

D. Weld Repair of the U.S. Capitol Dome

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Abstract

This report describes some options for weld repairs to the outer shell of the dome on the U.S. Capitol. During the past 140 years, corrosion products have built up within many of the joints, leading to cracking of some of the iron castings that form the shell. Since the dome is a national landmark, the goal is to restore the structural integrity of the original castings, replacing as few of the components as is absolutely necessary. While mechanical joining of the fractures or filling of the gaps with epoxy are alternative procedures, a fused (leak-tight) and ductile joint is preferred. A major challenge is that the castings were produced with 1850s' technology, so the composition is far different from current castings that are designed for weld repair. Therefore, we chose to develop some alternative approaches, designed specifically for the dome castings. Of the various options, oxyacetylene braze welding (a flame repair process where the filler metal melts at a temperature below that of the casting) with low-fuming bronze (about 60Cu-40Zn) worked best. The bronze forms joints that are very similar in strength to the castings. A joining trial in July 2002 demonstrated the utility of this technique in the flat and vertical positions at four corner cracks on the dome.

1 Background

In a visit with staff of the Office of the Architect of the Capitol, several of us offered to help with the planned restoration of the Capitol Dome. The restoration efforts have been given a high priority, now that moisture has leaked into some of the interior areas of the building. The goal is to restore the dome to its original condition, with minimum replacement of castings. Therefore, welding is an important option for repair of cracks and corrosion damage to the castings.

We learned that the present dome of the Capitol was designed in the 1850's by Thomas U. Walter and built between 1856 and 1866 to replace an earlier wooden dome. A masonry dome was ruled out because the existing Rotunda walls could not support the mass of the larger dome. However, calculations showed that the Rotunda could support a cast-iron dome, which could be cast with cutouts in areas where material was not required. The U.S. Capitol Dome was the second cast-iron dome in the world, and remains the world's largest iron dome to this day. Although the majority of the dome, complete with its inner and outer shells and lower skirt, is composed of cast iron, wrought iron was used in a few places. More information (including Walter's elevation and cross-section drawings from 1859) is available at the web site of the Architect of the Capitol [1].

In a tour through the dome, we saw that the interior rib structure (the supporting structure) was in good condition, but the outer shell had some cracks and visible corrosion at a number of the joints (where paint did not reach all the surfaces). The current moisture-leakage problems are _____

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attributed to gaps caused by expansion and contraction of the exterior shell and failing filler material in the joints between abutting plates. The leakage has led to corrosion at the joints of the outer shell and railings (castings or wrought structural forms about 1cm thick). The corrosion products accumulate in the joints until they stress the component castings beyond what can be accommodated by the mechanical fasteners, leading to cracking of the shell panels and railing components.

We saw a few weld repairs that were thought to have been performed about 40 years ago. Some of these welds had cracks that appeared to originate in the heat-affected zone (HAZ). There was no documentation on the procedures used for these welds, but the shiny surfaces (where the paint had been removed) suggested that they were of one of the nickel-rich compositions (commonly either nearly pure nickel or a 55Ni/45Fe alloy) that are typically used on cast irons, while the bead shape suggested that the welds were applied as a wide-weave bead with a high heat input (leading to a wider and more brittle HAZ).

2 Characterization of the Material

A few years ago, Lucius Pitkin Testing Laboratories [2] characterized several parts of the dome. They found that the dome ribs were ferritic gray cast iron, the skin was pearlitic gray cast iron, and the tension ring was wrought iron. On one cast-iron rib, they found the composition (in mass %) to be 3.39 C, 1.07 Mn, 0.92 Si, 0.61 P, and 0.10 S. The castings were quite low in strength (with tensile strengths measured between 17.8 and 18.8 ksi). The ASM Handbook [3] reports that currently produced gray-iron castings often have strength minima of 210 to 280 MPa (30 or 40 ksi) although there are grades as low as 140 MPa (20 ksi) and as high as 420 MPa (60 ksi). While gray-iron castings are not expected to have much ductility, a doubling of the maximum casting strength through improvements in technology during the last 140 years means that current castings may be able to tolerate double the deformation of the castings in the dome simply from the absorption of elastic strain. This means, however, that the traditional casting-repair technology designed for current castings might not be optimal for the historical castings found in the outer skin of the dome.

