EXPERIMENTAL INVESTIGATION OF POST-TENSIONED ANCHORED TRUNNION RODS OF NAVIGATION STRUCTURES

WAEL ZATAR*, HIEN NGHIEM†

* Professor, College of Engineering and Computer Sciences
Director, Encova Center for Engineering and Safety
Marshall University
One John Marshall Drive
Huntington, West Virginia, 25755, United States
e-mail: zatar@marshall.edu

† Marshall University Research Corporation
Encova Center for Engineering and Safety
Weisberg Complex Applied Engineering Complex
Huntington, West Virginia, 25755, United States
e-mail: nghiem@marshall.edu

Key words: Post-tensioned anchorage, Trunnion rods, Dam spillways, Navigation structures, Asset management.

Abstract. The United States Army Corps of Engineers employs Tainter gates to effectively regulate water flow through dam spillways from upstream to downstream of navigation locks and dams. Post-tensioned Tainter gate anchorages are widely utilized in numerous dams across the United States, predominantly within the Mississippi Valley, Great Lakes and Rivers, Southwestern, and Northwestern Divisions. Ten dams were tested between 2010 and 2017, and failed rods were found on eight of these dams. Testing 5,371 greased trunnion anchor rods showed that 22 rods were broken and 6 rods had slipped gripping hardware. In addition, 202 rods on Markland Dam and 76 rods on Greenup Dam experienced significant cantilever bending or corrosion, which may contribute to anchor rod failure. The objective of this study is to establish the effect of a failed rod, or rods, on the monitored stress for the remaining rods and on the capacity of the rod groups located in the same box. A comprehensive experimental study was conducted for post-tensioned anchorages with varying effective rod configurations. A scaled anchorage system that includes a post-tensioned concrete trunnion girder with nine high-strength post-tensioning rods was employed in the experimental investigation. Finite element analyses duplicating various trunnion rod failure scenarios were validated using data observed from the extensive experimental investigation. The numerical results accurately predicted the load changes of the rods under different loads and de-tensioning configurations. The findings of this study provide a valuable insight that would assist dam owners in planning appropriate proactive maintenance and remediation strategies for post-tensioned Tainter gate anchorages of navigation dams and lock assets.

1 INTRODUCTION

The United States Army Corps of Engineers employs Tainter gates to effectively regulate water flow through dam spillways from upstream to downstream of navigation locks and dams. Post-tensioned Tainter gate anchorages are widely utilized in numerous dams across the United States. Ten dams were tested between 2010 and 2017, and failed rods were found on eight of these dams. When looking at the collective performance of all the tested dams, the rates of failure are relatively low. However, a more detailed analysis of the failure rates within a single anchorage point presents a different picture. Within an individual anchorage, the failure rate of the rod ranged from 2 percent to 29 percent. This variation has the potential to significantly affect the anchorage's capacity and, consequently, the overall performance of the structure.

O'Donnell' presented key considerations for the design of prestressed concrete anchorages intended for large Tainter gates [1]. The following design criteria and requirements were outlined: 1) Concrete strength: Concrete with a minimum strength of 5000 psi is mandated for the construction of piers and girders. For larger gates, however, the use of higher-strength concrete may be necessary. 2) Magnitude of prestressing: The magnitude of prestressing should be determined based on various load conditions. The actual final load applied to the prestressing steel should not exceed 60 percent of the minimum ultimate strength of the steel. 3) In consideration of losses in steel stress caused by factors such as elastic shortening of the concrete, creep, and plastic flow, the initial tension applied to the steel immediately after the anchorage is seated should not exceed 70 percent of the ultimate strength of the steel. These guidelines provide essential parameters for the design and construction of prestressed concrete anchorages for large Tainter gates, ensuring the safety and integrity of these critical infrastructure elements.

Abela and Abela [2] analyzed an existing trunnion girder and its greased post-tensioned anchors prior to load testing. The analysis aimed to assess the capacities of the structural members by utilizing a finite element model. Abela and Abela [2] also explored the likelihood of a critical anchor failing, drawing on test data acquired through nondestructive dispersive wave propagation testing and load testing of similar anchors at other dam sites. The results of this analysis revealed a higher probability of a critical anchor failing than was expected. In particular, Abela and Abela claimed that a sufficiently large flood event could potentially lead to the failure of the entire post-tensioned anchorage system. In response to this finding, two contingency plans, using anchorage replacement and a steel exoskeleton wrapped around the trunnion girder with new anchors, were considered.

