The Pentagon Lightwell Walls

Repair, Rehabilitation, and Protection for the Next 50 Years

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Fig. 1: Typical lightwell wall damage showing spalling and exposed, rusting reinforcing bars

Fig. 2: Scaffolding constructed to allow direct access to walls

Constructed in just 16 months during World War II, the Pentagon, the world's largest office building, is undergoing a complete renovation, rehabilitation, and modernization program. A program with the goal of a minimum 50-year design life has been mandated by Penren (**www.pentagon.renovation.mil**), the governing agency for the Pentagon renovation. That's right, it is anticipated that repairs will last at least 50 years! Taking over 10 years to complete, every component—the walls, the floors, the roofs, the windows, the mechanical and electrical systems—is being renovated or replaced. This article is about one component—the most-used component in the Pentagon—concrete. All structural elements of the Pentagon, except one, are constructed of reinforced concrete. Sadly, that concrete is deteriorating. This article explains how to breathe at least 50 years of new life into deteriorating concrete.

The one element of the Pentagon not constructed of reinforced concrete is the outermost perimeter wall, made of limestone. This article focuses on the remainder of the 1 million ft^2 (92,903 m^2) of the lightwell walls, which are now undergoing a complete repair, rehabilitation, and protection program.

The Pentagon consists of five separate rings, each approximately 90 ft (27.4 m) wide with approximately 30 ft (9 m) between the rings. The space between the rings is known as the lightwells. Thus, we call the perimeter walls of each ring the lightwell walls. The lightwell walls, constructed of cast-in-place, reinforced concrete, are both bearing walls and shearwalls.

The problem is corrosion, that is, rusting, of the reinforcing bars in the lightwell walls and related spalling damage caused by the expansive forces created by the rusting bars. As steel rusts, it expands 4 to 10 times its original size, creating extreme tensile forces in the surrounding concrete. From these tensile forces, the concrete cracks and spalls. The Pentagon program is about the repair and rehabilitation of the more than 250,000 ft^2 (23,226 m^2) of spalling. The typical damage is represented in Fig. 1. The program also includes an innovative protection system designed to resist the damage for the next 50+ years.

Concrete testing prior to the implementation of the program revealed that the lightwell walls were constructed of approximately 3500 psi (24 MPa) concrete. However, the reinforcing bars were often placed less than 1/2 in. (12.7 mm) from the outer surface, and testing revealed carbonation extending into the walls a distance of 3-1/2 in. (89 mm) or more. Reinforcing bars, normally protected against corrosion by highly alkaline concrete, lose their protection as a result of the carbonation process, which lowers the alkalinity concrete from a pH of over 13 to less than 11. Without corrosion protection, approximately 20% to 30% of the walls have suffered spalling damage; corrosion rate testing reveals active corrosion in virtually every other section of walls.

Thus, the goal is to structurally repair and rehabilitate the corrosion-damaged concrete and protect the remainder of the walls to resist future damage for the next 50 years.

The Structural Engineer of Record for the concrete repair program designed the concrete repair work closely following the International Concrete Repair Institute guidelines for concrete repair. All damaged and spalling concrete, some 3 to 4 in. (76 to 102 mm) deep, is removed with 15-lb jackhammers, fully exposing rusting reinforcing bars. Where corrosion has extended around a bar, the bar is undercut; this allows the full surface of the bar to be sandblasted clean, removing all rust. Working closely with U.S. Concrete Products, Timonium, MD, the manufacturer of the repair concrete, a color-matching, low-shrinkage, pumpable repair concrete was developed to comply with the specifications, which require a color and texture match when viewed from a distance of 30 ft (9 m) (the view from any window across a lightwell). This is easier said than done. Although some of the repairs are as much as 4 in. (102 mm) deep, some repairs are less than 1 in. (25 mm) deep, and some are too small to economically build formwork. For the minor amount of hand-patching that is being performed on small repairs, a trowelable mixture was developed. For the remaining repairs, U.S Concrete developed a polymer-modified, plasticized, bagged material that is mixed on site. This material flows easily into the formed repairs with extremely little shrinkage cracking. The mixture allows repairs up to 4 in. (102 mm) deep without large aggregate extension, and almost no cracking. Simple external vibration is all that is needed for good consolidation. In addition, the concrete obtains at least 2000 psi (14 MPa) in less than 3 days to allow for early stripping.

Concrete Protection and Restoration, Inc., the concrete repair subcontractor, developed a formwork system (Fig. 5) that allows for easy placement of the repair concrete, as well as matches the

Fig. 3: Jackhammer demolition in progress, exposing corrosion-damaged reinforcing bars

Fig. 4: Close-up view of corrosion-damaged reinforcing bars taken after completion of jackhammer demolition. Note the severe loss of cross section at the bottom of the vertical bars in the photo

Fig. 5: Formwork in place constructed to match original formboard finish on the existing walls

Fig. 6: Portion of wall completed prior to application of silane and potassium silicate coating

Fig. 7: Complete wall ready for presentation

original form board finish. After trial and error, they quickly learned that the best method of forming was to use the same 2 x 12 board construction, just like the original contractor did in 1944, thus creating a perfect match to the original finish.

