Fiber Reinforced Polymer Materials in Construction Applications

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***Abstract*- Fiberreinforced polymer (FRP) matrix composites developed for other industries are relatively new in civil construction, both for the rehabilitation of existing structures and for the construction of new structures. In the last two decades a number of civil infrastructure applications have been constructed or rehabilitated with FRP components. Cost-effectiveness, durability, optimized structural panels, and satisfactory repair and retrofit methods have been achieved with the use of FRP in construction applications. The objective of this paper is to present the status of FRP composites asstructural materials in building and construction applications. Parameters that affect their mechanical properties are addressed. Development of codes and standards for FRP composites will widely contribute to their acceptance and adoption in building and construction industries.**

Keywords*- *CompositeMaterials; FRP;Retrofit; Rehabilitatio; Structures; Bridges

I. INTRODUCTION

Fiber reinforced polymer (FRP) composites are materials that have gradually been considered as structural materials in civil engineering and construction applications. Experimental research projects have, for the last two decades, been conducted to understand and examine the applicability of FRP composites in the design of new civil engineering structures as well as other applications such as rehabilitation and retrofitting of existing concrete and steel members. As for the construction industry, development of construction techniques, such as automated tools, and introduction of FRP in high strength concretes are,among other factors, considered to have contributed to the improvement and upgrading of this industry. However, the types of FRP composite materials utilized in construction applications are selected on the basis of the cost.Compared to traditional materials, FRP composites have higher strength and stiffness, lighter weight, better corrosion resistance, more flexibility to install, and lower maintenance cost. On the other hand, some of the FRP material properties such as low stiffness, low shear strength, lack of yielding, and high initial costs have represented significant challenges to their use in infrastructure applications. Late in 1980 California Transportation Agency used FRP composites successfully in bridges for seismic retrofitting. Since then, there have been numerous successful FRP materials applications in construction such as large FRP irrigation pipelines, sewer pipelines, and offshore/marine pipelines.Serious efforts have been made recently to develop design codes, testmethod guidelines, and construction and maintenance standards for the use of FRP composites in infrastructure and construction applications.

Referred to as the materials of the 21st century, several challenges are facing the full-scale applications of FRP composites in civil engineering. Researchers, engineers, and organizations should provide a better understanding on the FRP composite design, durability, reliability, and optimization. Most of civil infrastructure facilities around the world have been deteriorated due to aging,accidental damage to structures, and structural defects. Action, where the use FRP composites may be a good solution, should be taken to mitigate these problems. In transportation there is growing need for wideningthe transportation network structures, such as bridges, to accommodate higher volume of traffic. Better understanding of structural response and mitigation of natural loads has led to the importance of developing new design codes and the consequent needs to rehabilitate existing structures using composite materials to ensure their continued safety [1].

Conventional concrete and steel structural materials have proven to have a record of relatively low material cost and being suitable for many civil engineering and construction applications. However, for some demanding applications these conventional materials lack durability, and for some other cases, these conventional materials are subject to rapid deteriorations.This explains the searchfor high-performance construction materials to remedy the problems stated before. As defined by the Civil Engineering Research Foundation [2], high performance indicateshigher strength, better durability, faster installation, andlower life cycle costs. Seismic Retrofit and rehabilitation of existing concrete and steel members may not be practicalusing conventional materials. Therefore,there is anurge for developing new materials and technologies, with the ultimate goal of having efficient and functional structureswith increased durability and life span ([3], [4]).

FRP composites developed for other industries are potential candidatesfor civil infrastructure applications such as rehabilitation of existing structures and/or construction of new facilities. The objective of this paper is to present the status of fiber reinforced polymer compositesas construction materials in civil infrastructure applications. Parameters that affect the material properties of these composites as structural materials for rehabilitation and new construction are presented. Development of codes and standards for FRP composites will immensely contribute to their acceptance and adoption in building and construction industries.

II. FIBER REINFORCED POLYMER MATERIALS

Fiber reinforced polymers (FRP) are composites materials. Composite materials are the combination of two or more materials to form a new material with enhanced properties that are superior to those of the individual constituents. FRP material is a two-component composite material consisting of high strength fibres embedded in a polymer matrix. Fibre reinforced compositesrefer to fiberglass sheets soaked in resin, which acts aspolymer matrices or binders with a sufficient aspect ratio to provide strength in one or more directions.