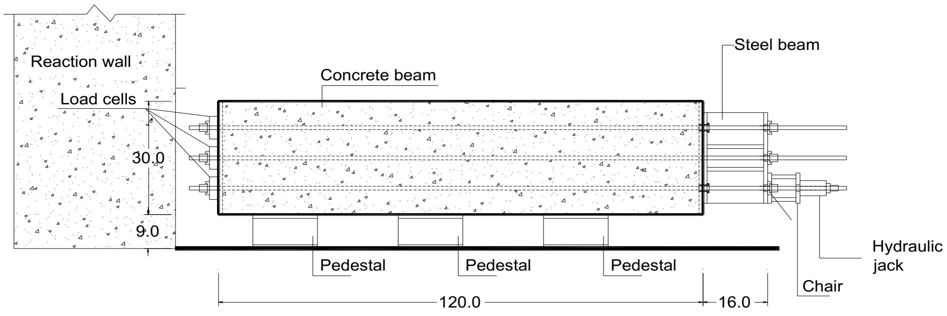
Abela [3] assessed the adequacy of a passive anchorage system in response to heightened hydrostatic loading. The evaluation included finite element analyses and refererces established structural and mechanically codified manuals. Key elements for the evaluation of an existing passive anchorage system include analyzing the behavior of the anchorage system using finite element analyses, considering von Mises stress and elongation of the anchorage system, understanding the old and current codified guidance, applying correct classification, and considering the corrosion of embedded anchors. Malik and Zatar [4,5] documented structural health monitoring approaches to evaluate the risk of waterway infrastructure. Zatar et al. and Nguyen et al. [6-8] proposed successful approaches to analytically and non-destructively testing concrete members.

The overarching purpose of this study is to characterize the lifecycle of embedded dam gate anchorages. The lifecycle analysis may account for relevant geometric, material, operational, and environmental variables. The lifecycle analysis may describe a measure of the reliability of anchor rods, or groups of anchor rods, if more appropriate, as a function of time given current conditions and knowledge. The objective of the study is to perform physical (experimental) testing and numerical modeling to determine the percentage increase in the trunnion rod forces. This paper presents the lab testing and finite element analyses conducted on a scaled model of a Tainter gate structure to evaluate the anchor rod force distribution, or force increase, due to failure of one to three anchor rods. The capacities of the groups of anchor rods should be reduced due to the failure of anchor rods.

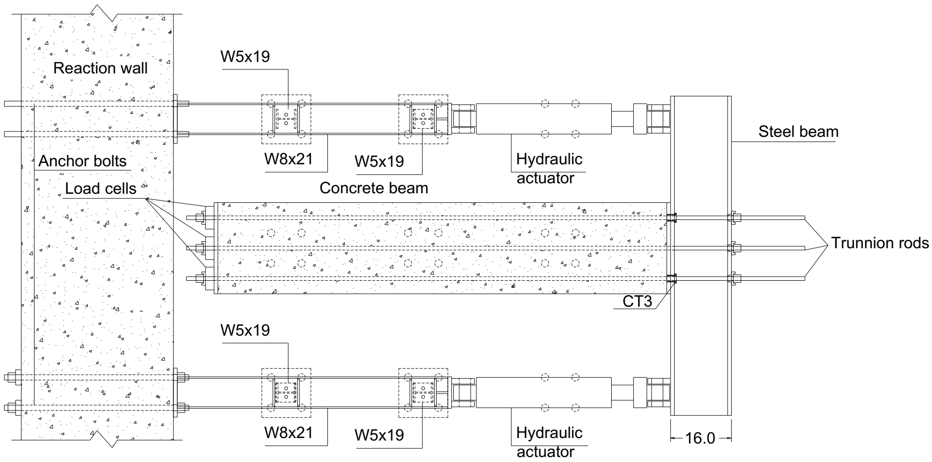
2 SCALED MODEL OF TAINTER GATE STRUCTURE

A scaled model of a Tainter gate structure was developed in the Advanced Materials Testing Laboratory at Marshall University. This well-equipped laboratory features a 20-ton overhead crane for handling heavy materials. The facility includes a pre-stressed L-shaped concrete wall measuring four feet in thickness and engineered to handle a load capacity of 100 kips per anchor. The anchors are organized in groups of four, spaced three feet apart. Additionally, the laboratory boasts a strong floor constructed with four feet of pre-stressed concrete, which can withstand loads of 100 kips per interior anchor and 50 kips per exterior anchor. For groups of anchors, both in tensile and compressive loading scenarios, the capacity is extended to 200 kips. This robust laboratory infrastructure ensures the safe and efficient testing of materials and structures.

