Folsom Dam Outlet Modification: Materials, Welding, and Corrosion

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1 Introduction

The current sluice gates (nearing 50 years old) at Folsom Dam are performing well, and there are no apparent problems with the materials. However, there is a need to increase the controlled release volume of the Dam to better protect Sacramento from flooding. This will be accomplished by increasing the size and number of gates at the Dam.

Replacing the 5-by-9-foot cast steel gates with new cast steel gates is unlikely, because fabrication methods have changed over the years. So, the new gates will be built with different materials. The applied stresses on the gates will also change, since the new gates will be larger than the old gates.

Here we review material performance and welding issues related to the design proposed by the Bureau of Reclamation (BOR) for the new gates at Folsom Dam. In figures 1 - 16, photographs and diagrams show some of the features of interest.

2 Executive Summary

The design and materials proposed by BOR for the new gates at Folsom Dam have been reviewed. We have made a number of suggestions and recommendations. For the most part, the issues we raise simply add further consideration to the process. However, we strongly recommend that the gate leaf be fabricated from a single type of material (as opposed to a mixture of stainless steel plate and steel bracing).

3 Background information and assumptions:

The downstream frame (body) of the existing gates at Folsom Dam are identified as Class 2 (QQ-S-681b) cast steel on the drawings. This corresponds to a unified number of G43400, which is a Ni-Cr-Mo alloy steel (AISI 4340). The material used for the gate leaves is not specifically identified, but we assume it is also a cast 4340 steel.

The piston stem material in Folsom Dam is specified as a 410 martensitic stainless steel stainless steel, in the T (tempered) condition. It is fastened to the leaf by a captive bronze threaded nut, loosely fit to the leaf. This is basically the design and material that will be used for the new gates. Similar types and levels of in-service loading are expected.

The leaf seals on the gates at Folsom Dam are bronze on stainless steel.
The grease ports are a common hole through the seat and gate-body with a grease pipe threaded into the embedded top face. The new gates will have a design similar to the existing gates, but different materials will be used and an 0-ring has been added between the bronze and the gate body (bronze seat in contact with A36 steel

body)

Other information we gathered from our meetings is as follows:

- The width of gates will change from 5 feet to about 9.33 feet;
- The height of the gates will change from 9 feet to 12 feet on the lower tier and 14 feet on the upper tier;
- The diameter of piston will change from 30 inches to 26 inches;
- The diameter of the stem will change from 9.5 inches to 9 inches;
- Two to ten cycles per year is typical for the opening and closing of the gates;
- The allowable tensile and shear stresses for an ASTM type 304 or 316 stainless steel gate material, shall be 40 % of yield or 25 % of ultimate (12,000 and 7,200 psi respectively);
- The allowable tensile and shear stresses for an ASTM A36 structural steel gate material, shall be 40 % of yield or 25 % of ultimate (14,400 and 8,640 psi respectively);
- A seat/leaf friction factor of 0.4 is used for calculating lifting and closing loads on the gate;
- The angular deflection of the leaf at the seal on the gate shall not exceed 180 seconds;
- A 1000 psi average bearing stress on gate seals is anticipated;
- The allowable shear stress for an ASTM B148 alloy (957 Al-Bronze) used for the seals shall be 60 % of allowable tensile stress (7920 psi);
- The allowable tensile stress for an ASTM B148 alloy (952 bronze) used for the seals shall be 33 % of yield or 16.5 % of ultimate (8,250 psi);
- A 2130 psi lift force is required (calculated) to open and close new gates;
- The ASTM (round bar A276) class 410 martensitic stainless steel (T condition) used in valve stems will have an allowable tensile stress of 40 % percent of yield or 25 % of ultimate (25,000 psi) and be sized to resist column buckling.

4 Materials Information and Issues

The gate leaves and bodies currently in use at Folsom Dam are believed to be cast 4340 steel. This is a medium-carbon low-alloy steel, alloyed with manganese, chromium, nickel, and molybdenum. It is an ultrahigh-strength steel that is heat treatable. The steel has a good balance of strength and toughness, good resistance to fatigue, and good weldability. Depending on thermal history, the ultimate and yield strengths of 4340 steel can range from about 950 to 1875 MPa (150 to 275 ksi) and 850 to 1675 MPa (125 to 245 ksi) respectively.

For the new gates, a mixture of austenitic stainless steel and structural steels is proposed. The leaf would be an austenitic stainless steel plate with A36 steel braces welded to it for stiffening. The gate bodies would be made from A36 steel.

A36 is a structural quality carbon steel, with ultimate tensile strengths ranging from about 400 to 550 MPa (58 - 80 ksi) and yield strengths from 220 to 250 MPa (32 - 36 ksi), depending on processing history. This steel has good toughness and it is very weldable.

The austenitic stainless steels are more resistant to rusting and staining than carbon and alloy steels, due to their high chromium contents (16 % or more), and they typically have good toughness due to their high nickel contents. (The nickel changes these steels from a ferritic body-centered-cubic crystal structure, like carbon and alloy steels, to an austenitic face-centered cubic crystal structure. This structure has higher toughness due to the additional slip planes inherent to the face-centered cubic crystal system). Minimum tensile and yield strengths of 300 series austenitic stainless steels typically exceed 500 MPa (75 ksi) and 200 MPa (30 ksi) in the annealed condition.

