Saving a Structure

Innovations in Strengthening and Protection

Lessons from the I-10 Broadway Curve at Western Canal

Western Canal
At a Glance

Presentation Overview

Project Introduction and Need

Serviceability Considerations

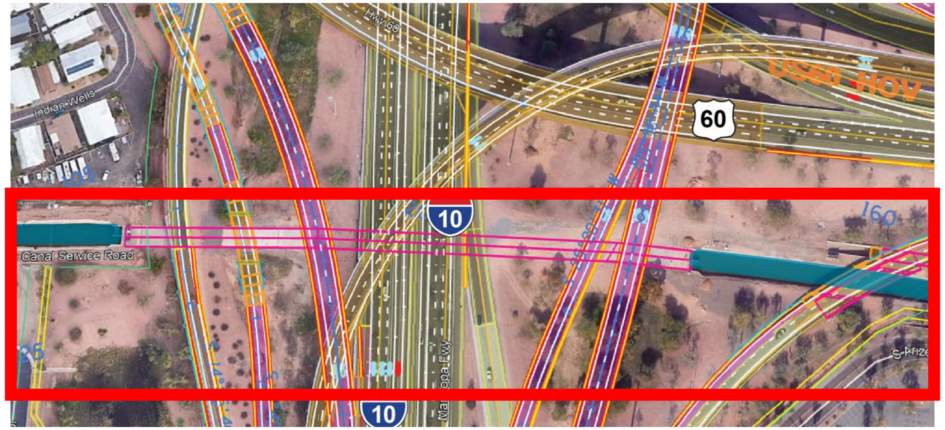
Strength Considerations

Project Introduction and Need

Western Canal Introduction

Project Location and Project Need

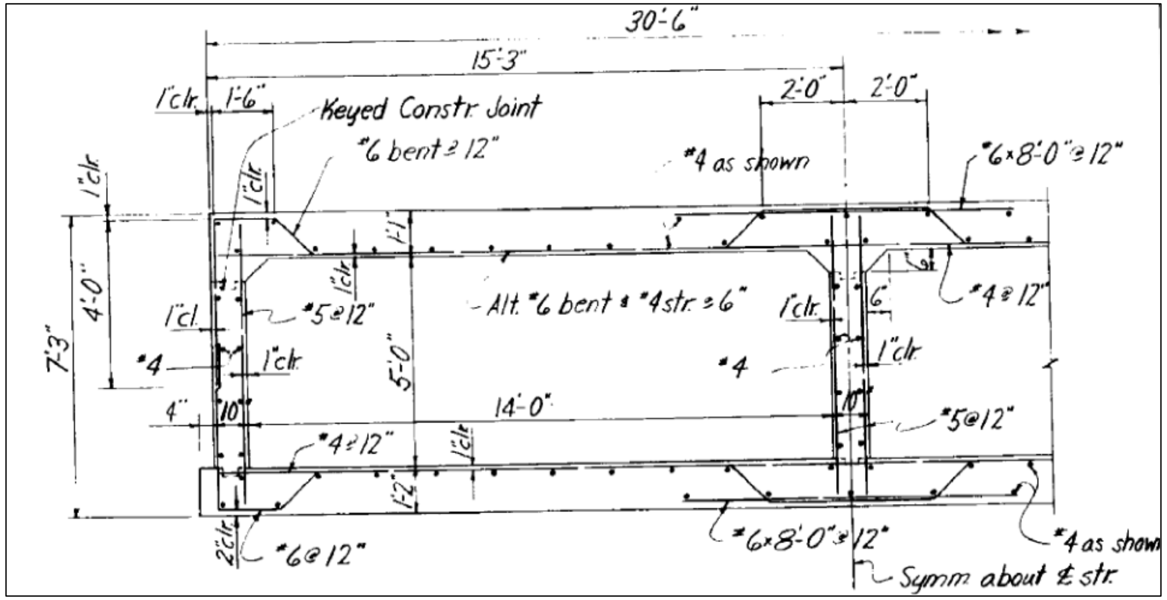
1. Located south of US-60 across I-10 in Phoenix, AZ



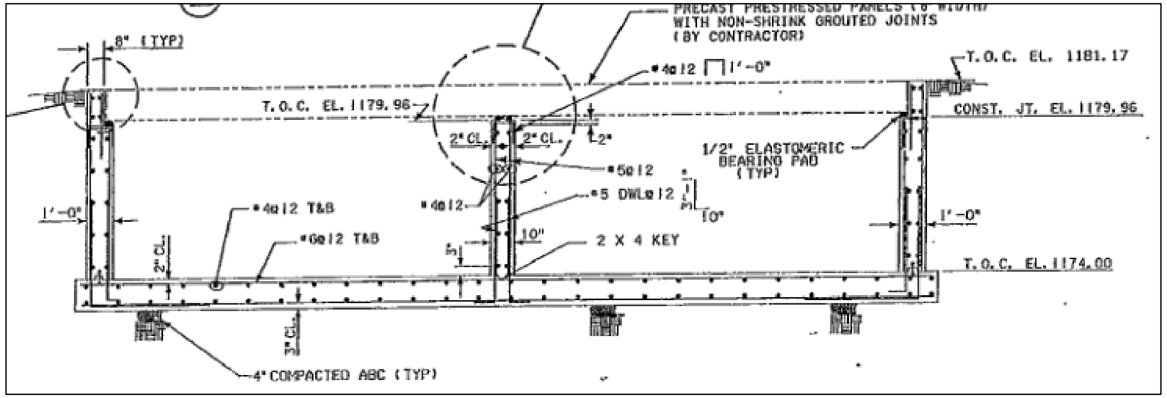
2. ADOT I-10 Broadway Curve Project
   a. Existing 2-cell reinforced concrete box culvert
   b. Active Canal managed by Salt River Project
   c. Adding General Purpose Lanes
   d. Adding Collector-Distributor Roads
   e. Total of 3 new crossings, 5 lanes

History of Western Canal

1. Originally Built in 1964
2. 1st Extension in 1967



3. 2nd Extension in 1993



Western Canal Introduction

History of Western Canal

1. **Signs of Corrosion identified during a routine structural inspection in 2017**
   a. Areas of Delamination
   b. Sporadic cracking throughout
   c. Majority of deterioration in soffit of top slab
2. **ADOT worked with SRP to rehabilitate the boxes**
   a. Removed deteriorated concrete
   b. Applied Zinc coating to exposed reinforcement
   c. Replaced severely deteriorated reinforcement
   d. Applied shotcrete grout to restore original section

Western Canal Identified as High Risk

I-10 Broadway Curve is a P3 Procurement

A key criteria on P3 Projects is how well a party can ***EVALUATE, SHIFT, or PRICE risk*** in design or construction.

Risk was assessed and evaluated during procurement and identified:

1. Wester Canal is owned by a Third Party
   A. Requires Third Party Approvals
2. Corrosion is a progressive condition
   A. Continues to worsen over time
3. Location impact entirety of mainline I-10
   A. Significant impact to MOT/Phasing

Approach to Risk

ADOT made the decision to Accept the risk and work with SRP on a solution.

Issues indicate two concurrent concerns:

SERVICEABILITY

Factors including durability, stability, cracking, and spalling. Not related to strength.

STRENGTH

Factors relating directly to ability of structure to carry applied loads imposed on the structure.

REPLACE or SAVE ?

Need to treat both issues if we are to save the structure!

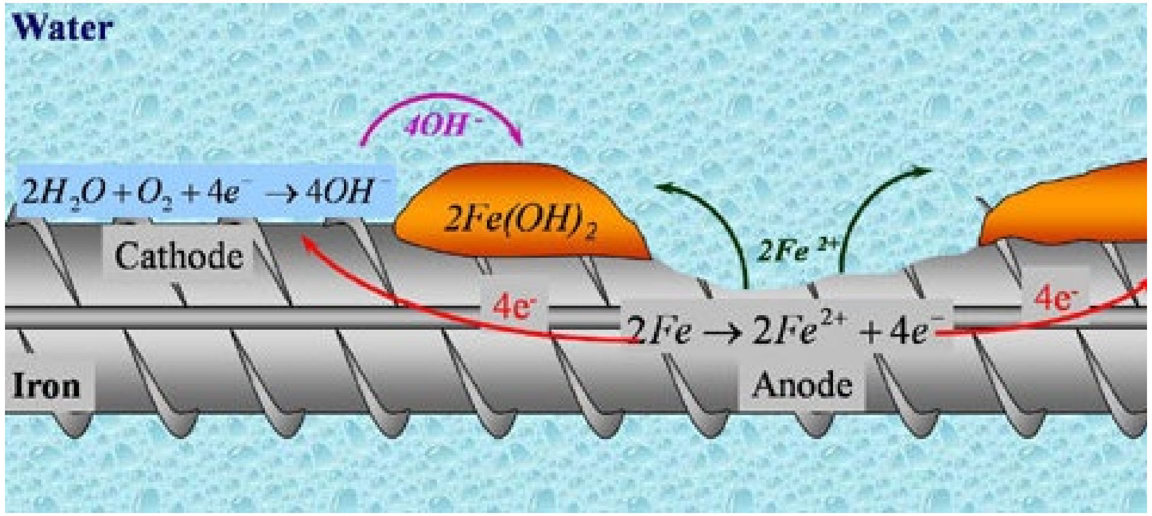
Serviceability Considerations

Mechanism of Corrosion

Serviceability concerns were driven by corrosion.

