FOUR DECADES OF PROGRESS: PERSONAL PERSPECTIVE

by A.E. Naaman

Synopsis: This paper reviews progress spanning a period of about four decades during which the author was intimately involved in research and teaching in three distinct yet related fields of civil engineering: prestressed concrete, fiber reinforced concrete, and ferrocement and thin cementitious products. In retrospect and for each area, key contributions are mentioned, milestones recalled, and prospects for the near future envisioned. Issues related to partial prestressing, external prestressing, high performance fiber reinforced cement composites, strain-hardening FRC composites, 3D textiles and the like are addressed. Technical advances are webbed with some personal milestones as well. Important research issues to address in the near future are pointed out.


Keywords: 3D textiles; external prestressing; ferrocement; fibers; fiber reinforced concrete; hpfrc; prestressed concrete; partial prestressing; sifcon; strain-hardening; strain-softening; textile reinforced concrete;
Antoine E. Naaman, FACI, is Professor Emeritus of Civil Engineering at the University of Michigan, Ann Arbor. He is a member of ACI Committees 544, Fiber Reinforced Concrete; 549, Thin Reinforced Cement Products; and Joint ACI-ASCE Committee 423, Prestressed Concrete. His research interests include high performance fiber reinforced cement composites, ferrocement, laminated cementitious composites, and prestressed concrete.

BRIEF BACKGROUND ON EDUCATIONAL AND PROFESSIONAL LIFE

I was born in Beirut, Lebanon, and graduated from Notre Dame high school in 1959 with a French Baccalaureate 2nd Part, mathematics option. I then went to Paris, France, first to College Stanislas (1959-1961) to prepare for engineering, and then to Ecole Centrale of Paris (ECP) where I obtained a diploma in Engineering, in 1964. I continued for a specialty degree in reinforced and prestressed concrete at the CHEC in Paris, in 1965. Following four years in consulting engineering practice, first in Lebanon for one year, and then in Montreal, Canada, I enrolled at the Massachusetts Institute of Technology in Cambridge in the Fall of 1969 to pursue graduate studies. I obtained my MS degree in 1970, and my Ph.D. degree in 1972, from MIT, both in Civil Engineering. It is during this period that I decided to pursue an academic career. I joined first California State University in Los Angeles, for the academic year, 1972-1973, then the University of Illinois at Chicago, from 1973 to 1983, and then the University of Michigan in Ann Arbor, from 1983 until my retirement in 2007.

MY STORY WITH PRESTRESSED CONCRETE

When young, there was no question that I would become an engineer. I dreamt of airplanes and aeronautics. I built flying airplanes models using balsa wood. My first serious toys were the “Mecano” systems of punched steel plates, rods, bolts and screws, used to build models of everything and spark imagination. When I was ten, my Christmas gift was a subscription to “Systeme D”, a French monthly magazine describing “handy-man” special projects and ideas, the equivalent of self-help Popular Mechanics, wood-working, and the like. I used to fiddle with everything, trying to understand how and why. After graduation from high school (Notre Dame of Jamhour, Lebanon, run by the Jesuits) I went to Paris, France to study engineering, a five year program. The fifth year is when students have to choose a specialty. Being of Lebanese descent, it would have been hard to choose Aeronautics, my first choice. Much of the practical work, labs, training, and technical visits to manufacturing sites required special clearance from the French government. Also, there was no aerospace industry in Lebanon or the Middle East. Upon consulting with my father and re-evaluation of my future, I decided to take Civil Engineering, a specialty that would allow me total freedom to practice my profession anywhere in the world.

Following graduation with a Diploma in Engineering from Ecole Centrale des Arts et Manufactures (ECP), in Paris, in 1964, I selected to specialize in what was considered then the most technically advanced subject in structural engineering, and where the French were considered ahead in the field. That was Prestressed Concrete. Thus I enrolled in the CHEC (Center for High Studies in Construction), section CHEBAP (Center of High (advanced) Studies in Reinforced and Prestressed Concrete) in 1964, and earned a specialty degree in 1965, that is equivalent to a US Master’s degree. For prestressed concrete, we used copies of manuscripts hand-written in French by Y. Guyon, a pupil of Freyssinet. My first job was in Lebanon in a newly created governmental agency baptized “Executive Council for Large Projects” where I was assigned the supervision of a highway segment with two RC bridges. Since the job required mostly supervision with little design and analysis and since I complained to my boss that I was not using my knowledge, he suggested to me to prepare an internal document to introduce Prestressed Concrete to the division where I worked. This is when I prepared my first analysis-design notes on prestressed concrete, entirely based on the documents I had collected during my study of the subject in France. This is also, I believe, when I discovered the pleasure of writing, synthesizing thoughts and information, and possibly teaching.

In 1966 I left Lebanon bound to France and Canada, where I worked with a company (Potenco Inc.) representing the Freyssinet prestressing system in Quebec. My field assignment (at Habitat 67 in Montreal) involved the supervision of prestressing operations on site, with particular attention to the sequence of prestressing and prestress losses. This is where I developed a much better understanding of prestress losses and how to minimize their effects. My position in the field eventually led to an office position as a design engineer with a medium size consulting engineering firm then called Lalonde Valois Lamarre Valois and Associates. It later became one of the largest consulting firms in Canada (snc-Lavalin). My first assignments included mostly the design of footings and retaining walls, then reinforced concrete elevated structures and tunnels of the Trans-Canada Highway segments going through Montreal.
To improve my knowledge, I took evening extension courses at McGill University in the Fortran language and Numerical Analysis. My love of prestressed concrete pushed me to select, as a project for the course, the writing of a computer program for the analysis and design of simply supported prestressed concrete beams. This was the time where each command required a punch card and there was little room for error. However, my program eventually worked very well and soon it was noticed by Professor Alfio Seni, from the Ecole Polytechnique of Montreal, who did consulting work for the company, and whom I approached to discuss some unusual findings. I was thereafter reassigned to work on a new project dealing with the analysis and design of precast prestressed concrete highway bridges for the province of New Brunswick. While working on this project, I improved my program to include optimum design as well as analysis and design of prestressed beams for service and ultimate limit states; I then developed design charts utilizing the then AASHTO-PCI standard prestressed concrete I-beams in composite bridge decks. This work eventually led to my first paper on prestressed concrete which was published in the PCI Journal, in the Jan.-Feb. issue in 1972.

