By Samer H. Petro, P.E.
Contributing Author

First-class upgrade

Series of bridges in Phoenix strengthened successfully

Bridges are an important way to connect travelers to their destinations. So it's no surprise that when just one bridge is under construction or out of service, significant delays and frustrations can result.

In an urban area of Phoenix, three short-span concrete bridges constructed during the late 1940s through the early 1960s had reached the end of their originally intended service life and required an immediate upgrade. Realizing the impact of repairing, strengthening or replacing the bridges, the city assembled an expert team to evaluate the structures and determine a method to upgrade them in the most cost-effective and time-efficient manner. While all possibilities were considered, including total replacement, the decision was made to strengthen the bridges with a time-saving, cost-reducing and innovative approach.

The use of externally applied carbon fiber reinforced polymer (CFRP) composite materials gave these bridges the strength and upgrade they needed to increase their load-carrying capacity and accommodate today's usage. Thanks to their favorable weight-to-strength ratio and ease of fabrication and installation, CFRP composites have been proven to be strong, noncorrosive and a long-term durable composite system suitable for bridge strengthening. The story of three Phoenix bridges illustrates how these critical structures can be upgraded faster, and at a significantly lower cost, than total replacement.

A triple take

The 19th Avenue Bridge is a three-span continuous concrete slab bridge originally constructed in 1946, with enhancements and widening implemented in the 1960s. The 19th Avenue Bridge is a typical slab bridge found in the city of Phoenix spanning the canal system and carrying an estimated average daily traffic (ADT) of 30,000 vehicles per day (vpd). Designed to accommodate traffic loads and volumes smaller than currently permitted, the structure demanded either an immediate upgrade or replacement.

A rating evaluation of the 19th Avenue Bridge prior to rehabilitation revealed that the structure was deficient by Federal Highway Administration (FHWA) standards. The bridge only scored a sufficiency rating of 46.3 out of a possible 100 on the FHWA scale. Also, ratings determine the safe load-carrying capacity of a bridge. They include operating rating (OR), which indicates the maximum load level, and inventory rating (IR), which is the load level the bridge can support on a daily basis without damaging the bridge for a vehicle classified as HS-20. The 19th Avenue Bridge had an OR of 26 tons and an IR of 15.6 tons for HS-20 (or 36-ton vehicle), which is less than the Arizona legal load capacity.

The 16th Street Bridge is a two-span continuously reinforced concrete slab bridge originally constructed in 1952 and widened in 1988. It carries an ADT of 32,000 vpd. Like the 19th Avenue Bridge, this bridge also showed deficiencies with an IR of 9.4 tons and an OR of 15.8 tons for the HS-20 vehicle.

Lastly, the Thunderbird Road Bridge over Cave Creek is a three-span continuous concrete T-beam bridge constructed in 1965 and carries an ADT of 36,000 vpd. On this bridge, 11 reinforced concrete girders spaced at 7.25 ft support the 7-in. reinforced concrete deck. A load rating resulted in an IR of 31 tons and an OR of 51 tons for an HS-20 vehicle.

The material properties of the existing reinforcing bars and concrete required for the strengthening system design were determined from existing construction drawings and verified in the field. Nondestructive evaluation methods, including ground-penetrating radar (GPR), were used to determine rebar spacing and depth of cover. Coring was performed to determine rebar size, concrete slab depth and concrete compressive strength.

For the 19th Avenue Bridge, the contractor performed mild destructive testing, including exposing rebar by removing cover, to verify the results of the GPR testing and determine existing reinforcement. The results indicated that the negative-moment regions, which are the top reinforcement over the piers, were insufficient and a

Tailor-made CFRP

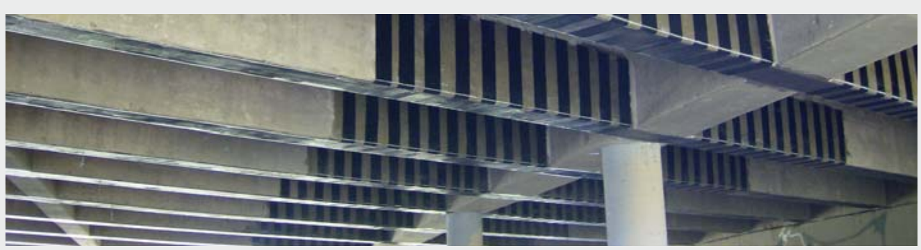
With each bridge presenting its unique challenges and deficiencies, a specific CFRP system was developed.

