FIBER REINFORCED POLYMER COMPOSITE IMPLEMENTATION IN NAVIGATION STRUCTURES

by

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ABSTRACT

This paper describes a process for the implementation of fiber reinforced polymer (FRP) composites in U.S. Army Corps of Engineers (USACE) navigation structures. The main driver for this work is to reduce fabrication and long term maintenance costs. Successful demonstration projects including FRP composite miter gate contact blocks and wicket gates are presented. Participation in international collaborative efforts for technology exchange is described. A path forward for implementation in increasingly larger gate structures is given which includes identifying specific locations, design considerations, knowledge gaps, and guidance development.

1. INTRODUCTION

The U.S. Army Corps of Engineers (USACE) maintains 12,000 miles of inland waterways in the United States which contain 200+ inland navigation structures such as locks and dams. Approximately 600 million tons of cargo is moved along these waterways and through these structures annually. The majority of these structures were constructed in the 1930-1950 time period with a 50 year design life. Due to national budgetary constraints, these aging structures are not being replaced, but simply maintained. However, the rate of degradation due to corrosion and wear is exceeding the rate at which they can be maintained. The risk of a prolonged failure of components to these structures, which could have a devastating effect to commerce, is becoming more likely every year. For this reason, USACE has placed a high priority on developing novel materials to repair or replace aging infrastructure in order to extend the structures working lifetime. Emphasis has been placed on cost reductions for both first costs and long term maintenance costs, reductions in labor to implement and maintain, as well as longer durability.

2. SUCCESSFUL DEMONSTRATION PROJECTS

2.1 General

In 2014, USACE researchers began collaborating with West Virginia University (WVU) to develop and deploy fiber reinforced polymer (FRP) composite components and structures to repair or replace deteriorating components in locks and dams. These demonstrations showed that significant cost savings in manufacturing and maintenance could be realized while extending the service life of the structures.

Additionally, these projects allowed USACE researchers to develop and demonstrate design and manufacturing techniques that will be appropriate for future implementation and design of FRP composite navigation structures. Two of the most successful of these demonstrations were the development of FRP composite miter blocks and FRP composite wicket gates.

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2.2 Miter Gate Contact Blocks

USACE and WVU developed an FRP composite contact block to replace carbon steel contact blocks on miter gates at the Auxiliary Lock of the Hiram Chittenden Locks in Seattle, WA. This lock has the highest amount of lockages per year than any other lock in the USACE inventory. According to the USACE Lock Performance Monitoring System (LPMS), the lock performed 52,500+ lockages between March 2013 and March 2018. The purpose of the miter blocks is to transfer the hydraulic load placed on the miter gates to the lock wall as well as provide a water tight seal. These blocks experience an abrasive force upon opening and closing that most coatings cannot withstand. Therefore, a microscopic layer of corrosion forms just at the surface of the miter block and is abraded away during operation; as shown in Figure 1. This section loss over time causes a loss in hydraulic seal resulting in a redistribution of loads and stresses in the gates. The material section loss due to abrasion at the Hiram Chittenden Auxiliary Lock was very pronounced on the miter blocks due the unusually high lockages experienced by the gate as well as the brackish water immersion conditions.

Figure 1: Corroded and Abraded Carbon Steel Miter Blocks

Because FRP composite materials are free of corrosion and have good abrasion resistance, a prototype FRP composite miter block was developed to provide a durable alternative to the corrosion prone steel blocks. As no commercial designs of FRP composite miter blocks were available, the prototype was developed through an iterative design process. The initial design requirements for the FRP blocks were to achieve a Factor of Safety of 3 for a 1400 psi working stress. Through several iterations, it was found that a monolithic block of FRP composite material was optimal. The blocks were fabricated using a thermal press technique. To create the blocks, a large panel was manufactured with a 10 mil surface veil and 96 layers of 24 oz. woven glass rovings of PPG Boron. The panel assembly was then vacuum sealed and cured at 120˚ F for 120 minutes. Once cured, the panel was cut into the desired block sizes which were then feathered and sealed using two coats of FR992 resin and wax additive. For a cross section of the blocks, see Figure 2. Laboratory evaluations of the blocks resulted in a maximum compressive strength of 51 ksi along the mitering surface which was significantly higher than that required.

