GUGGENHEIM MUSEUM:
LABORATORY AND FIELD EVALUATION OF CONCRETE REPAIR PRODUCTS

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Frank Lloyd Wright's Solomon R. Guggenheim Museum in New York, NY, is an icon of modern architecture known for its large curvilinear walls. Those walls were originally constructed using spray-applied concrete, or gunite, against plywood formwork. The repair of this material was recently addressed in laboratory testing and in-place evaluation programs. Compatibility, both mechanical and aesthetic, of the repair materials and historic fabric was the overriding objective in the research. This investigative program is the first holistic approach to conserving the building since its construction.

Archival records indicate that Wright disliked the formwork marks that were apparent in the gunite surface, as his vision was of smooth nonorthogonal walls.[1] The contractor responded by writing that the use of gunite and the building's design limited the ability to create perfect surfaces.[2] An attempt was made after the plywood was removed to reduce the formwork marks by grinding the surface of the gunite, but complete removal was never achieved; 50 years later, under several generations of coatings, the marks were still apparent.

Today, despite the availability of materials and methods that are able to create the vision of Wright's original intent, the design team deemed the gunite formwork marks worth preserving and not concealing. Those marks are historic evidence of the techniques used and were to be replicated in

The Solomon R. Guggenheim Museum before restoration

(Photographer: Amanda Thomas Trienens, ICR) the repairs. On the other hand, it was imperative to conceal other aspects of the repairs beneath the new coating system.

These two criteria—preserving the as-built imperfections and concealing the repairs—posed a challenge to this conservation program. This was the focus of a field investigation of constructibility and appearance.

SUBSTRATE CONDITIONS

The building has a long history of coating failures. As of 2005, total dry film thickness, representing many applications, was approximately 0.08 in. (2 mm). It was decided to remove all of this buildup to optimize future coating performance and to permit the design team to document conditions of the substrate, to evaluate cause-and-effect relationships of the pathology, and to determine conservation priorities.

The survey conducted by the design team noted primarily three conditions to be addressed: cracks, losses, and failed or inappropriate previous repairs. Core specimens were taken from the original gunite for testing of various properties. Some of these were examined by petrography to determine composition and carbonation depths. Compressive strength and coefficient of thermal expansion were measured to provide compatibility parameters for the repair materials; crack monitoring was also conducted.

The primary structural elements of the rotunda are the web walls. These are massive vertical cast-in-place concrete ribs positioned in a circle every 30 degrees. They rise from the ground to the roof and are connected to a spiraling cast-in-place concrete ramp.

Remarkably, most of the rotunda gunite walls are only 5 in. (130 mm) thick, yet embed vertical and horizontal steel reinforcement, 1-3/8 in. (35 mm) steel tees at every 10 degrees, and two layers of galvanized steel mesh. Thus, steel is no more than 1-1/2 in. (38 mm) from both the exterior and interior surfaces. No expansion joints were constructed within the entire circumference (approximately 375 ft [114 m]) of the exterior. The gunite walls are connected to cast-in-place lightweight aggregate concrete slabs that cantilever from the ramp.

The sixth floor varies significantly in its construction. Its exterior wall height is 16 ft (4.9 m), including a parapet that rises above the flat roof. At the northeast, this parapet is 8 ft (2.4 m) in height, without lateral support. Because of the height of the sixth floor wall, it was constructed with 2 in. (50 mm) steel tees, which in turn required the horizontal reinforcing steel to be discontinuous.

In 1998, the sixth floor gunite walls were "repaired" at the web wall locations and at some 10-degree steel tees. Joints, each 1 in. (25 mm) in width, were saw-cut at the tees, which also meant that the outer steel mesh was cut. They were filled with caulk and an acrylic topping and painted; these products were from several different manufacturers. Some areas along these joints were also patched during this campaign. These interventions had all grossly failed within just a few years.

PRELIMINARY PRODUCT SELECTION

For the laboratory testing program, crack fillers were reviewed assuming that a certain amount of seasonal movement would continue in the gunite walls as measured during the monitoring program. The criteria for the crack fillers were elongation capabilities consistent with crack width data, return of shape (to avoid permanent deformation), and low shrinkage. Another consideration was suitability for a variety of crack dimensions.