The scaled model of the Tainter gate structure includes several components, as depicted in Figure 1. The model includes a concrete beam, pedestals, steel girders, steel columns, and high-strength threaded rods. The concrete beam measures 120 inches in length, 24 inches in width, and 30 inches in height. Three steel pedestals, spaced 3 feet apart, supported the concrete beam. A steel girder, as shown in Figure 2, transmits the forces applied by two hydraulic actuators to the trunnion rods and, subsequently, to the concrete beam. The horizontal distance from each hydraulic actuator to the center of the concrete beam is 3 feet. Two steel columns with a wide-flange cross-section of W5x19 are employed to support the hydraulic actuators. The concrete beam, steel girders, columns, and pedestals were all manufactured in a steel fabrication facility. Nine high-strength threaded rods are arranged in a 3x3 grid. These rods are spaced at 8-inch intervals, replicating trunnion rods in Tainter gate structures. The properties of the threaded rods are outlined in Table 1. The forces exerted by the two hydraulic actuators simulate lateral loads resulting from water pressure and wind loads transmitted from the Tainter gate to the girder. Each actuator has a capacity of 196 kips, and the maximum pressure they can exert is 5000 psi. The test setup is equipped with nine load cells, positioned at the end of each rod at the rear of the concrete beam, as indicated in Figure 1. Additionally, two load cells are attached to the hydraulic actuators to monitor the transfer of forces. The load cells have a capacity of 50 tons and a sensitivity of 2.0 mV/V. Data collection is facilitated using HP Agilent Keysight equipment at a sampling rate of 1 sample per second.



a) Side view



b) Plan view

Figure 1: Schematic of the scaled model

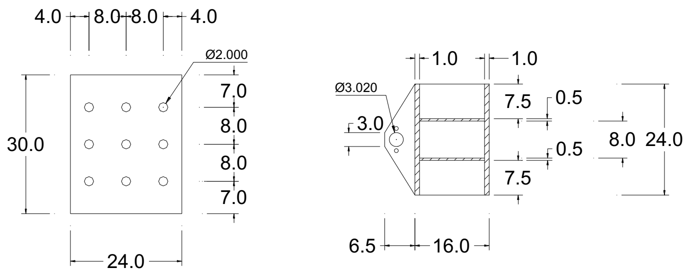


Figure 2: Cross sections of the concrete beam (left) and steel beam (right)

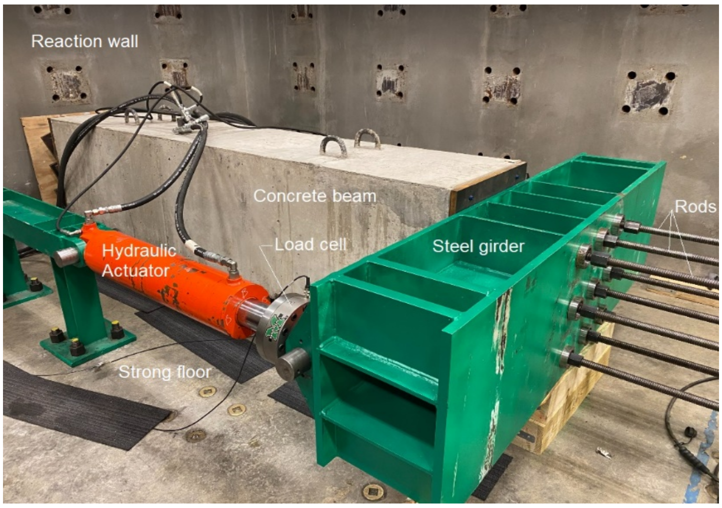


Figure 3: View ofthe testing setup

Table 1: Properties of threaded prestressing rods

Properties	Value
Diameter (in.)	1.0
Cross section area (in.^{2})	0.85
Minimum ultimate strength (kips)	128
Total length (in)	168