The 19th Avenue Bridge

- Commercially available high-strength, unidirectional carbon fiber wrap (SiKaWrap Hex 103C) was used for the rehabilitation of the slab soffit;
- Carbon fiber rebar (Aslan 200 Bar by Hughes Brothers) embedded in the concrete was used over the pier locations;
- For the positive-moment regions, two layers of SiKaWrap Hex 103C 12 in. wide by 15 ft long spaced at 36 in. on center were bonded to the soffit using a high-strength adhesive (Sikadur Hex 300) as recommended by the manufacturer; and
- For negative-moment regions over the piers, 63½-in.-diam. Aslan 200 CFRP bars were near surface mounted in grooves using high-strength adhesive (Sikadur 32) as recommended by the manufacturer.

The 16th Street Bridge

- Similarly commercially available SiKaWrap Hex 103C was used for the soffit;
- Aslan 200 CFRP bars were embedded in the concrete over the pier location;
- For the positive-moment regions, two layers of SiKaWrap Hex 103C 12 in. wide spaced at 20 in. on center were bonded to the soffit using a high-strength adhesive (Sikadur Hex 300) as recommended by the manufacturer; and
- For negative-moment regions over the pier, 43½-in.-diam. Aslan 200 CFRP bars were near surface mounted in grooves using high-strength adhesive (Sikadur 32) as recommended by the manufacturer.



The Thunderbird Road Bridge

- Required shear and flexure strengthening of the concrete T-beams;
- Strengthening this bridge for shear loads at the supports was achieved by applying a single layer of 6-in.-wide U-wrap SiKaWrap Hex 103C spaced at 12 in. with main fibers oriented in the vertical direction; and
- A single layer of continuous SiKaWrap Hex 103C wrap also was installed with main fibers oriented along the longitudinal beam axis on all beams.

Application of CFRP fabric strips at the soffit on the 19th Avenue Bridge.

CFRP U-wraps installed on T-beams of the Thunderbird Road Bridge.

departure from the design intent of the construction drawings.

Fabric hardener

The CFRP installation process called for specific and exact measurements. For both the 19th Avenue and 16th Street bridges, the design of the externally bonded CFRP fabrics called for 12-in.-wide strips spaced at either 36 in. or 20 in. on center for the positive-moment regions. The concrete surface that contained irregularities and cracks was restored with nonshrink mortar (Sikadur 30 or Sikatop 123). After surface preparation that included air blasting, CFRP strips were bonded to the concrete soffit.

The required number of near-surface-mounted CFRP bars was determined to be 63 for the 19th Avenue Bridge and 43 for the 16th Street Bridge. Also, ½-in.-diam. Aslan 200 CFRP bars were near surface mounted in grooves using high-strength adhesive (Sikadur 32) as recommended by the manufacturer. The CFRP bars were embedded in 1-in.-deep by ¾-in.-wide grooves cut into the bridge deck over the piers.

The T-beams of the Thunderbird Road Bridge required shear strengthening. To increase the shear strength of the existing concrete T-beams, a single layer of 6-in.-wide U-wrap SiKaWrap Hex 103C spaced at 12 in. with main fibers oriented in the vertical direction was installed to achieve full bond with concrete surfaces on the sides of the beam. The U-wraps were installed at locations of maximum shear over the supports.

Prior to installation of the CFRP system, it was necessary to minimize deck vibrations caused by traffic to allow the epoxy to cure. City of Phoenix personnel decided that closing the bridge for any length of time would not be feasible. Instead, efforts were made to limit the effects of traffic loads during strengthening operations. This was achieved by diverting traffic away from the lane directly above the CFRP installation each day.

With American Association of State Highway & Transportation Officials guidelines for this strengthening method pending, the design of the CFRP systems was carried out according to ACI 440.2R-08, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.

