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Advanced Composites For The Navy Waterfront Infrastructure

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Synopsis: Since 1992, the U.S. Navy, Naval Facilities Engineering Service Center (NFESC), has been involved in the study and use of advanced fiber reinforced plastic (FRP) composites for its waterfront infrastructure applications. Carbon FRP (CFRP) and glass (GFRP) composites were assessed and demonstrated at NFESC and at various sites throughout the Navy. CFRP sheets were used to upgrade reinforced concrete beams, slabs and piles. GFRP shells were also used for pile upgrade. Some of these components were reinforced and prestressed with CFRP rods and tendons. Finally, other composites, such as epoxy coatings for rebars and engineered wood were addressed. Long term durability issues are still being investigated. This paper represents an overview of the assessment and use of FRP materials in Navy reinforced concrete waterfront structures.

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INTRODUCTION

Since 1992, the U.S. Navy, Naval Facilities Engineering Service Center (NFESC), has been involved in the study and use of advanced fiber reinforced plastic (FRP) composites for its waterfront infrastructure applications. Advanced composites presented significant durability advantages for waterfront construction when compared to traditional materials, such as wood and steel. However, an understanding of these materials, and their short and long-term characteristics, was necessary to optimize their use in the areas where their properties made them best suited. The present paper shows a summary of development, test & evaluation, and application of these materials within the Navy infrastructure.

BACKGROUND

In fiscal year 1991 critical U.S. Navy waterfront deficiencies amounted to a total of $1.3 billion, of which $613 million were related to pier upgrades and repairs, and an estimated $219 million were needed for new construction. About 75% of all Navy piers and wharves were over 40 years old and required increased repair and maintenance. Most of the deficiencies were due to corrosion, in particular to corrosion of steel reinforcement. To prevent this corrosion, the use of galvanized and epoxy-coated reinforcing bars (rebars) was investigated. A recent alternative was the use of corrosion-resistant fiber reinforced plastic (FRP) components including reinforcing bars, prestressing tendons, structural shapes, and unidirectional or woven fabrics. All of these were already commercially available but were used with restraint due to the limited knowledge of their long-term behavior and the lack of uniform codes or design guidelines. In the meantime research was advancing rapidly and several demonstration structures had been constructed in Europe. In Japan, a government-sponsored national research project on the use of new materials in construction was focusing on the use of continuous fiber products in concrete construction.

In 1992 the Naval Facilities Engineering Service Center (NFESC) started investigating the potential of these new materials for Navy waterfront infrastructure applications. FRP reinforcing bars for concrete reinforcement were first evaluated.

In 1994 NFESC established the Advanced Waterfront Technology Test Site (AWTTS), to enable U.S. researchers to demonstrate their state-of-the-art composite applications on a waterfront reinforced concrete structure. This structure represents a typical Navy pier designed to withstand the highest existing Navy crane loads. It uses FRP materials as structural members or components. A parallel effort involved the assessment of structural upgrades using carbon FRP sheets.

In 1995 all components of the AWTTS were completed. Prestressing technology using graphite tendons was demonstrated in pile and deck construction. The feasibility of all-composite structural components was proven. Mechanical properties of FRP reinforcing bars had been evaluated. Structural upgrade using CFRP sheets was very successful and was scheduled for full-scale field applications. A first compendium was published in December 1995 covering research results through that date [1-12].

In 1996 half scale tests of composite upgrades were completed on the AWTTS reinforced concrete decks. Composite upgrades of operating piers at NAVSTA Norfolk, San Diego, and Pearl Harbor, were started. Additional work was completed in the areas of composite fender piles, composite hangers, and epoxy coatings for rebars. This work was included in the second compendium published in December 1996 [13-22].

The two first composite upgrades were completed in 1997 (NAVSTA Norfolk) and 1998 (NAVSTA San Diego). These efforts indicated that the mechanical characterization and use of these materials had matured. However, it became apparent that long-term characterization was still inadequate, and the 1998 technological development effort concentrated on durability issues. The latest compendium of publications gives an overview of NFESC's technology in advanced composites for infrastructure applications for calendar years 1997 and 1998 [23-30].

