# AMPTIAC

QUARTERLY

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# Special Issue:

# Protecting People at Risk:

## *How DOD Research Reduces the Impact of Terrorism*

AMPTIAC is a DOD Information Analysis Center Administered by the Defense Information Systems Agency, Defense Technical Information Center and Operated by Alion Science and Technology

# Issue focus:
# How DOD Research Protects People and Buildings



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***CLARIFICATION: The cover story for our last issue described the Army's exciting Mobile Parts Hospital project. Within that article, a technology called Laser Engineered Net Shaping™ was presented which can fabricate replacement parts using a combination of computational design templates, a computer-controlled laser, and powder metallurgy. Laser Engineering Net Shaping™ and the LENS® acronym are registered trademarks and service marks of Sandia National Laboratories and Sandia Corporation.***




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# Polymer Composite Retrofits Strengthen Concrete Structures

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## INTRODUCTION

This article describes Navy efforts to apply composite materials to pier decking and support columns for the purpose of repairing deteriorating installations and strengthening structures not designed for current load requirements. The successes of this program have laid the groundwork for a better understanding of how composite retrofits work in real-world, reinforced concrete structures serving in harsh environments. These retrofits have many similarities to some of the solutions proposed to retrofit buildings to make them more blast resistant. The approaches, if implemented, will increase load carrying capacity of floor sections, can enable sections designed only for gravity loading to withstand negative (upward) loads, and will reinforce support columns for higher strength and greater resistance to progressive collapse. Lessons learned in these Navy projects will help further advance the protection and hardening of land-based structures.

## BACKGROUND

The Navy has many waterfront facilities that are already old and continuing to degrade as they remain in use. Many of these facilities are mission critical piers and wharfs that were built during or soon after World War II. The replacement rate for these structures has been slow, with the average age continuing to increase. The cost of current deficiencies is approaching $1B for piers and wharfs.

The two primary reasons for these structural deficiencies are deterioration and mission changes. In some installations saltwater has migrated through cracks or permeated the concrete to initiate corrosion of the steel reinforcing bars. As the reinforcing bars corrode, they expand and cause cracking of the concrete, thus leading to more saltwater intrusion. There is also speculation that global warming is leading to higher tide levels and raising the level of the splash zone to further aggravate the problem. In more recent structures, there is also evidence of chemically-induced deterioration of the concrete due to curing processes or aggregate composition. Changes in mission and operating practices also lead to deficiencies in structural capacity of piers.

In the past, the Navy designed and built piers with rail-mounted cranes which typically had large beams under the rails to take the loads. Today, the Navy prefers truck-mounted mobile cranes. These allow more flexibility in operations, since they can set-up anywhere on the deck. However, not all areas of the decks are able to sustain the outrigger loads from such cranes. These loads are increasing, because more ship maintenance and repair operations are being conducted pier-side rather than in shipyards.

Conventional methods to reduce deficiencies are costly and disruptive to operations. Construction of new piers requires budget approval and subsequent funding. Approvals may take many years, and actual construction can prevent operations at the site of the project and at adjacent berths. Conventional repair practices tend toward brute force methods. A typical approach is to simply increase the thickness of the deck. However, the increased mass could lead to seismic problems. Further, if the corrosion products are not carefully removed and the areas sealed, the corrosion will continue. This situation has led to the search for new materials or technologies that the Navy could use to strengthen and repair these structures.

## TECHNOLOGY DEVELOPMENT

The Naval Facilities Engineering Service Center (NFESC), under sponsorship by the Office of Naval Research began a project in the early 1990's to explore the use of composite materials for repairing or strengthening waterfront structures. During that time the Navy teamed with the Army Corps of Engineers and what is now known as the Market Development Alliance (MDA) of the FRP (Fiber Reinforced Polymer) Composites Industry on a project for the Construction Productivity Advancement Research (CPAR) Program. The program involved testing of fender piles fabricated from FRP materials. The Navy uses fender piles* along the edges of piers to protect ships from impacts with the pier or wharf structure. Some of the piles were completely FRP, while others used an FRP casing around a concrete core [1][2]. This second type showed very good stiffness and strength properties under bending loads. The analogy to column wrapping for seismic upgrades was obvious.