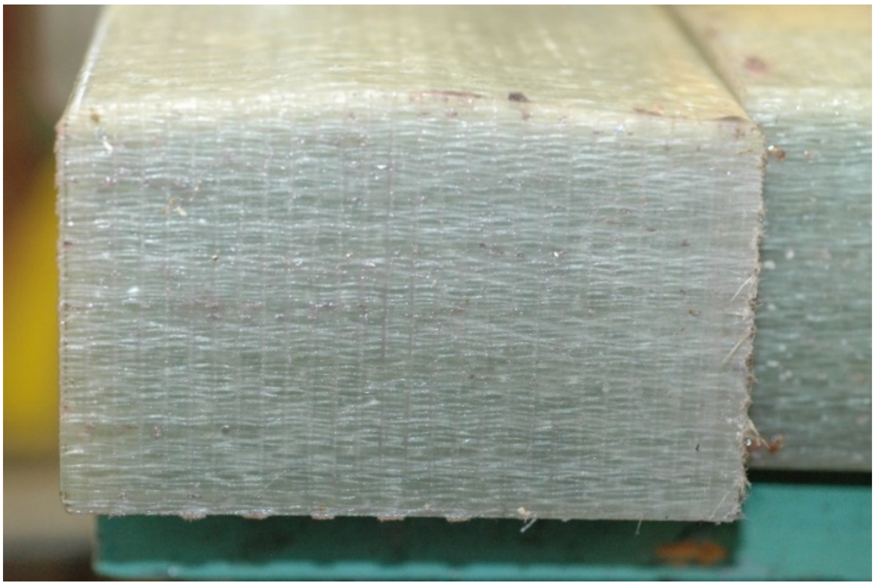

Figure 2: Cross section of FRP Composite Miter Block Prototype

After the compressive strength of the blocks was determined, the FRP miter blocks were installed in the auxiliary lock chamber's upstream gates. During installation, an additional advantage to the durability and corrosion resistance of the composite blocks was their light weight. Field personal were able to handle the miter blocks by hand for rapid installation and improved safety while steel blocks were heavier and required greater lifting capacity; as shown in Figure 3. The blocks were successfully installed in March 2015 and their performance is being monitored annually. The installation and development of these blocks was significant as it demonstrated that steel components on a larger structure could successfully be replaced with light weight, corrosion resistant composite materials with equivalent or greater mechanical properties.

Figure 3: Field Personnel Handling FRP Miter Blocks

2.3 Wicket Gates

Wicket dams were once prevalent throughout the USACE inventory. Now there are only a few wicket dams left. Two of these are on the Illinois River at the Peoria Lock and Dam and at the LaGrange Lock and Dam. In these dams, wicket gates are used to create an adjustable dam, depending on river conditions. During low water, the wicket gates are raised upright to maintain pool levels for navigation. During high water, the gates are lowered to the bottom, creating a navigable pass which allows river traffic to flow without locking through the lock chamber. Wicket gates are traditionally timber structures. The timber wicket gates located at Peoria Lock and Dam measure 4 feet x 16 feet 5 inch x 12 inch. They are manufactured in-house out of White Oak timber. The timber wicket gates are expensive to manufacture due to the fact that four 12 inch x 12 inch x 20 feet boards are needed for each gate. These timber wicket gates are prone to rot (see Figure 4) with a service life of only 10-20 years in the river environment. Replacing the deteriorated gates is a costly and dangerous process due to the high water flow surrounding the gates. Due to these factors, a FRP composite gate with lower fabrication and maintenance costs and an extended life span was highly desirable.

