WORLDWIDE OVERVIEW OF COMPOSITE APPLICATIONS FOR WATERWAY INFRASTRUCTURE

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ABSTRACT

Navigational structures using fiber reinforced polymer (FRP) composites have recently been designed, manufactured and installed in the United States of America, the Netherlands, Spain, China, and several other countries. This paper is aimed at summarizing the state of the art of FRP composites for hydraulic structures including design, construction, evaluation and repair. Emphasis is placed on successful applications of composites in waterfront, marine, navigational structures including lock doors, gates, and flood protection systems. Design of FRP hydraulic structures is specifically illustrated herein with FRP slide doors that serve as barriers to protect the area from the North Sea flooding in Netherlands. Use of composites, in general, not only enhances service life of navigational structures, but also lowers the embodied energy and even initial cost in some cases; thus partially fulfilling carbon footprint reduction goals of the Paris agreement.

1. INTRODUCTION

Fiber reinforced polymer (FRP) composites are made of at least two different constituents (for example, resin and glass or carbon fibers) differing in properties. In most cases, the thermo-mechanical properties of FRP composites are better than constituent material properties. The reasons for increased use of composites are attributed to their high corrosion resistance, magnetic transparency, excellent strength to weight ratio and ease of formability and maintenance. FRP composites can be designed for varying strengths and stiffness; thus offering advantages under highly stiff or overly flexible conditions.

Civil Works engineers however, have been hesitant to take advantage of these properties, partially because of absence of well documented success stories, accepted design, construction and inspection specifications. Admittedly, composites have limitations and can be difficult to design due to their complex behavior, higher initial costs per pound, product unfamiliarity and others.

For any successful and sustainable use of new materials, guidance must be provided in terms of: 1) properties of constituent materials, 2) mass-manufacturing, design, fabrication and field implementation, 3) standardized test methodologies to establish chemo-thermo-mechanical properties to predict service life of a structure, 4) nondestructive evaluation for reliable inspection, 5) long term maintenance, and 6) ease of field repair and rehabilitation techniques.

The present paper highlights several representative applications of FRP composites for structural systems in the field of navigation. This overview is part of a broader initiative being carried out by PIANC WG 191 that is aimed at providing general guidelines for production, design, and evaluation of composite hydraulic structures, in addition to recommendations for future guidance [1].

The main objective of the Working Group 191 is to identify "Best Practices" where composites provide a benefit over conventional materials for hydraulic structures and to gather any applicable guidance documents. The resulting report is expected to help designers and promoters of new and/or existing navigational structures throughout the world and provide guidance to develop and operate safe, economical and durable waterways systems.

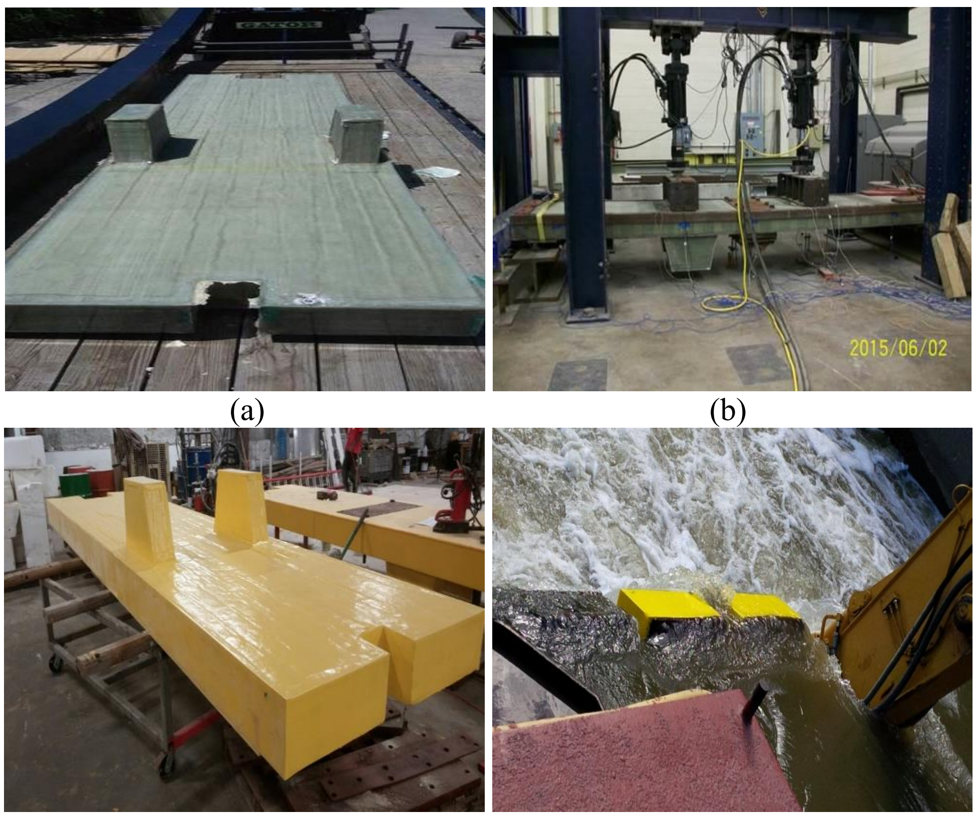
2. DEMONSTRATION PROJECTS IN THE UNITED STATES