Because FRP composites are madefrom two different materials, the overall FRP material properties depend on the properties of the individual constituents. The matrix is the paste of the FRP materials. It binds the fibres together, protects the fibres from degradation, transfers force between the fibres, and separatesor disperse fibres within the composite.The major criterion in the selection of the matrix material is to have a low densityso that the weight of the composite material is low. On the other hand, the fibers provide the strength and stiffness of the FRP material. Therefore, they are chosen to have high stiffness, high ultimate strength, low variation of strength between individual fibres, large length-to-diameter ratios , and uniform cross-section.The combination of the matrix phase with a reinforcing phase thus produces a new material system which is conceptually analogous to steel reinforced concrete.

In civil engineering applications, the commonly used fibre reinforcement materials are carbon (graphite), glass, and aramid. Typical thermoset polymer matrices used for composites in infrastructure are polyesters, epoxies, vinyl esters and phenolics [5]. Polyesters are the most widely used polymers in FRP components for construction/civil infrastructure applications due to their relatively low cost and ease of processing. The attractiveness of FRP composites as construction applicationscomes from the fact this material provides opportunities for developing innovative solutions to serious problems of deterioration and repair of existing structure. This also potentially grants the designer a wide variety of FRP composite material choices to fit the specific civil infrastructure application requirements.

One of the FRP applications is bridges where the Federal Highway Administration (FHWA) has set goals for “bridge of the future” by identifying certain performance requirements. FRP composite materials have the edge of fulfilling these requirements due to their material properties. The“bridge of the future” will have requirements that satisfy the following objectives:

- optimizing life cycle cost;
- reducing construction time;
- avoiding material degradation;
- resisting emergency load from floods and earthquakes;
- adaptingto new requirements.

In addition, the FHWA is promoting the use of accelerated construction techniques for rehabilitation of bridges. This is one application where FRP composite bridge decks and superstructures can be utilized to satisfy these objectives.

III. SOLUTIONS FOR CIVIL INFRASTRUCTURE DEMANDS

The problems associated with corrosion of steel reinforcement in concrete structures haveled to the pursuit of a new construction material that can offer strong and durable solution to these conventional material problems. Test results from a number of research projects on FRP composite materials haveshown a strong, fairly durable, easy-to-install, and lightweight solution to conventional construction strategies. As a result, FRP composite materials have been incorporated into several infrastructure applications, and their use in civil engineering applications has increased steadily around the world during the last two decades. Some of these civil engineering applications include externally-bonded FRP plates, sheets, and wraps for strengthening reinforced concrete and/or steel structural members, and prestressing FRP bars, rods, and tendons as internal and/or external reinforcement of concrete members.The externally-bonded FRP plates or sheetsare attractive because of their ability tobond well to main members in addition to their flexibility to follow irregular shapes.The use of FRPtendons and rods as external reinforcement of concrete and steelmembers has steadily been increasing in some civil and construction applications where their cost disadvantage is compensatedby a number of benefits. Therefore,strengthening of structural members using external FRP materials seems to bean attractive technique for manyrehabilitation and repair applications.

FRP composite materials utilized in civil infrastructure applications differ from those in other industries, such as aerospace composites. One example of this is the implementation of multi-axial heavy stitched E-glass fabrics for reinforcement of large structural components fabricated by pultrusion or vacuum assisted resin transfer moulding ([6], [7]).

IV. ADVANTAGES AND DISADVANTAGES OF FRP COMPOSITES

In an effort to slow down structure deterioration, industries and engineers have been looking for new structural materials that can fulfil this effort and prolong the span life of existing structures,and also can be used in construction of durable new structures. Fibre reinforced polymers (FRPs), non-corrosive and lightweight materials, demonstrate high-strength which makes them emerging as a solution to the effort above. It should be noted here that several different component shapes, end-use applications, and manufacturing techniques are available for FRP materials, but this paper addresses only those relevant to construction and/or civil engineering applications.

The characteristics of composite materials offer several advantages over conventional materials, such as concrete and steel, providing large incentives for contractors as a tool for ease and speed of installation. Additional advantages include high strength/weight ratios, high fatigue strengths (carbon FRP), low thermal conductivity, and outstanding durability in a variety of environments. However, FRP materials have a number of potential disadvantages such as material high initial cost, design restriction, and limited experiences that prevent their wide application in civil infrastructure.

A. Advantages

FRP composite materials have many advantages such as lightweight, fast construction, ease of transportation, high corrosion and fatigue resistance, and high live load capacity [8]. The FRP composites are manufactured in quality controlled surroundings and produced in mass quantities and different modular shapes ([9], [10]). Changing the density of the composite matrix, fibermaterials, number of layers, and orientation of the fibers will affect the FRP strength. This could be used tofulfil custom made strength requirements and improve cost effectiveness. In Bridges, for example, FRP bridge decks can replace deteriorated concrete deck in a relatively short time and put into service in just few hours rather than weeks compared to conventional materials [11]. Table A summarizes some of the FRP composite advantages.

