Materials For The Future

Innovative Uses For FRP Materials For Construction

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There are three types of Fiber Reinforced Polymer (FRP) materials, which are suitable for construction applications. These materials are made of carbon, glass, or aramid fibers in polymer resins, which are being used to fabricate different construction elements such as tendons, carbon fiber reinforced polymer (CFRP) plates, and carbon fiber reinforced polymer/glass fiber reinforced polymer (CFRP/GFRP) unidirectional and multi-axial fabric sheets. These materials are used to repair and strengthen deficient concrete/steel/masonry structures. In addition, various FRP structural sections (I, angle, channel, L-shaped angle element [Carboshear L; used for shear strengthening], dowel bars) are also fabricated and used for construction, repair or strengthening of weak structures. While tendons made of FRP are typically solid rods, a number of stranded and flat bar tendons have also been manufactured for pre-stressed concrete structural components. CFRP and GFRP rebars of lower strength than that of FRP tendons are available for reinforced concrete structures.

Carbon Fiber: Carbon fibers are the most commonly used fibers[1] in high performance composites. They are classified into two types of fibers, depending on the raw materials used for their manufacturing. The first type is fabricated using refined petroleum or coal pitch that is passed through a thin nozzle and stabilized by heating. This type is called "pitch" carbon fiber. The second type is made of polyacrylonitrile (PAN) fibers which are carbonized through burning. This type is called PAN carbon fiber. Both types of fibers are congregate bodies of imperfect black lead micro-crystals. The diameters of the pitch type fibers range from 9-18 micrometers while those for the PAN type fiber range from 5-8 micrometers.

Aramid Fiber: There are three types of aramid fibers on the market, bearing the trademarks of Kebler, Twalon and Technola. The Kebler and Twalon fibers belong to the whole-aroma family of polyamide fibers. These two aramid fibers have markedly high tensile strength, high rigidity, and high thermal resistance compared to other organic synthetic fibers. The Technola is an aroma-family polyethereal amide fiber and has a high resistance to chemicals, moisture and heat. All of these aramid fibers are approximately 0.3 micrometers in diameter[2]. In general, aramid fibers have excellent toughness and impact resistance, high strength, light weight, excellent creep and fatigue resistance and moderate cost. However, they have poor compressive and off-axis properties, relatively low stiffnesses, are susceptible to moisture absorption and difficult to machine.

Glass Fiber: Glass materials for continuous fiber reinforcement are classified into two main types, i.e. E-glass fibers and S-glass fibers[1]. E-glass fibers, which contain high amounts of boric acid and alluminate, do not have good alkali resistance. E-glass FRP materials are used for electrical applications. S-glass fiber was developed specifically for the structural applications and has greater resistant to alkali in comparison to E-glass fiber. S-glass fibers are also characterized by their dynamic qualities approximately equivalent to those for some types of aramid fibers (i.e. these fibers have high strength, good impact resistance, good thermal and dielectric properties) and low cost. However, these fibers have low stiffness and are relatively heavy. A new type of glass fiber (known as Z-fiber) is available in the market which has very high resistance to alkali. This fiber is produced by adding a considerable amount of zirconia to prevent it from being eroded by cement-systems.

Carbon Fiber Manufacturing Process

In this process, polyacrylonitrile fiber is supplied to an oxidation oven, which stabilizes the fiber so that it will survive the carbonization process. Here, the PAN precursor changes from a thermoplastic to a thermosetting polymer and molecules reorient themselves due to stretching. The oxidized fibers are sent to the carbonation furnace, which converts the PAN to carbon and drives off impurities present in the oxidized PAN. The fibers are then sent to the graphitization furnace where high temperature (~1500°C) is used to develop the final properties of the carbon fiber. Finally, the carbon fibers are given a surface treatment through an electrolytic surface treatment process, which enhances bonding of the fibers to the resin and increases their finished composite strength. Resins are applied to facilitate fiber handling in follow-on processing. After surface finishing, the carbon fibers are ready for packaging, i.e. they can be spooled, chopped or milled for their intended application.