Figure 4: Deteriorated Timber Wicket Gate

To develop the FRP composite wicket gate, USACE and WVU collaborated with a private industry polymer composite manufacturer, Composite Advantage of Dayton Ohio. There was no engineering design for the current timber wicket gates or design guidance on the expected service loads. The first step was to obtain an example timber wicket gate and reverse engineer it. Calculations were made to determine the capacities of a timber gate and to predict the service loads for various load cases. Since it was critical to maintain the same structural and operational performance, the new composite gates were required to have the same overall dimensions, weight, buoyancy, and center of gravity as the original timber gates. Once these values had been established, an FRP gate was engineered to provide an equivalent performance. Relevant mechanical properties are given in Table 1. In addition, it was decided that the FRP composite gate could be made to be 9 inches thick as opposed to 12 inches for the timber gates. The design bending stiffness of the composite gate was lower than that of the timber gates due to its reduced 9 inch thickness. Had the composite gate been designed with the same 12 inch thickness as the timber gates, its bending stiffness would have been nearly identical to that of the timber gates. It was determined that the lower bending stiffness did not affect operation under service loads.

Mechanical Property	Timber	FRP	FPR/Timber
Allowable Moment (kip-ft)	120	169	1.4
Allowable Shear (kip)	75	137	1.8
Bending Stiffness, EI (lbf-in^2)	6.6x10^9	3.1x10^9	.5

Table 1: Comparison of Timber and FRP Composite Wicket Gate Mechanical Properties

The composite gate was designed as a monolithic sandwich panel consisting of FRP composite faceskin laminates to provide the moment capacity with a bidirectional fiber wrapped closed cell foam core to provide the shear and punching shear strength along both directions of the gate. Vinyl ester resin was selected as the polymer matrix to provide optimum environmental resistance and long term durability in the immersion environment. The glass fiber used to manufacture the laminates and webs of the gate was E-glass. The type of closed cell foam blocks used in the core was polyisocyanurate foam. The foam, used to fill void space and shape the gate, was nonstructural with the entirety of the shear reinforcement being provided by the FRP webs.

The composite wicket gates were manufactured with a vacuum assisted resin transfer molding (VARTM) process, where multiple layers of fabric sequenced to produce the proper fiber architecture for the faceskins were laid into a form. The foam core wrapped with fiber reinforcement members were then placed on top of the faceskin fabric as shown in Figure 5. Once the top faceskin fabric layers were placed to encapsulate the fabric wrapped foam core, the gate was sealed with a vacuum bag and infused with vinyl ester resin to fully saturate the fibers.

