Fitness-for-Service Assessment on 1940's Era Wicket Gates

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Abstract

In addition to a large pumped storage hydropower plant, Tennessee Valley Authority (TVA) maintains twenty-nine conventional hydropower plants in the greater Tennessee River valley. A number of the conventional hydropower plants were commissioned around the 1940’s. Many of these hydropower plants are undergoing refurbishment, or have been refurbished. A recent wicket gate failure at the Guntersville dam prompted TVA to pursue engineering assessments of wicket gates found at similar vintage power schemes. Initial stress analyses indicated that a number of wicket gates were exceeding the assumed elastic limit of the vintage material during gate squeeze and shear-pin safety element activation. Additionally, crack-like flaws had been discovered in many of the wicket gate castings. TVA was concerned that the wicket gates were approaching the end of operational service life.

This paper covers the methodology that was used to determine if the wicket gates were fit-for-continued service and develop inspection recommendations and intervals.

The project consisted of several parts. Material testing of a previously replaced wicket gate of similar vintage was conducted to accurately determine the material properties of the vintage castings. This provided true stress-strain curves, fracture toughness and crack growth rates. Three dimensional elastic-plastic finite element analyses (FEA) were conducted using the “actual” material properties obtained from the material tests on a wicket gate design which was previously shown to be particularly sensitive to gate squeeze and shear-pin safety element activation.

The stress results from the FEA were evaluated to ensure that the wicket gate is protected against structural instability, local, and fatigue driven modes of failure. Crack-like flaw and fatigue crack growth assessments were also performed to provide an accurate estimate of damage tolerance of crack-like flaws and to provide a remaining life estimate which can be considered while determining inspection intervals.
This approach was performed in accordance with ASME FFS-1 Fitness-for-Service [1] guidelines and provided TVA with quantitative means to plan for regular inspections and end-of-life budgeting.

Introduction

A number of TVA’s hydropower plants are currently undergoing, or have undergone refurbishment and modernization. During these modernizations numerous flaws, or indications, were found in many of the 1940’s vintage wicket gate castings. This discovery, coupled with cascading wicket gate failures in unit-1 at the Guntersville power station in 2004 (Figure 1) prompted TVA engineers to pursue more comprehensive evaluations of similar vintage wicket gates. Other concerns for TVA were typical industry rehabilitation scope for wicket gates recommend reducing stem diameter and stress relief radii for the installation of stainless steel sleeves, which possibly introduces stress concentrations. Further and perhaps more fundamental, no standard for analyzing wicket gates exists.

As a preliminary approach, engineers at TVA developed a risk ranking criteria based on the calculated stresses due to the gate stem torque during shear-pin activation versus the yield strength of gate material. These findings were compared to linear elastic finite
element analyses (FEA) to help confirm ranking philosophy. Based on the gates evaluated, Hiwassee unit-2 was identified as posing the highest risk. However, questions still remained because nearly all moderate to high risk gates are constructed from ASTM - A27 or similar cast steel, for example:

- What happens to the gate when local stresses exceed yield?
- What are the actual material properties (e.g. fracture toughness)?

TVA worked with Quest Integrity to perform destructive material testing on a similar vintage wicket gate, also cast from ASTM - A27 steel. This provided accurate material properties values necessary for the comprehensive ASME Fitness-for-Service (FFS) evaluations performed by Quest Integrity on the Hiwassee Unit 2 wicket gate.

Hiwassee dam is situated along the Hiwassee River in Western North Carolina and was commissioned in 1940 and has a net dependable generating capacity of 124 MW [3]. The original design consisted of a single conventional Francis turbine with space in powerhouse for an additional unit. In 1956 TVA installed a reversible Francis pump-turbine (unit-2), which at the time was the world’s largest pump-turbine and was the first reversible pump-turbine in the country to efficiently use wicket gate control for both output and pumping [4].

Figure 2: Hiwassee dam [5]
Since 2012, TVA has operated unit-2 as a conventional Francis turbine. However, there are plans to return unit-2 to pumping operation in the near future.

**Objectives**

The main objective of this project was to provide TVA with a comprehensive condition assessment and remaining life estimate of the wicket gate family found at Hiwassee unit-2 that is based on quantitative evidence and supported by a recognized engineering standard.

