Design and Evaluation of an Integrated FRP Composite Wicket Gate

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ABSTRACT

Hydraulic gates need to be light-weight, corrosion-resistant, maintenance-free, and durable with high endurance under fatigue loads. All of these requirements could be challenges to be met using conventional materials like steel and concrete. However, with the emergence of advanced Fiber Reinforced Polymer (FRP) composites for waterway structures, it has now been possible to achieve all of these physical and performance requirements in a cost-effective manner. Due to their lightness, excellent corrosion and wear resistance along with superior thermo-mechanical properties, FRPs have emerged as one of the best alternatives in the field of civil infrastructure. This paper covers several aspects of the design, manufacturing, testing, analysis, and field implementation of a novel integrated FRP wicket gate in Mississippi River lock and dam. The cellular FRP panel with foam core and integrated stiffening and fastening components has been analyzed to compute the bending stiffness both theoretically and experimentally and a good correlation has been obtained.

Keywords: cellular FRP deck, sandwich panel, deck stiffness, hydraulic structure, wicket gate

1. Introduction

The U.S. Army corps of Engineers (USACE) owns, operates and maintains an extensive infrastructure of navigational, flood control and waterfront structures over a length of 19,000 km (12,000 miles) in the United States. Most of these structures are made up of traditional materials such as steel, concrete and timber which are now exhibiting significant amount of corrosion, decaying and aging [1]. According to USACE, more than \$13 billion is required by 2020 to maintain existing levels of unscheduled delays on inland waterways without exacerbating further [2]. Almost 73% of the budget is allocated to the rehabilitation of current lock and dam facilities [2]. Maintaining these steel, concrete and timber structures has become an arduous task as these materials are highly prone to undesirable deterioration under humid conditions in a short duration. Due to expensive regular maintenance and replacement costs of these structures combined with the recent advances in the development of fiber reinforced polymer (FRP) composites for use in civil engineering applications, USACE has shown interest in utilizing FRPs to minimize their construction and maintenance costs.

FRPs have been increasingly used for both rehabilitation and new construction in recent days due to their superior properties over conventional materials such as lightweight, high specific strength and resistance against corrosion, moisture and chemical attack [3-6]. They have proven their versatility and flexibility not only for ambient surface applications but also for fresh water and marine applications [4, 7-9]. Through this research, integrated wicket gates have been engineered with the use of noncorrosive FRP composites to mitigate extensive in-service maintenance and replacement of traditional timber and steel wicket gates in hydraulic locks and dams. FRPs are considered as one of the best alternatives to steel and timber in replacing hydraulic gates in locks and dams due to their excellent fatigue and wear resistance along with high durability [6, 10].

In the past, FRP composites have been used in several demonstration projects for water environments [11-13]. They have proven their feasibility and efficacy as load bearing piles, fender piles and sheet piles in marine and waterfront environments [11]. FRPs have also been used as oil and gas storage tanks, decking for ocean environment and cold water pipes [12]. In Japan, more than four hundred FRP hydraulic gates including different styles of gates such as slide gate, roller gate, miter gate etc. have been installed since 1960s [13]. A field study conducted on 40-year old FRP gates in Japan has shown no major deterioration except little discoloration in the appearance, despite the gates requiring very little or no maintenance in the past [13]. Further, the specimens obtained from those old FRP gates were tested in the laboratory for water and corrosion resistance by Tomiyama and Nishizaki and the study confirmed their excellent durability [13]. FRPs have also been used in replacing old timber miter gates in Noord Brabant, Netherlands in 2000 with significant cost and weight reductions as compared to the conventional materials [14]. Similarly, FRP composite was used to replace steel miter gates in Canal des Voges, France. The largest FRP lock gate of size 10.5 m x 13 m has been installed in the Wilhelmina canal in Tilburg, France [14-16]. Likewise, the research described in this paper describes designing, manufacturing, testing and field implementing of novel and integrated FRP wicket gates for lock and dam structures.

A wicket gate is a movable dam that is raised in times of low water and lowered when the water level is adequate for navigation. These gates have been utilized for navigation dams for over 100 years [17]. Although several types and designs of wicket gates have been utilized in the past, there are primarily two types of wicket gates. The first type is a bottom-hinged gate with a supporting prop and a remote-controlled hydraulic lifting system (Fig. 1a) and the second type is a horse type wicket gate which is supported by a horse and a prop-rod with manual lift (Fig. 1b).

Fig. 1. Types of wicket gate configurations: a) first type, b) second type [17, 18]

FRP composites were previously used to manufacture wicket gates for replacing old and deteriorated timber wickets in Olmsted locks and dam in Ohio River in 1993 but were not field implemented for some undisclosed reasons [19, 20]. A single prototype wicket gate using FRP composite and steel was manufactured for Olmsted lock and dam and tested in the field for short duration. The testing of the gate showed larger deflections due to lower stiffness of FRP and gate sides were damaged due to debris getting caught between adjacent units [21]. The study conducted by Chaudhary et al. [22] on a scaled model of the FRP wicket gate showed no severe damages under highly abrasive loading conditions except peeling off on both edges due to high velocity of water flow between the panels [22]. The study suggested the use of local steel plates to minimize out of plane loading during lifting and addition of steel angles on the side panels to increase the durability [18]. Structures such as hydraulic gates have a tendency to exhibit self-excited vibrations during overflow and underflow scenarios. In order to study this phenomenon, Chaudhary et al. [18] tested a scaled model of FRP wicket gate to evaluate its dynamic performance [22]. The study indicated the absence of a dynamic resonance for wicket gates used in the field. Strain measurements and fatigue analysis of hinges and connecting pins of the gate system also showed no signs of overstressing of the wicket gate components [22]. Another study by Bejar and Hall [23] has described a mathematical model to estimate hydrodynamic forces on a wicket gate based on two-dimensional potential theory as described in section 3.4.