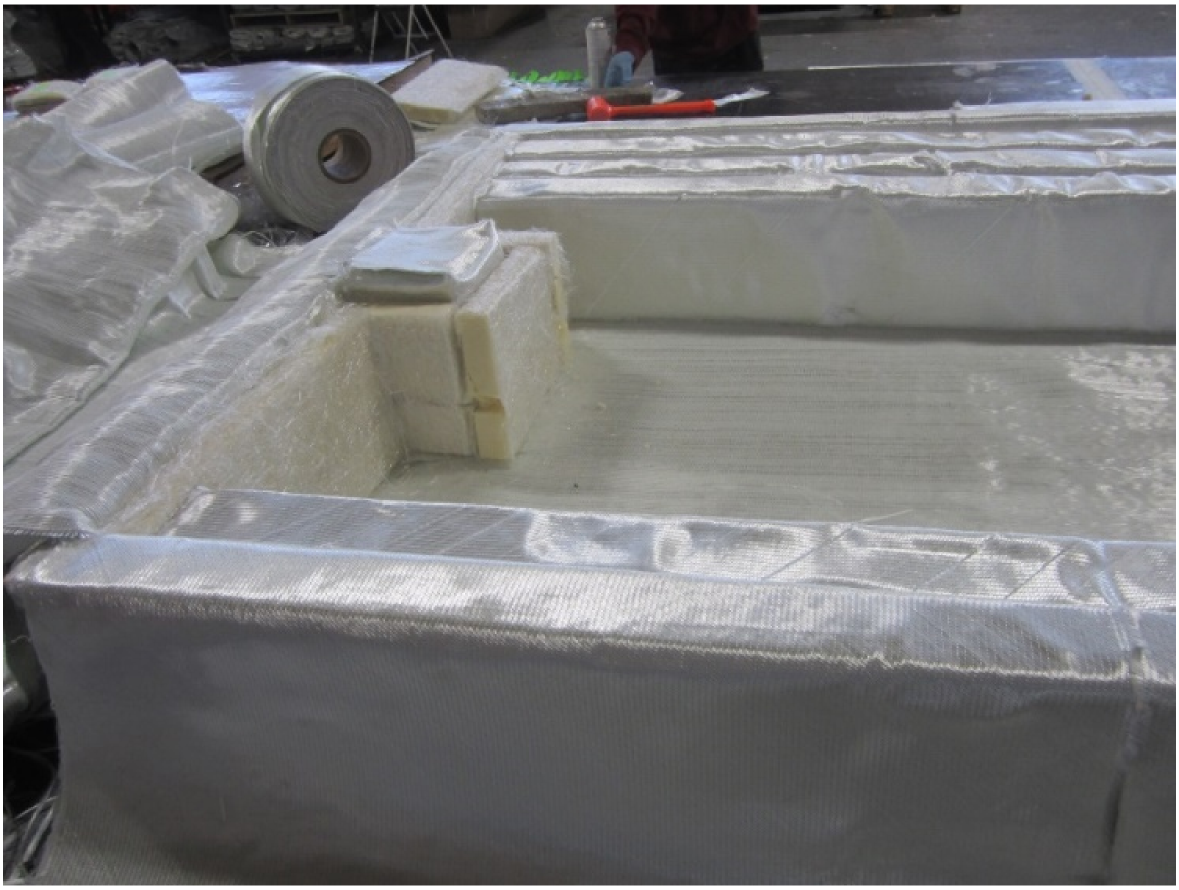

Figure 5: FRP Wicket Gate Fabrication Preparation

Once cured, the gate was removed from the mold and tested in a four point flexure test to validate the gate's flexural capacity; see Figure 5. Though not tested to ultimate failure, the gate was tested to a capacity exceeding the allowable design value and was therefore approved for installation.

Figure 6: Flexure Test of Prototype FRP Wicket Gate

After the proof testing, the team met and discussed changes to improve the design. There were concerns about abrasion resistance on the upstream surface and side walls. To address this, ultra-high molecular weight polyethylene (UHMWPE) was incorporated as a wearing surface on the upstream face and sides of the gate. Another change was to make the entire gate high-visibility yellow. Two additional FRP composite wicket gates were manufactured to incorporate these changes. The first prototype was painted with a yellow coating to match the other gates.

The composite prototypes were manufactured at two thirds the cost of the timber gates with an estimated life of 50 years as opposed to the 10 to 20 years of the timber wicket gates. The gates were placed into service at Peoria Lock and Dam on the Illinois River in August of 2015, as shown in Figure 7, and have shown no signs of damage or deterioration during periodic inspection. The wicket gate marked the first major implementation of FRP composite structures into USACE navigation systems. The demonstration of significant cost savings in production and maintenance using the VARTM process created interest in further developing FRP composite materials for larger gate structures.

Figure 7: Installation of FRP Wicket Gate with UHMWPE

3. INTERNATIONAL COLLABORATION

3.1 PIANC Working Group 191

In 2015, PIANC established a working group, WG 191 – "Composites for Hydraulic Structures". Representatives from both WVU and USACE are members of this working group. This international group is tasked with identifying where composite materials provide a benefit over conventional materials for hydraulic inland navigation structures and to develop a report identifying best practices of how to use composite materials, summarizing case studies with pros and cons, and to compile guidance documents to aid engineers when using composite materials in the demanding environments of hydraulic structures. This working group has allowed researchers to collaborate and exchange information with other agencies.

