

Destructive Testing of Dam Spillway Gates for Development and Validation of Structural Health Monitoring Methods

BRIAN EICK and KIRK ATWATER

ABSTRACT

Dams are used throughout the world to enable commercial traffic on rivers, provide hydropower and/or flood protection, as well as collect and store water for drinking and irrigation needs. Many dams have steel spillway gates that are used to release water or otherwise regulate flow through the dam. Failure of dam spillway gates can lead to uncontrolled release of water with significant risk to life safety and the economy. Structural Health Monitoring (SHM) of dam spillway gates is increasingly used to monitor these critical assets and provide information to enable proactive maintenance and prevention of catastrophic failures. Like most civil infrastructure, a key challenge to development of SHM systems is the acquisition of validation and/or training data of the structure in the damaged state. At Lock and Dam 22 on the Mississippi River, the spillway gates of the dam are being replaced, with the intention to scrap and recycle the old gates. This gate replacement provides a unique opportunity to perform destructive testing on the existing gates to deliberately induce damage and/or undesirable operational characteristics on the gates that would be valuable detection targets for an SHM system. This paper discusses the first sets of testing performed on the existing gates prior to their removal, where a sensor system was installed. Then, just prior to removal of the gate, a number of simulated cracks were flame-cut into. Additionally, extreme friction in the gate's pivot points was induced using a novel procedure, and skewed lifting of the gate was induced with the use of a crane. In each case, the gate was operated, and data was collected. This paper presents the preliminary analysis and conclusions of the data collected including simple methods for detection of trunnion friction and a surprising method of using accelerometers on structural components to measure and monitor for uneven hoisting of the gate.

INTRODUCTION

In their natural state, most rivers have insufficient depth to allow for commercially viable traffic. To overcome this challenge, dams This traffic supports the transportation of hundreds of billions of dollars in goods annually, and so, maintaining operability of

these dams are constructed to raise the depth of water so that the rivers can support traffic that enable transportation of goods worth billions of dollars annually. A typical river dam located on the Mississippi River is shown in Figure 1. Unlike typical reservoir dams, river dams generally have ten or more spillways, each of which typically has a steel spillway gate to regulate flow. Also, unlike reservoir dams, these spillway gates are almost always open to maintain flow in the river. The degree to which they are open depends on hydrologic conditions and the amount of flow through the dam that is necessary to maintain the appropriate river depth without allowing flooding.

Among the most common spillway gates on dams are radial gates, often referred to as Tainter gates. These gates swing through a circular path about a central pivot point known as the trunnion. The swinging is facilitated by a number of methods, with a particularly common method being cables or chains connected to each side of the gate which spool via a winch mechanism to raise and lower the gate. The most critical structural components on the gate are the strut arms, the trunnion, the horizontal girders, and the skin plate, which are labeled in Figure 2. Typically, the gates are designed to allow flow of water underneath, and so, raising the gates increases flow through the spillway.