Fig. 2. a) Horse wicket gates (timber and steel) supported by prop rod, b) deteriorated timber wicket gates [19]

This research focuses on the design, analysis and manufacturing of horse type wicket gates. Size of wicket gate typically ranges from 1.2 m to 3 m (4 to 10 ft.) in width and 4.6 m to 6.1 m (15 to 20 ft.) in length (height). These wicket gates are hinged individually just below their center point to the river bottom with the help of horse framing and are placed parallel across a navigation channel with 50 mm to 100 mm gap in-between and oriented at an angle of 65° to form a dam (Fig. 2a). These gates are hoisted into position manually with a gantry operated crane or winch cable and are held in an upward position with a prop-rod that slides into a hurter. These gates are generally constructed with timber sections enclosed in steel or iron framing. Figure 2 (b) shows the amount of deterioration in a timber wicket gate after just 15 years of service life. Thus, there is a great need to invest on research and development of FRP composite gates in order to save huge costs associated with the periodical maintenance and replacement.

Based on the literature review, reverse engineering of current timber wicket gates and applying the basic principles of composite mechanics and structural analysis, integrated FRP composite wicket gates are designed to satisfy field requirement. The main objective of this research is to overcome disadvantages of conventional timber wicket gates such as heavy weight, susceptibility to corrosion, abrasion, decay and high maintenance or replacement by developing a light weight, corrosion resistant, decay-free and low maintenance FRP composite wicket gates for field implementation.

2. In-service timber wicket gates of Rock Island lock and dam facility

Wicket gates made of white oak timber sections with peripheral steel angle frames that are currently in service at Rock Island lock and dam, IL were considered for replacement with integrated FRP wicket gates as per discussion with USACE. The length (height) and width of this particular timber wicket gate is 5.03 m (16.5 ft.) and 1.17 m (3.83 ft.), respectively. The gate is made of four individual timber beams with varying depth along the length with the maximum depth being 305 mm (12") at nearly one-third height from bottom end under operating position. Peripheral steel angles measure 89 mm x 89 mm x 6.35 mm (3.5"x3.5"x0.25") and are bolted to the edges of upstream face of the timber gate. Steel plates of size 12.7 mm x 152 mm (0.5"x6") and 45 mm x 458 mm (1.75"x18") are bolted on both upstream and downstream faces of the gate at the top and bottom, respectively (Fig. 3a). The downstream face of the gate consists of two steel plates of sizes 330 mm x 432 mm x 15.88 mm (13"x17"x0.625") that are connected by a shaft to which a prop-rod of diameter 152 mm (6") gets connected as shown in Fig.3b.

The timber used in the gate had a design bending stress of 8.96 MPa (1300 psi), shear stress of 1.41 MPa (205 psi), compression perpendicular to grain of 5.52 MPa (800 psi) and the modulus of elasticity of 12.27 GPa (1.78 msi) as per NDS supplement for wood construction [24]. A moisture factor of 0.67 was used for compression perpendicular to grain. Using working stress method, allowable design values of the existing timber gate was found. The allowable compressive force on the gate through two steel plate attachments of sizes 330 mm x 432 mm (13" x 17") was

1054.23 kN (237 kip), allowable shear force resisted by the gate was 333.62 kN (75 kip), allowable punching shear through steel plates was 1312.23 kN (295 kip), and allowable bending moment of a solid timber gate 1168 mm x 305 mm (46"x12") without considering any steel plates was 161.34 kN-m (119 kip-ft). These reverse engineered values were used as a basis to design the FRP wicket gate.

Fig. 3. Timber wicket gate: a) upstream face, b) downstream face with prop-rod on top

3. Analysis of forces on wicket gate

To facilitate wicket gate design, different loading scenarios were considered and the governing design forces were determined. The length and width of the gate are 5.03 m (16.5 ft.) and 1.17 m (3.83 ft.), respectively and a prop-rod is connected to the middle portion (top hinge) of the gate as shown in Figure 4. The location of the top hinge from the bottom of the gate is 2.44 m (8 ft.) along the gate length (Fig. 4). For analysis, four loading scenarios were considered.

- i. Operating position,
- ii. Resting position,
- iii. Lifting position, and
- iv. Hydrodynamic forces

Fig. 4. Wicket gate in operating position: a) with tail water, b) without tail water

3.1. Loads during operating position

During operating position (Fig. 4), the maximum angle between the gate and the ground is 65°. The calculation of forces including self-weight and hydraulic pressure are based on two scenarios:

- i) Presence of full height of water, i.e. 4.57 m (15 ft.) on upstream side (head water) and up to the height of the top hinge on downstream side (tail water), i.e., 2.23 m (7.3. ft.)
- ii) Presence of full height of water, i.e. 4.57 m (15 ft.) on upstream side and absence of water on downstream side

The self-weight of the FRP gate system is assumed as 26.7 kN (6 kip) and considered to be acting through the center of the gate for the ease of calculation. The average water pressure and hydrostatic force on the gate surface were calculated by Eqns. (1) and (2). Equating moment of forces about bottom hinge (Fig. 4), forces in the prop and gate section were calculated as shown in Table 1.

$$\text{Average water pressure on upstream side} = \frac{\gamma h}{2} = \frac{9.81 \times 4.57}{2} = 44.8 \frac{\text{kN}}{\text{m}^2} \quad (1)$$

$$\text{Hydrostatic force on the upstream side} = 44.8 \frac{\text{kN}}{\text{m}^2} \times 5.03 \text{ m} \times 1.17 \text{ m} = 263.65 \text{ kN} \quad (2)$$

3.2. Loads during resting position

During resting position on the river bed, the wicket gate stays on two support points, i) solid block and ii) bottom hinge. The maximum height of water above the resting gate is 4.6 m (15 ft.) and the space underneath the gate is filled with water. Thus, equal pressure is exerted on both sides of the gate assuming the depth of the gate is insignificant. Therefore, wicket gate will have practically negligible loads during resting position and their negative buoyancy should be ascertained.

