# Concrete Rehabilitation Design for the Historic 3rd Avenue Bridge, Minneapolis, Minnesota

by Arne Johnson, Tanner Swenson, Dan Enser

Fig. 1: Engineers utilizing three under bridge inspection units for close-up bridge inspection and sounding during the Phase 1 bridge inspection (photograph by WJE).

Instantly recognizable in countless photographs of the downtown Minneapolis skyline, the 3rd Avenue Bridge over the Mississippi River is an iconic historic concrete arch bridge that recently celebrated its 100th birthday. Rehabilitation to address advanced concrete deterioration is ongoing and expected to be completed in early 2023. This article summarizes the investigation and rehabilitation design for the historic concrete elements, which was led by the authors on behalf of the Minnesota Department of Transportation (MnDOT). After project completion, a follow-up article will report how the rehabilitation went and the lessons that were learned during the construction phase.

## HISTORY OF THE BRIDGE

The 3rd Avenue Bridge, originally designed and constructed in the early 1900s, is a classic example of the open spandrel concrete arch bridges that were common in that era. The 3rd Avenue Bridge stands out for its scale, its use of Melan reinforcing system and its S-curve geometry, which was necessary to avoid breaks in the limestone riverbed. The bridge, opened on Flag Day in 1918, is one of 24 bridges of prominent historic significance that MnDOT has selected for long term preservation, and it is included in MnDOT's Statewide Historic Bridge Management Plan. After the current effort is complete, the bridge will have undergone three major rehabilitations, with the first two in 1939 and 1980.

The bridge consists of seven original concrete arch spans in the river and approach spans on either end (non-original steel girders at the south end and prestressed concrete beams at the north end). Arch spans 1 through 5 consist of three arch ribs, while spans 6 and 7 consist of full-width barrel arches, both of which support spandrel columns that in turn support the bridge deck. The bridge was constructed using the Melan reinforcing system, patented in 1892 by Austrian bridge engineer Joseph Melan.[1] In the Melan system, there are no conventional steel reinforcing bars in the arches. Rather, the concrete arches are reinforced with internal steel trusses composed of double-angle chords connected with riveted steel gusset plates and diagonal cross braces.

Although the bridge had been rehabilitated before, most recently with extensive concrete repairs and a full deck replacement circa 1980, the bridge by the early 2000s was again displaying significant concrete deterioration and structural deficiencies that needed to be addressed. The purpose of the current rehabilitation was to address the bridge condition, raise the NBI rating from 4 to at least 6, and achieve a target service life of at least 50 years after the repairs are completed.

## CONDITION ASSESSMENT

As a first step in the rehabilitation of a historic concrete bridge, a well-conceived condition assessment is critical for success in achieving long-lasting repairs. Historic concrete has unique deterioration mechanisms that are considerably different than for modern concrete. Conditions can vary widely from area to area across the bridge due to the variability of the concrete resulting from early batching and placement methods, as well as multiple past repair projects. Deterioration conditions, which are often extensive, and historically significant features must be carefully documented for strategic repair and preservation of the structure. The objectives of the condition assessment are to characterize the construction and current condition of the structure, and, most importantly, to identify the deterioration mechanisms that are attacking the individual structure. Common deterioration mechanisms for historic concrete, including cyclic freeze-thaw damage, chloride-induced corrosion damage, and carbonation-induced corrosion damage, have been described elsewhere.[2, 3]

## PHASE 1—BRIDGE INSPECTION

The condition assessment for the 3rd Avenue Bridge was performed in two phases. Phase 1 consisted of a close-up, element-level bridge inspection and sounding of 100% of the exposed surfaces (Figure 1). Distress conditions and condition states (according to MnDOT standards) were digitally mapped on scaled drawings using WJE's in-house iOS-based tablet software. Each inspector carried a tablet pre-populated with base sheets and custom drop-down fields that allow every condition to be digitally described and recorded. The data are accessible simultaneously by all the inspectors in the field as well as in the future by any individual with sign-in credentials. The software also has powerful post-processing capabilities including direct download into Excel or CAD, which immediately provides unlimited sorting and searching capabilities, as well as quantity calculations.

