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Guide to ACI 562-16 – Design Example No. 3
Adaptive Reuse of Historic Depot

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Kip Gatto, PE, SE

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Tony Gueorguiev, PE, SE

Tony Gueorguiev, member of ACI is a senior engineer with Freyssinet, Inc. in Sterling, VA. Tony is an engineer with over ten years of professional experience in rehabilitation of existing reinforced concrete structures. He has a specialized experience in repair of post-tensioned structures and structural strengthening with external post-tensioning systems. He is currently a subcommittee member of ACI 562.

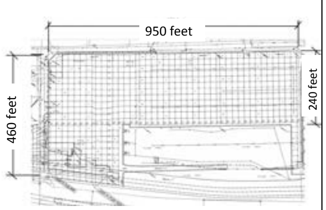
Tony is a registered Professional Engineer in the States of California, Virginia, Maryland, and the District of Columbia. He received his M.S. degree in Structural engineering from the University of Architecture, Civil Engineering and Geodesy in Sofia.

Outline

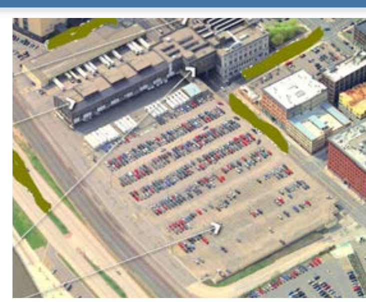
- Description of structure
- Project initiation and objectives
- Governing building codes
- Preliminary observations and evaluation
- Structural assessment
- Recommended repair program
- Contract documents
- Construction
- Quality assurance
- Project close-out

Description of Structure

- 300,000 sf
- Constructed in 1920s
- Designed for trains
- Converted to Postal Distribution in 1970s
- Columns on 21 ft. grid
- Portion is on grade

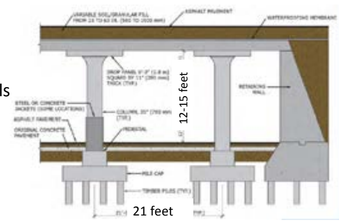


Description of Structure



Description of Structure

- 30 in. dia. columns
- 21 in. thick deck slab
- 11 in. deep drop panels
- Some steel jackets
- Fill and pavement on both levels
- Upper deck 12-15 ft. above lower deck



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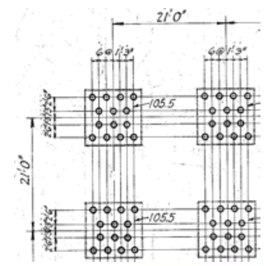

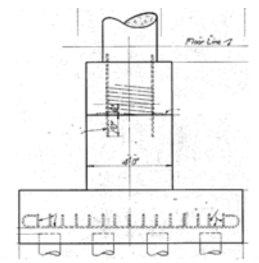

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Description of Structure

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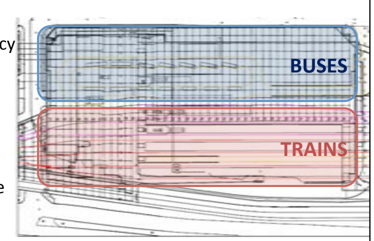
Project Initiation and Objectives (1.7)

- Adaptive reuse
- Structural adequacy
  - Buses
  - Trains
- Repairs
  - Freeze-thaw damage
- 50 year service life
- Evaluation and repair per ACI 562



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Governing Building Codes

Jurisdiction: Northern US City

- *Original building code (1.2.3):* Proposed Standard Building Regulation for the Use of Reinforced Concrete (ACI 1910 with Chicago ruling of 1915 for flat slab design)
- *Current building code (1.2.2):* 2009 International Building Code (2009 IBC)
- *Existing building code (1.2.1):* 2009 International Existing Building Code (2009 IEBC)
- ACI 562 supplements IBC and IEBC, except where conflict, then IBC and IEBC govern (1.1.2, 1.4.1)

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Governing Building Codes

- Jurisdiction has adopted an *existing building code (1.2.4)*
- Because *existing building code* is adopted, use Chapter 4 to determine *design basis code*
- Design is Level 3 Alteration per IEBC Chapter 11 (More than 50 percent of building planned for major renovations)
  - *Design basis code* (4.1): 2009 IBC (gravity and lateral loads)
  - Loads not covered in IBC in accordance with building official (AASHTO and AREMA)
  - Historic Structure requires consideration of Secretary of the Interior's Standards for the Treatment of Historic Properties

