NAVAL FACILITIES ENGINEERING SERVICE CENTER
PORT HUENEME, CA

SITE SPECIFIC REPORT
SSR-2285-SHR

DEMONSTRATION PROGRAM FOR WATERFRONT STRUCTURES REPAIR AND UPGRADING: SITE NO. 1: PIER 11 NAVAL STATION NORFOLK

BY
GEORGE WARREN

January 1997

SPONSORED BY

OFFICE OF NAVAL RESEARCH
PE 0603712N

Approved for public release; distribution is unlimited.

Executive Summary

The first of a series of three demonstration projects to apply external reinforcing to upgrade the strength of existing Navy piers was completed in December, 1996. The project was executed on a deck span of Pier 11 at Naval Station Norfolk. The project consisted of a load and condition assessment of the existing deck slab, the design of a graphite reinforced epoxy laminate composite overlay for the underside of the deck, preparation of the concrete surface, installation of the upgrade overlay, installation of monitoring sensors, and a load assessment of the upgraded deck slab. The entire project was executed while the pier continued in service for USS Kearsarge (LHD-3), USS Stennis (CVN-74) , and USS Enterprise (CVN-65).

Pier 11 was designed for 70-ton truck mounted cranes and limited use by 90-ton cranes. A recent A&E study identified deck slabs in the portable crane operating lanes in the 22-ft spans to have shortfalls that limited 70-ton crane service. The goal of the upgrade was to reinforce two crane operating lanes between bents 50 and 51 so that restrictions on 70-ton crane service would be removed.

Proof load tests verified the upgrade reinforcement to be integral with the deck and there should be no restrictions placed on operating 70 or 90 ton cranes in the upgraded span. The laminate overlay had little effect on the uncracked stiffness of the deck slab but will increase the service (cracked section) stiffness by as much as 5 percent, increase the strength by 10 percent while restricting crack growth and protecting the steel reinforcing from salt water corrosion. We expect the upgrade life to be approximately 20 years. The project demonstrated that graphite/epoxy laminate overlays can be used to extend the useful life of existing piers at substantial savings compared to deck replacement. composite laminate overlays. Given sufficient deck thickness, strength upgrades of more than 40 percent can be realized with external reinforcing of graphite/epoxy laminate.

Intermittent test and evaluation of the upgrade will be conducted over the next two years. Health and load monitoring sensors are in place and functioning under the deck for future tests.

DEMONSTRATION PROGRAM FOR WATERFRONT STRUCTURES REPAIR AND UPGRADING: SITE NO. 1: PIER 11 NAVAL STATION NORFOLK

The Upgrade Program

This project is part of an ongoing Naval Facilities Engineering Service Center (NFESC) program to demonstrate advanced technologies for increasing the strength of existing Navy piers. The program defines and demonstrates preparation and application techniques for upgrading pier decks and piling using fiber-reinforced plastic laminate systems and demonstrates sensor systems that provide measurements of performance. This project demonstrates a strength upgrade to correct an original design shortfall. In addition, the site provides an opportunity to evaluate the upgrade materials and methodology exposed to freeze-thaw cycles. With the assistance of Public Works Center (PWC) and Naval Station (NAVSTA) Norfolk Staff Civil Engineer, Pier 11 at NAVSTA Norfolk was the first site chosen to provide a platform for demonstration of pier deck upgrade and health monitoring instrumentation. The Pier 11 upgrade consisted of hand-laid, uniaxial graphite fiber-reinforced epoxy laminate applied to the deck underside of a selected span to increase flexural strength.

The application of external reinforcement to existing reinforced concrete slabs and beams was proven in an earlier NFESC advanced research project. Advanced materials such as graphite reinforced epoxy laminates were shown to be easily and rapidly applied to the underside of existing slabs and would add flexural strength and stiffness, mitigate crack growth, and increase the punching shear strength. Since the laminate was nonferrous and chemically resistant, we would expect the laminate to exhibit a longer useful life than ordinary reinforced concrete and would be capable of extending the useful life of existing waterfront structures that are being hard pressed to serve greater loads than they were originally designed.

Site Description

Pier 11 is located on the northern waterfront area of Naval Station, Norfolk, Virginia. It is a cast-in-place and precast reinforced concrete structure 1,400 feet (427 m) in length and 150 feet (76 m) wide (Figure 1). A nominal cross section is shown in Figure 2. Pier 11 is approximately 14 years old and was constructed from Naval Facilities Engineer Command Atlantic Division Drawings, JO No.542F8113, “Berthing Pier No. 11 Naval Station Norfolk Virginia”, 27 Oct 1981. Pier 11 serves nuclear carriers of the Atlantic Fleet. The structure is subjected to freeze-thaw cycles. It is one of the most active and visible piers at NAVSTA Norfolk.