To accommodate the Pentagon workers, noisy concrete demolition must be performed at night. Concrete placement and other "non-noisy work" is performed during the day, allowing a schedule of almost continuous activity. But the real challenge is yet to come—how to protect 1 million ft^2 (92,903 m^2) of wall surface from the impending damage resulting from rusting reinforcing bars for the next 50 years.

Protection must overcome two difficult deficiencies: bars too close to the surface and very deep carbonation. In a porous material, rain water is easily absorbed into concrete. With many of the bars 1/2 in. (12.7 mm) or less from the surface of the concrete, the bars are constantly wetted whenever it rains. Under the normally alkaline condition of good concrete with a pH of over 13, a passive oxide layer builds around each bar, effectively protecting the bar from corrosion even if the bars are wetted. The carbonation process forces the pH to drop below 11. When the pH drops below 11, the passive layer is destroyed and leaves the bar precariously exposed to corrosion. Therefore, the protection system must resist water penetration as well as compensate for the loss of alkalinity.

Compensation for the loss of alkalinity is provided by the recent technology of migrating corrosion inhibitors. Several methods of corrosion inhibition technology are available today, including corrosion rate reduction, corrosion threshold reduction, and chloride (or CO_2) absorption rate reduction. An amino-based corrosion inhibitor was selected for the Pentagon because of the ability of amino-based inhibitors to protect reinforcement in carbonated concrete, effectively reducing the rate of corrosion. Amino-based migrating inhibitors work in three ways: capillary action, vapor phase diffusion, and ionic attraction. During the capillary action, the concrete acts like a sponge, drawing the water-based inhibitor inside. Once inside the concrete, amino molecules have a vapor phase that allows them to diffuse throughout the concrete matrix. This diffusion is based on Fick's 2nd Law, which states that molecules will diffuse from areas of high concentration to areas of low concentration until they reach equilibrium. Finally, when the amino molecules get near embedded metals, they have a physical attraction to them that results in a tenacious bond to the metal.

MCI 2020 V/O by Cortec Corporation, of St. Paul, MN, was selected for its ability to migrate into a vertical surface to at least the depth of the reinforcing bars and for the additional enhancement of amine carboxylates. The carboxylate group on the MCI molecule is hydrophobic, meaning water repelling. When attached to the reinforcement, it repels water away and allows the amine group to have an even stronger affinity for the metal. Corrosion-rate monitoring has verified a reduction in the rate of corrosion from well above active corrosion to almost complete inactivity. Chemical testing of core extractions have shown the depth of migration beyond the outer layers of reinforcing bars.

Corrosion-rate reduction, however, is only half the battle. Without water, corrosion can be halted. The question arises: how to stop water from absorbing into the walls for 50 years? Further protection is provided by a system reducing the absorption of water into the walls. A 100% solids silane is applied to the wall surface, after the application of the corrosion inhibitor, to reduce absorption and to repel water. Silane repels only water and breaks down when exposed to ultraviolet light. To further protect the walls, a much more durable surface is needed, one which will last 50+ years and will prevent the breakdown of the silane. To accomplish this, potassium silicate was selected to enhance the surface and to protect both the water repellant and the corrosion inhibitor. Potassium silicate, originally developed and manufactured in Germany by Keim over 100 years ago, is reported in their literature to remain in service 100 years after initial application. The potassium silicate itself also resists water absorption by creating a tough, water-resistant mineral surface on the concrete. With both the potassium silicate and the silane, water now sheds off the surface of the concrete. In addition, a uniform color is achieved with the addition of pigments to the potassium silicate, further improving the repair to meet the required specification of a color match as seen across the lightwells.

With four separate products applied to an existing building, and on top of each other, compatibility was a major concern. During the design of the system, compatibility testing was performed by the manufacturers of the corrosion inhibitor, the silane, and the potassium silicate. Each issued not only a joint compatibility statement, but a 20-year warranty for the performance of the system components. Quality control by the Prime Contractor, Hensel Phelps, quality assurance by a third-party inspection agency, and quality assurance by Penren all ensure a complete installation.

The Penren design goal of repairs to last 50 years is achieved. Concrete repair has restored both the integrity and appearance of the lightwell walls, and future corrosion damage is resisted with a system designed to protect the Pentagon concrete for the next 50+ years.

Fig. 8: Corrosion-rate monitoring of corrosion activity in unrepaired portion of wall adjacent to exposed corrosion damage

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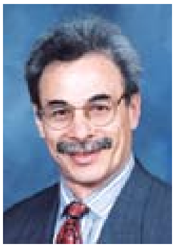

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