FIBER REINFORCED POLYMERS

Carbon fiber reinforced polymer (CFRP) reinforcing and carbon fiber composite cable (CFCC) strands provide unique possibilities for innovative precast, prestressed concrete structures.

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teel and concrete are likely the most compatible materials in the history of structures. Ever since the 1800s, when observers realized that cement mortar stuck fast to iron tools could promise more than a tough cleaning job, concrete and steel have meshed their synched material and mechanical properties in shaping much of the world’s infrastructure. Reinforced concrete remains a natural building system.

Engineers understand that the beauty of steel-reinforced concrete lies in each material’s ability to compensate for the structural weakness of the other; where concrete delivers compressive strength, steel provides tensile strength. Steel and concrete bond together so well that the two materials act as one in resisting loading, bending and shear forces in structures. Even the most compatible of materials, however, have their weaknesses; for steel reinforced concrete this weakness is susceptibility to corrosion.

For conventionally reinforced concrete such as precast concrete bridges and parking structures in aggressive environments, deicing salts applied during cold weather often result in corrosion of steel reinforcing, deterioration and shortened service life for precast concrete. This is where fiber-reinforced polymer (FRP) materials have emerged as a great advancement in structural durability in the precast, prestressed concrete construction industry.

As a non-corrodible alternative to steel reinforcing bars, highly tensile FRP bars are also nonconductive (nonmagnetic) and are therefore able to significantly extend infrastructure service life.

This article provides the specifying engineer with a brief overview of FRP material properties and their
advantages in prestressed concrete applications.

Steel corrosion led to advanced reinforcing materials

Ongoing deterioration of U.S. highway infrastructure is a well-known and serious problem for civil engineers in state and federal agencies who are charged with maintaining safe and durable bridges and roadways. In regions that experience cold weather, corrosion of reinforcing steel inside concrete members is the most

In June 2007, Lawrence Tech collaborated with the Maine DOT, the Federal Highway Administration and Figg Bridge Engineers in an owner-facilitated design-build process to replace six strands in three stays with carbon fiber composite cables (CFCC) in a first cable-stayed long-span bridge installation in the United States at Penobscot Narrows Bridge and Observatory. This owner-facilitated design-build process gave Maine DOT significant influence on final product in a rapid-delivery schedule. The strands are being monitored in order to evaluate this material for future use in bridge designs.
potent mechanism of deterioration in public infrastructure. During winter months, road maintenance vehicles disperse salt and deicing chemicals to melt ice and snow on concrete pavements in efforts to keep roadways as tractable and safe as possible for drivers.

What happens when these corrosive chemicals reach steel reinforcing bars through hairline cracks in the concrete? Rusting occurs, an oxidizing process that expands the volume of the steel reinforcing bars (creating internal pressures of 3,000 to 4,000 psi in the concrete) causing the surrounding concrete to crack and spall. Once corrosion-induced concrete spalling is initiated, traffic impact loads on bridges and roadways continue to exacerbate this structural deterioration. Corrosion damage and concrete deterioration can be alleviated through the structural application of advanced fibrous composite materials for reinforcing. In-service testing has proven that non-corrode FRP materials are a viable structural solution to premature corrosive deterioration of precast transportation infrastructure. While FRP offers high tensile strength, it displays nonductile behavior and does not significantly contribute to concrete compressive strength.

CFRP properties, products and producers

The strength-to-weight ratio of CFRP varies from five to 10 times that of steel and 50 times that of concrete. Similarly, the stiffness-to-weight ratio of CFRP is about three times that of steel and 25 times that of concrete. Of critical importance for durable highway bridges, CFRP is highly resistant to corrosion, fatigue and adverse environmental conditions. Worldwide, CFRP research continues, with some of the most notable work being conducted at Lawrence Technological University’s [Lawrence Tech] Center for Innovative Materials Research (CIMR) in Southfield, Mich. Carbon fiber reinforced polymers (CFRP) have these notable material advantages:

• Superior strength
• High strength- and stiffness-to-weight ratios
• Light weight and ease of handling
• Less corrosive and insensitive to magnetic effects
• Good bonding with concrete
• Produced in various shapes, strengths and stiffnesses
• Availability of FRP for reinforcing bars, prestressing tendons and strands, plates, stirrups and sheets
• Durability, long structural life and low maintenance

In addition to CFRP, other commercially available FRP reinforcing materials are continuous aramid FRP (AFRP) and glass FRP (GFRP) reinforcing bars.

