Assessing the Role of Quoin Gaps on Miter Gates Damage States Through Optimization

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ABSTRACT

Miter gates are cyclically loaded structures present along waterways that allow for ships and cargo to traverse significant changes in elevation. The miter gate leaves are mounted on either end of a lock chamber from a gudgeon anchorage system, typically in pairs, and function by being swung into place about a pintle assembly by mechanical operating machinery. Along either side of a miter gate leaf run the quoin and miter contact blocks. When gates are placed into service or undergo maintenance, engineers use procedures to set tolerance gaps between the quoin contact blocks and the lock wall. If the gaps are set too tight, then when the gates are brought to miter, premature contact can cause prying action between the gudgeon and wall. This causes significant increases in stress in the gudgeon anchorage, a failure critical member (FCM), and has been observed during several structural health monitoring (SHM) initiatives on in-service infrastructure. Alternatively, if the gap tolerance is not set tight enough, when hydrostatic load is applied to horizontally framed miter gates, the transfer of load causes the gate to thrust towards the wall until the quoin contact blocks bear against the lock wall. When contact is delayed or does not occur, the load is transferred to the pintle and gudgeon, which resist this thrusting, rather than the lock wall. This significantly raises the stresses in these regions and leads to damage. SHM techniques have been previously developed to detect the presence of quoin gaps using both contact sensors and vision-based methods in an effort to inform maintenance decisions. The specifics of gap sizes and locations can be confirmed under gravity load using instruments known as feeler gages. There is currently no standardized procedure for setting these quoin gaps; therefore, there is a need for a rigorous analysis to standardize gap lengths that assesses tolerance gap sizes and their consequences. In this study, a suite of experiments is run using finite element analysis (FEA) on a series of numerical models. Focus is placed on horizontally framed miter gates around the typical size of 60 ft tall. Within the numerical experiments, optimization techniques are employed to find the optimal quoin gaps sizes that results in the minimization of stresses in the gudgeon and pintle. Validation of this optimization will occur though the physical testing of a miter gate fully instrumented with an SHM system. The experimental test set up that is currently under development will also be discussed.

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INTRODUCTION

Hydraulic steel structures (HSS) play an important role in allowing navigation traffic to traverse inland waterways. Structural health monitoring of these structures is essential for ensuring continued function. This research focuses on the performance of horizontally framed miter gates. Miter gates are typically installed in pairs; the leaves acting as double doors to allow ships to enter and exit a lock chamber. The general behavior of horizontally framed miter gates is that under gravity, the vertical load is carried by the pintle while the horizontal load caused by the eccentricity of the gate is carried by the pintle and gudgeon as illustrated in Figure 1. As the gates are swung closed and brought to miter each leaf rotates about its pintle axis.

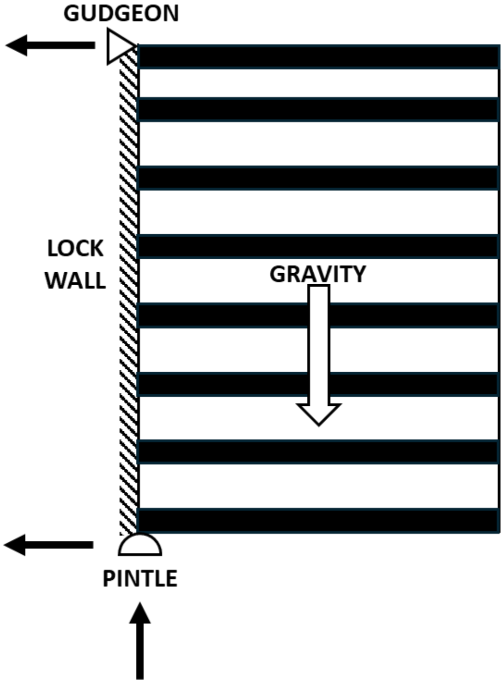

Figure 1: Load path of gravity

As the water level in the chamber adjusts, a hydrostatic load is applied against the skin plate. For a mitered (closed) gate the hydrostatic load is shared between the gate leaves and travels from the skin plate to girders and finally into the lock wall as illustrated in Figure 2. This interface between the contact block on the miter gate and contact block on the lock wall is referred to as the quoin. Ideally, when the gate is swung closed, there is no interference between these quoin contact blocks. Then, when the hydrostatic load is applied and the gate thrusts towards the wall, this small gap is sealed, evenly distributing the load into the lock wall. The occurrence of improperly adjusted quoin gaps will affect this load transfer [1]. If the proper gaps are not set, then portions of the load will travel to the pintle or anchorage, leading to higher stress cycles. An improper quoin gap, combined with issues such as weld defects or corrosion can lead to failure of fracture critical members (FCM) and significant loss of functionality.