I would like to note that when I completed my specialty degree in prestressed concrete at the CHEC in Paris, in 1965, there were very few books on the subject of prestressed concrete. In France, we used the notes of Guyon, which were initially published in 1953 and supplemented by many handed-out manuscripts. I was not aware of any other French published book on the subject and Guyon’s work was considered (with understandable French bias) the only true and tested solid source of information and knowledge on prestressed concrete. Later when I moved to Canada, in 1966, I searched for other books on prestressed concrete to further my knowledge and found the books by Magnel (Prestressed Concrete, 3rd Edition, 1954), Evans and Bennett (1958), Libby (1961), Lin (Design of Prestressed Concrete, 1963), Abeles (An Introduction to Prestressed Concrete, 1964), Leonhardt (Prestressed Concrete Design and Construction, English translation, 1964), and Preston and Sollenberger (Modern Prestressed Concrete, 1967). I purchased them all for my own learning. There were many similarities in their introduction and examples of applications, but clearly the subject was ripe and ready to expand with increasing research and applications. Before my Ph.D. graduation in 1972, three other books were published in English, one by Mikhailov from Russia (1969), one by Katchatourian and Gurfinkel (1969), and one by Gerwick (1971). During the ten years I taught at the University of Illinois in Chicago, that is, between 1973 and 1983, additional books on prestressed concrete became available including those by Ramaswamy (1976), Libby (2nd Edition, 1977), Nilson (1978), and Warner and Faulkes (1979).

I first taught a graduate level course on Prestressed Concrete at the University of Illinois in Chicago in 1974, and then offered it practically on a yearly basis. I quickly realized that much of the fundamental knowledge and thinking I had learned during my studies in France needed to be adapted to US approaches, economic conditions, the need to simplify, and field experience. Precast-prestressed concrete was way ahead in the US while post-tensioning was the norm in France. I also realized that the US experience could gain from the rationality of French analysis and design approaches. This led me to undertake the writing of a textbook on prestressed concrete, first published in 1982, and at the same time allowed me to accumulate a broader knowledge and expertise on the subject.

In the Mean Time

During my engineering studies in France, I met Ingrid Schneider (from Berlin) in 1964 and we got married in 1967, while in Montreal, Canada. There, while working as a structural engineer, I felt the need to seek additional knowledge in my field. In the Fall of 1969, I joined the Civil Engineering Department at MIT which was then famous for developing the new structural analysis software “STRESS.” However, my intent was to pursue my expertise in prestressed concrete. Unfortunately, upon my arrival, Professor Pahl, who was responsible for prestressed concrete at MIT, had left for Germany and there was no course on prestressed concrete. This is when I met then visiting Assistant Professor S.P. Shah who introduced me to his dream subjects of Ferrocement and Fiber Reinforced Concrete. I had never heard of them before and, at first, they did not seem too exciting to me; but I needed the research assistantship and thus I joined the team, did my best, and got hooked.

I never took a course on prestressed concrete at MIT or in the US. However, my love of the subject subsided. When I joined the University of Illinois at Chicago in September 1973, I was asked what new courses I would like to teach, and I immediately mentioned Prestressed Concrete. It was promptly approved and the next year I taught a graduate level course on prestressed concrete for the first time. I then got involved in the PCI’s technical activities and won a Student Fellowship award in 1975 to study Partially Prestressed Concrete. Essentially it was about ten years since I had completed my specialty in prestressed concrete in France, and so doing research on the subject was
to become the beginning of a long dream overdue. Thus started the real foundation of a productive work that eventually led to numerous contributions with my students to the field of prestressed concrete.

We started working on partial prestressing about 1975 and eventually published a paper in 1979 on the analysis and design of partially prestressed beams which won the ASCE T.Y. Lin award and the PCI Martin P. Korn award (Figs. 1 and 2). I also introduced a second graduate level course on advanced prestressed concrete in which I taught subjects related to partial prestressing, optimum design, unbonded tendons and the like. I joined the University of Michigan in 1983 and I continued offering two graduate level courses on prestressed concrete, one meant primarily for Master’s students and the other for Doctoral students. In the second course, I taught additional topics on non-linear analysis, analysis and design with unbonded tendons in the cracked and ultimate limit states, and external prestressing. Following collaboration with Professor J. Breen from UT at Austin, and Michel Virlogeux from France, I Co-Organized the first symposium on External Prestressing in Bridges during the ACI Fall convention in Houston, in 1988.

Partial prestressing, external prestressing, and the use of unbonded tendons were becoming common practice in prestressed concrete. With my students we conducted a number of studies focusing on their analysis and design and we published a number of related papers (Fig. 3) including how to predict the stress in unbonded prestressing tendons at ultimate (Fig. 4). These served as a basis for several sections related to bending and compression members in the AASHTO LRFD Bridge Design Specifications first published in 1995.

During the late 1980’s and early 1990’s fiber reinforced polymeric reinforcements became available for use in reinforced and prestressed concrete structures. I immediately got interested in the subject but quickly realized the limitations on ductility and shear resistance when using such reinforcements. While my fears were later confirmed in extensive experimental and analytical studies, the experience we gained helped us shift our focus on repair and strengthening using such materials.