NFESC fabricated a test site in Port Hueneme, CA to evaluate other FRP technologies in a controlled waterfront environment (Figure 1). The Army Corps of Engineers CPAR Program contributed funding and member companies of the Composites Institute of the Society of the Plastics Industry

Figure 1. **Advanced Waterfront Technology Test Site.**

Figure 2. **Placing Preformed Carbon Fiber Reinforced Polymer Rods Near the Top Surface.**

(forerunner of the MDA) contributed fabricated materials for the test site. Known as the Advanced Waterfront Technology Test Site (AWTTS), this structure has ten 10-foot test spans available for a variety of structural and materials specimens and two 20-foot spans holding an all-composite deck and a concrete deck with carbon fiber reinforced pre-stressing strands [3]. The South Dakota School of Mining and Technology contributed the pre-stressed concrete panel under a related CPAR project. The shorter spans simulate typical Navy piers at approximately one-half scale. Engineers, scientists and construction contractors have used the test site to evaluate the constructability and performance of concepts before taking them to an operational Navy application.

Numerical analyses, laboratory tests and tests at the AWTTS helped to validate the concepts for pier strengthening and repair. Small-scale beam tests showed that unidirectional carbon fibers bonded to the bottom (tensile stress) side of beams increased flexural strength and fibers bonded to the sides of the beams increased shear strength [4]. Adding both flexural and shear strengthening resulted in better load behavior with enhanced ductility and energy absorption.

Tests on small, under-reinforced, two-way concrete slabs showed that multiple layers of orthogonal carbon fiber sheets could increase both the flexural strength and punching shear resistance [5]. The increase in punching shear strength appeared to be consistent with the European code design guidelines. One-fifth scale laboratory tests and one-half scale tests at the AWTTS further demonstrated the increases in flexural strength, ductility and punching shear resistance with carbon fiber reinforcement bonded to the tension face [6]. The authors concluded that the increase in punching shear was attributable to the additional lateral constraint provided by the carbon fiber sheets.

Engineers also investigated the durability of the repair technique. A major concern was the durability of bonded carbon fiber strengthening on the topside of pier decks. On protruding or cantilevered sections of decks, or on continuous decks over pile bents*, the tension reinforcement must be on or near the top surface. Without proper protection, the carbon fiber would be damaged by vehicular traffic on the deck. The strengthening technique for the topside involved cutting a groove in the concrete surface, placing an epoxy adhesive in the groove, and embedding a preformed carbon fiber reinforced polymer rod in the groove (Figure 2). Laboratory tests demonstrated the strength and durability of strengthened members that depended on the bond between the epoxy, the rod and the concrete [7].

A similar series of tests also demonstrated the durability and strength of slabs with carbon fiber sheets bonded to concrete. Further tests evaluated the bond strength of adhesives to concrete under various moisture and temperature conditions [8]. These tests helped to establish the requirements for adhesive properties and surface preparation methods that would insure good load transfer between fiber sheets and the concrete substrate.

## DEMONSTRATION PROJECTS

The technology development phase removed many of the hurdles to implementing this technology into Navy shore facility applications. The efforts validated previously postulated design methodologies, and identified critical areas in the construction or installation process. The results provided sufficient data to take the program to the field.

The demonstration projects that follow provided Navy field activities with the data necessary to specify the use of FRP materials for repair and upgrade of Navy piers. Although they were demonstration projects, they all corrected real structural deficiencies on operational Navy piers. In all cases, the activity shared costs with the technology demonstration project.

Typically the work was performed via design-build contracts which allowed the selection of contractors on the basis of best qualifications and best value. Except for the first project, Government specifications were more performance-based rather than proscriptive. The reinforcement was specified in force per unit length rather than calling for a specific number of carbon fiber layers and a given adhesive material. Bidders