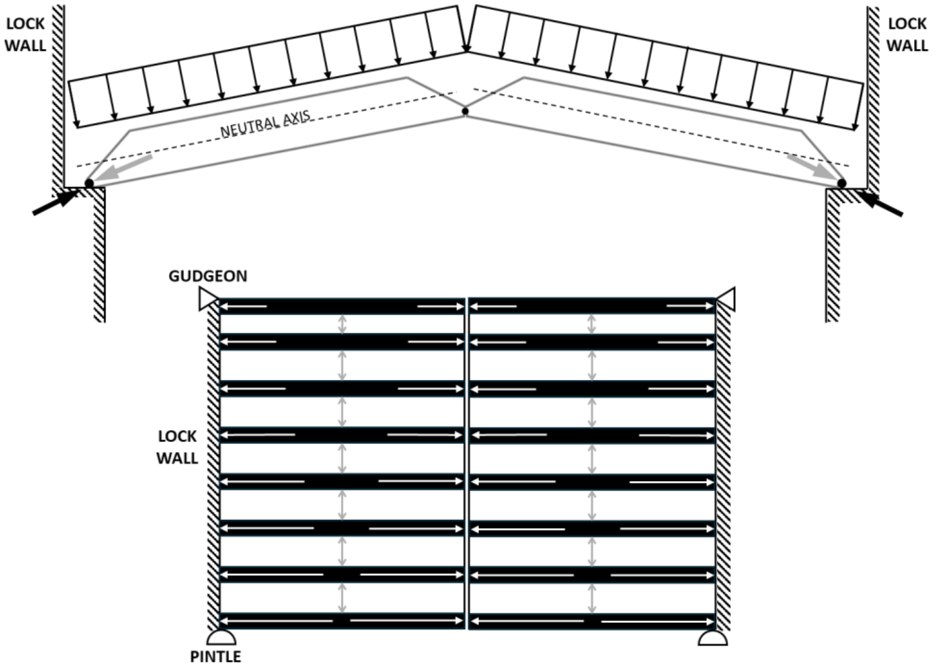

Figure 2: Load path of hydrostatic load on horizontally framed miter gate.

There is no current consensus on what the proper gap setting should be, but they are typically on the order of thousandths of an inch. Each USACE district uses their own methods to set the contact blocks based on procedures that have been used in the past and environmental factors such as temperature at the time of installation. After final adjustments are made to the contact blocks a backing material is poured as a filler to permanently set the blocks into position [2], such as in the contact block relationship shown in Figure 3.

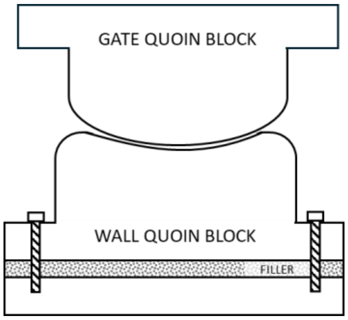

Figure 3: Quoin contact block relationship

Upon investigation by operations and maintenance crews, a number of pintle and anchorage failures that have occurred have found gaps to be too tight (leading to anchorage failures) or too large (leading to pintle failures). There are many factors that can contribute to the occurrence types of failures including improper gate alignment and improper adjustments [3]. Premature contact leads to a phenomenon known as "prying action" and excessive stress cycles in the anchorages. Prying action refers to when quoin contact is made between the gate quoin block and wall quoin block prior to the gates being fully mitered and causes increased tensile forces in the anchor bars and anchorages, both FCM, as the gates are forced closed [2]. This increases the stress experienced in each loading cycle, leading to accelerated fatigue damage. Ideally, each gate leaf should be allowed to swing freely about its hinge axis until the gate reaches the mitered position [2]. Alternatively, too large of a separation between the quoin blocks introduces additional stresses as the gates attempt to close the gaps and bear against the lock wall when the chamber water level is raised, applying the hydrostatic pressure. This load is typically transferred into the pintle and even has the potential to cause compressive stresses in the anchorage assembly. The generalized behavior of the primary anchorage load for normal alignment, too large of a gap, and prying action are overlayed and illustrated in Figure 4. The implementation of SHM monitoring systems can aid in identifying when these scenarios are taking place. When monitoring miter gates, because of the load path, SHM systems typically target monitoring the girders or the anchorages themselves.