The U.S. Army Corps of Engineers (USACE) maintains aging infrastructure along their navigable waterways and flood control facilities. For example, Tygart Dam near Grafton, WV was built in 1934 as the first of 16 flood control projects in the Pittsburgh District (Figure 1). Tygart Dam was constructed with maximum volume of concrete in any dam east of the Mississippi River with a staggering amount of 324,000 cubic yards. This concrete gravity dam has an uncontrolled spillway and measures 1,921 feet long and 209 feet thick at the base. As per U.S. Army Corps of Engineers, Tygart Dam protects areas from West Virginia to Pittsburgh, Pennsylvania and has prevented billions of dollars in flood damages to date. Also shown in Figure 1 is Lock and Dam #52 with its wooden wicket gates in up position, located on the Ohio River near Brookport, Illinois. The wooden wicket dam, controlling water flow, was completed in 1928 and the locking system consists of a main lock of 1200 ft by 110 ft and auxiliary lock of 600 ft by 110 ft.

Figure 1. Aging U.S. waterways. Left: Tygart Lake Dam, Grafton, WV; Right: Wicket Gates at Lock and Dam #52, Ohio River (courtesy of Richard Lampo).

However, corrosion, materials degradation, and damage during operations are taking toll on these aging facilities. In addition, the high costs associated with repair and replacement of critical components present many challenges in keeping these waterways open that are vital to the nation's economy and security. With recent material and processing advances, FRP composites offer the potential for repair, rehabilitation, and replacement of these critical structural components at a reduced cost [2], in addition to greater durability.

USACE team in cooperation with the researchers at WVU-CFC has been demonstrating the use of corrosion-resistant FRP composites for the repair and replacement of their hydraulic structures. More specifically, FRP composites were used to repair and replace select lock and dam components at Lake Washington Canal, Washington; Willow Island Lock and Dam, near Newport, Ohio; Heflin Dam near Gainesville, Alabama; Chickamauga Lock and Dam, near Chattanooga, TN; Lock and Dam #52 on the Ohio River, near Brookport, Illinois; and East Lynn Bridge, near Huntington, WV. These components consist of miter-blocks, tainter-gates, recess filler panels, discharge ports, wicket gates, and corroded steel H-piles [3,4,5].



(a) (b) (c) (d)

Figure 2. Composite wicket gate after demolding (a), Prototype gate under bending test (b), Finished wicket gate ready to be installed (c) and composite wicket gates in-service (d).

Current wicket gates are used at locks and dams by USACE to control water flow either by being raised or lowered depending on summer/rainy seasons. These wicket gates are fabricated from white oak and steel elements, and are degrading rapidly in-service. FRP composite material as an alternative to wood was used to manufacture composite wicket gates as direct replacement of wooden wicket gates. FRP wicket gates can be built to last with longer service life (50 years or more) at lower initial costs with no corrosion or gouging effects. Figure 2 shows composite wicket gate testing and installation at various stages. Three glass FRP (GFRP) wicket gates were installed at Peoria Lock and Dam in summer 2015, and they have been functioning extremely well as of April 2019.