Fig. 5. Bails on the wicket gate: a) top bail, b) bottom bail

3.3. Loads during lifting position

During lifting, a winch cable is tied to either top or bottom bail (Fig. 5). In order to achieve higher safety factor and design for the worst possible scenario, the gate is assumed to act like a simply supported beam with the two ends hinged. The full height of water above the gate is assumed to be 4.6 m (15 ft.) just when the lifting is started from the rest position. It is also assumed that no pressure is exerted from the downstream side of the gate during lifting from resting position and the gate resists the entire flow of water over its surface. Computed maximum shear force and corresponding maximum bending moment are shown in Table 1.

3.4. Loads due to hydrodynamic effects

The presence of turbulent flow of water around the gate can create a scenario where each gate can be subjected to forces that can locally compound the mean induced stresses [25]. Researchers in the past have conducted mathematical modeling to determine hydrodynamic forces on the gate based on the results obtained from the experimental analysis on 1:25-scale physical model of the gate at the U.S. Army Engineer Waterways Experiment Station [23]. The largest hydraulic force acting on the single central gate for a closed position in a three-gate aperture condition as shown in the Fig. 6a, which means lowering of the adjacent gates on both sides of the test-gate. This configuration was identified from experiments on a corresponding 1:25-scale physical model as one of the critical conditions to be considered in the gate design [25]. The study conducted by Bejar and Hall, 1997 showed the resultant hydrodynamic force acting on the vertical projection of the gate and the vertical distance (z) at which it acts from the bottom of the gate based on Eqns. (3) and (4).

Fig. 6. a) Three-gate aperture, b) velocity field on upstream side of the gate [22, 25]

$$F_H = \rho k_d^2 * \frac{\pi}{2} \left(\frac{\pi}{2} + 1 \right) * \frac{A_g}{(2a)^2} * \chi(\Delta\beta) * \sin \theta \quad (3)$$

$$z = 0.58h \quad (4)$$

Where, ρ is the density of water, k_d is the coefficient of actual flow (length²/time) obtained during experiment on the physical model, A_g is the area of the upstream face of the gate, $2a$ is the width of the test-gate including aperture on both sides, h is the height of the vertical projection of the gate, $\Delta\beta$ is the hydrodynamic pressure distribution and θ is the inclination of the gate. $\chi(\Delta\beta)$ is the equivalent normalized distance of the gate as defined by Eqn. (5).

$$\chi(\Delta\beta) = \frac{8(1-\Delta\beta)-1}{1+(1-\Delta\beta)} - \ln \left(\frac{2}{\Delta\beta} - 1 \right) = 0.62 \quad (5)$$

For calculating the hydrodynamic resultant force for the wicket gate discussed in this paper, k_d is taken as 0.0372 m²/s [25]. The area of the upstream face (A_g) and the width ($2a$) of the gate including 2" aperture on both sides for 1:25 scale model are taken as 0.009398 m² and 0.0508 m. Likewise, the hydrodynamic pressure distribution ($\Delta\beta$) and $\chi(\Delta\beta)$ are taken as 0.15 and 0.62, respectively. The inclination of the gate during the operating position is 65°. Therefore, the hydrodynamic resultant force for a 1:25 scale wicket gate model is provided by Eqns. (7) and (8) with appropriate scaling factor.

$$F_H = 1000 * 0.0372^2 * \frac{\pi}{2} \left(\frac{\pi}{2} + 1 \right) * \frac{0.009398}{(0.0508)^2} * 0.62 * \sin 65 = 11.39 \text{ N} \quad (6)$$

$$F_H = 25^3 * 11.39 \text{ N} = 178 \text{ kN (40 kip)} \quad (7)$$

Hydrodynamic force of 178 kN (40 kip) applied on the gate at a vertical height of $z = 0.58h$ for a height of $h = 4.57\text{m}$ (15 ft.) will result in a prop compressive force of 191.3 kN (43 kip). Based on the analysis of above four scenarios, the design of FRP wicket gate is governed by the shear, compression and bending forces induced during lifting of the gate. Table 1 shows the summary of forces acting on the gate and governing forces which are accounted for with sufficient safety factors as discussed in section 4.

Table 1

Summary of forces on wicket gate in different positions

	Loading scenarios	Prop force kN (kip)	Shear force on wicket gate section, kN (kip)	Bending moment on wicket gate section, kN-m (kip-ft)
1	Operating (with tail water)	91.8 (20.6)	50.9 (11.45)	37.5 (27.7)
2	Operating (without tail water)	102.3 (23)	40.9 (9.2)	27.7 (20.4)
3	Resting	0	0	0
4	Lifting	0	132 (29.6)	165.4 (122)
5	Hydrodynamic effects	191.3 (43)	105.4 (23.7)	78.2 (57.7)
	Governing forces for design	191.3 (43)	132 (29.6)	165.4 (122)

4. Design of an integrated FRP wicket gate section

In contrast to timber wicket gates consisting of four individual timber sections connected through bolts, FRP wicket gate was designed as a single sandwich section by integrating face sheets, webs and foam core. In addition, two steel plates were embedded inside face sheets which helped to enhance the moment of inertia of the section, reduce deflection and buoyancy and facilitate connectivity with existing horse and prop systems. Resting blocks (Fig. 2) were also integrated into the single FRP sandwich section which resulted in easier and stable assembly. Bolted steel angles on the sides of the wicket gate were replaced with the bonded ultra-high molecular weight polyethylene (UHMWPE) which helped reduce the use of steel and promised superior impact and abrasion performance. Negative buoyancy of the integrated FRP wicket gate was ensured through design and placement of embedded steel plates, core material and additional steel fixtures.