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Preliminary Observations and Evaluation

- Track deck and columns deteriorated from 90 years of exposure (1.3.1, 1.7.1)
  - Expansion joints
  - Column bases
  - Exposed edges
- LDP recommends an investigation and assessment
  - Concrete conditions
  - Material evaluation

Concrete Conditions, Methods (1.7.2)

- Track, deck, and columns visually surveyed
- Select areas identified for detail study (fill and steel jackets removed)
- Visual examination
- Hammer sounding
- Chain dragging
- Corrosion potential and rate testing
- Magnetic rebar location

Concrete Conditions, Findings

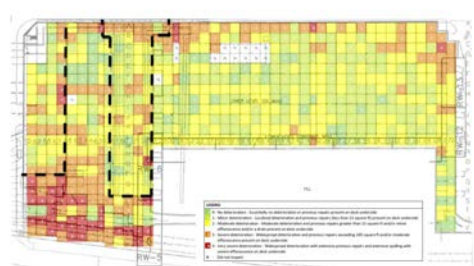
- Localized freeze-thaw deterioration on top surface of deck
- Corrosion related soffit spalls/delaminations prevalent at joints, drains, and openings
- Sounding revealed far more delaminations than visual examination
- Corrosion testing indicated moderate corrosion was occurring at deck soffit at joints, drains, and openings

Concrete Conditions, Findings

- Minimal corrosion activity at top surface of deck
- Deterioration of columns without jackets extended 1 to 2 feet above pavement
- Localized areas of corrosion above steel jackets
- Some jackets split along seams (underlying corrosion)
- Reinforcement layout consistent with design drawings

Concrete Conditions, Findings

Concrete Conditions, Findings



Material Evaluation, Methods (1.5.3, 8.4.3)

- Concrete coring (60 cores)
  - Petrographic examination
  - Chloride content analysis
  - Carbonation testing
  - Strength testing
- Reinforcement sampling
  - Material properties testing (Fy, Fu, E)

Material Evaluation, Findings

- Concrete typical of early 20th century site batching
- Typical to above average compressive strength
  - Average strength: 8130 psi
  - Strength range: 4790 psi - 9980 psi
- Concrete carbonated beyond reinforcing steel at slab soffit and columns

Material Evaluation, Findings

- Chloride levels near joints and drains above threshold values (ACI 222R)
- High chloride levels at column bases
- Highly porous concrete without air entrainment
- Intermediate grade reinforcing steel
  - Fy = 40,000 psi

Basis of Design Report

- Age, construction, codes, and historical overview
- Shortcomings in structure
  - Freeze-thaw susceptibility (high porosity and no air entrainment)
  - Soffit deterioration with joints and openings most deteriorated
  - High carbonation levels increase future corrosion potential
  - Chloride contaminated concrete increases future corrosion potential

Structural Assessment, Parameters

- Structural assessment requirements (6.2.2)
  - Evaluate columns and slabs for new truck and rail loadings
  - Consider both gravity and lateral loading
- Geometry (1.7.1, 1.7.2, 1.7.4, 6.2.4, 6.2.5)
  - Geometry obtained from original construction documents and verified in field

Structural Assessment, Parameters

- Concrete Strength (6.3.2, 6.3.3, 6.4.2.1, 6.4.3.1)
  - Concrete strength using core data and Equation 6.4.3.1

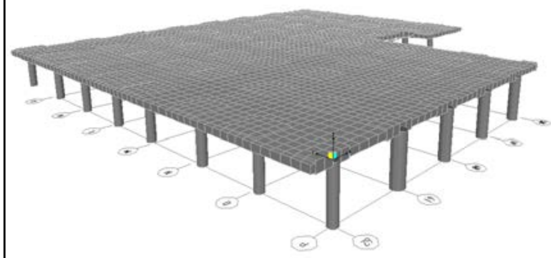
$$f_{ceq} = 0.9\bar{f}_c\left[1-1.28\sqrt{\frac{(k_c V)^2}{n}+0.0015}\right]$$

  - Slab: 6600 psi (5000 psi design)
  - Columns: 3900 psi: (3000 psi design)
  - Significantly greater than default of 2000 psi (Table 6.3.1a)
- Reinforcement
  - Field data consistent with design layout (6.4.4.1)
  - Fy = 40,000 psi (6.4.5.1, 6.4.6)