**Figure 3.** Pier 12 at San Diego.

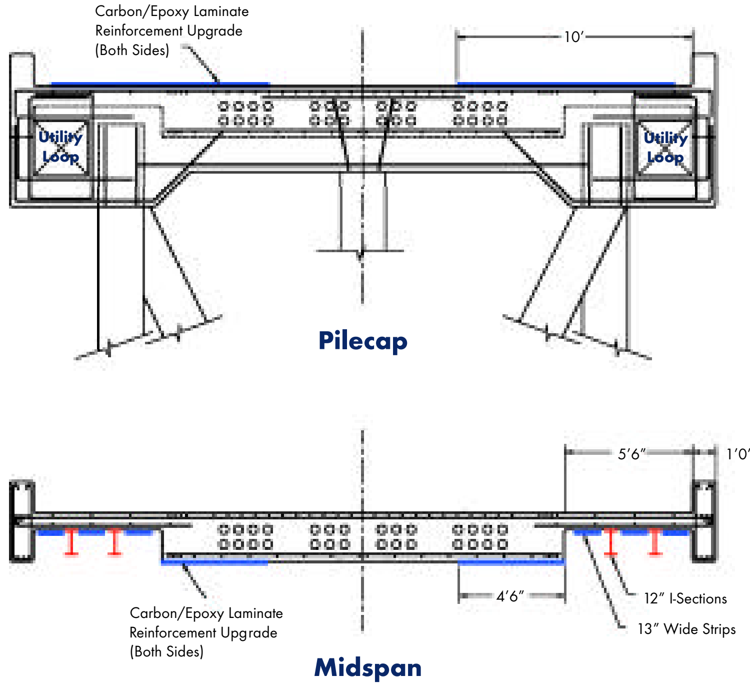


**Figure 4.** Cross Sections of the Reinforced San Diego Pier 12 at the Pilecap* and at Midspan Between Pilecaps.

had access to the test and development information developed by the Navy, but they were free to design their own retrofits. On successive projects, the bidders became more knowledgeable and more numerous. This led to more competition and lower unit cost for the technology. The engineering field divisions also became more knowledgeable in writing contracts for the work.

### Norfolk Pier 11

The first of the three demonstration projects to apply external reinforcement 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 [9]. 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. Contractors completed the entire project while the pier continued in service.

Pier 11 was designed for 70-ton truck-mounted cranes and limited use by 90-ton cranes. An engineering 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. As a result, there was no need to place restrictions on operating 70 or 90 ton cranes on the upgraded span. The laminate overlay had little effect on the stiffness of the uncracked deck slab. However, in the damaged areas the retrofits increased the service load stiffness by as much as 5%, increased the strength by 10% while restricting crack growth, and added protection from salt water corrosion for the reinforcing steel. The upgrade is expected to have a service life of 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.

NFESC is continuing to conduct intermittent tests and evaluations of the upgrade. Health and load monitoring sensors are in place and functioning under the deck for future tests.

### San Diego Pier 12

This project strengthened Pier 12 at the Naval Station San Diego to meet demands of operational changes accompanied by higher vertical loads [10]. It is a cast-in-place, reinforced concrete structure 1,458 feet (444 meters) long and 30 feet (9.1 meters) wide. Pier 12 was one of several piers constructed in 1946 to berth the mothball fleet stationed in San Diego after World War II. It is currently used for berthing large but relatively shallow draft ships such as amphibious ships and landing craft (Figure 3). Deck operations were limited to 30-ton truck mounted cranes that could operate only in limited areas.

The project included concrete repair, surface preparation, and strength upgrades for 14 spans. The specific project tasks included:

1. Repaired deteriorated concrete of the deck and replaced corroded reinforcing steel.
2. Sealed existing cracks in the deck with polyurethane.
3. Embedded high strength carbon composite reinforcing rods in the top surface of the deck.
4. Bonded wet lay up, high strength carbon laminate to the bottom surface of the 24-inch thick deck section.
5. Bonded pultruded, high strength carbon composite strips to

the bottom surface of the 8-inch deck section.

6. Bonded pultruded, fiberglass composite I-beams to the bottom surface of the 8-inch deck section and anchored ends to pile caps, utility loops (as seen in Figure 4), and bollard platforms.*
7. Installed pre-formed fiberglass cylindrical shells around batter piles* and filled gaps with shrink-resistant grout.

Contractors installed these upgrades at each berthing of Pier 12 (Figure 4). The upgrade methodology allowed pier operations to continue without interruptions. With these upgrades the deck is suitable for 50-ton mobile truck crane operations with 100,000 pounds (450 kilonewtons) maximum outrigger loads. There would be no restrictions on the locations for the crane outriggers. The deck is also capable of supporting a uniform load up to 750 pounds per square foot (36 kilopascals). (For comparison, the floor in a typical commercial building is rated at a uniform loading of about 150 psf.) Proof tests after completion of the project demonstrated the upgraded areas could support these new loads at stress levels in the reinforcement that remained well within service limits.

**Figure 5.** Applying Carbon Fiber Sheets to Underside of the Deck.

### Pearl Harbor Bravo 25

Bravo 25 at Naval Station Pearl Harbor is a cast-in-place, reinforced concrete deck and superstructure supported by precast concrete piles and is 550 feet (168 meters) long and 37 feet (11 meters) wide. The Bravo wharves are more than 50 years old. They were originally designed to support 50-ton (45 metric ton), rail mounted, portal cranes and train cars, as well as a distributed load of 900 pounds per square foot (43 kilopascals). In recent operations, truck-mounted, mobile cranes have replaced track-mounted cranes on the Bravo wharves. Mobile crane load limitations placed on Bravo wharves due to degradation were very restrictive. They limited crane outrigger loads to the track slabs and the rail girders. Other areas were restricted to truck and forklift wheel loads. Maximum uniform live load was limited to 490 pounds per square foot (23 kilopascals).