However, selection and design guidelines of FRP composite constituents and components have to be developed and approved by USACE as well as other specification bodies.

Similarly, the U.S. Coast Guard is looking into composite applications for Aids to Navigation (ATON) structures [6]. ATON structures are traditionally made of metal, concrete and timber which corrodes or deteriorates with time. FRP has a superior ability to withstand the harsh marine environments when compared against conventional materials. It is highly resilient to traditional modes of degradation such as biodeterioration (fungal decay, marine borers, microbiologically induced corrosion), freeze/thaw, and corrosion. The use of FRP for ATON provides large amounts of energy absorption if a FRP structure gets hit by a vessel, reducing the probability of a structural failure.

The U.S. Coast Guard Civil Engineering Unit (CEU) in Miami, Florida has implemented an initiative to use FRP in ATON to not only lower lifecycle costs but to increase safety for boaters navigating within the channel (Figure 3). FRP ATON is a much safer alternative to more rigid aids due to its ability to absorb high impact loads without permanent deformation or failure. Currently, there are approximately 25 FRP ATONs that have been installed since 2014 and only one reported knockdown within the last year. These aids are purposely installed in high knockdown areas where the survivability rate of the FRP over timber has been significantly higher. Continued use of FRP will result in lower annual maintenance costs and place less wear and tear on an aging Coast Guard construction fleet. CEU Miami has written a performance based specification for Defense Logistics Agency to assist in procuring the best and cost efficient FRP pile to be used for ATONs [6].

Figure 3. USCG Aids to Navigation (ATON) built using FRP piles [6].

It is safe to conclude based on US experience that FRP composites are cost-effective for hydraulic structures. All in-service composite structures are performing well and technically successful. Ryan's [4] presentation further concludes the in-service durability of FRPs for inland navigational infrastructure.

3. NETHERLANDS EXPERIENCE WITH FRP LOCK DOORS

Netherlands, under the leadership of FiberCore Europe, has taken a major lead in constructing many GFRP lock doors as well as bridges for both road and pedestrian usage [7]. Some of the lock doors were built in years 1999 and 2002 with each of the two doors having dimensions of about 10' in width and 20' in height. The installed GFRP gates can be seen in Figure 4, and are functioning well with no corrosion related degradation [7]. These doors were manufactured using vacuum assisted resin transfer molding (VARTM) process with low void content. More specifically, the lock doors in Werkendam were made by Polymarin while the doors in the Ter Apel kanaal were designed/manufactured by FiberCore Europe, with technology provided by InfraCore.

Figure 4. Werkendam FRP lock doors (left) and Erica Ter Apel lock doors (right) [7].

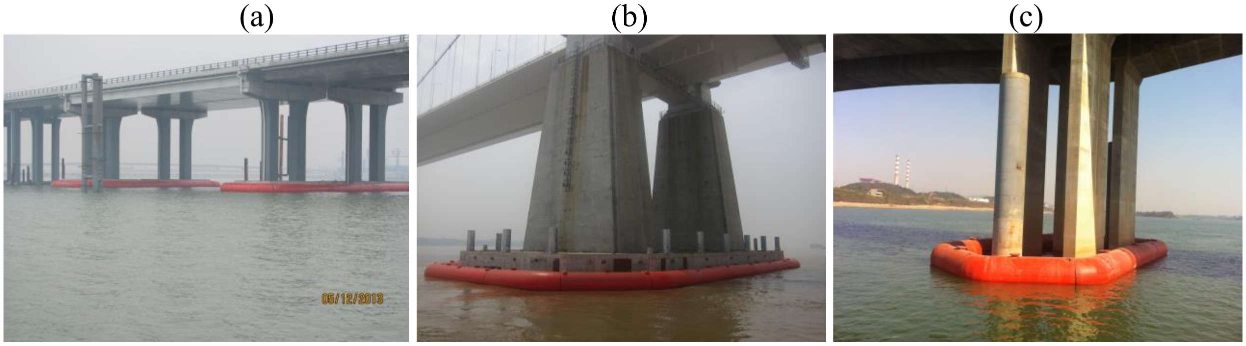
Figure 5. 2014 built world's largest FRP lock doors in the Wilhelminakanaal (courtesy of Wouter Claassen)