NIST data for annealed AISI 316 at 272 K (30 F) indicates a tensile strength of about 645 MPa and a yield strength of about 300 MPa, with a Young's modulus near 198 GPa (the modulus is fairly constant from 240 K to 300 K (-27.7 to 80.3 F, range from 201.6 to 196.3 GPa respectively).[1] The bulk and shear modulus for annealed 316 range from about 164.5 to 163.25 GPa and 78 to 74.75 GPa through this same temperature range. Handbook data indicated a Young's modulus of about 193 GPa for 316H (cast) in the annealed condition.

Type 410 martensitic (a body-centered tetragonal crystal structure) stainless steel is used for the stem on the gates at Folsom Dam, and will be used for the stem on the new gates. It can range in strength from about 485 MPa (70 ksi) tensile and 275 MPa (40 ksi) yield strength in the annealed condition to 690 MPa (100 ksi) tensile and 550 MPa (80 ksi) yield strength in the intermediate tempered condition.

Another type of stainless steel that might be of interest is duplex stainless steel, which has been developed and commercialized fairly recently (the past 20 years). These stainless steels are called duplex because they are a fine-grained mixture of austenitic and ferritic phases, in nearly equal quantities. They have a higher nickel content than the martensitic type to stabilize the ferritic structure against martensite formation. Their major advantages over austenitic (e.g. 304 and 316) stainless steels are a resistance to stress corrosion cracking and pitting, and a yield strength nearly twice that of the 300-series stainless steels.

A popular duplex grade is 2205 (S31803), with a composition near 22 Cr-5 Ni-3 Mo-0.1 N. This grade is commonly joined with a welding composition known as 2209. The total alloy content is similar to that of 304 or 316, while the cost seems to be about 30% higher (based on data for the welding electrodes). One electrode producer estimated retail prices of \$ 11.00 to 11.50 for types 308L and 316L stainless steel electrode, and a price of near \$ 14.40 for 2205 of a similar diameter and quantity. Handbook data indicates a Young's modulus of 200 GPa, a tensile strength of 620 MPa (plate annealed), a yield strength of 450 MPa (plate annealed), and a mean coefficient of expansion within the range from 20 to 100 C of 13.0×10^{-6} cm/cm/C.

Duplex stainless steels are being adopted in a broader range of applications and are now included in a variety of specifications and codes, such as ASTM A240 and ASME Section IX (where it is designated as a P-10H material). Other specifications cover shapes such as castings and bars. Wrought forms of duplex stainless are produced by domestic suppliers such as Carpenter and Eastern Stainless, and the filler (2209) by McKay and Esab.

5 Gate Designs and Issues

5.1 New Gate Design (300 series leaf plate with A36 steel bracing and 309 welds)

The handbook data we reviewed would indicate tensile and yield strengths for the A36 steel range from about 400 to 550 MPa (58 to 80 ksi) and 220 to 250 MPa (32 to 36 ksi) respectively. This is not too different from the minimum tensile and yield strength we find cited for the austenitic stainless steel plate of say 515 MPa (75 ksi) and 205 MPa (30 ksi) for a 316L annealed plate material. The Youngs modulus reported for A36 is 208-209 GPa.[2] The modulus for austenitic stainless steel is 190 - 201 GPa, which is about 5 to 8 % less. So, the use of A36 steel bracing has the advantage of a modist increase in the stiffness of the bracing and a cost savings (on materials).

In general, the welding issues can be resolved satisfactorily by carful consideration of the items discussed in the welding section on dissimilar metals. However, the corrosion issues are not so clear cut, and some are related to welding. One issue is that the residual stresses from the welding probably can not be removed by stress relief treatments, because the thermal contractions of the A36 steel braces and the 300 series stainless steel leaf plate during cooling from the stress relief treatment will differ significantly, and this will reduce the resistance to stress corrosion cracking for the gate. For example, the mean coefficients of expansion for an AISI type 1020 steel (like A36) and a 316 stainless steel are about 14.0 and 17.5 µm/m respectively between 20 and 500 C. So, cooling from stress relief treatments results in tensile stresses in the stainless plate and compression in the steel bracing. The cooling from room temperature to the service temperature will increase the residual tensile stress in the leaf plate a little more. The in-service stresses (bowing of the plate across the width) might produce some compressive stresses on the upstream plate face, but might increase the tensile stresses on the downstream side. Detailed analysis (considering the critical stress corrosion stress, the as-welded residual stresses, and the stress relieved residual stress) will be needed to determine if any stress relief treatment is useful for this design. Other corrosion issues concerning the mixing of dissimilar metals are related to galvanic couples. This particular gate design has local couples where A36 steel is welded or fastened to the austenitic stainless steel plate, and it has (in general) a higher stainless steel-to-steel ratio than previous designs for leaves.