No. 1 in its class

The 19th Avenue Bridge became the first structure in the state of Arizona to be rehabilitated and strengthened using CFRP composites. But that is not the only first. It is also the first smart structure in the city.

To evaluate the performance of the CFRP strengthening on the bridge, a continuous monitoring program was installed to measure strains in real-time, thereby making it a smart structure. The bridge was instrumented and tested before retrofit and shortly after installation of the strengthening system. The initial tests established a number of critical benchmark responses of the bridge, while the other tests provided information regarding the participation of the CFRP system.

The instrumentation program included a continuous monitoring system using displacement gauges, such as strain gauges or sensors, that were placed on both the CFRP and concrete soffit and gauges embedded over the CFRP rebar and in the concrete regions over the piers. The monitoring system was powered with a solar array, and data was uploaded wirelessly to a website, which can be easily accessed by the city of Phoenix for continuous monitoring.

The 19th Avenue Bridge was instrumented to measure concrete surface strains and CFRP strains at various locations to measure maximum responses in positive-moment regions and negative-moment regions for all spans.

Two city of Phoenix loaded water trucks were used for the static load testing. These trucks had a three-axle configuration with a gross vehicle weight of 60 kips.

Test of strength

Two city of Phoenix loaded water trucks were used for the static load testing. These trucks had a three-axle configuration with a gross vehicle weight of 60 kips. A single truck was positioned with the center of the rear axles at midspan of each of the three spans of the bridge to produce the maximum positive moment in each of the three spans, while two rear axles from both trucks were placed on either side of the piers to produce the maximum negative moment.

Similarly, instrumenting and load testing the 16th Street Bridge involved collecting strain data using foil strain gauges installed on the existing reinforcement at midspan of span one and span two to measure the maximum response in the positive-moment region. Concrete surface strain gauges also were installed at locations close to the foil gauges. Sensor locations were distributed to measure maximum responses in positive-moment regions and negative-moment regions in both spans before and after installation of the CFRP.

The impact of the CFRP retrofitting system on the performance of the bridges is best illustrated by comparing strains or stresses before and after installation of the CFRP system.

After installation of the CFRP wraps on the soffit, the concrete strain values at all locations were reduced significantly by the addition of the CFRP at the soffit in the positive-moment regions and the CFRP rods in the negative-moment regions. Results from testing the 16th Street Bridge reinforce the behavior.

Similar values were obtained for concrete surface strains, albeit the reductions in strains and stresses were not as significant to the reductions in the existing reinforcement. As for strain measurements from sensors placed on the CFRP wraps or rods, results indicate similar values in terms of strain.

The consistency of the results (i.e., drop in strain or stress) on the concrete surfaces and existing reinforcement, and the fact that CFRP measured strain values were approximately equal to or higher than the rebar strain values, indicates that the CFRP rods and CFRP wraps are well-bonded to the concrete slab and acting as an effective part of the cross section. Although instrumenting and load testing of the Thunderbird Road Bridge are still ongoing, preliminary reports indicate similar results as the other bridges.

Proven success

By all accounts, the retrofit of two existing concrete slab bridges and a third concrete T-beam bridge using externally applied CFRP composite materials illustrate the effectiveness of the technology.

Not only did the externally applied CFRP composite materials significantly enhance the flexural and shear load-carrying capacity of the bridges and improve their load rating, the job was done at a fraction of the cost of total replacement and at a fraction of the time. Using the technology, a bridge can be rehabilitated in a matter of days—as opposed to months. Plus, commuters don't have to suffer from construction delays, and this technology proved to be environmentally responsible, because it salvaged and recycled the original structures. A construction crew ranging from eight to 20 workers participated on each of the projects, along with a project team consisting of Gannett Fleming, Truesdell Corp., Bridge Diagnostics Inc., LifeSpan Technologies and Composite Designs Group.

The story of these bridges is only the beginning of how CFRP can provide a fast-paced, lower-cost approach to rehabilitation and improving load-carrying capacity. CP

Petro is the manager of West Virginia operations and a senior structural engineer with Gannett Fleming Inc., Morgantown, W.Va.