Advantages of this approach are:

- Increased safety
- Improved budgetary planning
- Prioritization of refurbishment and modernization projects
- Decreased inspection costs
- Reduced risk of costly unplanned shutdowns due to critical equipment failure

**Methodology**

This project was conducted following the guidelines of the API 579-1/ASME FFS-1 Fitness-for-Service [1] standard. This standard was developed to provide assessment methodologies for a variety of damage mechanisms (e.g. corrosion, erosion, crack like flaws, local and global structure instabilities, etc.) found primarily in pressure containing equipment. Analyses conducted in accordance to this standard provide support for targeted inspection, maintenance and operational decisions to maintain long-term economic viability, and to ensure safety of plant personnel and the public while older critical equipment continues to operate.

The following Sections describe the approach and methods used for evaluating the wicket gates found in unit-2 at Hiwassee power station.

**Geometry**

A 3D geometry model of a unit-2 wicket gate at Hiwassee was developed using SolidWorks [6] commercial CAD software, and was based on the information found in the engineering and refurbishment drawings provided by TVA. A feature of particular interest was the stem to leaf boundary region that had been subject to machining during a recent refurbishment.
At the request of TVA, and in order to maintain conservatism, the stress relief radius at this location, specified only by a 0.06 inch maximum, was assumed to be zero (Figure 3).

![Figure 3: Hiwassee wicket gate CAD model](image)

**Finite Element Model**

The solid geometry was discretized and meshed using Abaqus [7] CAE pre-processing software. Discretizing the geometry into “elements” of finite size allows for numerical approximation of the mathematical model representing the physical response of the structure subjected to various loads and boundary conditions. The stem, stem sleeves, and majority of the leaf and end plates were represented using reduced integration hexahedral elements. The leaf-collar and stem-collar boundary regions were modeled using quadratic tetrahedral elements. To accurately capture material response, the average characteristic element length was refined to 0.05 inches along the boundaries of interest (Figure 4).
Figure 4: Finite element mesh and refinement

Stem sleeves and end plates were allowed to structurally contribute through numerical tied contact.

**Material Test**

Material testing was conducted to obtain specific material properties of the vintage A27 leaf and stem material. Samples taken from a sacrificial gate of the same vintage material were analyzed and provided the material properties necessary for an accurate finite element analysis and fracture mechanics assessment.

The following list represents examples of necessary material input parameters which were taken directly from the test data, or calculated using recognized ASTM standards:

- Elastic modulus
- Yield strength
- Tensile strength
- Engineering and true stress-strain curves
- Fracture toughness
- Crack growth rates
Figure 5 shows the location along the sacrificial wicket gate from which the test specimens were taken.

Table 1 describes the type of test, location and number of specimens tested.

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Description</th>
<th>Number of specimens</th>
<th>Specimen Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile (Full engineering stress-strain)</td>
<td>Machine-out round or flat test specimens; conduct full Engineering Stress-Strain Tensile testing through failure</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>Machine-out CT test specimens at 45 degrees incline (for torsion); conduct fracture toughness testing</td>
<td>3</td>
<td>A,B,C</td>
</tr>
<tr>
<td>Fatigue crack growth</td>
<td>Machine-out CT tests specimen and conduct da/dN fatigue crack growth testing</td>
<td>3</td>
<td>B,C</td>
</tr>
</tbody>
</table>
**Stress Analysis**

To accurately model the physical response of the Hiwassee wicket gate, finite element modeling was conducted using Simulia’s Abaqus [7] FEA software. Multiple stress analyses were performed based on routine gate squeeze and safety element activation (shear-pin breakage) conditions. Gate squeeze loading represents the “daily” operation and a “shear-pin” event represents an upper-limit loading event. The frequency of gate squeeze events (730 events per year) was based on operational records supplied by TVA. The frequency of shear-pin activation events modeled was requested by TVA to be 1 occurrence in every 5 years.

Applied torque and directional forces for the loading cases were calculated from the supplied servo-motor rating, geometry, and gate arm shear-pin rating. These loads were distributed to the area of the stem contacted by the gate arm fitting via a kinematic surface coupling. In all cases, a hydrostatic pressure equivalent to a static head of 250 feet was applied to the wetted surface of the leaf.

