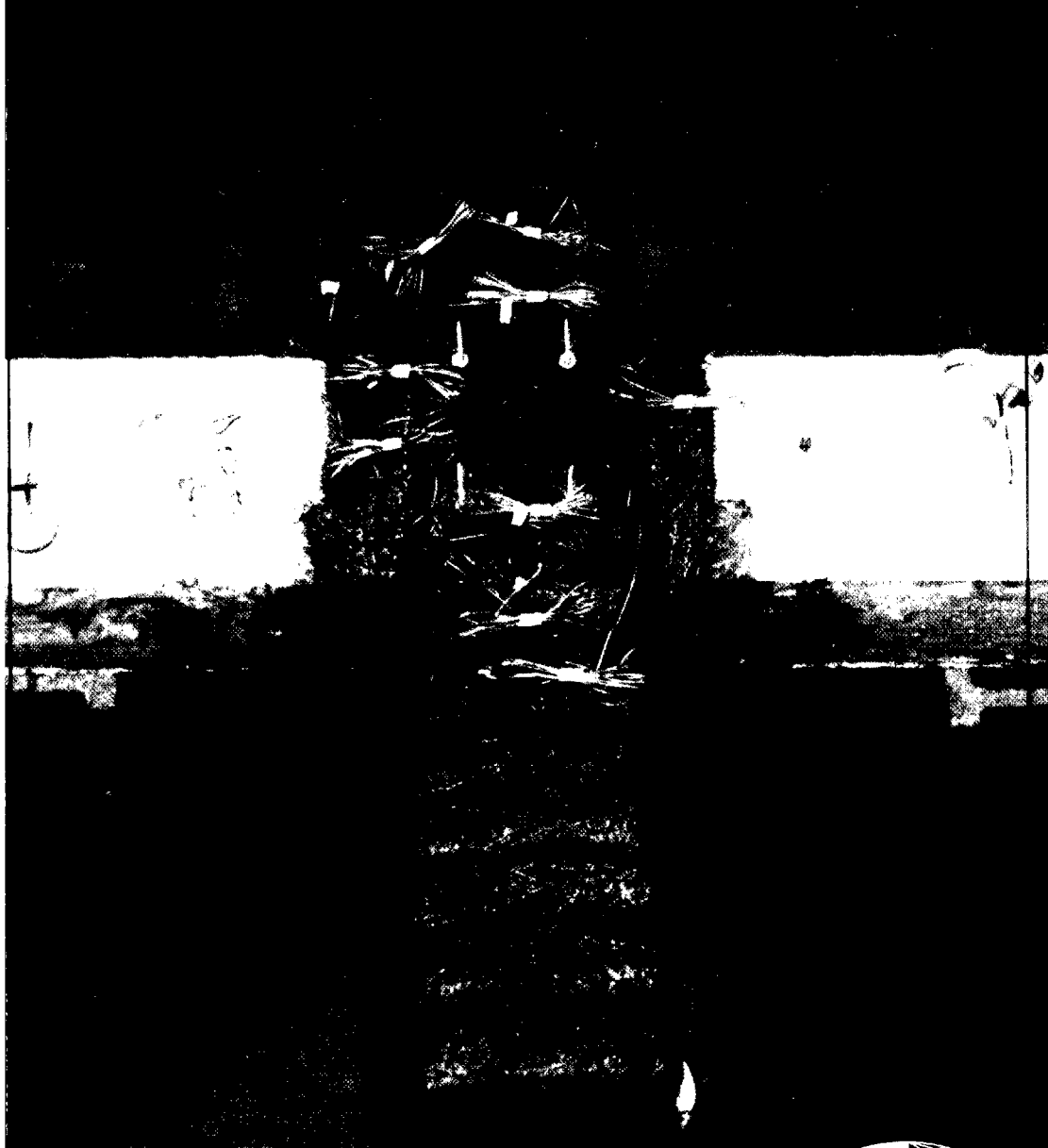


High-Performance Fiber-Reinforced Concrete

In Infrastructural Repair and Retrofit



SP-185 Editors: Neven Krstulovic,
Opara and Ziad Bayasi

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High-Performance Fiber-Reinforced Concrete in Infrastructural Repair and Retrofit

Editors

Neven Krstulovic-Opara
Ziad Bayasi
SP-185



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PREFACE

A rapidly aging and deteriorating civil infrastructure has created one of the major challenges facing the United States and its construction industry today. Since the cost of civil infrastructure constitutes a major portion of the national wealth, the development of long-lasting and cost-effective repair and retrofit solutions is essential for the well-being of the nation's economy in the next century. A promising way of addressing this issue is to use advanced composites such as high-performance fiber-reinforced concretes (HPFRCs), which exhibit features essential for long-lasting and cost-effective repair and retrofit solutions: high tensile strength, high ductility, and high durability.

Laboratory studies and field applications clearly show that HPFRC can be used to improve the performance of civil engineering infrastructure in a cost-effective manner. Due, however, to limited availability of information on: (a) the performance of HPFRC-based infrastructural repair and retrofit, and (b) specific design and construction guidelines, this novel material has not yet been widely used in the field. Therefore, the objective of this publication is to provide practicing engineers and specialists with state-of-the-art information on the mechanical properties and use of HPFRCs in infrastructural repair and retrofit.

Although it may be difficult to define a "high-performance" material or structure, the term "high-performance fiber-reinforced composites" (HPFRCs) is used herein to define fiber-reinforced concretes (FRCs) that in direct tension exhibit strain hardening and multiple cracking, leading to significantly increased tensile strength, ductility, and energy-absorption capacity. Materials such as slurry infiltrated fiber concrete (SIFCON) and slurry infiltrated mat concrete (SIMCON) fit this definition. However, as demonstrated in some papers in this publication, "high-performance" infrastructural repair or retrofit can also be achieved using "conventional" FRCs that do not exhibit pronounced strain hardening. "High-performance" repair and retrofit with "conventional" FRC are thus also addressed in this publication. Finally, FRCs and HPFRCs are not the only advanced composites that can be successfully used for durable and cost-effective infrastructural repair or retrofit. Other advanced composites, such as fiber-reinforced polymers, have also been used for this purpose. Therefore, while the main focus of this publication is on the use of advanced cement-based composites, it also includes a review paper on the use of fiber-reinforced polymer composites in infrastructural repair and retrofit.

Editors

Neven Krstulovic-Opara
Ziad Bayasi

DEDICATION
James P. Romualdi
1929-1993



This symposium volume is dedicated to Dr. James P. Romualdi, Professor of Civil Engineering, Carnegie Mellon University, for his many contributions to the research, development, and application of steel fiber reinforcement concrete and ferrocement. Dr. Romualdi was an educator, researcher, consulting engineer, and entrepreneur. Nearly all of his adult years were connected in some way to Carnegie Mellon University: he received his BS, MS, and PhD from Carnegie Institute of Technology, now Carnegie Mellon University, and joined the faculty of the Department of Civil Engineering, Carnegie Mellon University in 1955, where he was an active member until his death. He was also a member of several professional societies, including ACI, ASCE, NSPE, ASTM, and ASEE.

Dr. Romualdi's idea of applying linear elastic fracture mechanics to explain the mechanical properties of concrete with closely spaced steel reinforcement, developed in the late 1950s and early 1960s, was the beginning of the current worldwide interest in and application of a great array of fiber-reinforced cementitious materials. Like many developments in mechanics, Dr. Romualdi's crack arrest concept grew out of his earlier work on the effect of stiffeners and stiffener rivets on the growth and arrest of crack in large, stressed aluminum plates. He recognized the similarity between the arrest mechanism in a cracked and stiffened aluminum plate with the crack arrest mechanism in concrete made with closely spaced reinforcement. His concept of crack arrest by low volume of closely spaced, steel fibers incorporated in concrete was the basis of his patent for steel fiber-reinforced concrete. This concept also provided an explanation for the mechanical properties of ferrocement, material developed by Nervi in Italy before World War II and used by Nervi in the construction of many buildings and boats. The interest of the concrete engineering community in the concepts developed by Dr. Romualdi led to the formation of ACI Committee 549, Ferrocement (now titled Ferrocement and Other Thin Sheet Products) and ACI Committee 544, Fiber-Reinforced Concrete. Dr. Romualdi was a founding member and chairman of both committees.

Both as a student and throughout his professional career, Dr. Romualdi received many awards including a Fullbright Fellowship at the Technische Hochschule Karlsruhe, Germany, in 1954-55. He was also honored by the Pittsburgh Section of ASCE as the Young Civil Engineer of the Year. As an entrepreneur, Dr. Romualdi was a principal of D'Appolonia Associates, partner in GAI Consultants, and president of Romualdi, Davidson, and Associates. From 1966 to 1979, Dr. Romualdi also served as Director of the Transportation Research Institute, Carnegie Mellon University. As an educator he was very interested in both undergraduate and graduate education. Many of his students remember him as a teacher who made them think and helped them develop creative and innovative solutions. His speaking and writing style was clear, precise, and logical. The first draft of a paper was usually the final written version. These speaking and writing abilities contributed to his success as a teacher, consulting engineer, and forensic expert.

Dr. Romualdi and his wife, Diana, have three children: twin daughters Jean and Jessica, and a son John. He loved to sail and spent as much time as possible at their summer home on Martha's Vineyard.

This symposium volume honors an innovative, entrepreneurial teacher and civil engineer whose contributions to fiber-reinforced concrete and ferrocement will be of lasting value.

Dr. Gordon Batson
Professor of Civil and Environmental Engineering
Clarkson University

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SP 185-1

HPFRCCs: Properties and Applications in Repair and Rehabilitation

by A. E. Naaman

Synopsis: Following a brief introduction on the definition of high-performance fiber reinforced cement composites (HPFRCCs), this paper suggests that HPFRCCs are very well suited for repair and rehabilitation applications. It describes the range of tensile properties currently achievable using HPFRCCs, focusing in particular on the trade-off between strength and strain capacity and the importance of large strains, as evidenced by quasi-strain hardening behavior and multiple cracking. Particular attention is given to describing the tensile stress-strain response of slurry infiltrated fiber concrete (SIFCON), and the parameters influencing that response such as type of fiber, type of matrix, fiber orientation, fiber length, and fiber bond. Also a brief summary of three representative applications involving the use of HPFRCCs in repair and rehabilitation is given, namely: the use of fibers in the tensile zone area of reinforced concrete beams to control cracking and improve durability; the use of SIMCON for repair and rehabilitation of reinforced concrete beams and columns to satisfy seismic requirements; and the use of SIMCON as a jacket in reinforced concrete columns, also to improve seismic resistance. It is concluded that exceptional structural performance such as strength and ductility, particularly in reinforced and prestressed concrete structures, can be achieved if the matrix material is an HPFRC composite.

Keywords: composite materials; fiber-reinforced concrete; HPFRCC; rehabilitation; repair; SIFCON; SIMCON; tensile properties

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1. BACKGROUND AND JUSTIFICATION

1.1 Definition of HPFRCCs

Conventional fiber reinforced concrete (FRC) is nowadays a well established material. High Performance Fiber Reinforced Cement Composites (HPFRCCs) are a class of fiber reinforced concrete. Although it is difficult to set a fixed limit for what makes fiber reinforced concrete a "high performance" material, one approach has been to define a lower bound limit based on the shape of its stress-strain response in tension. If the stress-strain curve shows a quasi strain hardening (or pseudo-strain hardening) behavior (i.e. a post-cracking strength larger than the cracking strength, or elastic-plastic response or better) then high performance is achieved (Fig.1). Quasi-strain hardening behavior is generally accompanied by multiple cracking and related large energy absorption capacity. Another way to define the lower limit of high performance, is when localization of damage occurs immediately following first cracking of the concrete matrix, and leads to failure. Typically, conventional fiber reinforced concrete as used so far in pavement applications does not qualify as high performance. Two recent symposia were devoted to the characterization, properties and applications of HPFRCCs; the reader is referred to related references for further information [13, 16].