## PHASE 2—FIELD TESTING, MATERIAL SAMPLING, AND LAB TESTING

Based on the Phase 1 inspection, small study areas across the bridge were selected to represent the full range of conditions present. Phase 2 consisted of field testing and materials sampling at each study area, with the primary goal being to identify the severity and the mechanisms of deterioration occurring in the concrete for each element type. This is critical because the repairs will only be durable if they are designed to address the underlying deterioration mechanisms at each particular structure and element. The study areas were spatially distributed across the bridge to represent the range of conditions and material types present. At the 3rd Avenue Bridge, a total of 137 study areas were evaluated, and 81 concrete samples and 10 steel reinforcing steel samples were removed for testing in WJE's laboratories.

Field testing methods utilized on the 3rd Avenue Bridge included half-cell potential surveys, corrosion rate measurements, resistivity testing, carbonation testing, and ultrasonic thickness testing of steel truss members (Figure 2). Lab testing of material samples taken from the bridge included testing for mechanical properties of concrete and steel materials, chloride content analysis and chloride horizon profiling (particularly important for the deck and substructure elements below deck joints), and petrographic analyses of numerous cores to identify vulnerabilities specific to the concrete in this structure (i.e., freeze-thaw cracking, air content, carbonation depth, paste-aggregate characteristics, etc.). Service life projections were developed for each element type utilizing the test data that were collected, and this information was used to inform the development of rehabilitation alternatives and life cycle cost comparisons.

## CONCRETE REHABILITATION DESIGN AND CONSTRUCTION

After analysis of the rehabilitation alternatives, MnDOT selected the alternative that would achieve a service life

Fig. 2: Engineers utilizing three under-bridge inspection units for close-up bridge inspection and sounding during the Phase 1 bridge inspection (photograph by WJE).

of at least 50 years, which became the design criteria for the concrete repairs. A 25-year service life alternative was also considered but was, in the end, judged to be almost as expensive, logistically complicated, and considerably less durable.

For each alternative, the age, previous exposure conditions, and current testing results for each bridge element were evaluated to determine which elements could be repaired and which would need to be replaced. For example, the pedestals under the spandrel columns were all original to the bridge, even where columns had been previously replaced, and deck expansion joints had been relocated in previous deck replacements. As such, pedestals located below previous as well as current expansion joints required greater quantities of replacement to achieve the desired service life.

Customized concrete repair details were developed following consideration of the various state-of-the-art methods for addressing the deterioration that had been identified during the condition assessment. Many aspects of the repair design could be discussed, but for brevity just five are highlighted below.

## High Quality Surface Repairs for Historic Concrete

The details of the concrete repair design were developed and communicated through carefully prepared specifications and drawings to achieve historic sensitivity and high-quality, durable repairs. The guiding principle behind the repair design was to detail the repairs in ways that would address the root deterioration mechanisms identified in the structure. At the 3rd Avenue Bridge, the primary mechanisms were found to be chloride-induced corrosion and freeze-thaw damage, which are water-driven mechanisms. In simplified terms, the repairs will be durable if water is kept from penetrating, which means repairs that bond well, limit cracking, and limit separation at the repair perimeters. Based on the hands-on inspection of the bridge, concrete surface repairs were specified for all locations where delaminations, spalls, and previous repairs were present, and repair details were developed for each typical location. Unique details were provided to address the severe corrosion-related distress at the arch rib corners, longitudinal cracking at the tops and bottoms of the arch ribs, and areas where freezing-and-thawing damage was particularly deep. The specifications demanded high-quality concrete repair techniques, including perimeter saw cutting, removal to sound concrete using light chipping hammers, substrate preparation via sandblasting, sandblast cleaning and coating of exposed reinforcement, and anchorage using epoxy-grouted bars. The concrete repair specifications were designed to allow the contractor to choose form-and-pour, form-and-pump, or shotcrete methods with either prepackaged or ready mixed concrete for each type of repair. For each, a minimum as well as a maximum compressive strength was specified so that the properties of the repair materials would not be substantially different than those of the original concrete. The contractor chose to use predominantly prepacked wet-mix shotcrete for most repairs. In portions of the bridge most visible to the public, the new concrete repairs were specified with a form-board finish to match the original surface texture.