3.2 USACE – Rijkswaterstaat MOA

A Memorandum of Agreement (MOA) between the Ministry of Transport, Public Works and Water Management of the Netherlands Rijkswaterstaat (RWS), and USACE was established in 2004. The purpose is to promote a long-term relationship between RWS and USACE on collaborative efforts of mutual benefit to the Netherlands and the United States. One of the stated goals of this MOA is to share best practices, lessons learned and expertise. Under this MOA there is a working group on Navigation Infrastructure. This working group meets monthly by phone and twice a year face-to-face. Navigation infrastructure topics include standardization, structural health monitoring, structural life extending practices, innovative materials, life cycle management, and sustainability of hydraulic structures.

3.3 Site Visit

During a meeting of WG191 in June 2017, RWS hosted a site visit to the world's largest FRP composite miter gates at Lock III in Tilburg the Netherlands on the Wihelmina Canal, Figure 8. Designed to resist a hydraulic head of 7.8 meters, each gate leaf on the downstream side is 6.3 x 12.3 x 0.51 meters. The design life for these miter gates is 100 years. The gates were fabricated using a VARTM process as monolithic units. The gates were manufactured similarly to the wicket gates with faceskins connected with shear webs separated by non-structural polyurethane foam. In this case, however, the fiber in the skins and the webs was continuous. The gate was fabricated with E-glass fabric and polyester resin for durability and cost. Design guidance followed for this effort included the Dutch Design Recommendation CUR 96.2003 and revision 2014, VORSTENBOSCH KRABBE, J.P. (2015).

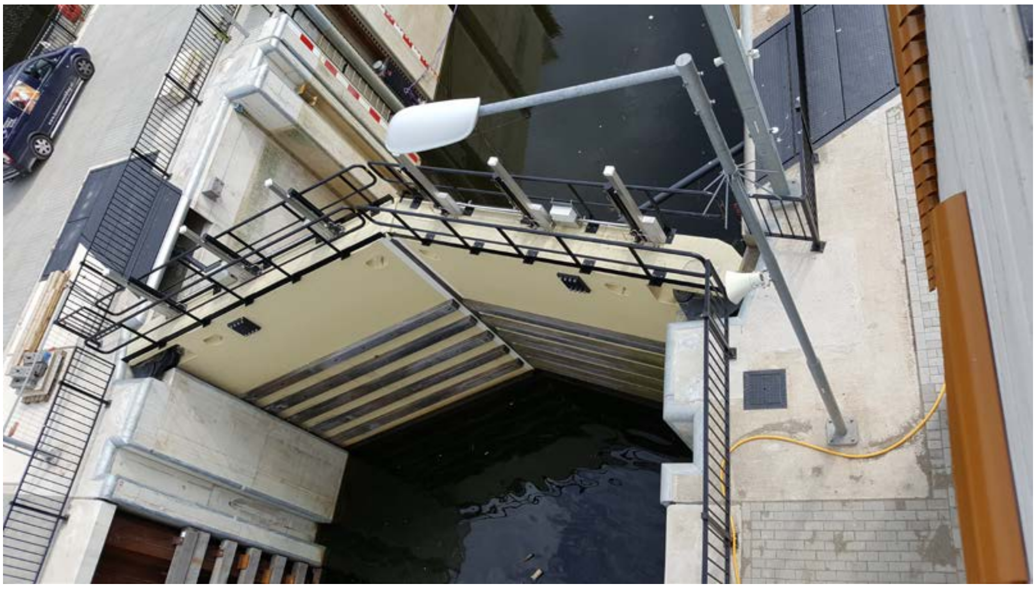

Figure 8: World's Largest FRP Composite Miter Gates at Lock III in Tilburg the Netherlands.

