Carbon Fiber Composite Cables for Gate Operation

ERDC Dredging Operations Technical Support Program (DOTS)

U.S. ARMY CORPS OF ENGINEERS BUILDING STRONG®

Response Summary:

Robert Henry of the Operations Division in the Nashville District submitted a Dredging Operations Technical Support (DOTS) request for assistance in studying the feasibility of carbon fiber composite cables (CFCC) for gate lifting operations. ERDC researchers traveled for a site visit, assembled historical information, and conducted market research to determine the risks associated, identify site-specific challenges, and generate a rough estimate for the number and size of cables needed to meet simplified load requirements and EM-1110-2-2610 guidelines. A combination of 4 CFCCs (19 strand, 1.35-in. diameter) provide an ultimate strength of approximately 1,200 kips with a factor of safety (FS) of 8.8, meeting the Engineer Manual FS requirement of 5. This arrangement of CFCCs would provide a higher FS than the existing chain design using AISI 4140 steel, subject to known risks discussed in this report. Design challenges remain in balancing the minimum bend radius on a drum within the available space on the existing machine platform. Material challenges remain in production and testing standards as well as long-term mechanical and environmental performance.

Chains are included in the analysis of ERDC SR-24-3, "Composite Material Applications and Research Roadmap for US Army Corps of Engineers Civil Works," though at extremely low priority with a Normalized Combined Component Score in Table B-4 of 0.00 out of 10. The subjective assessment on page 75 of the Research Roadmap does not recommend consideration of composite materials for this application at this time, as applicable research and development would be required for a sound design, considering the conditions of mechanical creep and wet-dry cycles as well as the lack of applicable manufacturing and testing standards.

Period of Performance:

15 November 2023 to 30 September 2024

Benefits of the Response to the USACE Dredging/Navigation Program:

The Navigation program benefits from extended engagement and communication of composite material prototypes and conceptual designs in support of Engineering and Construction Bulletin 2024-08, "Design of Fiber Reinforced Polymer Hydraulic Composite Structures." Composite structures bring the potential to avoid hundreds of millions of dollars of lifecycle maintenance costs across the enterprise when compared with in-kind steel replacements of failing components. Additional details are available in the Composite Material Research Roadmap.

Deliverable:

The ERDC compiled a Letter Report in order to disseminate existing specific information and expand applicability of the solution across the enterprise.

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ERDC/CERL Letter Report

Construction Engineering Research Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Dredging Operations Technical Support

Carbon Fiber Composite Cables for Gate Operation

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September 2024

Executive Summary

Robert Henry of the Operations Division in the Nashville District submitted a Dredging Operations Technical Support (DOTS) request for assistance in studying the feasibility of carbon fiber composite cables (CFCC) for gate lifting operations. ERDC researchers traveled for a site visit, assembled historical information, and conducted market research to determine the risks associated, identify site-specific challenges, and generate a rough estimate for the number and size of cables needed to meet simplified load requirements and EM-1110-2-2610 guidelines. A combination of 4 CFCCs (19 strand, 1.35-in. diameter) provide an ultimate strength of approximately 1,200 kips with a factor of safety (FS) of 8.8, meeting the Engineer Manual FS requirement of 5. This arrangement of CFCCs would provide a higher FS than the existing chain design using AISI 4140 steel, subject to known risks discussed in this report. Design challenges remain in balancing the minimum bend radius on a drum within the available space on the existing machine platform. Material challenges remain in production and testing standards as well as long-term mechanical and environmental performance.

1 Introduction

This report responds to a Dredging Operations Technical Support (DOTS) request for assistance in studying the feasibility of carbon fiber composite cables (CFCC) for gate lifting operations.

1.1 Background

A DOTS request was submitted by Robert Henry of the Operations Division in the Nashville District, part of the Great Lakes and Ohio River Division. Many dam projects on the Cumberland River use chains for Tainter gate lifting operation. These chains are typically constructed from high alloy steel, such as 4130 or 4140. District staff indicated that the replacement cost for 10 chains is approximately $1.6 million. Each chain at Cordell Hull is 66-ft. and 6-in. long. Chains are operated through a reducing gearbox by 10 horsepower motors which draw 13.3 A at 480 VAC.