Fig. 3: Bridge inspector recording notes utilizing proprietary iOS-based tablet inspection software (photograph by WJE)

## Accurately Estimating Concrete Repair Quantities

One of the biggest challenges in repairing historic concrete is accurately estimating and controlling the repair quantities. For the 3rd Avenue Bridge project, quantities were estimated by leveraging the inspection software described above to calculate the as-mapped areas that warranted a repair (Figure 3). Three factors were then applied to convert the as-mapped quantities into quantities for the repair plans: a squaring off factor (converting as-mapped areas to rectilinear shapes), a time delay factor, and an “other factor” intended to capture some of the typical unknowns in repairing aging concrete. In all, the total repair factor, sometimes called the growth factor, ranged from 1.8 to 2.2 for the various bridge elements. This is consistent with the authors’ experience on similar previous projects.

To control the repair quantities during construction, it is critical to have fair, clear, and workable repair measurement and payment procedures. An entire plan sheet and various other details throughout the plans were devoted to carefully defining and illustrating the way in which the quantities would be measured and paid. Saw-cutting the repair perimeters before chipping and avoiding combining repairs more than approximately one foot apart help limit unnecessary quantity growth. The original concrete at the 3rd Avenue Bridge has particularly large aggregates, so the sawcut depth was deepened to avoid irregular breakouts along the sawcut edges during the concrete removal process. Engineers experienced in historic concrete repairs should participate in the field to mark the in-situ conditions that warrant a repair (because some conditions are not detrimental and may be more durable if left untreated), as well as to measure the repairs and track the quantities in real time.

## *Deep Concrete Repairs for Freeze-Thaw Damage*

Freeze-thaw damage occurs when non-air-entrained concrete, which includes most concrete constructed before approximately 1950, is saturated with water and while saturated undergoes multiple freezing and thawing cycles. At the 3rd Avenue Bridge, this type of damage was often present below drain discharges or at arch springlines where water collects (Figure 4). Based on petrographic examination of core samples, most of the surface repairs were anticipated to be no more than 6 inches deep, but repair details were provided for depths up to 12 inches, which was the deepest damage observed in the core samples, except for at the pier bases. The contractor is required to excavate incrementally deeper until reaching sound substrate, and payment is on a unit price basis for either 6-inch, 8-inch, 10-inch, or 12-inch depth.

Even deeper freeze-thaw damage was present at the pier bases, near the waterline and below drain discharges. Maximum concrete erosion was up to 17 inches and freeze-thaw damage up to another 8 inches was present beyond that. Rather than removing all the freeze-thaw damaged concrete, the repair details required removal of a uniform 12 inches of concrete to reach what was defined as an "intact concrete substrate" (aggregates firmly embedded in solid paste but some freeze-thaw related cracking allowed), not necessarily a perfectly "sound concrete substrate." Deeper removals were performed in localized "pockets" to reach an intact surface. Longer epoxy-anchorages were installed deeper into the sound material beyond the removal depth, and a new grid of stainless-steel reinforcement was installed near the surface. New self-consolidating concrete was cast to for a new pier jacket that matches the ornate historic profile of the pier bases (Figure 5).

## *Mitigation of Future Freeze-Thaw Damage and Reinforcing Steel Corrosion (i.e., Extending Service Life)*

### Coating

The overarching goal for mitigating future freeze-thaw and corrosion-related deterioration mechanisms is to keep water out of the concrete. Coatings and sealers are widely used for this purpose, but film-forming coatings are often inappropriate for a historic structure according to preservation standards, unless the structure was coated historically. Research showed the 3rd Avenue Bridge had various surface treatments in its history, including complete coating in the 1980 rehabilitation. The original concrete is non-air-entrained and chloride contaminated, and therefore extremely vulnerable to future deterioration and loss of historic fabric if water penetrates. After thorough discussions between historians and technical experts, it was agreed that a high-performance, film-forming, water-resistant coating would be applied to all historic concrete surfaces. A relatively thin acrylic-based coating product (30 mils wet film thickness, 20 mils dry film thickness) was selected so as not to mask the original form-board lines. It can be removed, which is important for historic structures, and it enhances the appearance of the concrete by masking multiple generations of different colored patches.