Structural Assessment, Analysis

- Loads (1.3.8, 5.1.4, 5.2.3, 6.5.1)
  - In accordance with design basis code (IBC, AREMA)
  - Gravity, wind, and seismic
- Analysis (6.5.2, 6.5.3)
  - Portion of deck modeled using finite element methods
  - Repairs to be included in repurposing so modeling did not include concrete deterioration
  - Construction period loads considered members undergoing repair (6.7.1)
  - Capacities calculated in accordance with AREMA, which took precedence over Section 5.4 (5.1.3, 5.2.2)

Structural Assessment, Model



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Structural Assessment, Findings

- Gravity load effects (5.1.4)
  - Capacity acceptable for proposed repurposing
  - Structure undergoing repair will not require shoring (9.2.1, 9.2.2)
- Live Load effects
  - Inadequate slab flexural capacity to support Cooper E-80 train-axle loading (AREMA)
  - Slab adequate for light rail and bus
  - Columns adequate for all anticipated loads

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Structural Assessment, Findings

- Lateral load effects
  - Preliminary seismic analysis: low seismic demand, no further analysis required (1.7.3, 6.7.4.3)
  - Wind loads also relatively low
- Detailing requirements
  - Seismic design category A
  - Prohibitively expensive to upgrade seismic detailing to IBC and ACI 318 standards
  - Robust structure should perform acceptably in design event, local authorities agree with assessment

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Recommended Repair Program – Train Deck

- Structural assessment and evaluation work
  - Widespread repairs on deck soffit and localized repairs on top
  - Corrosion related delamination especially around joints, drains, and openings in the deck
  - Measures to protect topside from water ingress

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Recommended Repair Program – Train Deck

- Recommended repairs
  - Partial depth - top and bottom of the deck
  - Full depth repairs along expansion joints and near drains
  - Cracks and construction joint sealing
  - New expansion joints seals and new drains
  - Waterproofing/deck protection
  - Future periodic maintenance

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Recommended Repair Program – Train Deck – Partial and Full depth repairs

- Removal of unsound concrete
  - Shape of repairs shall be considered (re-entrant corners, stress concentrations – [Section 7.6.6C]
- Rebar undercutting of all exposed corroded bars
- Restoration of structural section with new concrete

7.6.6 *Repair geometry*—Configuration of repairs shall consider the potential for stress concentrations and cracking in both the existing structure and the repair area.

Recommended Repair Program – Train Deck – Partial and Full depth repairs

- Chloride contamination?
  - Limited to deteriorated areas, where concrete will be replaced, thus no need of special corrosion protection (cathodic or other)
- Carbonation?
  - Re-alkalization was considered to increase pH but not justified due to cost and benefits.

Recommended Repair Program – Train Deck – Crack injection and sealing

- Cracks (8.3)
  - Size, orientation, crack width
  - Cause for cracking
  - Crack locations
  - Water infiltration
  - Potential for future cracking and movement
- Effects of cracks on:
  - Durability and performance of repair
  - Service Life
  - Repairs

Recommended Repair Program – Train Deck – Elimination of water penetration

Elimination of water ingress – to slow the rate of steel corrosion [8.2.2]

- Installation of new expansion joint seals and drains
- Deck soffit coating with a breathable sealer
- Replacement of the entire topside of deck waterproofing protection [8.5.1, 8.5.2 – Surface treatments and coatings]
  - Buried-fully adhered, flexible waterproofing with concrete topping
  - Bonded high-performance concrete overlay
  - Bonded thin polymer-resin-based overlay

Recommended Repair Program – Train Deck – Durability and Service Life

Durability is complex process and thus Key Goal of ACI 562

- Consideration of structure exposure
- Consideration of structure use
- Consideration of the interaction between repaired area and entire structure [8.4.3 – consideration of "halo" effect]
- Requires future periodic maintenance
- Desired service life of the structure – <u>50 years</u>
  - ACI 562 does not indicate service life
  - Set by the LDP and the owner to achieve the most economical repair that will guarantee safety and serviceability

Recommended Repair Program – Train Deck

Conclusion (Selected repair Program by LDP and owner)

- Partial and Full Depth repairs of all designated areas
- No supplemental treatment for chloride contamination
- No supplemental treatment for the carbonated concrete
- Crack and construction joint sealing
- New seals for expansion joints and new drains
- New waterproofing/deck protection – Buried, fully adhered, flexible monolithic waterproofing with unbonded concrete topping selected
  - Chosen to improve durability of repaired and original deck
  - Mitigate water leakage at locations where new cracks could form after repair.