The 300 series leaf plate would be expected to provide improved general corrosion resistance for the gate leaf, compared with a cast steel or structural steel, but any anodic reactions may be concentrated on the A36 steel bracing (which would tend to accelerate their corrosion rate). It should also be recognized that even though the stainless steel is resistant to general corrosion, it can be seriously degraded by stress corrosion cracking, intergranular cracking, pitting, knife-line attack, and other localized corrosion processes. This is particularly true if welding, heat treatment, and alloy selection are not done carefully to avoid residual stresses and sensitization, and the service environment is not properly anticipated.

Sensitization can likely be avoided by proper alloy selection and processing, and this will reduce the tendency for intergranular cracking and knife-line attack. (Sensitization is a high-temperature process where carbon combines with chromium, depleting the chromium below the level required for corrosion resistance. It is minimized by reducing the time at the critical temperature, or by increasing the cooling rate.) Specifying an alloy that has low carbon (and maybe low nitrogen), will help ensure that chromium carbide precipitation during welding and heat treatment processes does not occur.

Welding a carbon containing alloy to a 300 series stainless steel will require special precautions to avoid sensitization in the heat affected zone the creation of crevices, and residual stresses. The importance of avoiding sensitization was discussed above. Designing the braces to avoiding the creation of crevices will help eliminate large crevices, but small crevices will be unavoidable in the weld bead etc. The NACE Corrosion Engineer's Reference Handbook recommends keeping the area of stainless steel small when galvanically coupling it to carbon steel in seawater. The corrosivity and conductivity of seawater is much greater than that of Folsom Lake water, but at the point of joining, the distance current has to travel in the water is very small.

Welding electrodes are available to join A36 steel and austenitic stainless steel. The 309 electrode cited in the drawing is one choice. The main issue here is to select an electrode that will provide good toughness and strength, and will be resistant to solidification cracking. An alternate is 309L, which is more resistant to sensitization than 309, or 309L Mo, which is even more resistant to sensitization and produces diluted compositions that match more closely to 316L base materials.

Stress relief treatments will likely be needed, but as mentioned, new residual stresses may form during cooling from the stress relief treatment, especially for structures with a range of coefficients of expansion. The goal will be to determine welding and heat treatment procedures that minimize the residual stresses. Vibration stress relief is sometimes substituted for thermal stress relief. Here, the part is subjected to mechanical vibrations that are said to remove the residual stresses. However, vibratory stress relief is still the subject of some controversy. Proponents offer case studies where the vibration treatment is claimed to have reduced stresses, while opponents claim that the vibration intensity is insufficient to affect the stress state.

Other issues for this design include: (1) Possible galling of the 410 stem to the holes in leaf bracing that it passes through, figure 4, and (2) captive areas around regions of the stainless steel that might result in stagnant water and loss of passivation. To address issue 1, a bronze overlay is prudent, if stainless steel or steel braces are used. This will help avoid seizure of these materials. In our discussions with BOR, issue number two is recognized, however, they are not aware of corrosion problems in like designs.

Our recommendations, specific to this gate design, are as follows:

- Do not allow the contractor to select the type 300 series alloy (304, 304L, 316, 316L, or other like alloys). We recommend that BOR specifies 316L as the material. The higher nickel content will be beneficial for the mixed metal weld (A36 and stainless steel) . The low carbon content will greatly reduce the chances for chromium carbide precipitation during welding or heat treating, which reduces the susceptibility to intergranular corrosion and knife-line attack corrosion.

- Specify a ferrite content for the weld of about 4 to 8 FN, to reduce susceptibility to solidification cracking. Require FN measurement as a quality control to monitor the ferrite content of welds.

- Specify the grain size for the plate and of the bracing. This will help ensure a homogeneous and reasonable microstructure that will improve corrosion and mechanical properties.

- Specify a 309 L Mo electrode, or one that has been shown to be as resistant to sensitization and has as good or better general weldability.

5.2 Alternate leaf Design #1 (316L leaf with 316L bracing and 316L welds)

This alternate leaf design is attractive because matching materials are used to avoid the complications associated with dissimilar metals. The austenitic stainless steels are very weldable, and no pre or post weld heating would be needed, except for stress relief. This change would likely increased the cost over the “A36 – 300-series combination” due to use of the more expensive stainless steel for the bracing. In addition, the section thickness of the bracing may have to increase to meet the deflection requirements, since the modulus of the austenitic is lower than the A36 steel. (The strengths of the two materials are similar.)

Full stress relief treatments at 900 C are probably not practical. If a critical stress level for stress corrosion at Folsom Dam can be estimated, then the usefulness of a partial stress relief treatment at lower temperature should be evaluated.

5.3 Alternate Leaf Design # 2 (Duplex Stainless Steel leaf, bracing, and welds)

This design, like alternate #2, uses matching materials. In this case, duplex stainless steels are significantly stronger and slightly stiffer than austenitic stainless steels, so the section size of the bracing may be reduced over a 300-series stainless steel. For example, AWS Specification A5.9 for stainless filler metals lists a minimum tensile strength of 690 MPa (100 ksi) for 2209 duplex versus a 483 MPa (70 ksi) for 316L and 517 MPa (75 ksi) for 316. The young's modulus for ferritic and austenitic stainless steels are 200 to 215 GPa, and 190 - 201 GPa respectively, so duplex stainless steel might be expected to be somewhere between these values.