In the NIST laboratory, we examined several sections of the original casting from a railing and confirmed that the microstructure was a pearlitic gray cast iron. We felt that it should be best classified as flake-graphite (type A in ASTM A247) gray cast iron, although the microstructure is quite complicated and there were some regions with graphite rosettes (type B). The microstructure of the iron is mostly pearlitic, but has some ferrite around the graphite flakes and also has a high content of a phosphorus-rich intergranular phase. This intergranular phase is the likely cause of the low effective strength and low ductility of the dome material, compared to most current cast iron.

The complicated microstructure (together with the low strength and low ductility) of the dome castings reinforced our desire to reevaluate whether the materials and electrodes that are currently recommended and used to repair cast irons were appropriate for use on the unique materials found in the dome. For example, the nickel electrodes designed for joining cast irons (designation ENi-CI-A in AWS Filler Metal Standard A 5.15) are required to meet a specified room-temperature yield strength range of 262 to 414 MPa (38 to 60 ksi) and tensile strength range of 276 to 448 MPa (40 to 65 ksi). [4] Current technology ENiFe-CI-A (55Ni/45Fe alloy) electrodes have yield strengths between 294 and 434 MPa (43 to 63 ksi) and tensile strengths between 400 and 579 MPa (58 to 84 ksi). These strengths are quite appropriate for gray iron

castings, which are manufactured in strength grades ranging up to 400 MPa (60 ksi). For current technology castings, this high-strength filler material keeps the strength of the casting above a specified minimum and reduces the likelihood that a repaired casting will fail in the weld repair through overload. For the castings found in the dome, however, the repair criteria are far different, focusing more on restoring the casting integrity (relatively low loads) and serving as a moisture barrier.

We concluded that the fundamental cause of the cracks in previous repairs was the residual stresses that formed as the weld cooled. These stresses promoted cracking in these low-ductility castings. Therefore, the optimal filler composition would seem to be one that is near to, or even below, the strength of the castings. A low-strength filler would both induce less stress in the casting (due to the build up of shrinkage stresses during cooling) and be able to selectively accept more of the strains developed during the weld repair and through the future service conditions. This approach of using filler materials of lower strength, but higher ductility, for the dome castings is justified by the fact that the repairs are not in structure-critical regions, but are needed simply to restore the dome's surface integrity.

3 Development of a Repair Procedure

In 1999, we tried an oxyacetylene flame spray repair procedure with a copper-based alloy, but experienced cracking when used on a complex casting in the dome. Some of the cracking may have been due to the low temperatures during the repair (in November), but part of the problem may also have been due to the relatively high preheat that was required for this procedure. In February 2002, we were offered access to the dome that summer (July) for another trial, and so developed a fast-track plan to lead up to an in-place trial with an improved procedure. We decided to design and start some experiments immediately, to be sure of having several options ready for the July field trial. Jerry Doherty and Roger Bushey suggested that we evaluate GTA (or TIG) brazing. This involves replacing the oxyacetylene flame heat source with an arc from a tungsten electrode. One of the main advantages of using TIG brazing is that the parent material is not melted and therefore the weld metal is not contaminated with the high levels of residual elements (especially P) that might be present in the parent metal. This process has been used successfully in the repair of iron castings and is a reasonable alternative for this project.

The TIG brazing evaluation included making a butt joint followed by a grinding or machining process to end up with a transverse tensile specimen. The test design also included finding the lowest possible interpass and preheat temperatures. The first series of tests used contemporary cast iron for the screening test. The consumables selected for the evaluation included:

1. Silicon Bronze Rods,
2. Phosphorus Bronze C Rods,
3. Aluminum Bronze Rods, and
4. Nickel-Based Rods.

Several joints with the oxyacetylene process and a low fuming bronze (60Cu-40Zn) filler material were also produced for comparison.

Special Metals also agreed to start on some evaluations. They selected the SMAW process, since it is widely used (so most welders would be familiar with it) and it produces a low heat input. They evaluated four electrodes: ENi-CI (a nearly-pure

nickel alloy), ECuNi (a copper- nickel alloy), ENiCu-7 (another copper-nickel alloy), and ENiFe-CI (a nearly 50-50 mix of nickel and iron). They found that ENiFe-CI produced the lowest heat-input settings (60 A, 18 - 20 V) when using stringer beads to butter the surface of a piece of a commercial gray cast iron (with no post- or preheat). They found it difficult to maintain an arc with the other consumables (at the very low heat inputs) and the other consumables produced a very rough weld bead.