TABLE I AADVANTAGES

Advantages
High tensile strength to weight ratio
Light material weight / fast installation
Potential resistance to various environments
Good durability
Lower maintenance cost
Alternative for innovative construction
Long life span
High fatigue resistance
Goodmaterial quality control
Flexibility of manufacturing in different shapes

B. Disadvantages

Despite having many advantages over the conventional materials, FRP composites haveseriousdisadvantages such as high materialinitial cost, unfamiliar design methods, lack of experiences, durability issues, and others. FRP high initial cost is the most concern for applications in civil infrastructure and construction.

The FRP material unit cost is often more expensive than that of conventional materials. Another concern with utilizing FRP compositesis the lack of experience within the construction industry, despite thefact that there have been few FRP structures, such as FRP bridges, in service for quitesome time. Other concerns are the lack of long term performance records and lack of design standards as addressed in Table B.

TABLEBDISADVANTAGES

Disadvantages
High material cost
Large deflectionsdue low modulus of elasticity of FRP materials
Low shear strength
Decomposition of FRP materials at high thermal variations
De-bonding/peeling off at crack locations
Tendency to creep under sustained stresses
Relatively new material in the construction applications
Lack of material long term behaviour records
Lack of full spectrum of codes and standards

In addition, FRP low modulus of elasticity leads to a deflection driven design which does not allow a designer to fully capitalize on the FRP strength. Also, currently available designs are proprietary so that there is no standard manufacturing process. In particular, response to thermal change is slightly different from concrete and steel so that it requires special consideration when an FRP deck is used on a concrete or steel superstructure.

Some of FRP material properties like strength and stiffness degrade over time. Therefore, long-term durability of FRP in field applications is a major concern because FRP composites do not yield. Ductile materials are advantageous because they have the ability to redistribute the internal forces yielding more structural safety, more dissipation of energy from impact loads, and warning of possible failure due to large deformations. Thus the lack of ductility at the material level can be a major drawback in the material application. To verify the durability of FRP composite materials, laboratory tests around the world have been conducted and documented. However, lack of standardisation of these tests and lack of a calibration based on external field tests have been delaying overcoming the durability concern of FRP materials in construction applications.

V. FRP DURABILITY AND DESIGN CONSIDERATIONS

Mechanical properties of construction materials are importantissues for the design. However, equal importanceis the environmental and durability considerations of the material applications.Exposure to adverse conditions can greatly affect the mechanical properties of FRP materials and; therefore, affect their performance. Failure to consider the effects of factors such as temperature, moisture, ultra-violet radiation, assorted chemicals, and fire can lead to unsatisfactory performance. Temperature is an extremely important factor in the design and use of FRP materials in construction applications. TheFRP decomposes at elevated temperatures, and in some cases burns. In addition, high temperature will damage the matrix-fibre interface or the bond between FRP and the substrate. FRP polymers also can absorb moisture until they are saturated. The amount of moisture depends on the compositions of FRP. It is generally believed that moisture ingress degrades the properties of the FRP composites.Ultra-violet radiation can also degrade FRP composites. This degradation can be prevented by using various matrix additives.

FRP composites are sometimes used as internal reinforcing bars/rods in concrete members to address the corrosion problems associated with conventional steel reinforcing bars.Concrete is a highly alkalinematerial, and this can be a concern for glass fibre bars/rods. Therefore, glass FRP barsare manufactured using alkali-resistant polymermatricesso they could be used in alkaline surroundings. If subjected to high temperature or fire, all polymer resins will burn releasing large quantities of dense, black, toxic, and corrosive smoke. Thus fire and high temperature are serious concerns for FRP composite applications, and potential measures must be considered during the design process for any structure incorporating FRP materials.

Although the analysis for flexural and shear capacities of members with FRP composite materials use the same assumptions for steel reinforcement, major differences between the material mechanical properties of FRP and steel materials require a shift away from the conventional concrete design method. For instance, the elastic stress-strain relationshipfor most FRP composites results in less ductile FRP-reinforced concrete member than that for conventionally reinforced concrete.Nominal flexural capacity of members with FRP composite materials is calculated using the concrete and FRP reinforcement strain compatibility and internal force equilibrium, assuming a perfect bond exists between the concrete and FRP. An equivalent stress block that approximates the actual stress distribution in the concrete at FRP rupture can be used, or the moment capacity can be determined using an estimated tension force moment arm. The concrete contribution to shear strength is reduced in beams with FRP longitudinal reinforcement because of smaller concrete compression zones, wider cracks, and smaller dowel forces. To estimate the shear strength of beams with FRP, areduction factor proportional to the modular ratio, E_{FRP}/E_{steel}, is applied to concrete shear contribution equations for conventional beams.Deflections and crack widths are typically larger in FRP reinforced concrete beams and slabs (especially glass FRP) than in steel-reinforced concrete beams due to FRP lower modulus of elasticity. Limits on deflection or crack width frequently control designs and are usually satisfied by using over-reinforced sections. Deflection prediction requires the effective moment of inertia of the member section. Various modified expressions for the effective moment of inertia have been proposed for use with FRP [12].

