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Developments in Elastic, Strength and Interface Fracture Properties of FRP-Concrete Systems

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ABSTRACT: Concrete is the most widely used construction material in the world and fiber reinforced polymer (FRP) composites are considered to be the wave of the future. Combined use of these two types of materials to overcome the challenges associated with existing and new infrastructures has become a major research field in Civil Engineering in the last two decades. Significant progress has been made in understanding the behavior and failure of FRP-concrete systems where FRP is used as internal or external reinforcement in addition to or instead of the conventional steel reinforcement. While structural engineers explore infrastructure related use of FRP-concrete systems, recent research breakthroughs regarding both concrete and FRP materials enabled by investigations at small scales have opened up new horizons for further improving the performance of FRP-concrete systems and coping with challenges. This paper summarizes the current state of research and progress related to FRP-concrete systems with emphasis on elastic, strength and interface fracture properties in an attempt to shed light on future research trends and potential improvements in the performance of FRP-concrete systems.

1 INTRODUCTION

Concrete is the most widely used construction material in the world with a consumption rate of approximately 1 m^3/capita/year, while FRP composites industry is among the fastest growing markets averaging in the order of 10% a year to make a sure mark on this century. Increasing availability and reducing costs of FRP composites have made their consideration for use in structural engineering possible in the late 1980s and since then there has been an exponential growth in the number of research projects and publications on combined use of concrete and FRP composites to cope with the challenges associated with existing and new infrastructures. Owing to the rapidly growing number of field applications, the construction industry currently takes the largest share in FRP composites shipments followed by the transportation industry (Kazmierski 2012). Considering that the current penetration of FRP composites into the construction market is only about 4%, there is much room for growth of FRP applications in structural engineering, a significant portion of which is composed by FRP-concrete systems.

As structural engineers engage in research and development activities to explore new and innovative uses of FRP-concrete systems for safe and sustainable infrastructures, recent research breakthroughs regarding both concrete and FRP materials enabled by investigations at small-scales have opened up new horizons for further improving the performance of FRP-concrete systems and coping with challenges. This paper reviews the current state of research and progress related to FRP-concrete systems with emphasis on the elastic, strength and interface fracture properties. A related study focusing on ductility of FRP-concrete systems was reported elsewhere (Gunes et al 2013). Recent research progress in advanced concrete and FRP materials is summarized in an attempt to shed light on future research trends and potential improvements in the performance of FRP-concrete systems.

2 MATERIALS BEHAVIOR AND PROPERTIES

FRP composite materials have several favorable characteristics that justify their use in concrete structures. Among these are the high strength and stiffness to weight ratios, tailorable material properties and geometry, ease of application, and exceptional durability against environmental and mechanical effects. Figure 1(a) shows the typical tensile stress-strain behavior of FRP composites in comparison with those of concrete in compression and structural steel in tension. Typical ductility ratios are also given in the figure to illustrate the scales. As can be seen from the figure, the stress-strain behavior of FRP composites is fundamentally different than those of concrete and steel which display a certain extent of inelastic deformation before failure, used as a measure of material ductility (Gunes et al 2013). This type of behavior is much valued in structural engineering since ductility not only results in warning before ultimate failure but also reduces the dynamic load demand through increased energy dissipation and damage. In this respect, the linearly elastic tensile stress-strain behavior followed by a brittle failure common to most FRP composites is a significant concern. A compensating property of FRP composites is their high toughness due to their typically much higher tensile strength and ultimate strain compared to those of concrete in compression and reinforcing steel at yielding. Since the ductility of reinforcing steel in a properly designed RC member is never fully realized due to concrete failure in compression, additional FRP reinforcement, when properly designed and installed, does not alter the failure mode and can significantly increase the load capacity with an acceptable level of ductility depending on the application (Buyukozturk et al 2004).