Figure 1. Carrier Pier 11 in the foreground with the USS Stennis (CVN-74) in the background.

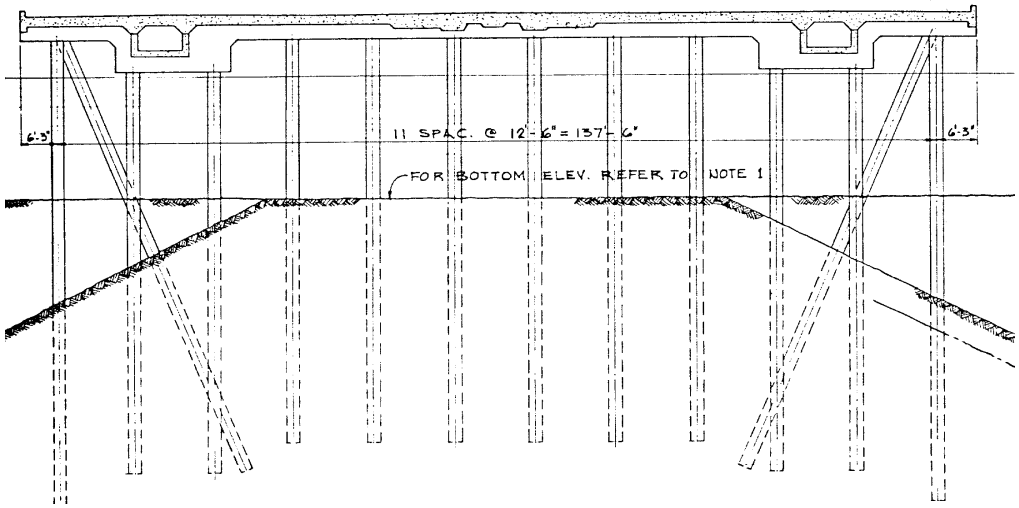

Figure 2. Nominal cross section of Pier 11 NAVSTA Norfolk.

The deck of pier 11 is supported by precast, 24-inch (61 cm) square piles each with a bearing capacity of 170 tons (1,500 kN). The piles are capped by transverse, cast-in-place beams (pilecaps) spaced at 20 feet (6.1 m) and 22 feet (6.7 m) on center that support the cast-in-place deck slab. Two utility trenches run below the deck along the full length of the pier. The design strength of the cast-in-place concrete is 4,000 psi (27 MPa) and the precast concrete is 5,000 psi (34 MPa). The nominal spans are 20 feet (6.1 m); however, there are five, 22-feet (6.7 m) spans where transformer vaults are located below the deck between the utility trenches. The deck slab is nominally 19 inches (48 cm) thick and reinforced with ordinary Grade 60 steel. Clear cover for the reinforcement is 2 inches (5 cm) on the top surface of the deck and 3 inches (8 cm) on the bottom surface. At midspan the deck reinforcement consists of No. 8 bars (2.5 cm diameter) at 4 inches (10 cm) on center on the bottom and No. 7 bars (2.2 cm diameter) at 6 inches (15 cm) on center at the top. Over the pilecap the deck is reinforced with No. 7 bars (2.2 cm diameter) at 6 inches (15 cm) on center at the top (negative reinforcement). Temperature (transverse) steel includes No. 5 bars (1.6 cm) at 12 inches (30 cm) on center both top and bottom of the slab.

As is the case with most of the Navy's berthing piers, pier 11 is heavily trafficked by large trucks and other vehicles which perform dockside maintenance on the carriers. The heaviest vehicles are truck-mounted portable cranes which operate while supported by four outrigger floats. Portable crane operations are generally limited to 25-feet (8 m) lanes adjacent to the curbs (that portion of the deck between the curbs and the second line of piles on each side of the pier). The interior width of the pier deck remains open for moving vehicles. Therefore, the outside lanes are required to support portable cranes servicing ships at berth thereby subjecting the deck slab to its most critical load case.

The pier is currently rated (and specifically designed) for 70-ton (620 kN) truck mounted cranes with limited use by 90-ton (800 kN) cranes. However, a PWC consultant engineering study identified the deck in the crane operating lanes of the 22-feet (6.7 m) spans to have design shortfalls that would limit 70-ton (620 kN) crane service. The 22-feet (6.7 m) span between pile bents 50 and 51 was chosen for upgrade demonstration. This span includes a transformer vault on each side of the pier centerline. Crane loading is not permitted on the vault hatches. Drainage holes (3 inch (8 cm) diameter) are located at midspan near each curb. Two large pipes extend across the center of each area and held in place by ordinary steel hangers suspended from the deck bottom. Photographs of the underside of the deck in span 50 -51 are shown in Figures 3 and 4.