Composite Fabrication Process and Their Applications

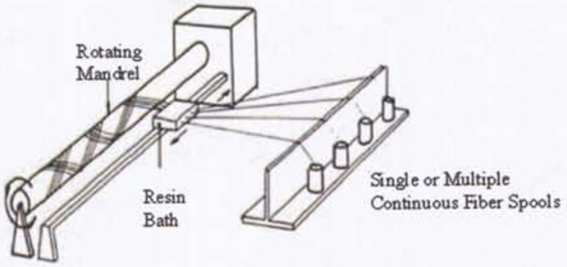
In fibrous composite materials, the fibers are the load carrying elements while the matrix keeps the fibers in position and also transfers the load from one fiber to the other. The major goals of FRP processing are as follows:

1. To translate the potential fiber and matrix properties into reality in the composite.
2. To insure process consistency
3. To minimize processing costs

Some methods of composite processing which are used to fabricate structural components are described below:

1. Hand Lay-up: In this process, fibers in the form of unidirectional, mats, fabric or braid are cut and laid up to produce laminate. This process is usually used for small quantities of complex and/or high quality parts. The process is very labor-intensive and thus expensive. Until recently, even high volume parts for aerospace applications were produced by this process. However, in the last few years, this process has been partially automated. Woven or non-woven fabric or uni-directional tape (usually in prepreg form) are used with this process. This process produces laminates with relatively higher fiber volume fractions (50-60%) and low void contents (1-2%). A variation in this process has occurred with the roll wrapping used to make fly rods and most golf club shafts.

2. Filament winding: In this method, fibers are pulled from single or multiple continuous fiber spools and passed through a resin bath. The resin impregnated fiber filaments are wound on a rotating mandrel to produce a shape such as a tube or pressure vessel. A variation in this process is tape winding, where prepreg tape is used. The primary advantage of the filament winding process is high processing speed (i.e., up to 700 lbs of material/hr) resulting in a low cost. In spite of higher capital costs, cost of filament wound parts can be one third of that of hand lay-up. Wet winding further reduces cost by avoiding the expense of prepare tape. Filament wound items include rocket motor casings, pressure vessels, light poles, oil pipes, aircraft fuselages, aircraft wings, rail car bodies, and wind turbine blades.



3. Pultrusion: In this process, continuous fiber reinforcement is impregnated with resin. The impregnated fibers are pulled through a forming die, consolidated, cured, cooled quickly, and cut to length; all as a continuous automated process. In spite of high initial costs, the high production volume of the pultrusion process results in a low cost/part. Production speeds are usually two to four feet per minute. Product quality is good to excellent with a low void content. However, dies are two-dimensional; it is not possible to vary cross sectional shapes within a given product. Also, the primary reinforcements are in the axial direction, and slow curing resins can not be used. However, a sophisticated modification of the pultrusion process called "pull forming" has been developed, which allows changing cross sections and fabrication of curved parts, etc. Examples of pultruded products include I-beams (for construction applications and oil platforms), rebar, prestressing strands and twisted cables, automotive drive shafts, corrosion resistant and high strength structural pipe, floor gratings and hand rails for off-shore oil platforms, fiber optic communication cables, nonconductive bar stock, foam core residential siding, and light weight nonconductive ladder rails.

4. Resin Transfer Molding (RTM): This is a closed mold, low pressure process. Matched male and female molds are loaded with dry reinforcement (which may be preshaped) and the mold is closed. Liquid resin is then pumped into the mold (usually with vacuum assistance) to impregnate the reinforcement. The composite is cured for a time at a temperature which depends on the resin system and part thickness. This process can produce composites of all sizes, complexities, performance levels, as well as three-dimensional reinforcement. It offers significant reductions in required raw materials and in lay-up time. However, process optimization for high performance applications has not yet occurred. Both void content and fiber volume are of concern, but these can be improved significantly by vacuum assistance.