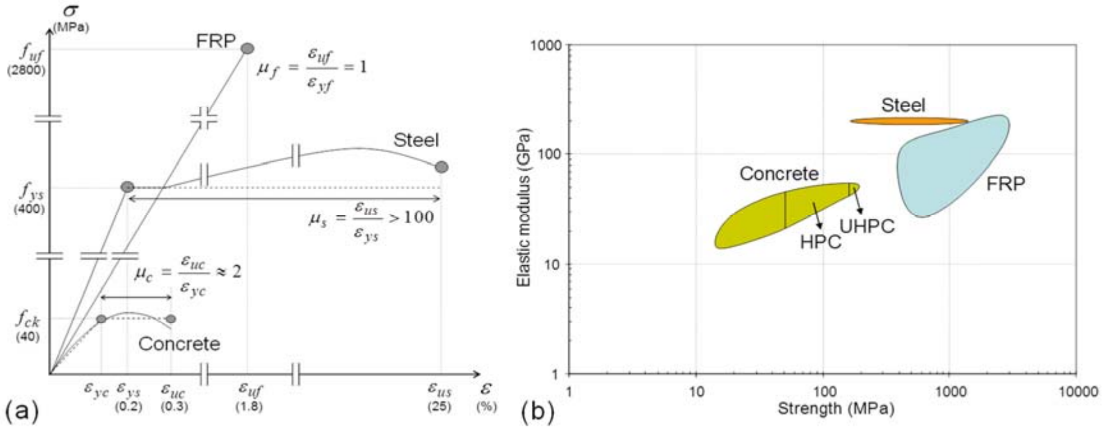

Figure 1. Stress-strain behavior (a) and strength-elastic modulus property ranges (b) for concrete, structural steel and FRP materials currently used in structural engineering

Figure 1(b) shows the ranges of strength and elastic modulus values for currently used FRP, concrete and reinforcing steel, including the high strength prestressing steels which have a stress-strain behavior somewhat different than depicted in Figure 1(a) although the comparative characteristics remain the same. The figure clearly demonstrates the superior strength and elastic modulus of FRP composites compared to those of concrete, including high performance concrete (HPC) and recently developed ultra high performance concrete (UHPC). The figure also shows that, compared to reinforcing steel, FRP composites can still have much higher tensile strength, especially compared to mild reinforcing steel shown in Figure 1(a), but their elastic modulus values are generally below that of structural steel, which is approximately 200 GPa. Figure 1(b) also shows why current applications of FRPs in structural engineering are mostly on concrete structures and why those on steel structures have lagged behind. FRP composites are most commonly used in strengthening and seismic retrofitting applications in structural engineering and in a strengthening application, the strengthening material is generally expected to have a similar or higher stiffness compared to the base material of the member being strengthened. While this is typically the case for FRP-concrete systems, only certain advanced composites have elastic modulus exceeding that of structural steel (Gunes 2013).

3 CONCRETE CHARACTERIZATION AND OPTIMIZATION THROUGH NANOINDENTATION TECHNIQUES

Advanced concrete materials such as UHPC achieve high performance objectives through tailoring their microstructures in a way to maximize the packing density using very fine minerals and by enhancing the matrix toughness using optimal fiber reinforcement (Gunes et al 2012). These improvements, although impressive, are based on limited information provided mainly by image analyses, experimental characterization of transfer properties, X-ray diffraction and thermo-gravimetric analysis, none of which are mechanical methods. Recently, statistical nanoindentation techniques were implemented on hardened cement paste to perform a quantitative assessment of what can be achieved in terms of elastic modulus and strength of concrete (Ulm et al 2007). Figure 2(a) conceptually illustrates the statistical nanoindentation technique that involves nanoindentation tests over a grid on the specimen surface. A nanoindentation test involves establishing contact between an indenter and a sample and measuring the load, P, as a function of the penetration depth, h. Figure 2(b) shows a typical P-h curve obtained from a nanoindentation test indicating the maximum force, $P_{\max}$ and the slope of the unloading curve, s. From analysis of this curve using continuum scale models, expressions for the indentation hardness, H, and the indentation modulus, M, are obtained as:

$$H = \frac{P_{\max}}{A_C} \qquad M = \frac{p}{2}\frac{S}{\sqrt{A_c}} \tag{1}$$

where A_c is the contact area. Figures 2(c) and (d) show the distribution of H and M as a function of the packing density, η, obtained from 300 nanoindentation tests. The figures show that both the elastic modulus and strength of materials correlate with the packing density of constituent materials, and by engineering the material to have a higher packing density, their elastic and strength properties can be improved. The method was successfully applied for characterization of UHPC through a four level scale model (Sorelli et al 2008).