CFRP reinforcing is available as prestressing strand, post-tensioning rope/cable, stirrups, reinforcing bars, two- and three-dimensional grids, reinforcing cages and mesh. Numerous products are available with carbon fiber reinforced polymers from producers all over the world. The main producers of CFRP products are: Mitsubishi Chemical Functional Products Inc., Japan; Tokyo Rope Manufacturing Company Ltd., also of Japan; Diversified Composites Inc., Kentucky; and Hughes Brothers Co., Nebraska.

CFRP research and current codes

Without a long history of structural reliability in
practice, a relatively new reinforcing material technology, like CFRP, faces conservative caution from civil engineers who view CFRP applications as unproven systems. That caution toward CFRP use in highway infrastructure is changing as monitoring data on successful CFRP performance for in-service structures continues to grow.

Worldwide research using innovative construction materials such as CFRP requires detailed documentation and continuous monitoring of implemented innovative structures over a long period of time. Only data showing long-term predictable behavior for this new technology can foster confidence for the specifier, producer and owner to bring the use of these materials into mainstream applications in transportation construction. Growing in-service performance data on CFRP and continued advances in research will form the foundation for design standards for innovative materials like CFRP. Currently, ACI Committee 440 has produced the “Guide for the Design and Construction of Concrete Reinforced with FRP Bars.”

**THREE BRIEF CFRP CASE STUDIES**

**Bridge Street Bridge**

The first CFRP prestressed concrete bridge constructed in the United States in 2001 was the Bridge Street Bridge Structure B in Southfield, Mich., funded by the Federal Highway Administration (FHWA), Michigan Department of Transportation (MDOT), the City of Southfield and the National Science Foundation (NSF). Long-term automated monitoring of unbonded longitudinal external CFRP post-tensioning strands and

![Top left] With the cradle design, cable stay strands serve as tensile elements that are individually threaded from the bridge deck through a high-density polyethylene sheath.

![Bottom left] A view of a CFCC anchor sleeve with nut and strand.

![Top right] Research continues at Lawrence Tech’s new Center for Innovative Materials Research. Photo shows the recently installed fire/loading chamber that can test structural components up to 2,300 F, approximating the conditions that precipitated the collapse of the World Trade Center on Sept. 11, 2001.

### TYPICAL TENSILE PROPERTIES OF VARIOUS REINFORCING BARS*

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>Glass Fiber Reinforced Polymer (GFRP)</th>
<th>Carbon Fiber Reinforced Polymer (CFRP)</th>
<th>Aramid Fiber Reinforced Polymer (AFRP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal yield stress, ksi [MPa]</td>
<td>40 to 75 [276 to 517]</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Tensile strength, ksi [MPa]</td>
<td>70 to 100 [483 to 690]</td>
<td>70 to 230 [483 to 1600]</td>
<td>87 to 535 [600 to 3690]</td>
<td>250 to 368 [1720 to 2540]</td>
</tr>
<tr>
<td>Elastic modulus, x103 ksi [GPa]</td>
<td>29.0 [200.0]</td>
<td>5.1 to 7.4 [35.0 to 51.0]</td>
<td>15.9 to 84.0 [120.0 to 580.0]</td>
<td>6.0 to 18.2 [41.0 to 125.0]</td>
</tr>
<tr>
<td>Yield strain, %</td>
<td>0.14 to 0.25</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Rupture strain, %</td>
<td>6.0 to 12.0</td>
<td>1.2 to 3.1</td>
<td>0.5 to 1.7</td>
<td>1.9 to 4.4</td>
</tr>
</tbody>
</table>

*Typical values for fiber volume fractions ranging from 0.5 to 0.7.
transverse unbonded post-tensioned strands has been ongoing. Data have been collected every two hours from vibrating-wire strain gauges, thermistors, deflection transducers and load cells installed within the bridge. This bridge continues to be monitored in order to obtain long-term data for 10 more years based on recently authorized funding by MDOT.

