Navy finds new ways to use old piers with composites

Upgrades have Naval engineers looking at carbon fiber/epoxy for a new modular pier designed to meet the needs of the next century.

After years of flying high in U.S. Navy aircraft, carbon fiber composites are finding a new niche in naval pier construction. Navy designers have successfully used a 51-year-old pier at their San Diego shipyard as a testbed for the use of high-performance composites in load-bearing marine structures. With a retrofit of carbon fiber and epoxy composites externally reinforcing its concrete infrastructure, the pier can now handle substantially heavier equipment, allowing it to meet changing military needs. In addition to spurring other retrofit projects, the success of the San Diego pier project is laying the foundation for high-performance composite use in a new pier concept that will serve the Navy into the future.

Mothballs to amphibians

The 1,200-ft-long Pier 12 in San Diego was built in 1947 to moor dozens of warships "mothballed" after World War II. Over time, the mission of the pier evolved as the mothballed ships were sold, or relocated. By the 1980s, the pier had become a berthing site for large, shallow-draft amphibious ships, and was to be used as a platform for removal and maintenance of heavy antennae and gun turrets. However, stress tests showed that the 30-ton portable cranes needed to handle this heavy equipment exceeded the pier's load capacity. The heaviest loads previously borne by the pier had been trucks carrying personnel.

Figure 1. To meet the needs of its evolving mission, Pier 12 at the U.S. Navy's San Diego shipyard is upgraded with carbon fiber composites.

"We used the pier upgrade as an opportunity to demonstrate the capability of high-tech materials," says Dr. George Warren, project leader at the Naval Facilities Engineering Service Center (NFESC, Port Hueneme, Calif.) and lead engineer of the Pier 12 upgrade. Before Warren's team selected an upgrade design and appropriate materials, it:

- assessed the pier's condition,
- evaluated the use of composites in a demonstration pier at Port Hueneme,
- tested candidate materials and
- created models of upgraded pier designs using finite element analysis.

Based on this in-depth analysis, the Navy selected several types of advanced performance composites to reinforce the pier's infrastructure with enough load capacity to add two 50-ton crane stations — a crane rating even higher than the 30-ton cranes originally proposed. Each side of the pier would have a new crane station, and each station would serve two berths.

Hitting the deck

The pier's concrete deck is 30 ft wide and rests on concrete pile caps, which are beams that run longitudinally under the deck. The section of deck directly supported by the pile caps is 17 ft wide and 2 ft thick. On either side of that, a 6.5-ft section extends beyond the width of the pile caps in a cantilever effect. These cantilevered sections are only 8 inches thick.

Three different material configurations were used to demonstrate the ability of composites to serve as an external reinforcement on the deck underside. The 8-inch-thick portions of the deck were upgraded by applying carbon fiber/epoxy strips and fiberglass/vinyl ester I-beams. The carbon composite CarboDur strips were pultruded to a 1.2-mm thickness by Sika USA (Lyndhurst, N.J.), the U.S. arm of Sika, the Swiss global construction supply company. A proprietary two-component epoxy paste adhesive bonds the strips to the exterior of concrete, masonry or timber. The standard CarboDur product has a 348,000 psi tensile modulus and a 1.9 percent elongation.

To achieve the required upgrade stiffness, the cantilevered 8-inch-thick deck sections needed an I-flange support that was not available in carbon fiber composites. As a result, glass fiber composite I-beams were installed along with the carbon composite strips. The composite I-beams are standard 1-ft-deep sections with 6-inch flanges and 0.5-inch thickness.

Strongwell (Bristol, Va.) pultruded the I-beams of continuous glass fiber roving and continuous strand mat in a vinyl ester resin. Using stainless steel bolts, the glass composite I-beams were mechanically anchored to the pile caps, as well as bonded to the underside of the deck with the same epoxy paste used to bond the carbon fiber strips.

The 2-ft-thick, 17-ft-wide center section of the pier deck is externally reinforced with Fibrwrap unidirectional tow sheet from Fyfe Corp. (San Diego, Calif.). Fyfe makes the composite sheet in-house, using carbon fiber material supplied by Akzo Nobel Fortafil Fibers Inc. (Rockwood, Tenn.). The standard roll width of the Fyfe product is 2 ft. The sheet was impregnated with a two-component epoxy at the job site and applied to the underside of the concrete deck in four layers.

The sheet material was held in place by Tyfo TC tack coat primer, an epoxy adhesive formulated for high tackiness. The primer was applied after the concrete surface was carefully prepared by grinding away high points and removing laitance (the powdery residue found on concrete). The adhesive's tackiness was necessary to hold the heavy composite sheets to the underside of the deck during curing.