Replacing these chains with CFCCs could simultaneously solve issues of corrosion, wear, and thermal expansion. The implementation of CFCCs within this system would directly contribute to the research and development priority of modernizing our nation’s infrastructure.

1.2 Objective

Our objective in this DOTS effort is to collect information about CFCCs in one place to check feasibility and aid decision-making for implementation of CFCCs in gate lifting applications.

1.3 Approach

Our approach began with conducting a site visit to gain a complete understanding of the geometric and operational limitations of the mechanical platform. We then collected our site visit findings and references in this report, along with simplified calculations to check for adequate static mechanical performance.

2 Site-specific challenges

The Cordell Hull Tainter gate mechanical system appears capable of supporting conversion to cable lift, subject to geometric limitations. To avoid changes to the machine platform structure, the width and diameter of cables and drums is limited (Figure 1 and Figure 2).

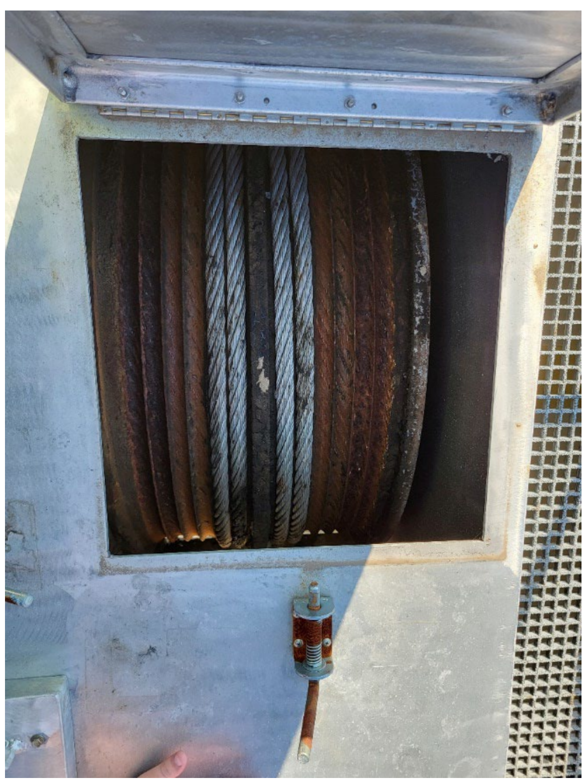
Figure 1. Existing mechanical platform at the Cordell Hull Dam.

Figure 2. Close-up of existing lift chain equipment at the Cordell Hull Dam.

During a separate visit to the Calcasieu Saltwater Barrier, we photographed drums carrying stainless steel lift cables that were installed during 1999 (Figure 3 and Figure 4). The cables and drums remain in good condition 25 years later. The drums can carry 6 winds, 2 of which being dead winds. With an approximately 2-ft. diameter drum, the 4 winds will hold around 25-ft. of operating length of cable. The Tainter gates at this project are 60-ft. wide and 21-ft. tall.

Figure 3. Overview of cable lift equipment at the Calcasieu Saltwater Barrier.

Figure 4. Cable drum at the Calcasieu Saltwater Barrier with provision for 6 winds of dual 1.25-in. cables.



As with most Tainter gate operating equipment, it would be beneficial to install low-friction guides on the gate to protect against abrasive wear on both the gate and the cable or chain (Figure 5).

Figure 5. Chain interfacing with the gate at Cordell Hull.

3 Carbon Fiber Composite Cable (CFCC)

The manufacturing of cables made from Carbon Fiber Reinforced Polymer (CFRP) is a bit different from the classic methods of steel cables. Steel cables are first drawn into wires from molten steel, worked down through mandrels, annealed or hardened in heat treatment processes, and eventually fed through a strander. CFRP cable, however, is constructed beginning with a matrix of polymer resin embedded within carbon fibers. This is done using a pull winding manufacturing method, which combines the pultrusion method with a constant spooling of the carbon fiber. These constructed wires are then twisted into a helix to create the final product. (https://usace.dps.mil/sites/KMP-IND/Shared%20Documents/Composites%20Users%27%20Group/Users%27%20Group%20Presentations/Slide%20Decks%20and%20Presentation%20Material/2023-02-02%20-%20Carbon%20Fiber%20Composite%20Cable%20-%20Tokyo%20Rope%20-%20Presentation.pdf)