Table 2: Operating loads and case specific boundary conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Hydrostatic Pressure (psi)</th>
<th>Shear-Pin Rating (lbs)</th>
<th>Applied Moment (x10⁶ in-lbs)</th>
<th>Stem Force Towards Tail (lbs)</th>
<th>Stem Force Towards OD (lbs)</th>
<th>Case Specific BC’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate Squeeze</td>
<td>108</td>
<td>N/A</td>
<td>1.26</td>
<td>16900</td>
<td>26600</td>
<td>Cyclic symmetric contacting condition at seals</td>
</tr>
<tr>
<td>Safety Element Activation</td>
<td>108</td>
<td>160000</td>
<td>2.88</td>
<td>38800</td>
<td>60900</td>
<td>Rigid obstruction enforced at top 30% of trailing edge seal</td>
</tr>
</tbody>
</table>

Boundary conditions and load applications along the wicket gate are illustrated in Figure 6.
Simulia’s Abaqus [7] standard finite element solver was used to compute the response of the discretized wicket gate to the gate squeeze and shear-pin loading conditions using elastic-plastic material behavior.

**Fitness for Service**

A fitness-for-service (FFS) assessment is a multi-disciplinary engineering approach to determine if a given structure is fit for continued service. The outcome of an FFS assessment supports decisions to operate as is, repair, retire, and re-rate. The FFS approach also provides a quantitative means for determining when and where to inspect.

Comprehensive guidelines for FFS assessments are contained in the API 579-1/ASME FFS-1 [1] (ASME FFS-1) standard, which is jointly published by the American Petroleum Institute (API) and the American Society for Mechanical Engineers (ASME).
This includes three levels of assessment for each damage mechanism outlined in the standard.

*Level 1* is a simplified and conservative analysis that is used for initial screening purposes.

*Level 2* is a basic engineering analysis that uses standard formulae to perform the FFS assessment. Typical Level 2 FFS calculations can be performed with a spreadsheet or custom software.

*Level 3* is an advanced assessment that may include computational fluid dynamics and finite element simulation to obtain a detailed response of a structure, or a system of structures, comprised of complex geometries and subjected to complex applied loads. These analyses may involve two-dimensional (2D) or three-dimensional (3D) modeling to accurately determine the stresses in the damaged areas. These stresses can then be evaluated to determine suitability of the component for continued service.

A *Level 3* FFS was used to evaluate the wicket gate. This approach ensures that the wicket gate is protected against global, local, and fatigue driven modes of failure. Crack-like flaw and fatigue crack growth assessments were also performed to provide an accurate estimate of the damage tolerance to crack-like flaws and to provide a remaining life estimate which can be considered while determining inspection intervals.

To evaluate the possible modes of failure, the following analyses were conducted:

- Elastic-plastic limit load analysis (plastic collapse)
- Elastic-plastic strain limit analysis (localized failure)
- Elastic-plastic ratcheting analysis (cyclic failure)
- Crack-like flaw stability analysis (damage tolerance)
- Fatigue driven crack growth analysis (cyclic failure)

**Global Stability**

A limit load analysis addresses the failure mode of ductile rupture and detects the onset of gross plastic deformation (i.e. plastic collapse) of the structure. It provides a lower bound limiting load of the structure as the solution to a numerical model. The limit load is the load at which overall structural instability occurs. It is numerically identified as a point in the analysis where for a small increase in load, equilibrium (convergence) is no longer achieved.
Limit load analyses were conducted for the primary loading configurations experienced by the wicket gate, namely:

1. Gate squeeze
2. Shear-pin activation

Stem loading was linearly ramped from gate squeeze loading until the onset of plastic collapse could be distinguished. The load ramping progression is shown in Table 3. The \textit{Load Factor} is a multiple by which the normal operational loads have been increased in that analysis step.

<table>
<thead>
<tr>
<th>Analysis Step</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Factor</td>
<td>1.0†</td>
<td>1.5</td>
<td>2.0</td>
<td>2.29‡</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

†Gate squeeze
‡Safety element activation (i.e. Shear-pin)

This analysis was conducted for each of the boundary conditions evaluated (i.e. once for the gate squeeze and once for the shear-pin activation).

**Local Failure**

In order to ensure that the wicket gate is protected against localized failure, elastic-plastic analyses were conducted. Equivalent plastic strain (PEEQ) was monitored at peak locations as the stem loading was linearly ramped to the onset of plastic collapse. Values were compared to the limiting strain as outlined in the ASME FFS-1 [1] standard. The strain damage was quantified at each load factor as the \textit{strain limit damage ratio} (SLDR). The SLDR compares the local PEEQ to the limiting strain defined by the ASME FFS-1 [1] standard. Locations of peak PEEQ on the wicket gate were considered acceptable for the specified load factor if the SLDR was less than or equal to unity.