Current Research at LTU

Current, research work at Lawrence Technological University (LTU) in Southfield, Michigan has focused on the use of CFRP/CFCC tendons/strands for prestressing simply supported[8] and multi-span continuous bridges[14] and on the use of CFRP plates[15] and sheets[15] for strengthening simple and continuous beams in flexure and shear. CFRP plates and sheets are also being used to strengthen bridge piers, columns and the negative moment regions of beams in flexure and shear. Research investigations addressing the use of CFRP/CFCC strands in simply supported bridges were completed in 1997. Additional experimental work began in 1998 is examining the feasibility of using externally draped tendons for post-tensioned prestressing of multi-span continuous bridges. A few of the experimental investigations related to the response of CFRP prestressed, reinforced, and strengthened beams are discussed below. Results from this research are currently being implemented in the design and construction documents for the first CFRP pretensioned concrete bridge in North America. This bridge was constructed in 2001 over the Rouge River located in the city of Southfield, Michigan.

I. Single Span CFRP Prestressed Bridge: To examine whether prestressing of bridges using CFRP internally bonded and externally unbonded draped tendons was possible, four simply supported bridge models (DT-1, DT-2, DT-15, and DT-30) were constructed and tested under static, repeated (7 million cycles), and ultimate loads[8]. Bridge model DT-1, consisting of a single double tee (DT) girder, was prestressed (internally and externally) using 7 wire twisted CFCC cables provided by Tokyo Rope Manufacturing Inc. GFRP rods were used as reinforcing bars in the webs, at the top of the flange and in the deck slab. Mild steel stirrups were used for shear reinforcement. The second bridge model (DT-2) consisted of two DT girders. These girders were prestressed using Leadline tendons provided by Mitsubishi Chemical Corporation, Japan in longitudinal direction (internally and externally) and in the transverse directions. The same Leadline bars were used for reinforcement in the webs, at the top of the flange, and in the deck slab. Mild steel stirrups were used for shear reinforcement. Bridge model DT-30 had a 30-degree skew angle and Leadline CFRP rods were used for internal prestressing in the longitudinal and transverse directions and for the externally draped tendons. Reinforcements in the two DT girders and in the deck slab of this bridge were also provided by Leadline bars. The fourth bridge model (DT-15) had a 15-degree skew angle and consisted of three DT girders and five cross beams. The same Leadline CFRP rods and stirrups were used for its construction as for the DT-30 bridge model.

The combined effect of factors such as draping angle, deviator diameter, number of attached die-casts used to anchor the tendons, presence of cushioning materials between deviator and tendon, and twist angle of the externally draped tendons on the strength of tendons was examined[8]. It was observed that the use of externally draped CFRP tendons in bridge construction improves the ductility of the bridge system, resulting in a compression failure of the bridge due to significant inelastic deformation. It was also noted that increasing the deviator diameter and using cushioning material at the deviator minimize the reduction in breaking force of the draped tendons. It was recommended that the designers should combine internally bonded tendons with externally draped tendons to ensure better ductility and to force the structure to fail by crushing of the concrete rather than by rupture of the internally bonded tendons.

II. Two-Span Continuous CFRP Prestressed Bridge: Since the results from simply supported bridges were encouraging, the feasibility of using these same tendons in two-span continuous bridges[16] was examined by subjecting additional bridge models CDT1 and CDT2 to the static, repeated and ultimate load tests. Each bridge model consisted of (i) four precast modified DT girders (two girders formed one span of the bridge) pretensioned with straight and draped CFRP Leadline tendons, (ii) transverse unbonded CFRP tendons post-tensioned through the tendon deviators and cross beams, (iii) a CFRP reinforced continuous deck slab, (iv) CFRP stirrups or CFRP three-dimensional NEFMAC grids (provided by Autocon Composites Inc., Ontario, Canada) which projected beyond the top flange of the DT girders, cross beams, and tendon deviators, and (v) continuous externally draped CFRP tendons.