1.1 Applications of HPFRCC

Applications of high performance fiber reinforced cement composites can be grouped according to the following (Fig. 2): 1) stand-alone applications in light structural elements such as cement boards, corrugated sheets, and roofing tiles, 2) selected zones of structures where their enhanced properties are needed, such as in the connection regions of seismic resistant frames (Fig. 3), 3) new structures or structural elements in combination with conventional reinforced and prestressed concrete, such as in super high rise buildings, and 4) in repair and rehabilitation work such as in bridge decks, bridge piers and columns (Fig. 4). Fibers are added to reinforced or prestressed concrete structures for many reasons, among which to improve energy absorption, toughness, ductility, cracking, shear resistance, and durability (Fig. 5). Such properties are also essential in repair applications.

1.2 Some Background on Conventional FRC Composites

The use of conventional fiber reinforced concrete in combination with reinforcing bars and prestressing tendons has been so far relatively limited in comparison to its use in stand-alone applications. Numerous studies have concluded of the beneficial effects of adding fibers to improve the flexural response, ductility, shear, torsion, and impact resistance of reinforced and prestressed concrete structures. In most cases, a relatively low fiber content was used (steel fibers in less than 1.5% by volume), and the improvement due to fiber reinforcement was relatively small, suggesting difficult choices of trade-off between additional cost and improved performance. While the additional cost of fiber reinforcement may be given as the main reason for such slow progress, there is also evidence that the use of low end fiber reinforced concrete did not satisfy convincingly the expected performance. Examples include the early application of fiber reinforced concrete in the punching shear zones around columns in slab systems, and the beam-column connections in seismic frames. However, high fiber content fiber reinforced concrete such as SIFCON was extensively used in military applications suggesting that there are cases where the use of HPFRCC is justified in spite of cost. It is believed that in order for fiber reinforced concrete to truly penetrate the reinforced and prestressed concrete market, whether in combination with new structures or repair of existing structures, it must provide significantly improved performance to the structure; the particular characteristic of HPFRCC to develop multiple cracking and quasi-strain hardening behavior with substantial energy dissipation may indeed be the answer to such development.

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1.3 Properties of Interest in Repair Applications

High performance fiber reinforced cement composites have been used in applications involving repair, retrofit and strengthening such as in tunnel lining by shotcreting, primary and secondary linings, spillway repair, expansion joints, and cover repair for beams and columns where fibers are used alone or in combination with continuous meshes. Properties of particular interest in such applications include the ability of the repair material to accommodate differential elastic moduli and thermal expansion, as well as the ability to provide good ductility, good crack distribution, and small crack widths. The large strain capacity of HPFRCCs and their excellent multiple cracking behavior in tension allow them to satisfy such requirements.

1.4 Cost Considerations

The cost of repair and rehabilitation is always, in relative terms, substantially higher than the cost of the initial structure. Repair generally requires a relatively small volume of repair materials but a relatively high commitment in labor. Moreover the cost of labor in developed countries is so high that the cost of material becomes secondary. Thus the highest the performance of the repair material is, the more effective is the repair in the long run. This implies that material cost is not really an issue and that the fact that HPFRCCs demand generally high fiber content is not a constraining drawback.

1.5 Organization of this Paper

This paper provides first a description of the range of tensile properties currently achievable using HPFRCCs followed by a brief summary of three representative applications involving the use of HPFRCC in repair and rehabilitation. They include the use of fibers in the tensile zone area of reinforced concrete beams to control cracking and improve durability [11]; the use of SIMCON for repair and rehabilitation of reinforced concrete beams and columns to satisfy seismic requirements [6-10]; and the use of SIMCON as a jacket in reinforced concrete columns, also to improve seismic resistance [5].

2. TENSILE PROPERTIES OF HPFRCCs

Figure 1 shows a typical tensile stress-strain response of HPFRCCs. Of particular interest are the stress and strain coordinates of points A and B. Real curves can be developed to provide a wide range of coordinates

For instance, Li [3] has developed a very ductile fiber reinforced cement composite (which he defines as engineered cementitious composite, ECC) with a relatively large strain capacity and a large fracture energy (Fig. 6). Such properties were achieved using only 2% by volume of polyethylene fibers (Spectra fibers). Also the composite developed a superior multiple cracking behavior. Li suggested that such a composite can be used in the tensile zone of reinforced concrete beams to control crack widths. It can be argued that the same conclusion holds if the material is used as a repair material to replace the cover of concrete in beams or columns after spalling of the concrete cover due to corrosion of reinforcement.

The composite described by Li (Fig. 6) has a large strain capacity but a relatively low tensile strength. As in many other materials, higher strength can be achieved at the expense of ductility. Naaman et al. developed a wide variety of SIFCON (Slurry Infiltrated Fiber Concrete) composites using relatively high volume fractions of steel fibers. Details of the experimental procedure are given in [12,14,15]. The ascending branch of two typical stress-strain curves obtained from direct tensile tests are shown in Fig. 7. Figures 8a to 8d provides a number of stress-elongation curves where various parameters are explored, such as the effect of fiber orientation, the effect of fiber length and volume fraction, the effect of different slurry matrices, and the effect of using two different fibers, a deformed and a hooked steel fiber. Finally Fig. 9 shows that, because of the strong

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mechanical component of bond present in deformed fibers such as hooked fibers, quasi-strain hardening behavior can be achieved even if fibers are sprayed with a silicon debonding agent. Figures 7 to 9 illustrate the range of characteristics that can be achieved in SIFCON, namely a tensile strength that can exceed 4000 psi (28 MPa) at maximum strain capacity of the order of 1%. In selected special cases [12,15], the tensile strength exceeded 5 ksi (35 MPa). To the best of the author's knowledge, no higher strength has been ever reported in the technical literature especially as obtained from similar size specimens subjected to direct tension.

In SIFCON the fibers are preplaced in the mold to form a fiber network which is then infiltrated by a fine slurry matrix. The SIFCON process may not be very effective in repair applications. A relatively new process called SIMCON (Slurry Infiltrated Mat Concrete) developed by Hackman et al. [4] may be more suitable. SIMCON is made by infiltrating continuous steel fiber-mats, with a specially designed cement-based slurry [1,2]. An important advantage of continuous fiber-mats is the increased fiber length and fiber aspect ratio, which lowers the critical fiber volume fraction necessary to achieve strain hardening. SIMCON has been reported to reach tensile strengths of up to 17 MPa at strains of up to 1.5% with only 5.29% fiber volume fraction [6-10]. Distribution and orientation of fibers within fiber-mats can also be more accurately controlled, which further increases fiber efficiency. Finally, continuous fiber-mats, which are conveniently delivered in large rolls, can be easily installed by wrapping around or laying over existing reinforced concrete elements. Application in several projects involving repair of beam columns connections for seismic retrofit are reported by Krstulovic et al. Applications involving wrapping of columns for confinement and seismic retrofit are reported by Hackman [5]. A typical tensile stress-strain curve of SIMCON is given in Fig. 10 [6].

Figure 11 is a composite figure developed from Figs. 6 to 10 to compare the range of tensile stress-strain curves of HPFRCCs reported in the technical literature. Only the ascending branch of each curve can be used to translate elongation into strain. It can be observed that a gain in strength generally leads to a loss in strain capacity and vice-versa. It can also be observed that HPFRCCs generally offer a wide range of properties which can be beneficially used in repair and rehabilitation applications.

3. EXAMPLES OF APPLICATIONS

3.1 Repair and Rehabilitation of Beam-Column Connections Using SIMCON

As part of an NSF Earthquake Hazard Mitigation Project on "Repair and Rehabilitation of Non-Ductile R.C. Frames Using High Performance Fiber Reinforced Cement Composites," Krstulovic-Opara and Uang [6-8] are investigating the behavior of composite structural elements made of conventional reinforced concrete combined with a Slurry Infiltrated Mat Concrete (SIMCON) as shown in lower left sketches of Figure 2. Fiber volume fraction of SIMCON used in this investigation was 5.25%. Beams were tested in four point bending. Based on the observed experimental and analytical investigation they concluded that SIMCON can successfully interact with conventional reinforced concrete elements, substantially increasing both load and energy-absorption capacities. Adding a layer of SIMCON in the compression zone and/or tension zone increases both the lever arm and strength of the compression and tension zones, respectively. This leads to a significant increase in strength and energy absorption capacity of the beam.

In the case of specimens investigated [6-10] both flexural capacity and energy absorption up to the maximum moment exhibited an increase of 2.2 and 1.9 times the reference values, respectively. Furthermore, observable cracking started only at 80% of the flexural strength, while maximum crack widths were well within the crack size limits of 0.2 mm (0.0078 in.) required by ACI standards for reinforced concrete elements exposed to severe environments.

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Krstulovic et al. concluded that the construction of a SIMCON-based retrofit was much simpler than similar retrofit solutions using short fiber FRCs, reinforced concrete, steel plates or different non-cement based fiber composites. It is thus anticipated that the proposed technique is less labor- and equipment-intensive and more economical than conventional jacketing methods. It uses widely available construction equipment and building expertise, and can thus be easily introduced to the field without major re-training and changes in existing construction practices.

3.2 Crack Width Control in Reinforced Concrete Beams

Maalej and Li [11] suggested a new design for reinforced concrete flexural members in which a HPFRCC is used in the tensile zone essentially acting as a concrete cover. This is illustrated in one of the sketches of Fig. 2. The intent is to improve durability by substantial decrease in average crack spacing and width, thus leading to a reduction in steel corrosion and minimizing spalling of concrete cover. Based on a study of water flow through cracked concrete by Tsukamoto [17] they argued that the flow of aggressive substance into a RC member could be significantly reduced. Since above the critical crack width, the flow rate scales with the third power of the crack width, a small reduction in the crack width translates into a significant reduction in the flow rate. They demonstrated the use of the technique on a reinforced concrete beam where they showed that the crack width at ultimate remained below 0.14 mm. Although the above technique has been demonstrated using a new reinforced concrete beam, it can be used as effectively in the cover of beams needing repair, say after corrosion of the reinforcement.

3.3 Column Wrapping Using a SIMCON Jacket

Ribtec in conjunction with the University of Illinois at Urbana, demonstrated the feasibility of using SIMCON for repair and retrofit of bridge columns for seismic loading [5]. The objective of the test program was to demonstrate the use of fiber mat for repair of columns that have failed under lateral load. The test columns were 24 in. (610 mm) in diameter and 144 in. (3.6 m) in length. The main approach was to wrap the base of each column with a single layer of stainless steel fiber mat (1 in. or 25 mm thick) to a height of 48 in. (1220 mm) and pour a cement slurry leading to a 2 in. (50 mm) thick composite jacket confining the column. It was reported that the repair technique restored the columns to either full strength or greater than full strength. Additional tests are under way. The importance of the technique is that it offers a cost effective alternative to steel jackets or fiber reinforced plastic jackets.

4. CONCLUDING REMARKS

Fiber reinforced cement composites use a wide range of volume contents of discontinuous fibers ranging from 0 to 25%. While applications with a low volume fraction of fibers (less than 1 to 1.5%) in conventional reinforced and prestressed concrete structures do show some improvement attributed to fiber reinforcement, the improved performance could not be described as exceptional. In some cases, it was hardly noticeable. However, exceptional improvement in structural behavior was generally observed with relatively high fiber contents ($V_f \geq 2\%$) [13,16]. Since such fiber contents exceed the critical volume fraction, V_{fcr} , of fibers needed to develop quasi-strain hardening and multiple cracking behavior, and since such behavior is specific of HPFRCCs, one can therefore conclude that the use of HPFRCCs is essential to develop superior structural behavior. This is schematically illustrated in Fig. 12, for different properties defined as A, B, C, D, etc., which shows that the rate of improvement in performance for $V_f > V_{fcr}$ is substantially larger than for $V_f < V_{fcr}$. Moreover, test results suggests that the use of HPFRCCs allows exploitation of the properties of conventional reinforcements to their full strain capacity. Thus, it seems that the true success of fiber reinforced cement composites, whether in

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stand-alone applications or in combination with reinforced and prestressed concrete, in new structures or for repair and retrofit, will be appreciated only when the critical volume fraction of fibers is exceeded. Unfortunately, this opportunity has been barely explored so far and it should be viewed as the next generation of applications of fiber reinforced cement composites.