FiberCore Europe extended their polymer composites expertise by building the largest FRP lock doors in the Wilhelminakanaal in Tilburg in 2014 as shown in Figure 5, thanks to Rijkswaterstaat management team for their support, approval and acceptance that made it possible for these gates to be built in FRP. The size of the world's largest FRP doors is approximately 17.5' in width and 43' in height. These FRP structures have been in service since 1999 and performing well with excellent durability and low maintenance. The initial cost of these GFRP structures is mostly lower than those made of conventional construction materials because the high strength closed cell foam core has relatively low initial cost. Also, durability of properly designed GFRP hydraulic structures is superior to those from steel, concrete or timber. In addition, GFRP can be used to rehabilitate conventional structures at low costs.

4. CHINESE FRP BUMPER SYSTEM FOR BRIDGE PIER PROTECTION

An innovative Large-scale Composite Bumper System (LCBS) for bridge piers against ship collision was developed by researchers at Nanjing Tech University of China. The modular segment of the LCBS is made of GFRP skins, GFRP lattice webs, Polyurethane (PU) foam cores and ceramic particles thru Vacuum Assisted Resin Infusion Process (VARIP). This novel bumper system offers several remarkable advantages, such as self-buoyancy in water, modular fabrication of segments, efficiency for on-site installation, excellent corrosion resistance, as well as ease in repair or replacing damaged segments [8]. In 2012, LCBS was field installed to protect piers of RunYang Yangtze River Bridge. Since 2010, there are more than 60 bridge protection projects using LCBS in China.

(a) (b) (c)



(d) (e) (f)

Figure 6. Some applications of LCBS on bridge protection projects in China.

The typical projects include Huanggang railway Yangtze River Bridge with 3.5m-diameter LCBS against 5000 DWT (Deadweight Tonnage) ship (Figure 6a), Langqi Min River Bridge with 4.0m-diameter LCBS against 10,000 DWT ship (Figure 6b), Chongqi Yangtze River Bridge with 3.5m-diameter LCBS against 3000 DWT ship (Figure 6c), Guangshen Highway Bridge with 2.0m-diameter LCBS against 1000 DWT ship (Figure 6d), Maanshan Yangtze River Bridge with 4.0m-diameter LCBS against 10,000 DWT ship (Figure 6e), Xiangtan Xiang River Bridge with 2.5 m-diameter LCBS combined with independent steel post column against 2000 DWT ship (Figure 6f).

Composite bumper systems have evolved with time in enhanced design, manufacturing efficiency and performance. They have demonstrated certain advantages over conventional materials which are: design flexibility, ease of installation, high impact energy absorption, low maintenance, and durability under harsh environments.

5. SPAIN EXPERIENCE

ACCIONA Construction of Spain has developed several leading applications with FRP composites under seawater environmental conditions. One of these applications was to develop composite caissons (dolphins) at Rosario port, Fuerteventura in Spain [9]. Fuerteventura is an island which receives about 2 million tourists a year. The port authority decided to expand the docking capacity in order to receive large cruise ships. The work involved the construction of two caissons that would serve as new mooring points. Glass fiber reinforced epoxy resin composites were considered as the material of choice because of their excellent corrosion resistance and environment-friendliness. As shown in Figure 7, the dolphin solution was based on the assembly of modular prefabricated composite panels to make two caissons of 12m in diameter and 13.5m in height, each consisting of 12 modular panels, along with FRP composite foot bridges to extend 86m long docking capability, resulting in a total length of 390m dolphin line. It was reported that these composites would reduce carbon dioxide emissions in comparison to steel construction by 75% and minimize the need to carry out extensive maintenance work.