**Prestressed Concrete: Looking Ahead**

I believe that the following statement made by Freyssinet in the 1950’s remains valid today: "There exists no field of structural activity, and I say none, after careful thought, to which the idea of prestressing does not provide the possibility of solutions frequently unforeseen.”

Since the time of Freyssinet, prestressed concrete has advanced far beyond the developmental stage and has established itself as a major structural material. Similarly, prestressing techniques have evolved into a reliable technology. Prestressed concrete has made major contributions to the construction and the cement industries. It has led to an incredible array of structural applications from bridges to nuclear power vessels and offshore structures. Seldom is a major project planned today without considering prestressing as one of the viable alternative solutions. Moreover, some innovative large scale structures could not be conceived without prestressed concrete.

A careful analysis of prospects and opportunities indicates that the future of prestressed concrete is very bright. Constructed facilities and infrastructure systems will keep expanding not only in volume but also in reach. To achieve daring limits and efficiency, prestressed concrete will be needed. This is true for terrestrial structures as well as marine structures, under-water structures, under-ground structures, space structures, and structures needed to support new technologies such as wind-turbines and solar towers.

New technologies will also open new directions for prestressing. Shape memory materials may one day become sufficiently cost effective to be used in self-stressed prestressed concrete applications. Imagine even fibers and micro fibers randomly and uniformly distributed in a concrete matrix acting as stressing reinforcement at all levels.

Current market penetration for prestressed concrete in the United States is estimated at about 10 percent, and it is believed that a penetration of 30 percent will be achieved eventually. The same trend is expected in the future at the educational level. Design courses in prestressed concrete will very likely move from the list of elective courses to the list of required courses in structural engineering curricula.

Prestressed concrete structures contain all the beneficial attributes of concrete as a construction material plus those inherent to prestressing. The current widespread use of prestressed concrete in developed countries is astonishing.
Because of its many advantages, particularly its durability, it is expected to remain one of the strongest construction systems on the market for the foreseeable future.

Knowing too much on a given subject can blur innovation. Although it is generally simpler to measure achievements in terms of longer bridge spans, “longer span” is not necessarily the most important or critical research issue today for prestressed concrete. Some more rewarding and exciting topics include the use of fiber reinforced concrete matrices in combination with prestressed concrete structures (precast, pretensioned or post-tensioned), the use of concrete matrices that are not only of higher strength but also of significantly higher durability (such as ultra high performance fiber reinforced concrete) and more impervious to various environmental attacks; the possible use of advanced fiber reinforced composites to replace prestressing strands; the development of shape memory materials for self-stressing; and seismic applications.

**MY STORY WITH FEROCEMENT**

The use by Joseph Louis Lambot of ferrocement to build a small boat in 1849, and the patent granting that followed in 1855 for “Fer-ciment” represent in effect the birth of modern reinforced concrete. While reinforced concrete took off thereafter at a rapid pace, ferrocement saw a period of stagnation with very slow progress for almost one hundred years. Only in the 1940’s and 1950’s did Pier Luigi Nervi of Italy recognize the possible advantages of ferrocement not only for boat building but for terrestrial applications as well, and carried out some experiments on its mechanical properties. He reported that ferrocement showed exceptional elasticity, flexibility, strength, and resistance to cracking. Technical reports to support these statements, with sufficient details as would be expected with similar reports today, were simply not available, not synthesized, or were written in a different language. Significant interests by mostly amateur boat builders in ferrocement and its applications grew in the early 1960’s, particularly in the UK, Canada, New Zealand and Australia. Some activities were also reported in Russia and China. Many fisheries were interested in the new material. Reports of experiences with ferrocement by boat builders were available in publications targeted to boat building and fisheries. These were largely anecdotal in nature (such as this boat survived a 15 knots wind and 20 ft waves), and provided very little technical information. The notion that ferrocement is a crack free material was common in these reports. The extension of the use of ferrocement to terrestrial structures was not yet clearly recognized and was greatly hindered by the lack of clear analysis, design methods, design criteria and guidelines.

Prior to joining MIT in 1969, I had never heard of ferrocement. I went to MIT hoping to further my graduate studies in prestressed concrete; however, since Professor Pahl, who taught prestressed concrete, had left (back to Germany) just prior to my arrival, I turned down the next topic offered to me for research (structural reliability) and took on the subject of ferrocement and fiber reinforced concrete introduced to me first by none other than Suru Shah, then visiting assistant professor at MIT. As part of my Master’s thesis, I started a comprehensive experimental program on the mechanical properties and reinforcing mechanisms of ferrocement in tension. However, I could find very little solid technical information. Even the engineering library at MIT and its search and borrowing resources could hardly locate more than a handful of references on the subject. I dismissed anecdotal information suggesting that ferrocement does not crack and is impervious to water, and eventually realized the importance of the specific surface of reinforcement and its effect on reducing crack width and spacing. I thoroughly enjoyed understanding the significant influence of this relatively new parameter. My M.S. thesis, completed in 1970, was perhaps the first fundamental research study on the tensile behavior of ferrocement and its modeling.

Increased scientific approach to studying and predicting ferrocement properties was encouraged by a panel of the US National Academy of Sciences, Chaired by J. Romualdi, formed in 1972, and whose report was released in 1973. This led to the formation of the American Concrete Institute’s Committee 549 on Ferrocement, in 1975, and the establishment, shortly thereafter, in 1976, of the International Ferrocement Information Center (IFIC) at the Asian Institute of Technology in Bangkok, Thailand. Publication of the Journal of Ferrocement (which started as a publication by the New Zealand Ferro Cement Marine Association) was then consolidated at IFIC. A RILEM scientific committee on ferrocement was later formed in 1979. Progress accelerated during the 1980’s through fundamental research, publications, symposia, short courses and applications

I served as Chair of ACI Committee 549, Ferrocement, starting in 1981 over a period of six years. During my tenure the committee produced the first "State-of-the-Art Report on Ferrocement." In a second phase, in 1988, the Committee developed the first "Guide for the Design, Construction and Repair of Ferrocement," which gained
instant success worldwide among practitioners using ferrocement and became the basis of many local codes on ferrocement. The guide contained two chapters, one on design criteria and one on testing, almost entirely based on research work I had carried out with my students.

