



Rachel J. Detwiler

# Innovating Step by Step

## Deploying carbon-fiber-reinforced polymer composites in precast, prestressed concrete bridges

**C**orrosion of steel reinforcement and prestressing strand is often the limiting factor in the service life of concrete structures. Ways to slow corrosion include epoxy coating, galvanic coating, improved concrete quality, cathodic protection, and stainless steel. Another approach altogether is to substitute synthetic materials for the steel.

When Nabil Grace started as a professor at Lawrence Technological University in the late 1980s, he applied to the National Science Foundation for a grant to conduct pioneering research on carbon-fiber-reinforced polymer (CFRP) reinforcement in prestressed concrete bridges. John Scalzi, program director at the National Science Foundation, turned it down as impractical. Grace told Scalzi that he would continue to write proposals.

“You keep writing, I’ll keep declining,” Grace remembers Scalzi saying. Grace’s third proposal received three positive reviews out of three from the review panel, and Scalzi agreed to fund his research along with additional work related to polymer-based composite materials.

After 11 years of laboratory research, Grace says he felt confident that if he could put together the right team, they could deploy the technology in the field.



The Bridge Street Bridge in Southfield, Mich., completed in 2001, was the first bridge in the United States to use carbon-fiber-reinforced polymer (CFRP) reinforcement, CFRP pretensioning tendons, and carbon-fiber-composite cable post-tensioning throughout. Monitoring of this bridge will continue until 2020, providing long-term data on its performance. **Photo courtesy of Nabil Grace.**



The cast-in-place concrete deck of the Pembroke Bridge in Southfield, Mich., is curing. Photo courtesy of Paul Grigonis.

## Bridge Street Bridge

In 1999, Grace received federal funding for his first field application, a bridge in Southfield, Mich., incorporating CFRP reinforcement and carbon-fiber-composite cable (CFCC) strand. The Michigan Department of Transportation (MDOT), however, proposed building two bridges side by side, one using conventional reinforcement and the other incorporating the new materials, to provide a direct comparison.



The second post-tensioning of the carbon-fiber-composite cable places the cast-in-place concrete deck of the Pembroke Bridge in compression. Photo courtesy of Paul Grigonis.

The testing performed at Lawrence Technological University had used half-scale beams. The test results became the basis for the parameters for analysis and design. To verify the accuracy of the analytical predictions and the performance of the full-scale beams for the first bridge, a prototype beam was instrumented and tested to failure.<sup>1</sup> The pretensioning forces, transfer lengths, camber, concrete strains, and initial post-tensioning forces were all measured at the pre-cast concrete plant. The beam was then transported to a laboratory for testing. Additional strain gauges were installed, in addition to a 3 in. (75 mm) concrete topping cast on the flange of the double tee. The beam was then tested to failure in four-point loading. Strains in the concrete and in the CFRP pretensioned, post-tensioned, and nonprestressed reinforcement, as well as the beam displacements, were monitored during testing.

Based on the observations of the full-scale test beam, some modifications were made to the design. What had been draped pretensioning strand in the test beam became straight strand in production. Loris Collavino, president of Prestress Systems Inc., developed a coupler to connect his plant's chuck for stressing steel strand to a chuck for gripping the CFRP tendons. Collavino indicated that the CFRP tendons and CFCC cables required special handling. For example, they could not be dragged on the ground and had to be tied with nonmetallic ties.

Grace et al.<sup>2</sup> describe the construction of the Bridge Street Bridge in 2002 *PCI Journal* article "Design-Construction of Bridge Street Bridge—First CFRP Bridge in the United States." Twelve double-tee beams were fabricated in Windsor, ON, Canada, and transported to the site in Southfield. As with the prototype beam, much of the instrumentation was installed at the plant, and pretensioning forces, transfer lengths, camber, concrete and CFRP strains, and initial post-tensioning forces were all measured there. For long-term monitoring of the deflections, a taut stainless steel wire was strung between anchorage points near the ends as a reference. Displacement transducers were then installed at several points along the span. Grace indicated that monitoring of deflections, concrete strains, and CFRP and CFCC strains will continue until 2020.