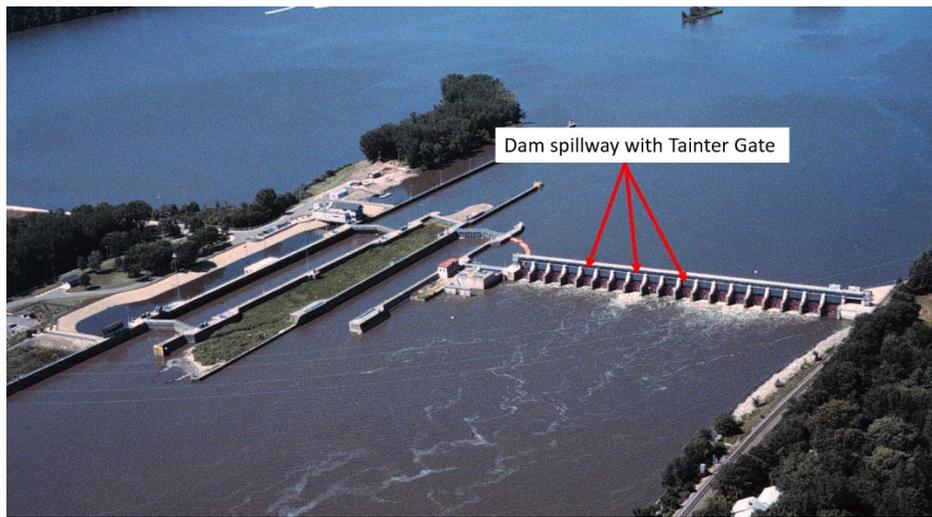


Figure 1. Lock and dam on the Mississippi River, with multiple Tainter gates

While uncommon, there are several documented instances of Tainter gate failures [1] [2] [3] [4]. The literature suggests a myriad of causes of Tainter gate failures. Of particular interest to this paper is fatigue, trunnion friction, and uneven hoisting. Fatigue is an issue with Tainter gates due to both the cyclic nature of the loading experienced when they're raised and lowered, and for the vibrations caused as water flows under the gate. To exacerbate the fatigue concerns, in the US, many Tainter gates have been in service well beyond their design life and have been subjected to hundreds of thousands of load cycles, and fatigue cracks are commonly found. Excessive friction in the trunnion is problematic due to the additional forces this creates on structural components as the gate swings up and down, further exacerbating fatigue. Similarly, uneven hoisting of the gate, where the cables on one side of the gate carry more of the weight of the gate, will exacerbate fatigue and potentially lead to instability-type failures.

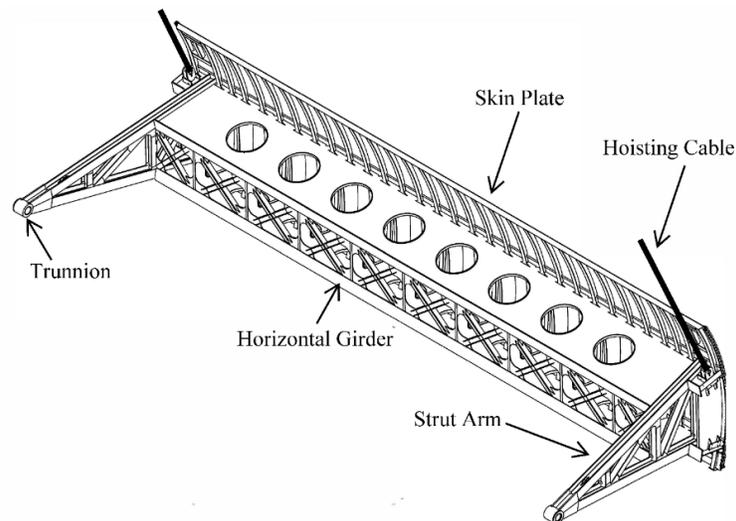


Figure 2 Isometric view of a Tainter gate, with critical components labeled

Given the importance of riverborne transportation, and the key role that Tainter gates provide, obtaining high quality and consistent information on the condition of these structures to enable timely maintenance and prevent failures is of critical importance. With the difficulty of inspection of these structures, structural health monitoring has become increasingly common for Tainter gates as outlined in Alexander, et al [5], and Eick, et al [6]. In this paper, a unique opportunity to further validate existing SHM approaches, while also developing new approaches, is discussed. Specifically, the Tainter gates at Lock and Dam 22 on the Mississippi River are being replaced, with the old gates being removed and scrapped. As the existing gates will no longer be used, approval was given by the US Army Corps of Engineers Rock Island District to perform destructive testing on these gates to simulate common damage modes and determine the efficacy of approaches of detection. To that end, fatigue cracks were flame cut into components of the gate, trunnion friction was deliberately induced, and uneven hoisting was simulated with the aid of a crane. The testing efforts and initial results are discussed herein, with clear indications of the successful ability of even rudimentary sensing methods to detect trunnion friction and uneven hoisting. Unexpectedly, a new method was also developed using vibration measurements on easily accessible components of the gate to infer the tension in the hoisting cables to detect uneven hoisting. This method is discussed at length by Eick, et al. [7], and summarized herein. While only one gate has been tested thus far, the results of this initial test will be leveraged to further refine future instrumentation and testing plans, the results of which are expected to lead to more robust SHM approaches for this critical infrastructure.