The epoxy formulations for both the primer and lamination resin are proprietary to Fyfe. The resins were designed for ambient cure, with initial cure occurring overnight and 95 percent cure within a week. The finished composite has a tensile modulus of 12 to 13 million psi and an elongation at break of only 1 percent.

Reinforcing the negative

The pier upgrade included reinforcing the remaining "negative moment," a phenomenon caused by the difference in deck thickness. The objective was to make the thinner deck portion (that cantilevers out on each edge) equal in stiffness to the thicker deck portion. When a "positive moment" load was applied to the thinner portion of the deck, an opposite, reactive negative moment occurred where the deck changes thickness.

To add stiffness to the topside of the deck, parallel slots were saw-cut into the concrete slab across the lines where the deck changes thickness. Then, an individual 3/8-inch-diameter pultruded carbon fiber/epoxy dowel rod was laid into each slot and encapsulated, using a two-component epoxy paste.

DFI Pultruded Composites Inc. (Erlanger, Ky.) pultruded the rods using a high-tensile-strength polyacrylonitrile-based unidirectional carbon fiber tow. The tow was impregnated with a two-part Epon 9300 Series amine cure epoxy resin system from Shell Chemical (Houston, Texas). The cured carbon composite rod has a fiber volume of 65 percent and a measured tensile modulus of 20 million psi. The rods delivered for the Pier 12 upgrade have a measured tensile strength of 220,000 psi.

Figure 2. Fyfe Corp. workers impregnate unidirectional carbon fiber tow sheet onsite before applying it to the underside of the San Diego pier.

After the San Diego pier upgrade was completed in March 1998, the deck was tested by applying a 100,000-lb live load to the weakest areas in the deck span design. The test measured deformation which was converted to stress in the composite materials. The unit used to measure the deformation was a microstrain, which is a one-millionth change in length per a given length (e.g., one-millionth of an inch per inch).

Before the live load test, finite element analysis of upgraded pier models predicted worst-case deformation in the range of 600 to 700 microstrains. In live load testing, performance was better than predicted when results showed a deformation of only 500 microstrains. Above 700 microstrains, the concrete in the pier exhibits visible cracking.

Lateral upgrade, too

"That took care of the deck," Warren says. "We were also looking into upgrading the pier to resist lateral loads from the berthing of ships or a seismic event. The finite element analysis of lateral loads showed that we would probably have trouble at the intersection of the piles and the pile caps. The [vertical] pile looked to be weaker than the pile cap [the horizontal beam upon which the deck rests]. We had enough longitudinal steel in the concrete pile to provide axial strength. What we needed was a way to increase lateral strength."

The solution was to strengthen the top 8 ft of the piles by confining them with a composite shell just below the pile cap. The cylindrical composite shell was made in two sections, split down the cylindrical axis. The halves were joined by interlocking into each at "H" joints along the edge and bonding with Plexus A425, a two-part methacrylate adhesive from ITW Plexus (Danvers, Mass.). The cavity between the new composite cylinder and the existing concrete section was filled with a nonshrink grout. In effect, the top 8 ft of the piles were expanded from 20-in^2 concrete to 31-inch-diameter composite-jacketed cylinders.

Hardcore Composites (New Castle, Del.) fabricated the composite shell pieces using the Seeman Composites Resin Infusion Molding Process (SCRIMP), with a Dow Chemical (Midland, Mich.) Derakane vinyl ester resin. The reinforcement is a stitched, triaxial fabric from Brunswick Technologies Inc. (Brunswick, Maine) that supplies the component with quasi-isotropic properties. The finished shell with grout provides 4,000-lb-per-linear-inch of confinement. Part of the new 8-ft section extends into the water. Below the composite shell, about 50 ft of the original precast concrete pile extends into the water and sea floor.

Looking for more

Success in San Diego has the Navy looking at other locations that could benefit from high-strength composites. An upgrade of a facility at Pearl Harbor, Hawaii, is scheduled for completion April 23, 1999. The Pearl Harbor pier was originally designed to use rail-mounted cranes to load and unload ships. The pier has since switched to truck-mounted cranes, which provide extra mobility to better serve the fleet and lower the cost of ship maintenance.

