conducted on the use of advanced fiber cementitious materials in earthquake-resistant structures, there are still significant research needs from both material and structural viewpoints. In terms of material research, there is need to improve the workability of HPFRCCs with various fiber types such that they can be mixed and cast in large-scale operations using currently available construction techniques. Material research is also needed on the development of low-cost fibers and geometry optimization for high-performance response, as well as material constitutive models for a wide range of HPFRCCs under various loading conditions. It should be mentioned that some of this work is currently underway (for example, Han, Feenstra, and Billington 2003), and thus it is not unrealistic to expect these advanced materials to be widely available in the near future.

To be in tune with performance-based seismic design procedures, behavioral and design models not only for strength prediction but also for deformation and damage estimations are required for various structural applications of HPFRCCs. To achieve this goal, damage progress models, correlated with various performance states, need to be developed for flexural and shear-critical members. In addition, design guidelines are needed such that appropriate relaxations in conventional transverse reinforcement requirements can be applied based on expected demands without compromising structural safety. Parallel to these developments, extensive experimental research on behavior of HPFRCC members under displacement reversals is essential for calibration of performance-based design models.

SUMMARY AND CONCLUSIONS

A brief overview of recent and potential applications of HPFRCCs in earthquake-resistant structures is given in this paper. Because of their tensile strain-hardening response, HPFRCC materials are ideal for use in members with shear-dominated behavior or in flexural members under high shear stresses, for which substantial reinforcement detailing is required to ensure adequate seismic behavior. In addition, the large compression strain capacity of HPFRCCs makes these materials attractive for reducing the amount of confinement reinforcement required to increase concrete ductility. Through results from several experimental investigations, it has been shown that HPFRCC materials represent a viable alternative to enhance structural performance in members subjected to large displacement reversals. In particular, HPFRCC materials were shown to increase shear strength, displacement capacity, and damage tolerance of flexural and shear-critical members, even when little or no transverse reinforcement was used.

HPFRCC members with shear-dominated response possess excellent shear distortion and damage tolerance capacity, as evidenced by test results of beam-column connections, low-rise walls, and coupling beams. HPFRCC materials have also shown tremendous potential for use in plastic hinge regions of flexural members. Beam plastic hinge regions with no transverse reinforcement under reversed cyclic shear stresses as high as $0.4\sqrt{f'_c}$ (MPa) have exhibited rotation capacities of up to 6.0% with no significant shear strength decay. In addition, compression strain capacities in excess of 1.0% have been measured in unconfined HPFRCC members. All of this indicates that substantial reductions or even elimination of transverse reinforcement requirements are possible through the use of HPFRCC materials.

In summary, it has been shown that HPFRCC materials represent a feasible alternative for use in earthquake-resistant structures when limited displacement capacity and damage tolerance, and/or significant reinforcement congestion are the result of current practice. The development of design guidelines, however, is necessary for the safe an optimum use of these materials in large-scale structural applications.

ACKNOWLEDGMENTS

The author would like to acknowledge the support of the National Science Foundation and the University of Michigan, which have provided funding for several of the research programs referred to in this paper. Ongoing work at the University of Michigan is funded by the National Science Foundation under Grant No. CMS 0324519, CMS 0001617, CMS 0421180, and CMS 0408623. The opinions expressed in this paper are those of the author and do not necessarily reflect the views of the sponsor. The suggestions of Antoine E. Naaman and James K. Wight are greatly appreciated. The author would also like to thank Kulsiri Chandrangsu, B. Afsin Canbolat, Kwang Yeon Kim, Sean Peterfreund, Shih-Ho Chao, and Praveen Chompreda for providing some of the material data presented in this paper and contributing as researchers to several of the projects discussed in this paper.

REFERENCES

ACI Committee 318, 2002, "Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (318R-02)," American Concrete Institute, Farmington Hills, Mich., 443 pp.

Adebar, P.; Mindess, S.; St.-Pierre, D.; and Olund, B., 1997, "Shear Tests of Fiber Concrete Beams without Stirrups," *ACI Structural Journal*, V. 94, No. 1, Jan.-Feb., pp. 68-76.