### Critical Zones

In addition, in critical zones at the arch spring lines, where water tends to collect and where cracking from thermal cycling is possible, the concrete surface repairs, except for arch undersides, are specified to be cast in place and wet cured to minimize shrinkage cracking. The repairs in these zones require an extended "cure out period" during which time almost all shrinkage cracks and bond line separations should develop. Next, the surfaces in these zones will be treated with two coats of silane to refusal, which will seal the narrow cracks and separations. Wider cracks will be routed and sealed and then pre-striped with an elastomeric patching compound before installation of the coating over the entire surface.

Fig. 4: Deep freeze-thaw deterioration near springline of arch rib below drain discharge (photograph by WJE)

Fig. 5: Concrete removals completed, reinforcing steel being placed, and new pier jacket concrete being formed and placed (photograph by WJE)

## Targeted Cathodic Protection at Arch Corners

The deterioration in the arches was concentrated at the arch corners where exposure is the worst due to direct runoff and two-side exposure to moisture and freeze-thaw cycling. Corners that were distressed were repaired using a custom detail that included careful reinforcement to control cracking and ensure long-term bond as well as continuous cathodic protection anodes to protect portions of the Melan angles that were not exposed, cleaned, and coated (Figure 6a, Figure 6b). The design team collaborated with MnDOT's engineers regarding potential methods to mitigate future deterioration along the arch corners. After reviewing various approaches together with the owner, it was agreed that, to slow future corrosion damage at segments of the arch corners that were currently sound but known to be marginally chloride contaminated and hence vulnerable to future distress, a targeted cathodic protection approach would be implemented. In this approach, cathodic protection anodes would be installed only in areas found, based on testing, to have an elevated risk of corrosion activity. The anodes were specified to be field located based on half-cell potential testing performed during the construction phase in the corner areas between those marked for repair. Where readings indicated potential corrosion activity, anodes were installed in cored holes that were staggered on either side of the Melan angles (Figure 6c, Figure 7). Selected anode locations were wired to test stations for monitoring to verify their effectiveness upon installation and to track their effectiveness at this structure over time.

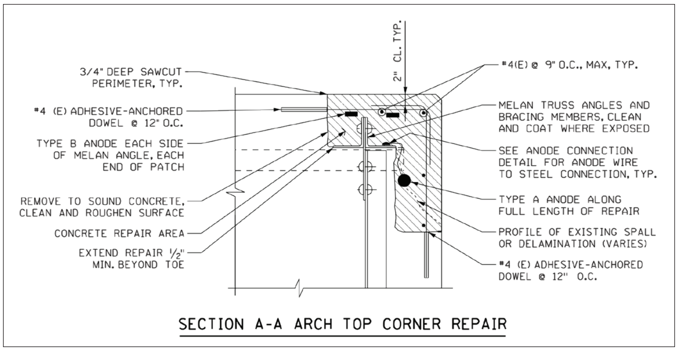

Fig. 6a: Typical detail for arch corner repair where concrete was unsound

Fig. 6b: Arch corner repair prepared for concrete placement

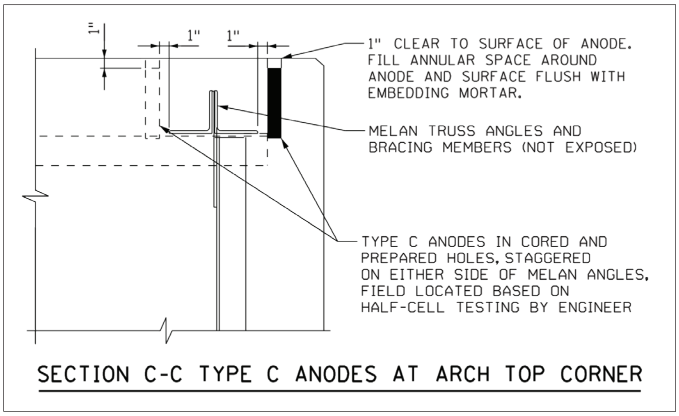

Fig. 6c: Typical detail for arch corner repair where concrete was sound but half-cell testing indicated potential for active corrosion