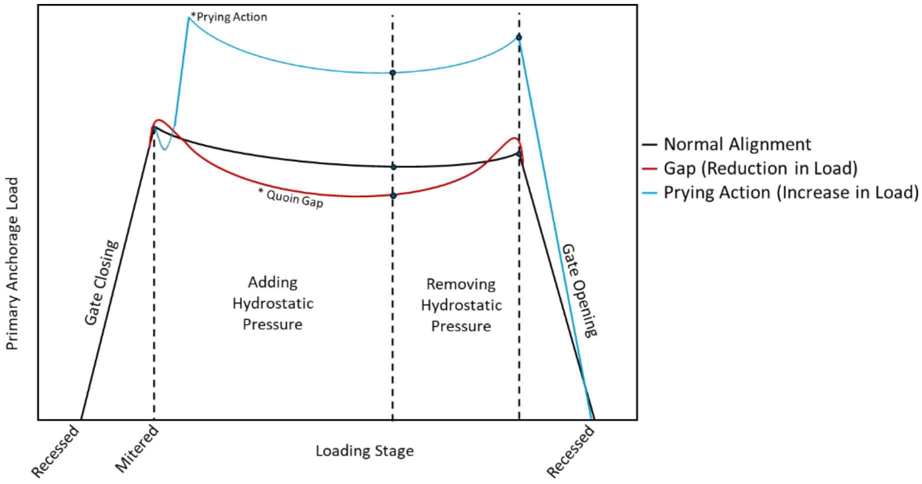

Figure 4: Generalized primary anchorage load cycle for normal alignment (black), gap misalignment (red), and prying action (blue)

STRUCTURAL HEALTH MONITORING OF MITER GATES

There have been several research studies completed in SHM to detect the presence of gaps along the quoin. The presence of quoin gaps has been confirmed using feeler gages, instrumentation, and vision-based methods. Eick et al. [4] [5] developed a methodology that implements an SHM system to identify the occurrence of damage in miter gates in the form of the development of a gap at the gate/wall interface. This was applied to a horizontally framed miter gate and uses data from strain gages and water level gages at Greenup Lock and Dam. Principal Component Analysis is applied to identify significant changes in a damage sensitivity feature defined using the correlation between the strain readings and water levels. Fillmore et al. [6] approached monitoring quoin contact using vision-based displacement measurements. Model updating was implemented using high-resolution images collected when the lock chamber was full and when the lock chamber was empty and feature tracking. These studies differ slightly in that they are looking at the progression of damage over time as deteriorating boundary conditions that can lead to loss of contact, while this study is considering how the initial setting of the quoin gaps influences gate performance.

At Boggs Lock & Dam (L&D) maintained by the USACE Vicksburg District along the Red River and at Port Allen Lock maintained by the USACE New Orleans District which links the Mississippi River and Gulf Intercoastal Waterway (GIWW), there were major anchorage failures in 2023 and 2024, respectively [7]. At both sites, the debonded anchorages are embedded in concrete, but excessive movement of the anchorage was observable, or edges of the cracks because visible. In each case, after the surrounding concrete was removed, large cracks were found growing across one of the two anchorages at each lock such as pictured in Figure 5 for Boggs L&D, which led to the locks being temporarily shut down while repairs were made.

Figure 5: Location of crack at Boggs Lock and Dam

Structural health monitoring plans, illustrated in Figure 6, in the form of strain gages were subsequently installed on both sides of the anchorage frame that captured the effect of gaps on miter gate behavior. Focus was placed on the load traveling into the anchorage, especially as it crossed the weld repairs. It was during these periods of monitoring that prying action was observed within the collected data. There is a spike present just as the gates are brought to miter indicating that premature contact is being made with between the contact blocks. This was later verified at Boggs L&D using paint along the quoin block to determine the regions where premature contact was being made (See Figure 7). Several adjustments were made at Boggs L&D during the duration of the repairs. The strain gage data showed a reduction in the force traveling into the anchorage between the initial and final adjustments. Unfortunately, information was not available from the corresponding districts on what the initial setting of the quoin blocks were and what was found during post-failure inspections. It was believed that in both cases, the increased magnitude of the stress cycles due to prying action in combination with weld defects lead to accelerated fatigue cracking in the anchorage member.