Stress corrosion cracking susceptibility of the duplex stainless steel is midway between that of austenitic and ferritic stainless steels. Crevice corrosion susceptibility is less than that for ferritic or austenitic stainless steels of similar chromium content. High nitrogen grades have better as-welded corrosion resistance than other duplex alloys (less segregation), but can have precipitation that lowers the corrosion resistance.

5.4 Alternate leaf design #3 (Steel leaf and bracing with matching welds)

The gate leaves in-service at Folsom Dam are cast steel, and they have performed well for about fifty years. If a wrought steel leaf can be fabricated, which would be expected to match the mechanical, corrosion, and wear properties of the present gates, this alternative would be of interest and may offer a cost savings.

5.5 Alternate leaf design #4 (solid steel gate)

A solid gate (thick plate, no bracing) has no crevices or dissimilar metals to increase the corrosion rate, which is attractive. However, a solid gate would need to have approximate dimensions of 9 X 14 X 2 ft (by BOR estimates). The additional weight for the leaf associated with this option would require a substantial increase in the hoist capacity (by BOR estimates), compared with the currently proposed design. Also, to purchase steel or stainless steel plate this thick strains the production capacity of a steel mill or foundry. If it is impossible to obtain cast gates of the current design, it is unlikely that solid slabs could be obtained. (Our inquires indicate that 10 to 12 inch plate thickness is about the thickest stainless steel plate available.)

Another variation to achieve the same effect is to build a sealed box. The box would have two leaves (up and downstream) with the bracing on the interior sealed from the water. The interior could be empty, or be filled with some inert media such as an oil that could bear hydrostatic loads.

6 Stem Issues

A 410 alloy in the T (tempered) condition is specified for the stem. This material is used as the stem material currently, and would be expected to serve well on the new gates.

Handbook data indicates that this alloy is typically tempered at 540 to 650 C (1000 to 1200 F), and stress relieved at temperatures up to about 480 C (900 F). The ASTM specification for 410 bar products is A276 (A176 for plate).

We recommend that both a minimum and maximum strength for a T – condition is specified (unless the ASTM standard already does this). This will help to ensure that the material has adequate strength, but is not stronger than necessary. It is important to get a good balance of strength and toughness, and allowing the strength to be too high unnecessarily lowers the toughness of the stem.

The allowable ultimate tensile stress (by BOR) for the 410 stem is 25% of the ultimate tensile strength (172 MPa, 25ksi). This would indicate an intermediate temper for the 410 material with a hot finished. This would be expected to provide a minimum tensile strength of 690 MPa (100 ksi), which is adequate.

7 **Galling**

The stems now in-service are a Ni-copper alloy, and no overlay is known to be present.

8 **Leaf seals**

The material chosen for the seals (Orcot) is a high-density-polythylene (HDP) non-metallic composite material. This material is attractive because it has a low coefficient of friction (compared with the bronze seals used in the past). The lower friction reduces the force needed to open and close the gate leafs. One concern here is that this material will change too much over time, compared with a metal. Another is that the material may be permeable to oxygen, which may change the corrosion environment at the leaf surface.

The general design of the seal is shown in Figure 15. This is essentially the same design now used at Folsom, with added bronze guides to restrain the leaf more tightly. The design plans to use the HDP material as a seat, with stainless steel inserts as necessary.

Our recommendations concerning the seals are as follows:

- BOR should check with manufacture of the HDP material to determine if the material is permeable to oxygen. If it is, this is a new situation (bronze seals were used in the past) and the effect on corrosion of the stainless steel leaf in contact with it should be considered.

- BOR should measure the wear of the HDP that has been in service on one of their sites for about 10 years.

- BOR shoud consider other materials, such as Teflon for seals.
- BOR should consider designing the joints with a bevel or finger joint (to smooth the transition from one piece to another).

9 Anchoring of the gate into the concrete

Gate bodies are designed to directly transfer loads to the surrounding concrete. The approach for holding the new gate bodies in place is similar to how the gate bodies at Folsom are now held in place. Gate body "surface texture and geometry" and grout are the primary mechanisms holding the them in place, and apparently, this is adequate. BOR is not aware of any problems in the past with this approach. However, BOR calculations indicate that if the seam between the gate body and the concrete were pressurized to the full head pressure of the reservoir, the gate body could be crushed inward. So work to document the anchoring performance of the existing Folsom Dam gate bodies is recommended.

To gather data that would help clarify this issue, test holes could be drilled through the cast steel that forms the present gate bodies. These holes could determine whether the upstream water has penetrated part-way around the gate body, and so indicate whether better sealants or a more serpentine path (more ribs on the exterior of the gate body) should be used in the new design. Although no gate bodies have ever collapsed from water pressure building up around the outside of the gate body, this would be a relatively low-cost way to get data on such a potential failure mechanism. Also, the old gate body exteriors should be examined (for evidence of corrosion or water penetration) as they are being removed, as a further source of information on this mechanism.