Because much of the old concrete pier deck at Pearl Harbor was not designed to carry mobile truck-mounted cranes, the Navy decided to use the new external retrofitting technology and materials that worked in San Diego. "When we build a new pier for portable cranes, we can reinforce the concrete internally," says Warren. "But since the pier is already built, we are going to reinforce it externally." For the Pearl Harbor deck upgrade, the composite rods will be used in the area over the pile caps, in addition to the areas where the deck thickness changes. The Pearl Harbor rods will also have a much higher tensile strength than those used in San Diego, at more than 300 million psi.

"We will use carbon fiber unidirectional tow sheets under the deck — the MBrace system provided by Master-Builders Inc. (Cleveland, Ohio)," says Warren. "And we will use carbon rods supplied by DFI to resist the negative moment on top of the deck." The contract for the deck upgrade at Pearl Harbor has been awarded to ACE Restoration (Fullerton, Calif.).

Pier of the future

The need to upgrade Navy piers to keep up with the requirements of evolving missions bodes well for continued composite use. The Navy is considering composite upgrades for piers in the Puget Sound of Washington State and on the island of Guam following completion of the Pearl Harbor project. Approximately 40 percent of the piers at U.S. Naval facilities are potential candidates for retrofit using external carbon fiber reinforcement.

Figure 3. The deck is reinforced with carbon fiber rods, placed in slots cut in the concrete and bonded in place with epoxy.

The remaining 60 percent of the Navy's piers are not candidates for upgrades and will need to be replaced over a period of decades. For the next generation of piers, under the Hybrid Waterfront Structure program, the Naval Facilities Engineering Service Center is developing a new modular design concept. Modularity will allow reconfiguration of the waterfront to meet changes in ship characteristics and force realignments, as well as the possibility of relocating a pier, or pier component.

"Our concept is a floating pier," adds Warren. "It will be a light-weight structural shell that will act like a boat. A floating pier is seismically isolated because it's sitting on water. With a floating pier, the freeboard [distance between the pier deck and ship deck] is constant — the ship doesn't go up and down while the pier stays put." Two different techniques are being explored for keeping the pier in place. First, the floating pier could move up and down positioning piles that are driven into the mud. Second, the pier could be anchored to cables that adjust in length as needed.

The new pier is expected to have a double deck — a design concept that has been in great favor since it was introduced in the 1980s. "With the double deck, you keep things clean because you have nothing but operations on the top. All the utilities, such as pipelines and electrical lines, are on the bottom deck and out of the way, but are still easily accessible."

The "21st Century Pier" will be used to berth medium-sized surface combat ships, such as missile cruisers or missile destroyers. As a result, the pier must be able to withstand the lateral loads from large ships and seismic events. The total berthing space must be 2,400 to 2,800 ft long to allow ships to berth two abreast in 40 ft of water.

The operational deck must be 100 to 120 ft wide and have a live load capacity of 1,200 lb/ft^2. The pier will have to support 140-ton mobile crane operations with 240,000-lb outrigger loads. A mobile crane reduces crane capacity requirements by about 40 percent. Stationary cranes typically require higher

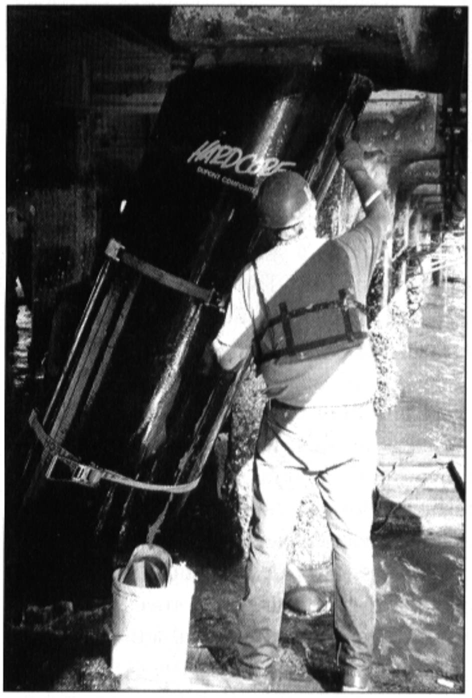

Figure 4. Installation of the pile shell.

ratings to meet the need for extended reach.

The opportunity to design an entirely new pier from the water up also allows the Navy to address the issue of longevity, Warren says. Technical goals for a new pier include a service life of more than 140 years. Over that time period, maintenance costs for the new pier should be 80 percent lower than those of conventional piers.

Materials working together

Although concrete will remain the primary material for the Hybrid Waterfront Structure, the goal of the program is to have concrete and composites working together. Advanced composites play a major role in the structural performance of the emerging design. Naval designers are striving to strike a balance among weight savings, strength and structural stability. For a pier, there is a point at which a materials system could be too low in weight. Mass provides a measure of stability that helps mitigate vibrations and deflection.