VI. FIELD APPLICATION AND QUALITY CONTROL

Applications of FRP composites in major and innovative concrete structures have been soughtdue the development of smart structuresthat are equipped with sensors, thus reducing the lack of long-term field data for FRP-reinforced structures. Recently, FRP composites have been developed with fibre-optic sensors (FOS) as part of their internal structure.FRP composites with FOS are an emerging technology which when utilized in structures will provide constant monitoring of their behaviour. Canada Intelligent Sensing for Innovative Structures (ISIS) project targets the development of smart structures with fiber-optic sensor technology in combination with research on FRP infrastructure applications. As long-term fieldperformance data become available, designers are feeling more comfortable considering FRP composites in concrete and steel structures. The long term filed data will also serve to propose analysis methodologies for the FRP long term durabilitywhich will assist experienced engineers around the world to develop standard design codes and specifications for FRP ininfrastructure applications. Construction standard specifications should also be developed to ensure quality control in field applications of advanced composite materials.

VII. TECHNICAL ISSUES OF FRP COMPOSITES AS STRUCTURAL MATERIALS

In almost all FRP composite projects to date, it is the stiffness requirement butnot the strength requirement that governs the design of structures with FRP and the repair of deteriorated concrete and/or steel members. The strength requirement issue must be satisfied before these composites are accepted on a large scale. Long term durability and epoxy adhesive bonding to connect or join structural components are to be satisfied and implemented. In addition, some of other issues listed in this section should also be addressed. Research projects, records for long term performance of FRP in building applications, development of standard codes will help dissipate the industry scepticism of FRP composites in structures.

Future FRP research program should address technical concerns some of which is listed below:

- expensive materials as opposed to conventional ones;
- relatively new materials in the industry;
- no approved standard design codes and specifications;
- brittle behavior of materials;
- lackof long term performance record.

VIII. REHABILITATION USING FRP

FRP materials are becoming increasingly attractive for retrofit and rehabilitation of steeland concrete structures. FRPstrips, plates, or sheets are used with epoxy resin/adhesive to externally repair deteriorating existing structural members. FRP rebars or tendons arealso usedas externalpost-tensioning bars to upgrade the strength of concrete and steel members.

IX. CONCLUSIONS

Fiber reinforced polymers composites are combination of two or more materials to form a new material with enhanced properties that are superior to those of the individual constituents. FRP composites have been gradually used in construction and civil engineering applications such as construction materials, retrofitting and rehabilitation of concrete and steel structures, structural systems, bridge decks, and pre-stressing bars and rods. Considering FRP materials in these applications has been determined by the material attributes such as high tensile strength to weight ratio, light material weight, ease of installation at the project site, and resistance to corrosion. However, there has not been a widespread adoption of FRP material in civil infrastructure and construction industries due to lack of developed standards for this material despite the fact that codes and guidelines for FRP composites either exist or are being developed in a number of countries. Also, durability is a major concern when considering FRP. No proposed techniques have been recommended to verify FRP composites durability. This could partially be fulfilled by cooperation with the industry, and by conducting long term testing. Recommended techniques to evaluate FRP durability issues and proposed measures for these issues would certainly enhance standards and codes. It is anticipated that FRP composites will be widely spreadas their properties and durability are quantified and standards for their use are developed.

FRP composite high strength and stiffness, high fatigue resistance, lightweight, and good corrosion resistance are properties that are well documented for other industries, and also are recommended in civil engineering applications. However, for civil applications more researchesareneeded to develop the most effective and durable composites and to produce more cost effective composites to compete with conventional materials in civil infrastructure applications. Codes, standards, and specifications are important protocols for the construction industry and for the design of new structures as well as inspection, maintenance, and repair existing structures. For FRP composites to be widely utilized in the above applications, guidelines and specifications need to be developed by knowledgeable and experienced engineers. It is anticipated that when approved design standard codes and specifications for FRP composites applications are available, FRP composite technology and applications in civil and construction industries will have a new era and will widely spread around the world.The authors are currently studying the life-cycle cost of using this material and will present the findings of this study in thefuture paper.This research also needs to continue to cover the effects of different types of fibers and resins and different sets of orientation and location of reinforcing fibers on structure behavior characteristics such as stiffness, strength, ductility, and durability.

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