The criteria for patching were that the material have good adhesion to the gunite, be similar in compressive strength and coefficient of thermal expansion, have low shrinkage, and have good resistance to freezing and thawing. A slow-setting patching compound was desirable, as some sculpting would be necessary to recreate the formwork marks.

Coating selection was based on evidence of a certain level of success in some aspects of the original coating (Cocoon). It is believed that the Cocoon greatly contributed to the low depth of carbonation of the almost 50-year-old gunite walls due in part to its thickness. Excellent adhesion, color stability, and crack bridging capabilities were important considerations for the new coating.

A number of manufacturers were invited to discuss their products in early 2006. Six manufacturers were ultimately asked to recommend a single product in each of the three categories to be evaluated through the testing program. Participation was limited to companies producing all three of the required products (crack fillers, patching compounds, and coatings) for a manufacturer-approved "system" approach, which led to better quality control during implementation.

TEST PANEL PREPARATION

Due to the tremendous number of test panels necessary for laboratory research, using original building fabric was not an option. Instead, a material had to be developed that was similar to the original. To establish that replication formula, petrography, wet analysis, and reflected light microscopy were employed. Molds were then made of plywood, with cracks and losses simulated in the panels. More than 100 panels were produced, each cured in a high relative humidity environment for 28 days.

Application of the products to the cured test panels generally followed manufacturers' recommendations. Some difficulties were noted during application, which were considered in the final assessment of the products.

TESTING PROGRAM

The testing program was designed to be aggressive in an attempt to induce thermal- and moisture-related failure in a relatively short period of time. There were two sequential rounds of QUV and freezing-and-thawing testing. The first included a crack filler and a coating from six companies. Three companies' products made it into the second round, to be tested in conjunction with one of their patching compounds.

ACCELERATED WEATHERING BY QUV-SPRAY

In the QUV-spray[3] accelerated weathering apparatus, test panels were exposed to conditions of ultraviolet (UV) light, condensation (and associated heat), and cool water spray. Comparative evaluation of the nature and severity of failure patterns was done visually and with two tests that are discussed further below. Two rounds of 1500 hours per program were conducted. In this test, two product systems performed relatively well.

ACCELERATED WEATHERING BY FREEZING AND THAWING

The freezing-and-thawing test was a modification of an ASTM standard. The cycle was 16 hours thawing in 72°F (22°C) water followed by 8 hours of freezing in –8°F (–22°C) air. The test was run for 30 cycles for both rounds with two product systems performing well.

WATER VAPOR TRANSMISSION RATE

Water vapor transmission rate (WVTR) testing was conducted on 18 coated original gunite samples and three controls consisting of uncoated original gunite. Sealed assemblies were placed in a controlled environment chamber with constant temperature and relative humidity. Water vapor transmitted through the specimen was determined by measurement of weight loss over successive 24-hour periods. All coatings exhibited some permeability in the test. Lower permeability was preferable as it relates to less exposure of the gunite on the building to carbon dioxide and water vapor in the future.

The research program also included testing to record changes in coating adhesion and color, pre- and post- accelerated weathering.

ADHESION TESTING

Testing was conducted to establish the adhesion of the coatings to the test panel substrate before and after the first round of QUV accelerated weathering, according to a standard visual grading system. After QUV weathering, two coatings decreased in adhesion performance.

Sample preparation being conducted in the laboratory

(Photographer: Amanda Thomas Trienens, ICR)

QUV-Spray weathering machine with mounted samples

(Photographer: Amanda Thomas Trienens, ICR)

SPECTROPHOTOMETRY

To provide an objective method of monitoring color change of the coatings as a result of laboratory weathering, a reflectance spectrophotometer[4] was used. All of the coatings changed in all spectral components to some degree after QUV weathering; however, only one coating changed significantly.

IN-PLACE MOCKUPS OF REPAIR MATERIALS

Laboratory testing, in conjunction with some observations concerning the difficulty of product application, resulted in the elimination of three product systems. In-place mockups were designed and implemented to evaluate the constructibility and performance of the other three repair systems on the building. Selection of the mockup locations ensured that the three systems were installed in similar conditions. As the sixth floor walls of the rotunda exhibited the most severe conditions, it was chosen for two mockups for each repair system: at a web wall and a 10-degree steel tee. A third location incorporated hairline shrinkage cracks in gunite not on the rotunda.

