LONGFELLOW TOWERS 1 AND 4

Boston, MA

Abstract

The prestigious Longfellow complex is located in the heart of downtown Boston on the Charles River. This submittal focuses on two 38 story apartment buildings which were constructed between 1970 and 1972. Inspections conducted in 1997 identified numerous areas of spalls due to corrosion of the steel reinforcement. More recently, sealant joints at the sliding glass doors, ac units and windows were failing and allowing water to leak into the apartments.

In 2001, inspecting engineers carried out a comprehensive investigation to determine the extent of damage and the root cause. Among other things, they determined spalling had increased by 25% since 1996. Exposed column faces, balcony edges and floor slab edges had the least cover and most spalls. There was chloride contamination, carbonation and low cover throughout. Wherever the cover was less than 2” there was high levels of active corrosion. The goal of the Owner and the Engineer was to repair the spalled concrete and leaking joints and to provide long-term protection to the building.

A repair program was designed to repair the spalls and leaking joints and protect the building by mitigating active corrosion. A preview was completed to confirm the design met the objectives. The contractor completed the installation using an organized work plan that was sensitive to the owners scheduling requirements, provided a comprehensive checklist for installation and involved an inspection engineer to confirm compliance with the design documents. Finally, areas of the building were monitored to confirm effectiveness of the repair and protection program. All of this resulted in a repair program that will no doubt provide long-term durability for this Owner.

Structure Characteristics

The prestigious Longfellow complex is located in the heart of downtown Boston on the Charles River. The complex consists of two 38 story apartment buildings, two midrise apartment/office buildings and four underground parking garages. This submittal focuses on the two 38 story apartment buildings which were constructed between 1970 and 1972. The beams, columns, 2-way slabs as well as the exterior fascade are all constructed of cast in-place reinforced concrete.

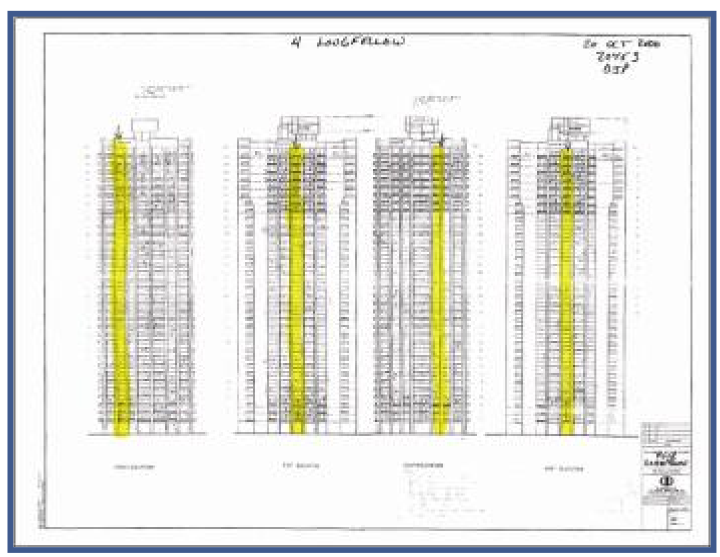
Problems That Prompted Repair

Inspections conducted in 1997 identified numerous areas of spalls. Despite attempts to repair the spalls, their number continued to grow over time. More recently, sealant joints at the sliding glass doors, ac units and windows were failing and allowing water to leak into the apartments.

Inspection/ Evaluation Methods

In 2001, inspecting engineers carried out a comprehensive investigation to determine the extent of damage and the root cause.

One drop of each elevation of each building was inspected representing approximately 15-20% of the surface area.



Visual and Sounding Survey by tapping with a hammer and visual observation.

Summary of Surveyed Areas

	Longfellow 1			Longfellow 4		
Façade Element	Number of Observed Spalls and Delaminations	Surveyed (sf)	% of Total Area of Element	Number of Observed Spalls and Delaminations	Surveyed (sf)	% of Total Area of Element
Column-front faces	89	4,705	20%	249	11,900	50%
Column-sides	3	9,550	20%	15	24,200	50%
Slab edges	130	2,670	17%	268	6,470	43%
Shear Walls	35	6,300	22%	0	0	0%
Balconies	67	4,600	10%	83	11,900	27%
Parapet walls	3	605	7%	4	1,350	15%

Cover Survey using a cover meter.