Local failure analyses were conducted for the primary load configurations experienced by the wicket gate, namely:

1. Gate squeeze
2. Shear-pin activation
Local equivalent plastic strains were monitored as the stem loading was linearly ramped from normal operating levels to those causing the onset of plastic collapse.

**Cyclic Fatigue – Ratcheting**

Cycle-by-cycle accumulation of equivalent plastic strain (i.e. ratcheting) is a mode of fatigue where crack like flaws can initiate in a few number of load cycles. To ensure that the wicket gate is protected against ratcheting, computationally intensive cycle-by-cycle elastic-plastic analyses including kinematic material hardening were conducted. In the FEA model, each loading and unloading is represented by an analysis step.

After being subjected to the minimum prescribed cycle-by-cycle loadings found in the ASME FFS-1 [1] standard, the component is considered protected against ratcheting if any one of the following conditions is met:

1. There is no plastic action in the component
2. There is not a permanent change in the overall dimensions of the component
3. There is an elastic core in the primary load-bearing boundary of the component

**Crack Stability and Limiting Flaw Curves**

One of the first tasks of a damage tolerance analysis is the estimation of critical flaw sizes. The failure assessment diagram (FAD) method found in the ASME FFS-1 [1] standard describes the measure of acceptability of a component that contains a crack-like flaw. The FAD method considers both unstable (brittle) fracture and limit load (plastic overload). In a FFS of a crack-like flaw, the results from stress analyses, stress intensity factor and limit load solutions, material strength, and fracture toughness are combined to compute a non-dimensional toughness ratio, $K_r$, and load ratio, $L_r$. The computed $K_r$ (vertical coordinate) and $L_r$ (horizontal coordinate) point represents the crack-like flaw’s acceptability. If the point falls on or below the FAD curve, the component is considered safe for continued operation. If the computed $K_r$ and $L_r$ point falls outside of the curve the component is considered unsafe for continued operation. An example of the FAD curve is shown in Figure 7. A point to the upper left of the FAD will fail by brittle fracture, while a point on the far right will fail by plastic collapse.
Alternatively, a technique exists for evaluating a component that has not been identified as having a crack-like flaw. This technique is based on the FAD method and evaluates a number of potential crack-like flaw depth-to-length aspect ratios. One way to represent this critical crack information is by plotting a limiting flaw curve (LFC) based on methods found in the ASME FFS-1 [1]. Combinations of flaw length and depth are determined which pose a risk for sudden failure due to brittle fracture or plastic collapse. Thus, these flaw dimensions represent points that fall exactly on the FAD. If the characteristic flaw dimensions (e.g. length, height) fall under the limiting flaw curve, then the flaw is considered acceptable. If the characteristic flaw dimensions fall outside the limiting flaw curve, then the flaw would be considered unacceptable. The limiting flaw curve provides a means to evaluate many combinations of potential flaw sizes. An example of the limiting flaw curve is shown in Figure 8.
Fatigue Driven Crack Growth

Once critical flaw sizes are determined, the next task in the damage tolerance approach is to grow a flaw to failure. The outcome of this analysis will provide an estimate of remaining life and govern how inspection intervals may be determined.

Extensive empirical data has demonstrated that the rate of fatigue crack growth in metals can be characterized by the following expression:

\[
\frac{da}{dN} = \begin{cases} 
C\Delta K^n & \Delta K > \Delta K_{th} \\
0 & \Delta K \leq \Delta K_{th}
\end{cases}
\]  

where \(a\) is a characteristic crack dimension (length or depth), \(da/dN\) is the crack growth per load cycle, \(\Delta K\) is the cyclic stress intensity factor, \(\Delta K_{th}\) is the threshold value of \(\Delta K\),
and $C$ & $m$ are material constants. The stress intensity factor, $K$, is a fracture mechanics parameter that characterizes the stresses near the tip of a crack. Figure 9 illustrates the typical crack growth behavior in steels for which Equation (1) was derived.

The cyclic stress intensity factor is defined as the difference between the maximum and minimum value of $K$ in a given loading cycle. It is related to stress and crack size as follows:

$$\Delta K = Y\Delta \sigma \sqrt{\pi a}$$

(2)

where $Y$ is a geometry factor that depends on the crack dimensions as well as the size and shape of the component; $\Delta \sigma$ is the cyclic stress.