1. **Electrical response to environment**
   a. Steel contributes electrons to water vapor and oxygen
   b. Resulting hydroxide combines with free iron
   c. Results in rust build-up and section loss

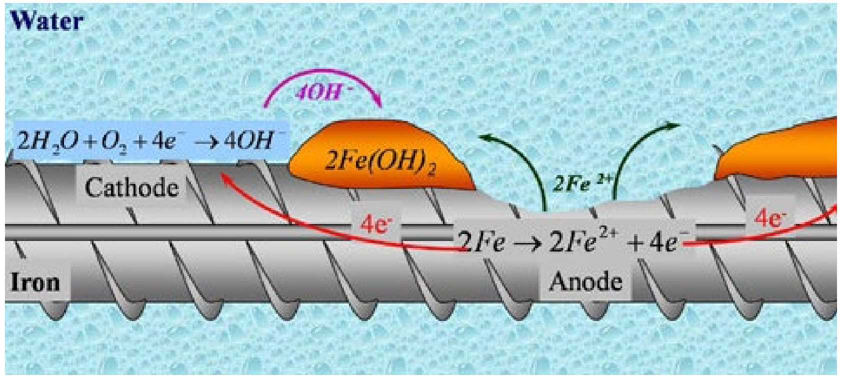
2. **Requirements**
   a. Oxygen
   b. Water source (Cathode)
   c. Donor Material (Anode)
   d. Electrical Potential



Courtesy of "https://www.cement.org/learn/concrete-technology/durability/corrosion-of-embedded-materials"

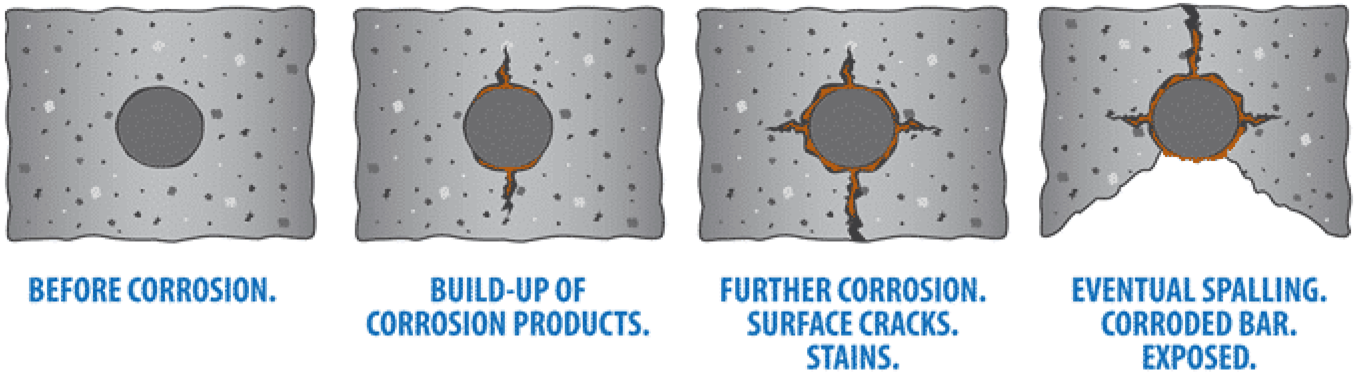
Mechanism of Corrosion

1. **Response in Fresh Concrete**
   a. Concrete is Alkaline (high pH)
   b. Initial Protective "Passive" Coating



Courtesy of "https://www.cement.org/learn/concretetechnology/durability/corrosion-of-embedded-materials"

2. **Deterioration over time**
   a. Chlorides and Carbonization reducing pH
   b. Cracks form allowing water/oxygen intrusion
   c. Results in more cracks and spalls



Courtesy of "https://theconstructor.org/concrete/corrosion-steel-reinforcement-concrete/6179/"

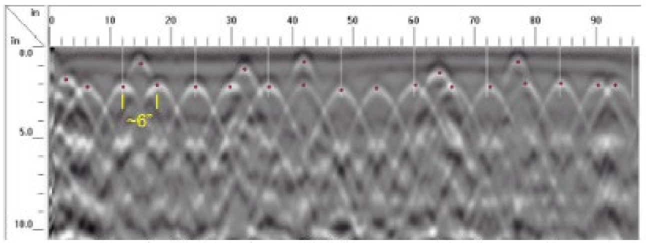


Figure 2: 2nd Extension – Soffit, Transverse Reinforcement

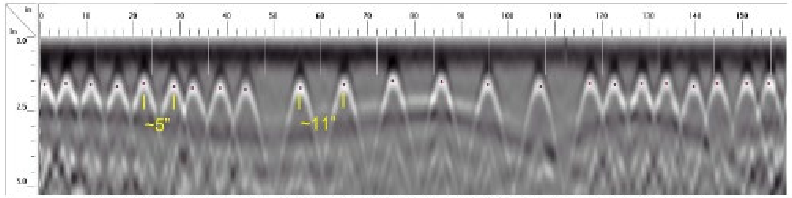


Figure 3: 2nd Extension – Soffit, Longitudinal Reinforcement, Full Width of Slab

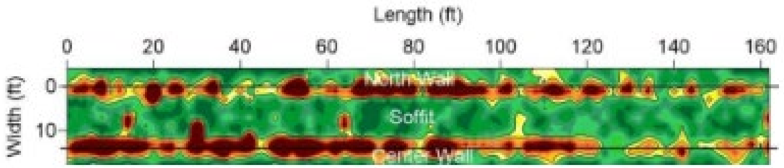


Figure 13: Original Section, North Cell – Delta Values

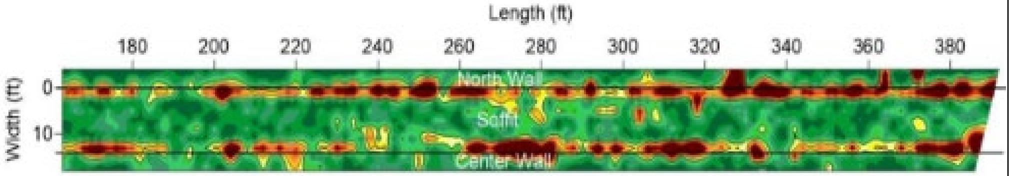


Figure 14: 1st Extension, North Cell – Delta Values

Ground Penetrating Radar

- Confirmed reinforcement spacing with Record Drawings
  - *Exception* - 2nd Extension longitudinal reinforcement above transverse layer
- Cover is within typical construction tolerances for current RCBC construction practices (ADOT SD 6 Series)

Corrosion Potential

- Corrosion Potential based on threshold
  - 90% shows low potential
  - 10% moderate to high at wall/soffit
  - Low potential likely due to arid climate
- Corrosion Potential based on Deltas
  - Higher values of corrosion potential
  - Concentrated in walls and wall/soffit
  - 43% to 99% above threshold in walls
- High potential considered indicator of likely corrosion in next 6 years