COMPONENT UPGRADE

Piles

In its seismic retrofit program, the California Department of Transportation (CALTRANS) has been a leader in assessing and allowing the use of FRP composite materials for column wrapping [31]. These wraps have been shown to significantly enhance the columns' ductility during seismic events. In the Navy, several of the same wraps were evaluated and used for upgrading piles, most notably at the pile to pile cap connection, where the pile would typically lose its concrete cover by crushing [24]. Among the types tested and used: a wet carbon FRP lay-up with underwater curing resin, which will retain the original appearance of the pile, and various prefabricated cylindrical glass shells which are placed around the pile, the gap between shell and pile being filled with concrete grout. Either system was shown to properly confine the pile concrete, allowing for increased ductility of the pile to pile cap

connection [24] (Figure 1). Pile wraps have also shown potential application to the upgrade of structures to resist blast effects [32].

Beams

Some of the original work in this area was started in Switzerland [33]. NFESC carried out some testing to verify that both bending and shear enhancements were possible, and that the overall energy dissipation was also enhanced [3,8]. Satisfactory shear enhancement was obtained by wrapping CFRP sheets on 3 faces only (sides and bottom).

Slabs

Navy pier decks are characterized by reinforced concrete slabs over pile caps, with spans of about 20 ft (6.1 m). Although the FRP wraps were known to increase the bending capacity, the mode of failure for Navy slabs is punching shear under the high concentrated loads from mobile crane outrigger pads (up to 240 kips over 30 by 30 inch areas) (that is 1070 kN over 76 by 76 cm areas). Laboratory 1/5 and 1/2 scale tests showed that carbon FRP (CFRP) wraps were able to enhance the punching shear strength as well, by up to 50% [1,15] (Figure 2). Lately, carbon rods, glued into grooves in the top deck, were used to resist the negative moment due to live loads [24]. Upgraded slabs were then subjected to full-scale tests to demonstrate their upgraded capacity (Figure 3).

NEW CONSTRUCTION

Piles

Over the last few years, several FRP piles have entered the market, both for fendering and bearing applications. NFESC has tested fender piles of various types: (1) recycled plastic with glass FRP reinforcing rods, (2) pultruded glass or carbon shells (filled or not with concrete), (3) filament wound and scrimp shells, (4) FRP structural shapes (Figure 4). Some Navy activities have adopted some of these piles for secondary fendering, the main fendering typically consisting of foam-filled fenders resting against partially prestressed reinforced concrete piles, also developed at NCEL [34]. Some prestressed concrete bearing piles were also constructed at the South Dakota School of Mines and Technology using CFRP tendons and spirals, and driven in the Port Hueneme harbor [7,9].

Slabs

Standard Navy 18-inch deep concrete slabs prestressed exclusively with CFRP tendons were used in a demonstration pier deck in 1995 [7,9]. Ongoing test & evaluation is determining the suitability of CFRP tendons for reinforcement purposes by assessing their bond capacity. An all-composite deck composed of glass FRP tubular sections was completed [7,9], and single large pultruded sections are currently being investigated.

Pier Concepts

Under a recent project, NFESC is looking at the feasibility of a new generation of piers that would take even more advantage of the new materials. Concepts being investigated include double-deck pile-supported and floating piers, incorporating CFRP prestressed/reinforced decks and hulls, as well as pultruded FRP sections and appurtenances.

DURABILITY ISSUES

Sustained Stresses

Glass FRP (GFRP) composites are not being used in applications were sustained, long term, or cyclic stresses are present. GFRP are appropriate for pile wrapping, where the composites are subjected only to occasional large live loads, but not so much for deck retrofits where dead loads, or highly cyclic loads, can be present. Concrete beams reinforced with single CFRP sheets and loaded to 50% of the CFRP strength have been exposed to the inter-tidal zone in the Hueneme harbor for about 4 years without failure.