ACKNOWLEDGMENTS

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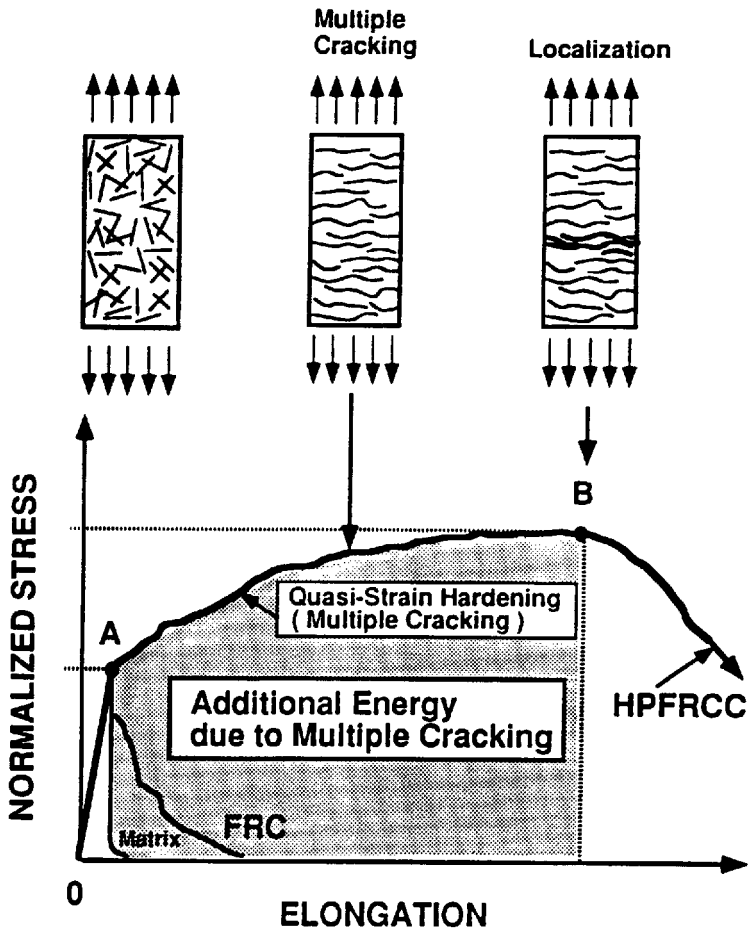
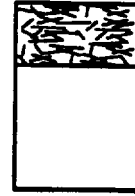
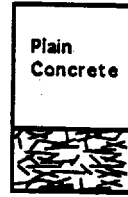
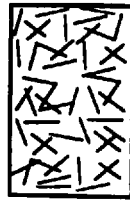


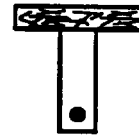
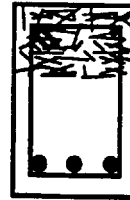
Fig. 1—Typical stress-elongation curve of high-performance fiber-reinforced cement composites (HPFRCCs) and the breakdown of elongation into strain and crack width.

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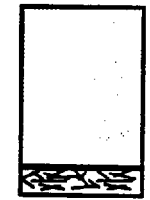
Stand Alone Applications of HPFRCC



HPFRCC in Combination with Reinforced and Prestressed Concrete



Applications in Repair and Rehabilitation



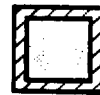
Beams, Slabs



Bridge Decks



Beams



Columns

Fig. 2—Typical application of HPFRCCs.

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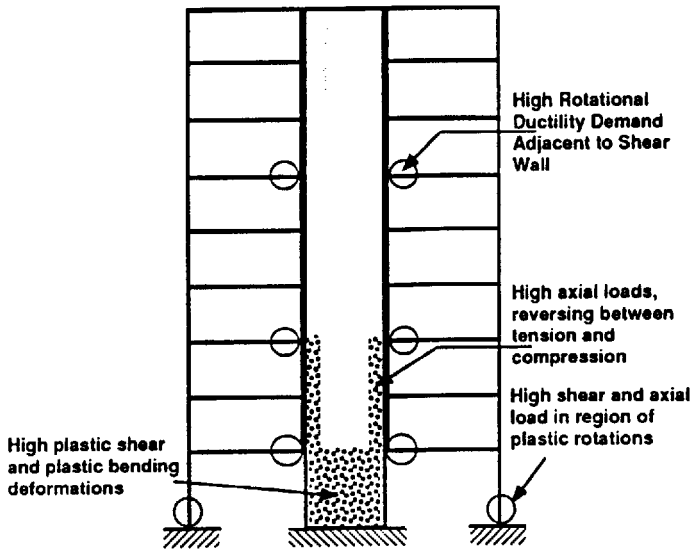


Fig. 3—Typical examples of selective use of HPFRCCs in seismic resistant structures.

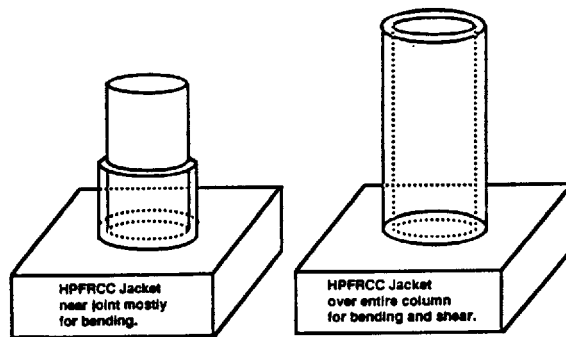


Fig. 4—Typical applications of HPFRCCs for repair and strengthening of concrete columns.

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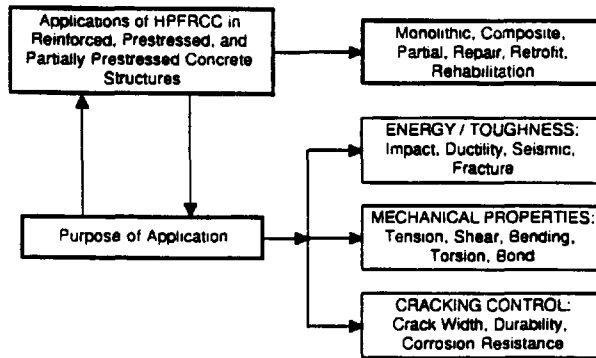


Fig. 5—Purpose of using HPFRCCs in concrete structures.

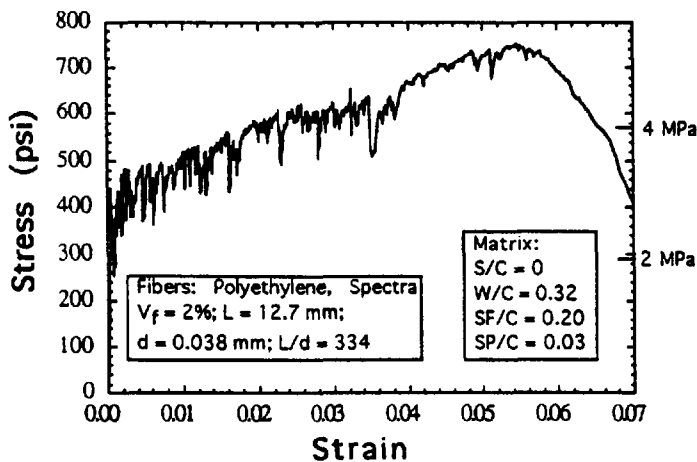


Fig. 6—Uniaxial tensile stress-strain curve of engineered cementitious composites using 2% polyethylene fibers (after Li).

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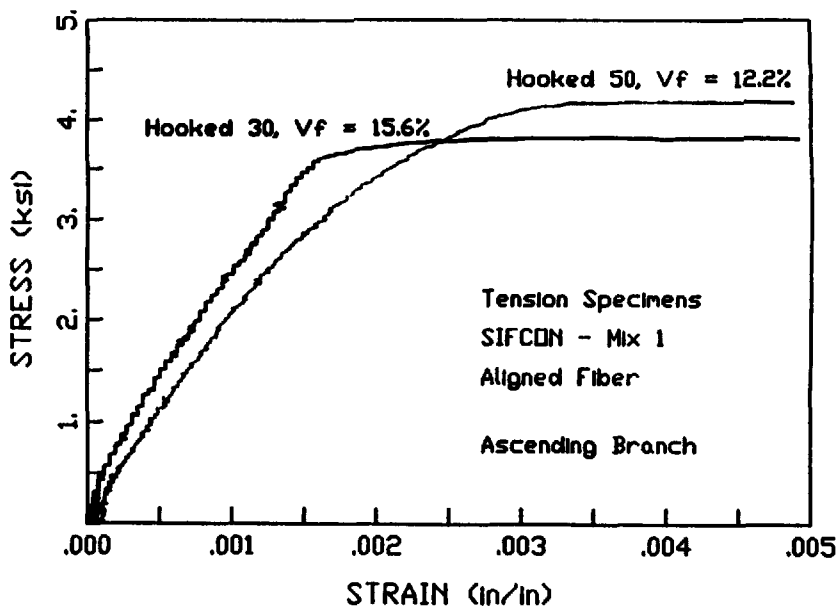


Fig. 7—Typical ascending branch of stress-strain curve for SIFCON with either 50 or 30 mm long hooked steel fibers (1 ksi = 6.9 MPa).

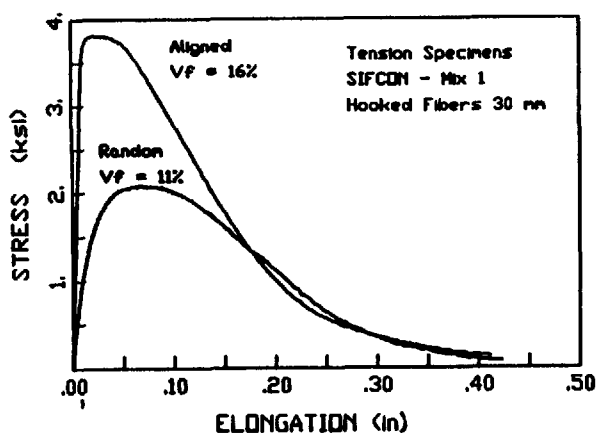


Fig. 8(a)—Examples of tensile stress-elongation curves of SIFCON composites illustrating effect of fiber orientation (1 ksi = 6.9 MPa; 1 in. = 25 mm).

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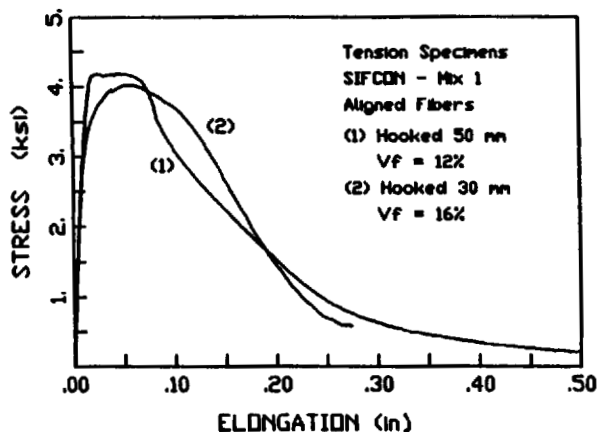


Fig. 8(b)—Examples of tensile stress-elongation curves of SIFCON composites illustrating effect of fiber length and volume fraction (1 ksi = 6.9 MPa; 1 in. = 25 mm).

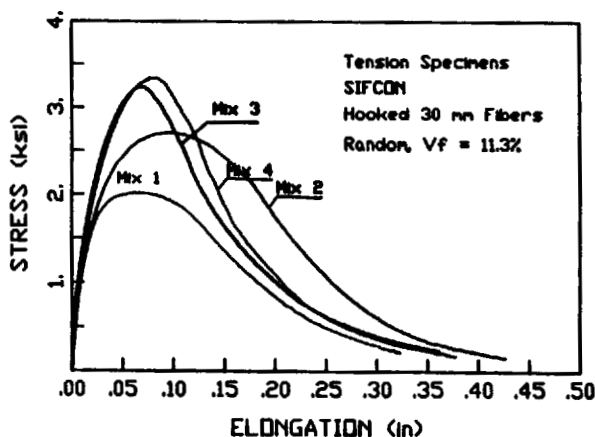


Fig. 8(c)—Examples of tensile stress-elongation curves of SIFCON composites illustrating effect of different slurry matrices (1 ksi = 6.9 MPa; 1 in. = 25 mm).