The condition of the reinforced concrete in span 50 - 51 is excellent and there is no evidence of deterioration except some hairline cracking and minor efflorescence . The top concrete surface has minor, random cracking but no concrete spalling or delamination. An inspection of the underside of the deck in March, 1996, revealed some minor cracking and one case of minor efflorescence where water seeps

through the deck on the north side of the selected span. Some rust stains produced by steel tie wire, form anchors, reinforcement chairs, and the pipe hangers were visible. No biological fouling was observed. The concrete area was sounded for delaminations and was found to be sound and free of delaminations. The most serious detail was the presence of several 5/8-inch (2 cm) deep form transition marks and irregularities (Figure 4).

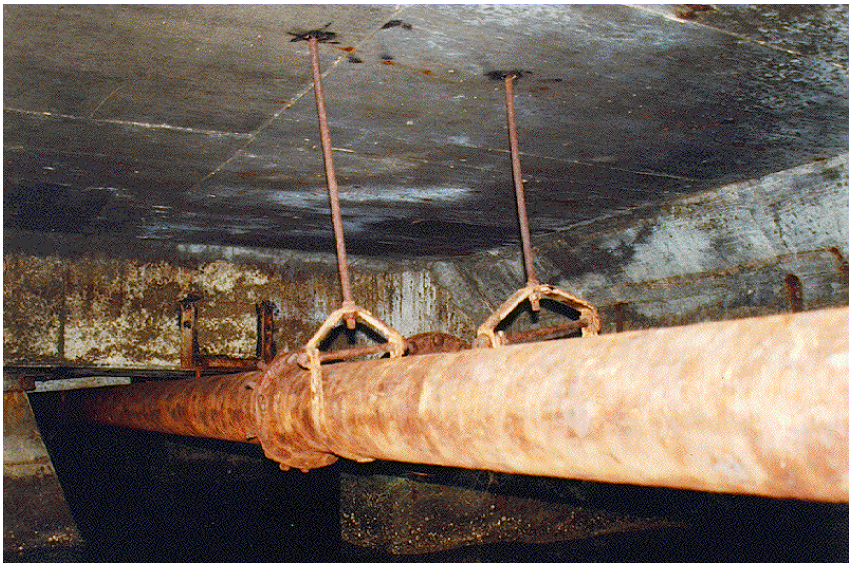

Figure 3. Under side of Pier 11 deck span 50-51 on the south side looking west..

Figure 4. Pipe hanger and deep cut form marks in the under side of Pier 11 north lane.

Pre-Upgrade Load Tests

NFESC engineers conducted a series of impact load tests in March, 1996, on the areas between bents 46 and 54 as part of a load assessment (Figure 5). The purpose of the tests was to compare the structural response of the proposed upgrade area with that of surrounding spans and pile bents. From the structural response we also searched for anomalous behavior indicative of corroded rebar and loss of concrete

strength. We applied the measured response to validate a finite element model the deck slab which we used for detailing additional reinforcement. Typical deflection responses for impact loads of 55,000 lbs (245 kN) appear in Figure 6. The tests were conducted in the middle of the crane operating lanes along Line B (9 ft - 7 in (2.92 m) from the north curb) and Line D (9 ft - 7 in (2.92 m) from the south curb). The series of plots in Figure 6 contain the deflection (Z axis) pattern at each load point (pile caps and midspan - Y axis) as a function of distance from the impact load point (X axis). The horizontal axis in the graphic's foreground represents longitudinal line over the deck near the center of the crane lane. The deflection response of the pile caps was equivalent. The response of the proposed upgrade span (50-51) was greater than all neighboring spans. This is indicative of the proportionally less reinforcing for length than that employed in the other spans (slab thickness and concrete strength were the same). This manifests in less structural stiffness and more displacement than neighboring spans. The tests did not reveal any mechanical damage in the area.