Figure 7. Caissons made of composites in Puerto Del Rosario, Fuerteventura

Another innovative application is a composite lighthouse in the Spanish city of Valencia, built by ACCIONA which received the “Innovation in Infrastructures” award in the JEC World 2016 for being the first lighthouse in the world built from composite materials [10]. This 32m tall, five-story structure (Figure 8) weighs 19 tons and was formed by eight carbon FRP tubular columns made by pultrusion along with GFRP and polyurethane octagonal sandwich panels made by resin infusion. An FRP spiral staircase is placed in the center of the structure, going from its base to its top. To increase the lateral stiffness of the structure, carbon FRP columns are connected along the perimeter of the lighthouse using horizontal glass FRP pipes forming four octagonal rings. Again this application highlights advantages of composite materials in innovation, design flexibility, durability and better performance.

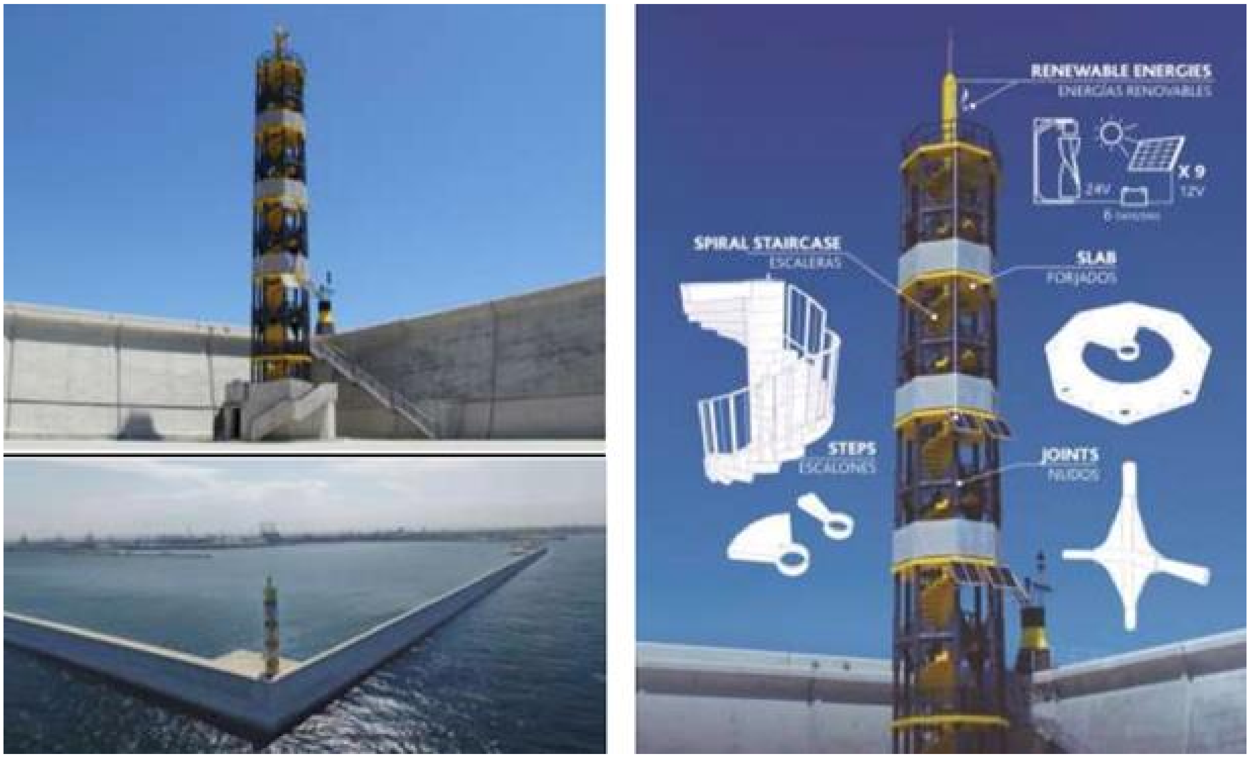


Figure 8. FRP lighthouse in the north extension of Valencia Port [10].