THE TAITER GATE AT LOCK AND DAM 22

Lock and dam 22 is located on the Mississippi River, just downstream of Hannibal, Missouri. This dam consists of ten Tainter gates and three roller gates, with each of the Tainter gates scheduled to be replaced in the forthcoming years. The scheduled replacement has presented a unique opportunity to perform destructive testing on in-situ gates, enabling collection of data for validation of existing SHM methods, as well as potential development of new methods. The first such gate to be destructively tested

was removed in 2024, with the instrumentation and testing plan, as well as some results, discussed below. The gate being prepped for testing and ultimate removal is shown in Figure 3.



Figure 3 Tainter gate being prepped for testing and removal at Lock and Dam 22

Instrumentation

Instrumentation on the gate consisted of numerous inclinometers and strain gages placed along the strut arm of the gate. The inclinometers are intended to enable inferring the position of the gate as it swings, while also potentially detecting uneven hoisting. The strain gages were placed strategically near the trunnion of the gate to detect the additional bending moment that would be caused by trunnion friction. To do this, at a particular cross section, one strain gage was placed at each of three corners to measure axial strain, with the specific location of strain gages shown in Figure 4

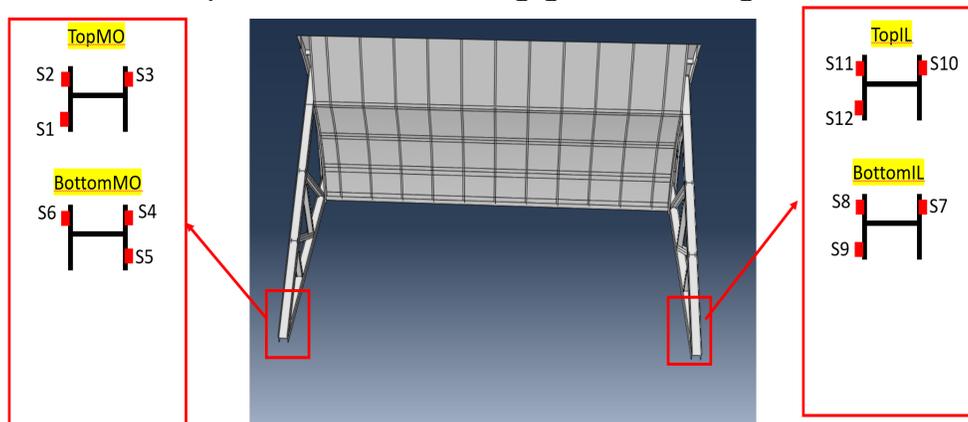


Figure 4 Location of strain gages on the Tainter gate.

The axial load, P , and the bending moments M_x and M_y , about the x and y axes respectively, can be resolved per equation 1

$$\begin{bmatrix} P \\ M_x \\ M_y \end{bmatrix} = \begin{bmatrix} \frac{1}{A} & \frac{c_{x_1}}{I_{xx}} & \frac{c_{y_1}}{I_{yy}} \\ \frac{1}{A} & \frac{c_{x_2}}{I_{xx}} & \frac{c_{y_2}}{I_{yy}} \\ \frac{1}{A} & \frac{c_{x_3}}{I_{xx}} & \frac{c_{y_3}}{I_{yy}} \end{bmatrix}^{-1} \begin{bmatrix} E \epsilon_1 \\ E \epsilon_2 \\ E \epsilon_3 \end{bmatrix} \quad (1)$$

Where A is the cross-section area, I_{xx} and I_{yy} are the x and y moments of inertia, E is the Young's modulus of steel, ϵ_i is the measured strain at gage i , and c_{x_i} and c_{y_i} are the signed distances of gage i from the respective neutral axis of bending. In addition to the aforementioned sensors, accelerometers were also placed on the strut arms and horizontal girders of the gate with the goal of investigating modal analysis methods. Cameras were also used to investigate non-contact monitoring approaches, which is discussed at length in Wang, et al., [8], and so not discussed further here.