As a broader implementation of the above recommendation, a metallurgist or corrosion engineer should examine the old gates, seals, and gate bodies as they are being removed, for evidence of degradation (wear, corrosion, cracking, etc.). If significant effects are found, these data might be used to develop plans for similar gates in other dams. It will also provide data and understanding for future projects. The data will not be available in time (prior to the award of contracts) to be of much use on the Folsom gate design. However, it would not be too late to consider the data (and the implications) for changes to the Folsom project if necessary.

10 Welding

10.1 Welding of Dissimilar Metals

For the gate bodies, leaves, and stems, the materials of interest include structural steels, alloy steels, and stainless steels. Each of these steels are complex, and their mixtures (welding, joining, fastening) with other steels even more so. A ferrite constitution diagram offers a way to visualize some of the key issues when welding dissimilar steels. Figure 1 shows the 1949 Schaeffler constitution diagram.[3, 4]

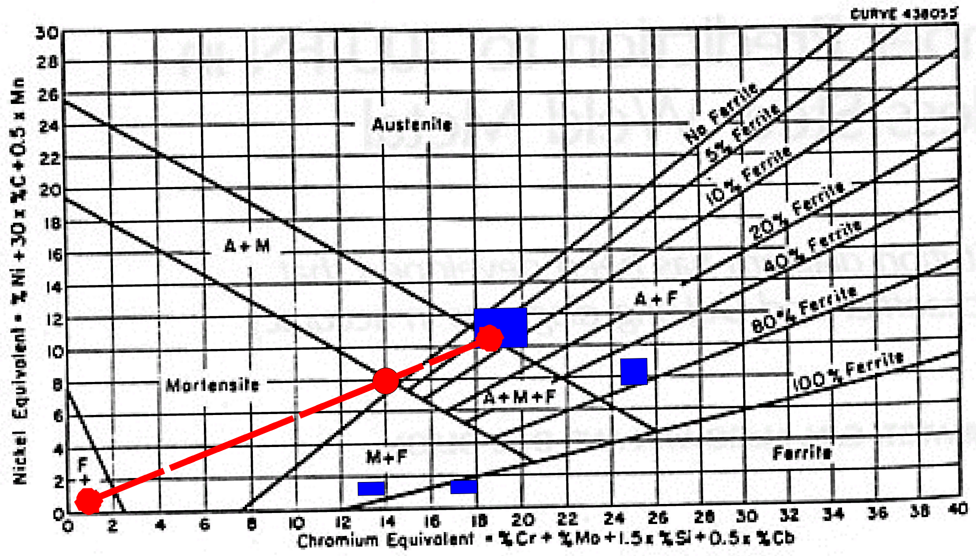

Fig. 1 – The Schaeffler constitution diagram for stainless steel weld metal

Although it has now been replaced by more accurate diagrams, its scope is the broadest and includes most common structural steels. The two scales are Nickel Equivalent (all the elements that behave like nickel in stabilizing the austenite phase) and Chromium Equivalent (all the elements that behave like chromium in stabilizing the ferrite phase).

Regular structural steels (like A 36) are in the far lower left of the diagram, near the origin. Common austenitic stainless steels (like 304 and 316) are near the center of the diagram, near a Nickel Equivalent of 10 or 12 and a Chromium Equivalent of 18 or 20. Common ferritic stainless steels (like 409) are at the bottom right of the diagram, near a Nickel Equivalent of 1 or so and a Chromium Equivalent of 17 or 18. Common duplex stainless steels (mixtures of austenite and ferrite, like alloy 2205) are near the right center of the diagram, near a Nickel Equivalent of 8 and a Chromium Equivalent of 25 or so. Common martensitic stainless steels (like 410) are near the bottom of the diagram, with a Chromium Equivalent near 13. (A more exact prediction of the phases that exist in a composition can be made from calculating the actual Nickel and Chromium Equivalents from the certified composition for an alloy.)

In general, the austenitic stainless steels are the lowest in strength, with the ferritic stainless steels, the low-alloy structural steels, the duplex stainless steels, then the martensitic stainless steels, showing respectively higher strengths. Toughness of a steel is usually inversely related to strength. Thus, the austenitic stainless steels are the highest in toughness, with the ferritic stainless steels, the low-alloy structural steels, the duplex stainless steels, then the martensitic stainless steels, showing respectively lower toughnesses. Martensitic stainless steels can be made tougher (more resistant to cracking) by a tempering treatment, with only a small loss in strength. However, they should not be welded later, because welding will offset the tempering treatment, and greatly reduce the toughness. Thus, the tempered 410 stem rods have a good balance of properties. Their high strength gives a good load-bearing capacity, while the tempering treatment has increased their resistance to brittle fracture and crack growth.

When an austenitic steel is welded to a low-alloy structural steel, special alloys (such as 309L) must be used. Otherwise, the resulting alloy mixture will fall somewhere between the two compositions. Figure 1 shows that a mixture of A 36 and 304 stainless will likely result in a composition near a Nickel Equivalent of 8 and a Chromium Equivalent of 14 (joint design and associated mixing determine the final alloy composition on the line). Such a composition would have a complex mixture of martensite and ferrite and very poor toughness. Thus, dissimilar joints between low-alloy steels and austenitic stainless steels are a usually welded with a 309L composition with a Nickel Equivalent near 14 and a Chromium Equivalent near 24. Even when diluted by an A 36 composition, this alloy will still produce welds that are predominately austenitic and exhibit high toughness.