6. UNITED KINGDOM EXPERIENCE

Pont y Ddraig (Bridge of the Dragon) at Foryd Harbour was constructed in 2012-2013 [11]. Both bridge spans on this project were designed and built in FRP with localized CFRP reinforcement on the bridge deck and soffit. This enabled the loads to be directly transferred from the caisson hinges to the central lifting cable (Figure 9). Bridge weight was an important consideration due to the number of superstructural lifts per day to allow waterway traffic to pass into the harbor. Weight reduction was also a key factor in the speed of lift and consumption of energy in the deck lifting operations.

The double bascule lifting design required a slender lightweight structure consisting of two 10 meter wide bridge decks each spanning 36 meters to a central caisson in the middle of the harbor, incorporating the lifting mast for both bridge spans. The main body of the bridge was built using Ampreg Epoxy resin system and layers of multiaxial glass reinforcement with structural Corecell M foam and directionally orientated carbon fiber reinforcement. This was supplied by Gurit UK. This bridge was designed to serve for 100 years with minimum maintenance.

Figure 9. Cycle/footbridge across the River Clwyd at Rhyl Harbour, North Wales

Figure 10. Composite subsea Cocoons for wellhead.

Another great application demonstrating lightweight, excellent corrosion resistance and durability of composites is Subsea Cocoon and Shroud developed by Pipex Protection Systems (Figure 10). 36 Cocoons in 5.5m high x 6.2m wide have been installed over 10 years in North Sea. The design of these Cocoons allows full access for wellhead maintenance. A durability study of this Subsea structure after 7 years of submergence revealed that the material has retained excellent mechanical properties under high hydraulic pressures [12].

7. DESIGN STEPS OF A FRP COMPOSITE SLIDE DOOR

The Eastern Scheldt storm surge barrier is a closeable barrier in Southwest Netherlands, which protects the Southwestern Delta from North Sea flooding. The barrier is constructed with lifting steel slides, which corrode rapidly in the salty environment (shown in Figure 11). The service life of the coating is too short to maintain all the slides before calling for serious maintenance. More specifically the current closable storm surge barrier consists of 65 concrete piers and 62 steel slides and was built in 1985. Therefore, the slides deteriorate rapidly and the maintenance costs could exceed the costs of replacement of the slides, calling for an engineering solution [13].

FRP composites could be used in the replacement of the existing slides due to their high strength properties, low self-weight and low maintenance. A conceptual design using FRP was conducted by Roeland van Straten in 2013 and is extracted hereafter to illustrate the five essential design steps and general considerations for a FRP composite hydraulic structure. Additional details can be found in [13].

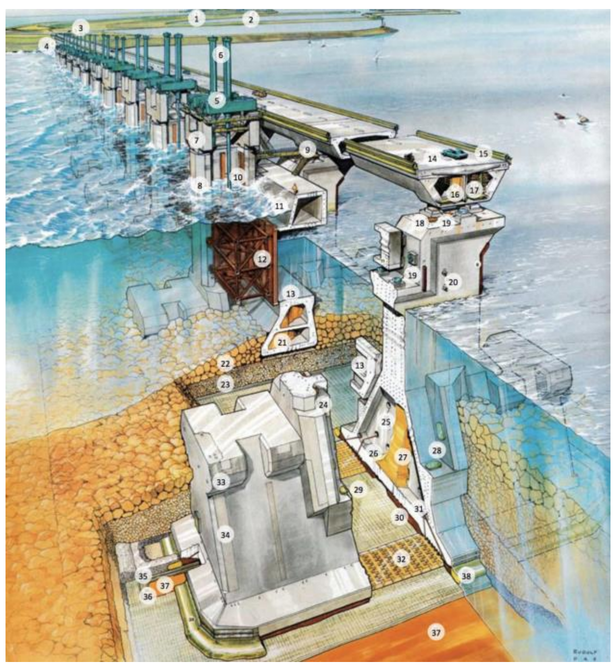


Figure 11.Overview of the storm surge barrier with slide doors [13].