The measured concrete strains, deflections and forces in the longitudinal and transverse post-tensioning strands over a period of five-years indicate that the bridge is performing as expected. The measurements also confirm that carbon fiber composite cable strands and their anchorages are intact and effectively serving within environmental conditions at the site.

External CFRP post-tensioning strands provide remarkable ductility for bridge beams. Before building the Bridge Street Bridge, ultimate load tests were conducted on double-tee continuous bridge models with externally draped CFRP post-tensioning strands or tendons. Research showed failure in one bridge test model was initiated by crushing of the concrete at the bottom of the webs.

For full-scale tests on prototype beams prior to bridge construction, visit http://qbx6.ltu.edu/nabil/.

Unbonded CFCC transverse post-tensioning

Research indicates that transverse post-tensioning [TPT], with unbonded carbon fiber composite cable [CFCC] strands can prevent formation and arrest propagation of these longitudinal cracks.

Tests authorized and funded by MDOT were conducted on a half-scale 31-foot [9.5-meter] span 30-degree skew side-by-side box-beam bridge at Lawrence Tech. The bridge model was comprised of four adjacent precast, prestressed concrete box beams integrated with the construction of full-depth shear keys, reinforced composite deck slab, and TPT using unbonded CFCC strands. Results of the study show that the application of high levels of TPT forces effectively enable the bridge system to serve as a monolithic plate and improve load distribution.

Transverse post-tensioning with transverse CFCC

A close up view of a bridge cable anchor.
strands prevents the development and propagation of longitudinal cracks as a result of limiting differential deflection and rotation between adjacent box beams due to eccentric service loads. Similar post-tensioning arrangements were also tested and proven in the field during the Bridge Street Bridge project.

**CFRP strand at Penobscot Narrows Bridge and Observatory**

Harsh winter conditions and corrosion in the Waldo Hancock Bridge in Maine led to the premature deterioration of the 75-year-old steel suspension structure. Concerned Maine Department of Transportation (Maine DOT) officials implemented a fast-track bridge replacement project. While developing the bridge design, the project team realized this was an opportunity to demonstrate the reliability of using post-tensioned carbon fiber strands. So carbon fiber composite cable (CFCC) strands in three stays of a new 2,120-foot-long (646-meter) replacement bridge to assess CFCC construction deployment and performance under service conditions.

In June 2007, six traditional epoxy-coated steel strands were removed from the cable stays without changing the bridge’s structural integrity and replaced with CFCC strands. A newly patented cradle system had been installed in the new bridge to provide long-term durability and ease of cable maintenance. With the cradle design, cable stay strands serve as tensile elements that are individually threaded continuously from an anchorage at the bridge deck through a free length of high-density polyethylene sheath, through the cradle in the pylon and back through another sheath and anchorage at the bridge deck on the opposite side of the pylon. This allowed easy replacement of the steel strands with CFCC strands for the demonstration project.

A nested layering of protection for the strands includes: epoxy coating on the strands; dry air environment within the annular space surrounding each strand; and HDPE sheathing that works with the cradle system to create a closed environment. Monitors record...
The anchorage at the bridge deck allowed easy replacement of the steel strands with CFCC strands.

any fluctuations in pressure, allowing Maine DOT to observe the bridge’s health without expense, special equipment or interruption to traffic.

The future of CFRP

Substantial funding for CFRP research and development proves the enormous potential of CFRP applications for bridge structures. At Lawrence Tech, $1.1 million in funding has been provided by the U.S. DOT to develop an AASHTO type girder; MDOT and MECD (Michigan Economic Development Corp.) provided $1 million to develop and evaluate the use of CFRP in prestressed box beam bridges; and NSF provided $320,000 to test the use of pretensioning and post-tensioning of box beam bridges.

The transportation industry’s struggle with maximizing the use of limited funding sources requires a constant focus on methods to improve the long-term durability characteristics of our bridge structures. Many new innovative strategies are being investigated as methods of eliminating the potential for corrosion. Given the concern for corrosion of steel elements that would require replacement at some point in a 125-plus-year bridge service life, it would be beneficial if the durability of CFRP strands could eliminate that possibility.

The success of CFRP applications at the Bridge Street Bridge and the Penobscot Narrows Bridge potentially sets the stage for even more conventional applications of CFRP in future long-span bridges.

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