9.2 Welding Procedures

Before construction, the contractor must prove the ability to produce the structure to the design requirements. This can be done through the production of a Procedure Qualification Record, a record of the production of a joint (using the specified base and weld materials), and then the testing of that joint to show the required properties and dimensions (including such measurements as tensile strength, impact energy, side bend tests, penetration, etc.). Later, the contractor may use Welder Qualification Records to show that all the welders on the job can meet the requirements, and Material Qualification Records to show that additional lots of base and weld materials can meet the requirements. Finally, a series of Procedure Qualification Records can be combined into a Welding Procedure Specification (typically with a range of welding conditions) that guide the final fabrication, and are the benchmark for the welders and inspectors.

9.3 Codes and Standards

The gates and associated structures should be fabricated according to a commercial construction code. There are a number of codes from which to choose (ASME, D 1.1, D 1.6, D 14.4, etc). Most of the following discussion is based on D 1.1 The ANSI/AWS Structural Welding Code- Steel, which has a very long history of successful use and refinement, although other codes might have applicability as well. (D 1.6 Structural Welding Code Stainless - might be used for the gates if they are made of stainless steel, but has only been in existence since 1999, and so has less history of successful use. D 14.4 Specification for Welded Joints in Machinery and Equipment might have greater applicability to the combination of static and dynamic load in the gates, but has only be in existence since 1997 and so has less history of successful use. D 1.4 Structural Welding Code - Reinforcing Steel might be used to control the joining of the reinforcing steel before the concrete is placed.)

9.4 Inspection

D1.1 includes inspection by two parties; the traditional inspection by the contractor as a regular check on the fabrication staff, and inspection by the owner (BOR) as an independent check of the production and installation quality. While most of this discussion refers to the inspection tasks that you require the contractor's inspector to perform, BOR should retain the right to independent checks of any steps in the process, from review of qualification records to final assembly. Also, D 1.1 has an appendix with a useful commentary (C6) on inspection that provides more background on the application of the techniques that are listed in the usual Section 6 on inspection requirements.

D 1.1 requires more than just inspection during the production and installation steps. It begins with development of an inspection plan, inspection of the incoming materials, review of mill test certificates, and checking the training of operators. BOR can obtain the services of a certified inspector or certified welding engineer to help to develop a detailed inspection plan, or use the general guideline in the following paragraphs.

Visual inspection is the most common type of inspection, primarily because it is so inexpensive and yet can catch so many problems. In fact, it is essential in checking the wide variety of fit-up tolerance and workmanship issues required by almost any Code. It should definitely be included in the inspection program and be used to check for any problem that would appear on the surface, however it is not suitable for buried imperfections. The other major limitation is that it is dependent on the training and visual acuity of the inspector.

Non-destructive examination would typically include MT or Magnetic Particle Testing, which uses prods and a low-voltage power source to induce magnetic fields in ferritic materials. It is best suited to emphasizing surface cracks and is fairly inexpensive to perform. Because it depends on a ferritic structure, it is not applicable to austenitic or duplex stainless steel construction.

Liquid Penetrant Testing uses a multi-step process to insert a colored dye into surface-breaking inperfections, then draw it out with a developer. Sometimes the technique is used with fluorescent dyes for greater sensitivity in low-light conditions. The advantages are portability, and low equipment cost. The disadvantages are a higher consumable cost (cost per meter of length inspected) because of the materials and that surface roughness may give false indications. We recommend that it be used to supplement visual inspection for critical welds, such as the welds that join the stiffeners to the back of the leaf.

RT or Radiographic Testing uses a variable-voltage or gamma source to produce a shadow image of the material in the structure. Any regions with lower density (such as cracks or pores) show up by a change in the contrast. The advantages of this technique are the ability to penetrate large thickness of metal, production of a permanent record, and variable voltage level (to enhance contrast). The major disadvantages are the radiation hazard (not a problem with proper shielding or area restrictions), higher skill level for operators and inspectors, and the difficulty in detecting planar imperfections oriented normal to the beam. We recommend that this technique be used on critical welds, but can be limited to some fraction of the welds (such as 10 %) to asses the typical quality, while reducing the cost.

UT or ultrasonic testing uses an ultrasonic beam to probe the interior of a part. Any reflections of the beam from surfaces other than the outer surfaces are indications of internal flaws. An advantage of this technique is a high sensitivity to planar imperfections that are oriented normal to the beam. Disadvantages include the requirement of a fairly smooth surface, a higher skill level for operators, and problems with diffraction in large grained materials (like stainless steel). Thus, this technique should be limited to the foredeck steel joints.

Destructive Examination can be performed on some qualification parts or other test parts to reevaluate the properties. For example, BOR could require one test weld (perhaps a butt weld that simulates the joints between the stiffeners and the leaf) to be produced each month and tested for strength, fatigue, and impact properties.