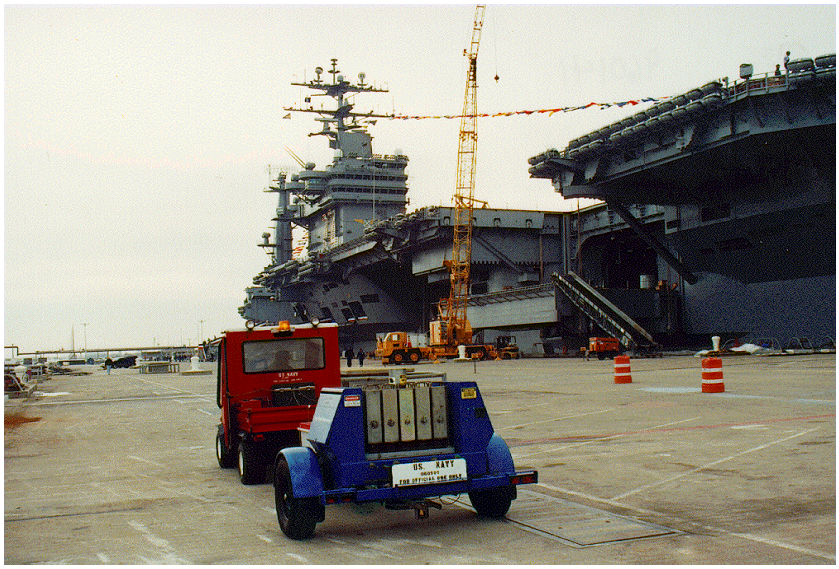

Figure 5. Falling weight deflectometer used to load test pier 11.

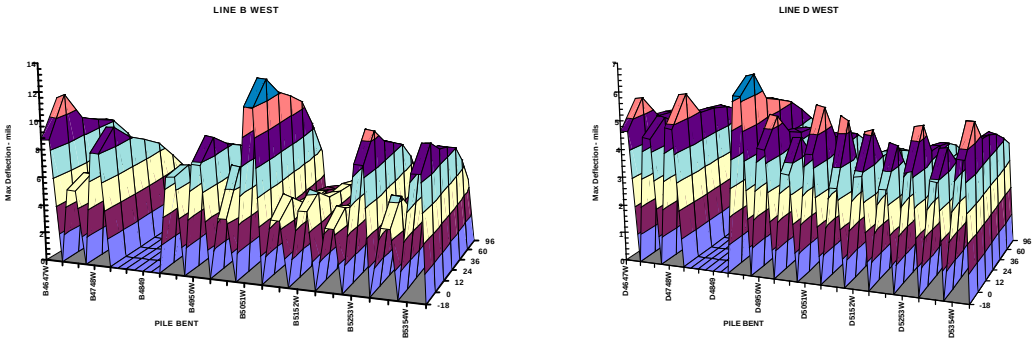

Figure 6. Deflection response at pile caps and midspans in areas of upgrade. The south side is represented on the left and the north side on the right.

The Upgrade

NFESC designed a carbon graphite composite laminate upgrade for two crane operating areas near each curb of the 22-feet (6.7 m) span between pilecaps 50 and 51 to increase the deck strength to the same level as the 20-feet (6.1 m) spans. The required strength increase was approximately 10 percent. NFESC has demonstrated strength increases of more than 40 percent in similar applications but such a dramatic

accretion was not needed in this case. The upgrade areas are 19 ft - 2 in (5.84 m) in the longitudinal direction and 15 ft - 11in (4.85 m) in the transverse direction. The areas are adjacent to the curbs and outboard of the utility trenches. These are relatively small areas of less than 35 yds^2 (30 m^2) on each side of the pier. Figure 7 is a detail of the upgrade area on the north side of Pier 11. The maximum outrigger float load is 155,000 lbs (590 kN) applied on a 24-inch (61 cm) pad. The uniform live load requirement is 1000 psf (50 kPa). The upgrade consisted of adding external, biaxial reinforcing on the underside of the deck equivalent to 9.9 kips/foot-width (17.4 kN/cm) (ultimate strength) in the longitudinal (strong) direction and 3.3 kips/foot-width (5.8 kN/cm) in the transverse (weak) direction. Piles are more than adequate to support 70 and 90-ton (620 and 800 kN) cranes plus lateral loads from mooring and berthing. Therefore, the piles did not require upgrading. The utility trench shown in Figures 3 and 7 was also not included in the upgrade. There were no damage or corrosion mitigation requirements for the concrete or reinforcing steel. The calculated bending resistance in the strong (longitudinal) direction of the existing slab was:

Mcr = 342 in-kip/ft width
My = 1931 in-kip/ft
Mu = 2805 in-kip/ft

While that in the weak (transverse) direction was:

Mcr = 342 in-kip/ft
My = 262 in-kip/ft
Mu = 464 in-kip/ft

With the upgrade carbon laminate reinforcement added to the underside of the deck, the bending resistance in the strong direction was increased to:

My = 2168 in-kip/ft (12 percent increase over baseline)
Mu = 3267 in-kip/ft (16 percent increase over baseline)

While the resistance in the weak direction was increased to:

My = 390 in-kip/ft (48 percent increase over baseline)
Mu = 1308 in-kip/ft (180 percent increase over baseline)

The punching shear strength of the existing slab is approximately 310 kips for a 24-inch square outrigger pad. Based on test experience, NFESC expects the upgraded slab to have a punching shear strength of over 350 kips.