The International Ferrocement Society (IFS) was founded in 1991, under the Chairmanship of Rick Pama from the Asian Institute of Technology, and I was one of the founding members. Its main objectives were to foster development, disseminate knowledge, and encourage practical applications of ferrocement, particularly terrestrial structures. The most urgent need of this new professional society was to develop a building code for ferrocement. I was selected to chair its committee, and the first Ferrocement Model Code was published in 2001, essentially setting the stage for guided expansion, imagineering and developments.

I never lost enthusiasm for ferrocement. I participated in many related conferences and symposia, the first such symposium dedicated to Nervi, in Bergamo, Italy, 1979, co-organized by Oberti and Shah. About two decades later, in 1998, I organized the 6th International Symposium on Ferrocement, which was dedicated to Lambot. I have been closely involved with the organization of the Seventh, Eighth, and incoming 9th Symposium on the subject. Feeling the need to synthesize the knowledge I had gained on ferrocement and the urge to disseminate that knowledge, I wrote the first existing textbook on the subject, “Ferrocement and Laminated Cementitious Composites,” which was published in 2000.

**Ferrocement: Looking Ahead**

What are the near-future prospects for ferrocement materials, applications, and technology? It should be noted that many advances in materials and technology as summarized next simultaneously influence ferrocement and fiber reinforced concrete.

We are witnessing a considerable evolution in materials and materials technology. At the matrix level, while the basic cement and sand components remain the same, an increasing number of additives are becoming available. These additives allow for many properties to be easily obtainable, such as improved workability, flowability, setting time, strength, bonding, high durability, and high impermeability. Mortar compressive strengths exceeding 100 MPa can be readily achieved and will be utilized. High performance and ultra-high performance cement matrices, containing finer particles such as silica fume, glass powder, and the like will be increasingly used in cost competitive applications.

To decrease the reinforcement, improve efficiency, and reduce labor cost the idea of replacing several layers of mesh reinforcement in a ferrocement by only two extreme layers, while adding fibers to the matrix, was shown to be technically effective, provided the mesh reinforcement is of high strength and high modulus (Fig. 5). To further reduce labor cost, the idea of using a fiber mat as a core spacer between the two extreme layers of mesh, thus forming a sandwich-like self-contained reinforcing system was explored and also proven to be effective, performance and cost wise (Fig. 6). At the reinforcement level, while steel meshes remain the primary reinforcing material, other materials such as carbon fiber meshes and organic synthetic meshes offer some advantages, particularly with respect to corrosion resistance and weight (Figs. 6 and 7). In industrialized countries, including the U.S., synthetic meshes such as polypropylene, PVA [poly (vinyl-alcohol)], carbon, Kevlar, and polyethylene (Spectra) meshes can be produced to specification and delivered to site, some at a cost competitive level with steel or organic natural meshes (sisal, jute, bamboo). Three-dimensional meshes (fabrics, textiles) of either steel or polymeric materials or hybrids will become increasingly available. Examples suitable for ferrocement are shown in Fig. 8. While 3D-meshes have taken a separate path as part of textile reinforced concrete, they will be most competitive in thin reinforced cementitious products such as ferrocement. Since a single three-dimensional mesh may replace several layers of plain 2D mesh, substantial savings in labor cost are expected. Further savings can be achieved when the mortar matrix is mechanically applied as in shotcreting, extrusion, or pultrusion. Also, given modern trends in manufacturing, it is likely that robotics techniques will be applied to the production of ferrocement precast elements, eventually leading to substantial reduction in labor cost. The use of 3D textile using polymeric fibers will also see increasing applications in products using lightweight cement matrices.

Also, with the increasing concern about green environment and ecology, there will be growing efforts to use natural fibers (jute, fique, bamboo) in the form of textiles for ferrocement applications, particularly in terrestrial structures (housing, agricultural structures) and in combination with lightweight cement matrices. Treating the textile fiber or the cement matrix to improve durability remains a key obstacle for taking full advantage of this solution.
At the other extreme, stronger reinforcements, whether steel or polymeric such as carbon or aramid, will become common in ferrocement and thin cement-based products. Current examples, using steel, include Fleximat® from Bekaert and Hardwire® which provide tensile strengths in the range of 2400-3100 MPa (Fig. 9). These will be particularly compatible with high performance and ultra-high performance cement matrices. Figure 10 illustrates the bending response of (0.5 in. or 12.5 mm thick) ferrocement plates using only two layers of these high strength steel systems and fibers where equivalent elastic bending strength or modulus of rupture can exceed 130 MPa. Given that the total volume fraction of reinforcement in these composites, including the fiber, is less than 3.7% and given that with conventional steel wire mesh reinforcement, a modulus of rupture of only about 50 MPa could be achieved at about 8% total reinforcement, it can be observed that a four-fold increase in performance is achievable.

Applications of ferrocement in small size structures and structural elements have mushroomed in developing countries. Examples include water tanks, grain silos, domes, barges, earth shelters, floating wharves, pontoons, roofing beams, and oil tankers. In a way, ferrocement has become an "all purpose" material for thin products and its potential combination with other materials (such as fibers and prestressing) is a testimony to its versatility. It is believed that increased utilization of ferrocement will continue. In industrialized countries this may take the form of mechanized production of small size elements such as cement sheets and pipes to replace asbestos cement products. The housing market has become most suitable at this time for the use of cladding, roofing and exterior skins made out of ferrocement.