Life assessment can be performed by integrating Equation (1), and because constant-amplitude loading (i.e., $\Delta \sigma$ does not vary from one cycle to the next) was assumed, the number of loading cycles required to grow the crack from an initial flaw size, $a_o$, to a final size, $a_f$, is given by

$$N = \frac{1}{C\left(\Delta \sigma \sqrt{\pi}\right)^m} \int_{a_o}^{a_f} \frac{da}{Ya^{m/2}}$$

(3)
It should also be noted that Equation (1) includes a threshold, $\Delta K_{th}$, below which the crack growth rate is zero. Consequently, some of the load cycles may not contribute to fatigue damage because $\Delta K$ is below the threshold. The threshold cyclic stress is given by

$$\Delta \sigma_{th} = \frac{\Delta K_{th}}{Y \sqrt{\pi a}}$$

(4)

Figure 10 illustrates an example of a grow-to-failure plot for a fatigue driven crack growth analysis.

![Normalized grow-to-failure example](image)

Figure 10: Example of a crack "grow-to-failure" plot.

Advanced programming or the use of custom software is needed for both the limiting flaw and crack growth analyses. Signal™ Fitness-for-Service [8] software, a verified and commercially available FFS software package developed by Quest Integrity, was used in this project.
**Inspection Interval**

After the "life" of the component has been estimated from the crack growth assessment, the final step in the *damage tolerance* approach is to determine inspection intervals.

The fitness-for-service method is interlinked to nondestructive evaluation (NDE). The results from an NDE can be used as input for both the crack stability and crack growth analyses. The outcome of which can be used to define inspection intervals. Further, any flaws that might be detected during an inspection can be evaluated directly using the limiting flaw charts for acceptability and inspection intervals can be re-evaluated to ensure that the measured flaw size will not grow to failure between inspections.

The primary objective of the damage tolerance approach is to provide assurance that flaws will not reach failure between inspections. The methods for achieving this goal depend on practical circumstances. For example, TVA is currently budgeting for a thirty year window between major disassembly/overhauls for wicket gates. In this case, the FFS assessments were evaluated against the desired inspection interval targets for acceptability.

The following describes a basic overview for the determination of the inspection intervals for a structure where flaws have yet to be detected. First, critical locations of the component are identified using stress and FFS analyses. These locations form the basis of the inspection points along the component. Next, an initial flaw size ($a_0$) corresponding to the largest flaw size that might be missed during an inspection is assumed for the crack growth analysis. This flaw size should not be confused with those described by the accuracy of the NDE, which, under best conditions, typically refers to the smallest detectable flaw (i.e. detection limit). In practice, initial flaw sizes have been found to be significantly larger than the detection limit of the NDE method. This is due to the variability associated with the precision of the inspection method and the skill of the inspector.

Next, the flaw is grown-to-failure (Figure 10). Inspection intervals are developed based on the acceptability to fit within the desired outage schedule as described above. For example, Figure 11 illustrates an inspection interval based on "half-life". If the outage requirements are within that window, then there is an approximate factor of safety of two on time-to-failure.
Inspection methods (e.g. wet fluorescence A/C magnetic particle, longitudinal or phased array ultrasonics (UT), etc.) based on industry best practice were recommended depending on location, access to inspection point and type of material to be inspected.

**Results**

The following Sections review the results from the material test, the stress analyses, and the FFS assessments.

**Material Test**

Experimentally derived stress-strain curves were used to model the material response of the vintage A27 wicket gate material. Engineering stress-strain curves sufficiently

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1 For more details regarding material tests and results please contact Eric Scheibler at e.scheibler@questintegrity.com
describe the material response of the uniaxial test specimen for small strains and are based on the original cross-section of the specimen. However, for large strain analyses the material's true stress-strain response is needed and is based on the "actual" or instantaneous cross-sectional area of the test specimen.

For the global stability and local failure analyses, a monotonic true stress-strain curve with isotropic hardening was used. For the ratcheting assessment, a bi-linear true stress-strain curve with kinematic hardening was used. Figure 12 illustrates the measured engineering stress-strain curve and the derived true stress-strain curve used in the elastic-plastic stress analyses.

Figure 12: Measured engineering and derived true stress-strain curves

Figure 13 illustrates the measured toughness values of the nine specimens ('□' symbol) taken at room temperature. These results were fit to the fracture toughness master curve following the procedures found in the ASME FFS-1 [1] standard. A minimum of six samples are needed for this procedure. This approach provides a means for which the toughness of the material can be modeled probabilistically as a function of temperature based on the distribution of measured toughness data. For example, based on the measured toughness data for the samples taken at room temperature and using a five-percent lower bound cumulative probability function, the estimated fracture toughness of
the wicket gate, at minimum operating temperature, is illustrated by the green diamond in Figure 13. Stated another way, there is a five-percent chance that the fracture toughness at the minimum operating temperature is at or below that value. The lower bound value was used for the evaluation of the wicket gate to ensure an appropriate level of conservatism.