Meanwhile, some members of the team wanted to evaluate the situation firsthand, so we scheduled a meeting at the dome. Also, we requested and received a section of a casting that had been removed from the dome during replacement of a badly damaged railing.

After the tour of the dome, we chose to develop several procedures for the field trial:

- Use the TIG process to apply a nickel-based buttering layer to the casting, then follow this with TIG brazing using low-fuming bronze;
- Use oxyacetylene welding to close the cracks with low-fuming bronze; and
- Use the TIG process to join the cast iron with a nickel-based composition (base-line test).

Special Metals' work on very-low-current welding with a nickel-based composition could also be used to produce a buttering layer on the cast iron.

Using the material from the dome, ESAB welded and braze welded a number of joints and provided sections for testing at NIST. The most promising was the oxyacetylene braze weld with low-fuming bronze, followed by the TIG weld with a nickel-based composition.

Standard tensile specimens were machined from the test welds and were tested in tension following the procedures in ASTM Standard E8 "Standard Test Methods for Tension Testing of Metallic Materials".

The nickel-based specimens (with the bend) broke in the casting's heat-affected zone as the grips were tightened, so no strength data were developed on these. Obviously, a joint this brittle is not a good candidate for repairs to the dome, so we excluded this technique from further consideration.

Two low-fuming bronze specimens, WM-1 and WM-2, were tested successfully. We collected data on ultimate strength and elongation as follows:

Table 1. Strength and Elongation Data on the Brazed Joints

<u>Specimen</u>	<u>Ultimate Strength</u>		<u>Elongation (Total Strain to Failure)</u>
	<u>MPa</u>	<u>ksi</u>	<u>%</u>
WM-1	150	21.8	0.22
WM-2	156	22.6	-

Both tensile specimens broke in the HAZ, indicating that both the base metal and the welds were stronger than the HAZ. We obtained accurate strain data only for specimen WM-1, where we collected data from strain gages on both the base material and on the bronze filler. No yield strength is listed because the specimen did not attain

a plastic elongation of 0.2 %, which is the usual definition of yield. The use of strain gages rather than a clip gage allowed us to distinguish the plastic strain after failure in both the base metal and bronze. We measured a plastic strain of 0.05 % in the cast iron and 0.14 % in the bronze, indicating that both materials do exhibit a small amount of plastic deformation before fracture. The higher strain in the bronze confirmed that a softer filler shields the sensitive casting from some strain damage. Although we did not obtain strain data for specimen WM-2, a very similar strength and load-versus-time curve appearance would suggest a similar plastic strain.

After the tensile tests, specimen WM-2 was examined with optical and scanning electron microscopes, and the hardness was measured across the filler-base metal interface. The most important observation was the lack of any martensite. We attribute the lack of martensite to the braze welding technique (with applied flux) being applied at a relatively low temperature. This very desirable result further supports the choice of braze welding with low-fuming bronze for the repairs to the dome.

Figure 1 shows the cross section through the low-fuming bronze joint at a magnification of about 10 X. The bronze shows good fusion to the cast iron and no porosity is visible at this magnification. Figure 2 shows the cast iron-bronze interface at higher magnification (about 100 X). This image, taken before etching the surface, clearly reveals the carbon flakes in the cast iron (on the left), and a few pores in the bronze, especially along the interface. Since no fracture or cracks occurred at the pores, they have no effect on the integrity of the joint. The interface between the cast iron and bronze is straight (confirming the expected low solubility of the cast iron in the bronze), yet with good wetting (confirming the ability of the bronze to bond to the cast iron surface). A microhardness traverse was made across the braze weld in specimen WM-2. The hardnesses in the weld and HAZ were quite similar indicating the absence of martensite in the HAZ.

Meanwhile, in preparation for the field trial, we collected the equipment that we would need. The maintenance staff for the Capitol agreed to furnish acetylene and oxygen bottles and hoses. ESAB furnished one of their portable TIG units, which we could carry to the roof. Although this unit provided only 200 A, Jerry Doherty determined that it would be sufficient for the trial.