The technology of ferrocement will continue to span a very wide range, from a fairly simple technology requiring only a small investment in tools and equipment, to a very advanced technology where robots will replace labor at a fraction of the cost.

While existing codes and guidelines for reinforced concrete offer a good starting point, there will be increasing needs for improved guidelines and codes specifically geared toward ferrocement and thin cement-based products. In the U.S., for instance, fire resistance requirements regarding minimum concrete cover to the reinforcement do not and cannot apply to ferrocement. Yet such requirements hinder its use. On the "analysis-design" side, in the future, particular attention should be given to simplifying the analytical involvement, providing design aids and reducing the total effort devoted to the "analysis-design" process. As the majority of builders of small ferrocement structures are non-technical, it is not realistic to assume that they will be able and willing to follow complex design methodologies. Some progress toward simplification has already been made through the Ferrocement Model Code published by the International Ferrocement Society. It should facilitate the acceptance and implementation of ferrocement throughout and pave the way for un-hindered future developments.

As with many structural materials, increased educational activities and increased applications will move in steps, and will be strongly correlated. It is likely that the subject of ferrocement will find its way into courses related to reinforced concrete, plates and shells, and brittle matrix composites.

**MY STORY WITH FIBER REINFORCED CONCRETE**

During my early graduate studies at MIT, I quickly understood the importance of strength versus ductility and stiffness, nominal stress versus stress concentration, and fracture toughness and fracture sensitivity. My doctoral thesis dealt with developing a rational theory to predict the tensile strength of fiber reinforced concrete. At the time only plain circular steel fibers were available and their bond to the concrete matrix was very poor. This led to very poor post-cracking strength and in a way little structural ductility. In a separate research term project for a course, I tried to imagine a method to improve fiber bond and toughness. I came up with a tri-dimensional fiber structure that looks like two footballs placed in line with each others axis and linked along their axis. In one configuration, the structure of the fiber consisted of four wires, one straight positioned along the axis of the football, and 3 surrounding wires forming the football skeleton (Fig. 11a). They were all connected at the link by twisting the wires like a cord. I then built a hand driven machine to fabricate the fibers and I tested them in small mortar beams. The fibers could not be premixed; but they were placed into a mold until its full capacity and then a mortar matrix was poured in. Fiber content varied between 1.35% and 3.1% by volume. The test beams led to superior performance in terms of strength, multiple cracking and deflection. A U.S. Patent (No. 3,852,930) was then filed by MIT and granted.

SIFCON and HPFRCC
About ten years later, Lankard and co-workers introduced a manufacturing process for fiber reinforced concrete called SIFCON (Slurry Infiltrated Fiber Concrete), a process by which straight steel fibers (single plain or deformed fibers) were placed into a mold up to its full capacity and then infiltrated by a cement-based slurry. This process was similar to the one I used with the 3-D fibers, but more complex because the cement slurry was to be fine enough to infiltrate the very dense fiber network of high fiber content, made of straight steel fibers. During the 1980’s, with several students, we worked extensively on the mechanical properties of SIFCON, particularly compression and tension. SIFCON provided unique tensile behavior with multiple cracking and strain-hardening after cracking (Fig. 11b), and a record performance among all types of fiber reinforced concretes in terms of strength, ductility and toughness (Fig. 12). However it used a relatively large volume fraction of fibers ranging, at the time, from about 7% to 15% by volume. SIFCON was then extensively used in numerous defensive and protective structures by the Department of Defense. It is based on my better understanding of SIFCON tensile properties that I introduced in 1987 the concept of High Performance Fiber Reinforced Cement Composites (HPFRCC) which were defined as those developing a stress-strain response in tension with a post-cracking strength larger than their cracking strength and with multiple cracking occurring following first cracking. The figure I used is reproduced in Fig. 11b. Later on, such behavior was termed “pseudo strain-hardening,” “quasi strain-hardening,” or simply “strain-hardening” behavior and is now a generally accepted term among researchers. A discussion that led to the closure of the 4th International Workshop on High Performance Fiber Reinforced Cement Composites (in Ann Arbor, Michigan, 2003) led to a recommended simple classification of all fiber reinforced cement composites according to their tensile behavior as either strain-softening or strain-hardening; such behavior is illustrated in Fig. 13.

SIFCON demonstrated that strain-hardening in tension with multiple cracking can be achieved by FRC composites, without adding reinforcing bars. Post-cracking tensile strength as high as 30 MPa was achieved, with tensile strain capacity exceeding 1% (Fig. 12b). In compression SIFCON achieved 210 MPa with a strain capacity at peak of about 10%. One drawback of SIFCON was the high volume fraction of fibers needed and their related cost. Again Lankard and co-workers imagined a prefabricated mat made with long steel fibers. The mat would be preplaced in a mold and infiltrated by a cement slurry. SIMCON (or Slurry Infiltrated Mat Concrete) was born. One advantage of SIMCON is that it led to a volume fraction of fibers ranging from about 4% to 7% (significantly smaller than SIFCON) while achieving competitive strength and toughness. Additional work later by Krstulovic-Opara and others showed that while, overall, the performance of SIMCON was not as good as that of SIFCON, it offered an excellent trade-off when performance to cost ratio was considered.

While developments at the material level were progressing during the 1980’s, many researchers attempted to use fiber reinforced concrete in structural applications in combination with conventional reinforced concrete. The use of SIFCON for example, in combination with conventional reinforcing bars, led to superior (but also very costly) reinforced concrete structures which were mostly used by the department of defense for protective structures. In 1990 I was awarded a Senior Scientist Award by the Alexander von Humboldt Foundation from Germany to work with H.W. Reinhardt. We initially selected to work on the influence of SIFCON in applications with conventional reinforced concrete beams; this was the beginning of a continuing and productive collaboration which led to the organization of five international workshops on High Performance Fiber Reinforced Cement Composites, between 1991 to 2007. During the late 1980’s, Bache from Denmark introduced Compact Reinforced Concrete, a concrete reinforced with a high reinforcement ratio of reinforcing bars in both tension and compression, and simultaneously reinforced with a relatively high volume fraction of short steel fibers. The resulting beams showed an almost elastic-plastic response up to failure, exhibiting both high resistance and high ductility.