![Material toughness as a function of temperature for the wicket gate specimens](image)

Three additional test specimens (‘+’ symbol), remaining material from the sacrificial gate, were analyzed at the minimum operating temperature and plotted against the toughness master curve in Figure 13 for comparison. It should be noted that the measured value of toughness for the specimens tested at the minimum operating temperature are within the “scatter” predicted by the toughness master curve developed from the room temperature specimens (‘□’ symbol).

Figure 14 represents crack growth data for the six specimens tested and are commonly referred to as “da/dN” curves and are plotted on a log-log scale. Three samples each were taken from location B and C (refer to Figure 5 and Table 1). These results were...
conservatively fit using a power law to determine the appropriate coefficients for the fatigue driven crack growth analysis.

![Log-Log Plot of Crack Growth Material Test Data](image)

Figure 14: Measured fatigue crack growth data

Other material properties (e.g. density, Poisson’s ratio, etc.) necessary for the FEA were assumed to be equal to typical values found in carbon steel. Minimum specified material properties were used for the stem sleeve and end plate materials. In the instances where specific material properties were limited or unavailable, lower bound values were assumed to maintain conservatism.

**Stress Analysis**

Stress results for each load case, gate squeeze and safety element activation, were verified against closed form calculations (e.g. shear stress in shaft cross-section due to torsion) to confirm correct application of loads and boundary conditions. The entire wicket gate was evaluated and “key” locations of interest were identified for further fitness-for-service evaluation. Figure 15 illustrates an example of key areas of interest along the boundary of the upper journal and the leaf of the wicket gate.
Fitness-for-Service

Global Stability

The applied moment and directional loads were increased until numerical convergence of the elastic-plastic analysis was no longer achieved. As the applied loads increased both the gate squeeze and shear-pin activation models underwent four distinct stages:

1. Initial linear global response until the local elastic limit was reached.
2. Plastic, or non-recoverable, strains occurred at local stress raisers along the leaf-collar and stem-collar boundaries.
3. The outer material of the upper stem, along the smallest radii, reached yield. As loading increased, plastic strains increased throughout the cross-section of the upper stem.
4. The upper stem became fully plastic and global stability was lost.

The progressive response of the component during load ramping is shown in Figure 16. The color grey in the false color stress contour shown in Figure 16 indicates areas that have exceeded the von Mises yield criterion.
By monitoring the angular displacement at the top of the stem, the point of global instability could be distinguished and is shown in Figure 17.

**Angular Displacement of Stem**

![Angular Displacement of Stem](image)

Figure 17: Angular displacement (degrees) of upper stem to monitor global stability
Under both load cases, the onset of plastic collapse begins at roughly 3.5 times loading at gate squeeze, or about 1.5 times loading at shear-pin activation. The convergence of the solution at both gate squeeze and shear-pin activation loading satisfies the global stability criteria and ensures the wicket gate is protected against plastic collapse.

Local Failure

Results of monitoring the SLDR at peak locations across the areas of interest are shown for the gate squeeze and shear-pin activation conditions in Figure 18.

Figure 18: Peak SLDR values for gate squeeze and shear-pin activation conditions

The peak values for each load case are shown in Table 4.
Table 4: Maximum SLDR values for both load cases

<table>
<thead>
<tr>
<th>Load Factor</th>
<th>Maximum SLDR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gate Squeeze</td>
</tr>
<tr>
<td>1.0†</td>
<td>0.03</td>
</tr>
<tr>
<td>1.5</td>
<td>0.068</td>
</tr>
<tr>
<td>2.0</td>
<td>0.108</td>
</tr>
<tr>
<td>2.29‡</td>
<td>0.134</td>
</tr>
<tr>
<td>2.5</td>
<td>0.153</td>
</tr>
<tr>
<td>3.0</td>
<td>0.204</td>
</tr>
<tr>
<td>3.5</td>
<td>0.262</td>
</tr>
<tr>
<td>4.0</td>
<td>0.379</td>
</tr>
<tr>
<td>4.5</td>
<td>0.547</td>
</tr>
</tbody>
</table>

†Gate squeeze
‡Safety element activation (i.e. Shear-pin)

For the current shear-pin rating of 160 kips, the maximum expected wicket gate loading produces a SLDR of 0.281. Therefore, the local equivalent plastic strain is less than the limiting strain at every location and the wicket gate satisfies the criteria for protection against local failure.