Western Canal Serviceability Considerations

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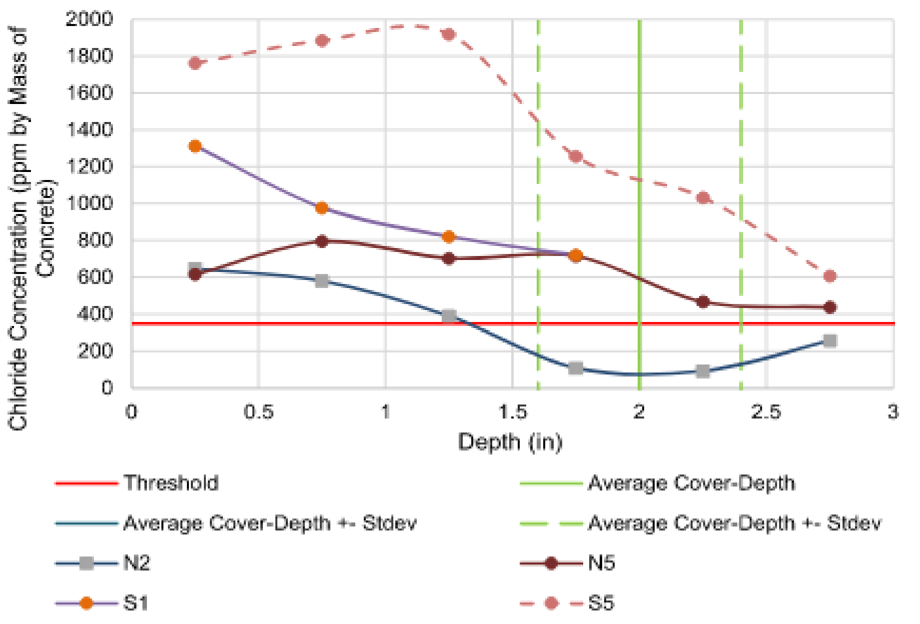
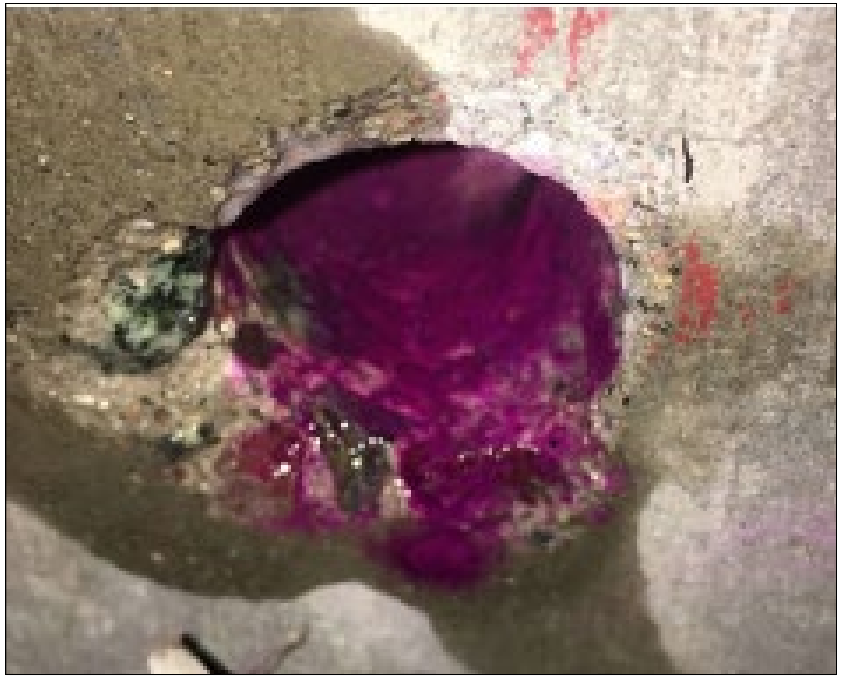


Figure 18: Chloride Concentration in Samples Extracted from the Walls

Chloride Penetration

- Chloride lowers pH increasing potential
- Soffit indicated minimal chloride penetration
- Walls indicate suitable chloride levels for corrosion
  - Likely due to chlorides in the water which leach into walls during saturation



Carbonation Testing

- Dye test indicates presence of carbonation
- Carbonation lowers concrete pH
- No carbonation detected in testing

Investigation Conclusions

1. **Spacing and cover of reinforcement generally agreed with as-built conditions**
2. **Corrosion potential in walls is moderate to high**
   a. Chloride concentration is elevated in walls
   b. 43% to 99% is likely in active corrosion
   c. Submerged section lower likelihood of corrosion
3. **Corrosion potential in soffit is generally low with some moderate to high**
   a. Low levels of chlorides

Recommendation Options

1. **No Mitigation, Base Repairs as needed**
   a. Treats the symptom, not the cause
   b. Repair area and frequency likely to increase
   c. Long-term degradation of reinforcement
2. **Cathodic Protection**
   a. Mitigates corrosion in reinforcement by providing sacrificial anode
   b. Provides long-term protection
   c. Is replaceable for continued protection
3. **Chloride Extraction**
   a. Enhances passivity of concrete
   b. Not recommended due to long de-watering requirements
4. **Sealants and Liners**
   a. Not recommended as it seals in moisture and hides deterioration
   b. Sealants have questionable life in saturated conditions

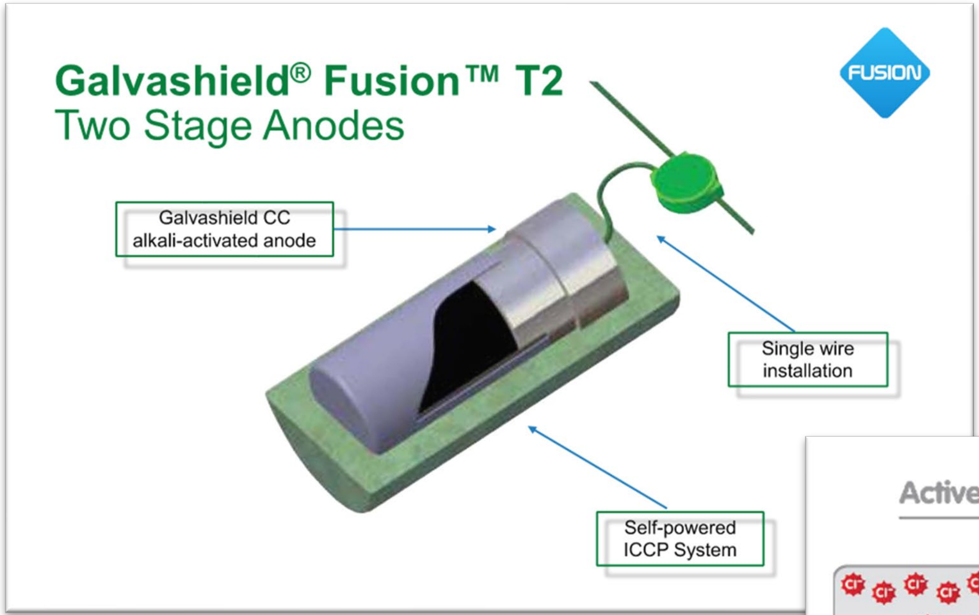
Recommendations for Serviceability

1. **Use combination of Base Repairs and Cathodic Protection**
   a. Potential maps can identify corrosion areas missed in last repair
   b. Repair spalled and delaminated areas
   c. Ongoing ADOT inspections on 4-year cycle to observe condition
2. **Cathodic Protection (Bulk Anodes) in Walls**
   a. Bulk Anodes in the walls, requires saturated concrete
   b. Only applicable to the walls
   c. 20–30 year service life, replaceable
3. **Cathodic Protection (Drilled Anodes) in Soffit**
   a. Install in areas with moderate to high corrosion potential
   b. More can be added in future if needed
   c. 20–25 year service life