The cross-section of 215.5 mm (8.5”) deep FRP composite wicket gate designed through this research is shown in Fig. 7. There are 14 webs across the 1.17 m (46”) wide section wicket gate with top and bottom flange thickness of 13.28 mm (0.523”) each and web thickness of 10.16 mm (0.4”) each. Moment of inertia of a single FRP wicket gate module without steel attachments is 39,250.6 cm⁴ (943 in⁴). Timber wicket gates have additional steel attachments on top and bottom of the gate along with edge steel angles as shown in Figures 3 and 5, which contribute to the overall strength and stiffness of the gate. In this section, design checks have been performed on only FRP module without considering the additional strength and stiffness contributions from any steel attachments.

Fig. 7. Cross-section of FRP composite wicket gate without any steel attachment

4.1. Check for bending stresses in the face sheet

$$\text{Bending stress in the face sheet } (\sigma) = \frac{Md}{2I} = \frac{165.4 \text{ kNm} \times 215.5 \text{ mm}}{2 \times 39250.6 \text{ cm}^4} = 45.5 \text{ MPa (6.6 ksi)} \quad (8)$$

where, d is the depth of the section. Eqn. (8) gives a maximum bending stress of 45.5 MPa (6.6 ksi) for the gate section. The failure bending stress of the FRP panel without any steel attachment is 196.5 MPa (28.5 ksi), which is discussed in section 7.1. Based on this bending stress, total resisting bending moment of the selected FRP wicket gate is 696.6 kN-m (513.8 kip-ft.). Thus, a factor of safety of 4.3 against bending failure (196.5/45.5) is obtained. After considering a live load factor of 1.6, factor of safety against bending failure is 2.7.

4.2. Check for shear in webs

$$\text{Shear stress in the webs } (\tau) = \frac{1.5V}{n_w t_w h} = \frac{1.5 \times 132 \text{ kN}}{14 \times 10.16 \text{ mm} \times 202.2 \text{ mm}} = 6.88 \text{ MPa (0.99 ksi)} \quad (9)$$

where, n_w and t_w are the number of webs and thickness of single web, respectively and h is the height of webs between mid-planes of face sheets. Eqn. (9) gives a shear stress of 6.88 MPa (0.99 ksi) across the wicket gate section. The in-plane failure shear strength of the FRP webs is established to be 113.1 MPa (16.4 ksi) from manufacturer's test results. Based on this stress, factor of safety against shear failure is 16.4 (113.1/6.88).

4.3. Check for web buckling

Total prop force of 102.3 kN (23 kip) is distributed to the gate through two plates of sizes 330 mm x 432 mm (13" x 17"). In each of this area, there are 4 webs of 10.16 mm (0.4") thickness. Conservatively, considering total prop force coming to only one steel plate, each web is subjected to 26.7 kN (6 kip). For an inch length of the web, moment of inertia about its minor axis is 2,218.5 mm⁴ (0.00533 in⁴). Considering the modulus of elasticity of the FRP webs to be of 24131.66 MPa (3.5 msi), the buckling load for 25.4 mm (1") length of the web is given by Eqn. (10).

$$P_{cr} = \frac{\pi^2 EI}{h^2} = \frac{\pi^2 \times 24131.66 \times 2218.5}{202.2^2} = 12.9 \text{ kN (2.9 kip)} \quad (10)$$

The buckling load for a single web of length 432 mm (17") underneath the steel plate is 219.3 kN (49.3 kip), which gives a factor of safety of 8.2 (219.3/26.7) for the webs against buckling. However, the factor of safety of FRP webs against buckling is more than 8.2 due to higher buckling load value of webs than 12.9 kN (2.9 kip). Fixity of the webs near top and bottom face sheets will halve their effective height which will result in quadrupling of the buckling resistance.

5. Theoretical calculation of strength and stiffness of FRP wicket gate section

The designed cellular FRP sandwich deck consists of face sheets, primary and secondary webs, core material and embedded steel as shown in Fig. 8. In this section, the elastic analysis of sandwich cellular FRP deck with two embedded steel plates has been conducted. This analysis can be used to evaluate stresses in the face sheets, webs and core and also to calculate the flexural rigidity of the deck. The sandwich panel has a total width of b and the depth of d . The face sheets, primary webs and secondary webs have thicknesses t_f , t_{pw} and t_{sw} , respectively. The core material have a thickness c and two embedded steel plates have width b_s and thickness t_s , as shown in Fig. 8.