Measured Concrete Cover Over Reinforcing Steel

	Longfellow 1			Longfellow 4		
Location	Min	Average	Max	Min	Average	Max
Column-front faces	1	1-3/4	3-1/4	½	1-1/2	3
Column-sides	2	2-1/2	3-3/4	1-1/4	2	3-3/4
Slab edges	1	1-3/8	4	¾	1-1/4	2-5/8
Shear Walls	2	2-1/2	3	n/a	n/a	n/a
Parapet walls	1-3/4	2-1/4	3	1-1/2	2-1/2	3
Balcony edges	0	½	1-1/2	¼	¾	1-1/2

Half-Cell Potential and Corrosion Rate using galvanastatic pulse measurements.

Summary of Corrosion Activity

	Concrete Cover		
Measurement	**<1 in.**	**1 to 2 in.**	**> 2 in.**
Corrosion Rate*	0.3014 mA/cm^2	0.2174 mA/cm^2	0.0297 mA/cm^2
Corrosion Potential	243mV	114 mV	80 mV
Concrete Resistance	24 kΩ	20 kΩ	31 kΩ

* **Low rate**	**< 0.1 mA/cm^2**
Moderate rate	**0.1 to 0.2 mA/Cm^2**
High rate	**> 0.2 mA/cm^2**

Petrographic Analysis and Carbonation Analysis:

Cores were extracted in the field and sprayed with phenothailen for carbonation penetration. The cores were than brought to the lab and examined petrographically.

- Carbonation depth ranged from 0.20 to 0.75 in.
- The w/c ratio was estimated to be 0.44 to 0.54
- In general the air content was 2 to 4%

Chloride Analysis: Holes were drilled and dust samples collected at varying depths.

		Chloride Ion content	
Sample ID and Depth		**%**	**lbs/yd^3**
1S-M	¼ in.	0.023	0.9
1S-M	1-1/4 in.	0.013	0.5
1E-33	¼ in.	0.033	1.3
1E-33	1-1/4 in.	0.047	1.8
4E-15	¼ in.	0.030	1.2
4E-15	1-1/4 in.	0.046	1.8
4N-23	¼ in.	0.025	1.0
4N-23	1-1/4 in.	0.017	0.7

Summary of Inspection and Cause of Deterioration

- Spalling increased by 25% since 1996
- Exposed column faces, balcony edges and floor slab edges had the least cover and most spalls
- Concrete was non-air entrained in some locations
- Concrete contained admixed chlorides

Most importantly, all areas where the reinforcing steel had less than 2” of cover **were actively corroding.**

Repair System Selection

The goal of the Owner and the Engineer was to repair the spalled concrete and leaking joints and to provide long-term protection to the building. In order to achieve this goal the following program was specified.

1. Delaminated concrete and the failed sealant were removed and the substrate properly prepared.
2. Embedded corrosion rate monitoring probes were installed to monitor the initial and future effectiveness of the repairs.
3. A three-component, epoxy-modified, cement-based bonding agent and corrosion coating was applied to the substrate and exposed reinforcing steel.
4. Polymer-modified, silicia-fume enhanced repair mortars were specified to repair the delaminations.
5. An amino-alcohol, multi-functional, surface-applied corrosion inhibitor applied to all exposed concrete surfaces.
6. A two component, polyurethene sealant to seal all the joints at the sliding doors, windows and AC units.

7. An anti-carbonation crack-bridging coating to all the vertical surfaces in order to prevent future water, chloride and CO_2 penetration into the concrete.

Before finalizing the specification a preview was completed in order to verify constructibility and effectiveness of the design.

Discussion of the Preview

A discrete area was chosen and two systems were evaluated. Corrosion rate probes were first installed into both areas and initial data was collected.