The experimental data presented in Figures 2(c) and (d) together with theoretical model predictions suggest that for a packing density of one, the limits of indentation hardness and modulus values for hardened C-S-H converge to approximately 4 GPa and 63 GPa, respectively. Such a packing density may not be possible in practice but relatively much higher packing densities could be obtained by use of nano-scale fillers shown in Figure 3(a) (Sobolev and Gutierrez 2005a,b). Approximating the limit values of H and M to the macroscopic strength and elastic modulus limits of a hypothetical fully packed concrete for a rough comparison, and plotting together with existing data for normal and HPC (Tomosawa and Noguchi 1993) as well as that for UHPC (Gunes et al 2012), Figure 3(b) shows that an order of magnitude increase in the strength of concrete could be possible in the future through use of nanotechnology.

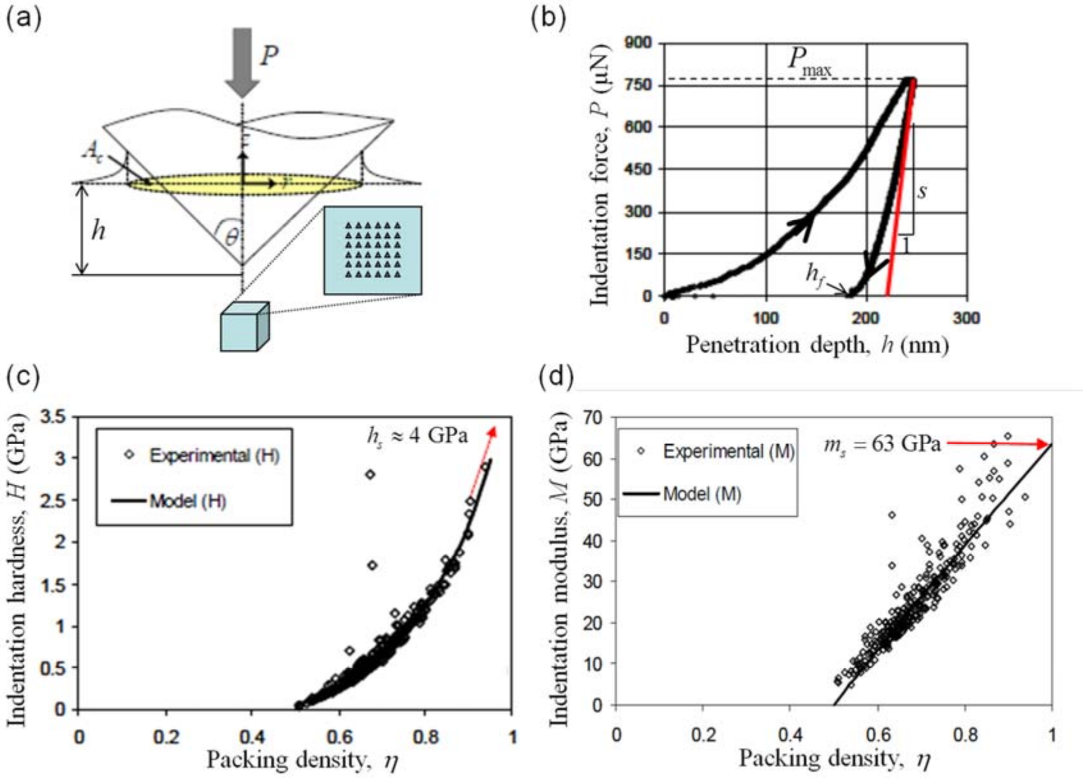

Figure 2. (a) Nanoindentation tests over a grid on specimen surface, (b) typical indentation force – penetration depth response; packing density scaling relations obtained for indentation hardness (c) and indentation modulus (d) of white cement paste (Ulm et al 2007, Sorelli et al 2008).