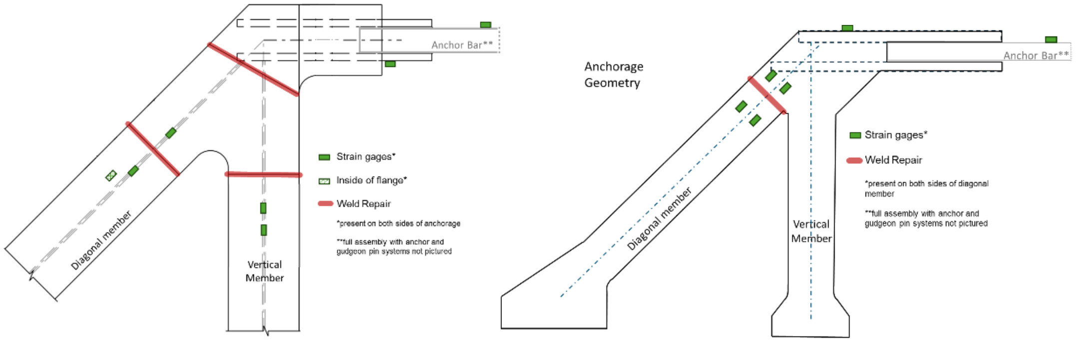

Figure 6: Instrumentation diagrams for Port Allen Lock and Boggs L&D, respectively

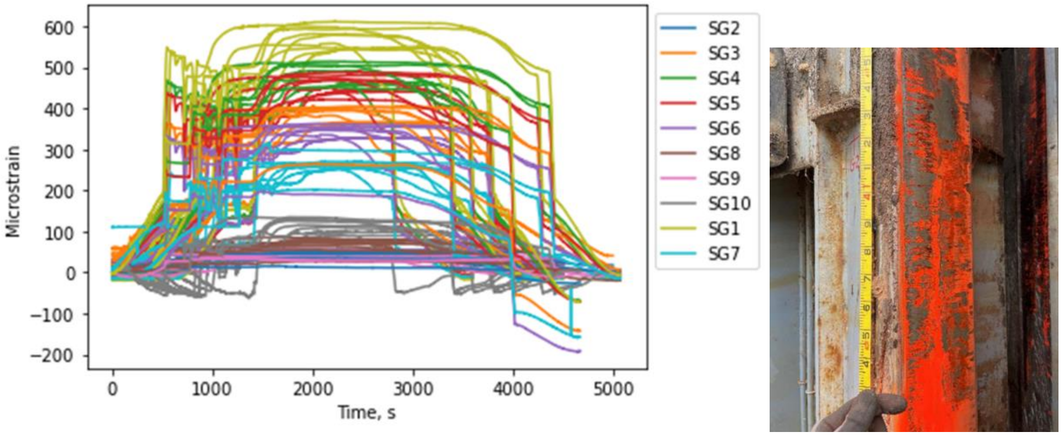

Figure 7: Evidence of prying action in strain readings and rubbed paint along quoin indicating region of premature contact

Alternatively, several pintle failures have occurred that are thought to possibly be due to excessive quoin gaps. Lockport L&D in 2025 maintained by the USACE Chicago District located along the Illinois River; Wilson Lock in 2024 maintained by the Tennessee Valley Authority along the Tennessee River each experienced pintle failures [8] [9] [10] [11] [12]. Marseilles L&D, Brandon Road L&D, and Dresden L&D maintained by the USACE Rock Island District along the Illinois River each found cracks in the pintle region during the miter gate inspections in 2023. Although not yet confirmed for the pintle failures, the Rock Island District found gaps larger than their expected target of 0.010 inches along the quoin contact blocks and had to reestablish quoin contact during repairs. At Lockport L&D, the bottom two girders near the pintle of each gate leaf were instrumented in such a way that the path of the load as it travels to the lock wall could be monitored as illustrated in Figure 8. Data from this instrumented site is not yet available.