Embedded corrosion rate monitoring probe

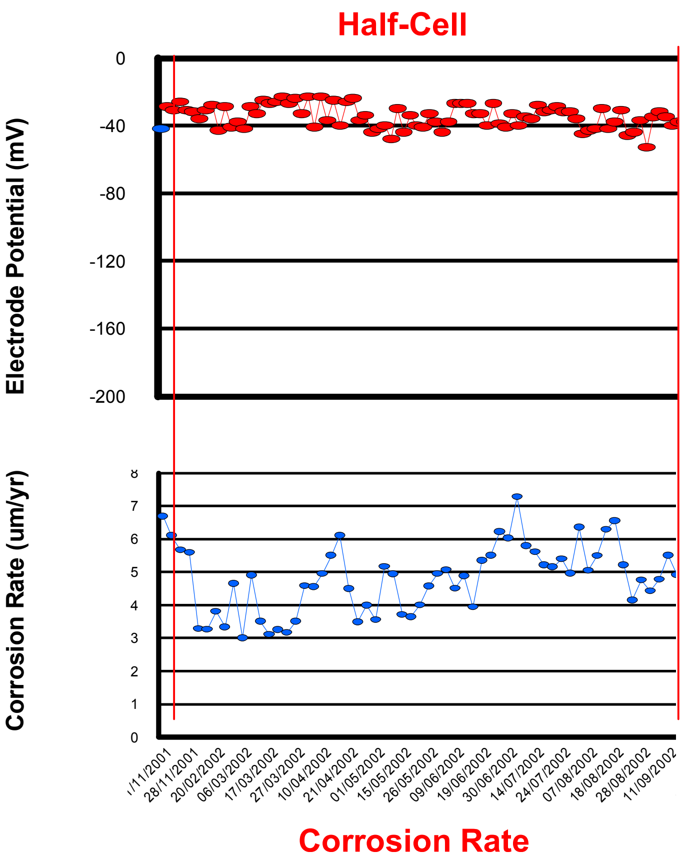
Area 1

A leveling mortar was first applied followed by two coats of the elastomeric coating.

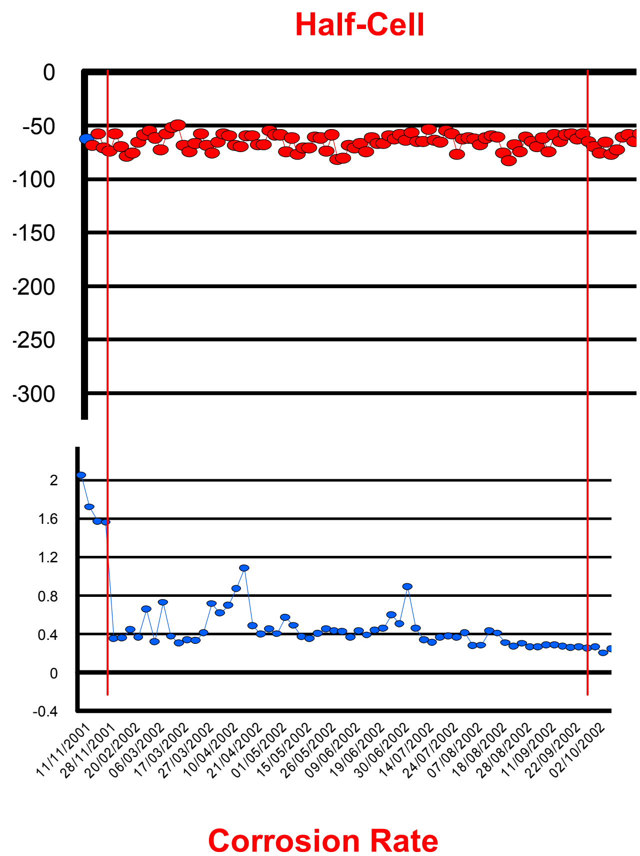
Area 2

A corrosion inhibitor was applied followed by two coats of the elastomeric coating.

AREA 1



AREA 2



All corrosion rate data reported as uM/year (microns per year of cross sectional steel loss)

Passive	**< 2 uM/year**
Low to moderate	**2-5 uM/year**
Moderate to high	**5-10 uM/year**
High	**> 10 uM/year**

Both areas were monitored remotely throughout the 11 month evaluation period. The results indicate the following

1. While half-cell potentials indicate low probability of corrosion in both treated areas, the corrosion rate at area 1 is actually moderate.
2. The corrosion rate at area 1 behaves somewhat erratically throughout the test period. Initially there appears to be a benefit; however, as time goes on the rate fluctuates and tends back toward the initial corrosion rate.
3. The corrosion rate at area 2 starts at a somewhat passive condition; however, there is little fluctuation throughout the test period and the trend seems to be an overall decrease in corrosion activity.