3.1 Mechanical Properties of Steel and CFCC

Mechanical properties listed for AISI 4140 steel in the previous lifting chain calculations (COR Lifting Chain Calculation – OCA Rating Change Justification, 03 Aug 2020) include Brinell hardness of 275-300, yield strength of 121 ksi, and ultimate strength of 138 ksi. Tokyo Rope, a CFCC manufacturer, provides a cut sheet including their 19-strand cable product with diameter of 34.3 mm (1.35-in.) and breaking load of 1,342 kN (301.69 kips). Due to the limited of ductility of carbon fiber materials, we will only compare the breaking load with the ultimate tensile strength of steel, as the yield strength of CFCC is similar to the breaking load. The cable will need to lift 137 kips and maintain a factor of safety (FS) of 5 according to EM-1110-2-2610. For 19-strand CFCC, 4 cables would be needed to generate an ultimate strength of 1207 kips and FS of 8.8. According to the 2020 calculations, the FS of the 4140 chain side bars and pins are only 2.41 and 2.65, respectively.

Due to the restriction of available space on the existing machine platform, increasing the drum width or the number of drums to accommodate 4 cables per gate may be infeasible. Two of the 19-strand CFCCs can carry approximately 603 kips at an FS of 4.4. Maintaining FS of 5 would require at least 3 cables, and complete redundancy would require 4 cables, potentially necessitating machine platform modifications.

3.2 Known Manufacturers and Suppliers

Due to the recent onset of CFCC technology and limited quantity of research publications, we found few manufacturers currently producing this product for sale. Known suppliers include the Tokyo Rope Manufacturing Company (https://tokyorope-intl.co.jp/cfcc/cfcc.html), KONE (https://www.kone-major-projects.com/high-rise-solutions/ultrarope.aspx), and Carbo-Link (https://www.carbo-link.com/).

3.3 Known Risks

Along with many benefits already realized by the elevator and reinforced concrete industries, we recognize at least 7 key known risks involved with the implementation of CFCCs on hydraulic infrastructure projects.

- Fire resistance
- Anchorage and coupling
- Wet-dry cycling of epoxy resin
- Freeze-thaw cycling in salty environments
- UV resistance
- Lubrication and guides
- Mechanical creep

According to a review done by Yue Liu, Bernd Zwingmann, and Mike Schlaich, CFCCs have poor fire resistance when exposed to extreme temperatures. Therefore, proper precautions should take place in the development and use of these cables (https://doi.org/10.3390/polym7101501).

Proper anchoring and coupling can pose challenges when using CFCCs due to their orthotropic characteristic and brittle behavior. Improper anchorage can lead to premature failure, which is well documented in prestressed and post-tensioned concrete tendon applications in state-of-the-art reports maintained by the American Concrete Institute.

In a reliability study done by Hongjun Liang, Shan Li, Yiyan Lu, and Ting Yang, results from testing tensile bars made from CFRP composites exposed to wet-dry cycling with a solution designed to mimic seawater showed that while elastic modulus only slightly decreased around 0.85%, tensile strength decreased by around 9.3%. Tensile strength decreased more in the early stages of the cycling and then began to level off at the end stages. This same trend of rapid early degradation followed by more consistent long-term performance was found for creep elongation rates (https://doi.org/10.3390/app8060892).

Along with wet-dry cycles, according to an analysis done by the ASCE (American Society of Civil Engineers), in extreme temperature conditions, freeze-thaw cycles can bring an array of other risks including matrix hardening, microcracking, and fiber-matrix bond degradation. With the presence of salt, these effects can create an effect of rapid degradation as salt deposits exacerbate the fatigue effects of swelling and drying in wet-dry cycles (https://doi.org/10.1061/(ASCE)1090-0268(2003)7:3(238)). The study on wet-dry cycles and the analysis from the ASCE was done with focus on CFRP and FRP coupons, so it should be noted tests were not performed specifically on CFCC.