Upgrade construction was completed in November, 1996. The form marks and surface discontinuities were knocked down by removing concrete with a small, compressed-air-driven hammer. The concrete surface was ground smooth and cleaned by sand blasting. Protruding tie wires, reinforcing chairs, and rust stains were also removed by grinding. Large surface indentations that remained after grinding were filled and smoothed with hydraulic cement grout. After surface preparation an epoxy primer was applied to the concrete and allowed to cure. Epoxy void filler (putty) was then used to fill in small voids and other surface irregularities larger than 0.04 inch (1 mm). On the south side a thin layer of putty was trowelled over the entire surface area while on the north side putty was applied in small patch areas. Installation of carbon fiber composite laminate began within an hour of applying the putty. The composite consisted of uniaxial carbon graphite fiber sheets and epoxy resin matrix (saturant). The laminate was hand laid and cured without the aid of external heating or vacuum bags. Tonen Corporation's Forca Tow Sheet FTS-C1-30 ™ was installed by Structural Preservation Systems (SPS) on the south side of the pier and Mitsubishi Chemical Company's Replark 30 Type ™ system was installed by SCI Services Group, Incorporated, on the north side. The carbon fiber sheets of each system are very similar. Both have a tensile strength of 3.3 kips/inch-width (5.8 kN/cm-width) and areal fiber weight of 0.06 lb/ft^2 (300 g/m^2).

Both are epoxy impregnated so that individual fibers are coated with resin. Tonen sheets are 20 inches (50 cm) wide while Mitsubishi sheets are 13 inches (33 cm) wide.

SPS covered the entire surface with three layers of Tonen graphite sheet: Two layers were aligned longitudinally (strong direction) and one layer was aligned transversely (weak direction). In addition, another 20-inch (50-cm) sheet was added longitudinally near the curb for additional longitudinal reinforcement. Epoxy saturant was applied by hand roller to the carbon fiber sheet prior to placement. The first layer was applied longitudinally directly to the uncured putty. The second layer was applied in the transverse direction. Successive sheets were applied by rolling epoxy on the sheet as well as to the previous layer. Excess saturant and bubbles were brushed, squeegeed, rolled, and otherwise "worked out by hand" from each layer. A 3-inch (8 cm) diameter hole was cut in the composite at the drain located near the curb at midspan. Gaps were also cut near midspan for the pipe hangers. Fibers were cut and sheets were lapped near midspan. Sheet laps were 4 inches (10 cm) or more in length. An outside layer of saturant was rolled over the entire area. The finished Tonen laminate thickness was approximately 0.05 inches (1 mm) and covered the entire area under the crane operating lane (Figure 8).