3 TEST PROCEDURE AND RESULTS

One of the main purposes of performing the tests is to establish the effect of a failed rod, or rods, on the monitored stress for the remaining rods and on the capacity of the rod groups located in the same box. The experimental program was designed to understand the effects of the failure of one to three rods. To simulate this scenario, the experimental setup allowed for the detensioning of one, two, or three rods, reflecting different cases of rod failure. If three rods fail, representing a severe situation where the supporting mechanism might lose as much as one-third of its capacity, more than 30 testing configurations were examined. Each test involved five levels of pre-tensioning of the rods, with the pre-tension force set at 15%, 30%, 40%, 50%, and 60% of the ultimate strength of the rods. The testing process for each configuration included three steps:

- Pre-tensioning all rods with a tolerance of 1.0 kip between the maximum and minimum forces
- Detensioning selected rods to represent cases of rod failure
- Applying forces from the hydraulic actuators

During the pre-tensioning of one rod, the pre-tension forces on the other rods changed, and adjustments were needed. Therefore, the pre-tensioning process was repeated until the difference between the maximum pre-tension force and the minimum pre-tension force was less than 1.0 kip.

During the tests, the pressure applied to the hydraulic actuators was gradually increased and held at four pressure levels: 1200 psi, 1700 psi, 2200 psi, and 2700 psi. These pressure levels corresponded to total forces of 92 kips, 130 kips, 169 kips, and 207 kips exerted by the two hydraulic actuators. After completing the loading process, the hydraulic actuators were unloaded until the pressure reached zero.

The paper compares the scaled model testing results with those of the finite element analyses (FEA) for six configurations (C1 to C6), as shown in Figure 4. The rods were numbered from 1 to 9, and the de-tensioned rods do not appear in the configurations C2 to C6.

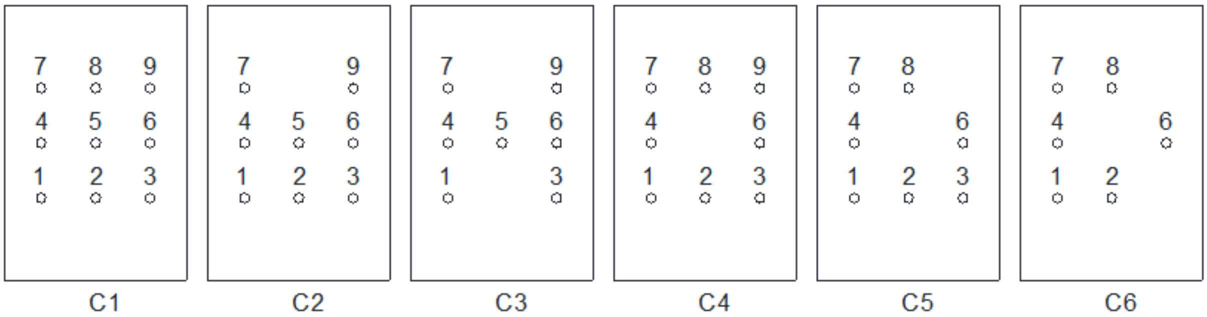


Figure 4: Configurations C1 to C6

Table 2: Comparison of rod forces

Rod Number	Rod Force (kips)						Changes from C1 (%)				
	C1	C2	C3	C4	C5	C6	C2	C3	C4	C5	C6
1	77.25	77.23	77.73	77.62	76.57	76.18	0.02	0.62	0.48	0.88	1.38
2	76.41	76.44	0.00	76.75	76.70	78.63	0.05	0.00	0.46	0.38	2.91
3	77.20	76.96	77.91	77.53	78.65	0.00	0.31	0.93	0.43	1.88	0.00
4	77.64	78.24	78.41	78.87	78.43	77.31	0.78	0.99	1.59	1.02	0.43
5	77.31	77.51	77.80	0.00	0.00	0.00	0.26	0.64	0.00	0.00	0.00
6	77.49	77.60	78.02	77.93	79.78	83.86	0.14	0.69	0.57	2.96	8.22
7	77.80	79.45	79.18	78.55	78.92	76.85	2.12	1.77	0.97	1.44	1.23
8	77.10	0.00	0.00	77.42	78.65	78.81	0.00	0.00	0.40	2.00	2.22
9	77.40	78.17	78.02	77.80	0.00	0.00	1.00	0.81	0.52	0.00	0.00

As indicated in Table 2, all rods in configurations C2 to C6 experienced force increases. The forces from the failed rods are transferred to the surrounding rods, increasing the surrounding rod forces by a range of 0.02% to 8.22%. The most critical situation occurs in configuration C6, where the force in rod #6 experienced a substantial force increase of 8.22% (Figure 5). This observation highlights the significant impact of rod failure on the forces within the system of configuration C6.