Adhesives

The long term durability of the resins used to apply FRP composites to concrete is still being investigated. This is especially important for deck retrofits, where the whole retrofit is dependent on the adhesion of the CFRP to the concrete. Short-term effects of temperature, humidity, and chloride content were addressed [26,27]. Long-term freeze-thaw effects showed only a slight effect on CFRP load carrying capacity after 1000 cycles between –30ºF and 130ºF [24].

ADVANCED COMPOSITES FOR CONVENTIONAL MATERIALS

Epoxy Coatings

While epoxy coating of steel rebars has been used for many years, sometimes with mixed results, NFESC recently participated in the development of ASTM A934 epoxy coatings which show better adhesion (they are fusion bonded), have less defects and exhibit increased UV resistance. ASTM A934 epoxy coatings have been used recently in the Ford Island Bridge in Hawaii [29], as well as other commercial applications [29]. Coated and uncoated bars should not be used side by side.

Engineered Wood

Within this category, the Navy is looking into materials composed of at least 50% wood flour by weight. The remainder of the mixture includes either high density polyethylene (HDPE) or polyvinylchloride (PVC), and several

additives. Moduli of rupture in the order of 3000 psi (21 MPa) and elastic moduli in excess of 500 ksi (3.4 GPa) can be obtained, and these materials are currently being considered for chock, wale and deck replacements. For pile applications, these materials may need to be reinforced, and the inclusion of continuous carbon tows in both pultrusion and extrusion processes is being investigated.

CONCLUSIONS

Advanced composites have already replaced conventional materials in many applications. In the infrastructure, composites are competitive with steel in the upgrade of columns or piles, and provide economical alternatives for structural upgrade of decks. It is expected that the use of these materials will keep increasing, both for upgrade and new construction applications.

REFERENCES

1. Inaba, C.M., Warren, G.E., Malvar, L.J., “Rehabilitation of Navy Pier Decks with Composite Sheets,” First International Conference on Composites in the Infrastructure, ICCI 96, Tucson, AZ, January 1996.

2. Malvar, L.J., Warren, G.E., Inaba, C.M., “Rehabilitation of Navy Pier Square Piles with Composite Sheets,” Technical Memorandum TM-2148-SHR, Naval Facilities Engineering Service Center, Port Hueneme, CA, September 1995.

3. Malvar, L.J., Warren, G.E., Inaba, C., “Rehabilitation of Navy Pier Beams With Composite Sheets,” Second FRP International Symposium, Non-Metallic (FRP) Reinforcements for Concrete Structures, Gent, Belgium, August 1995, pp. 533-540..

4. Malvar, L.J., Bish, J., “Grip Effects in Tensile Testing of FRP Bars,” Second FRP International Symposium, Non-Metallic (FRP) Reinforcements for Concrete Structures Gent, Belgium, August 1995, pp. 108-115.

5. Warren, G.E., Malvar, L.J., Inaba, C., Hoy, D., "Life Extension for the Navy’s Waterfront Infrastructure," Extending the Life of Bridges, Civil and Building Structures, Proc. of the 6th International Conference on Structural Faults and Repair, Westminster, London, July 1995.

6. Malvar, L.J., "Tensile and Bond Properties of FRP Rebars," ACI Materials Journal, vol. 92, no. 3, May-June 1995, pp. 276-285.

7. Warren, G.E., Malvar, L.J., Inaba, C., Hoy, D., "Rehabilitating the Navy's Waterfront Infrastructure," Ports 95, 7th Conference on Port Engineering and Development for the 21st Century, Tampa, FL, Vol. 2, pp. 1158-1169, March 1995.

8. Inaba, C., Warren, G.E., Malvar, L.J., "Reinforced Concrete Beams Strengthened with CFRP Sheets," Technical Memorandum TM-2110-SHR, Naval Facilities Engineering Service Center, Port Hueneme, CA, January 1995.

9. Warren, G.E., Malvar, L.J., Inaba, C., Hoy, D., Mack, K., "Navy Advanced Waterfront Technology," International Conference on Corrosion and Corrosion Protection of Steel in Concrete, University of Sheffield, U.K., July 1994, pp. 1310-1319.