**Cyclic Fatigue – Ratcheting**

Six elastic-plastic “cycle-by-cycle” gate squeeze load and unload cycles were modeled representing approximately three days of operation. Eight elastic-plastic “cycle-by-cycle” shear-pin activation load and unload cycles were modeled representing approximately 40 years of occurrences. The top row of Figure 19 illustrates the accumulation of plastic strain at peak locations due to “cycle-by-cycle” applied gate squeeze and shear pin activation loading conditions. The area of peak plastic accumulation was consistently found to occur at the leaf-collar boundary. Because the plastic strain continues to accumulate and does not elastically “shakedown” in both cases the “no plastic action” criterion cannot be used to ensure protection from plastic ratcheting. These results are useful, however, in identifying the leaf-collar region as a possible site of crack initiation.
Nodal displacements were also monitored at locations of peak plastic strain over the repeated load and unload cycles. The bottom row of Figure 19 shows the displacement of nodes during cyclic loading under gate squeeze and shear-pin activation conditions. Any observed change in displacement occurred in the limit of numerical precision (e.g. sixth decimal place) and were deemed negligible. No permanent change in the overall dimension is a condition sufficient to satisfy the protection against ratcheting.

Von Mises stress was extracted over critical regions at the end of the “cycle-by-cycle” analyses of the gate squeeze and shear-pin activation conditions (Figure 20). The von Mises stress is an invariant stress that can be used as a yield criterion. It provides a means to compare multi-axial stress values found in components subjected to multi-axial loading (e.g. wicket gate) to yield strength values from uniaxial tensile specimens. These results were used to evaluate the amount of yielded to elastic material across the primary load bearing cross-section of the gate.
Figure 20: Von Mises stress (psi) at the end of cycle-by-cycle ratcheting for gate squeeze (top) and shear-pin activation (bottom)
Figure 21 shows that even under the most extreme and expected condition of shear-pin activation, the wicket gate maintains an elastic core across the primary-load-bearing cross section. Demonstration of an elastic core satisfies the protection against ratcheting due to cyclic loading criteria.

**Crack Stability and Limiting Flaw Curves**

Based on the stress analysis, the most likely scenario for the formation and propagation of a crack like flaw would occur along the stem to collar and leaf to collar boundaries. Upper bound primary through thickness stress profiles that occurred at the maximum stress location in both the stem to collar and leaf to collar boundaries were used in the FFS assessment. The limiting flaw curves were calculated with the material parameters gathered from the material tests using Signal™ Fitness-for-Service [8] software.

Figure 22 and Figure 23 represent examples of limiting flaw curve plots for the leaf to collar boundary and the stem to collar boundary respectively. The solid curve represents limiting aspect ratios for surface breaking semi-elliptical crack-like flaws, and the reference point below the curve represents the largest possible flaw that might be missed in an ultrasonic inspection.
Figure 22: Limiting flaw curve for a vertical flaw in the leaf-collar boundary region

Figure 23: Limiting flaw curve for a horizontal flaw in the stem-collar boundary region
Crack dimensions that fall below the curves are considered sub-critical, whereas those that fall outside of the curves are critical. Thus, these curves represent combinations of crack lengths and depths that could pose a significant risk of sudden failure. These curves were used to determine future inspection requirements and to evaluate the stability of any measured linear indications.

Limiting flaw curves were created for the remaining sections of the wicket gate following the procedures outlined above. This provided TVA with limiting flaw curve plots for future inspection reference guides for the wicket gate.

**Fatigue Driven Crack Growth**

One of the final steps in the damage tolerance approach is to estimate the remaining life of the component by growing a flaw to failure. A “grow-to-failure” analysis consists of growing an initial flaw size using the material properties determined from the material tests and constant amplitude cyclic stress until the flaw becomes unstable. The point of instability, or failure, is where the final crack dimensions are on or outside limiting flaw curve. Based on the results from the stress, crack stability and fatigue driven crack growth sensitivity analyses conducted, it was determined that horizontal crack-like flaws along the stem to collar boundary would represent the “limiting” case for the remaining life assessment.