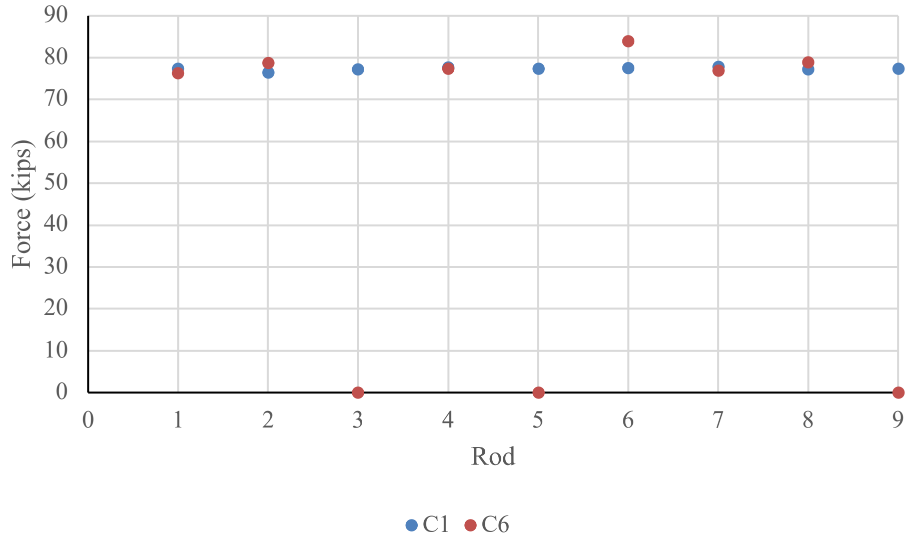


Figure 5: Comparison of rod forces in testing configurations C1 and C6

4 FINITE ELEMENT ANALYSES

A finite element (FE) model, created using the SSI3D computer code [9] (Figure 6), was developed to simulate the scaled model testing. This model incorporates a total of 1440 solid elements, 752 shell elements, 9 bar elements, and 58 interface elements to represent the various components, including the concrete beam, steel girder, trunnion rods, and their interactions. The model includes interface elements to simulate the contact between the concrete beam and the steel girder. The interface elements only permit transferring compression. De-tensioning of the rods is simulated by deactivating the corresponding bar elements. These deactivated bar elements have zero stiffness and do not contribute to the model's behavior. Material properties such as Young's moduli, Poisson's ratios, compressive strength, and yield strengths are specified in the model, and their values are provided in Table 3. The FE model considers geometry and material nonlinearities with its detailed elements and material properties. The model allows for accurate simulation of the behavior and interactions of the components in the scaled model.

Table 3: Material properties

Material	Young’s modulus (ksi)	Poisson’s ratio	Strength (ksi)
Concrete	4095	0.2	4
A36 steel	29000	0.3	60
150 ksi steel	30500	0.3	120