UV (ultraviolet) radiation is a known risk when selecting any CFRP product with epoxy resin. Testing results from a journal article written by Ayman Mosallam, Haohui Xin, Shaohua He, Ashraf AK Agwa, Suleyman Adanur, and Mohamed A Salama show that UV radiation has clear effects on the fatigue life of CFRP triaxial composite laminates (https://doi.org/10.1177/00219983211055828).

A lubrication plan for CFCC would differ from traditional steel cables. The constant rubbing on the gate can cause damage from abrasion and affect the structural integrity of the CFCC. Low-friction guides or plates attached to the gate may help mitigate this issue.

Lastly, it is highly encouraged that tests are run on contractor submittal materials to develop and validate predictive models for creep elongation rates (https://doi.org/10.1016/j.compstruct.2024.117965).

4 Context of Official Guidance

EM 1110-2-2610 guides the design and specification of cable lifting systems for gate operation.

4.1 Redundancy Requirements

Section 2-3 of EM 1110-2-2610 states the gate operating equipment design should include redundancy or interchangeable components. This statement suggests deploying multiple lift cables that can support the gate and prevent racking in case of failure of one cable. It remains the responsibility of District design staff to determine whether a redundant cable system or spare cables available onsite would be most appropriate for Cordell Hull.

4.2 Bend Radius

A detail note in Plate B-59 of EM 1110-2-2610 states that the minimum bend radius for a wire rope shall not be exceeded. Further discussion of bend radius takes place throughout the sections in Chapter 2 discussing grooved drums and sheaves for wire ropes. The user manual provided by Tokyo Rope (https://tokyorope-intl.co.jp/content/pdf/civil/March%202023%20CFCC%20Manual%20V1.00.pdf) clearly requires a minimum bend radius of 40 times the diameter of the cable, well above any of the guidance presented in EM 1110-2-2610.

In the case of the 19-strand cable under consideration here, this 40 times cable diameter guidance would necessitate a drum diameter of approximately 9 feet. This is clearly not feasible given the current conditions of the machine platform. The District design team ought to consider a smaller diameter CFCC, such as one of the 7-strand varieties made by Tokyo Rope. However, a higher quantity of smaller cables, and thus wider or higher quantity of drums, would be needed to meet the required FS of 5.

4.3 Alternative Design

Figure 2-43 of EM 1110-2-2610 shows a pin plate connected to multiple wire ropes. A keen designer can conceive a plan to replace only a minimal section of the existing chain, retain the existing chain equipment, and attach the chain to a pin plate connected to multiple CFCC that then connect to the gate and experience the challenging immersion service conditions.

5 Conclusions and Recommendations

Chains are included in the analysis of ERDC SR-24-3, “Composite Material Applications and Research Roadmap for US Army Corps of Engineers Civil Works,” though at extremely low priority with a Normalized Combined Component Score in Table B-4 of 0.00 out of 10. The subjective assessment on page 75 of the Research Roadmap does not recommend consideration of composite materials for this application at this time, as applicable research and development would be required for a sound design, considering the conditions of mechanical creep and wet-dry cycles as well as the lack of applicable manufacturing and testing standards.

5.1 Conclusions

This report serves as a collection of information to aid the decision-making process and help identify the next steps to explore applicable research and development tasks while pursuing the implementation of CFCCs for gate lifting operations. After combining market research with site-specific information and guidance from EM-1110-2-2610, simplified calculations show that CFCCs could provide a high FS of 8.8, which compares favorably to AISI 4140 steel chains. Challenges of creep and wet-dry cycling that stem from the epoxy resin used in commercial-off-the-shelf cables, as well as relatively large minimum bend radius, lead us to recommend pausing consideration of CFCC for this application. Stainless steel cable remains a viable alternative to chains.