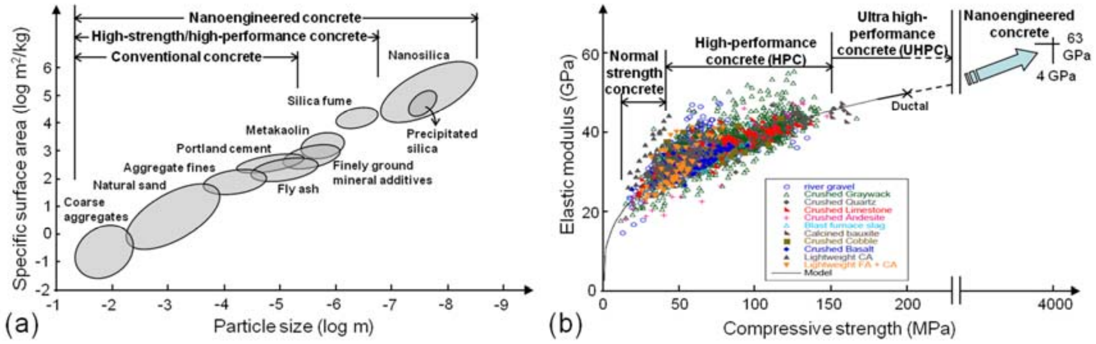

Figure 3. Particle size and specific surface areas of concrete filler materials (a) and the current as well as limit strength and elastic modulus values for different concrete classes (adapted from Sobolev and Gutierrez 2005a, Tomosawa and Noguchi 1993, Ulm et al 2007).

4 CARBON NANOFIBER AND CARBON NANOTUBE COMPOSITES

FRP composites in their current state are considered advanced materials in many engineering disciplines including Civil Engineering. Since early 1990s, while structural engineers have been exploring use of these advanced materials in infrastructure applications, composites engineers have been developing the next generation of reinforcements (fillers) for FRP composites by use of nanotechnology. Just as structural engineers realize the potential benefits of FRP-concrete systems in terms of increasing the performance and sustainability of civil infrastructures, composites engineers have proven the vast potential of newly developed carbon nanofibers and carbon nanotubes in most engineering fields. Hence, existing knowledge of FRP-concrete systems combined with the potential improvements in the mechanical properties of FRP and concrete materials enabled by use of nanotechnology constitutes an open field of research with high impact potential for structural and materials engineers.

The basic structure and typical diameters of carbon nanofibers and nanotubes are shown in comparison with conventional carbon fibers in Figure 4(a) (Coleman et al 2006, Thostensona et al 2001, De Jong, and Geus 2000). Carbon fibers are full cylindirical fibers with diameters in the range of 5-10 µm while carbon nanofibers are constituted by wrapped walls of graphite in parallel or fishbone shapes with typical diameters in the range of 100-500 nm. Carbon nanotubes have a more distinct shape formed by a single or multiple hexagonal lattice sheets rolled seamlessly to form a cylinder with a diameter or order of 1 nm for single-walled nanotubes (SWNT) and up to 100 nm for multiple-walled nanotubes (MWNT). Figure 4(b) shows the ranges of elastic modulus and strength of carbon fibers, nanofibers, and nanotubes (Coleman et al 2006). As can be seen from the figure, carbon nanotubes have superlative mechanical properties due to their optimized structure and higher specific surface area.

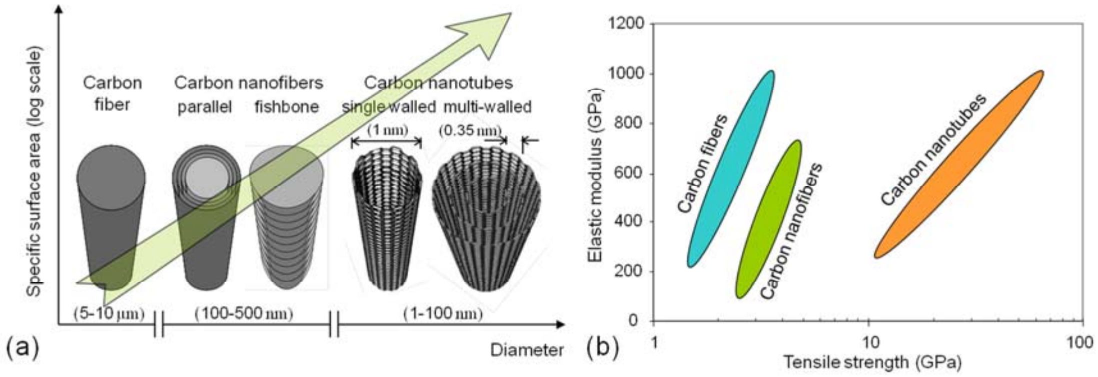

Figure 4. The basic structure and typical diameters of carbon nanofibers and nanotubes compared to carbon fibers (a) and their respective elastic and strength property ranges (Values compiled from Coleman et al 2006).