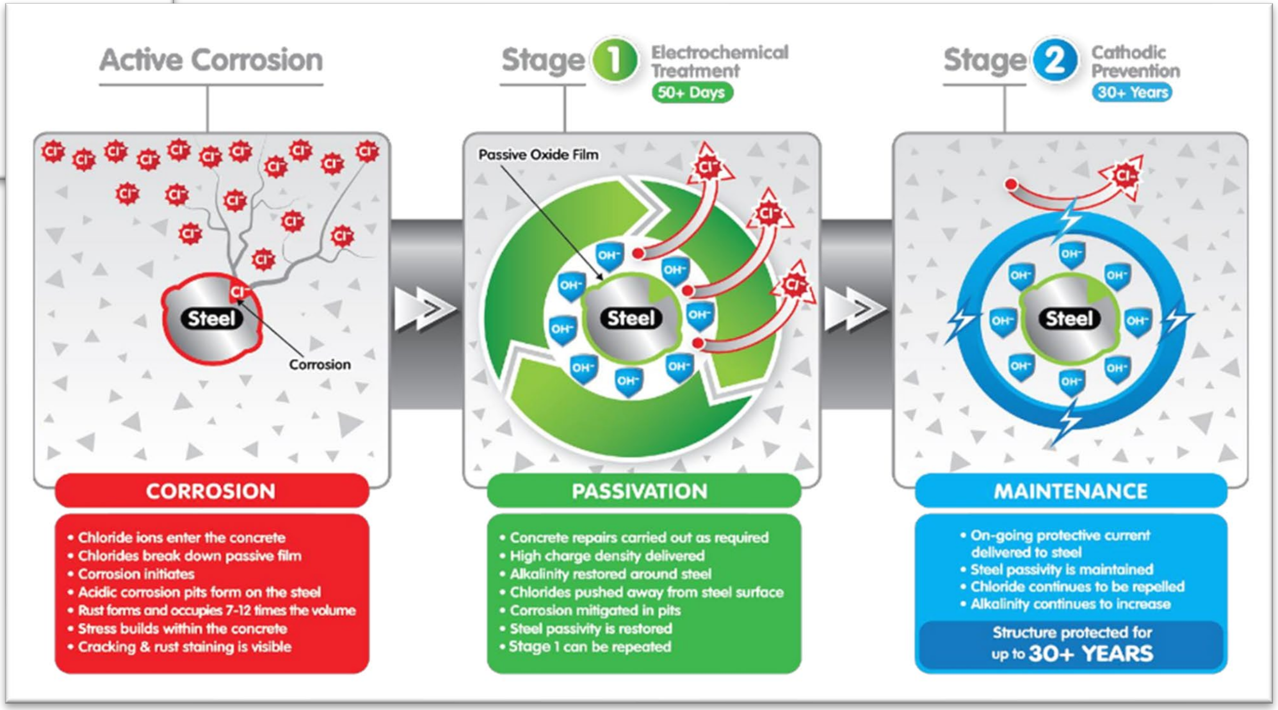
Western Canal

Recommendations

Recommendations for Serviceability



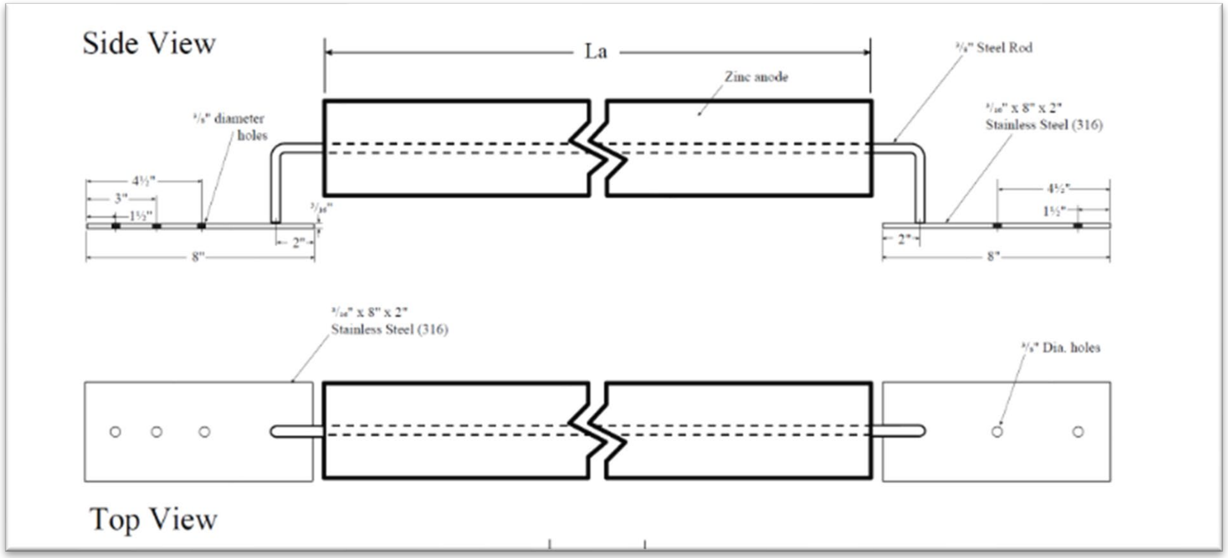
Courtesy of Vector Corrosion Services



Western Canal

Recommendations

Recommendations for Serviceability



Courtesy of Vector Corrosion Services

Strength Considerations

Western Canal Strength Considerations

Load Ratings

Capacity Evaluations through Load Ratings

Evaluation Approach

- Evaluation Methods
  - AASHTOWare BrR
  - Hand Calculations
  - Florida Box Design
- Existing Load Rating
  - Original
  - 1st Extension
  - 2nd Extension
- Post-Strengthening Load Rating
- SRP CONDOR Truck Evaluation