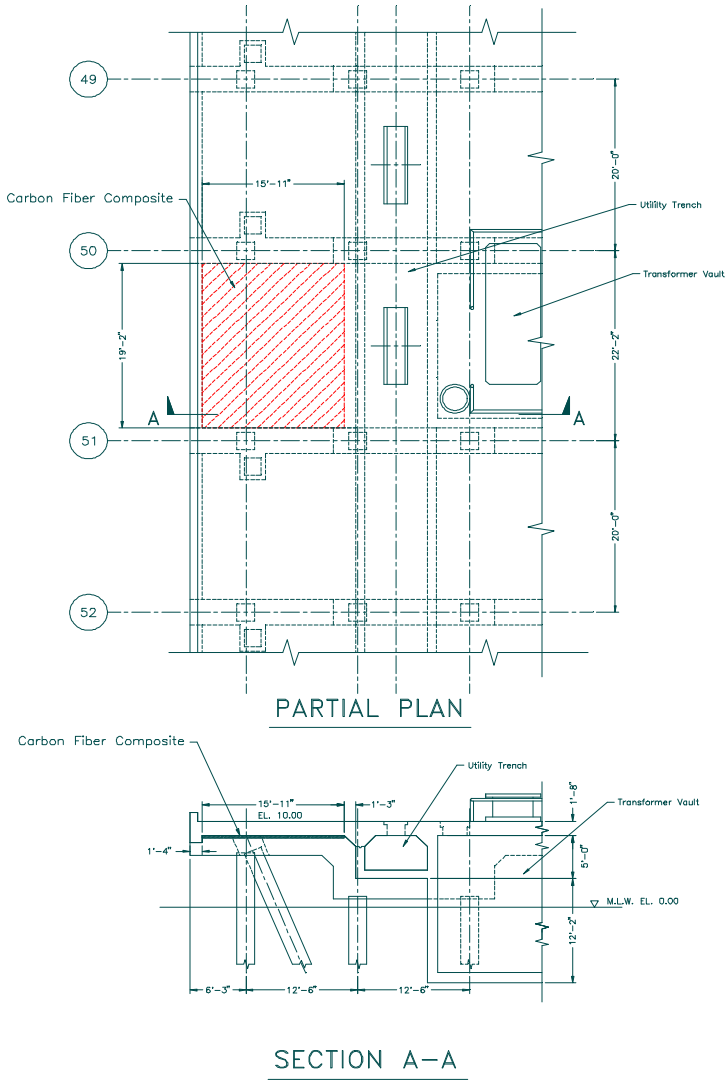

Figure 7. Detail of deck upgrade in north side crane operating area.

Figure 8. Finished installation of graphite laminate on the south side lane.

The installation process on the north side was similar to the opposite side. Rather than coating the entire surface, SCI used epoxy putty sparingly to patch small anomalies that remained after the primer coat had cured. They laid the Mitsubishi graphite sheets (strips) with approximately 6-inch (10-cm) space between them (20 inches (50 cm) on center). Spaces between the strips are to allow water to pass that leaks through the deck. The orthogonal (longitudinal and transverse) reinforcement layout resembled a grid (Figure 9). The number of sheet layers in each direction varied between 1 and 5. There were 12 transverse strips (weak direction). The middle 4 strips had double layers and the remainder were single layers. Nine strips were placed longitudinally in the strong direction. The 4 strips near the curb were 5 layers thick while the 4 strips near the utility trench were three layers thick. The remaining strip near the center was 4 layers. The strip spacing was adjusted slightly to miss the drain hole near the curb and the pipe hangers in the middle of the span. The 19 ft - 2 in (5.84 m) long longitudinal sheets were all continuous. The 15 ft - 11 in (4.85 m) long transverse strips included a staggered, 8-inch (20 cm) lap near midspan. SPS did not pre-apply epoxy saturant to the carbon strips. Epoxy saturant was applied only to the surface overhead and the saturant was worked through the fiber layers with hand rollers.

Figure 9. Finished installation laminate reinforcing grid on the north lane.

Monitoring and Instrumentation

The area on the north side was instrumented to follow the life cycle of the composite and its response to applied patch loads (see impact load tests above). Instrumentation included strain sensors located at grid points to measure maximum load response (Figure 10) and distribution as well as damage sensors along the edges and at the point of maximum load response. The former are traditional wire strain gauges attached to the laminate and aligned with the uniaxial graphite fibers. The gauges are capable of sensing strain in excess of 1.5 percent and will sense flexural cracks as load is applied to the deck.

The second set of sensors is piezoelectric patches attached to the laminate. The patches are sensors for a new impedance-based qualitative health monitoring technique to detect incipient damage in the composite laminate developed by the Center for Intelligent Material Systems and Structures (CIMSS) at Virginia Polytechnic Institute and State University. The technique relies on frequency tracking driving-point impedance of the structure above 30 kHz to identify damage. The qualitative damage detection is made by looking at changes in the structural coupling to a piezoelectric sensor/actuator by monitoring the change in electrical impedance of the bonded transducer. CIMSS engineers epoxy-bonded 25 piezoelectric actuator/sensors to the laminated area: 5 at each corner and 5 near the center at load point B identified in Figure 10. The patches excite and sense high frequency signatures in the near vicinity and will provide real-time structural health monitoring by sensing initiation of edge delaminations and structural damage in the laminate. Sensor data is collected by a central data logger and impedance analyzer at the site where it can be accessed and evaluated. The data logger can also be upgraded to be accessed by telephone modem for remote structural assessment.

After installation baseline measurements were taken by CIMSS. Converting the real time data to the frequency domain yields real and imaginary components. Only the real values will be used for health monitoring. Figure 11 is an example of real impedance from sensor Group C on the southeast corner of the north lane laminate area. The real impedance response of all sensor groups exhibited low dynamic activity (few peaks and valleys) over a large frequency range. This behavior was expected due to the high stiffness of the structure and the damping nature of the composite laminate. This behavior is an advantage when monitoring debonds and delaminations since such defects will quickly induce new dynamic activity over the frequency range that will be easy to detect.