In-place mockup of repair materials being conducted

(Photographer: Amanda Thomas Trienens, ICR)

Demolition for in-place mockup

(Photographer: Amanda Thomas Trienens, ICR)

The first set of mockups eliminated one of the three repair systems that had done well in the laboratory. The manufacturer's crack filler was largely cementitious and apparently could not accommodate the building's movement. It cracked and separated from the gunite in the sixth floor mockups in less than 2 months.

Two repair systems remained, which comprised acrylic crack fillers and coatings and polymer-modified patching compounds. They went through a second set of mock ups (at a sixth floor web wall and a 10-degree steel tee). A new design was developed for the web wall locations, which had to allow for greater movement than was initially supposed, due to updated crack monitoring data. It also had to be visually unobtrusive and be feasible for large-scale implementation.

Prior to the second set of mockups, the 1998 patching at the saw-cut joints was removed. A 1/8 in. (3 mm) thick piece of steel was temporarily placed over the now-exposed tee, perpendicular to the plane of the wall, to create a separation within the repair. The patching was done on either side of this spacer. While green, the patches were carefully sculpted to replicate the formwork marks of the adjacent gunite. The spacer was then removed. Once the two-part patch had cured, hand-held diamond grit cup grinders and sanding pads were used for areas that were determined by raking light to need modification. A reticulated polyethylene strip was then inserted into the space to within 1/2 in. (13 mm) of the exterior surface and covered with a crack filler. The entire mockup area was coated.

After the laboratory testing, two sets of mockups (and a 9-month review of the first set of mockups), a repair system was selected for full-scale implementation. Its patching compound exhibited the least shrinkage. Its crack filler and coating showed the greatest capacity to move without failure and these field observations were confirmed by measurements of elongation by an independent testing laboratory.

Almost at the completion of the design phase, even larger crack movements were discovered through the ongoing monitoring program, necessitating the use of some additional products. The repair system company's technical staff provided existing test data on proposed materials and collaborated with the architectural conservators on supplemental laboratory testing and mockups. The result was a high-build partially-cementitious waterproofing membrane applied over all surfaces. In the areas of typically large movements (over the sixth floor web walls and intermediate tees), a polyethylene fabric was embedded in the membrane.

Implementation of the repairs was completed in the summer of 2008. The interventions undertaken were done successfully—visually blending with (and protecting) Wright's original gunite while preserving the formwork marks that are an unusual characteristic of this architectural masterpiece.

CITED REFERENCES

1. Letter from Frank Lloyd Wright to George Cohen, October 2, 1958.
2. Letter from George Cohen to Frank Lloyd Wright, dated October 6, 1958, "These forms, like any other forms, must show form marks. That is the nature of concrete."
3. QUV-Spray by Q-Lab Corp.
4. Gretag MacBeth Color Eye 580 Reflectance Spectrophotometer.

OTHER REFERENCES

Laboratory Testing and Architectural Conservation Services: Integrated Conservation Resources, Inc. (ICR), New York, NY.

Repair System Supplier: MAPEI Corporation, Deerfield Beach, FL.

The Solomon R. Guggenheim Museum after restoration

(Photographer: Amanda Thomas Trienens, ICR)

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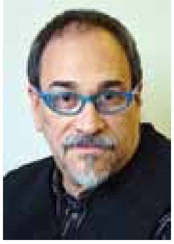
In 1988, ***Glenn Boornazian*** *started what would become ICR, and Integrated Conservation Contracting, Inc. (ICC), to integrate investigative architectural conservation services with high-quality conservation and restoration contracting. Today, as President of ICR and ICC, Boornazian draws on his extensive knowledge of building materials conservation to provide conservation services for historic buildings and monuments. His expertise includes specialized conditions investigation, materials testing, analysis and assessment, and the implementation of treatment recommendations. He was Director of Restoration for the Nantucket (Massachusetts) Historical Association, and after studying at Columbia University's Graduate Program in Historic Preservation, served as Staff Conservator for the Center for Preservation Research.*



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