The effects of repeated load on various parameters such as post-tensioning forces in the continuous externally draped tendons, deflections, and concrete strains were examined before and after the post-tensioning adjustment (that is, the increase in the post-tensioning forces after 7.5 million cycles of repeated loads). It was observed that the effect of repeated load on the forces in post-tensioned externally draped tendons is negligible. The presence of continuous externally draped CFRP tendons (in the positive and negative moment regions) together with NEFMAC grids (on both sides of the webs and in the continuous deck slab), and the increase in the level of external prestressing forces resulted in a very ductile CFRP continuous bridge system. It was also observed that the measured energy ratio (that is, the inelastic energy stored in the system divided by the total energy) increased by 48%, whereas the maximum mid span deflection at ultimate load was reduced by 75%, in comparison to that of the simply supported bridge system of the same construction components. The ultimate load carrying capacity of this bridge model was observed to be about eight times the service load

III. Use of CFRP/GFRP in Reinforced Concrete Beams: This study[17] consisted of experimental observations of the response of seven simply supported and seven continuous beams reinforced with FRP materials. The reinforcing bars and stirrups were made of steel, CFRP and GFRP materials. A modified method for the determination of the ductility of the system was introduced. This method takes into account the modulus of elasticity and strength of the reinforcements, the type of reinforcing bars and/or stirrups, the failure mode, and softening of the concrete at compressive flexural failure. This method does not require the existence of a yield point. Furthermore, a classification based on energy ratio was also proposed to categorize the failure of beams as ductile, semi-ductile, or brittle. It was observed that the ultimate load capacity of simple beams was nearly the same regardless of the type of reinforcement used, but the failure modes and ductility differed. Other important observations include the use of GFRP stirrups led to significant shear deformations that increased beam deflections and reduced ductility, the mode of failure was shear when reinforcement consisted of GFRP stirrups and FRP reinforcing bars while it was flexural-shear when GFRP stirrups and steel were used for reinforcement. Also the replacement of steel stirrups with GFRP stirrups yielded a larger number of small inclined cracks covering almost two-thirds of the span and the dowel effect is very critical in FRP reinforced continuous beams; the failure mode is mainly governed by the type of FRP reinforcement bars.

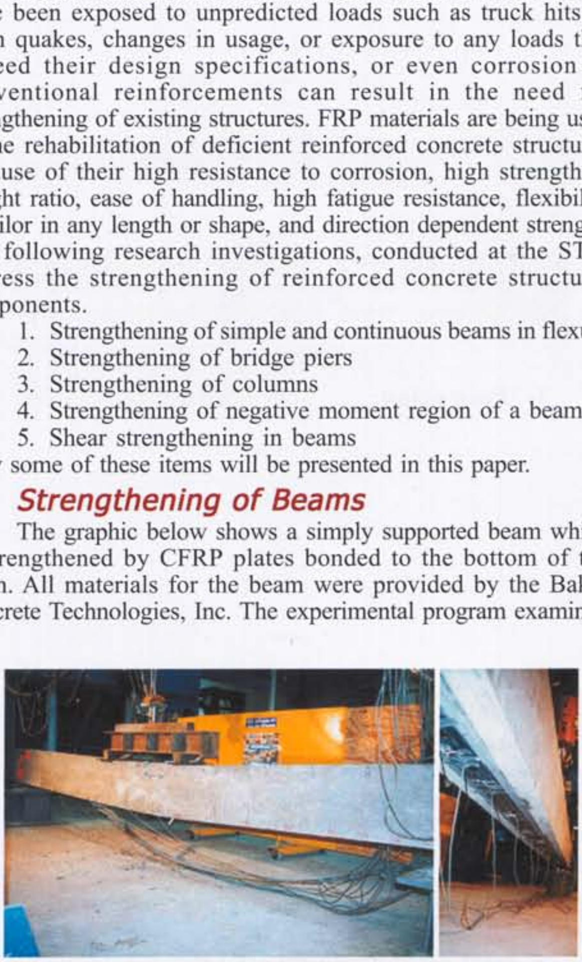
IV. Strengthening of Structures: Many reinforced concrete structures throughout the United States are showing serious signs of deterioration before their life expectancy is reached. There are also structures which are not compatible with upgraded design standards, which have mistakes in design or construction, or which have been exposed to unpredicted loads such as truck hits or earth quakes, changes in usage, or exposure to any loads that exceed their design specifications, or even corrosion of conventional reinforcements can result in the need for strengthening of existing structures. FRP materials are being used in the rehabilitation of deficient reinforced concrete structures because of their high resistance to corrosion, high strength to weight ratio, ease of handling, high fatigue resistance, flexibility to tailor in any length or shape, and direction dependent strength. The following research investigations, conducted at the STC, address the strengthening of reinforced concrete structural components.