## Pembroke Bridge

The two-span Pembroke Bridge, completed in Southfield in 2011, comprises two side-by-side box beams post-tensioned laterally at twelve transverse diaphragms, six along each span. Half of the post-tensioning force was applied before placement of the bridge deck and half after the deck had gained suf-

ficient strength for post-tensioning. Unlike the Bridge Street Bridge, the Pembroke Bridge used conventional steel for the longitudinal prestressing and shear reinforcement of the girders. Only the transverse post-tensioning cable and the deck reinforcement were CFRP. This more conservative approach was a result of a difference in ownership of the bridge, says Matt Chynoweth, engineer of bridge field services at MDOT. The Bridge Street Bridge is owned by the city of Southfield, while the Pembroke Bridge is owned by MDOT, which is developing design standards and waiting for the American Association of State Highway and Transportation Officials (AASHTO) to develop design standards before it considers use of carbon-fiber reinforcement as anything other than experimental.

Laboratory testing of a half-scale model<sup>3</sup> had been used to examine the influence of transverse post-tensioning force and number of diaphragms on the load-distribution behavior of the bridge. It also demonstrated the feasibility of replacing a beam and reconstructing the deck should the bridge be damaged by collision from an overheight vehicle. The design of the Pembroke Bridge was based on a previous determination<sup>4</sup> of the minimum number of diaphragms and transverse post-tensioning force necessary to eliminate longitudinal cracking between the box girders. That study demonstrated the need for more diaphragms and greater post-tensioning force than specified in the *MDOT Bridge Design Guide*<sup>5</sup> at that time. MDOT modified its *Bridge Design Guide* in accordance with the findings of Grace et al.<sup>4</sup> in February 2011, says Chynoweth.

In both the Bridge Street Bridge and the Pembroke Bridge, Grace and MDOT have worked closely with the contractors to help them understand how best to work with the carbon-fiber cable and reinforcement.

Tom Weinmann, manager of structural health monitoring at Applied Geomechanics, designed and installed the instrumentation for the long-term monitoring for both the Bridge Street Bridge and the Pembroke Bridge. He indicated that the instrumentation for both bridges was similar except for the measurement of the deflections. On the Bridge Street Bridge, the taut wire reference had proved problematic because of its attractiveness as a perch for birds. Their nests and debris interfered with the remote monitoring. Deflections of the Pembroke Bridge are being monitored using lasers installed at the supports and reflective targets along the span. The Pembroke Bridge was only the second application of this method; the first was in the construction of the Huey P. Long Bridge in Louisiana.



Jaimy Juliano adjusts a laser for long-term monitoring of deflections on the Pembroke Bridge. This type of laser technology was first used to monitor instantaneous out-of-plane deflections to prevent buckling of members being installed in the Huey P. Long Bridge in Louisiana. **Photo courtesy of Applied Geomechanics.**



Juliano installs a reflective target for monitoring deflections on the Pembroke Bridge. The target is at a 45-degree angle to the laser beam. **Photo courtesy of Applied Geomechanics.**

## Future projects

MDOT has plans for two additional bridge projects incorporating carbon-fiber-reinforced polymer composites. The first, scheduled to begin construction in April 2012, will be on Michigan Route M-50 and will be a three-span side-by-side box-beam bridge using CFCC for the transverse post-tensioning and epoxy-coated steel for the deck reinforcement. Chynoweth indicated that the epoxy-coated reinforcement costs less than carbon-fiber-based reinforcement and has worked well in previous projects. The second project, on Route M-102 at Plum Creek, will comprise two parallel bridges reinforced, prestressed, and post-tensioned entirely with carbon-fiber-reinforced polymer composites. It is in the design phase now and is scheduled for construction in 2014.

The American Concrete Institute's Committee 440 has published design guidelines for the use of FRP in prestressed concrete.<sup>6</sup> AASHTO is scheduled to vote this year on the use of CFRP elements for strengthening bridges but has not yet addressed CFCC for post-tensioning. In support of developing standards for design using CFCC, Grace will begin a research project in 2012 that will run concurrently with the design and construction of the M-102 Plum Creek Bridge.

According to Chynoweth, the use of CFCC in bridges is still an experimental technology. Other states, including Virginia, Florida, and Maryland, are all experimenting with it, but so far no one is using it routinely.