Since the first introduction of modern fiber reinforced concrete in the US by Romualdi, Mandel, and Batson, in the early 1960’s, the most common method of production was to premix the fibers with the concrete. Such a method, even with today’s advances and modern fibers, allowed the proper premixing of steel fibers in amounts not exceeding about 2% by volume, in a conventional concrete with aggregates. In the lab, we could go up to 4% provided smaller length fibers were used with a fine mortar matrix. However, there were many trade-offs to consider. For instance, a longer deformed steel fiber is more efficient, bond wise, than a shorter plain steel fiber. Yet the longer fiber is more difficult to mix and tends to segregate and form balls more easily than the short fiber. During the late 1980’s and beginning of 1990’s, it had become clear that “strain-hardening” behavior in tension is essential for the full success of fiber reinforced cement composites, not only in stand alone applications but also in structural applications where fiber reinforced concrete can be used in combination with conventional reinforced and prestressed concrete.
TOREX Fiber

Shortly after joining the University of Michigan, I introduced a graduate level course on Fiber Reinforced Cement Composites, first taught in 1985. I believe it may have been the first such complete course in a US university. The course covered ferrocement, laminated cement composites with continuous reinforcement, and fiber reinforced concrete with discontinuous fibers. The course was generally taught once every two years. In it, I covered the mechanics of how to predict cracking and maximum post-cracking strength in fiber reinforced concrete under tension as essentially developed in my Ph.D. thesis, in 1972. The methodology assumed round fibers and the resulting prediction equations used the fiber aspect ratio, L/d, that is, length divided by diameter, as one of the causal variables. One of the questions that was sometimes asked by students was: what would happen to L/d if the fiber is not round? and my answer was that we could derive an equivalent diameter from the fiber cross sectional area and use that as a first approximation. During the Fall of 1991, when teaching the course, I decided to put my teaching notes in typewritten form. I decided then to solve the case of “non-circular” fiber as a special case. However, it became soon evident to me that the “non-circular” fiber should be the general case and the circular fiber a particular case of it. The formulae revealed that a most important factor is the ratio of fiber lateral surface area per unit length divided by the fiber cross-sectional area, which I later termed the FIER (Fiber Intrinsic Efficiency Ratio). For circular fibers, FIER becomes proportional to the fiber aspect ratio. Soon I realized that polygonal fibers (triangular, square, rectangular) have higher values of FIER than circular fibers of same cross section, and thus are theoretically more efficient, bond wise; the formulae were clearly confirming this result; moreover, thin flat fibers would be most efficient, but not practical since they are more difficult to mix and also since they provide too much interruption in the continuity of the matrix. So I focused attention on fibers of square and triangular cross section and observed that triangular fibers would be about 28% more efficient than circular fibers of same cross section. I also worked on substantially square or substantially triangular cross-sectional fiber shapes that showed theoretical FIER values 200% to 300% those of circular fibers.

Extensive prior investigation on the pull-out behavior of fibers from concrete had revealed that frictional and adhesive bonds were much less effective than mechanical bond, such as in the case of hooked ends fibers or deformed fibers. So it was obvious for me to imagine that polygonal fibers could also benefit from a mechanical component of bond. Since twisting is a good way to anchor a screw or a non-circular nail, the idea of twisting the fiber came naturally. Hence, what I called later the Torex fiber for identification was conceptually born (Fig. 14). The theoretical findings on the importance of the FIER and on twisting were then revealed in a confidential seminar in September 1994 to a fiber producing company, with the intent to launch a new family of fibers. However, interest was shown; the main reason given was that it would be difficult to produce the Torex fiber and there were insufficient experimental results to demonstrate its theoretically “predicted” superior performance. It took an additional three to four years before the results could be demonstrated first from pull-out tests and then in small scale fiber reinforced concrete specimens. Experimental tests revealed that the behavior of Torex fiber during pull-out depended on numerous parameters including the fiber twisting ratio, and the fiber and matrix mechanical properties. The most important new observation was that the parameters can be tailored in such a way that the fiber un-twists during pull-out providing enormous amount of energy (three to four times what the best fibers on the market could achieve) while maintaining a high pull-out resistance. The results were so impressive and convincing that a patent was filed by the University of Michigan and granted in 1999 almost seven years after initial conception. An additional provisional patent followed in 2000. Three doctoral students should be credited for the extensive experimental work on the bond properties and performance of Torex fibers: Jamil Alwan, now Chief Engineer at Ford Motors Co., Patricia Guerrero, now Professor at Universidad del Valle in Cali, Colombia, and Chuchai Sujivorakul, now Associate Professor at King Mongkut University in Bangkok, Thailand.

The performance of the Torex fibers opened new opportunities for fiber reinforced concrete. Extensive tensile tests on FRC specimens revealed that strain-hardening behavior in tension using Torex fibers could be achieved with a volume fraction less than 2% and in some cases close to 1%. Strain capacity up to 1% in direct tension was possible at stresses 2 to 3 times the strength of the non fiber reinforced matrix. Moreover, crack widths prior to maximum
strain and localization were less than 50 microns, implying a good service and durability performance of the composite whether used alone or in combination with reinforced and prestressed concrete. The above two results have greatly simplified the way to possible large scale application of fiber reinforced concrete in both structural and not structural applications. With mixing constraints of higher volume fractions of fibers for ready mix trucks taken into consideration, the use of self-consolidating fiber concrete became the next challenge.