1) Design Requirements and Assumptions

The requirements of new FRP slides are based on the requirements of the current slides, including the geometric boundary conditions and loads on the slides. The geometric boundary conditions focus on the dimension of the slides, fatigue cycles and the range of temperature that the slides can be movable. The loads discussed for the FRP slides are vertical wave loads, dead load, torsion, longitudinal loads, ice loads, wind loads, water flows, collision and terrorist attack condition. Based on the situation of the current slide and surrounding environments, several assumptions are made for the FRP slides design.

2) Material Selection

The properties of FRP and its manufacturing process have driven the selection of constituents of polymer composites. The lamina properties of FRPs are calculated and the material safety factors and design values are determined. The manufacturing methods which are suitable for composite slides in the Eastern Scheldt barrier should have been designed to achieve high fiber contents, to improve the strength and stiffness of the material. In the material safety factor, the uncertainties due to the combination effects corresponding to various knock-downs (under temperature, moisture, sustained stress/creep, and fatigue) should be taken into account. Also the uncertainties regarding targeted material design properties are taken into account.

3) Structural Concepts

The structural concepts of the proposed FRP slides can be defined by the following three important aspects: i) Use of limited number of connections, ii) Optimal design under wave impacts loads and leakage flows, iii) Uniform load transfer over the entire height of the slide bearings.

The design includes guiding principles for the structural concepts, description and calculation of different variants. Then the most suitable variant is selected. Structures of sandwich, horizontally curved shell and the box girder are compared. The comparison concluded that the box-girder with varying thickness offers close to optimal design and can fulfill the strength and deflection requirements. The deflection is so big that the slide could hit the upper beam of the barrier if the thickness of the slide were not reduced, which brings to the next step [13].

4) Deflection requirements

The maximum deflection requirement influences the design of a composite slide since the stiffness of the composite is low for GFRP. Also, the slide should be adjusted to an oblique bottom to prevent vibrations by flow [13]. Hence, an option called rigorous solution requiring extra adjustments on the current barrier to vanish the deflection requirement was attempted, where the upper beam should be removed, the sill beam should be replaced and the rabbets should be increased. Second option required the increase of leakage gap or application of a camber to meet the stiffness requirement of FRP slide by using carbon fibers at a different cost scenario.

5) Cost comparison

The cost comparison is made among different variants which can withstand sea level rise to arrive a feasible solution. Also a life cycle analysis should be carried out to compare the investment costs of an FRP slide with the maintenance costs of the current barrier. The life cycle costs of an FRP slide are much lower over 100 years, the payback time of the FRP slides is between 40 and 50 years. The research concluded that it's technically feasible and financially attractive to replace the current steel slides with larger FRP slides.

8. SUMMARY

Composites have been evolving over the years and are making major in-roads into the marine, aviation and other industries where corrosions and self-weight are the major impediments to advancing the state-of-the-art. This paper deals with composites for hydraulic structures. Focus is placed on applications of composites in waterfront, marine, navigational structures. Several applications on navigational structures are highlighted. All those applications have demonstrated the advantages of composites over conventional materials under harsh environments, including design flexibility, non-corrosion, high performance per unit weight and durability etc. Design considerations consisting of 5 design steps for a composite hydraulic structure are illustrated. The main focus herein is to summarize information on composites and design methodologies that are applicable to waterway structures and to promote composite applications for hydraulic structures.

The hydraulic structural applications cover the construction and rehabilitation of facilities such as locks, dams, levees and pump stations. These systems are comprised of various elements such as valves, gates, walls, piling, mooring facilities, etc. Even based on limited in-service data, it is safe to conclude that in-service GFRP composite systems for hydraulic structures are leading to longer service life, lower initial costs and reduced life-cycle costs with enhanced structural performance. It is extremely important to note that proper selection of the manufacturing process as well as the constituent materials (resins, fibers, additives) for a tailor-made composite structure is essential to meet minimum design and performance requirements.

9. ACKNOWLEDGEMENTS

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