After the preview the specification described above was finalized with the following adjustments:

1. A leveling mortar would not be used.
2. Voids and honeycombs greater than ¼” in diameter would be filled prior to coating.
3. No primer was necessary for the elastomeric coating.

Project Installation

Site Preparation

The combination of the need to access 100% of the building exterior surfaces from the outside and the configuration of the panels and balconies; particularly, toward the top of the buildings would require 20 drops in total or 10 drops per building. To accomplish this, the contractor used mast climbers on 16 drops and a swing stage on 4 drops.

Before proceeding with the work the contractor developed a thorough sequence work plan that entailed many inspections at the end of each step. **(See Attachment)** The work plan was identical for each of the 20 drops and consisted of the following steps:

- Install rigging and protection
- Inspect and document drop
- Concrete removal and preparation
- Install monitoring
- Clean reinforcing steel
- Application of steel coating and primer
- Engineer inspection
- Concrete repair
- Seal door, window, AC unit joints and railing base
- Pressure wash fascade
- Apply two coats of corrosion inhibitor
- Pressure wash fascade
- Provide access to corners for handrail painting
- Apply two coats of elastomeric coating
- Cleanup and disposal
- Final inspection

Demolition Method

Spalled concrete was removed down to sound concrete using 15 lb. chipping guns.

Surface Preparation

Exposed corroded steel reinforcing was grinded to bright metal. Bond breaker tape was applied to the existing sealant in preparation for the sealant application. The building was pressure washed at 2,500 psi prior to the application of the corrosion inhibitor. The fascade was pressure washed again at 2,500 psi prior to the application of the elastomeric coating.

Application Method Selection

Work on Tower 4 started in April 2003 and was completed in November 2003. Work on Tower 1 started in March 2004 and was completed in October 2004. The contractor generally had two to three mast climbers and one swing stage in operation at any given time with an average crew size of 16-20 men.

The steel coating and substrate primer was applied by a brush just prior to the repair reinstatement. The same repair material was hand applied for all horizontal, vertical and overhead repairs. The sealant was gunned out and tooled to the proper width:thickness ratio. The corrosion inhibitor was roller applied to the proper consumption requirements in two applications. Last, two coats of the elastomeric coating was applied by roller to the proper thickness.

Quality control played a very important role during this project. The contractor hired an engineering firm to do the following:

- Inspect and document work
- Inspect surface preparation just prior to mortar application
- Advise on rebar removal if required
- Advise on field conditions contrary to that anticipated
- Final inspection

Final quantities are summarized below:

REPAIR QUANTITIES

Scope	Dimensional Quantity	Material Quantity
Concrete Repair	9,500 sf	2,900 bags
Sealants	60,000 lf	800 units
Corrosion Inhibitor	366,000 sf	70 drums
Pore filler		200 bags
Wall Coating	296,000 sf	6,000 gallons
Deck Coating	70,000 sf	34 drums