10. Malvar, L.J., "Bond Stress-Slip Characteristics of FRP Rebars," Technical Report R-2013-SHR, Naval Facilities Engineering Service Center, Port Hueneme, February 1994.

11. Malvar, L.J., "Unidirectional Core-Shell Hybrids for Concrete Reinforcement," Technical Report R-2011-SHR, Naval Facilities Engineering Service Center, Port Hueneme, Feb 1994.

12. Malvar, L.J., "Bond Stress-Slip Characteristics of FRP Rebars," Proceedings, Session on Bond of FRP Rebars, ACI Convention, San Francisco, CA, March 1994.

13. Malvar, L.J., Warren, G.E., Inaba, C.M., "Composite Applications in the Navy Waterfront Infrastructure," Materials for the New Millenium, 4th ASCE Materials Conference, Washington, D.C., November 1996.

14. Malvar, L.J., "Literature Review of Durability of Composites in Reinforced Concrete," Special Publication SP-2008-SHR, Naval Facilities Engineering Service Center, Port Hueneme, CA, August 1996.

15. Malvar, L.J., Warren, G.E., Inaba, C.M., "Large Scale Tests on Navy Reinforced Concrete Pier Decks Strengthened with CFRP Sheets," Second International Conference on Advanced Composite Materials for Bridges and Structures, ACMBS-2, Montreal, Quebec, Canada, August 1996.

16. Inaba, C.M., Warren, G.E., Malvar, L.J., "Upgrade of Navy Piers with Composites," 41st International SAMPE Symposium and Exhibition, Society for the Advancement of Material and Process Engineering, March 1996, Anaheim, CA.

17. Inaba, C.M., Warren, G.E., Malvar, L.J., "Strengthening Navy Piers with Composites," Fourth Annual Wilson Forum on Existing and Potential Applications of Composite Materials in the Infrastructure, San Francisco, CA, March 11-12, 1996.

18. Novinson, T., “Polymer Composite Utility Pipe Hangers,” Technical Data Sheet, TDS-2025-SHR, Naval Facilities Engineering Service Center, March 1996.

19. Hoy, D., “Plastics for Piles,” The Military Engineer, Vol. 88, No. 576, February-March 1996.

20. Davis, D., Hoy, D., “Fender Piling,” The Military Engineer, Vol. 88, No. 579, August-September 1996.

21. Hoy, D., Warren, G.E., Davis, D., “Environmentally Acceptable Piling for Use in Navy Pier Fender Systems,” Materials for the New Millenium, 4th ASCE Materials Conference, Washington, D.C., November 1996.

22. Burke, D., “Prefabricated Epoxy-Coated Rebar for the U.S. Navy,” Materials for the New Millenium, 4th ASCE Materials Conference, Washington, D.C., November 1996.

23. Warren, G.E., “Demonstration Program for Waterfront Structures Repair and Upgrade: Site No 1: Pier 11 NAVSTA Norfolk,” Site Specific Report SSR-2295-SHR, Naval Facilities Engineering Service Center, January 1997.

24. Warren, G.E., “Waterfront Repair and Upgrade, Advanced Technology Demonstration Site No. 2: Pier 12, NAVSTA San Diego,” Site Specific Report SSR-2419-SHR, Naval Facilities Engineering Service Center, November 1998.

25. Malvar, L.J., “Durability of Composites in Concrete,” First International Conference on Durability of Composites for Construction, CDCC’98, Sherbrooke, Quebec, Canada, August 1998, pp. 361-372.

26. Joshi, N.R., “Effect of Moisture and Temperature of Cement Mortar Surfaces on Quality of Adhesive Bond,” Contract Report CR-98.18-SHR, Naval Facilities Engineering Service Center, September 1998.

27. Beran, J.A., “Correlation of Surface Chloride Concentration of a Pile Exposed To The Marine Environment To The Adhesiveness of a Commercially Available Epoxy,” Contract Report CR-98.19-SHR, Naval Facilities Engineering Service Center, September 1998.