Fig. 8. Cellular FRP sandwich deck: a) 1/4th model with primary and secondary webs, b) part of the cross section

During bending, it is assumed that the face sheets remain bonded to the core and the section bends with no curvature in the YZ-plane and the cross-section of the panel remains perpendicular to the longitudinal axis. The flexural rigidity D of the sandwich cellular FRP panel section in the longitudinal direction is given by the algebraic summation of longitudinal stiffnesses of face sheets, primary webs, core and embedded steel plates as shown in Eqns. (11) to (14). The contribution of secondary webs to the flexural rigidity in the longitudinal direction is less and can be neglected.

$$D_{face\ sheets} = \frac{E_{fx} b t_f^3}{6} + E_{fx} b t_f (h_1^2 + h_2^2) \quad (11)$$

$$D_{primary\ webs} = \frac{n_{pw} E_{pw} t_{pw} (h_1 + h_2)^3}{12} + n_{pw} E_{wx} t_{pw} (h_1 + h_2) \left(d_1 - \frac{d}{2} \right)^2 \quad (12)$$

$$D_{core} = \frac{E_{cx}(b - n_{pw}t_w)c^3}{12} + E_{cx}(b - n_{pw}t_w)c\left(c_1 - \frac{c}{2}\right)^2 \quad (13)$$

$$D_{embedded\ steel} = \frac{E_s b_s t_s^3}{12} + E_s b_s t_s \left(d_2 - t_f - \frac{t_s}{2}\right)^2 \quad (14)$$

Where, h_1 and h_2 are distances between center of gravity (CG) of the panel and the mid-planes of upper and bottom face sheets, respectively. d_1 and d_2 are distances between CG of the panel and the bottom and top of the face sheets, respectively and c_1 and c_2 are distances between CG of the panel and the bottom and top of the foam core as shown in Fig. 8. Likewise, n_{pw} denotes the number of primary webs in the section. E_{fx} , E_{pwx} , E_{cx} and E_s are the in-plane young's moduli of the face sheet, primary webs, core and steel respectively along the longitudinal axis of the panel. The first term of Eqns. (11) to (14) corresponds to the bending of the respective sections about their own centroid axes, while the second term corresponds to the bending about the centroid axes of the whole panel section. When the modulus of elasticity of the core material is very less compared to that of the panel, its contribution to the flexural rigidity of the entire panel section can be neglected. The contributions from the first term of Eqns. (11), (14) and second term of Eqn. (12) are also negligible. Thus, the flexural rigidity or the bending stiffness of the sandwich cellular FRP panel with embedded steel plates can be simplified as shown by Eqn. (15).

$$D_x = E_{fx} b t_f (h_1^2 + h_2^2) + \frac{n_w E_{wx} t_{pw} (h_1 + h_2)^3}{12} + E_s b_s t_s \left(d_2 - t_f - \frac{t_s}{2}\right)^2 \quad (15)$$

The out-of-plane shear stiffness of the cellular FRP sandwich deck in the longitudinal direction (F_x) is expressed as:

$$F_x = n_{pw} G_{pxy} t_{pw} h \quad (16)$$

Where, G_{pxy} is the in-plane shear modulus of primary webs and h is the depth of the web between the mid-planes of face sheets. The transverse bending stiffness of the cellular FRP sandwich deck is mainly achieved from the bending stiffnesses of the face sheets and the secondary webs as shown by Eqn. (17). The effects of primary webs and second moment of area of face sheets about their own centroids are neglected.

$$D_y = E_y l t_f (h_1^2 + h_2^2) + \frac{n_{sw} E_{swx} t_{sw} (h_1 + h_2)^3}{12} \quad (17)$$

Where, E_y is the modulus of elasticity of the panel in y-direction, l is the length of the panel in longitudinal direction, n_{sw} and t_{sw} are the number and thickness of secondary webs in the section and E_{swx} is the in-plane young's modulus of the secondary webs. Similarly, the transverse shear stiffness (F_y) for the cellular FRP sandwich section can be obtained by considering the structure as a vierendeel frame in the transverse direction [27].

$$F_y = n_{sw} G_{sxy} t_{sw} h + \frac{12 E_y}{b \left(\frac{h}{I_w} + \frac{b}{2 I_f} \right)} \quad (18)$$

Where, G_{sxy} is the in-plane shear modulus of secondary webs and the moment of inertias are defined as:

$$I_f = \frac{l t_f^3}{12}; I_w = \frac{l t_w^3}{12} \quad (19)$$

The theoretical bending and shear stiffnesses of cellular FRP sandwich deck panel were verified with experimental results obtained from 3-point and 4-point bending tests of the panel in later sections. The central deflection of the deck can be computed from their corresponding bending and shear stiffnesses as shown in Eqns. (20) and (21).

$$\delta = \frac{PL^3}{48 D_{x\ or\ y}} + \frac{PL}{4 \kappa F_{x\ or\ y}} \text{ (3-point bending)} \quad (20)$$

$$\delta = \frac{23 PL^3}{1296 D_{x\ or\ y}} + \frac{PL}{6 \kappa F_{x\ or\ y}} \text{ (4-point bending)} \quad (21)$$

Where, P is the total load applied, L is the length of the span, κ is the shear correction factor (assumed as 1.00 in this analysis) and D, F are the bending and shear stiffness in either longitudinal or transverse direction based on loading and support conditions.

6. Manufacturing of an integrated FRP wicket gate

The FRP composite wicket gate was manufactured by using vacuum assisted resin infusion process (Fig. 9). The reinforcement in the face-sheet skins and webs are E-glass fiberglass fabrics. Wicket gate face sheet skins and webs consisted of highly directional E-glass fabrics with fibers running primarily in the 0° direction along the length of the gate for resisting bending loads and tri-axial fabrics with fibers in the $\pm 45^\circ$, 90° directions for resisting in-plane shear and transverse forces. Wicket gate consisted of thirteen closed cells and water resistant web cores. Web cores used in the panel were reinforced with $\pm 45^\circ$ fabrics which when infused with resin formed very strong and stiff shear webs for the sandwich cross-section. Closely spaced webs provide very good crushing resistance to potential concentrated loads. Local skin deflections are generally assumed negligible when the face sheet is supported by the webs. The redundancy of multiple webs provides improved damage tolerance as compared to thick and wider-spaced webs.