Destructive Testing Procedure

The destructive testing plan was devised to enable to get the most useful information within the limited time available for planning, procurement of materials (such as sensors) and time on site to physically perform the testing. Testing had to occur within a small window of time during the gate replacement procedure to minimize impact to the construction schedule. In order to remove the gate for replacement, the trunnion pin, about which the gate rotates, needed to be broken free from the trunnion hub. This procedure requires using the weight of the gate and relying on the gate's structure to forcibly break the corrosion-induced bond between the gate and the pin. Because this procedure relies on the gate's structure and is necessary to remove the gate, it was performed first. After the trunnion pin was broken, 5 cracks were flame cut into the gate. Crack 1 completely fractured each of the downstream flanges of the horizontal girders on the gate. Crack 2 ran through half of the flange of the lower chord of the strut arm truss. Crack 3 simulated complete fracture of one of the diagonals on the strut arm truss. Cracks 4 and 5 simulated cracks through half of each flange of the bottom truss chord immediately next to the trunnion. The location of the cracks is shown Figure 5. After the cutting of each crack, the gate was operated up and down and the data recorded. Finally, the last procedure performed before the gate was removed was using the crane to simulate uneven hoisting of the gate. To do this, the crane was connected to one side of the gate and the gate was raised as though only one set of cables was present, while data was recorded

RESULTS

Not surprisingly, the strain gages were ineffective at detecting the induced cracks numbers 1 and 2. Conversely it was surprising that the strain gages were also ineffective at detecting the remaining cracks. Crack 3 effectively simulated the removal of an entire member from the structural system, while cracks 4 and 5 were very near the strain gages and in a region of significant stress gradient due to the trunnion support nearby.

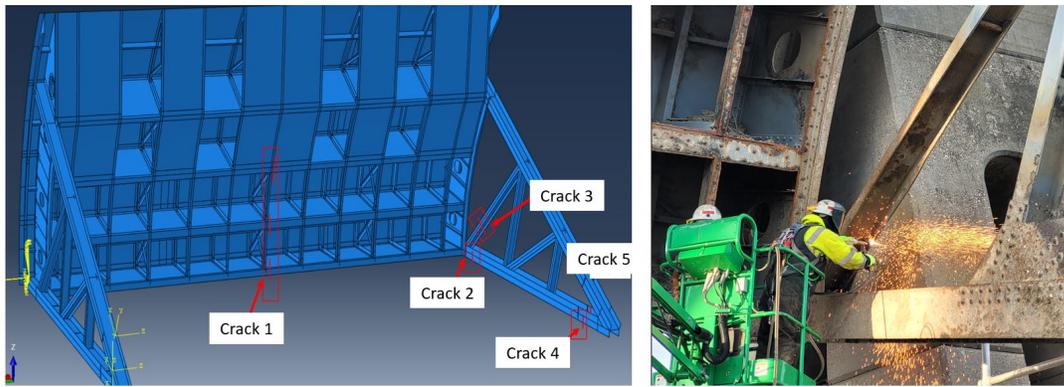


Figure 5 (left) location of cracks (right) process of cutting crack 3, to completely fracture truss diagonal

These three cracks were expected to noticeably alter the load path through the strut arm, but changes in measured strain were negligible. It is expected that exploring modal analysis and system identification methods might be more fruitful, particularly with detection of crack 3, as this crack will alter the global stiffness of the structure. Utilizing the accelerometer data for modal analysis is an ongoing effort, with results forthcoming.

Detection of trunnion friction

During the trunnion pin breaking procedure, strain gage data was collected and converted to axial loads and bending moments as in equation 1. The resulting estimates are shown Figure 6, where the black series show estimates from a normally operating gate, and the red series show the estimates from extreme trunnion friction induced by the pin breaking procedure. These results are plotted versus the position of the gate, as measured by the installed inclinometers. As seen, trunnion friction is readily detected during both cases, where there is an initial spike in bending moments due to static friction. During the pin breaking procedure, the initial static friction needed to be overcome is clearly significantly larger.