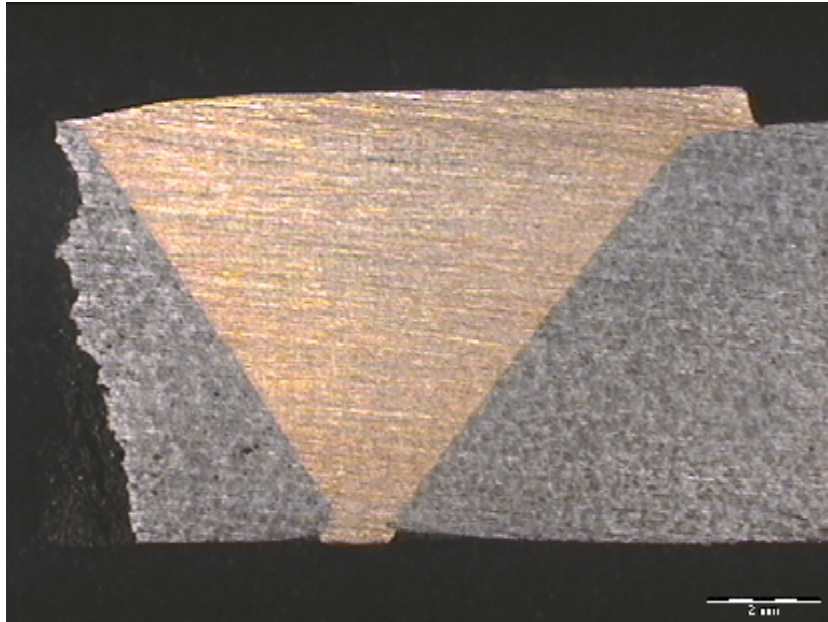


Figure 1. Cross section through specimen WM-2, showing the 75 deg. included angle.(10 X)

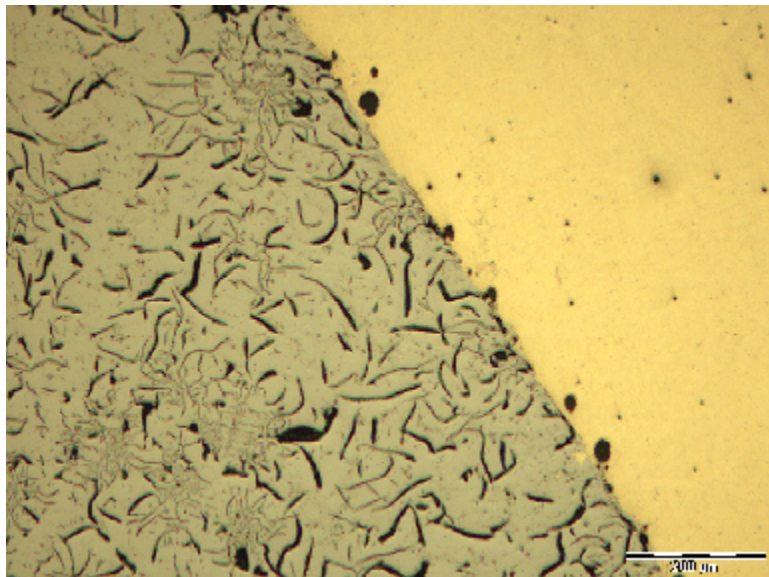


Figure 2. Higher magnification view of Figure 1, showing the interface between the cast iron (left) and the low-fuming bronze (right). Carbon flakes are visible in the cast iron. (~ 100 X)

4 Field Trial

On July 18th, Jerry Doherty, Roger Bushey, Tom Christ and Tom Siewert went to the Capitol to test several repair procedures. Also in attendance were Kevin Hildebrand, and about ten others associated with the Architect's Office or Capitol staff.

We repaired a total of four cracks, in two locations. Figure 3 shows the repair being performed at location 1, at a corner (just about 0.5 m above the roof of the main

part of the Capitol) where two castings met. The actual cracks were on the horizontal shelf between about 8 and 14 cm from the corner of the casting, one crack on each casting. One crack passed through a bolt hole (used to fasten the corner), and proceeded at about a 45 deg. angle from one edge to the other, a distance of about 8 cm. The other crack propagated above the bolt, also at about a 45 deg. angle and over a distance of about 12 cm.