1. Strengthening of simple and continuous beams in flexure
2. Strengthening of bridge piers
3. Strengthening of columns
4. Strengthening of negative moment region of a beam
5. Shear strengthening in beams

Only some of these items will be presented in this paper.

Strengthening of Beams

The graphic below shows a simply supported beam which is strengthened by CFRP plates bonded to the bottom of the beam. All materials for the beam were provided by the Baker Concrete Technologies, Inc. The experimental program examined the efficiency of the CFRP plates and their adhesive in the stiffening and strengthening of the RC beams. This was accomplished by initially loading all flexural specimens to a predetermined cracking load to simulate a deficient structure. These cracked beams were strengthened with CFRP plates using the proper epoxy adhesive. Specimens were then instrumented and loaded to failure. It was observed that the CFRP plates, when added to the deficient structures, significantly improved the load carrying capacity of the beams. Debonding of the plates and concrete shear failure at the level of the reinforcing bars were the predominant flexure failure modes in all of the strengthened beams.[15]



Strengthening of Negative Moment Regions of RC Beams

This performance of Sika Carbodur CFRP strips used in strengthening the negative moment region of precast reinforced concrete beams was evaluated in this work. Two cases of strengthening were considered. The first dealt with strengthening of beams designed to fail in flexure, while the second dealt with strengthening of beams designed to fail in shear. Five beams were tested for each case.

It was observed that the beams designed to fail in flexure failed by the onset of delamination between the CFRP strips at the top of the beam and the concrete surface. This delamination also led to the spalling off the concrete cover at top reinforcement at one end of the delaminated zone. All the beams exhibited ductile failures with a minimum ductility ratio of 67%.

However, all the beams designed to fail in shear failed by diagonal cracking with local debonding at the top of the beam. The beam with 3 CFRP plates at the top showed the highest load carrying capacity. Placing CFRP sheets on both sides of the beams did not improve their load carrying capacity.

It is worth mentioning that the CFRP plates did not experience their ultimate strength at the failure load of the beams. The maximum stress experienced in the CFRP plates was observed to be 52% of their ultimate load carrying capacity for the beams designed to fail in flexure and 28.5% for the beams designed to fail in shear.

Shear Strengthening

The strengthening of beams in shear was dealt with using three different layups (45°, 0°/90°, and 0°/90°/45°) of CFRP fabric sheets on the beams. The numerical values of a particular layup refer to the fiber orientation in the fabric sheets with respect to the longitudinal axis of the beam. A total of four beams were tested at the STC. Three beams were strengthened with uni-directional fiber CFRP sheets with layups of 45°, 0°/90°, and 0°/90°/45°, respectively, while the fourth beam was unstrengthened and served as the control beam. Experimental investigations focused on finding the optimum layup for sheets used to strengthen the RC beams in shear. It was observed that the 45°, 0°/90°, and 0°/90°/45° beams have 23%, 17%, and 38% higher strength than the control beam, respectively. It was also noted that there exits a critical value of shear force up to which there is no appreciable strain in the beam. This critical value of shear force marks the ultimate shear resistance of the control beam. However, the strengthened beams show significant strength even beyond this critical value of the shear force.

Extensive research on construction applications of FRP materials in reinforced and prestressed concrete structure is currently being conducted (throughout the world). It has been concluded that CFRP tendons and strands are good replacements for steel strands. Carbon, glass, and aramid fibers (in prepreg form) can be used to produce outstanding FRP fabric and structural components for use in construction applications. CFRP/GFRP sheets and CFRP plates have also been successfully used in construction activities, i.e. for strengthening and retrofitting of deficient steel and Reinforced Concrete structures. However, widespread use of these materials may take up to 40 to 50 years due to a current lack of design codes and test methods, as well as high cost of the materials.

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