Post-Upgrade Load Tests

NFESC conducted load tests on the upgraded section in December, 1996, using the same methodology used to for the original structural assessment. The composite laminate upgrade had not yet been subjected to freezing temperatures. Maximum load levels were less than 60 kips (270 kN) applied to an 11-inch (28 cm) diameter platen. The structural response was less than the cracking strength of the reinforced concrete. We determined that the graphite composite was acting integrally with the reinforced concrete. An inspection of the underside of the pier revealed that the composite had fully cured although some discoloration had appeared. We determined that the response of both sides were equivalent. Figure12 is the longitudinal strain and deflection distribution response to a patch load of 58.5 kips (260 kN) applied at the midpoint of the upgraded north crane lane. Figure 13 is the patch load-deflection response at midpoint on the upgraded south lane. Comparing previous load response without external reinforcement, we found little change in slab stiffness after adding the external reinforcement (Figure 13). The longitudinal strain response at the load point was linear in the range of measurement because the concrete remained uncracked (Figure 14). We expect the concrete to crack at about 100 microstrain (100×10^{-6} in/in (m/m)). If the response is extrapolated beyond cracking, the expected strain in the reinforcement would still be well within a service range of less than 200 microstrain responding to an applied patch load of 155,000 lbs (590 kN), the maximum outrigger load (Figure 15). The steel reinforcement will be stressed to much less than half its yield strength and cracks that are formed during loading should close after the load is removed.

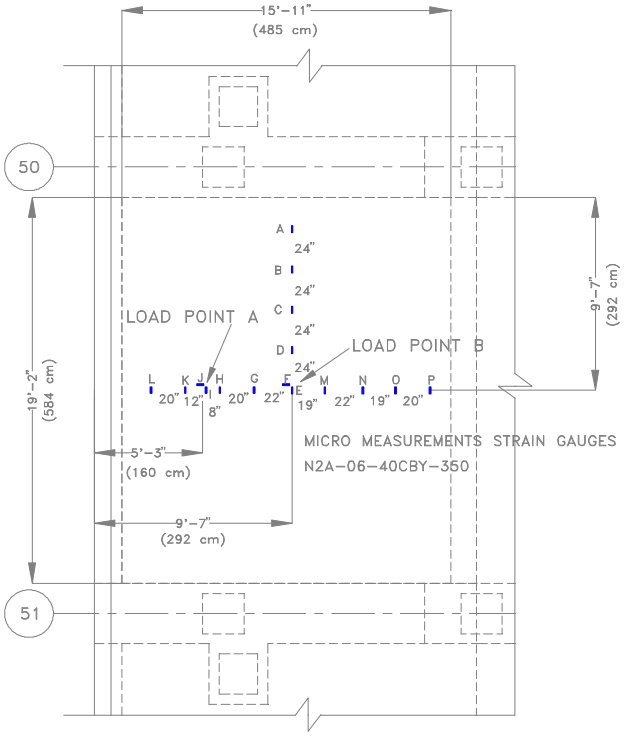

Figure 10. Strain gauge layout of the north side upgrade of pier 11.

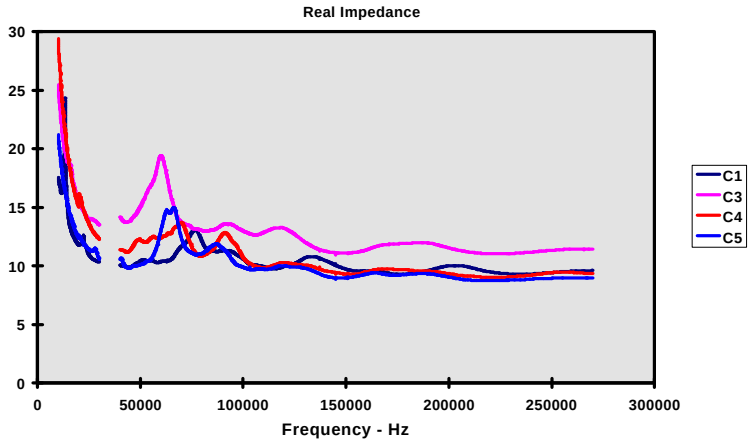

Figure 11. Initial real impedance measurements of the PZT sensors in Group C.

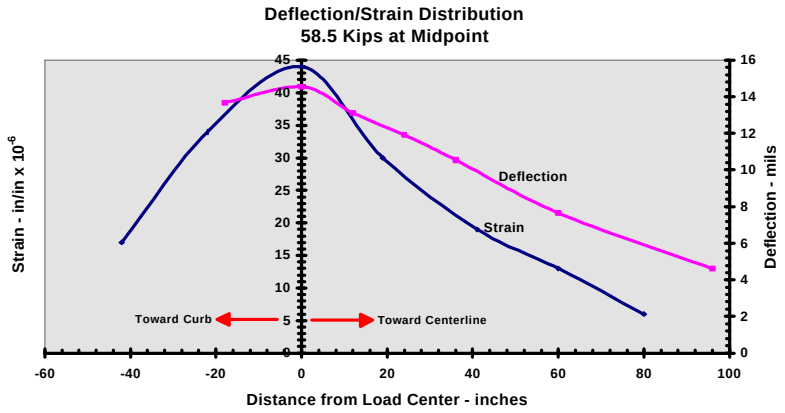

Figure 12. Measured longitudinal strain and vertical deflection distribution about 58.5-kip patch load applied at midspan aligned with Line B (point B near geometric center of upgrade area).