28. Warren, G., Burke, D., Harwell, S., Inaba, C., Hoy, D., "A Limited Marine Durability Analysis of CFRP Adhered to Concrete," Second International Conference on Concrete under Severe Conditions, Environment and Loading, CONSEC '98, Tromsø, Norway, June 1998, pp. 1351-1362.

29. Burke, D.F., Tsutahara, M.T., "Use of New Generation Epoxy-Coated Rebar In the Admiral Clarey Bridge", Proceedings, 1998 NACE Western Area SSPC & Joint Military Corrosion Conference, Honolulu, Hawaii, 13-23 October 1998.

30. Warren, G., "Limited Flexural Tests of Plastic Composite Pile Configurations," Special Project SP-2005-SHR, Naval Facilities Engineering Service Center, August 1996.

31. Sultan, M., Hawkins, G., Sheng, L-H. (1995), "CALTRANS Program for the Evaluation of Fiber Reinforced Plastics for Seismic Retrofit and Rehabilitation of Structures," Proceedings, FHWA National Seismic Conference, San Diego, CA.

32. Crawford, J.E., Malvar, L.J., Wesevich. J.W., Valancius, J., Reynolds, A.D., " Retrofit of Reinforced Concrete Structures to Resist Blast Effects," ACI Structural Journal, vol. 94, no. 4, July-August 1997, pp. 371-377.

33. Meier, U., Kaiser, H., "Strengthening of Structures with CFRP Laminates," Advanced Composite Materials in Civil Engineering Structures, ASCE, Las Vegas, NV, January 1991, pp. 224-232.

34. Warren, G.E., "Laterally Loaded Partially Prestressed Concrete Piles," Technical Report R-927, Naval Civil Engineering Laboratory, Port Hueneme, CA, September 1989.

Figure 1. Retrofitted piles, NAVSTA San Diego.

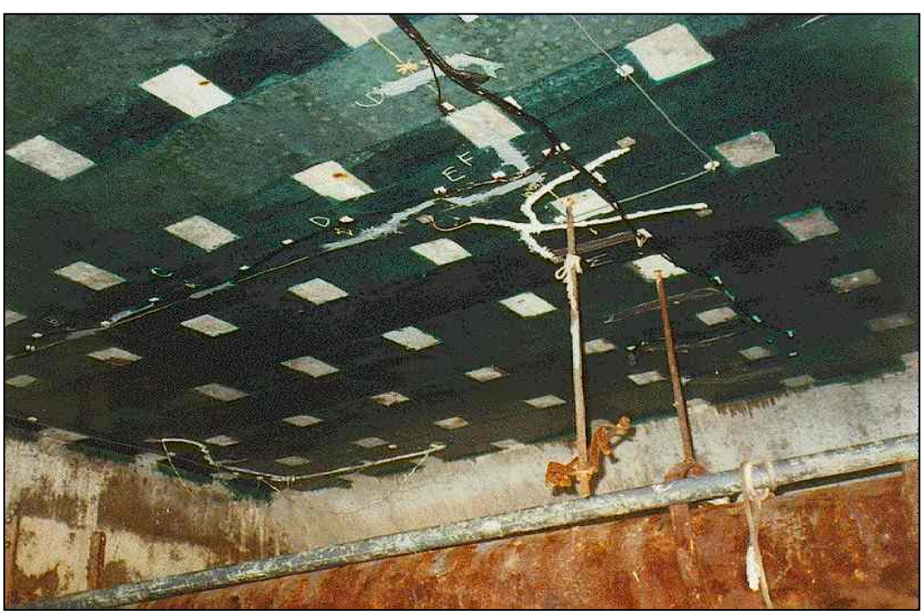

Figure 2. CFRP punching shear retrofit, NAVSTA Norfolk.

Figure 3. Full scale testing of CFRP upgraded section NAVSTA San Diego.

Figure 4. Fender pile testing.