Instead of serving as external reinforcement for the concrete, the carbon fiber composites will be used in the new design to reinforce the concrete internally. The concrete will most likely be prestressed using cable tendons made of pultruded carbon fiber/epoxy rods. Steel — the traditional material for prestressed cable — is susceptible to corrosive attack in marine environments. The pier structure will be formed by pouring concrete around carbon fiber/epoxy cables (pretensioned). After the concrete is cured, the composite cabling will be relaxed, transferring its energy into the concrete, and placing it under compression. (See Update: The piles of Port Hueneme, pp. 18-19, *High-Performance Composites*, January/February 1999.)

Carbon fiber composite was selected for internal reinforcement in spite of its cost premium over glass fiber composite. "Glass fibers tend to lose strength when exposed to an alkaline environment such as that found in concrete," says Warren. "Even if the composite exterior is coated to protect the fiberglass inside, the composite cracks and the alkalis can leach to the glass."

According to Warren, glass composites will likely be used for other aspects of the new pier design. Nonstructural applications such as grating and handrails will be glass composite, and piling may be glass composite tubing filled with expansive or non-shrink concrete. "But for any application exposed to high stresses and embedded in concrete, the Navy will specify carbon fiber materials. In addition to being basically inert to alkaline attack, carbon fibers offer higher strength and stiffness with less material. This is especially evident in the upgrades where we are using very thin materials. You need a significantly thicker section to achieve the same mechanical properties with glass."

The largest obstacle for the future of the hybrid material pier is up-front cost. The cost to build the initial prototype may be up to 20 percent higher than the cost of building a conventional structure. As the technology matures, engineers project that the cost differential can be brought down to 5 percent. But even that difference may be too high for a publicly funded structure in the Department of Defense budget. "Over time, the hybrid pier will surely have a lower life-cycle cost than a conventional pier," Warren states. "But from our experience in Naval waterfront construction and budget procurement, initial cost is the most important factor."

Getting ready for 2004

The target date for building the first concrete/composite hybrid pier is 2004. The program will move toward that target in three phases. In Phase I, the Navy will develop structural concepts, study the characteristics of the materials to be used and evaluate methods of construction. Computer modeling and laboratory tests will validate feasibility, constructability and performance of the design.

During Phase II, pier concepts will be refined using computer models. One-half scale models of pier components will be manufactured to test and design operational and load responses. Piles, pile caps, beams and decks will be evaluated by laboratory testing.

In Phase III, a one-half scale pier section will be constructed and tested at the NFESC Advanced Waterfront Technology Test Site (Port Hueneme, Calif.). The concept will be tested for constructability, load response and service monitoring. The Port Hueneme field tests of the new design will be an extension of work already conducted there on demonstration decks made of composite-reinforced concrete.

The Navy initiative for a new pier concept has the potential to be a significant proving ground for high-performance composites in both marine and civil infrastructure. The high visibility of huge new piers reinforced with carbon fiber composite may help take the design from a developmental idea to a commercial reality. HPC

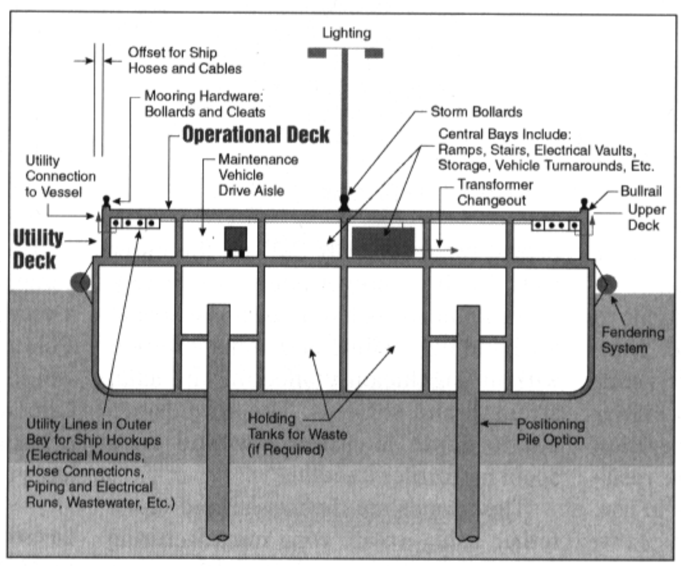

Figure 5. Concept for hybrid floating pier held in place by positioning piles.