The fiber/fabric layup of the composite top and bottom face sheets are symmetric to middle surface with “Composite Advantage® bidirectional core” at the center. Symmetric layers from outside to inside are 0.75oz CFM (non-structural), 55oz unidirectional (0°), 40oz triaxial (90°), 40oz triaxial (0°), 55oz unidirectional (0°), 40oz triaxial (90°), 40oz triaxial (0°), 55oz unidirectional (0°), 40oz triaxial (90°), 40oz triaxial (0°) and 55oz unidirectional (0°) fabrics.

Fig. 9. Manufacturing of FRP wicket gate on a molding table with resting block core

7. Testing and Results

Laboratory tests were performed on FRP coupon specimens, timber and FRP wicket gates. Loading levels were within 40% of the ultimate loads. Bending and shear strains were measured both on the upstream and downstream sides of the gate at the center of the panel and hinge and prop locations. Deflections were measured through LVDTs. Shear gages were instrumented on side walls. During reverse engineering analysis, it was found that the bending loads were more critical as compared to shear. Following tests were performed in the laboratory:

- i. Tensile test on FRP wicket gate coupon specimens
- ii. Four point bending test on timber wicket gate and FRP wicket gate with steel fixtures
- iii. Three point bending test on FRP wicket gate after removing steel fixtures
- iv. Fatigue test on FRP wicket gate
- v. End plate/bail pull test

7.1. Tensile test on FRP wicket gate coupon specimens

Tensile tests were conducted on FRP coupon specimens representing face sheet of the FRP wicket gate to obtain modulus of elasticity (E) of the FRP laminate. These face sheet coupons were selected to represent smooth and potential wrinkling near the outer surfaces or edges (Fig. 10). Samples with dimensions of 1067 mm x 50.8 mm x 10.9 mm in the longitudinal and transverse directions were prepared and tested in tension. The strain gages were located at the mid-height region of the sample. Table 2 shows the test results and Fig. 10 shows the stress vs. strain plot for specimens with and without wrinkling in the longitudinal direction. The modulus of elasticity for both types of specimens was identified and found to be 30.34 GPa (4.4 msi).

Fig. 10. a) no-wrinkle sample, b) wrinkled sample, c) stress vs. strain plot for long direction for both samples

Table 2

Tensile stress and stiffness of face sheet coupon specimens with and without surface wrinkles

Sample	Wrinkle	Width mm (in)	Thickness mm (in)	C/S area mm ² (in ²)	Avg. peak load kN (kip)	Avg. stress MPa (ksi)	Stiffness GPa (msi)
Longitudinal (along length)	No	50.8 (2)	10.9 (0.43)	555.5 (0.86)	272.7 (61.3)	490.9 (71.2)	30.34 (4.4)
	Yes	50.8 (2)	10.9 (0.43)	555.5 (0.86)	272.2 (61.2)	490.2 (71.1)	30.34 (4.4)
Transverse (along width)	No	50.8 (2)	10.9 (0.43)	567.7 (0.88)	138.8 (31.2)	250.3 (36.3)	-
	Yes	50.8 (2)	10.9 (0.43)	567.7 (0.88)	133 (29.9)	239.9 (34.8)	-

The tensile strain to failure for the coupon specimens is 18,000 micro-strain as seen in Fig. 10. Bending failure stress of the entire panel was obtained by applying a knock-down factor of 0.6 and a stress concentration factor of 0.6 which leads to the bending strain to failure of the gate as 6,480 micro-strains. Thus, stress to failure for bending is given by Eq. (22).

$$\text{Bending stress to failure} = 30.34 \text{ GPa} * 6480 \times 10^{-6} = 196.5 \text{ MPa (28.5 ksi)} \quad (22)$$

7.2. Four point bending test on timber wicket gate and FRP wicket gate with steel fixtures

Four-point bending loads were applied at L/3 distance from both ends of the FRP gate without removing external steel fixtures (Fig.11). These fixtures such as steel edge angles and connecting plates (top and bottom) enhance flexural rigidity and provide abrasion resistance. Five shear strain gages and 15 axial strain gages were bonded at different locations of the gate and LVDTs were used to measure deflections. Load of 267 kN (60 kip) each was applied with two MTS hydraulic actuators at L/3 distance for FRP wicket gate and similar load of 155.7 kN (35 kip) each was applied to the timber wicket gate. Table 3 shows the results of the testing. The maximum bending strains at L/2 (center) and L/3 distances were 3352 micro-strains and 2001 micro-strains, respectively. Maximum shear strain of 2230 micro-strains was measured at a distance 'd' from the support, where 'd' is the gate depth. Strains during bending failure in FRP shapes is noted to be in the range of 10,000 to 15,000 micro-strains and in the range of 8000

to 10,000 micro-strains during shear failure. These induced strains are about 1/4th to 1/3rd of the failure strains but may vary based on the fiber-fabric architecture, L/d ratio, and local failure modes.

Fig. 11. Bending tests: a) on timber wicket gate, b) on FRP wicket gate

Table 3

Four-point bending test results of timber and FRP gate

Items	Timber gate	FRP gate
Test span, m (ft.)	4.57 (15)	4.57 (15)
Load distance from supports, m (ft.)	1.52 (5)	1.52 (5)
Total load, kN (kip)	311.4 (70)	534 (120)
Maximum moment, kN-m (k-ft)	237.3 (175)	406.7 (300)
Maximum bending strain at center (micro-strain)	1312	3352
Maximum shear strain (micro-strain)	129	2230
Maximum deflection at center (L/2), mm (inches)	26.42 (1.04)	58.75 (2.313)
Maximum deflection at L/3, mm (inches)	24.13 (0.95)	51.8 (2.04")

7.3. Three point bending test on FRP wicket gate without steel fixtures

After removing steel fixtures, FRP wicket gate was loaded in 3-points for a span of 4.57 m (15 ft.) with a load of 89 kN (20 kip) as shown in Fig. 12. Strains were measured at different locations of the gate and the vertical displacements were measured at the center and one-third distance. At the maximum load of 89 kN, the maximum deflection obtained at the center and one-third of the span was 14.81 mm (0.583") and 12.78 mm (0.503"), respectively.