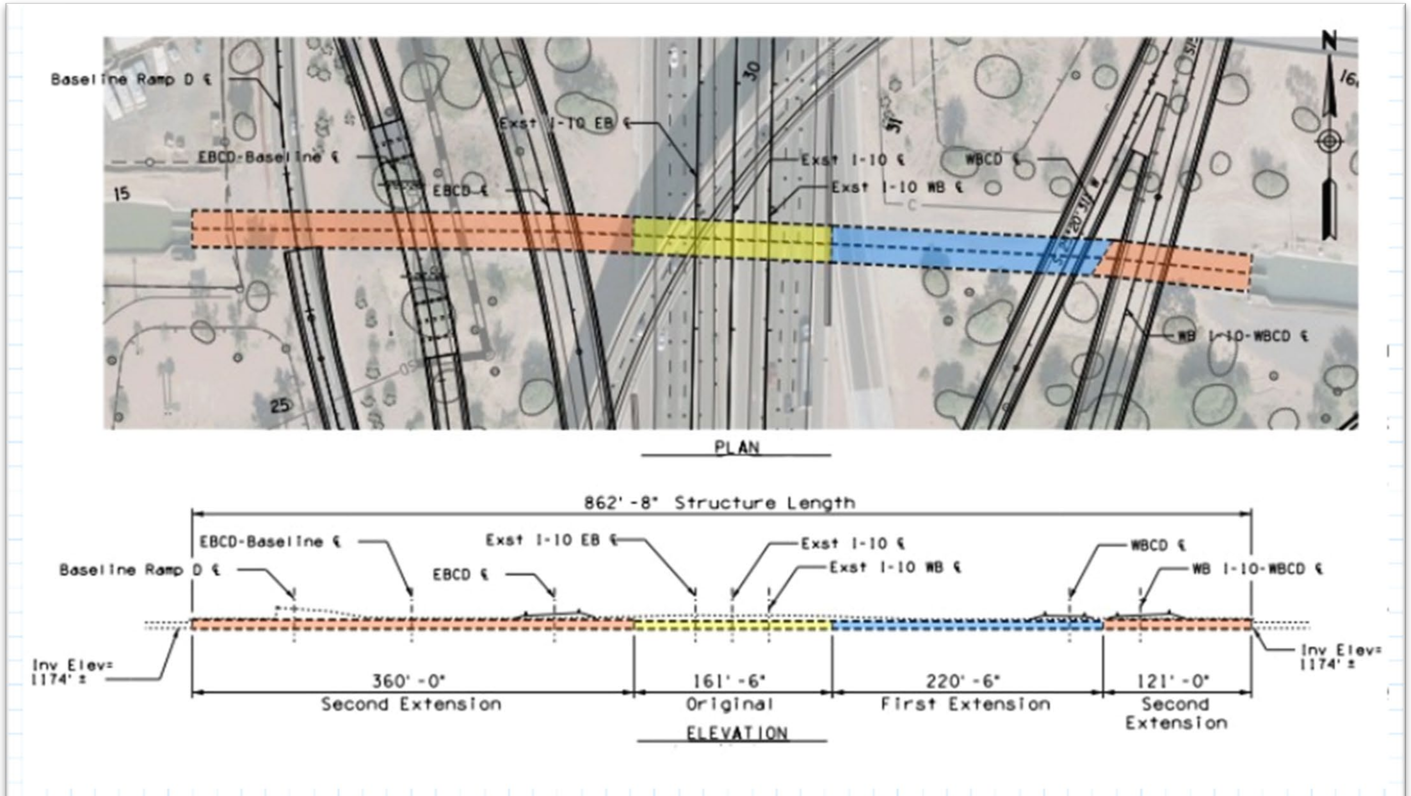


Figure 1: Western Canal Layout

Western
Canal
Strength
Considerations
Load Ratings

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Load Rating

Western Canal Load Rating Summary

Model	Fill Height	Rating Method	Limit State	Load Rating Results: Rating System	Load Rating Results: Location	Load Rating Results: Demand (k-ft)	Load Rating Results: Capacity (k-ft)	Load Rating Results: Inv. LR	Verification Results: Rating System	Verification Results: Location	Verification Results: Demand (k-ft)	Verification Results: Capacity (k-ft)	Verification Results: Inv. LR	Deflections (Service Limit State): Live Load Deflection** (in)	Deflections (Service Limit State): Dead Load Deflection (in)	Deflections (Service Limit State): DL + LL Deflection (in)
Original CBC & First Extension: Exst Condition	2 ft	LRFR	Strength I	BrR	0.10L (M-)	-3.54	-3.12	0.57	FL Program	0.06L (M-)	12.4	15.5	1.30			
		LRFR	Strength I	BrR	0.40L (M+)	28.17	23.78	0.68	FL Program	0.50L (M+)	28.0	20.8	0.74	0.18	0.024	0.204
		LRFR	Strength I	BrR	0.96L (M-)	-27.01	-32.06	1.11	FL Program	0.94L (M-)	35.0	28.9	0.90			
	5 ft	LRFR	Strength I	BrR	0.1L (M-)	-0.72	-3.12	1.79	FL Program	0.06L (M-)	10.8	15.2	1.80			
		LRFR	Strength I	BrR	0.40L (M+)	24.42	23.78	0.72	FL Program	0.50L (M+)	23.3	20.8	0.80	0.18	0.045	0.225
		LRFR	Strength I	BrR	0.96L (M-)	-28.73	-32.06	1.01	FL Program	0.94L (M-)	36.0	28.9	0.58			
	6.5 ft	LRFR	Strength I	BrR	0.10L (M-)	0.17	-3.12	2.40	FL Program	0.06L (M-)	11.0	15.2	2.00			
		LRFR	Strength I	BrR	0.40L (M+)	25.04	23.78	0.56	FL Program	0.50L (M+)	23.8	20.8	0.70	0.18	0.056	0.236
		LRFR	Strength I	BrR	0.96L (M-)	-31.38	-32.06	0.68	FL Program	0.94L (M-)	39.0	28.9	0.05			
Original CBC & First Extension: Strengthening Alternative 1 (Increase Chamfer + FRP)	2 ft	LRFR	Strength I	BrR*	0.07L (M-)	-3.35	-34.14	6.32								
		LRFR	Strength I	BrR	0.40L (M+)	29.50	38.95	1.25						0.18	0.020	0.200
		LRFR	Strength I	BrR*	0.93L (M-)	-22.39	-34.14	1.13								
	4 ft	LRFR	Strength I	BrR*	0.07L (M-)	-1.78	-34.14	9.82								
		LRFR	Strength I	BrR	0.40L (M+)	25.78	38.95	1.67						0.18	0.031	0.211
		LRFR	Strength I	BrR*	0.93L (M-)	-21.83	-34.14	1.35								
	6 ft	LRFR	Strength I	BrR*	0.07L (M-)	-1.08	-34.14	13.70								
		LRFR	Strength I	BrR	0.40L (M+)	25.90	38.95	1.97						0.18	0.042	0.222
		LRFR	Strength I	BrR*	0.93L (M-)	-24.99	-34.14	1.22								
Second Extension: Precast Slab	2ft	LRFR	Strength I	Hand Calc.	M(-)	321.16	391.32	1.40	Conspan	0.10L M(-)	164.40	281.30	2.50			
		LRFR	Strength I	Hand Calc.	M(+)	312.30	557.90	2.40	Conspan	0.40L M(+)	364.30	590.90	2.17	0.042	0.060	0.102
	5ft	LRFR	Strength I	Hand Calc.	M(-)	256.59	391.32	1.83	Conspan	0.10L M(-)	171.80	281.30	2.43			
		LRFR	Strength I	Hand Calc.	M(+)	220.80	557.90	5.46	Conspan	0.40L M(+)	382.50	590.90	2.10	0.042	0.077	0.119
	6 ft	LRFR	Strength I	Conspan	0.10L M(-)	175.50	281.40	2.40								
		LRFR	Strength I	Conspan	0.40L M(+)	391.70	590.90	2.06						0.042	0.086	0.128

* BrR is used to calculate load demands, but capacity is calculated by hand.

** Maximum Allowable Deflection due to vehicular LL = Span/800 = 0.21 in.

Western Canal Strength Considerations

Load Ratings

Load Rating

Western Canal Load Rating Summary									
Load Rating Results					Verification Results				
Rating System	Location	Demand (k-ft)	Capacity (k-ft)	Inv. LR	Rating System	Location	Demand (k-ft)	Capacity (k-ft)	Inv. LR
BrR	0.10L (M-)	-3.54	-3.12	0.57	FL Program	0.06L (M-)	12.4	15.5	1.30
BrR	0.40L (M+)	28.17	23.78	0.68	FL Program	0.50L (M+)	28.0	20.8	0.74
BrR	0.96L (M-)	-27.01	-32.06	1.11	FL Program	0.94L (M-)	35.0	28.9	0.90
BrR	0.1L (M-)	-0.72	-3.12	1.79	FL Program	0.06L (M-)	10.8	15.2	1.80
BrR	0.40L (M+)	24.42	23.78	0.72	FL Program	0.50L (M+)	23.3	20.8	0.80
BrR	0.96L (M-)	-28.73	-32.06	1.01	FL Program	0.94L (M-)	36.0	28.9	0.58
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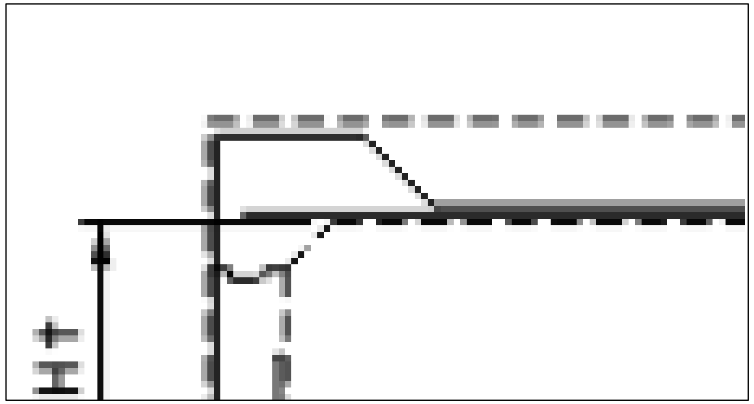
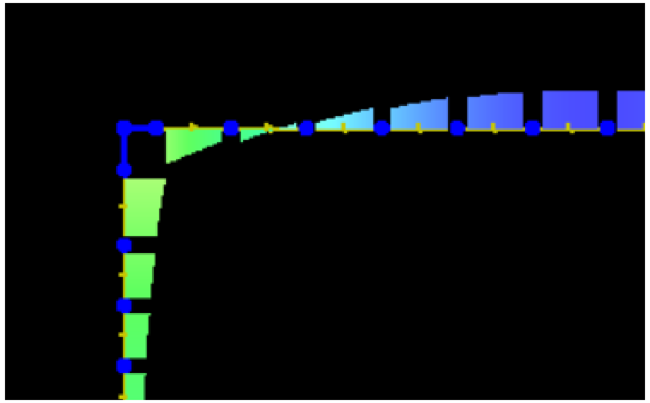




Programs reported differences in negative and positive moments.

Appeared to be tied to stiffness of wall to slab connections assumed within programs