9.5 Considerations of Welding Residual Stresses

The shrinkage that occurs due to cooling after welding sets up yield-level stresses in structures. These stresses lead to service problems through mechanisms such as stress-corrosion cracking. They can be reduced by post weld heat treatment, where the structure is heated to a temperature where it softens and the stresses are relaxed. These temperatures are determined by the materials that are used, and so can not be specified until either a grade of steel or stainless steel is selected.

The residual stresses can be reduced by weld preheating, where the base material is heated before the weld. However, this only has a limited effect. Weld preheating is most effective in reducing the cooling rate for materials that are subject to martensite formation. In this case, preheat slows the cooling rate so softer, more ductile phases form. Again, preheat will depend on which base material is selected.

10 Corrosion Issues & Prevention

10.1 General

The proposal to replace the carbon steel leaves, which have served successfully for decades, with stainless steel should be reviewed with caution. Examples without adequate reviews are in case histories cited by O. W. Siebert in his articles on classic corrosion blunders published in Materials Performance [Siebert, 1983 #1566; Siebert, 1978 #1565].[5,6] In these articles several examples are cited where a material, which had demonstrated many years of successful service, was replaced by a considerably more expensive stainless steel which failed in a much shorter time. Usually, these failures were due to either chloride induced stress corrosion cracking or pitting which should not occur in the lake water at Folsom Dam (if good materials and fabrication processes are used).

10.2 Localized Corrosion of Stainless Steel

While the chemical composition of the lake water has a low chloride (or other halide) ion concentration, there are still issues with the selection of stainless steels that should be considered. Stainless steels owe their corrosion resistance to the formation of a thin, continuous, and transparent surface film of corrosion products that protects the remaining underlying metal from the environment. These films forms spontaneously as a result of corrosion in aerated environments. Normally, alloying to promote self passivation, as done in stainless steels, is an ideal scheme for protection against corrosion because it lowers corrosion rates by several orders of magnitude with a self healing surface film that produces a bright and shiny surface.

Typically, most corrosion problems in stainless steels are the result of the combination of oxidizing conditions and halide ions. This combination results in attack at localized or occluded sites where the passive film is having difficulty reforming when it is chemically or mechanically damaged. Localized corrosion phenomena such as pitting corrosion, crevice corrosion, and intergranular corrosion occur in stainless steels under these conditions. When mechanical stresses are applied, stress corrosion cracking may result. Since 316 typically has very good resistance to stress corrosion cracking in lake-water environments, we did not find a K_{1SCC} number for it. (For infomation, 4340 has a K_{1SCC} of 33 MPa $\sqrt{m}$ (30 ksi $\sqrt{in}$) for 1650 MPa (240 ksi) yield strength material in distilled water. For a 304 in boiling MgCl (154C) a K_{1SCC} of about 8 MPa $\sqrt{m}$ might be expected.)

The major problem with these localized forms of attack are that they are hidden in the occluded sites where they can nucleate after some period of service and propagate unobserved until catastrophic failure results. The low concentration of chloride and other halide species in the lake water diminishes concern with these types of failure modes, but some caution should be exercised in design and alloy selection as wetting and drying cycles can concentrate even trace salts to saturation levels and contamination of surfaces by human or animal traffic should also be considered. It should be noted that we have seen intergranular cracking in both 302 and 410 stainless steels at Hoover Dam, but in both cases the materials were sensitized.[7,8]

Unless some chloride ion concentration mechanism is operational, unsensitized 300 series stainless steels are considered immune to stress corrosion cracking at low temperatures in low chloride-containing surface waters similar to Folsom Lake. However, with sensitization, cracking can occur at very low chloride levels (e.g. swimming pool water, ≈1,000 ppm). Cracking in sensitized samples has been reported at very low halide ion concentrations at elevated temperatures in presurrized water (<0.1 ppm at 260 ˚C). Therefore, avoiding sensitization is important even at Folsom. Once sensitization is eliminated, stress corrosion cracking becomes a lesser concern and localized forms of attacked such as pitting and crevice corroison become the main concerns. The added Ni and Mo content of 316L would help avoid these forms of attack.

Taking these issues into account, two precautions seemed warranted. First, if stainless steels are used, low carbon content alloys should be selected and proper welding procedures used to avoid chromium depletion at grain boundaries by chromium carbide precipitation and stainless steels should not be welded to carbon steels. Second, while unsensitized 304L should be immune to stress corrosion cracking in Folsom lake water, cracking of this alloy under conditions where bright sunshine heats the surface evaporating water and concentrating salts is not uncommon. For applications where this happens, 304L is usually replaced with 316L. Alloy 316L (CF-3M) is similar in composition to 304L (CF-3) with the main difference being the addition of 2-3 mass percent of Mo. The addition of Mo to this alloy dramatically improves the effectiveness of Cr in passivating the surface improving the resistance of these alloys to localized attack and stress corrosion cracking. This alloy has been used successfully for highly stressed, above deck, wire rope fittings on boats for 2 or 3 decades. It should be noted that 304L and 316L are wrought alloy designations and the equivalent cast alloy designations are 304L=CF-3 and 316L=CF-3M (ASM Handbook 8th Ed. Vol1)