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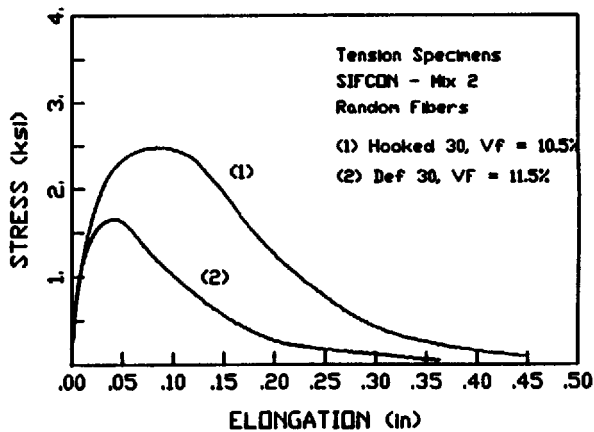


Fig. 8(d)—Examples of tensile stress-elongation curves of SIFCON composites illustrating effect of two different fibers: hooked and deformed (1 ksi = 6.9 MPa; 1 in. = 25 mm).

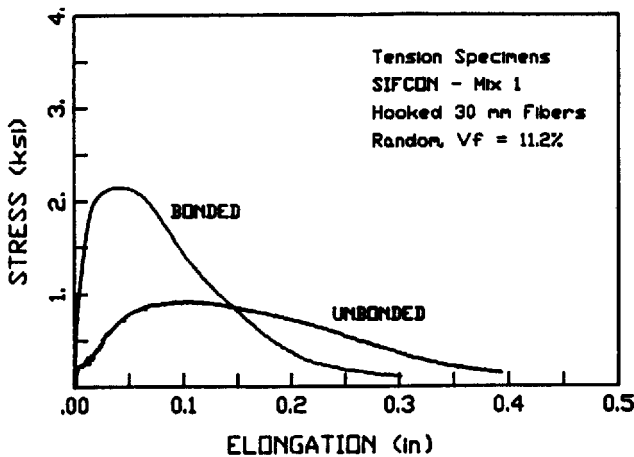


Fig. 9—Tensile stress-elongation curve of SIFCON composite illustrating the effect of mechanical component of bond; unbonding was achieved by spraying the fibers with silicon based spray (1 ksi = 6.9 MPa; 1 in. = 25 mm).

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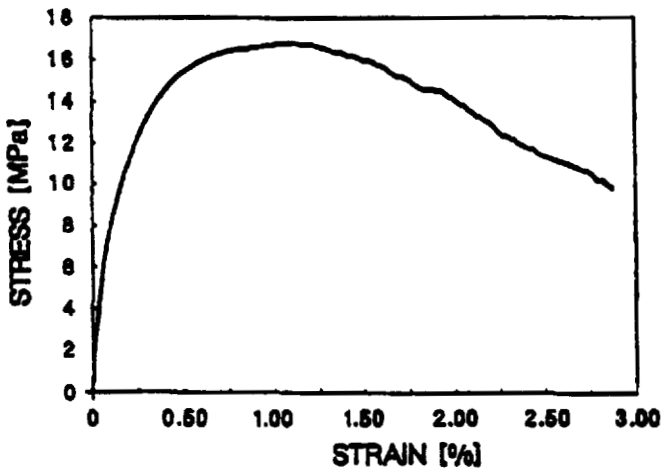


Fig. 10—Typical tensile stress-strain curve of SIMCON composite (after Krstulovic-Opara et al.).

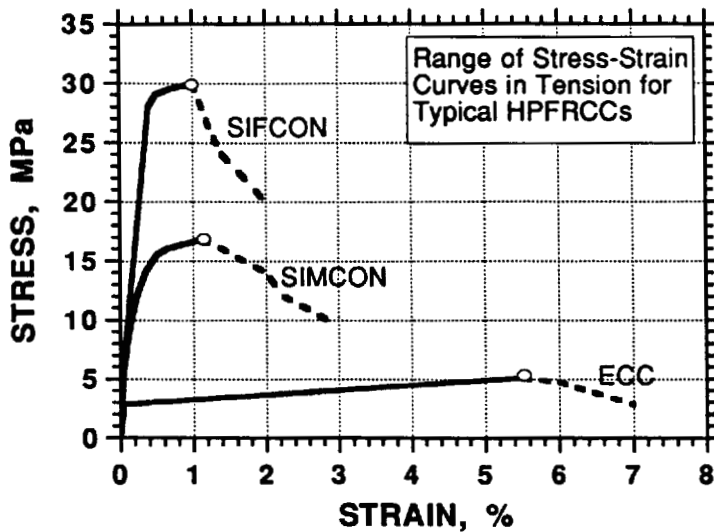


Fig. 11—Schematic tensile stress-strain curves of HPFRCCs illustrating the range of tensile properties demonstrated from experimental tests.

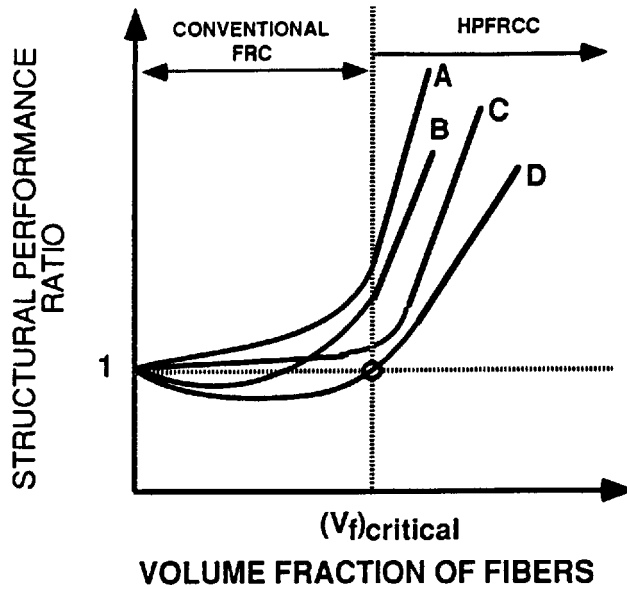


Fig. 12—Schematic representation of structural performance as influenced by fiber reinforcement.

SP 185-2

Parameters Affecting High-Performance Response in Fiber-Reinforced Concrete

by Y. Shao, R. Srinivasan, and S. P. Shah

Synopsis:

High performance fiber reinforced cement composites (HPFRC) are defined as the materials which exhibit a postpeak strain hardening type of response with a multiple crack pattern. Such a ductile behavior makes the HPFRC an ideal material to be used in structural repair and retrofit for dimensional stability, tensile-load carrying capacity, impact resistance, flexibility and long term impermeability.

The critical parameter for continuous fiber reinforced cementitious materials to obtain the high performance response is the minimum fiber volume ratio with well dispersed fibers. As long as continuous fiber composites have a sufficient number of fibers to bridge the cracks, strain hardening and multiple cracking can always happen. However, there is no single dominant parameter which can control the multiple cracking process in discontinuous fiber composites. Various parameters can affect the postpeak response of discontinuous fiber reinforced cementitious materials. They are related to fibers, matrix and the processing methods. Parameters relating to the reinforcement include the type of fiber, fiber length, fiber volume ratio, fiber orientation, state of fiber dispersion and the degree of adhesion to the matrix. These primary variables are in turn influenced by selection of the matrix type, presence of additives, and the processing conditions. The latter acts through controlling the state of dispersion, establishing a fiber orientation pattern and enhancing the adhesive bond between fiber and matrix. To design a high performance fiber reinforced cementitious repair material, the approach in which the repair will be carried out should be considered simultaneously.

Keywords: cracking; high-performance concrete; fiber-reinforced concretes; repair materials; strain hardening

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INTRODUCTION

Repair and rehabilitation of our deteriorating infrastructure need lasting repair materials. For concrete structure repair, the basic criteria for selecting a durable repair material include, as compared to concrete substrate, low shrinkage potential, compatible thermal expansion and modulus of elasticity, high tensile strength, improved fatigue and impact resistance, low permeability by controlling crack opening and enhanced flexibility under bending (1-2).

The repair materials for concrete structure can be categorized into three groups: cementitious mortars, polymer-modified cementitious mortars and resinous mortars (3). To achieve the compatibility of physical, chemical and electrochemical properties between repair materials and existing substrates, cement based repair materials have the priority, especially in partial depth or full depth repair of large areas. However, because of their low tensile strength, conventional cement based repair materials can not withstand any excessive tensile action due to the physical and mechanical loading. To improve the tensile strength and toughness of the material, fiber reinforcement has been introduced. While conventional fiber reinforced cement materials exhibit a strain softening type of response due to the conventional casting procedure and low fiber content, their energy absorption capacity has still been greatly enhanced compared to the matrix alone. However, the high performance fiber reinforced cement materials (HPFRC) have depicted a postpeak strain hardening response and a distributed

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multiple matrix cracking pattern. This is important for repair materials in that the multiple matrix cracking dissipates energy in a large area and prevents crack opening localization. The high performance response contributes tremendously to the dimensional stability, the tensile-load carrying capacity, the impact resistance, the flexibility and the long term impermeability.

A high performance response of fiber reinforced cement material can be achieved through both continuous fiber reinforcement and discontinuous fiber reinforcement. A variety of parameters can affect significantly the response from strain softening to strain hardening, or from single localized crack to sequential multiple cracking. This paper will discuss the effects of those parameters on the high performance response in FRC.

CONTINUOUS FIBER REINFORCEMENT FOR HPFRC

The application of continuous fiber reinforcement in concrete structure repair can be found in the form of mesh or wool mat reinforcement. Slurry infiltrated mat reinforced concrete (SIMCON) is one of the examples. The fibers or meshes could be metallic, polymer or composite. Since fibers used in cementitious composites are always stronger and tougher than matrix, the first crack strength σ_c can be expressed as following based on the rule of mixture:

$$\sigma_c = \sigma_{mu} \left[1 + V_f \left(\frac{E_f}{E_m} - 1 \right) \right] \quad (1)$$

where σ_c is a function of fiber volume ratio V_f , and E_f and E_m are the elastic moduli of the fibers and the matrix, respectively. To induce multiple cracking and postpeak strain hardening, fibers should take over the additional load shed by the cracked matrix and transfer the load to the adjacent matrix. Thus, the ultimate strength $\sigma_{cu} (=V_f \sigma_{fu})$ should be larger than or equal to the first crack strength. A minimum fiber volume ratio is needed, over which the strain hardening and multiple cracking always happens (4): The minimum fiber volume ratio, $(V_f)_{min}$, can be expressed as:

$$V_f^{min} = \frac{\sigma_{mu}}{\sigma_{fu} + \left(1 - \frac{E_f}{E_m} \right) \sigma_{mu}} \quad (2)$$

where σ_{mu} and σ_{fu} are the ultimate strengths of the matrix and fiber, respectively. Equations 1 and 2 do not consider the fiber dispersion effect. Experiments have shown that first crack strength σ_c is not only the function of fiber volume ratio. It is also influenced by the fiber dispersion (5). For the same fiber content, the

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composite strength is higher for the case where the fibers are more uniformly dispersed.

For this study, two types of composites reinforced by different continuous fibers were investigated. They were composites reinforced by continuous steel fibers and by continuous polyvinyl alcohol (PVA) fibers. Steel fiber had a high modulus of 200 GPa with the yield strength of 1200 MPa, and PVA fiber had a low modulus of 29 GPa with tensile strength of 900 MPa. The uniaxial tensile stress - strain curves of the composites are shown in Fig. 1. High sensitivity Moire interferometry was used to study the multiple matrix cracking process (6). Typical moire fringe patterns taken at the end of multiple cracking are also shown in Fig. 1.