Completed Project

Unforeseen Conditions Found

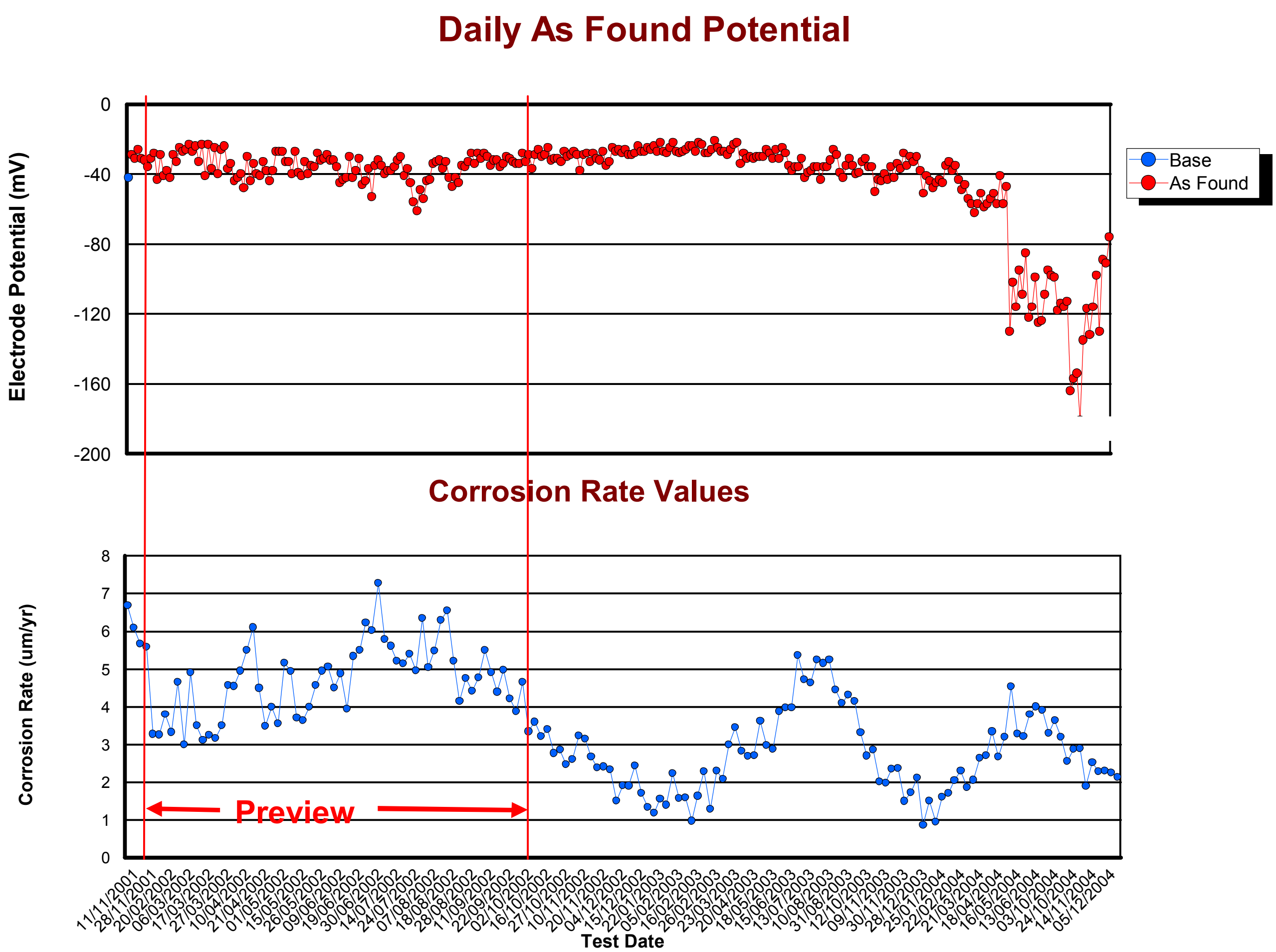
After the contractor sounded 100% of the surfaces, the number of spall locations grew from 5,000 estimated during assessment to 9,500. Steel that was too close to the surface when exposed after demolition was removed as instructed by the inspection engineer. The schedule and sequencing required flexibility to accommodate a fully occupied building during repairs. Even the Democratic National Convention affected the project as the owner desired no street – facing work during this period.