The objective of this project was to rehabilitate the concrete, protect existing reinforcement from corrosion, and increase the load capacity of the areas at each end of the Bravo 25 berthing [11]. This upgrade provided platforms with the ability to support mobile crane outrigger loads up to 125,000 pounds (560 kilonewtons) and a uniform load up to 750 pounds per square foot (35 kilopascals). To accomplish this, unsound concrete was removed and replaced, an impressed-current cathodic protection system was installed to protect the existing steel reinforcement, and carbon/epoxy composite reinforcement was added to the top and bottom surfaces of the deck and track slabs (Figure 5). The upgrade was completed with minimal interruptions to normal pier operations.

### APPLICATION TO THE STRUCTURAL PROTECTION COMMUNITY

The applications of composite materials described in this article deal with strength upgrades for primarily static loads. The objective was to extend the life of structures with a minimal cost and disruption of activities on the piers. The Navy is doing follow-on work to consider the use of composite materials in the construction of new piers. But the work, which is still in progress, has indicated that the economics for employing composites in new construction are not as favorable as those for retrofits. The development effort to date indicates that a modular floating double deck pier constructed of high volume fly ash concrete with conventional post-tensioning strands and stainless steel secondary reinforcement has the most promise of providing a long life, low maintenance pier at a minimal increase in initial cost. In this case, dynamic or blast resistant design is not a major element.

Designers need to use caution when applying FRP technology to upgrades of slabs or panels for resistance to explosions. Carbon fiber may not be a good choice because of its cost and potential for a brittle failure. Also, the wet lay-up method presented here does not provide shear resistance around the periphery of the slab or panel. This may be a critical design parameter for some blast loading conditions. However, carbon fibers bonded to the bottoms and sides of reinforced concrete beams or girders could improve the overall strength of frame structures and help in the prevention of progressive collapse.

The process is analogous to providing external reinforcement for bending members. Even in an office building, this upgrade can be accomplished with minimal disruptions to operations.

The use of pre-formed FRP shells around existing columns may help to provide additional ductility under blast loads. This was the technique used on batter piles in San Diego. In many cases workers may need to gain access to a column by chipping away the adjacent walls. The two-piece round cylinder can be placed around any shape column and the workers fill the gap with non-shrink grout. This effectively increases the size of the column and provides confinement for additional strength and ductility. However, like the slab strengthening, it does not help transfer shear or moment to girders.

Another application of wet lay-up bonded carbon fibers might be in providing upgrades to floor slabs that were originally designed for gravity loads. Threat situations in which the blast loading could be coming from below the floor slab provide a unique situation, because the designer places the reinforcement to resist downward loads. Typically, there is little steel to resist negative (upward) loadings. To resist this type of loading, workers could bond carbon or other fiber sheets to the floor surface and place a floor covering over them to protect the fibers. This involves minimal disruption to the strengthened area.

All of these potential applications of FRP upgrades for blast resistant design have proven very effective for upgrading piers for new loadings. We have demonstrated and proven the technology in the relatively severe marine environment. Furthermore, by implementing the process through the people who design and specify upgrades to docks and piers, the methodology has transitioned to practical use. In addition to producing more test data for reducing risks of applying the same technology to blast design upgrades, we need to develop a similar strategy for the implementation process. This will insure the greatest number of qualified designers, suppliers and contractors and will help reduce the costs.

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## ENDNOTE

* The following description of terms used in the construction of piers might be helpful to the reader. Piles are usually timber or reinforced concrete poles driven into the ground. Groups of piles (bents) are typically capped, and a flat deck is built across the pile bents. Batter piles are driven diagonally to help stabilize the structure from side loads. Fender piles line the edges of the pier to help protect both the pier and docked vessels from damage. Bollards (bulbous posts usually made of steel and concrete on Navy piers) and cleats (horizontal bars supported in the middle) are attached along the edge of the pier to tie off vessels at rest.

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**AMPTIAC Celebrates Its 6th Birthday**

On November 1st, AMPTIAC's staff took a few minutes out of their busy day to mark the IAC's sixth birthday. The six years have flown by, but are replete with accomplishments. We are proud of our success serving the DOD materials and processes community and look forward to continued service in the future.