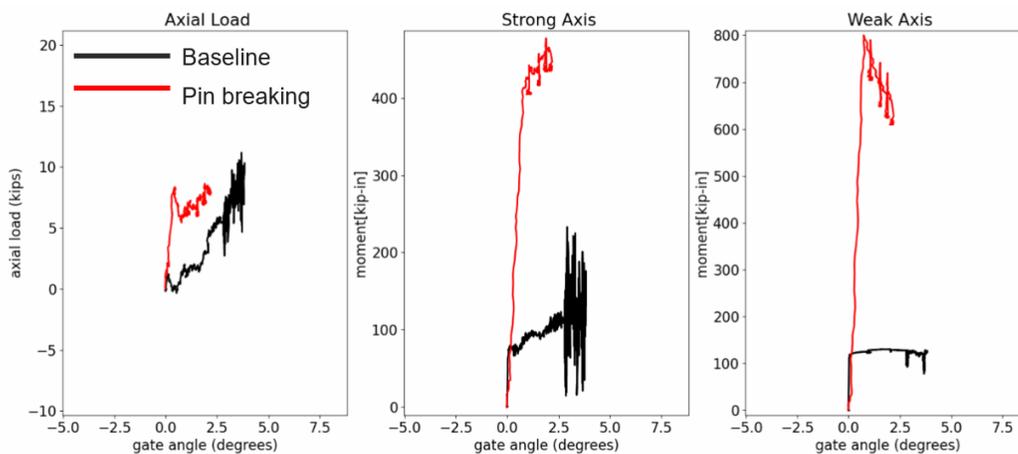


Figure 6. Axial load and bending moments estimated during normal operations and during extreme trunnion friction

Detection of uneven hoisting

From the data collected during the induced uneven hoisting, the strain gages were readily able to detect asymmetry in the axial loads and bending moments caused by the extreme unevenness induced in the gate. More surprising, however, is that the accelerometers installed on the strut arms of the gate were able to detect uneven hoisting during normal operations of the gate. A brief overview of the approach to use accelerometers on the easily accessible strut arms to detect uneven hoisting is provided herein, with far more detail provided in Eick, et al., [7], including details on laboratory testing to validate the approach. The approach relies on the fact that the Tainter gate is raised and lowered by link chains on each side. When these chains unspool from the hoisting mechanism, the links pop into a particular configuration. This popping works as an impact load, exciting the fundamental frequency of the chains. The induced free vibration of the chains is then picked up by the accelerometers on the strut arms. To detect uneven hoisting, the tension in the chains on each side of the gate is estimated based on the well-known relationship between tension, T , in a string and the fundamental frequency of vibration, f , shown in eq. 2.

$$f = \frac{1}{2L} \sqrt{\frac{T}{\mu}}, \quad (2)$$

where L is the length of the string and μ is the linear mass of the string (mass per length). For identical chains on each side of the gate, the main driver for a difference in fundamental frequency in the chains is a difference in tension necessarily leading to a skew in the gate during hoisting, and thus an unevenly hoisting gate. During the gate operation events performed during this testing, the acceleration records were collected from the accelerometers on the strut arms, and a short-time Fourier transform was used to extract frequency content with respect to time. Two distinct trends in the frequency content were seen for each event of gate operations, corresponding to the fundamental frequency of the chains on each side of the gate as seen in the left of Figure 7. These trends clearly demonstrate the differing tension in the chains indicative of an unevenly hoisting gate, whereas an evenly hoisting gate would have equal tension in each chain. The estimated tension in the chains is shown in the right of Figure 7