Monitoring Results

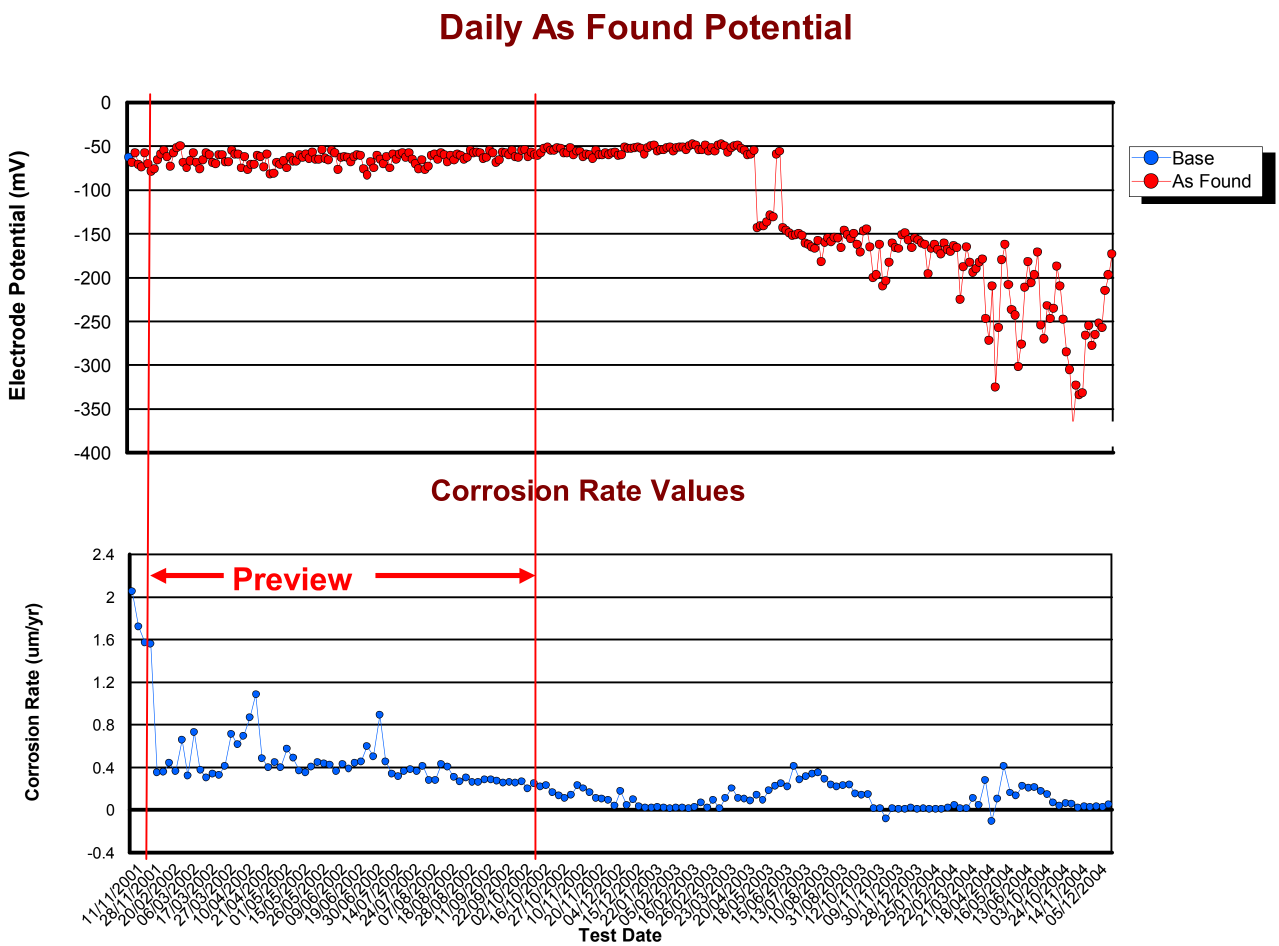
A pair of both half-cell potential and corrosion rate probes were installed roughly on every fifth floor in a bay on Tower 1. The preview data, previously mentioned, is now over the course of three years while the remaining data is over the course of five months.

Preview Data With 3 Year Update

AREA 1



AREA 2



All corrosion rate data reported as uM/year (microns per year of cross sectional steel loss)

It is interesting to note the following:

1. Half cell potential in both areas continue to indicate low probability of active corrosion until approximately June of 2004 in Area 1 and January 2004 in Area 2.

2. Generally speaking, as half-cell potentials decrease, the probability of active corrosion increases.

3. Area 1 corrosion rate continues to fluctuate. In fact it seems to be mirroring the time of the year in that rates increase during the hot/humid summer months and decrease during the cold/drier winter months.

4. Area 2 corrosion rate has little fluctuation and continues to be passive. This is particularly significant in light of the half-cell potential readings and underscores the importance of not relying solely on half-cell potential since it is only an indicator of corrosion and not a measurement of actual corrosion.