4. NEXT STEPS

Through lessons learned from previous FRP projects and technology exchange meetings, USACE intends to develop and install FRP gates and valves for inland navigation structures. USACE has a sizeable inventory of miter, tainter (radial), and vertical lift. These gates are larger and more complex in design than wicket gates. Each of these gates presents a unique challenge. While composite materials can provide solutions to many of these challenges, further development will require an incremental process to overcome the various challenges present in scaling up the design. Using information gathered from previous collaborations and implementing intermediate water control structures, many of these uncertainties can be addressed.

Discussions are underway with Rock Island District and the Illinois Waterway (IWW) to design, fabricate, and install an FRP composite culvert valve with UHMWPE slides as a follow up to the wicket gate. They have a current effort to redesign the existing steel culvert valves and incorporate UHMWPE slides. The current culvert valves (also known as slide gates) are a common design across multiple locks along the IWW allowing the valves to be used interchangeably. The current steel valves are designed for a maximum hydrostatic head of 39 feet and 12 feet wide by 9 feet tall. To open and close, the gates are operated with a hydraulic actuator attached to a strong back. Steel rollers provide the sliding mechanism. However, due to corrosion, these steel rollers are prone to seizing up. Once seized, the rollers wear against the slots resulting in flat spots on the rollers and damage to the slots. The new steel culvert valves replaced the rollers with UHWMPE slides to eliminate this issue. The plan is to design and fabricate an FRP composite culvert valve with UHMWPE slides for installation along with the new steel valves.

By designing a slightly larger gate than the composite wicket gates, a few challenges will have to be addressed. To meet flexural stiffness requirements, an embedded steel frame may need to be incorporated into the design of the culvert valve requiring an effective design methodology for hybrid steel structures to be established. To connect the actuator to the top of the gate and mechanically fasten the UHMWPE slides to the gate, additional embedded steel components may be needed. Methods for integrating these components into the composite gate while protecting them from corrosion from moisture diffusion will also need to be investigated. To determine the fatigue resistance of the gate, the fatigue resistance of the embedded steel frame, the FRP composite materials, and the bond between them will need to be estimated independently. Once these resistances are more defined, the fatigue resistance of the gate as a unit will be understood.

By following similar design procedures to the Tilburg miter gates and knowledge gained through the culvert valve, USACE researchers will be able to move to even larger gates with more complex designs. Due to their size and intended use, they will be subjected to greater loading conditions and stresses. The large size of these of gates will likely require them to be manufactured in large monolithic pieces using a VARTM process. Research and development will need to be conducted to limit the amount of pieces required to construct an entire FRP composite gate.

5. POTENTIAL RESEARCH TOPICS

5.1 Structural Health Monitoring

Structural health monitoring of inland navigation structures using strain gages and accelerometers has proven to be a valuable Operations and Maintenance (O&M) tool to monitor the functionality and integrity of these large structures. The VARTM manufacturing process allows for a new and innovative way to include sensors within the structure rather than adhered to it. Further research and development will be required in order to select the appropriate type of sensors, optimal sensor placement locations, and data acquisition techniques.

5.2 Inspection Techniques

When FRP composite materials are damaged, it may be difficult if not impossible to visualize the damage from the surface. Forms of damage can range from fiber failure, delamination between lamina layers, and expansion of voids initially caused by poor resin penetration. Non-destructive testing (NDT) techniques such as a digital tap hammer, ultrasonics, thermography, radiography, and shearography need to be explored in an attempt to not only discover possible damage areas such as delamination and voids, but to also quantify the damage.