The strain hardening response of continuous steel fiber composites was influenced by the high modulus of the fibers and the interface debonding. The fairly equally-spaced multiple matrix cracking stopped at a composite strain which was about twice as large as the first crack strain (Fig. 1A). When the first matrix crack passed through the whole specimen width, the other matrix cracks had already grown to a certain length. For low fiber volume ratio composite, interface debonding started to initiate as soon as the matrix crack had run across the fiber (Fig. 1B). While for composite having high fiber volume ratio, the interface debonding started to grow only after the multiple matrix cracking had stopped (Fig. 1C). After the end of multiple cracking, the work done by the applied load was mostly consumed by fiber elongation and progressive interface debonding. Interface failure had almost progressed the entire interface at a composite tensile strain four times the first crack strain, leaving only a small portion of interface still in bond condition. It is the high modulus of fibers and the energy absorbed in debonding between steel fiber and cement matrix which contribute to the strain hardening behavior.

For the continuous PVA fiber composites, the postpeak slope of the tensile stress - strain curve was flatter than that for the steel fiber reinforced composites. This was most likely caused by the low modulus of the fibers. The first matrix crack did not have a stable propagation. It occurred in a sudden fashion running through the whole specimen width. The multiple matrix cracking thereafter did not show equally-spaced cracks as seen in steel fiber composites. Instead, they appeared in the form of crack bands (Fig. 1D). The bond between PVA fibers and matrix is more ductile than that between steel fibers and the matrix. As a result, no significant debonding was observed. The energy absorption was in the extensive stretching of the low modulus PVA fiber. The performance of continuous fiber composites thus seems to depend on (1) fiber dispersion, (2) modulus of fibers and (3) interfacial bond. Closely spaced fibers are needed to improve the first cracking strength. Small diameter fibers also help in enhancing the bond between fiber and matrix. During multiple cracking, the additional energy can be consumed by progressive debonding as well as stretching of fibers. The relative extent of these contributions were

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different for steel and PVA fibers. The higher modulus of steel fiber led to the higher postpeak slope for the composite.

The key parameter for continuous fiber composites to achieve high performance response seems to be the minimum fiber volume ratio with certain type of fiber dispersion. Fiber spacing distribution has significant effect on first crack strength. The fiber modulus can influence the postpeak strain hardening stiffness. Interfacial bond between fiber and matrix can change multiple cracking pattern from equally-spaced single crack to nonuniformly distributed crack band.

DISCONTINUOUS FIBER REINFORCEMENT FOR HPFRC

Use of discontinuous fiber reinforcement can be found in partial depth and full depth bridge deck repair and in rehabilitation of tunnels (e.g. fiber reinforced shotcrete). The discontinuous fibers used as reinforcement for HPFRC can similarly be metallic or polymeric.

To better understand the parameters that can influence the strain hardening type of response, several tests were conducted. The multiple fracture process of high performance cementitious composites was studied by Moire interferometry. Composites reinforced by discontinuous PVA fibers and exhibiting postpeak strain hardening type of response were fabricated through extrusion processing (7). The postpeak strain hardening type of response of the extruded discontinuous PVA fiber composites was similar to that of the continuous PVA fiber composites. The distributed sequential multiple matrix cracking was the mechanism for achieving the postpeak ductility. The tensile stress - strain curve of extruded composite and the typical Moire fringe patterns at first crack and during multiple cracking are shown in Fig. 2. The composite had a fiber volume ratio of 4.2% with the fibers 6 mm in length and 14 μm in diameter. At bend-over-point, the first through-width crack appeared (Fig. 2A). Typical crack bands with certain width were observed, in which cracks interacted with each other in the form of branching and deviation. The multiple matrix cracks were initiated in a sequence throughout the whole loading history. New cracks were observed to form even at a composite tensile strain about 1.36%, which was 15 times larger than the first crack strain at BOP (Fig. 2B). The contribution of the crack bands in brittle matrix composites is analogous to that of plastic zone in plastic material which consumes large amount of strain energy. However, unlike the localized plastic zone, the crack bands in HPFRC composites are distributed along the whole specimen length, and have dissipated strain energy in a large area and have prevented the composite failure from localized crack opening.

Various parameters can affect the postpeak ductility of the discontinuous fiber composites in a matter of combination. They include material parameters,

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such as fiber length, fiber diameter, fiber dispersion, fiber-matrix bond property, sand content in matrix, in addition to the processing methods.

Fiber Diameter, Length and Bond to Matrix

Fiber diameter, length as well as its bond to matrix can affect directly the postpeak ductility. An example is given in Fig. 3 in which tensile response of two types of composites are compared: steel fiber composite with fiber length of 1-3 mm and diameter of about 100 μm , and PVA fiber composites with fiber length of 4 mm and diameter of 14 μm . Tensile strength and modulus are 1.4 GPa and 200 GPa for steel fiber, and 0.9 GPa and 36 GPa for PVA fiber respectively. Both of them were fabricated by extrusion processing and had same fiber volume ratio. Microsteel fiber composite exhibited a higher tensile strength but strain softening type of response. In contrary, PVA fiber composite demonstrated a strain hardening response. It is obvious that the postpeak behavior is dependent on fiber modulus and the bond capacity of fibers to matrix.

The bond properties of steel fiber and PVA fiber to the matrix were studied using the fiber pullout tests. The typical fiber pullout load - slip curves are shown in Fig. 4 (8,9). They had the same embedment length of 13 mm. It is evident that steel fiber exhibited a slip softening behavior, and PVA fiber had a slip hardening response. The postpeak slip behavior of the fiber pullout curves indicates that steel fibers had a more brittle bond with cement matrix as compared to PVA fibers.

Moire fringe patterns from continuous fiber composite in Fig. 1 have also depicted the bond properties in both composites. Interface debonding was dominant after multiple matrix cracking in continuous steel fiber composite, but not in PVA fiber composite. The multiple cracking in continuous PVA fiber composite ended at a much high tensile strain with unequal crack spacing (Fig. 1), and debonding happened only in the vicinity of the matrix crack band. A large area of interface in front of debond crack remained intact. It indicates that in order to achieve postpeak strain hardening response, the material system should be chosen such that fibers have strong bond with matrix to inhibit interfacial debonding and to prevent fiber pullout.

Fiber length is another parameter relating to reinforcement. The longer the fiber, the higher possibility for fibers to bridge the cracks. Fig. 3 also compares 1-3 mm long microsteel fiber composite with 6 mm long PVA fiber composite at the same fiber volume ratio. Although interfacial bond plays important role in postpeak ductility, the longer fiber length can also contribute to a strain hardening behavior.

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Fiber Dispersion

Fiber dispersion can affect both strength and toughness. Recent research has proven that the larger the fiber spacing, the lower the first crack strength (9). The difference could be as high as five times if maximum fiber spacing in the specimen changed from 0.08 mm to 0.45 mm.

In order to relate the fiber orientation and dispersion to the sequential multiple matrix cracking, the same specimen that was used in Moire interferometry test as shown in Fig. 2 was used again for microscopic observation. After Moire test, the specimen was cut along the Moire grating edges. Crack patterns were preserved. The Moire specimen grating on the specimen surface was polished out and the fiber orientation and dispersion were investigated along each crack band at different locations as marked in Fig. 2B. The crack bands were numbered on the sequence of their appearance. Fig. 5 shows four typical micrographs taken from four crack surfaces. Fig. 5A was taken at the place where the first crack initiated. Fiber distribution in the vicinity of the first crack was fairly random. Fibers of relatively long length were not seen. Fig. 5B shows the fiber distribution at the second crack band. Fibers seemed also randomly distributed, although crack deviation and branching occurred in this area. In some other places, fibers orientation was not as random. For example, at the third and fourth cracks shown in Figs. 5C and 5D, fibers exhibited good alignment in loading direction (or in extrusion flow direction) and uniform dispersion almost everywhere along the crack surface.

After comparing the fiber orientation and dispersion in the vicinity of different cracks, it was found that fibers were distributed more randomly and less oriented along the first crack. It indicates that the first matrix crack and its corresponding first crack strength are associated with the microstructure of the composite, and is a function of the statistical dispersion of the fibers. The heterogeneous microstructure inherently consists of a weakest link along which the composite damage can easily initiate and propagate.

Sand Content in Matrix

Since bond between fiber and matrix is the critical parameter in achieving high performance response, the amount of sand in matrix may impair the bond and finally change the postpeak response. The sand content effect was studied by choosing the material system of PVA fiber and mortar matrix with fibers of 2.8% by volume. Fig. 6 shows the typical flexural stress - deflection curves from 3-point bending tests. Obviously, postpeak strain hardening was affected significantly by the sand content in matrix. Composite having no sand exhibited a largest deflection at the peak load. Moreover, with the increase in the amount of sand in matrix, the deflection corresponding to peak load decreased.

Processing Methods

Different processing will change the fiber bond to matrix and alter the fiber dispersion and orientation, leading to a different postpeak response. Tests were conducted in order to compare the behavior of the composite made by extrusion processing to the one made by the conventional cast method. For both processes, fiber volume ratio, fiber length and matrix composition were kept the same. To improve the workability of the material for casting, more high range water reducer was used in cast specimens. The comparison of their tensile response is plotted in Fig. 7. The extruded composite has an increased tensile strength and a postpeak strain hardening up to a tensile strain of 0.7%. It was noticed that the difference between samples cast 1 and cast 2 was due to the different vibration time during casting. Specimen of cast 2 was vibrated at a longer time than the specimen of cast 1, and showed a slightly increased strength and toughness, suggesting a better fiber-matrix bond. This phenomenon was also observed when different vibration frequency (60 and 120 Hz) was used in casting to alter the postpeak response for steel fiber composites (10).

The microstructures of the composites made by different processing methods are quite different, especially the fiber dispersion and orientation in the composites. This is demonstrated in Fig. 8. Fig. 8(A) shows the fiber distribution in the extruded composite and Fig. 8(B) the fiber distribution in the cast composite. It is obvious that short fibers are oriented to some degree along the extrusion direction in the extruded composite, yet they are randomly distributed in the cast composite. Oriented fibers have high probability to bridge cracks and induce multiple matrix cracking. The increase of composite strength in extruded composites is mainly due to compaction during the die forming process in extrusion.

Other processing methods have also been used to fabricate high performance FRC. Slurry infiltration technique was used in making discontinuous steel fiber concrete (SIFCON) (11), and spray-suction technique was developed for fabrication of discontinuous glass fiber composites (12). Although the special techniques are not straightforwardly applicable to concrete repair in the field, they provide certain insight in developing HPFRC repair material for field applications. The important contribution of the processing methods to high performance response in FRC is the compaction force added to the material system, irrespective of whether the force is provided by die forming (extrusion), by pressing (spray-suction), or by high frequency vibration (casting). The compaction force densifies the packing between fibers and matrix, and leads to an enhanced bond of fibers to matrix.

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DISCUSSION AND CONCLUSION

Research has demonstrated that it is possible to design a fiber reinforced cementitious material with strain hardening response and multiple cracking pattern by various methods. For continuous fiber or mat reinforced cementitious materials, minimum fiber volume ratio with a uniform fiber dispersion is the critical parameter which determines the postpeak ductility. For discontinuous fiber reinforced cementitious materials, however, the high performance response is not always readily achievable. The contributions to the high performance response of discontinuous fiber cement composites are probably determined by several parameters relating to the reinforcement: the type of fiber, fiber length, fiber volume ratio, fiber orientation, state of fiber dispersion and degree of adhesion to the matrix. These primary variables are in turn influenced by selection of the matrix type, presence of additives that may interact with fibers, and the processing conditions. The latter acts through controlling the state of dispersion, establishing a fiber orientation pattern and enhancing the adhesive bond between fiber and matrix. Therefore, it appears that HPFRC is a viable option for repair and rehabilitation, provided a particular application method is available for the field work.