## *Matching Concrete Repairs to Original Concrete Texture and Color*

Matching concrete repairs to the original concrete texture and color is an important step in the rehabilitation process for historic concrete bridges. For this project, the coating to be installed will result in a uniform color and surface texture, and no color matching was required by the historic agencies for the concrete repairs. For portions of the bridge most visible to the public, form board finish was

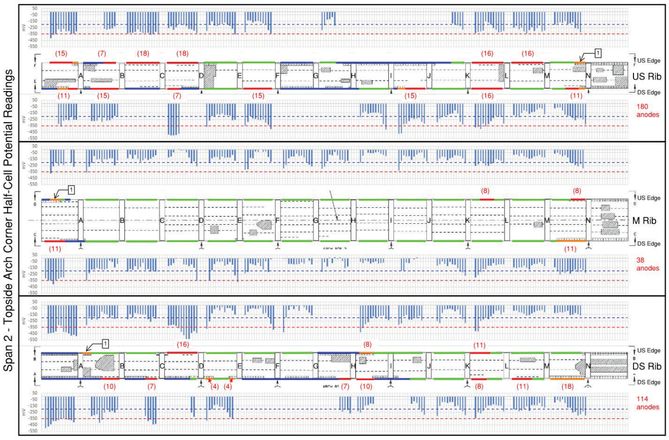

Fig. 7: Example data sheet showing the results of half-cell potential testing to locate the anodes in the zones of sound concrete between the corner repairs (see detail in Figure 6b) (image courtesy of WJE).

Fig. 8: Example of board-form finish achieved using hand floats in shotcrete surface repair (photograph by WJE).

required in the repairs. To create the board-form texture in the repair concrete, the contractor used form liners for the cast-in-place pier jackets and hand floated the board-form lines into the fresh shotcrete surface repairs to match adjacent areas of remaining original concrete (Figure 8). The project specifications required mockups to be performed in three steps: shop samples, made in the shop and transported to site; field samples, made at the site next to point of placement; and trial repairs, made on the structure and left in place if accepted. This stepwise process provides confidence that the repairs will be historically appropriate and consistent with the specified quality requirements.

Fig. 9: Recent drone image showing status of the in-progress construction (photograph by WJE)

Construction is underway under a full bridge closure and an aggressive schedule (Figure 9). Once rehabilitation is complete, the lessons learned from execution of the concrete repairs will be shared.

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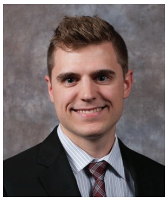
**Arne Johnson** is a Principal and structural engineer with over 30 years of experience at WJE, Northbrook, IL. He has expertise in structural inspection, condition assessment, field and laboratory testing, service life and durability evaluations, vibration monitoring, and repair/rehabilitation design, particularly for historic concrete structures. Notable historic concrete assessment and rehabilitation projects include the 3rd Avenue Bridge, Franklin Avenue Bridge, St. Paul Union Depot, Soldier Field, Wrigley Field, and Fenway Park. Arne received his BS in civil engineering from the University of Illinois at Urbana-Champaign and his MS in structural engineering from the University of California, Berkeley. He is a licensed professional engineer in multiple states.



**Tanner Swenson** is an associate level structural engineer with 7 years of experience at WJE, Minneapolis, MN. His experience includes condition assessment, field testing, and repair/rehabilitation of concrete structures, including the 3rd Avenue Bridge. Tanner received his BS in civil engineering and MS in structural engineering from the University of Minnesota. He is a licensed professional engineer in multiple states.

**Dan Enser** is an Associate Vice President with HNTB Corporation in Golden Valley, MN where he has worked for the last 27 years in design, construction, and management. Most recently he has been focused on bridge rehabilitation projects. He served as the design Project Manager for the rehabilitation of the historic 3rd Avenue Concrete Arch Bridge over the Mississippi River. Dan’s previous experience includes managing the rehabilitation design and construction of the historic Franklin Avenue Concrete Arch Bridge over the Mississippi River under an accelerated 116-day closure. He has also managed several independent peer review projects, including the extradosed St. Croix River Crossing Bridge and the rehabilitation of truss Bridge 5900 (Winona TH-43) over the Mississippi River. He received his degree in civil engineering from the University of Minnesota.