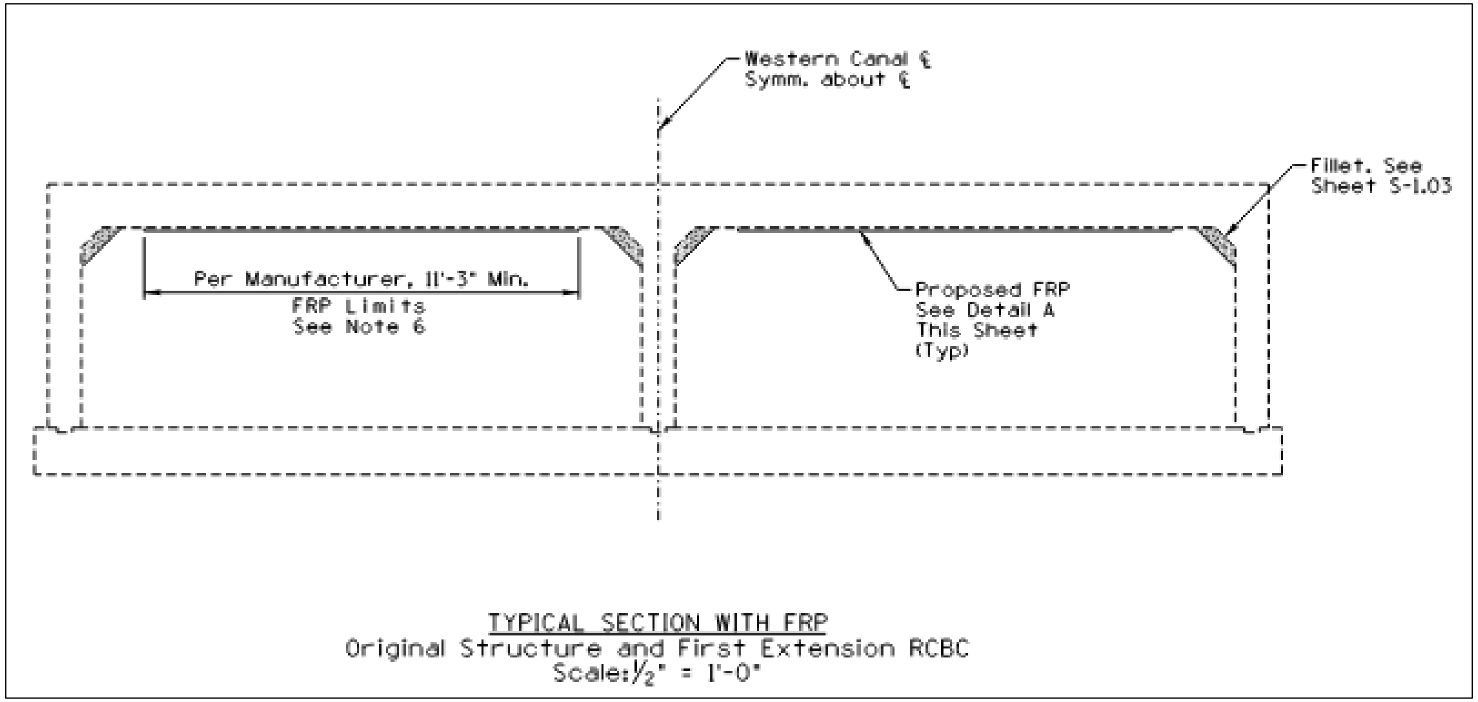
Strengthening Approach

Strengthening Approach

- Work needed to be accomplished from inside the box cell
- Needed to increase positive moment → FRP Systems
- Needed to increase negative moment → Deepen “beam” using fillet

Alternative approach:

Allow negative moment region to hinge, and only strengthen positive moment region.



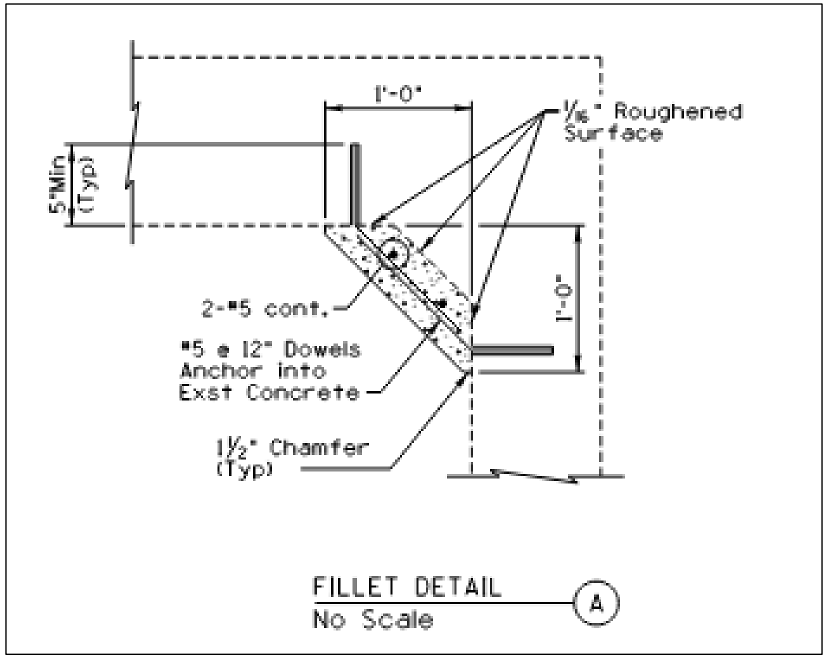
Western Canal Strength Considerations

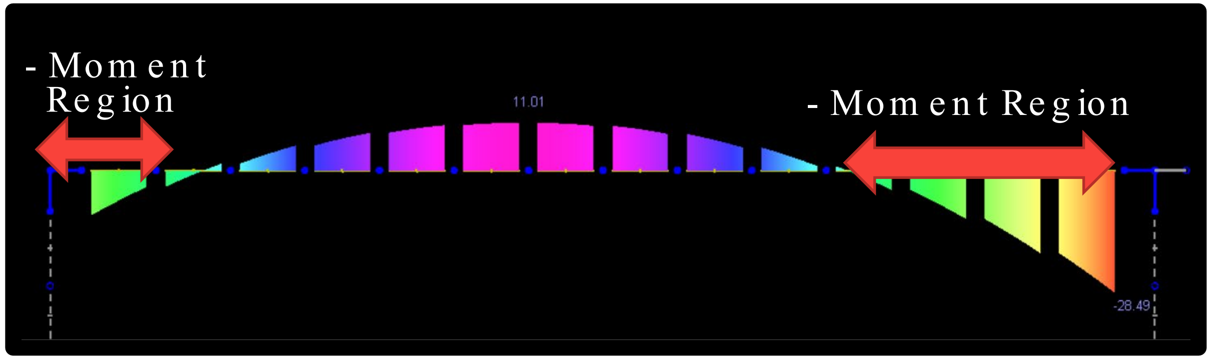
ADOT Strengthening

Strengthening Approach – Negative Moment Region

Fillet Strengthening

- Increase depth to reinforcement
- Requires composite action
- Improves Negative Moment Capacity
- Improves Shear Capacity