ACKNOWLEDGMENT

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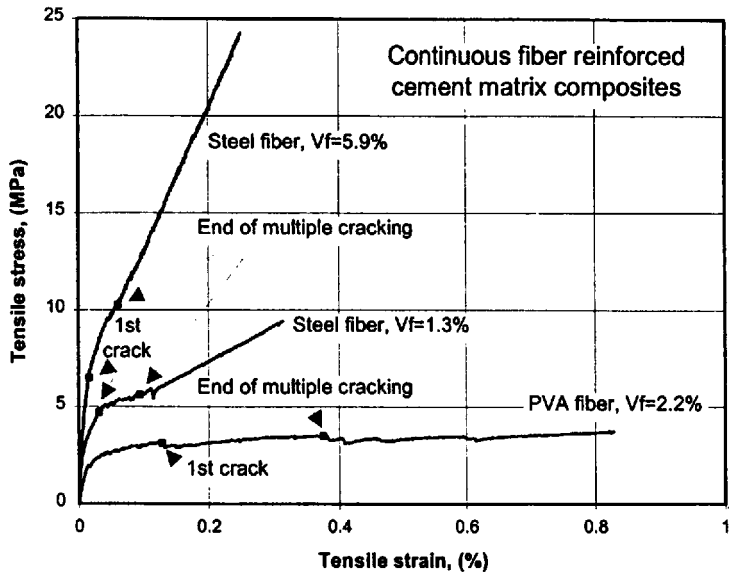


Fig. 1(a)—Continuous fiber-reinforced cement matrix composites: stress-strain curves of continuous fiber cement composites.

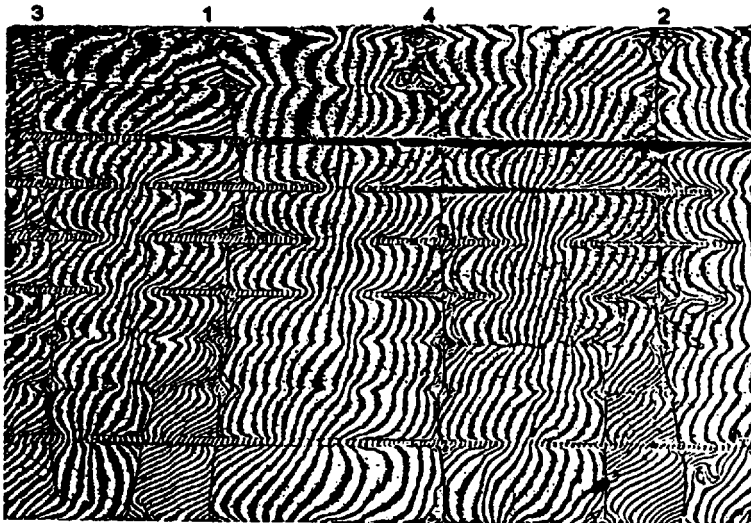


Fig. 1(b)—Continuous fiber-reinforced cement matrix composites: Moire fringe pattern for steel fiber composite ($V_f = 1.3\%$; stress = 5.6 MPa).

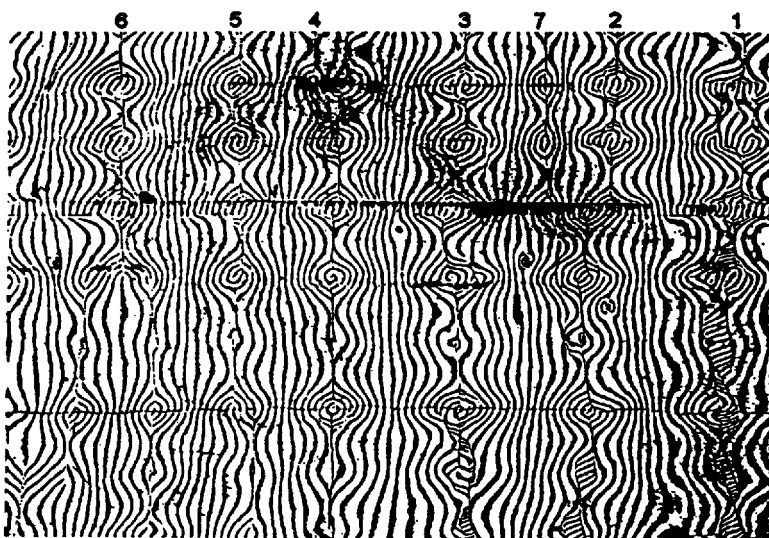


Fig. 1(c)—Continuous fiber-reinforced cement matrix composites: Moire fringe pattern of steel fiber composite ($V_f = 5.9\%$; stress = 10.3 MPa).

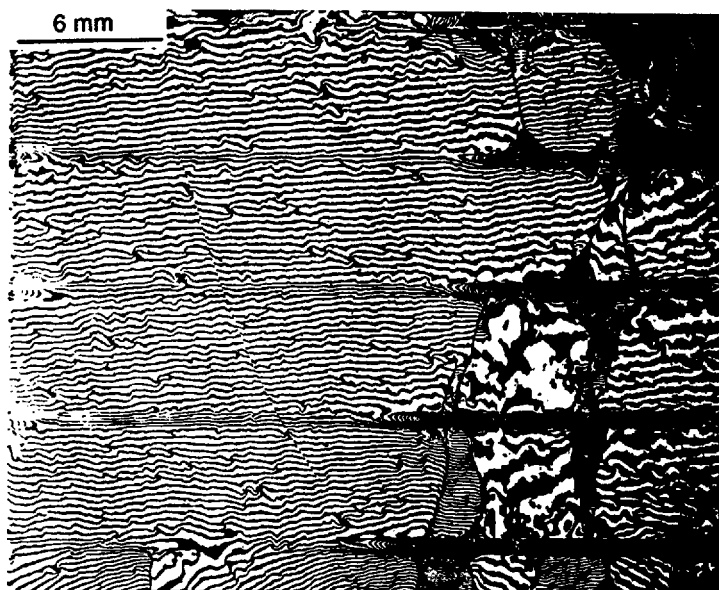


Fig. 1(d)—Continuous fiber-reinforced cement matrix composites: Moire fringe pattern of PVA fiber composite ($V_f = 2.2\%$; stress = 3.48 MPa).

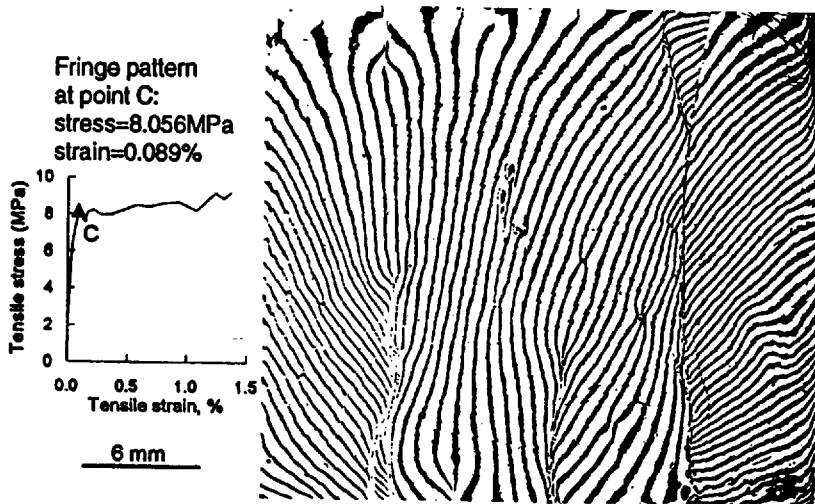


Fig. 2(a)—Multiple matrix cracking in discontinuous fiber cement composite ($V_f = 4.2\%$); Moire fringe pattern at a tensile strain of 0.089%.

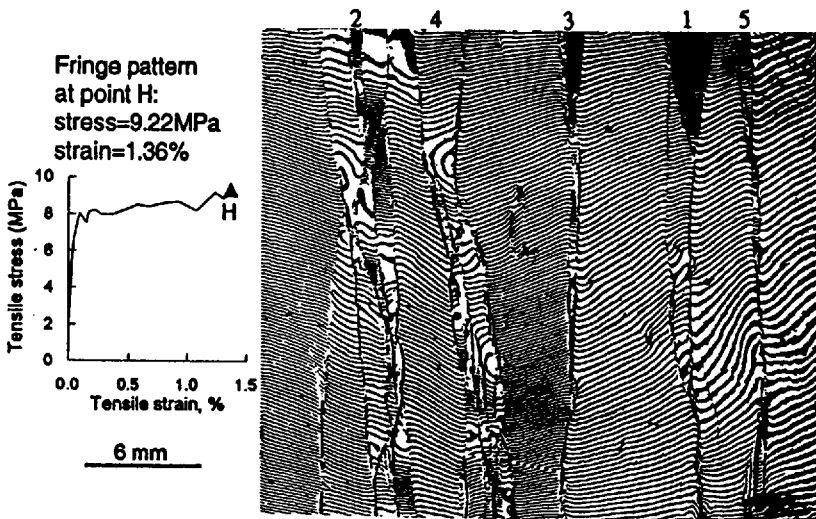


Fig. 2(b)—Multiple matrix cracking in discontinuous fiber cement composite ($V_f = 4.2\%$); Moire fringe pattern at a tensile strain of 1.36%.

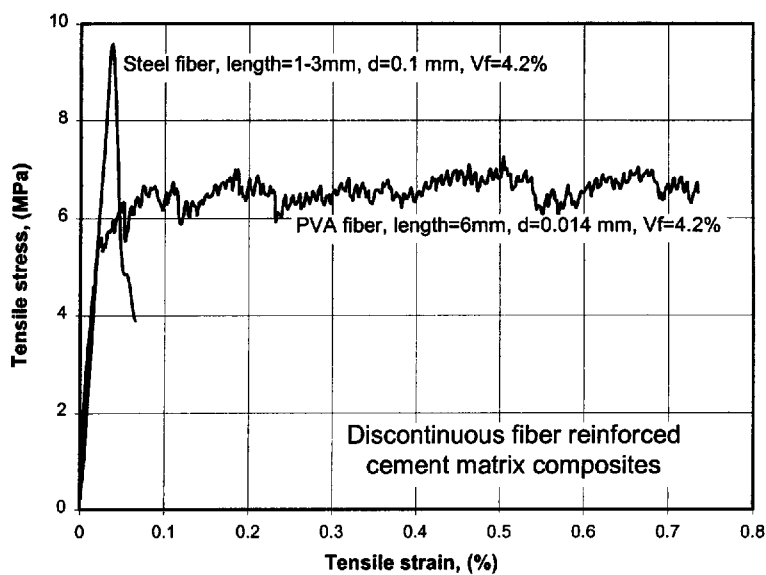


Fig. 3—Tensile response of steel fiber and PVA fiber composites with different fiber volume ratios.

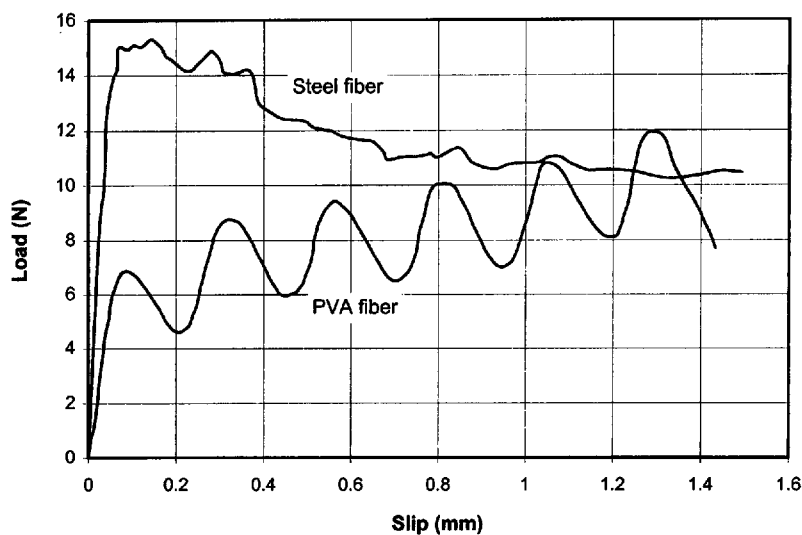
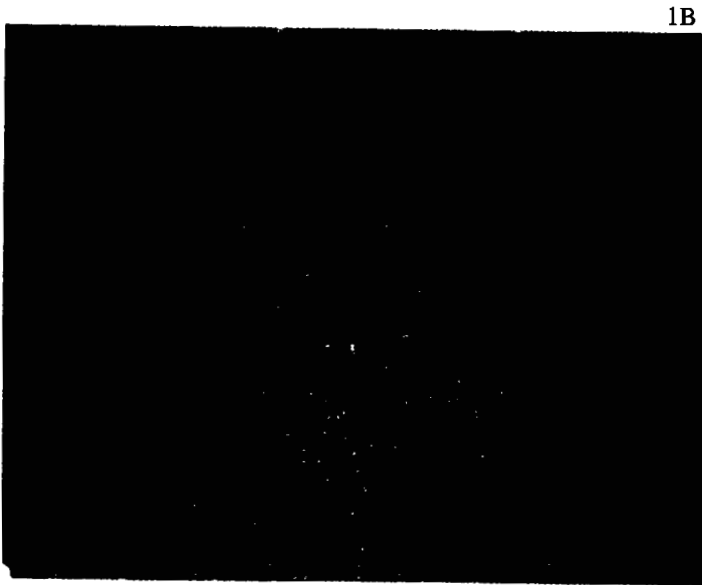


Fig. 4—Fiber pullout load-slip curves for steel fiber and PVA fiber.