Recommended Repair Program – Columns

- Several constraints limit the rehabilitation alternatives:
  - Tightly spaced spirals – 3 inch pitch
  - Potential of buckling of the vertical bars
  - Shoring not feasible – cost and schedule prohibitive
  - Condition of existing steel jackets
- Rehabilitation considerations:
  - Corrosion mitigation methods with vertical bars left in chloride contaminated concrete with no undercutting.
  - Installation of new 5 foot tall steel or concrete jackets for impact protection of column bases
  - Localized conventional partial depth surface repairs above the new jackets

Recommended Repair Program – Columns

Four repair alternatives were presented by the LDP to the owner:

- Alternative 1 – Fully welded steel jacket with sacrificial galvanic anodes
- Alternative 2 – Structural steel jacket with corrosion-inhibiting admixture
- Alternative 3 – Concrete jacket with sacrificial galvanic anodes
- Alternative 4 – Concrete jacket with corrosion-inhibiting admixture

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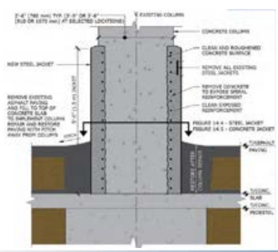
Recommended Repair Program – Columns – Alternative 1 – 50 year service life

Fully welded steel jacket with sacrificial galvanic anodes



- Structural confinement by steel jacket
  - Spiral reinforcement would not require repair
  - Barrier to future water ingress and Chloride infiltration
- Sacrificial galvanic anodes
  - Long term protection against ongoing corrosion

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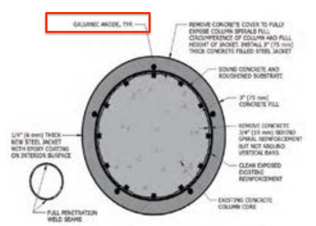
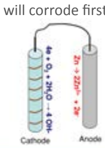
Recommended Repair Program – Columns – Alternative 1 – 50 year service life

Fully welded steel jacket with sacrificial galvanic anodes



Zinc anodes can be used. Use the difference in electrical potential where Zinc is a less noble metal, i.e. it is the sacrificial metal that will corrode first.



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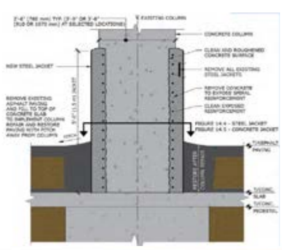
Recommended Repair Program – Columns – Alternative 2 – 20-30 year service life

Concrete filled steel jacket with corrosion inhibitor admixture



- Structural confinement by steel jacket
  - Spiral reinforcement would not require repair
  - Barrier to future water ingress and chloride infiltration
- Corrosion inhibitor
  - Not as effective, will reduce corrosion of spirals but will not stop the ongoing corrosion of vertical bars

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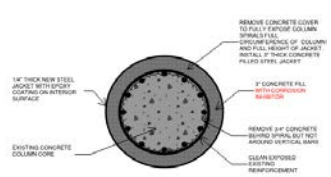
Recommended Repair Program – Columns – Alternative 2 – 20-30 year service life

Section



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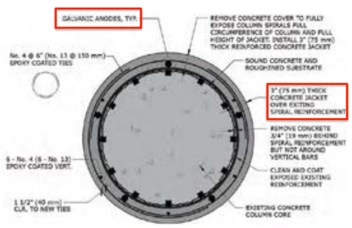
Recommended Repair Program – Columns – Alternative 3 – 50 year service life

Concrete jacket with sacrificial galvanic anodes



- Galvanic anodes are installed within 3" concrete jacket – active protection, i.e., longer service life
- Concrete jacket will alter the visual appearance of the columns

Recommended Repair Program – Columns – Alternative 4 – 20-30 year service life

- Same as Alternative 3 with the following exceptions:
  - No galvanic anodes
  - New concrete has corrosion-inhibiting admixture
- Lower service life compared to Alternative 3:
  - Corrosion inhibitor will help to reduce the corrosion of the spirals, but will not be effective in preventing the ongoing corrosion of the vertical bars that remain embedded in chloride contaminated concrete.

The owner selected <u>Alternative 1</u> – fully-welded structural steel jackets with sacrificial galvanic anodes to meet 50-year service life criteria and maintain historic nature of structure

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Concrete Repair Details and Sections of ACI 562 – Interface Bond Section 7.4

- Bonding of new concrete for partial and full depth repair of the deck considered critical for the performance of repair
- Horizontal shear demand at the interface of repair (new repair to existing concrete) calculated as **v_u=45 psi**
- Shear capacity was verified by pull-off tests with a average capacity of 100 psi, i.e. $v_u \leq \phi^* v_{ni}$ – satisfied

7.4.1.1 Interface shear stress shall be designed based on:

$$v_u \leq \phi v_{ni} \qquad (7.4.1.1)$$

where v_{ni} is nominal interface shear stress and ϕ is in accordance with 5.3.2.