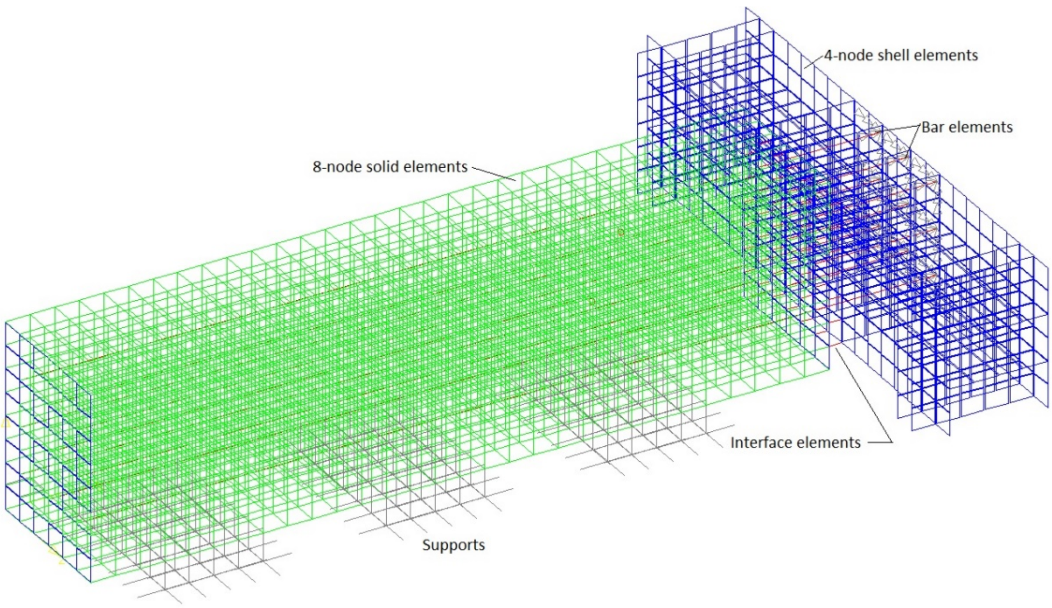


Figure 6: Three-dimensional view of FE model

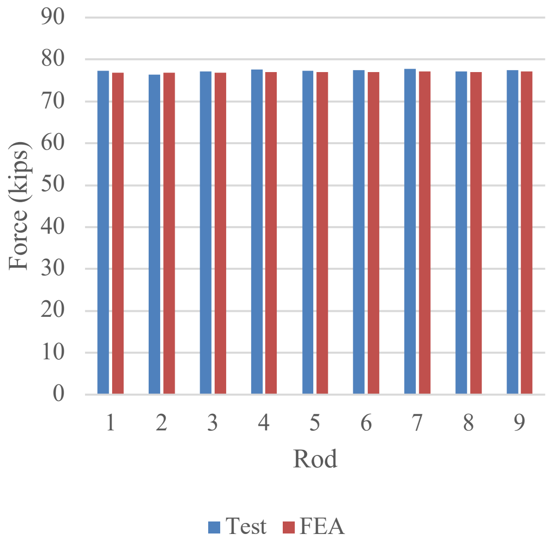
The finite element analyses (FEAs) were conducted for six selected configurations (C1 to C6) as shown in Figure 4. Tables 4 and 5 present the forces in each rod for selected configurations C1 to C6 for the pre-tension of 60% and pressure level of 2700 psi from the scaled model tests and FEAs. Figure 7 also inlustrates the forces in each rod for FEAs and the scaled model tests. The comparison shows that the FEA results are in good to excellent agreement with the scaled model tests in all configurations with descrepancies vary from 0% to 4.6%. The difference in accuracy between FEA and experimental testing results increases as the number of de-tensioned rods increases, which can be attributed to contact nonlinearity behavior occurring when girder becomes detached from concrete beam.

Table 4: Comparison of forces in the rods for C1, C2, and C3 configurations

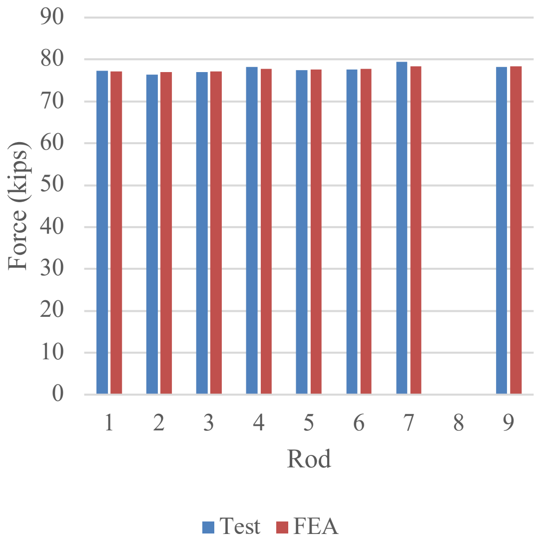
Rod Number	C1			C2			C3		
	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)
1	77.3	76.9	0.5	77.2	77.1	0.2	77.7	77.9	0.2
2	76.4	76.8	0.5	76.4	77.0	0.7	0	0	0.0
3	77.2	76.9	0.4	77	77.1	0.2	77.9	77.9	0.1
4	77.6	77.0	0.8	78.2	77.7	0.7	78.4	78.2	0.3
5	77.3	76.9	0.5	77.5	77.7	0.2	77.8	78.2	0.5
6	77.5	77.0	0.6	77.6	77.7	0.1	78.0	78.2	0.2
7	77.8	77.1	0.8	79.5	78.3	1.4	79.2	78.5	0.9
8	77.1	77.0	0.1	0	0	0.0	0	0	0.0
9	77.4	77.1	0.3	78.2	78.3	0.2	78	78.5	0.6