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At 1st crack



2T

At 2nd crack

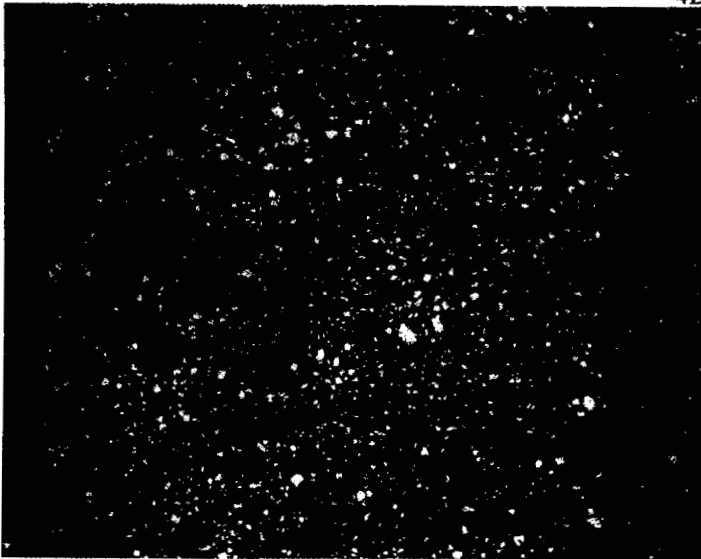
Fig. 5—Fiber orientation and dispersion at sequential multiple matrix crack surface.

3M



At 3rd crack

4B



At 4th crack

Fig. 5 (cont.)—Fiber orientation and dispersion at sequential multiple matrix crack surface.

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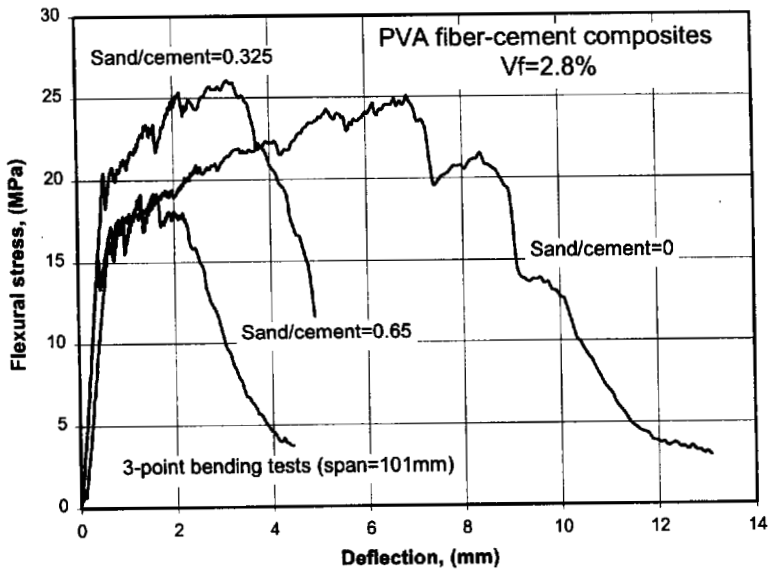


Fig. 6—Effects of sand content on postpeak response.

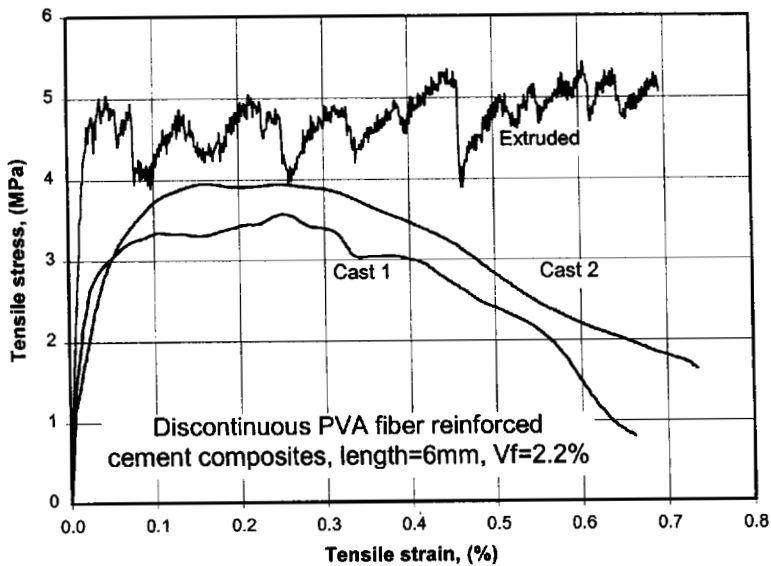
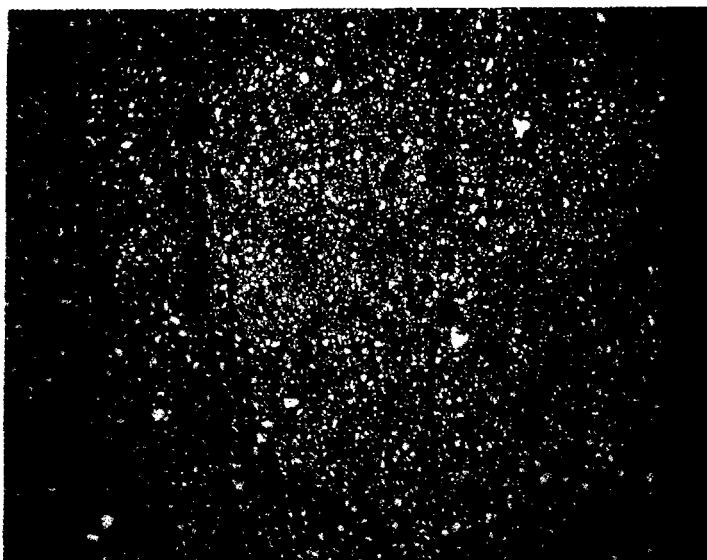
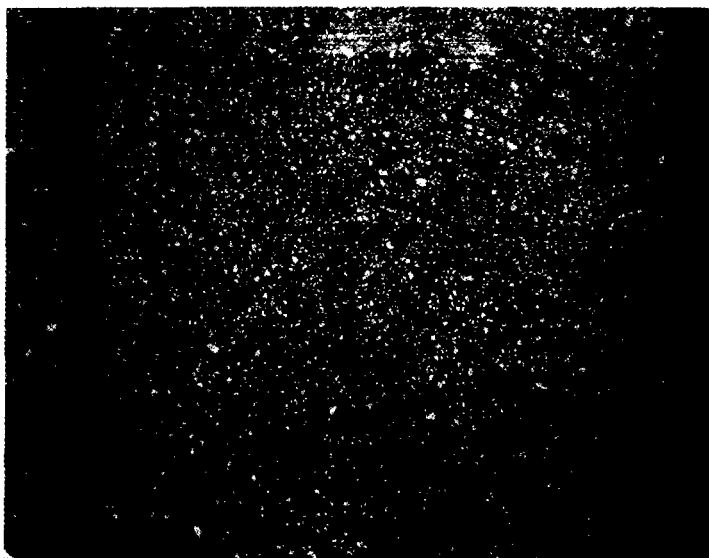


Fig. 7—Effects of processing on postpeak response.



(A) Extruded FRC composite (extrusion direction is vertical)



(B) Cast FRC composite

Fig. 8—Fiber orientation and dispersion in extruded and cast composites: (a) extruded FRC composite (extrusion direction is vertical); and (b) cast FRC composite.

SP 185-3

Fiber-Reinforced Concrete (FRC) Encased Steel Joints for Seismic Resistance

by S. C. Goel and M. Khuntia

Synopsis: This paper reports the results of an investigation on the performance of FRC-encased open web steel joists under cyclic loading. The system completely eliminates the need for any shear connectors between steel joists and surrounding FRC as well as that for conventional longitudinal and transverse reinforcing bars, all of which are quite labor intensive. Cyclic load tests on some half-scale specimens consisting of composite beams with end connections were carried out. The parameters included the configuration of web steel elements, and the amount of steel in longitudinal and web elements of the joists. The results are most encouraging. The two materials interact in a way so as to provide stable hysteretic behavior with excellent energy dissipation and ductility. The study indicates that shear strength of the composite beam can be remarkably enhanced by addition of steel fibers in concrete, thus making it very suitable for seismic resisting structures. The flexural capacity is also considerably increased. It can be quite accurately calculated by analytical models based on full composite action.

Keywords: composite beams; cyclic loading; ductility; energy dissipation; flexural strength; shear strength; steel fibers; steel joints

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INTRODUCTION

It is widely recognized that uses of two or more different materials in a structure generally lead to more efficient system for resisting seismic forces (9). The use of composite and hybrid structures in seismic regions of the U.S. as well as Japan has increased in recent years. Most composite structural frames in current practice use steel reinforced concrete (SRC) or concrete-filled tubes (CFT), especially for columns. SRC composite members are concrete-encased rolled steel shapes (more commonly wide flange sections), whereas, CFT columns are round or rectangular tubular sections of steel filled with concrete. CFT columns are often used with no or minimum reinforcing bars, but the SRC columns require significant longitudinal as well as transverse reinforcement. SRC columns also require shear connectors in order to achieve composite action between concrete and steel. It has been reported recently (1) that encased composite columns possess exceptional cyclic strength and ductility if buckling of the longitudinal reinforcement is inhibited, which needs considerable amount of web reinforcement in critical regions. Besides, the RC structures in seismic regions need significant amount of confinement in connection and joint regions for required toughness and ductility. All this work is quite labor intensive, and therefore, may not be very cost effective, especially if the labor costs are high.

Open web steel joists are very efficient structural members for resisting bending, and bending combined with axial forces. However, they show rather poor hysteretic behavior under cyclic loading, mainly due to buckling of chord or the web members. Encasement of open web steel joists in concrete is one way to prevent buckling of the steel members, thus, increasing their compression strength up to yield level as well as drastically improving the overall hysteretic behavior of the composite member. In these composite members open web of the steel joists can also provide adequate bond between steel and concrete through better interlocking effect, which may eliminate the need for shear connectors that are needed in conventional SRC members. However, use of conventional concrete can result in considerable cracking and spalling after few cycles of loading.

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Investigations conducted during the last decade (2,3,4,5,6,7) have shown that the use of discrete fibers substantially increases the strength, stiffness, and ductility as well as it preserves the structural integrity beyond the ultimate failure load of a conventional reinforced concrete (RC) member. In RC beams, fibers can be used as a partial replacement for transverse reinforcement (3,4). Addition of steel fibers to concrete also aids in changing its brittle characteristic (associated with shear failure) to a ductile one (associated with flexural failure). It improves the shear capacity of the beam substantially in addition to some improvement in the flexural capacity. Due to its higher tensile strength and higher ultimate compressive strain FRC renders confinement effect to the encased steel section, similar to the confinement in RC members provided by transverse reinforcement.

A typical sub-assemblage of a FRC-encased steel joist framed structure is shown in Fig. 1. The test specimens investigated in this study and as shown in Fig. 2, represent beam AB of the sub-assemblage. This paper reports the behavior of these specimens under reversed cyclic flexural loading. The purpose of this research was: (1) to experimentally determine the strength and ductility of composite beams under cyclic loading; (2) to assess the effectiveness of interaction between FRC and open web sections for resisting shear and moment; (3) to develop analytical model to calculate the ultimate strength of this type of composite members; (4) to ascertain the effectiveness of these members for lateral load resisting systems.