Using Signal™ Fitness-for-Service [8] software crack growth modeling was performed on eight unique combinations of loading cases, crack orientations and initiation sites. Based on peak equivalent plastic strains and stress locations, likely crack initiation sites were found to be at the leaf-collar and stem-collar boundaries. For each of these locations, vertically and horizontally oriented flaws were subjected to the constant amplitude cyclic stresses that occur in the normal direction to the crack face under repeated gate squeeze and shear-pin activation conditions.

It should be noted that, in order to ensure conservatism for this type of analysis, shear-pin activation was modeled as occurring at the same frequency as gate squeeze (i.e. twice daily instead of 1 occurrence every five years). This was deemed necessary because of the varied and unpredictable influence that loads due to obstructions may have on the behavior of a crack. Applying the upper bound resultant stress state (shear-pin activation) on the most frequent loading interval (gate squeeze) assures appropriate conservatism in the analysis. All cracks were grown from an initial depth of 0.125” and length of 0.375”. These dimensions statistically represent the largest flaw that might be missed in a given inspection using ultrasonics.
Failure was defined when crack dimensions grew to reach those of a critical crack size as defined by the critical flaw analyses. Table 5 contains the remaining life estimates of the wicket gate under each of these scenarios. The crack-like flaws modeled in the stem-collar boundary region produced the limiting cases.

Table 5: Remaining life estimates

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Flaw Initiation Site</th>
<th>Orientation</th>
<th>Cycles per Year</th>
<th>Time to failure, years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate Squeeze</td>
<td>Leaf-Collar Boundary</td>
<td>Vertical</td>
<td>730</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal</td>
<td>730</td>
<td>1586</td>
</tr>
<tr>
<td></td>
<td>Stem-Collar Boundary</td>
<td>Vertical</td>
<td>730</td>
<td>4775</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal</td>
<td>730</td>
<td>2280</td>
</tr>
<tr>
<td>Shear-Pin Activation</td>
<td>Leaf-Collar Boundary</td>
<td>Vertical</td>
<td>730</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal</td>
<td>730</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>Stem-Collar Boundary</td>
<td>Vertical</td>
<td>730</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal</td>
<td>730</td>
<td>46</td>
</tr>
</tbody>
</table>

Figure 24 shows the "limiting" case crack growth with respect to the projected inspection interval of 30 years.
Stated another way, the desired interval for inspection of 30 years for major
disassembly is acceptable with a factor-of-safety of 1.5 on time.

Conclusion

Based on the analyses the following conclusions were established:

1. The global stability criterion, which ensures protection against plastic collapse,
   was satisfied by the model’s numerical convergence to a stable solution under
   expected loading conditions. Analyses showed a continued linearly stable global
   response up to about 3.5 times the loading at gate squeeze, or about twice the
   loading required to break the shear-pin.
2. The highest equivalent plastic strain experienced under gate squeeze conditions
   was about 5% of the limiting strain value. Shear-pin activation conditions
   elevated the maximum equivalent plastic strain to 30% of the limiting value.
   Since both conditions produced a maximum below the failure condition defined at
   100%, the wicket gate satisfies the requirement for protection against local
   failure.
3. Under both gate squeeze and shear-pin activation loading conditions, cyclic
   loading of the component revealed isolated areas of plastic equivalent strain
   accumulation. However, the retention of an elastic core in the primary-load-
   bearing cross section of the component satisfies the ratcheting assessment.
4. Conservative modelling of fatigue driven crack growth produced a remaining life
   estimate of 46 years. This provides 16 years in excess of the proposed
   disassembly and wicket gate inspection interval of 30 years. This implies that if
   crack initiation were to occur, the crack could be detected by routine inspection
   prior to causing failure.

The above analyses support the conclusion that the wicket gate design satisfies the
fitness-for-service evaluation criteria and is considered acceptable for use under the
provided operating conditions.

Based on the limiting case described herein, TVA can meet the desired 30 year interval
between major disassembly, before a required inspection of the wicket gates.
Authors

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Evan Jones is a Consulting Engineer with Quest Integrity Group. His knowledge of finite element and fracture mechanics methodologies has involved him in a variety of projects across the power generation, petrochemical and petroleum industries. Evan specializes in performing fitness-for-service evaluations for a variety of structural types and unique components. Evan has a Master’s of Science degree in Civil Engineering from Colorado State University with a focus in computational solid and fluid mechanics.
References


[6] Dassault Systèmes, "SolidWorks Premium, x64 SP5.0 ed.".


[8] Quest Integrity Group, LLC., "Signal Fitness-for-Service Software, V.4.0".