5.2 Recommendations

The EM-1110-2-2610 should be followed when running calculations of factored loads to meet required redundancy and FS. Once calculations for quantity and diameter are complete, market research should be thoroughly performed for pricing of the appropriate cable needed. A sample from the manufacturer (approximately 20 to 40 feet) should then be obtained for testing of all risks relevant to the safety and proper operation of the gate. Some recommended tests and development tasks include, but are not limited to:

- tension fatigue testing of the cable both with and without appropriate anchorage couplers attached

- mechanical creep rupture tests to obtain creep elongation rates throughout the development of cumulative damage
- testing for moisture absorption and strength loss after water immersion (wet-dry cycling) due to the use of epoxy resin
- testing strength after accelerated exposure to UV radiation
- developing vinyl-ester solutions with a partnered manufacturer to avoid environmental stressors
- testing for damage after freeze-thaw cycles
- testing fire-resistance
- developing certainty of performance of anchoring systems through firm installation guidance
- developing a lubrication plan and abrasion testing

Appendix A: White Paper Research Proposal

Research Proposal

Date: October 23, 2023; Prepared by: US ARMY ERDC-CERL (CEERD-C)

Summary:

Steel and stainless-steel cables and chains have been used for raising and lowering dam and weir gates in numerous USACE projects. These chains are prone to corrosion, which increases maintenance costs and premature failure. Fiber-reinforced polymer (FRP) ropes have emerged as a viable alternative to steel cables and chains due to their exceptional corrosion resistance and specific strength. In American Concrete Institute documentation, the classifications of FRP tendons encompasses four distinct types: aramid FRP (AFRP), carbon FRP (CFRP), glass FRP (GFRP), and basalt FRP (BFRP). When considering the fatigue strength limits of various FRP tendons, it is widely acknowledged that CFRP tendons have the lowest susceptibility to fatigue failure (Jianfeng Zhao 2020). The notable **advantages** of CFRP include:

1. Good fatigue strength, as much as three times that of steel (Zou 2003)
2. Tensile strength is higher than that of steel cables; for instance, the tensile strength of Tokyo Rope CFCC is 2.1 GPa compared to 1.5 GPa for steel (Yue Liu 2015)
3. Good corrosion resistance.
4. Low thermal expansion allows CFRP to be used in widely varying climatic conditions.
5. Electromagnetic neutrality, high resistance against abrasion, and excellent chemical resistance.
6. Easy to handle in construction due to its low density.

The **disadvantages** of CFRP tendons are as follows:

1. Premature failure at the anchorage is widely known as a common failure mode of CFRP tendons due to their orthotropic characteristic.
2. Lower elastic modulus than that of steel cables. As an illustration, the elastic modulus of Tokyo Rope CFCC is 137 GPa as opposed to steel's 160 GPa.
3. Brittle failure behavior that may not visually warn users prior to a catastrophic failure (although steel cables often suffer similar fate).

The cost of CFRP cables is high (10 -15 times that of steel), but can be economically competitive if life cycle and maintenance costs are considered.

There are several manufacturers (*e.g.*, Tokyo Rope, Carbo-link, and Kone) offering different types of CFRP cables and strips for structural applications. To date, CFRP cables are mostly used in bridges, where cables experience sustained static loads. Their usage in dynamic loading conditions as well as wet environments is minimal. Hence, there is not enough benchmark experimental data on commercial CFRP available for dynamic loading. In recent years, a commercial CFRP product named 'UltraRope' has been used in lifting elevators of high-rise towers, for instance, at Marina Bay Sands Resort in Singapore (Utrarope n.d.,

Dong-Jun Kwon 2019). Apart from fatigue, the mechanical evolution behavior of CFRP in service environments (underwater and marine) is a matter of concern. In CFRP, carbon fibers are embedded into epoxy resin (Zou 2003, Saadatmanesh 1999), which may adsorb water if submerged for a long time. Water uptake of resin can lead to swelling, which can cause micro-cracking in the matrix and debonding at the fiber-epoxy interface. Furthermore, epoxy resin may become brittle if it is exposed to freezing temperatures for a prolonged period of time.

We propose to conduct an experimental investigation to check the feasibility of using CFRP cables as an alternative to steel cables or chains. Our study includes the following tasks:

1. Dynamic loading tests of CFRP cables with different anchorage systems in wet and dry environments.
2. Investigate the degradation of CFRP, especially epoxy, under wet conditions and freezing temperatures.
3. Evaluate the economic feasibility of CFRP relative to steel chains.

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