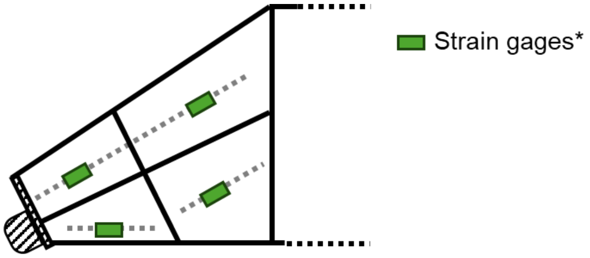

Figure 8: Instrumentation diagram for bottom girder of Lockport Lock

NUMERICAL MODEL

To further investigate the effect of the set quoin gap on the performance of the miter gate, a numerical study is planned to simulate the application of the hydrostatic load. The gate under investigation will be Greenup Lock located in Kentucky on the Ohio River. The hydrostatic load is applied in stages of 19, 21, 25, 35, and 44 feet to represent the chamber gradually filling with water. By separating these loads into individual steps, the strain response as the load is applied can be observed. Within the model assembly is the body of the gate, the pintle assembly, and the quoin and miter contact blocks. Gravity is initially applied to the model, then the hydrostatic load is applied incrementally. Temperature is not included within this initial model but will likely be considered in later studies. A symmetrical boundary condition is applied to the mitered end of the gate to simulate the identical adjacent leaf. Displacements are restrained in the pintle which is tied to the bottom girder of the gate, and only rotation about the vertical axis is allowed at the gudgeon. The mesh contains a total of 578,803 elements total (1,408 linear line type B31; 82,156 quadratic tetrahedral elements of type C3D10; 354,174 linear tetrahedral elements of type C3D4; 126,288 linear quadrilateral elements of type S4R; 7,943 linear triangular elements of type S3; 6,834 quadratic hexahedral elements of type C3D20R). The tolerance is set by adjusting the distance of the lock wall contact block part from the quoin block tied to the gate where a hard contact interaction has been specified. Contact is confirmed by requesting the contact stress as an output. The goal of this numerical analysis is to find the optimal quoin gap tolerances that results in the minimization of stresses in the gudgeon and pintle. To maintain consistency when comparing the stress on the gudgeon and pintle as the gap is adjusted, a set of elements will be selected for extraction. This analysis has not yet been completed.

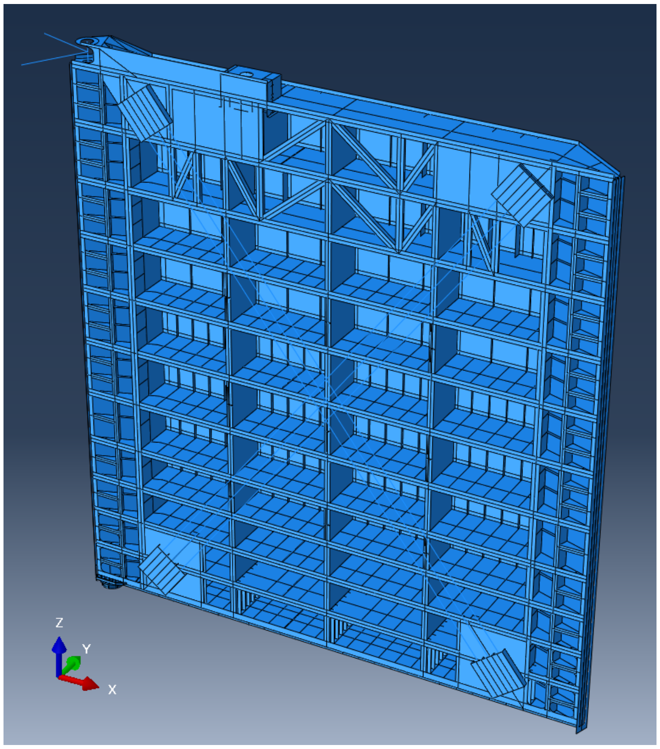

Figure 9: Abaqus model – Greenup Lock

PHYSICAL TESTING

Physical testing will be used to validate the methodology used in analysis the numerical models. A scaled miter gate model based on the flexibility of McAlpine Lock located along the Ohio River is currently being designed to be 3D printed. The scaled model will be approximately nine feet tall and the total number of girders is being reduced from thirteen to six to ensure the gate has enough flexibility to respond to the reduced hydrostatic load. The physical testing will take place at the Coastal Hydraulics Lab at the USACE Engineering Research and Development Center located in Vicksburg, MS. It will be in an enclosure where the hydrostatic load will be applied to only the skin plate side of the gate. Various quoin gap tolerances and setting techniques from across USACE will be adapted and implemented. The physical model will be thoroughly instrumented to document the response of the gate as the hydrostatic load is applied. Adhesive strain gages will be attached to the girders, pintle, and gudgeon to help identify the load path. Load cells will be used in the pintle and along the quoin. By additionally creating a numerical model of the scaled model, the methodology used to determine the optimal quoin gap for a full sized miter gate model can be validated.

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