Table 5: Comparison of forces in the rods for C4, C5, and C6 configurations

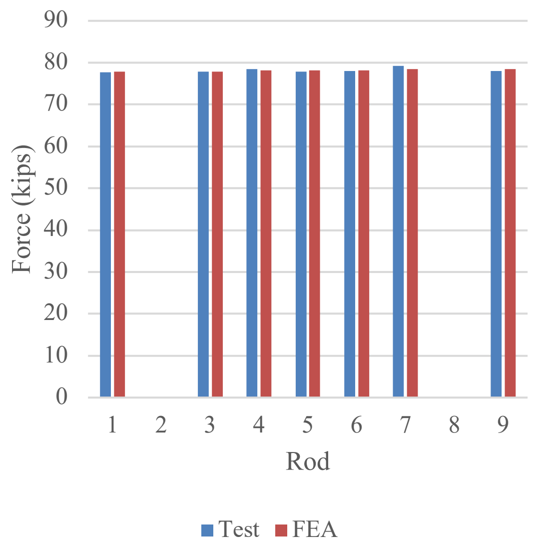
Rod Number	C4			C5			C6		
	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)	Test	FEA	Dif. (%)
1	77.6	77.4	0.3	76.6	77.1	0.7	76.2	77.3	1.4
2	76.8	77.3	0.8	76.7	77.5	1.1	78.6	78.3	0.4
3	77.5	77.4	0.2	78.6	78.0	0.8	0	0	0.0
4	78.9	77.7	1.5	78.4	77.8	0.8	77.3	77.8	0.6
5	0	0	0.0	0	0	0.0	0	0	0.0
6	77.9	77.7	0.3	79.8	78.9	1.1	83.9	80.0	4.6
7	78.6	77.8	1.0	78.9	78.3	0.7	76.8	78.1	1.6
8	77.4	77.8	0.5	78.6	78.9	0.4	78.8	79.2	0.4
9	77.8	77.8	0.0	0	0	0.0	0	0	0.0