While localized corrosion due to oxidizing conditions and halide ions is a low concern at Folsom due to the low halide ion concentration in the lake water, another concern is what may happen at locations where the water becomes depleted in oxygen. That is, stainless steels rely on a passivating oxide film to prevent corrosion. If there is insufficient oxygen in the local environment to maintain this oxide film, then the film may break down resulting in corrosion. This is not uncommon in stainless steel freshwater storage tanks when the water becomes stagnant and the oxygen dissolved in the water is consumed or sediment collects in the bottom of the tank, preventing oxygen from reaching the surface of the metal. Under a sediment layer, the metal may begin to corrode, increasing the metal ion concentration between the sediment and the now unpassivated stainless steel. These metal ions may hydrolyze to produce metal hydroxides and hydrogen ions, lowering the pH under the sediment, making repassivation more difficult and allowing galvanic currents produced at more aerated locations to drive corrosion to rates that would normally produce passivity. Problems of this type can be prevented by designing to avoid stagnant conditions and designing to enable the easy cleaning at locations where sediment may collect (organic material can be particularly bad). Regular maintenance, periodic testing, or a slow flow rate may also be used to prevent corrosion by depassivation by local reducing conditions.

10.3 Galvanic Corrosion/Area Effect

When using different types of metal or different alloys, one alloy will frequently be more active or noble than the other alloy. This difference in potential will result in the flow of a current between the alloys, if they alloys are in electrically conductive contact with each other and ions can be exchanged between the solutions contacting the surface of the alloys. This current will lower the corrosion rate of the more noble or cathodic alloy while accelerating the corrosion rate of the more active or anodic alloy. This effect can be trivial with favorable area ratios or it can result in catastrophic failures if area ratios become unfavorable. That is, a large cathode which produces a little extra current per unit area can result in very high corrosion rates in an anode of small area. At Folsom, the stainless steel components will assume a more noble potential than the carbon steel parts. As a result, the stainless steel parts will produce anodic currents in steel parts that are in galvanic contact. If the area of the anodic steel in contact with the solution is much smaller than the area of stainless steel, then failure may occur in a relatively short time. On the other hand, if the area ratio is reversed, failure may never occur (eg. stainless bolts can be used to hold steel plates together, but not the reverse). While this issue may not be a new issue to an experienced designer, it is a surprisingly common occurrence (an example is included in Siebert's classic blunders papers [Siebert, 1983 #1566; Siebert, 1978 #1565]) for someone to later notice corrosion of the large anodic area and paint it. This results in a sudden reversal of the area ratio as the anodic current now becomes focused into flaws and small scratches in the coating resulting in perforation of the component in a relatively short time. As a result, it is recommended that if dissimilar alloys are used in contact with each other in the final design that maintenance directions identify these locations and identify where coatings may and may not be used.

10.4 Evaluation of water chemistry

Conductivity measurements were made from a sample of Folsom Lake water, taken from the lake at the boat ramp located near the dam on June 21, 2002 and mailed to Gaithersburg for measurement. The conductivity was determined by measuring the current required to oscillate the potential between two platinum electrodes over a 100 mV range in a sinusoidal manner at 30 Hz using a potentiostat. The cell constant was checked using NIST solution conductivity standard reference materials: SRM 3191 and 3193. The conductivity was estimated from the indicated cell constant and two other solutions were measured at the same time for comparison: deionized tap water and an aqueous solution with 0.5 mol/L of NaCl. The results are given in the table below.

Table 1: Measured Electrical Conductivity of Folsom Lake Water.[*]

Solution	△I, A(p-p)	R, ohms	1/R, S	Cell Constant, µS/cm	
NIST SRM 3191	1.01E-05	9.91E+03	1.01E-04	100	0.991
NIST SRM 3193	1.01E-04	9.95E+02	1.01E-03	1000	0.995
	△I, A(p-p)	R, ohms	1/R, S	Cell Constant, µS/cm*	
Deionized tap water	5.07E-07	1.97E+05	5.07E-06	0.993	5.0
Folsom Lake Water	6.64E-06	1.51E+04	6.64E-05	0.993	65.9
0.5 mol/L NaCl	4.24E-03	2.36E+01	4.24E-02	0.993	42,100

[*] The uncertainty in solution conductivity measurements of this type have been found to be less than 1% [ref 1 below]

The electrical conductivity of the water sample taken from Folsom lake is low and indicates that the influence of galvanic coupling should be seen over significantly less distances than observed in many other solutions. The acceleration of corrosion due to galvanic coupling decreases in an exponential manner with the distance between the coupled metals due to the resistance of the solution to the galvanic current. As a result, the rate of this decrease with distance will be much greater for the water at Folsom dam than many other surface waters such as seawater where the conductivity should be close to that of the NaCl solution in the table. This does not eliminate galvanic attack. The relative area ratios will still be important and attack may still occur at joints, but it will limit the distances that one needs to consider in design and inspection to ensure that this form of attack is not occurring.[9]

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