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Underwater Carbon Fiber–Reinforced Polymer (CFRP)–Retrofitted Steel Hydraulic Structures (SHS) Fatigue Cracks

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PURPOSE: Recent advances in the use of fiber-reinforced polymers (FRP) to retrofit steel structures subjected to fatigue cracks have shown to be a viable solution for increasing fatigue life in steel hydraulic structures (SHS). Although several studies have been conducted to evaluate the use of FRP for retrofitting metal alloys and the promising potential of such has been well-demonstrated, the application has never been implemented in underwater steel structures. This Coastal and Hydraulics Engineering Technical Note presents the implementation of FRP patches to repair fatigue cracks at Old Hickory Lock and Dam miter gate.

BACKGROUND: The conditions of SHS can threaten the integrity of the structure and need to be continuously inspected and repaired. Effective and economical retrofit practices are essential for ensuring continuous operation and mitigation for the level of risk associated with possible catastrophic failure. Current methods of repair fatigue cracks of SHS are adopted primarily from the bridge engineering industry and have proven to be ineffective in many cases because of excessive corrosion and deterioration of the design boundary conditions of the SHS, and in some cases to differences in operation and loading conditions (Riveros et al. 2022). In addition, the cost and time associated with the implementation of conventional repair methods can be rather significant.

Various studies have been carried out to assess the use of FRP for the rehabilitation of the increasingly aging and deteriorated civil structures and infrastructure systems in the United States. The deterioration is typically manifested in terms of fatigue cracking or corrosion cracking. Most previously conducted studies were aimed at investigating the use of FRP for flexure and shear retrofitting of concrete structures (Maruyama 1997; Meier and Betti 1997; Neale and Labossiere 1997; Täljsten 1997; Benmokrane and Rahman 1998; Thomas 1998; Triantafillou 1998; Miramiran et al. 2004). The studies highlighted the significant potential of such an application as demonstrated by the numerous field implementations of FRP repair of concrete structures. Much less research has been conducted on the use of FRP in strengthening metallic structures, with most studies geared toward flexure retrofitting of aluminum panels in the aviation industry (ASCE Committee on Composite Construction 2006). In general, research efforts on retrofitting steel elements have examined the repair of naturally deteriorated steel girders, repair of an artificially notched girder or steel plates to simulate fatigue cracks, strengthening an intact section to increase stiffness, and increasing the composite action between the steel girder and concrete deck in bridge application (Shaat et al. 2004).

Experimental and analytical studies on investigating crack growth of adhesively repaired steel panels were conducted on flat steel specimens and have shown an increase in fatigue life in comparison to the unrepaired specimens (Young and Roore 1992; Colombi et al. 2003; Jones and Civjan 2003; Duong and Wang 2004; Yue et al. 2004; Hansen et al. 2007; Liu et al. 2009). Very few studies have been conducted on fatigue crack propagation in CFRP-repaired large-scale specimens representing real structural members (Bassetti et al. 1999; Mertz et al. 2002; Tavakkolizadeh and Saadatmanesh 2003; Jiao and Zhao 2004; Shield et al. 2004; Vatandoost 2010; Kim and Harries 2011; Mahmoud and Riveros 2013; Mahmoud and Riveros 2014; Riveros and Lozano 2019; Riveros et al. 2018). Although in some of the large-scale studies the conclusion on fatigue life improvement is not clearly discussed, it can be generally concluded that a three- to seven-fold increase in fatigue life was observed for retrofitted specimens when compared to their un-retrofitted counterparts.

OLD HICKORY MITER GATE: Old Hickory Lock is located at mile 216.2 on the Cumberland River and is approximately 11.5 mi northeast of Nashville, TN. Old Hickory Lock is open to pass navigation traffic 16 hours a day, 365 days a year. Old Hickory Lock was opened to navigation traffic in June 1954. The lock chamber is 397 ft long and 84 ft wide. During normal lake levels, the lock will lift a boat 60 ft from the river below the dam to the lake above the dam. The project consists of a navigation lock, spillway, and powerhouse. The downstream miter gate is horizontally framed with twenty-three girders and two sets of diagonals. The gate leafs are 76.0 ft high, 48.0 ft wide, and about 5.0 ft deep (Figure 2).

Figure 1. Old Hickory Lock and Dam.

Figure 2. Old Hickory downstream miter gate.

A total of 3,940,698 tons of commerce and 1,112 recreational vessels locked through Old Hickory in 2014. The commercial traffic is mostly coal bound for the Tennessee Valley Authority's Gallatin Steam Plant, which is located at mile 242.0, 25 mi above the Old Hickory Lock and Dam.