We had planned, in the time that was available, to evaluate both oxyacetylene braze welding with low-fuming bronze and GTA buttering with nickel, however, we ran into a problem with the GTA technique when gases started to bubble from the pool. We think this may have been due to contamination (this area had been repaired before), and so just continued to use low-fuming bronze for the remaining repairs.

Figure 4 shows the final appearance at location 2, on a wall (about 2 m above the roof of the main part of the Capitol) where two castings met. These two castings were almost perfectly flat. The actual cracks were about 15 to 20 cm in from the abutting corners of the two castings, one crack on each casting. Each crack passed through a bolt hole (used to fasten the corner), and proceeded at about a 45 deg. angle from one edge to the other, a distance of about 15 to 20 cm. During final grinding, we found a small crack (about 6 cm long) propagating at right angles to the repair. We think that this was a preexisting crack that had been hidden by the paint until the grinding operation. This crack was prepared by light grinding and was also filled with bronze. This other crack was at a right angle to the main crack, and proceeded down at a 45 deg. angle into the plate.



Figure 3. Location 1 - making the repair by braze welding.



Figure 4. Location 2 - after finish grinding, but before painting.

The low-fuming bronze technique worked equally well in both the horizontal and vertical orientations. The oxyacetylene process requires a modest preheat of the casting around the repair, and the temperature during brazing never exceeds a red heat, certainly less than the temperature reached during welding.

One repair ended with a bend in the joint, where the far corner of the casting was about 1 cm out from flush. The braze weld was reheated and the corner was gently hammered back to where it should be. Such an adjustment would never have been possible with a high-strength filler. Each repair was completed in less than an hour, and might proceed faster once the grinding and fixturing procedures are optimized. The grinding operation was purely for aesthetic reasons; it smoothed the surface and removed any excess buildup.

The final inspection showed that the repairs were sound, and checks since then have not revealed any delayed cracking. In all, we proved that we can repair corner cracks, but may need to go back again some time to demonstrate repairs on the more complex geometries.

4.1 Repair Procedure used in Field Trial

Joint preparation: To get good fusion, the joint was opened up to give access to the bottom of the joint and to allow room to manipulate the puddle. The joints were ground to give a 2 mm (about 3/32 inch) root opening (minimum), and the sides were beveled to produce a 70 deg. (minimum) included angle.

The filler material was flux-coated low fuming bronze (60Cu-40Zn) meeting the requirements of American Welding Society (AWS) Standard A5.8, class RBCuZn-C. It is nominally 60 % Cu and 40 % Zn, but also contains about 1 % Sn, 1 % Fe, and smaller amounts of some trace elements. The diameters used for this repair work were 2.4 and 3.2 mm (3/32 and 1/8 inch).

The flux coating on the bronze was supplemented with a powdered flux, meeting AWS A5.31 Class FB3-F. This red-brick colored flux improved the wetting of the low fuming bronze filler rod to the cast iron. Also, the melting point of this flux

served to indicate that the joint was hot enough to accept filler material and fuse properly.

Before braze welding, the cast iron was preheated by continually moving the torch over the cast iron (never keeping it in any place long enough to overheat the casting). The preheat temperatures were approximately 260 to 315 deg. C (500 to 600 deg. F) in an area 10 to 13 cm (4 to 5 in.) adjacent to the joint to be brazed. The actual temperature used for the braze welding is near 982 deg C (1800 deg F). A neutral flame was used throughout the repair operation.

Approximately 4 to 5 passes were used to fill the joints in the cast iron (nominal thickness of 8 mm). After completion, the joints were ground to match the height of the cast iron.

5 Conclusions and Recommendations

- Oxyacetylene braze welding with low-fuming bronze (60Cu-40Zn) produced four fully-acceptable repairs in the simple corner-crack geometries tested during the field trial. Mechanical testing and microstructural evaluation of the procedure on cast iron from the dome also confirmed the suitability of the procedure. Therefore, this seems to be a very realistic option for many of the cracks in the dome. Additional tests on more complex geometries and conditions will help to define the acceptable range of this repair technique. Also, the integrity of these four repairs should be monitored occasionally.
- The recommended repair procedure is listed in section 4.1.

References

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