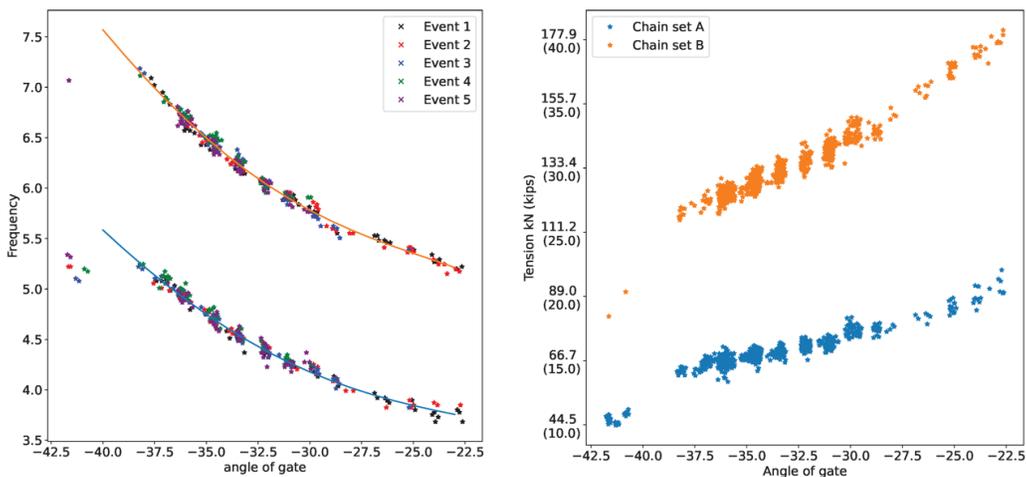


Figure 7 (left) Extract frequencies and (right) estimated tension in each set of chains versus gate position.

CONCLUSIONS

The upcoming replacement of Tainter gates at Lock and Dam 22 on the Mississippi River has presented a unique opportunity to perform destructive testing on the old gates to collect data for verification of existing SHM methods, as well potential development of new methods. This paper outlines the testing performed on the first such gate to be removed and replaced. This gate was instrumented with strain gages, accelerometers, inclinometers, and string potentiometers. Several damage scenarios were directly implemented on the gate, including flame cutting cracks, complete removal of structural components, inducing extreme trunnion friction, and simulating uneven hoisting of the gate. For each scenario, data was collected and processed to identify features that could be used to detect the damage that was implemented. The strain gages were particularly effective in identifying trunnion friction and uneven hoisting. Additionally, a new method was developed to detect uneven hoisting by using accelerometers on the easily accessible strut arms. Future work will involve further exploring system identification methods for detecting the expected loss of structural stiffness due to the simulated fracture of structural components. Ultimately, this work will lead to better remote condition assessment tools for Tainter gates, and the results herein will be leveraged to further refine additional testing scheduled to take place when the remaining gates are removed.

REFERENCES

- [1] W. J. Graham and R. C. Hilldale, "Spillway Gate Failure or Misoperation: Representative Case Histories," Department of the Interior, 2001.
- [2] N. Ishii, K. Anami and C. W. Knisely, "Introduction: History of Gate Failures and Overview of Vibration Mechanisms," in *Dynamic Stability of Hydraulic Gates and Engineering for Flood Protection*, Hershey, PA, IGI Global, 2018, pp. 1-43.
- [3] M. Kalantarnia, "Reliability Analysis of Spillway Gate Systems (PhD Thesis)," McGill University, Montreal, Quebec, 2013.
- [4] J. Lewin, G. Ballard and D. S. Bowles, "Spillway gate reliability in the context of overall dam failure risk," Charleston South Carolina, 2003.
- [5] Q. G. Alexander, M. D. Smith and B. A. Eick, "Development of SMART Gate decision support tools for large inland navigation USACE infrastructure: The Dalles Tainter gate," in *PROCEEDINGS: 2017 International Workshop on Structural Health Monitoring*, Stanford, 2017.
- [6] B. A. Eick, T. B. Fillmore, M. D. Smith, Q. Alexander and B. F. Spencer, "Detection of uneven hoisting of a Tainter Lock gate: a case study for The Dalles Lock and Dam," *Journal of Civil Structural Health Monitoring*, vol. 10, no. 1, pp. 557-571, 2020.
- [7] B. A. Eick, B. Kim, K. Atwater and B. F. Spencer, Jr., "Self-excited hoisting chain tension measurements for dam spillways gates and identification of uneven hoisting," *Journal of Civil Structural Health Monitoring*, vol. 15, pp. 1289-1304, 2024.
- [8] S. Wang, T. Fillmore, J. Lee, B. A. Eick and B. F. Spencer, Jr., "Reference-free ego-motion compensation for vision-based measurement of structural deformation of miter gates," *Structural Health Monitoring*, vol. 0, no. 0, p. 10.1177/14759217241297248, 2024.