Ahmad, S. H., 1981, "Properties of Confined Concrete under Static and Dynamic Loads," PhD thesis, University of Illinois at Chicago Circle, Department of Materials Engineering, Chicago.

Aschheim, M., and Moehle, J. P., 1992, "Shear Strength and Deformability of RC Bridge Columns Subjected to Inelastic Cyclic Displacements," *Report* No. UCB/EERC-92/04, Earthquake Engineering Research Center, University of California at Berkeley, Berkeley, Calif.

Balaguru, P. N., and Shah, S. P., 1992, *Fiber Reinforced Cement Composites*, McGraw-Hill, Inc., 530 pp.

Bayasi, Z., and Gebman, M., 2002, "Reduction of Lateral Reinforcement in Seismic Beam-Column Connection via Application of Steel Fibers," *ACI Structural Journal*, V. 99, No. 6, Nov.-Dec., pp. 772-780.

Bonacci, J. F., and Wight, J. K., 1996, "Displacement-Based Assessment of Reinforced Concrete Frames in Earthquakes," *Mete A. Sozen Symposium: A Tribute from His Students*, SP-162, J. K. Wight and M. E. Kreger, eds., American Concrete Institute, Farmington Hills, Mich., pp. 117-138.

Brunnhoeffer, G. C.; Farrell, M. B.; Hawkins, N. M.; Gamble, W. L.; and Shkurti, F. P., 2000, "Repair of Reinforced Concrete Columns Using Steel Fiber Mat Reinforced Slurry Concrete," *High-Performance Fiber-Reinforced Concrete in Infrastructural Repair and Retrofit*, SP-185, N. Krstulovic-Opara and Z. Bayasi, eds., American Concrete Institute, Farmington Hills, Mich., pp. 187-205.

Campione, G.; Mindess, S.; and Zingone, G., 1999, "Compressive Stress-Strain Behavior of Normal and High-Strength Carbon-Fiber Concrete Reinforced with Steel Spirals," *ACI Materials Journal*, V. 96, No. 1, Jan.-Feb., pp. 27-34.

Canbolat, B. A.; Parra-Montesinos, G. J.; and Wight, J. K., 2005, "Experimental Study on the Seismic Behavior of High-Performance Fiber-Reinforced Cement Composite Coupling Beams," *ACI Structural Journal*, V. 102, No. 1, Jan.-Feb., pp. 159-166.

Chompreda, P., and Parra-Montesinos, G. J., 2005, "Deformation Capacity and Shear Strength of Fiber Reinforced Cement Composite Flexural Members Subjected to Displacement Reversals," *Report* No. UMCEE 05-03, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Mich.

Dogan, E., and Krstulovic-Opara, N., 2003, "Seismic Retrofit with Continuous Slurry-Infiltrated Mat Concrete Jackets," *ACI Structural Journal*, V. 100, No. 6, Nov.-Dec., pp. 713-722.

Filiatrault, A.; Pineau, S.; and Houde, J., 1995, "Seismic Behavior of Steel Fiber-Reinforced Concrete Interior Beam-Column Joints," *ACI Structural Journal*, V. 92, No. 5, Sept.-Oct., pp. 543-552.

Fischer, G., and Li, V. C., 2002, "Effect of Matrix Ductility on Deformation Behavior of Steel-Reinforced ECC Flexural Members under Reversed Cyclic Loading Conditions," *ACI Structural Journal*, V. 99, No. 6, Nov.-Dec., pp. 781-790.

Griezic, A.; Cook, W. D.; and Mitchell, D., 2001, "Seismic Behavior and Retrofit of Outrigger Beam-Column Frames," *Journal of Bridge Engineering*, ASCE, V. 6, No. 5, pp. 340-348.

Han, T.-S.; Feenstra, P. H.; and Billington, S. L., 2003, "Simulation of Highly Ductile Fiber-Reinforced Cement-Based Composite Components under Cyclic Loading," *ACI Structural Journal*, V. 100, No. 6, Nov.-Dec., pp. 749-757.