Miter Gate Inspection: An inspection of the land and river side leafs was conducted with the purpose to find all fatigue cracks on the gates and areas with severe corrosion. Corrosion was not an issue in this gate, but several areas with fatigue cracks were found, and poor welding was also observed and documented. Figure 3 shows a poor welding connecting the diagonal gusset plate with the girder downstream flange. The two green circles show rough weld profile. The big circle shows weld undercut, while the small circle is pointing to intersecting welds. Figure 4 shows cracks that developed at the intersection between the end diaphragm downstream flange with the tapered end section flange and the end diaphragm downstream flange with girder flange. Cracks at the intersection of intermediate diaphragm and girder flanges are shown in Figure 5. Figure 5 also shows a rough weld profile and weld undercut. Finally, cracks at the downstream tapered end section flange and end plate flange and rough weld profiles are shown in Figure 6.

Figure 3. Poor welding quality at diagonal gusset plate (river side).

Figure 4. Crack at end diaphragm downstream flange with tapered end section flange and at end diaphragm downstream flange with girder flange.

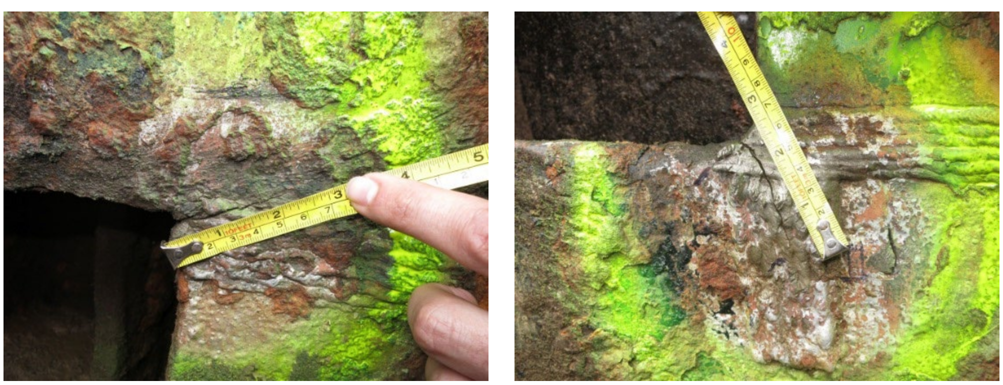

Figure 5. Cracks at intersection of intermediate diaphragm and girder flanges.

Figure 6. Cracks at downstream tapered end section flange and end plate flange.

Installation Procedures: To perform an installation of the FRP fatigue cracks repairs, the following steps must be performed.

a. Fabric preparation. After inspection, precut all fabrics before mixing any epoxy. Cutting fiber 24 in to 36 in long (Figure 7) is preferred.
b. Surface preparation. The required surface preparation is largely dependent on the type of element being repaired and strengthened. In general, the surface must be clean, dry, and free of protrusions or cavities, which may cause voids behind the Tyfo composite. Discontinuous wrapping surfaces (beams) typically require a sandblast, grinding, or other approved method to prepare for bonding. For SHS, the surface must be clear to the base metal. This can be accomplished either by grinding or sandblasting (preferable method) the surface and cleaning with acetone (Figure 8).
c. Mixing FYFE Tyfo S Epoxy. FYFE Tyfo S Epoxy is a two-component epoxy. The A component color is normally clear to amber with a thick consistency and slight resin smell. The B component is normally clear to yellow with a very thin consistency similar to water and has an ammonia-like smell. The FYFE Tyfo S Epoxy matrix material is combined with the FYFE Tyfo fabrics to provide a wet-layup composite system for strengthening structural members. Premix each component: 100 parts of component A to 34.5 parts of component B by weight. Mix thoroughly for 5 minutes with a low-speed mixer at 400 to 600 RPM until uniformly blended (Figure 9).
d. Mixing FYFE Tyfo TC Adhesive. FYFE Tyfo TC Adhesive is a two-component, solvent-free, NSF-certified epoxy matrix material specially formulated to provide improved adhesion of the FYFE Tyfo Fibrwrap System to vertical and overhead applications. It has proven effective on all USACE applications. Mix ratio: 100 parts of component A to 23.3

parts of component B by weight. Mix thoroughly for 5 minutes with a low-speed mixer at 400 to 600 RPM until components are thoroughly dispersed. Excessive mixing will shorten pot life (Figure 9).

e. Installation. The FYFE Tyfo SCH-41 is a custom, uni-directional carbon fabric orientated in the 0° direction. The material properties are listed in Table 1. Due to the cathodic reaction that occurs when carbon fibers interact with steel, a layer of FYFE Tyfo WEB glass fabric is installed between the steel and carbon fibers. Following are the steps performed during the installation of the CFRP.

1. Apply adhesive to the clean surface (Figure 10).
2. Install one layer of glass fiber (FYFE Tyfo WEB glass fabric) (Figure 11).
3. Apply adhesive to the glass fiber.
4. Carbon fiber saturation. It is recommended that Tyfo S is applied to one side of the carbon fiber with a roller. Then the semi-saturated layer of carbon fiber is applied to the glass fiber with adhesive. Once the carbon fiber is installed to the glass fiber, use a roller to complete saturation of the carbon fiber.
5. If a second layer of carbon fiber is needed, apply adhesive to the carbon fiber already installed, and apply Tyfo S to one side of the new carbon fiber layers with a roller. Once the carbon fiber is installed to the carbon fiber, use a roller to complete saturation of the carbon fiber (Figure 12).