5. Half-cell potentials are a useful general indicator of the likelihood of steel corrosion. Corrosion rate; however, is important to determine actual steel corrosion.

Summary of Data

Level (Floor)	Probe (Location)	Corrosion Rate (uM/year)		% Reduction of Corrosion rate	Duration
		Benchmark	Last Reading		
GF	Area 1	6	2	67	3 years
GF	Area 2	Passive	Passive	0	3 years
8	1	9	10	-11	5 mos
8	2	9	5	44	5 mos
13	1	8	3	63	5 mos
13	2	9	4	56	5 mos
18	1	passive	passive	0	5 mos
18	2	passive	passive	0	5 mos
23	1	4	5	-25	5 mos
23	2	3	3	0	5 mos
28	1	passive	passive	0	5 mos
28	2	passive	passive	0	5 mos
32	1	9	4	58	5 mos
32	2	9	5	44	5 mos
35	1	5	5	0	5 mos
35	2	4	4	0	5 mos
38	1	18	7	81	5 mos
38	2	4	2	50	5 mos

All corrosion rate data reported as uM/year (microns per year of cross sectional steel loss)

Eighteen corrosion rate probes were installed. Nine areas prior to repair (benchmark) had either low or passive corrosion rates. Nine locations had either moderate or high corrosion rates. Five months after repairs, seven of the nine moderate to high areas have seen an average of 50% reduction in corrosion rates. Areas that were passive prior to repairing have remained passive. This is important as it relates to the incipient anode phenomena often reported after repairs.

Overall all, the Owner is pleased with the outcome of the project. The assessment indicated that there was chloride contamination, carbonation and low cover. Wherever the cover was less than 2” there was high levels of active corrosion. A repair program was designed to repair the spalls and leaking joints and protect the building by mitigating active corrosion. A preview was completed to confirm the design met the objectives. Finally, the contractor completed the installation using an organized work plan that was sensitive to the owners scheduling requirements, provided a comprehensive checklist for installation and involved an inspection engineer to confirm compliance with the design documents. All of this resulted in a repair program that will no doubt provide long-term durability for this Owner.

Special Features

Uniqueness

- Quality - Contractors attention to detail with a comprehensive checklist of work activities **(see attachment)**
  - Contractors hiring of an independent engineer to perform inspection services during construction.
- Logistics - Use of mast-climbers to access 100% of the exterior from the outside. Additionally, shoring schemes were designed to accommodate construction loads.
- Design /Build - Team approach consisting of the owner, engineer, contractor and material manufacturer to design a solution that addresses the root cause of the problem while maintaining the owners budget.

State-of-the-Art Methods

- Assessment - Use of multiple test methods such as galvanastatic pulse equipment for half-cell potential and corrosion rate surveys, powder extraction and titration for chloride contents as well as petrographic analysis for w/c ratio, air voids and general concrete quality analysis.

- Monitoring - Embedded, remote monitoring used to confirm design during pre-construction and long-term effectiveness of repairs after construction.

Use of Materials

- Material Selection - The engineer and the Owner completed the necessary steps to determine the root cause and to develop a program to identify the proper repair materials.

- Pre-qualification of Materials - Selected materials were applied in the specified manner and monitored for 11 months to determine suitability before the specification was finalized.

Functionality

- Completing the necessary steps prior to construction: determine root cause, identify the Owners needs, specify repair material and method of placement, test specifications before finalizing, and thorough QA/AC on site. The end result when these critical steps are followed is a very successful project for the entire construction team.

- The buildings have been repaired to the highest standards to ensure long-lasting, high-performing durability.

Value Engineering

- Pre-qualification of Materials - Testing and verification before construction allowed for the elimination of the leveling mortar and coating primer without compromising the integrity of the design

- Hand Rail Inspection - The contractor enlisted an engineer to test the integrity of the handrails and adhesion of the paint to provide significant cost savings to the owner with respect to reducing the scope of work to simply recoating the handrails.

Aesthetics:

All of the concrete surfaces are now coated with a coating with waterproofing and anticarbonation characteristics as well as excellent UV resistance. This will ensure the building will look its best for many years to come.