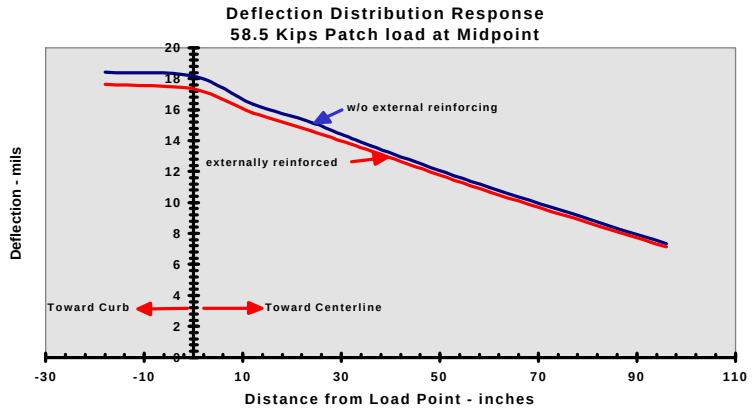

Figure 13. Deflection distribution about load point at midpoint of upgrade area.

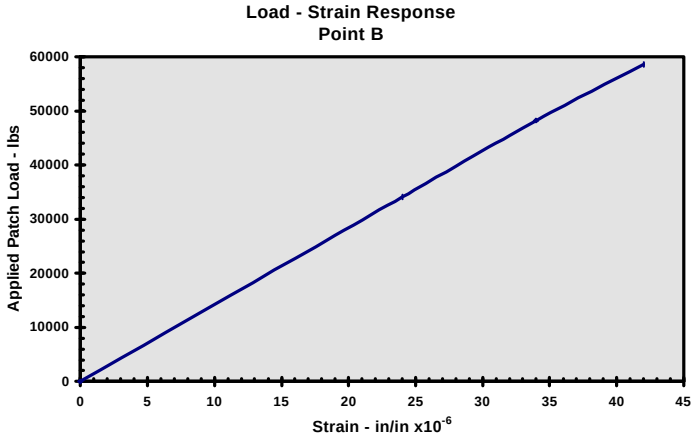

Figure 14. Longitudinal strain response from patch load applied at midspan - Point B

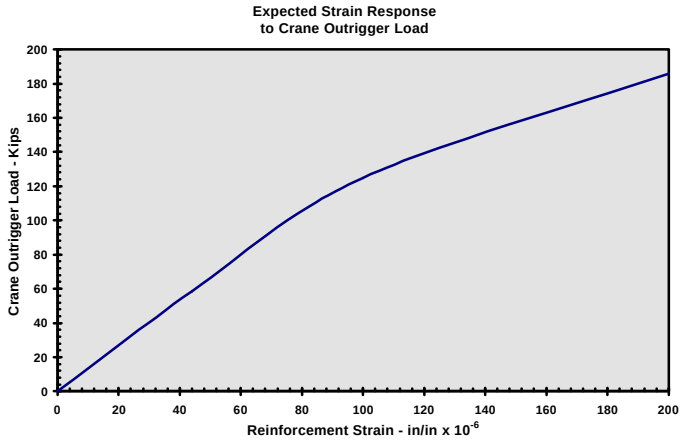

Figure 15. Expected longitudinal strain response in the external reinforcement due to outrigger load placed at midspan.

Conclusions

Adding external composite reinforcement to existing pier decks is a viable means of upgrading the deck strength. In those cases where the reinforcement is added to the underside of the deck, the pier can remain in service during installation. Graphite composite laminating materials are very expensive \$150/lb (\$70/Kg) or \$82/yd^2 (\$90/m^2 per layer) but the installation time is fast and labor costs are expected to be less than \$55/yd^2 (\$60/m^2). Given that graphite is 8 to 12 times stronger than steel, there is little or no down time of the structure, and we anticipate the life of a graphite composite should be longer than traditional pier construction materials (it is noncorrosive), external composite reinforcement can be an attractive upgrade alternative to demolition and reconstruction. For existing piers with sufficient deck thickness, strength upgrades of more than 40 percent can be realized with external composite reinforcing.