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; HPFRCC; partial prestressing; prestressed concrete; SIFCON; strain-hardening; strain-softening; textile reinforced concrete.

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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 4 years in consulting engineering practice, first in Lebanon for 1 year, and then in Montreal, Canada, I enrolled at the Massachusetts Institute of Technology (MIT) in Cambridge in the Fall of 1969 to pursue graduate studies. I obtained my MS degree in 1970, and my PhD 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 1972-1973 academic year, 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 Meccano 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 5-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 reevaluation 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 U.S. 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*, third 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 PhD 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 10 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 (second 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 U.S. approaches, economic conditions, the need to simplify, and field experience. Precast-prestressed concrete was way ahead in the U.S. while post-tensioning was the norm in France. I also realized that the U.S. 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 meantime

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 U.S. 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 10 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 (Fig. 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 nonlinear 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 unbounded 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 1980s and early 1990s, 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 1950s 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, underwater structures, underground 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 microfibers 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%, and it is believed that a penetration of 30% 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 matrixes 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 FERROCEMENT

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 100 years. Only in the 1940s and 1950s 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 1960s, 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 Ferrocement Marine Association) was then consolidated at IFIC. A RILEM scientific committee on ferrocement was later formed in 1979. Progress accelerated during the 1980s 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 6 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 (14.5 ksi) can be readily achieved and will be used. 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, polyvinyl alcohol (PVA), 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 (3D) 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 3D mesh may replace several layers of plain two-dimensional (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 to 3100 MPa (348.1 to 449.6 ksi) (Fig. 9). These will be particularly compatible with high performance and ultra-high performance cement matrixes. Figure 10 illustrates the bending response of (0.5 in. [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 (18.9 ksi). 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 (7.3 ksi) 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 unhindered future developments.

As with many structural materials, increased educational activities and increased applications will move in steps, and will be strongly correlated. It is