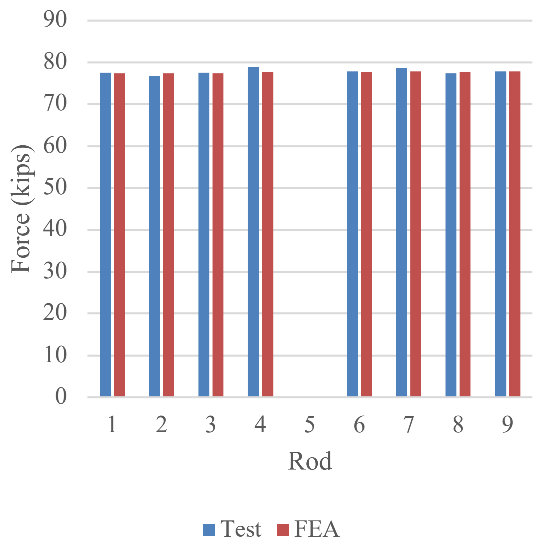
a) C1



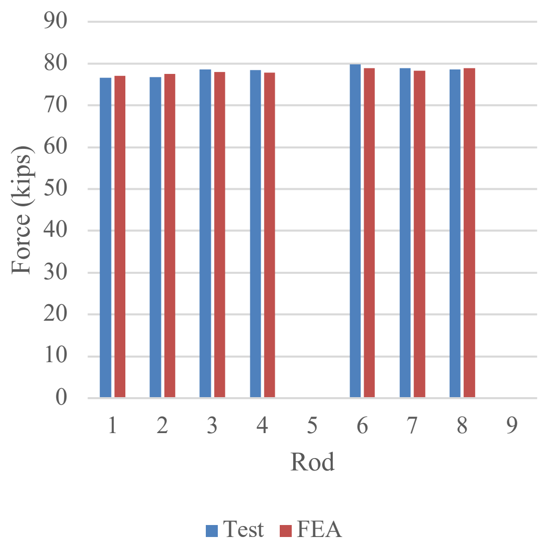
b) C2



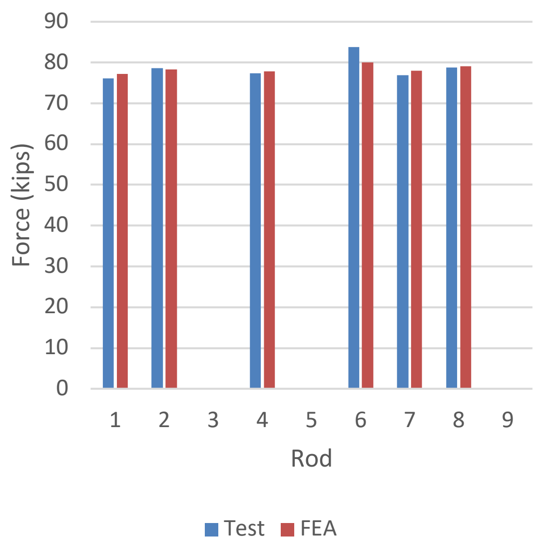
c) C3



d) C4



d) C5



e) C6

Figure 7: Comparison of forces in the rods

5 CONCLUSIONS

The objective of this study is to understand the effect of a failed rod, or rods, on the monitored stress for the remaining rods and on the capacity of the rod groups located in the same box. A comprehensive experimental study was conducted for post-tensioned anchorages with varying effective rod configurations. A scaled anchorage system that includes a post-tensioned concrete trunnion girder with nine high-strength post-tensioning rods was employed in the experimental investigation. Finite element analyses simulating various trunnion rod failure scenarios were validated using data observed from the experimental investigation. The results obtained from the numerical simulations accurately predicted the changes in rod forces for the various loading conditions and de-tensioning configurations. The capacities of the groups of anchor rods should be reduced due to the failure of anchor rods. The study will assist dam owners in assessing degradation rates and planning maintenance and remediation strategies for post-tensioned Tainter gate anchorages within navigation dams and lock assets proactively.

ACKNOWLEDGMENT

The Engineer Research and Development Center (ERDC) and the U.S. Army Corps of Engineers (USACE) sponsored this project. The financial support provided by the ERDC-USACE under ERDC Cooperative Agreement W81EWF-20-SOI-0036 is gratefully acknowledged. The authors would like to sincerely appreciate the outstanding and thorough mentorship provided by ERDC experts, Mr. Jason Ray, at the Sensor Integration Branch of the Information Technology Laboratory, Dr. Brian Eick, Program Manager of the Structural Health Monitoring Program, and Dr. Matthew Smith, Technical Director for Water Resources Infrastructure Research and Development. The authors would also like to thank the research team at FDH Infrastructure Services for the great assistance provided.

REFERENCES

[1] O'Donnell, K.O. Prestressed concrete anchorages for large Tainter gates. *In Proc., 10th Annual Convention of the Prestressed Concrete Institute, Precast/Prestressed Concrete Institute, Chicago* (1965).

[2] Abela, C. M., and Abela, A. A. Evaluation of an Existing Steel Box Trunnion Girder and Its Post-tensioned Anchors before Lift-off Testing: Case Study. *Practice Periodical on Structural Design and Construction* (2015) 20(4), p.04014052

[3] Abela, C. M. Evaluating Existing Passive Anchorage Systems for Tainter Gates. *ASCE Practice Periodical on Structural Design and Construction* (2017) 23(1), p.04017032

[4] Malik, H., and Zatar W. Software agents to support structural health monitoring (SHM)-informed intelligent transportation system (ITS) for bridge condition assessment. *IWSHM 2019*, Stanford University, CA (2019).

[5] Malik, H., and Zatar W. Agent based routing approach to support structural health monitoring-informed, intelligent transportation system. *Journal of Ambient Intelligence and Humanized Computing* (2020) Volume 11, PP1031-1043

[6] Nguyen, H. Zatar W., and Mutsuyoshi, H. Hybrid fiber-reinforced polymer girders topped with segmental precast concrete slabs for accelerated bridge construction. *Journal of the Transportation Research Record* (2014) Volume 2407, issue 1, pp83-93

[7] Zatar W., and Nguyen, H. Condition assessment of ground-mount cantilever weathering-steel overhead sign structures. *Journal of Infrastructure Systems* (2017) Volume 23, Issue 4,.

[8] Zatar, W., Nguyen, H., and Nghiem, H. Ultrasonic pitch and catch technique for non-destructive testing of reinforced concrete slabs. *Journal of Infrastructure Preservation and Resilience* (2020) Volume 1, Issue 1, pp1-13,.

[9] Nghiem, H.M. *Soil-pile-structure interaction effects on high rises under seismic shaking.*

University of Colorado at Denver (2009).