Henager, C. H., 1977, "Steel Fibrous, Ductile Concrete Joint for Seismic-Resistant Structures," *Reinforced Concrete Structures in Seismic Zones*, SP-53, N. M. Hawkins and D. Mitchell, eds., American Concrete Institute, Farmington Hills, Mich., pp. 371-379.

Jiuru, T.; Chaobin, H.; Kaijian, Y.; and Yongcheng, Y., 1992, "Seismic Behavior and Shear Strength of Framed Joint using Steel-Fiber Reinforced Concrete," *Journal of Structural Engineering*, ASCE, V. 118, No. 2, pp. 341-358.

Joint ACI-ASCE Committee 352, 2002, "Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures (ACI 352R-02)," American Concrete Institute, Farmington Hills, Mich., 37 pp.

Kesner, K. E., and Billington, S. L., 2004, "Tension, Compression, and Cyclic Testing of Engineered Cementitious Composite Materials," *Technical Report* MCEER-04-0002, Multi-disciplinary Center for Earthquake Engineering Research, State University of New York at Buffalo, 122 pp.

Kim, K., and Parra-Montesinos, G., 2003, "Behavior of HPFRCC Low-Rise Walls Subjected to Displacement Reversals," *High Performance Fiber Reinforced Cement Composites (HPFRCC 4)*, Proceedings of the Fourth International RILEM Workshop, A. E. Naaman and H. W. Reinhardt, eds., RILEM Publications S.A.R.L., Cachan Cedex, France, pp. 505-515.

Krstulovic-Opara, N., 1999, "Use of SIMCON in Seismic Retrofit and New Construction," *High Performance Fiber Reinforced Cement Composites (HPFRCC 3)*, Proceedings of the Third International RILEM Workshop, H. W. Reinhardt and A. E. Naaman, eds., RILEM Publications S.A.R.L., Cachan Cedex, France, May, pp. 629-649.

Krstulovic-Opara, N.; LaFave, J. M.; Dogan, E.; and Uang, C.-M., 2000, "Seismic Retrofit with Discontinuous Slurry Infiltrated Mat Concrete (SIMCON) Jackets," *High-Performance Fiber-Reinforced Concrete in Infrastructural Repair and Retrofit*, SP-185, N. Krstulovic-Opara and Z. Bayasi, eds., American Concrete Institute, Farmington Hills, Mich., pp. 141-185.

Krstulovic-Opara, N., and Malak, S., 1997, "Tensile Behavior of Slurry-Infiltrated Mat Concrete (SIMCON)," *ACI Materials Journal*, V. 94, No. 1, Jan.-Feb., pp. 39-46.

Li, V. C., 1993, "From Micromechanics to Structural Engineering—The Design of Cementitious Composites for Civil Engineering Applications," *JSCE Journal of Structural Mechanics and Earthquake Engineering*, V. 10, No. 2, pp. 37-48.

Martín-Pérez, B., and Pantazopoulou, S. J., 1998, "Mechanics of Concrete Participation in Cyclic Shear Resistance of RC," *Journal of Structural Engineering*, ASCE, V. 124, No. 6, pp. 633-641.

Mishra, D., and Li, V. C., 1995, "Performance of a Ductile Plastic Hinge Designed with an Engineered Cementitious Composite," *UMCEE Report* No. 95-06, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Mich.

Naaman, A. E., 1987, "High-Performance Fiber-Reinforced Cement Composites," *Concrete Structures for the Future*, IABSE Symposium, Zurich, pp. 371-376.

Naaman, A. E., 1999, "Fibers with Slip Hardening Bond," *High Performance Fiber Reinforced Cement Composites (HPFRCC 3), Proceedings of the Third International RILEM Workshop*, H. W. Reinhardt and A. E. Naaman, eds., RILEM Publications S.A.R.L., Cachan Cedex, France, May, pp. 371-385.