Figure 7. Cutting fibers to specific lengths. At left, CFRP.At right, basalt fibers.

Figure 8. Sandblasting and cleaning the surface with acetone.

Figure 9. Mixing epoxy and adhesive.

Table 1. Material properties.

Material	Tensile Strength (MPa)	Elastic Modulus (GPa)
Steel	448	207
CFRP	4,000	230
BFRP	3,000–4,840	93–110
Epoxy (Tyfo S)	72.4	3.18
Adhesive (Tyfo TC)	22.7	1.2

Figure 10. Adhesive application.

Figure 11. Glass fiber installation.

Figure 12. CFRP installation.

Old Hickory Application: CFRP patches were applied on five locations on the Old Hickory gate: on cracks, on top of weld repairs of cracks, and on locations with no crack but with a potential to crack due to poor welding. Locations are shown in Figure 13 for the land side (left) and river side (right) leafs.

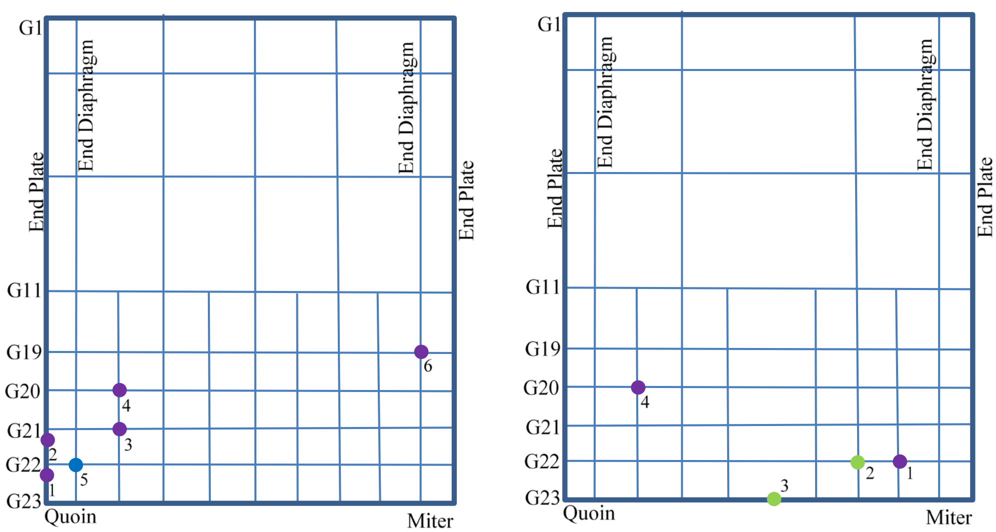

Figure 13. Land (left) and river (right) side leafs showing CFRP applications. Purple: Cracks with CFRP repairs, Blue: Cracks welded and repaired with CFRP. Green: No cracks, poor welds strengthened with CFRP.

Figures 14 through 20 show different locations on Old Hickory miter gates that where repaired. All the pictures start with the crack section and end with the final CFRP repair.

Figure 14. Repairs at locations 1 and 2. At left, glass fiber. At right, carbon fiber.

Figure 15. Crack pattern and CFRP repairs at locations 3 and 4.

Figure 16. Welded crack repaired with CFRP at location 5.

Figure 17. Crack repaired with CFRP at location 6.

Figure 18. River-side crack repaired with CFRP, location 1.

Figure 19. River side showing CFRP repairs when no cracks are present, locations 2 and 3.

Figure 20. River-side crack repaired with CFRP.

Conclusions: The retrofit methods using both CFRP and BFRP described and shown herein are a viable solution to repair fatigue cracks on SHS. First, FRP is an innovative method for fatigue crack repairs on SHS; second, the actual fatigue life is expected to be long lasting, due to the following:

a. FRP creating a seal against the environment on the crack and corrosion area
b. Increase in ductility, strength, and toughness by arresting or preventing cracking

Third, the FRP repairs are a low-cost and effective repair technique. Fourth, use of FRPs lower the time and risk needed to make repairs, increasing safety. Fifth, the FRP does not just arrest the fatigue crack, it also provides additional strength to the cross section.

ADDITIONAL INFORMATION: For additional information, contact Dr. Guillermo A. Riveros, Information Technology Laboratory, US Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180 at (601) 634-4476, (601) 415-1047, or by email at Guillermo.A.Riveros@usace.army.mil. This effort was funded through the Navigation Systems Research Program. The Program Manager is Morgan M. Johnston, phone (601) 634-2365, email Morgan.M.Johnston@erdc.dren.mil. This CHETN should be cited as follows:

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