### A CULTURE OF INNOVATION

"Better, faster, cheaper, safer, smarter," the motto for reinventing the Michigan Department of Transportation (MDOT), sets the tone for innovation. Kirk Steudle, the state transportation director, wants not only to solve today's problems with today's technology but to keep the focus on the future. Even with tight budgets, MDOT continues to support practical research and demonstration projects. Technology offers the possibility of great service with a staff that is 15% smaller than it was in 2009. That is one way of being smarter.

MDOT has fostered advances in technology in both the infrastructure and the vehicles that drive on it. For example, MDOT has modified its specifications for concrete and asphalt pavements for greater durability. The public can readily recognize the value of less-frequent repairs and fewer delays due to lane closures even if the initial cost of paving is higher; however, the advantages of a bridge that lasts 75 years rather than 50 years can be more difficult to appreciate. Although the costs of a new material such as carbon fiber may appear prohibitive at the beginning, MDOT tries to find ways to implement the technology anyway. Often the price comes down as the material becomes more widely used.

For a public agency, public support is essential. MDOT works with communications experts to show the public what it is doing and why. Steudle says that there will always be those who oppose any change, so it's important to get the message out ahead of time. Also, when people don't hear anything, they assume nothing is happening. It's natural for engineers to want to avoid publicity, but Steudle believes we need to take the initiative and let the public know.

# Conclusion

Implementing CFRP composite technology in bridges required the cooperation of the university, the engineer of record, the department of transportation, the contractors, the precast concrete fabricator, and the testing laboratory. Taking a methodical approach to adopt the technology a little at a time allowed everyone to learn how best to use it and lends confidence to its application.

The use of CFCC might not become routine until design standards are in place. However, laboratory and field research to provide the basis for these standards continues.

# References

1. Grace, Nabil F., Tsuyoshi Enomoto, George Abdel-Sayed, Kensuke Yagi, and Loris Collavino. 2003. Experimental Study and Analysis of a Full-Scale CFRP/CFCC Double-Tee Bridge Beam. *PCI Journal*, V. 48, No. 4 (July–August): pp. 120–139.
2. Grace, Nabil F., Frederick C. Navarre, Richard B. Nacey, Wayne Bonus, and Loris Collavino. 2002. Design-Construction of Bridge Street Bridge—First CFRP Bridge in the United States. *PCI Journal*, V. 47, No. 5 (September–October): pp. 20–35.
3. Grace, Nabil F., Elin A. Jensen, Tsuyoshi Enomoto, Vasant A. Matsagar, Eslam M. Soliman, and Joseph Q. Hanson. 2010. Transverse Diaphragms and Unbounded CFRP Post-tensioning in Box-Beam Bridges. *PCI Journal*, V. 55, No. 2 (Spring): pp. 109–122.
4. Grace, Nabil F., Elin A. Jensen, and Mena R. Bebawy. 2012. Transverse Post-tensioning Arrangement for Side-by-Side Box-Beam Bridges. *PCI Journal*, V. 57, No. 2 (Spring): pp. 48–63.
5. Michigan Department of Transportation (MDOT) Construction and Technology Support Area. 2006. *MDOT Bridge Design Guides*. 2006 edition. Lansing, MI: MDOT.
6. ACI Committee 440. 2004 (reapproved 2011). *Prestressing Concrete Structures with FRP Tendons*. ACI 440.4R. Farmington Hills, MI: ACI.

## About the author



Rachel J. Detwiler, PhD, P.E., is editor-in-chief of the *PCI Journal*.

## Abstract

The Pembroke Bridge in Southfield, Mich., a side-by-side box girder bridge, is post-tensioned with carbon-fiber-composite cable (CFCC). This experimental bridge implements CFCC technology developed at Lawrence Technological University. Deploying this technology required a cooperative effort on the part of the university, the Michigan Department of Transportation (MDOT), the engineer of record,

the precast concrete fabricator, and the contractor. Adopting innovations in a step-by-step fashion has allowed users to gain confidence and understand how to incorporate CFCC in bridge design. However, CFCC has not yet been addressed by the American Association of State Highway and Transportation Officials.

## Keywords

Bridge, carbon-fiber composite cable, CFCC, corrosion, diaphragm, post-tensioning, side-by-side box girders.

## Reader comments

Please address any reader comments to [journal@pci.org](mailto:journal@pci.org) or Precast/Prestressed Concrete Institute, c/o *PCI Journal* 200 W. Adams St., Suite 2100, Chicago, IL 60606. ¶