Fig.12. Three point bending test of FRP wicket gate

7.4. Fatigue test on FRP wicket gate

FRP wicket gate, without any steel fixtures, was tested in fatigue with a load-range of 53.4 to 106.8 kN (12-24 kip) at a frequency of 1 Hz in a three-point bending setup with a span of 4.57 m (15 ft.) for 50,000 cycles. As obtained from USACE, the gate operating sequences are based on seasonal variations of water level and are highly unlikely to exceed 5,000 cycles in a 100-year life cycle. For a typical FRP material, applied stress (S) vs. number of cycles (N), i.e., S-N curve can be expressed in a linear manner as shown in Eqn. (23), when the number of cycles is less than one million cycles [28, 29].

$$\frac{\sigma_{applied}}{\sigma_{static}} = A + B \log N \quad (23)$$

where, $\sigma_{applied}$ is the applied stress or stress range, and σ_{static} is the ultimate static strength. A and B are material constants. At a very low stress range, the S-N curve gets flattened indicating the infinite life of the material [29]. For the FRP wicket gate designed in this research, the maximum load that gets transferred to the gate through prop rod via prop connecting steel plates during operating position is 91.8 kN (20.6 kip) (Table 1), therefore the load applied on the gate was in the range of 53.4 to 106.8 kN (12-24 kip), where the maximum stress applied to the gate is just 17% of its ultimate strength. Generally, this limit of stress falls below the endurance limit for FRP composites and at this stress, the fatigue life of the FRP material is considered to be infinite [30, 31]. In addition, after 50,000 cycles of loading, three-point static bending test was performed on the gate with the central load of 178 kN (40 kip). The maximum tensile strain obtained at the center of the gate was 975 micro-strains compared to 978 micro-strains before fatigue. The strain levels indicated that the stiffness and strain energy absorption capacity of the gate was not reduced due to fatigue loading and will not be affected during its service life.

7.5. End plate/bail pull test

FRP wicket gate was placed horizontally on two end supports with top of the gate fixed against horizontal movement. A chain was attached to the top bail (weaker than the bottom bail) and pulled horizontally with a force of 84.1 kN (18.9 kip) (Fig. 13). The pulling force on the bail is transferred to the FRP face sheets through the bolt attachments. Few strain gages bonded to the FRP surface below the bail recorded a maximum strain of 104 micro-strains. These low strains indicate that the gate can safely withstand the bail pullout forces with a high factor of safety.

Fig. 13. Pulling of the FRP gate with the chain attached to the top bail

8. Stiffness of the FRP wicket gate

In this section, the stiffness of the FRP wicket gate is experimentally evaluated and compared with the theoretical value. Center of gravity (c.g.) of the wicket gate with two embedded steel plates is calculated as shown in Table A1 (Appendix A). Low stiffness of the core material (foam) is ignored in the calculations. Two embedded steel plates act compositely with the FRP section. Using a stiffness (E) value of 28.3 GPa (4.1 msi) for face sheets and primary webs, a modular ratio of 7.1 was obtained for steel plates embedded in the integrated FRP wicket gate. The density

of steel plates is 7861 kg/m^3 (0.284 lbf/in^3) as compared to 996.5 kg/m^3 (0.036 lbf/in^3) for FRP composites. It is necessary to compute composite moment of inertia of the FRP cellular deck including embedded steel attachment in order to find the overall stiffness of the FRP gate. The composite moment of inertia has been computed and shown in Table A2 of Appendix A.

Fig. 14. Cross-section of a FRP wicket gate with embedded steel plates

The center of gravity of the cellular FRP section with embedded steel plates is located at distance of 134.1 mm (5.28") from the surface marked as X-X in Fig. 14 and the total moment of inertia is $481.1 \times 10^6 \text{ mm}^4$ (1155.8 in^4) (Appendix A). From 3-point bending tests on the FRP wicket gate (see section 7.3) without steel fixtures, the total deflection of 14.81 mm (0.583") was obtained for a span of 4.57 m (15 ft.) and a central load of 89 kN (20 kip). By using Eqn. (20), the total deflection is separated into bending and shear deflections. With a shear modulus of 3.1 GPa (447 ksi) for FRP primary webs, the shear stiffness of the cellular FRP gate in the longitudinal direction is obtained as 88822.1 kN ($1.997 \times 10^7 \text{ lbs.}$) based on Eqn. (16).

After accounting for shear related deflection, the experimental bending rigidity is $1.31 \times 10^{13} \text{ N.mm}^2$ ($4.55 \times 10^9 \text{ lbf.in}^2$), which correlates well with the theoretical bending rigidity calculated using Eqn. (15) (Table 5). Addition of steel fixtures (edge angles and connecting plates) increased the flexural rigidity to $1.67 \times 10^{13} \text{ N.mm}^2$ ($5.82 \times 10^9 \text{ lbf.in}^2$) which resulted in a 28% gain.