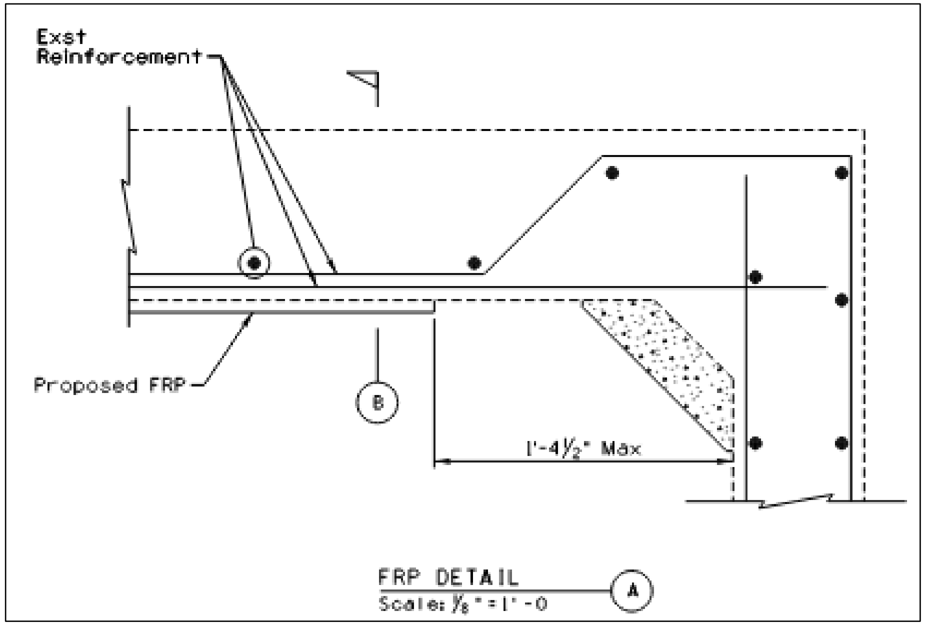


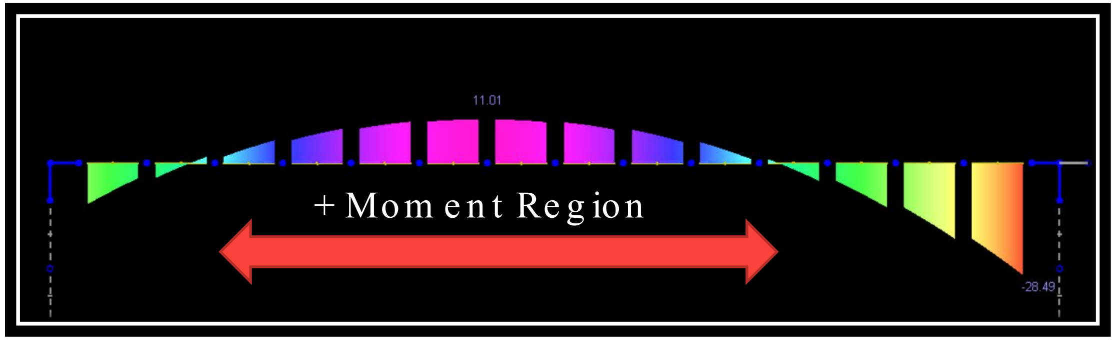


Strengthening Approach – Positive Moment Region

FRP Systems

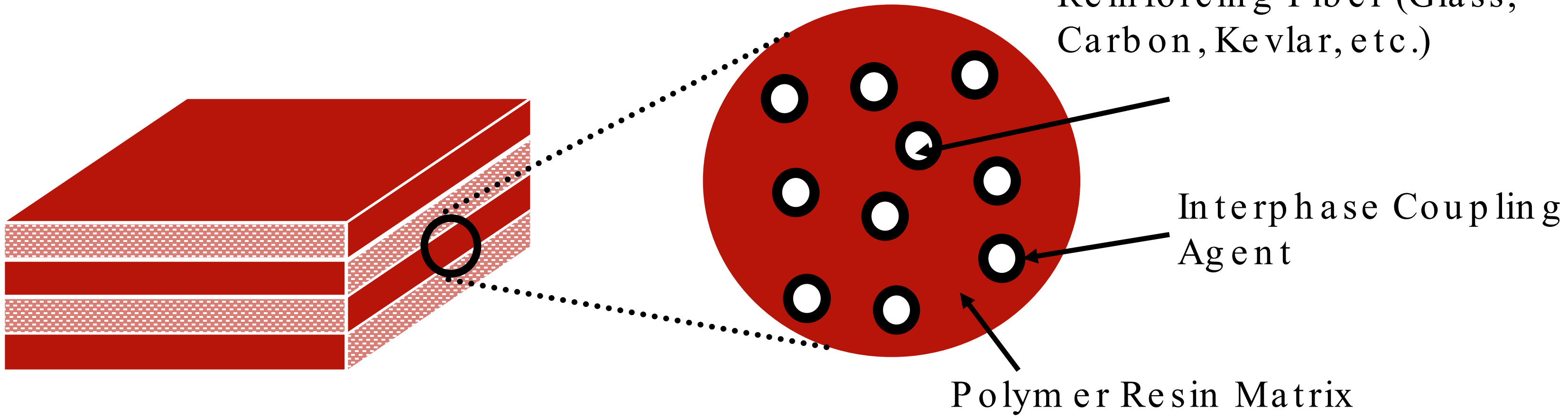
- Fiber Reinforced Polymers
- Increases "Reinforcement"
- Improves Positive Moment Capacity
- Installed from below top slab





Fiber Reinforced Polymer (FRP)

- A Polymer (i.e. epoxy, vinyl ester, etc.) that has been reinforced with a Fiber (e.g. carbon, glass, etc.)
- FRP is non-homogeneous.
- FRP does not have the same strength in all directions; these types of materials are called anisotropic.



Western Canal Strength Considerations Strengthening

Strengthening Approach

Post Construction Load Ratings

- Iterative Process
- Exterior Wall
- Bottom Slab

AASHTOWare BrR Results
Project: I-10 Broadway Curve
Model: Western Canal – Strengthened Structure

2' Fill Condition:

Live Load	Live Load Type	Rating Method	Inventory Load Rating (Ton)	Operating Load Rating (Ton)	Legal Load Rating (Ton)	Permit Load Rating (Ton)	Inventory Rating Factor	Operating Rating Factor	Legal Rating Factor	Permit Rating Factor	Inventory Component	Inventory Location (ft)	Inventory Location (%)	Operating Component	Operating Location (ft)	Operating Location (%)
HL-93 (US)	Axle Load	LRFR	48.61	63.01			1.350	1.750			Top Slab 1	11.20	80.000	Top Slab 1	11.20	80.000
HL-93 (US)	Tandem	LRFR	25.65	33.25			1.026	1.330			Ext. Wall 1	3.00	60.000	Ext. Wall 1	3.00	60.000

Inventory Limit State	Operating Limit State	Legal Limit State	Permit Limit State	Impact	Lane
Flexure	Flexure			As Requested	As Requested
Flexure	Flexure			As Requested	As Requested

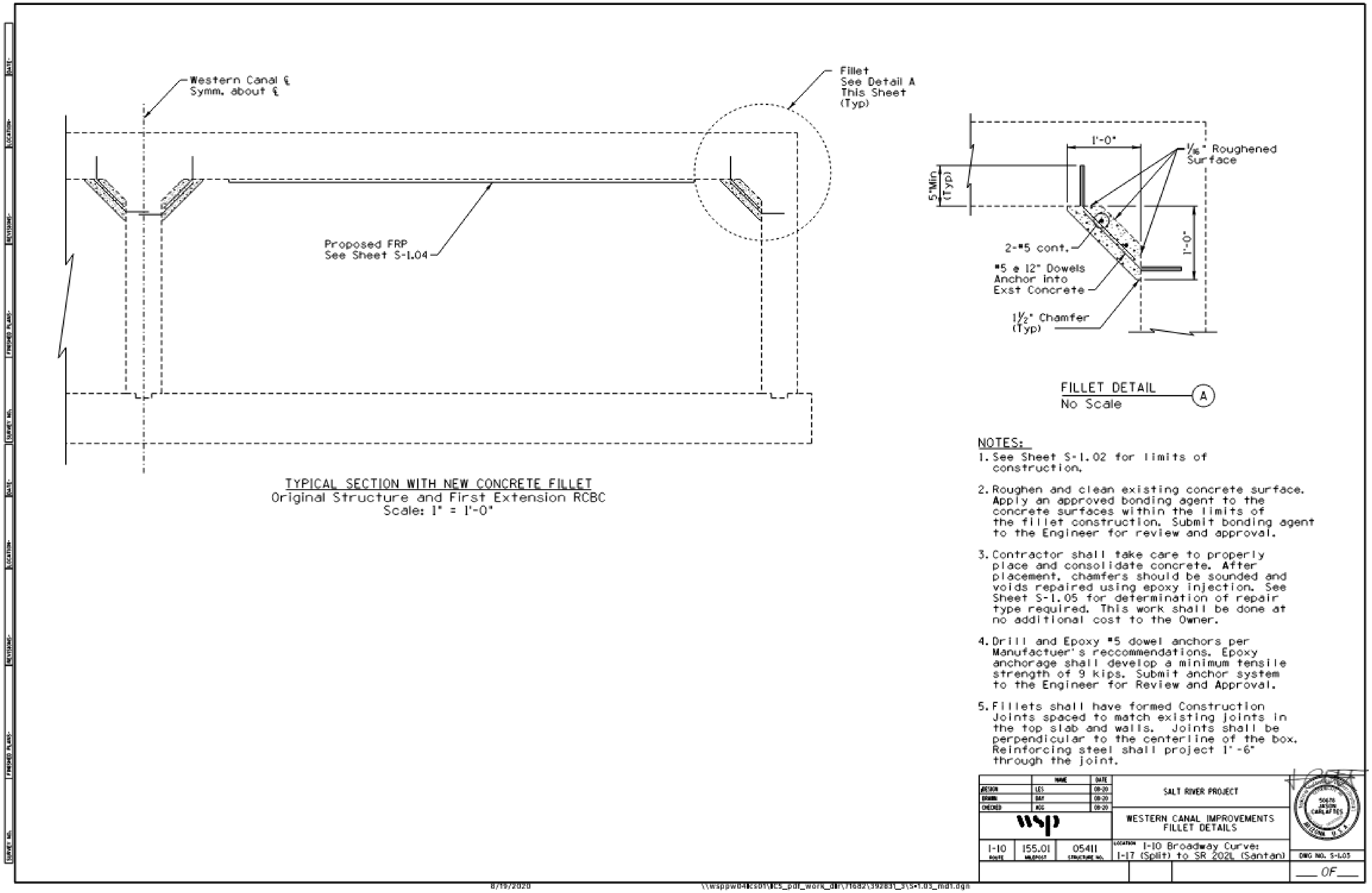
6' Fill Condition:

Live Load	Live Load Type	Rating Method	Inventory Load Rating (Ton)	Operating Load Rating (Ton)	Legal Load Rating (Ton)	Permit Load Rating (Ton)	Inventory Rating Factor	Operating Rating Factor	Legal Rating Factor	Permit Rating Factor	Inventory Component	Inventory Location (ft)	Inventory Location (%)	Operating Component	Operating Location (ft)	Operating Location (%)
HL-93 (US)	Axle Load	LRFR	71.08	92.14			1.974	2.560			Ext. Wall 1	3.00	60.000	Ext. Wall 1	3.00	60.000
HL-93 (US)	Tandem	LRFR	37.82	49.03			1.513	1.961			Ext. Wall 1	3.00	60.000	Ext. Wall 1	3.00	60.000

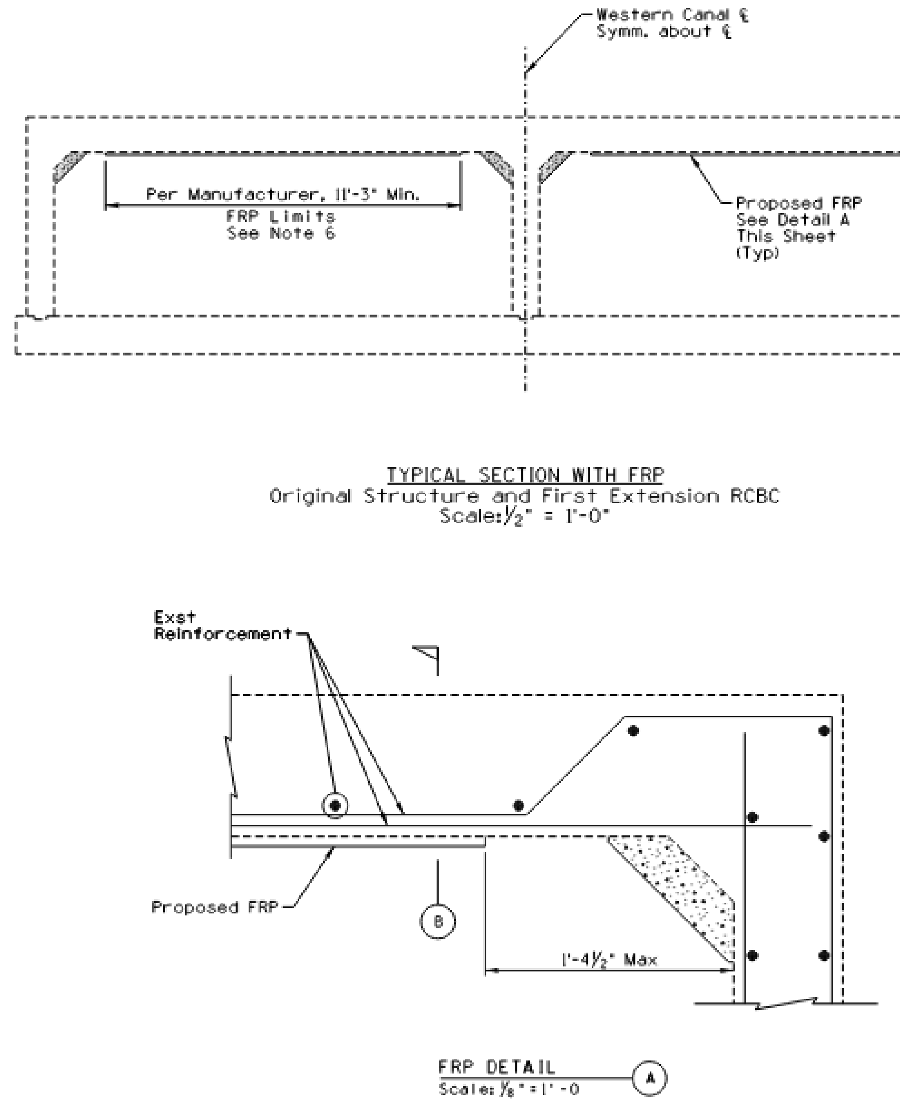
Inventory Limit State	Operating Limit State	Legal Limit State	Permit Limit State	Impact	Lane
Flexure	Flexure			As Requested	As Requested
Flexure	Flexure			As Requested	As Requested

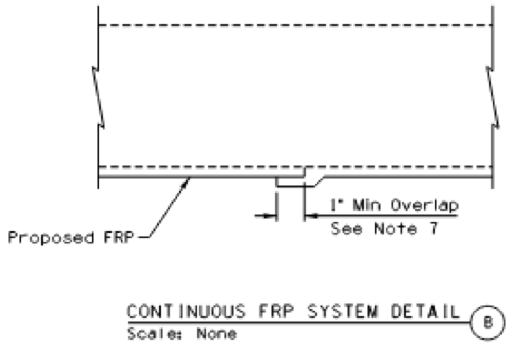
Western Canal Strength Considerations

Strengthening



Western Canal Strength Considerations





NOTES:

1. See Sheet S-1.02 for limits of construction.
2. Prior to installation of FRP material, any spalling or cracking of the culvert shall be repaired per Sheet S-1.05.
3. Clean the surface around the repair area. Surface shall be clean of laitance, oil, dust or debris prior to application of FRP material.
4. The FRP Strengthening system shall meet the requirement shown in the Construction Specifications. System shall be sumitted to the Engineer for review and approval prior to the ordering of any material.
5. System shall accomodate future drilled anodes as part of the future Cathodic Protection System.
6. Limits Shown are the minimum width of FRP to strengthen the positive moment region of the slab. The Fabricator shall ensure that the FRP system is fully developed within these limits and provides full strength capacity as noted in the special provisions.
7. A minimum overlap of 1" in the direction of the main fibers shall be provided as shown to maintain a continuous FRP system. FRP systems with discrete elements must show system provides strength along the entire length of culvert within the limits shown. Discrete systems must be approved by the Engineer. All systems shall be submitted for review and approval prior to ordering any materials. See the Special Provisions for additional information.

SALT RIVER PROJECT

WESTERN CANAL IMPROVEMENTS
FRP DETAILS

ROUTE	MILEPOST	STRUCTURE NO.	LOCATION	DWG NO.
I-10	155.01	05411	I-10 Broadway Curve: I-17 (Split) to SR 202L (Santan)	S-1.04

Conclusions

1. Base Schedule November 2020 to March 2021

a. Aggressive Schedule

b. FRP Construction with Vector Corrosion Services Selected

c. Salt River Project (Owner) Managed the Construction

d. WSP and VCS provided Post Design Services through ADOT

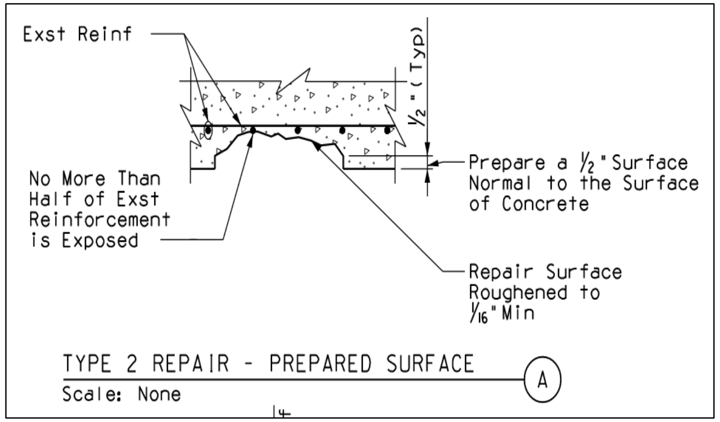
2. Base Repairs – Plan Vs Reality

APPROXIMATE QUANTITIES	
Class "S" Concrete (Fillet Only)	Reinforcing Steel
CY	LBS
29	2045

Galvanic Cathodic Protection by Bulk Anodes...348 EA
Embedded Galvanic Anodes, Type 1A Class C........750 EA
Embedded Galvanic Anodes, Type 2A Class C.......175 EA
Miscellaneous Work (FRP Strengthening)...........382 LF

Type 1, 2 and 3 repair quantities shall be determined in the field. Quantities shown are for estimating purposes only. Items will be paid for actual quantities determined in the field.

Miscellaneous Work (Type 1 Repair) .... 50 LF
Miscellaneous Work (Type 2 Repair)......................... 600 SF
Miscellaneous Work (Type 3 Repair)......................... 150 SF



- **Repairs took 2 ½ months and $1.3M**
- **Estimated replacement cost $25M**

Thank You!

ADOT Project Team
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ADOT Bridge Engineer – Noon Viboolmate, PE
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FRP Construction Team | QuakeWrap Design Tea
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Questions?