5.3 Repair Techniques

If a damage area can be quantified as critical, then a repair of the structure will be necessary. Proper surface treatment is essential for a successful composite repair. Material removal can be accomplished by mechanical milling or with pulsed lasers. Depending on the nature of the composite, a patch, scarf patch, or step repair will need to be chosen as a repair technique. Once the damaged area has been excavated, the exposed surfaces will need to be further cleaned for the final repair patches. This is typically accomplished by plasma burning surface contaminates, using lasers to remove matrix material in order to expose fibers, or improving surface wettability for adhesives by photochemical reactions induced by UV-laser light. Once the surface is prepared, a patch is typically applied under vacuum and high temperature. Field repairs are typically done using a hot bonder whereas more complex repairs requiring a higher quality repair are done using an autoclave. Further research is necessary to develop what repair methods, materials, equipment, and cure time will be needed for particular structural components. Additionally, NDT and monitoring procedures will need to be developed to ensure the quality and integrity of the repair.

6. DESIGN GUIDANCE AND CONSIDERATIONS

The design guidance available for hydraulic steel structures, USACE (2014), was consulted as a template to follow for developing guidance for the design of hydraulic composite structures. Categories that will be incorporated from this guidance will include materials, member types, analysis methods, inspection methods, plans and specification, fabrication and erection procedures, design for fatigue and fracture, and design and detailing of connections. The guidance was also consulted to identify considerations unique to miter, tainter (radial), and vertical lift gates, USACE (2014).

6.1 Miter Gates

Miter gates are large vertical lock gates operating under moderate to high lift. Components of a miter gate include skin plates, girders, diagonals, quoin blocks, and gudgeon connections. During normal operations, the gates are exposed to hydrostatic loads, hydrodynamic loads, machinery loads, and barge impacts. When opening and closing, the gates are also exposed to significant torsional loading. Due to high hydraulic heads and constraints on maximum gate thickness from existing lock geometries, embedded steel frames may be need in to meet deflection requirements. Depending on the size of the gate, fabricating the gates as monolithic units may not possible which would require modular fabrication techniques instead. Guidance for designing connections between the composite gates to operational machinery and gudgeon assemblies for both strength and fatigue resistance will be needed.

6.2 Tainter Gates

Tainter gates used for spill way control on navigation structures are exposed to significant discharge. Components of a tainter gate include radial skin plates, horizontal girders, end frames, and trunnions. The gates experience loads from hydrostatic pressure, gate lifting systems, ice impacts, side seal friction, trunnion pin friction, hydrodynamic pressure, and wind. Due the discharge, the gates experience significant vibrational loading. While composite materials can be optimized to provide damping against such vibrations, guidance must be provided to design for sustained fatigue to prevent delamination and mirco-cracking. Additionally the complex geometries of the gates require that they be fabricated from separate components. Special attention will be paid to designing the anchorage systems for attaching lifting cables and actuators to the profile of the gates.

6.3 Vertical Lift Gates

Vertical lift gates are used as both lock and valve gates for low to moderate heads and can be of an overhead or submersible configuration. The lift gates components include skin plates, framing systems (girders, trusses, tied arches, or vertical framing), and end supports that allow vertical motion (fixed-wheels, rollers, or slide). Vertical lift gates experience many of the same loads as miter gates but are also subjected to vertical loads from the lifting machinery, thermal differentials, and wind loads in the case of overhead gates. Embedded steel plates or frames may be necessary to prevent pull out of the lifting connection.

7. CONCLUSIONS

Successful demonstrations utilizing FRP composite materials for USACE navigation infrastructure components has shown the viability and cost reductions that can be realized with these materials. Collaborations with other international waterway agencies has provided further evidence that FRP composite materials can be used to fabricate even larger navigation structures. By leveraging the lessons learned in these successes and collaborations, as well as current industry innovations, a path towards the design and procurement of even larger FRP composite structures has been developed. As part of this path forward, knowledge gaps related to structural health monitoring, inspection, and repair techniques will be filled in. Ultimately, the knowledge obtained from this effort will be developed into comprehensive design guidance to equip engineers with the tools needed to widely implement FRP composite navigation structures with confidence.

8. REFERENCES

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