**Self Consolidating FRC.** Since it was possible to obtain strain-hardening FRC composites with less than 2% steel fiber by volume, and since premixing more than 2% steel fiber (of length exceeding 30 mm) by volume was quite difficult, the next objective was to focus on simplifying the mixing and site delivery process. One of the most promising ongoing developments is the production of a self consolidating fiber reinforced concrete, possibly delivered in ready-mix trucks, with the potential of achieving a strain hardening behavior in tension after cracking and a fiber content not exceeding 2% by volume. This will provide an enormous impetus for wide scale applications in earthquake, impact, and blast resistant reinforced and prestressed concrete structures. As of this writing, self-consolidating fiber reinforced concrete and fiber reinforced mortar mixtures have been developed and shown to exhibit strain-hardening behavior in tension. Since such mixtures can be used in ready-mix trucks they will become readily available to non specialized practitioners.

**In a Nutshell - FRC Progress**

Over the past few decades, we have learned that fibers affect various properties of concrete at the fresh, hardening, and hardened state. The effect is rather negative (balling, segregation, harsh mixtures, etc.) in the fresh state and positive in the hardening (plastic shrinkage cracking) and hardened state. We have learned that bond between fiber and matrix is paramount for composite action and that the stiffness of the fiber material should be significantly larger than that of the matrix in order to improve hardened properties. Practically all mechanical properties, in the post-cracking state, improve with fiber reinforcement. At the material level, fracture toughness, energy absorption capacity, and fracture energy all improve as well. When added to reinforced and prestressed concrete, the benefits from fiber reinforcement can be predicted using various non-linear analysis models where the constitutive properties of the materials are considered. It is therefore expected to observe improvements in ductility, energy absorption capacity, impact and blast resistance, and resistance of the structure to various solicitations in bending, shear, tension, biaxial loading and the like. Average crack widths at service load are expected to be smaller. There is also clear evidence that numerous intangible benefits result from the use of fibers such as reduced spalling of cover under cyclic loading, reduced fragmentation under impact loading, improved bond of reinforcing bars and prestressing strands, improved durability, and reduced permeability and leakage.

A single sentence used by Parra-Montesinos sums up the intangible contributions of the fiber to structural concrete and that is “fibers improve the damage tolerance of the structure.”

In summarizing the path of fiber reinforced concrete over the past century the following observations can be made:

- The initial objective of most patents on fiber reinforced concrete was to improve the tensile strength of concrete, that is, by mixing in the reinforcement.
- The real benefit (initially un-recognized) was to improve toughness and fracture toughness, ductility, energy absorption capacity and impact resistance of the material.
- Another key benefit recognized much later (today) is the improved performance of conventional reinforced and prestressed concrete using matrices with fibers (bond, ductility, cyclic response, etc.), that is, leading to a highly “damage tolerant structure.”

At the practical experience level, we have learned that while concrete and fiber reinforced concrete seem very simple at first glance, tailoring and optimizing their properties for a high level of performance, such as high tensile strength and strain-hardening behavior, can be very complex and challenging.
Looking Ahead: Fiber Reinforced Concretes

The previous paragraphs suggest already a number of ongoing developments including the increasing use of fibers in combination with reinforced and prestressed concrete structures, the increasing use of strain-hardening FRC composites, and the increasing availability of self-consolidating fiber reinforced concrete for delivery in ready-mix trucks. Recent ACI code adoption of fibers to replace minimum shear reinforcement is a first but daring step that will allow penetration of fiber reinforcement in many codes, standards and guidelines world-wide, and thus will have great impact on all applications. Simultaneously, at the educational level, either graduate courses on fiber reinforced cement composites will be increasingly offered, or the treatment of fiber reinforcement will find its way into various courses on concrete materials, brittle matrix composites, and reinforced concrete analysis and design.

In one statement summarizing the future impact of prestressed concrete, Freyssinet once said: "Prestressing will renew, from tip to toe, the present day conception of the ship, the port, and the port accessories." Fiber reinforcement is about at the same stage. We can safely say today that fibers will renew from tip to toe the present day concept of structural concrete in all civil infrastructure applications.

To those who, like me, have worked on fiber reinforced cement composites some time during or over the past four decades, I would like to restate our secret dream which will keep challenging our minds and imagination, and those of our students, that is, to mix fibers into concrete like sand or aggregate to achieve a moldable, strong, ductile and durable composite for construction applications (with similar strength and ductility as reinforced concrete or steel). Nothing less.

ACKNOWLEDGMENTS

However hard I tried, the list of acknowledgments would be too long and surely will not be complete. If I had to work on this enormous task, I would certainly include very many colleagues not only in the US but also in many countries abroad, friends, family, professional societies, funding agencies, students, visiting scholars, the universities which provided the exciting work environment for my academic career, institutions who hosted my visits during leaves and sabbaticals, and of course the organizers of this symposium and its proceedings.

DEDICATION

Often life is compared to a tree. Significant encounters lead to branches with their own path and fruit carrying ability. Eventually the tree stops growing taller but the branches blossom and the tree gains strength. With my students, I have had intersections in my life which led to new branches and new trees. These have changed my life and gave my work meaning, satisfaction and joy. In hindsight, I look back and wonder how lucky I was and I am humbly grateful.

I would like in particular to cite the following doctoral students whose path and mine crossed and converged to become each a venture, which led to most satisfying professional experience and friendship. These dissertations offer glimpses into their work.