Naaman, A. E.; Paramasivam, P.; Balazs, G.; Bayasi, Z. M.; Eibl, J.; Erdelyi, L.; Hassoun, N. M.; Krstulovic-Opara, N.; Li, V. C.; and Lohrmann, G., 1996, "Reinforced and Prestressed Concrete using HPFRCC Matrices," *High Performance Fiber Reinforced Cement Composites 2 (HPFRCC 2)*, Proceedings of the Second International RILEM Workshop, A. E. Naaman and H. W. Reinhardt, eds., E&FN Spon, London, pp. 291-347.

Naaman, A. E., and Reinhardt, H. W., 1996, "Characterization of High Performance Fiber Reinforced Cement Composites—HPFRCC," *High Performance Fiber Reinforced Cement Composites 2 (HPFRCC 2)*, Proceedings of the Second International RILEM Workshop, A. E. Naaman and H. W. Reinhardt, E&FN Spon, London, pp. 1-24.

Pantazopoulou, S., and Bonacci, J., 1992, "Consideration of Questions about Beam-Column Joints," *ACI Structural Journal*, V. 89, No. 1, Jan.-Feb., pp. 27-36.

Parra-Montesinos, G., 2003, "HPFRCC in Earthquake Resistant Structures: Current Knowledge and Future Trends," *High Performance Fiber Reinforced Cement Composites 4 (HPFRCC 4)*, Proceedings of the Fourth International RILEM Workshop, A. E. Naaman and H. W. Reinhardt, eds., RILEM Publications S.A.R.L., Cachan Cedex, France, pp. 453-472.

Parra-Montesinos, G. J.; Peterfreund, S. W.; and Chao, S.-H., 2005, "Highly Damage-Tolerant Beam-Column Joints Through Use of High-Performance Fiber-Reinforced Cement Composites," *ACI Structural Journal*, V. 102, No. 3, May-June, pp. 487-495.

Parra-Montesinos, G., and Wight, J. K., 2000a, "Seismic Behavior, Strength and Retrofit of RC Column-to-Steel Beam Connections," *Report* No. UMCEE 00-09, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Mich., 296 pp.

Parra-Montesinos, G., and Wight, J. K., 2000b, "Seismic Response of Exterior RC Column-to-Steel Beam Connections," *Journal of Structural Engineering*, ASCE, V. 126, No. 10, pp. 1113-1121.

Parra-Montesinos, G., and Wight, J. K., 2002, "Prediction of Strength and Shear Distortion in R/C Beam-Column Joints," *S. M. Uzumeri Symposium: Behavior and Design of Concrete Structures for Seismic Performance*, SP-197, S. A. Sheikh and O. Bayrak, eds., American Concrete Institute, Farmington Hills, Mich., pp. 191-214.

Paulay, T., 1971, "Coupling Beams of Reinforced Concrete Shear Walls," *Journal of the Structural Division*, ASCE, V. 97, No. ST3, pp. 843-862.

Paulay, T., and Binney, J. R., 1974, "Diagonally Reinforced Coupling Beams of Shear Walls," *Shear in Reinforced Concrete*, SP-42, V. 1, American Concrete Institute, Farmington Hills, Mich., pp. 579-598.

Vasconez, R. M.; Naaman, A. E.; and Wight, J. K., 1998, "Behavior of HPFRC Connections for Precast Concrete Frames Under Reversed Cyclic Loading," *PCI Journal*, V. 43, No. 6, pp. 58-71.

Wight, J. K., and Sozen, M. A., 1975, "Strength Decay of R.C. Columns Under Shear Reversals," *Journal of the Structural Division*, ASCE, V. 101, No. ST5, pp. 1053-1065.

Xia, Z., and Naaman, A. E., 2002, "Behavior and Modeling of Infill Fiber-Reinforced Concrete Damper Element for Steel-Concrete Shear Wall," *ACI Structural Journal*, V. 99, No. 6, Nov.-Dec., pp. 727-739.

Yoon, J. K., and Billington, S. L., 2002, "Experimental and Numerical Studies of Precast Unbonded Post-Tensioned Bridge Columns with Engineered Cementitious Composites," *Research Report 02-03*, Cornell University, Ithaca, N.Y.