Proper surface preparation required to achieve capacity – 7.4.3 and ICRI310

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Concrete Repair Details and Sections of ACI 562 – Interface Bond Section 7.4

- Interface Capacity – sections 7.4.2 and 7.4.3 of ACI-562
  - Permits bond contribution to interface-shear capacity up to 60 psi with no shear reinforcement crossing the interface
  - QC/QA

We are here
v_u = 45 psi

Table 7.4.1.2—Testing requirements where v_u is partially or totally resisted by the concrete

v_u	Reference	Testing requirements
Less than 30 psi	7.4.2	Bond-integrity testing
Between 30 and 60 psi	7.4.3	Quantitative bond strength testing
Greater than 60 psi	7.4.4	Quantitative bond strength testing

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Concrete Repair Details and Sections of ACI 562 – Additional Items

- Re-entrant corners were avoided in both repair and existing concrete Interface Capacity – [7.6.6]
  - Geometric irregularities should be avoided in any repair to reduce stress concentrations and potential for cracking.
- Exposed existing reinforcing bars were cleaned and coated with corrosion-inhibiting material to reduce future corrosion except in areas where galvanic anodes were installed – [8.4.4]
  - Corrosion should always be considered so that a durable repair is developed.

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Concrete Repair Details and Sections of ACI 562 – Additional Items

- New epoxy coated reinforcing bars were lapped with existing bars where existing bars have lost significant cross-sectional area – [7.6.3.1]. Uncoated bars were used in areas where galvanic anodes were installed
- Since concrete cover remains unchanged for most of the structure, alternative corrosion reduction methods were developed to reduce future corrosion activity [8.2.2, reference to ACI 515]
  - Inadequate concrete shall be addressed accordingly by increasing the cover or by alternative means "equivalent cover"

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Concrete Repair Details and Sections of ACI 562 – Additional Items

- Replacement concrete was developed to have similar properties to existing concrete and adequate air content for freeze-thaw cycles
  - Compatibility concept [8.1.2]
- Deck soffit repairs were formed with planks to simulate the same appearance as of the original concrete.
- Repaired sections were designed to have equal or similar strength and stiffness to the original sections [7.1.1 and 7.2.1]
  - The effect of locked-in internal forces and deformations on the safety of the structure must also be considered [7.2.2]

Concrete Repair Details and Sections of ACI 562 – Additional Items

- Repaired slab was designed to have similar fire resistance as the existing structure [7.9.1]
- Column surfaces including steel jackets were coated to limit future moisture penetration [8.5.1 and 8.5.2]

Construction Items

- LDP established limits of concrete removal and required monitoring of the removal work. In case these limits are exceeded, integrity of the structure needs to be re-examined or shoring needs to be designed by specialty engineer employed by GC [9.1c and 9.2.1c].
- LDP required that GC monitors the structure during repair for unexpected or unsafe conditions. GC was also required to notify LDP for rebar loss of more than 10%. Temporary shoring may be necessary.
  - ACI 562 requires that temporary shoring or bracing requirements are specified in contract documents. LDP determines global stability and stability of individual members.

Quality Assurance

- Review of material submittals
- Visual inspection of the work in progress
- Sounding of concrete surfaces
- Observation of prepared concrete surfaces.
- Testing of repaired concrete (compressive strength; void content, etc.)
- Bond strength testing
- Electrical connectivity testing of the reinforcement
- Moisture testing by ICRI certified technicians before installation of coating

Project Close-out and Periodic maintenance

- Periodic maintenance requirements were discussed between the LDP and owner and schedule was developed and provided to the owner. Always should be documented in the Basis of Design report. [1.5.3.1 – maintenance protocol]
- Why needed?
  - To help owners to protect their investment
  - To assist and protect LDP

Project Close-out and Periodic maintenance

- Major Items of the periodic maintenance were:
  - Periodic inspections of the train deck soffit and columns every 3 to 5 years
  - Limited concrete deck soffit and column repairs every 5 years
  - Epoxy Injection of leaking train deck cracks every 5 to 10 years
  - Coating repair or recoating of concrete and steel jackets

Thank You