Just as the very high indentation hardness and modulus limits for hardened C-S-H shown in Figures 2(c) and (d) do not mean that the same values can be achieved in typical concrete, exceptionally high elastic and strength values of carbon nanotubes shown in Figure 4(b) do not mean that their bulk composites will have similar properties as they will also depend on the much lower properties of the matrix polymer besides many other factors. In the simplest possible case where the matrix is modeled as an isotropic and elastic material and that the fibers span the full length of the specimen, the composite tensile modulus, E_C, and composite strength, σ_C, can be obtained using the well-known rule of mixtures as (Coleman et al 2006):

$$E_C = (E_f - E_m)V_f + E_m \qquad \sigma_C = (\sigma_f - \sigma_m)V_f + \sigma_m \tag{2}$$

where E_f is the fiber modulus, E_m is the matrix modulus, V_f is the fiber volume fraction, and σ_f and σ_m are the fiber and matrix strengths, respectively. Many deviations from this ideal case may take place depending on the length and orientation of fibers as well as the properties of the fiber-matrix interface, which result in modification of E_f and σ_f in Eq. (3) with appropriate factors. In some cases the interaction between the matrix polymer and the nanotube may result in the formation of an interfacial polymer region that differs with its mechanical properties than the bulk polymer. In such cases, failure may take place at the interface between the bulk polymer and the interfacial polymer and the composite strength is given by:

$$s_C = (1+2b/D)[t_s l/D - (1+2b/D)s_m]V_f + s_m \tag{3}$$

where b is the thickness of the interfacial region, D is the fiber diameter, and t_s is the interface shear strength.

Besides properties of the nanotube and matrix, the composite strength depends on the strength and fracture properties of the interface, fiber aspect ratio, dispersion, and alignment. Carbon nanotube composites are certainly not free of problems in these areas, examples of which are the difficulty of producing long nanotubes, the difficulty of adhesion to graphite walls, sensitivity to defects and the quality problems with certain processing methods (Coleman et al 2006). Still, through research on processing methods, improved adhesion through functionalization, and optimization of fiber dimensions, it would be realistic to expect drastic improvements in the elastic and strength properties of FRP composites in the future.

5 FRP-CONCRETE INTERFACE FRACTURE

Conventional design of FRP-concrete systems based on ultimate strength analysis of sections are based on the assumption that the FRP-concrete interfaces are always intact. Studies have shown that FRP-concrete interface debonding can significantly affect the strength and deformation behavior of the system and may result in new and undesirably less ductile failure modes that take place at premature load levels (Buyukozturk et al 2004). Hence, in addition to properties of the individual materials, failure behavior of the FRP-concrete system significantly depends on the properties of the interface between concrete and FRP, in which interface comes into play as an additional component influencing failure mode and performance.

An effective way of improving interface behavior at different scales is to enforce or include fracture processes that take place in shear mode rather than in opening mode. This can be achieved at nano-scale by nanotube bridging of crazes in the polymer matrix. Figure 5(a) shows the bridging effects of MWNT fibers in a thin film matrix (Qian et al 2000) and Figure 5(b) shows the different failure mechanisms that take place at the interface (Gojny et al 2005). All of these processes result in energy dissipation and hence improve the fracture performance of materials and their interfaces.