1. Pao-Tsan Wang, Ph.D., October 1977, "Complete Stress-Strain Curve of Concrete and its Effects on Ductility of Reinforced Concrete Members," (Co-Chair with S.P. Shah)
2. Perumalsamy N. Balaguru, Ph.D., October 1977, "Static and Fatigue Properties of Ferrocement in Bending," (Co-Chair with S.P. Shah)
3. Shan Somayaji, Ph.D., March 1979, "Composite Response, Bond Stress-Slip Relationship and Cracking in Ferrocement and Reinforced Concrete," (Co-Chair with S.P. Shah)
6. Siri Watcharamnuay, Ph.D., April 1984; "Deflection of Partially Prestressed Beams Under Sustained and Cyclic Fatigue Loadings".
7. Mohamed H. Harajli, Ph.D., May 85; "Deformation and Cracking of Partially Prestressed Concrete Beams Under Static and Cyclic Fatigue Loading".
8. Rajeh Zaid Al-Zaid, Ph.D., April 1986, "Fatigue Reliability of Prestressed Concrete Girder Bridges"; Co-Chair with A. Nowak.
9. Kosa Kenji, Ph.D., April 1988, "Corrosion of Fiber Reinforced Concrete." (Co-Chair with W. Hansen)
10. Duane Otter, Ph.D., Fall 1988, "Fiber Reinforced Concrete under Cyclic and Dynamic Loading".
12. Messaoud Founas, Ph.D., December 1989, "Deformation and Deflections of Partially Prestressed Concrete T Beams under Static and Random Amplitude Cyclic Loading."
15. Fadi Alkhairi, Ph.D., Fall 1991, "On the Flexural Behavior of Beams Prestressed with Unbonded Internal or External Tendons."
23. Rosa Maria Vasconez, Ph.D., Fall 1996, "Behavior of Fiber Reinforced Concrete Connections for Precast Frames under Reversed Seismic Loading." (Co-Chair with J.K. Wight)
28. Zuming Xia; Ph.D.; December 2001; "Behavior and Modeling of Infill FRC Damper Element for Steel-Concrete Hybrid Shear Wall."
29. Kulusi Chandrangsu; Ph.D., April 2003; “Innovative Bridge Deck with Reduced Reinforcement and Strain-Hardening FRC Composites.”
30. Thanasak Wongtanakitcharoen; Ph.D.; December 2004; “Control of Plastic Shrinkage Cracking of Concrete by Fibers.” (Co-Chair with W. Hansen)
31. Shih-Ho Chao; Ph.D., September 2005; “Bond Characterization of Reinforcing Bars and Prestressing Strands in High Performance Fiber Reinforced Cementitious Composites under Monotonic and Cyclic Loading.” (Co-Chair with G. Parra Montesinos)
32. Visut Likhiruangsilp; Ph.D.; April 2006; “Moment-Rotation and Punching Shear of High Performance Fiber Reinforced Composites Structural Elements.” (Co-Chair with G. Parra Montesinos)
33. Dong Joo Kim; Ph.D.; December 2008; “Strain Rate Effect on High Performance Fiber Reinforced Cementitious Composites Using Slip Hardening High Strength Deformed Steel Fibers.” (Co-Chair with Sherif El-Tawil)
34. Supat Suwannakarn; Ph.D.; December 2008; “Post-Cracking Characteristics of High Performance Fiber Reinforced Cementitious Composites.” (Co-Chair with Sherif El-Tawil)
Figure 1 -- Partially prestressed beams: analysis in the elastic uncracked, elastic cracked and ultimate range of behavior – work completed in the late 1970’s.

Figure 2 – Schematic moment curvature of reinforced, prestressed and partially prestressed beams for same ultimate resistance – work completed in the late 1970’s.
Figure 3 -- Typical external prestressing applied to reinforced, prestressed or partially prestressed beams with bonded or unbonded tendons – generalized case for unified solution studied in the 1980’s

Figure 4 – Summary solution to predict the stress in unbonded tendons at ultimate with recommended value of strain reduction coefficient, \( \Omega_u \) for use in design – late 1980’s to date
Figure 5 – (a) Typical section of ferrocement with several layers of mesh. (b) Typical section of efficient hybrid composite with only two extreme layers of mesh and fibers.

Figure 6 – a) Typical ferrocement sandwich construction where a fiber mat acts as core and spacer of the two extreme layers of mesh reinforcement. b) Typical aramid (10x10 mm opening) and carbon (25x13 mm opening) meshes made with high performance fibers embedded in a polymeric matrix.

Figure 7 – Typical fiber reinforced polymeric meshes (or textiles of fabrics) suitable for use in ferrocement and thin cementitious composites (mesh openings about 3 to 5 mm).
Figure 8 – Examples of three-dimensional (3D) mesh systems with FRP (textile) reinforcements fabricated at the ITA in Aachen, Germany: a) 3D spacer-sandwich textile; b) 3D spacer stiff textile (about 15 mm in thickness)

Figure 9 – Unidirectional high strength steel meshes using strands with tensile strength exceeding 2400 MPa (350 ksi) for use in ferrocement type applications (strand spacing about 3 mm)

Figure 10 – Illustration of bending response of ferrocement plates using high strength steel reinforcement (from Fig. 9) and comparison with limit achieved using conventional steel wire meshes
Figure 11 -- a) 3D steel fiber (1974 US patent) designed to deform (the wires tend to confine the matrix inside the ball structure) during pull-out in order to improve pull-out resistance and ductility. b) Tensile response of high performance fiber reinforced cement composite (HPFRCC) as first defined in 1987.

Figure 12 – Examples of stress-strain properties of SIFCON as compared to plain concrete in: a) compression, and b) tension (research carried out during the 1980’s)
Figure 13 – Characterization and classification of tensile response of fiber reinforced cement composites: a) strain-softening, and b) strain-hardening (also termed HPFRCC)

Figure 14 -- Twisted triangular, square, and rectangular Torex fibers (1999 US patent) designed to untwist during pull-out in order to improve composite ductility while maintaining high tensile stresses in the fiber