Table 5
Flexural rigidity and Stiffness of the cellular FRP wicket gate

Bending test	Central load kN (kip)	Central deflection mm (in)	Experimental flexural rigidity (D) N.mm ² (lbf.in ²)	Theoretical flexural rigidity (D) N.mm ² (lbf.in ²) (Eqn. 15)	Experimental stiffness (E) GPa (msi)	Theoretical stiffness (E) GPa (msi)	Difference (%)
3-point (Section 7.3)	89 (20)	14.81 (0.583)	1.31×10^{13} (4.55×10^9)	1.29×10^{13} (4.49×10^9)	27.2 (3.94)	26.8 (3.89)	1.3

9. Deflection of FRP wicket gate system due to water load

Figure 15 shows the distribution of hydrostatic pressure on the upstream (u/s) and downstream (d/s) side of the gate during operating position. The maximum deflection at the tip of the gate (free end) occurs when there is full level of water on upstream side and only up to the level of the top hinge (prop location) on the downstream side. After deducting the hydrostatic pressure of the d/s side from the u/s side, the distribution of load is obtained as shown in Figure 15. For the given load distribution and hinge boundary conditions at A and B, the deflection at the tip (free end) can be obtained from Eqn. (24), obtained from virtual work principles. The lengths (L_1 and L_2) are shown in the Fig. 16 and the flexural rigidity of the cellular FRP deck with steel fixtures is obtained from section 8 as $1.67 \times 10^{13} \text{ N.mm}^2$ ($5.82 \times 10^9 \text{ lbf.in}^2$).

$$\text{Deflection at the tip (free end) } (\delta) = \frac{wL_1^3L_2}{24EI} - \frac{wL_2^4}{30EI} - \frac{wL_2^3L_1}{18EI} \quad (24)$$

Fig. 15. Operating position: a) hydrostatic pressure on both sides, b) d/s pressure deducted from u/s pressure

Fig. 16. Loading during operating position of a wicket gate

The deflection obtained from Eqn. (24) is 3 mm (0.12") which correlates well with the deflection of 3.11 mm (0.122") obtained from commercial structural analysis software. The deflection at the free end of the gate is equivalent to the ratio of $(L/660)$ for the cantilevered portion of 2.49 m and is acceptable for field implementation.

10. Field implementation of FRP wicket gates

The prop connection zone, shear pins and connecting devices at the base are the most susceptible components in the wicket gate assembly through which loads are transferred from one part to another. At present, connections of the FRP wicket gate at prop location, horse assembly utilize existing steel fixtures. However, it is intended in the future to develop and replace the entire assembly with FRP composites. Four FRP wicket gates were manufactured for field installation. One of these gates had all the existing steel attachments, while the other three gates had no steel angles on the edges of the gate, instead UHMWPE (Ultra high molecular weight polyethylene) plate was bonded on the upstream face and sides of the gates in order to minimize the use of steel attachments and also to monitor the effectiveness of UHMWPE plate on resisting abrasion and barge impacts in comparison to the steel. Figure 17 (a) shows the existing steel angle on the sides of the gate while Fig. 18 (b) shows UHMWPE plate on the sides covering the entire depth. All of the four gates have been installed in Mississippi River at Rock Island lock and dam, IL in August, 2015 as shown in Fig. 18. The monitoring of the gate will be done periodically to establish the relationship between strength and durability.

Fig. 17. FRP wicket gate, a) steel angle on the sides, b) UHMWPE on the sides

Fig. 18. Field installation of FRP wicket gates: a) lifting of the gate during installation, b) gates in 65° position

11. Conclusions

Following conclusions are drawn based on the design, testing and evaluation of integrated FRP wicket gates.

1. Integrated FRP wicket gate was successfully developed as a replacement to the existing timber wicket gate consisting of an assembly of several timber leaves and support blocks held together by an assortment of steel plates and angles that are fastened with numerous bolts and welds.
2. Based on the non-destructive bending load tests, FRP gate resisted an applied bending moment of 406.7 kN-m (300 k-ft.) with a maximum induced bending and shear strains of 3352 and 2230 micro-strains, respectively. These induced strains are about 1/4th to 1/3rd of the failure strains.
3. Design factors of safety for the wicket gate in bending, shear, and buckling are in the range of 4.3 to 16.4.
4. The experimental and theoretical stiffness values of the full-scale cellular FRP sandwich wicket gate without steel fixtures were found to be 27.2 GPa (3.94 msi) and 26.8 GPa (3.89 msi), respectively, showing an excellent correlation between the two.
5. Maximum theoretical deflection of the FRP wicket gate during operating position is 3 mm (0.12") at the tip of the gate and corresponds to an acceptable ratio of L/660 for the cantilevered portion (Fig. 16).
6. The field implementation of the FRP wicket gates was successfully performed. These gates will be monitored periodically to further evaluate their performance under actual field conditions consisting of turbulent water flow.

Appendix A

Table A1

Center of gravity of the FRP wicket gate with two embedded steel plates

Items		Dimension mm (in)	Areas mm ² (in ²)	Areas in terms of FRP mm ² (in ²)	CG from x-x, Fig.14 mm (in)
Two embedded steel plates	width	76.2 (3)	1452 (2.25)	11177.4 (17.33)	198 (7.79)
	depth	9.53 (0.375)			
FRP section	width	1168 (46)	57484 (89.1)	57484 (89.1)	108 (4.25)
	flange thickness	13.28 (0.523)			
	no. of webs	14			
	web thickness	10.16 (0.4)			
	depth	215.5 (8.5)			
Center of gravity of cellular FRP gate from bottom X-X (Fig. 14)					134.1 (5.28)

Table A2

Composite moment of inertia of FRP gate section with two embedded steel plates

Components of FRP gate cross-section	Moment of Inertia mm ⁴ (in ⁴)	Moment of inertia in terms of FRP mm ⁴ (in ⁴)
Two embedded steel plates	5.91 x 10 ⁶ (14.2)	42 x 10 ⁶ (100.8)
FRP section	439.1 x 10 ⁶ (1055)	439.1 x 10 ⁶ (1055)
Total moment of inertia of the FRP deck with two embedded steel plates		481.1 x 10⁶ (1155.8)

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