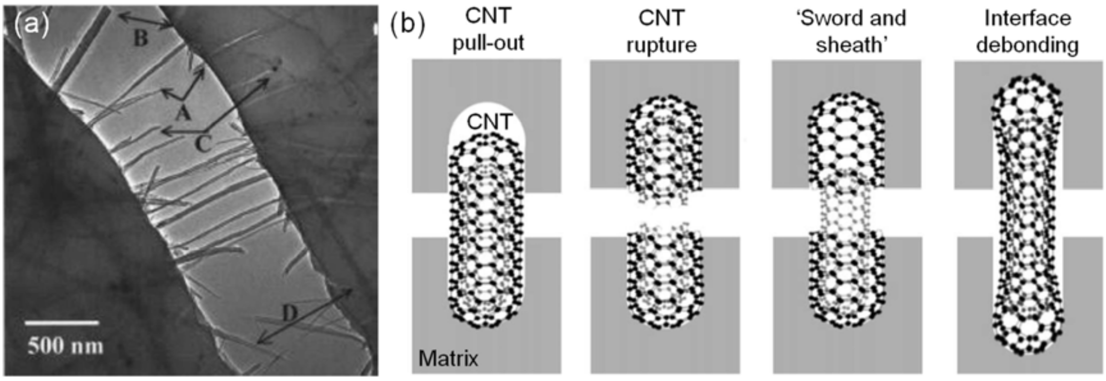

Figure 5. MWNT bridging of a polymer matrix crack (a) and the failure modes at the fiber-matrix interface (b) (Qian et al 2000, Gojny et al 2005).

Fiber bridging at nano-scale can demonstrably be used in the concrete, FRP and the epoxy adhesive materials that form the FRP-concrete system (Gojny et al 2005). Feasibility of achieving this in a practical strengthening application, however, is questionable at best since there are multiple materials and multiple solid phases that does not permit fiber-bridged interfaces. A notable study in this respect involved growing carbon nanotube forests on FRP fabrics prior to bonding though hand layup to increase interface fracture toughness (Veedu et al 2006). Without altering the 2D stack design of the composite application, a 3D composite material was obtained by growing multi-walled nanotube forests that provide enhanced multifunctional properties in the thickness direction. Figure 6(a) provides conceptual illustration of the steps of manufacturing the 3D composite by growing MWNT forests on the 2D plies in a hand-layup process. The resulting improvements in the interlaminar fracture toughnesses in opening and shear modes are shown in Figure 6(b), which reveal significant improvements in both fracture modes. Adoption and further improvement of this strategy for FRP-concrete systems could help improve the strength and fracture properties of interfaces and help prevent brittle debonding failures. Such 3D composite configurations would also reduce the adverse effects of environmental exposure on the material interfaces.

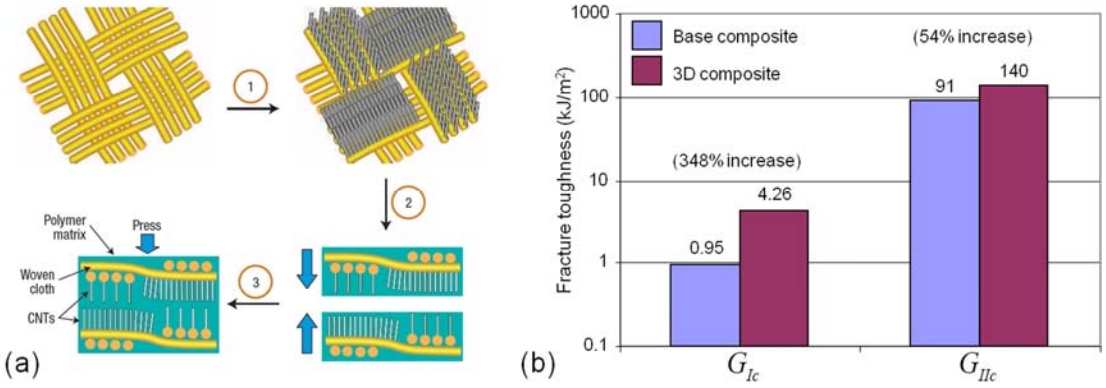

Figure 6. Conceptual illustration of the steps of manufacturing a 3D composite through building MWNT forests on fabric plies (a) and the resulting improvements in the opening (G_{Ic}) and shear (G_{IIc}) mode fracture thoughnesses (Adapted from Veedu et al 2006).

6 DISCUSSION AND CONCLUSION

At the structural scale, FRP-concrete system design entails working with the given material properties to establish a system that is sufficiently stiff, strong and fracture resistant throughout its service life. At smaller scales, investigations help better characterize material behavior and properties and better understand the physical phenomena that present problems in structural performance. At the nano-scale, design means much more than working with what is given or selecting from alternatives. It also means designing the material that will produce the desired macro properties at the structural scale.