RESEARCH SIGNIFICANCE

Although several semi-empirical relations have been suggested to determine the ultimate shear and flexural capacity of fiber-reinforced concrete beams containing conventional longitudinal bars with or without stirrups, no data are available on the shear and bending response of FRC-encased open web steel joists under monotonic or dynamic loading. Design procedures and codes for common design practice are currently non-existent. Recognizing the increasing use of composite structures in seismic regions and the need for standard design provisions, a new chapter on composite structures was added to the 1994 NEHRP Seismic Provisions (8). The research reported in this paper shows that FRC-encasement of open web steel members results in substantial increase in their shear as well as flexural strength. This type of composite members possesses outstanding cyclic strength and ductility. The proposed analytical model bears an acceptable agreement with the available data.

EXPERIMENTAL PROGRAM

Test Specimens

The test program consisted of fabricating three beam specimens and testing them under cyclic loading as shown in Figs. 2 and 3. Specimen 1 was designed as conventional open-web steel joist and was encased in FRC to prevent buckling of compression members. Specimen 2 was designed as conventional

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reinforced concrete member without cover. Double angle chord members were used to act as main longitudinal reinforcement with flat bars providing shear reinforcement. One extra flat bar was attached near the critical moment region (i.e. close to gusset plate-angle connection) to increase the shear capacity (Fig. 2b). Specimen 3 was designed identical to Specimen 2 except three changes. First, to determine the shear resistance of FRC without web reinforcement no web bars were provided within the upper half of the cantilever beam, as shown in Fig. 2(c). Second, the bars were attached laterally with 1.5 in. side in horizontal position. This was done to have better wedge action of concrete struts in case of development of possible truss action. Lastly, a clear cover of 30 mm was provided. The details of the test specimens are shown in Fig. 2 and Table 1.

The shear span, a , was kept constant at six feet in these tests. The main variable during these tests was the configuration of the open-web steel joists to study its influence on energy dissipation capacity and ductility.

Materials

For resistance against seismic loading, the beams were reinforced on both sides (doubly reinforced) with double angles of size $1.5 \times 1.5 \times 3/16$ in. The web bars were $1.5 \times 3/8$ in. for the first specimen and $1.5 \times 3/16$ in. for the other two. The yield strength and ultimate strength of the angle section were 330 MPa (47.9 ksi) and 506 MPa (73.4 ksi), respectively, and those of the flat bars were 255 MPa (37 ksi) and 410 MPa (59.5 ksi), respectively, as measured from coupon tests. For the angles, strain hardening began at about 12 times the yield strain. These measurements were taken under monotonic loading.

For concrete, hooked-end dramix steel fibers 30 mm long and 0.5 mm diameter (l_f/d_f ratio of 60) were used. The volume fraction, V_f , of the fibers was 2%. The concrete mix was made with ordinary Portland cement (type I) for Specimen 1, and with early strength cement (type III) for Specimen 2 and Specimen 3. About 1% (by weight of cement) of superplasticizer was added for better workability. Also, in order to avoid balling and to have better dispersion of fibers, smaller size aggregate was used in Specimen 2 and Specimen 3. Mixing was done in a rotary mixer in which cement, sand, and coarse aggregate were first thoroughly mixed. The required amount of water was then added with a part of superplasticizer. After about 3 minutes of initial mixing, fibers were added and dispersed manually. Mixing was continued until a homogenous mix was obtained. One significant aspect with open web steel joists was that the problem of workability is much less critical as compared with conventional fiber reinforced concrete beams because of more congestion of reinforcing bars in the later. The details of mix proportions, and important strength properties of each specimen are shown in Table 2. In all, six cylinders were cast along with each beam and tested for compressive strength on the day of testing the specimen. The tensile strength of FRC was calculated by using the equation given by earlier investigators (11,12).

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Test procedure

The beams were tested by using an actuator of 50 kips capacity and maximum stroke length of +5 in. The actuator was connected to the top of the specimens for loading as a cantilever. The double angles acting as main reinforcements were welded to a steel plate and the plate was connected to a base plate by welding. The base plate was bolted to the support frame as shown in Fig. 2(a).

Electrical resistance strain gages were attached to the longitudinal steel elements (the angles) and also to the web bars at selected points. Two potentiometers were used to measure the lateral displacement of the beam at two points, one at 39 in. and the other at 17 in. from the loading position, and another two potentiometers were attached to the base of the frame to measure the base rotation. All strain gages and potentiometers were connected to a data acquisition system for recording the data. The data were recorded at an interval of one second to determine the complete response history.

Loading History

As the tests were aimed at determining the performance of these composite beams under earthquake type of loading, the displacement history as shown in Fig. 3 was used. The loading was displacement controlled. The load was applied initially to about half of the displacement at yield (calculated) for one cycle, and then, it was increased to yield displacement (δ_y). The yield displacement was determined from the computer screen monitor when the strain gage reading at critical points indicated the yielding of the chord steel. After that the displacements were increased in multiples of yield displacement as shown in Fig. 3. At each displacement level, two cycles of loading were applied followed by one cycle of loading at yield displacement level before going to next displacement level.

TEST RESULTS AND ANALYSIS

The lateral load-displacement plots (hysteretic loops) for the three tests (Specimens 1, 2, and 3) are shown in Fig. 4. Tables 3 and 4 show salient features of the observed behavior of the three specimens.

Among the three tests of the series, Specimen 1 did not perform very well in comparison with the other two (Table 3). It failed prematurely due to stress concentration at the welding region between diagonal bar and the chord angles (Fig. 5). During initial cycles, many fine flexural cracks were observed - an important feature of using FRC. However, after the 5th cycle (at displacement ductility level of 2) the strain at the critical region (shown in Fig. 5) reached the ultimate value, thereby, causing the fracture of steel angles at that point. This was due to stress concentration effect at the narrow portion near the connection. The

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moment capacity was quite large compared with bare steel joist due mainly to (1) elimination of buckling of compression members, and (2) contribution of FRC towards the bending resistance of composite beam. As expected, due to low reinforcement ratio, fibers contributed about 40% more strength (Table 4). Due to adequate shear strength, there was absence of visible diagonal cracks inhibiting the development of full truss action in FRC. For these reasons, the second and third specimens were designed differently.

Designed similar to RC beams with steel bars as web reinforcement, Specimen 2 behaved very well. It showed excellent performance under cyclic loading giving a displacement ductility of more than 6 and drift ratio of about 5% (Fig. 4(b) and Table 3). Initially, the cracks were distributed over the high moment regions and were finer. After some cycles the cracks were concentrated at few locations. At higher displacement level, there were three distinct wide cracks in the plastic hinge region contributing to increasing hinge rotation. As there was no concrete cover provided in this specimen, the steel angles acting as main reinforcement came into action before any prominent flexural cracking occurred in the concrete. The cracks in the cover concrete may be detrimental under cyclic loading in the sense that they may enhance the stress intensity factor at the crack tip, thereby, expediting the crack propagation at fewer points with little crack distribution. For better seismic performance, it is desirable to have many distributed fine cracks rather than a few wide cracks in the plastic hinge regions. Due to higher reinforcement ratio compared with Specimen 1, the steel fibers contributed only 17% more strength in flexure (Table 4).

Designed identical to Specimen 2 with a few changes, Specimen 3 behaved well under cyclic loading (Fig. 4(c)). Even though there was no web reinforcement in upper half of the specimen, no diagonal shear cracking was observed over that region. This indicates that the resistance of FRC encased steel joists in shear is much higher than that given by the ACI equation. Also, it shows that there must be some contribution of chord steel members in shear, which needs to be studied further. Though the flexural strength of Specimen 3 was higher than that of Specimen 2 at first yield, its resistance dropped afterwards because of loss of fiber contribution. This happened due to concentration of one crack at the critical moment region. The cracks were wider than those in Specimen 2 at similar displacement level. However, the displacement ductility and drift ratio of 5.8 and 4%, respectively, were quite comparable with those of Specimen 2. The cracked specimens near the end of the tests are shown in Fig. 6.

The shear strength and moment capacity of the FRC encased steel joists can be computed by using conventional reinforced concrete theory with modification for fiber and steel joist contribution. The procedure is outlined in Appendix A.

As it was desired for the specimens to have ductile flexural mode of failure, the composite beam was provided with shear reinforcement in the form of web bars. The total shear resistance of FRC encased steel joists containing no web reinforcement is composed of three components, namely concrete contribution (V_c), fiber contribution (V_{fb}), and contribution from steel joist (V_s).

$$V_{frc} = V_c + V_{fb} + V_s$$

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In the present study, the exact contribution from steel joists towards shear strength could not be measured. Complete absence of any significant diagonal tension cracks and resistance of the beam against shear after the development of wide flexural crack over full depth of the section (Fig. 6(c)) clearly indicate that the chord angles alone must be providing a major portion of the shear strength at those sections. In the absence of data to quantify the contribution of joists to shear resistance, the shear strength was calculated based on the contribution from concrete and from the fibers, which far exceeded the applied shear as shown in Table 4. Although, there was complete absence of any significant diagonal cracking, the strain gage readings on the web plates indicate existence of some micro-cracks, which were not visible to naked eye.

Even though it is generally believed that bond between concrete and the steel sections can not be very good, the test results indicated that adequate bond between the FRC and the open web steel joists existed during loading cycles up to 2 to 3 times the yield displacement. The problem of bar pull-out in these members does not arise because of welded connections of longitudinal steel elements at the ends. Therefore, application of conventional reinforced concrete beam theory to FRC-encased steel joists to determine the nominal flexural capacity can be justified. The fiber contribution toward flexural capacity should be taken into account because of substantial tensile strength of FRC. This contribution becomes marginal with higher reinforcement ratio. In general, increase in fiber content, V_f , increases the shear resistance more than the increase in flexural strength of a beam, whereas, increase in longitudinal reinforcement ratio, ρ , increases the bending strength much more than the shear strength. These observations made by previous investigators³⁻⁵ are confirmed by the present tests as well. Table 4 shows the calculated moment capacity including the contribution of fiber as well as by neglecting it. The results indicate significant underestimation of strength if the tensile strength of FRC is not taken into account. The difference is more prominent for beams with lower reinforcement ratio (Specimen 1). The calculated values of flexural strength compare very well with the values obtained from the tests (Table 4). Besides, higher tensile strength should be taken for higher strength concrete due to its better matrix-fiber interface bond. This is indicated by larger difference between test and analytical results for Specimen 1, which has higher concrete strength than the other two specimens.

Table 4 also shows that the applied shear force was less than the diagonal cracking shear strength, and much lower than the ultimate shear strength. This was confirmed by complete absence of any visible diagonal cracks. In the regions where flexural cracks widened after a number of cycles, the shear strength must be mainly resisted by the longitudinal reinforcement, i.e. double angles on both tension and compression side.

Table 3 shows the displacement ductility (the ratio of ultimate displacement to the displacement at first yield) and drift ratio (the ratio of ultimate displacement to the length of the member) of the three specimens. Specimen 2 shows highest ductility and drift ratio and Specimen 1 shows the least due to premature failure in the latter caused by stress concentration. Specimen 3, although behaved well, shows somewhat lower ductility than Specimen 2, possibly because of lesser distribution of cracks in the plastic hinge region in Specimen 3.

CONCLUSIONS

From the experimental observations and analysis reported in this paper, the following conclusions can be made:

1. The shear strength of concrete beams can be remarkably enhanced by addition of steel fibers and using open web steel sections in place of conventional reinforcing bars. The use of conventional reinforcing bars, which is labor intensive, can be completely eliminated by using FRC-encased open web joists.
2. The FRC-encased open web joists possess excellent cyclic strength and ductility needed for structures in seismic regions.
3. There is much less degradation of stiffness and no pinching of hysteretic loops unlike in reinforced concrete members.
4. The ultimate flexural strength of FRC-encased steel joist composite beams can be conservatively calculated by using conventional reinforced concrete beam theory with minor modifications. The contribution of fibers should be taken into account.
5. The open web steel joist needs to be detailed carefully so as to avoid the possibility of stress concentration in critical plastic hinge regions.
6. More research is needed to determine the contribution of open web steel joists toward shear resistance.

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