Nanotechnology presents tremendous opportunities for improving the elastic, strength and fracture properties of FRP-concrete systems and their performance as a system. Presented discussions show that through nanotechnology material properties of concrete and FRP materials are likely to increase significantly in the near future, some of which may possibly be an order of magnitude higher than the present values. Although conducting research at nano-scale requires large investments, the design flexibility and the potential of innovation and impact are also high. Considering the variety of possible FRP applications to concrete structures and the anticipated progress related to both types of materials, it is easy to foresee that the first half of the twenty first century will be anything but boring for structural and materials engineers much like the broader engineering community.

In this paper, the current status of FRP-concrete systems including material properties and recent progress in research through investigations at small scales was reviewed. Potential improvements in the elastic, strength and fracture properties of FRP-concrete systems through fundamental research particularly at nano-scale were discussed with illustrative examples.

REFERENCES

Büyüköztürk O, Gunes O, and Karaca E. 2004. Progress review on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. *Construction and Building Materials*. 18:9-19.

Coleman JN, Khan U, Blau WJ and Gun'ko YK. 2006, Small but strong: A review of the mechanical properties of carbon nanotube-polymer composites, Carbon, 44(9), 1624–1652.

De Jong, K.P. and Geus, J.W. (2000), Carbon Nanofibers: Catalytic Synthesis and Applications, Catalysis Reviews: Science and Engineering, 42(4):481-510.

Gojny, F.H., Wichmann, M.H.G., Fiedler, and Schulte, B.K. (2005), Influence of different carbon nanotubes on the mechanical properties of epoxy matrix composites – A comparative study, Composites Science and Technology 65:2300–2313.

Gunes O. 2013. Types of Failures in FRP Applications and Preventive Measures. In: N U, editor. *Developments in Fibre-Reinforced Polymer (FRP) Composites for Civil Engineering*. Cambridge, UK: Woodhead Publishing.

Gunes, O, Lau, D, Tuakta, C and Buyukozturk, O. 2013. Ductility of FRP-Concrete Systems: Investigations at Different Length Scales, *Construction and Building Materials*, http://dx.doi.org/10.1016/j.conbuildmat.2012.10.017.

Gunes, O., Yesilmen, S., Gunes, B. and Ulm, F.-J. 2012, Use of UHPC in Bridge Structures: Material Modeling and Design, *Advances in Materials Science and Engineering*, Volume 2012, Article ID 319285, 12 pages. doi:10.1155/2012/319285.

Kazmierski, C. 2012, Growth opportunities in global composites industry (presentation), The Composites Exhibition and Convention (Composites 2012), February 21-23, 2012, Las Vegas, NV.

Qian D., Dickey E.C., Andrews R. and Rantell T. (2000), Load transfer and deformation mechanisms in carbon nanotube-polystyrene composites. Applied Physics Letters, 76(20):2868–70.

Sobolev, K. and Gutierrez, M.F. (2005), How nanotechnology can change the concrete world, American Ceramic Society Bulletin, 84(10):14-17.

Sobolev, K. and Gutierrez, M.F. (2005), How nanotechnology can change the concrete world, American Ceramic Society Bulletin, 84(11):16-20.

Sorelli, L., Constantinides, G., Ulm, F.-J., and Toutlemonde, F. (2008), The nano-mechanical signature of Ultra High Performance Concrete by statistical nanoindentation techniques, Cement and Concrete Research 38:1447–1456.

Thostensona, E.T., Renb, Z., and Choua, T.-W. (2001), Advances in the science and technology of carbon nanotubes and their composites: a review, Composites Science and Technology 61:1899–1912.

Tomosawa, F. and Noguchi, T. (1993), Relationship between Compressive Strength and Modulus of Elasticity of High-Strength Concrete, Proc. Third International Symposium on Utilization of High-Strength Concrete, V.2, Lillehammer, Norway, pp. 1209-1216.

Ulm, F.-J., Vandamme, M., Bobko, C., Ortega, J.A., Tai, K., and Ortiz, C. (2007), Statistical indentation techniques for hydrated nanocomposites: Cement, Bone, and Shale, Journal of the American Ceramic Society, 90(9):2677-2692.

Veedu, V.P., Cao, A., Li, X., Ma, K., Soldano, C., Kar, S., Ajayan, P.M. and Ghasemi-Nejhad, M.N. (2006), Multifunctional composites using reinforced laminae with carbon-nanotube forests, Nature Materials, 5:457-462.