Applications of Non-Destructive Evaluation (NDE) for Detection, Ranking and Quantifications of Deterioration

Prestressed Concrete Box Beams
Reinforced Concrete Bridge Decks

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Concrete Deterioration Due to Corrosion of Prestressed Strands and Rebar

Corrosion of steel & concrete spalling

Box beam deterioration due to corrosion of prestressing strands and steel reinforcement

Lake View Drive Bridge failed under service loads

Boston.com; December 27, 2005; State Route 1014 over Interstate 70 in Washington County, PA

Lake View Drive Bridge

Forensic examination

- Fabrication errors: inadequate bottom flange thickness, bottom concrete cover as well as wall thickness
- High chloride levels and carbonation.
- Clogged drain holes
- Strand exposures and ruptures due to collision and corrosion damage

Other damage:

- Longitudinal cracking near bottom strand
- Exposure, corrosion , and fracture of prestressing strands
- Spalling of bottom concrete cover
- Efflorescence as well as leakage of water between beams.

Naito et al.' Forensic Examination of a Noncomposite Adjacent Precast Prestressed Concrete Box Beam Bridge,' ASCE JOURNAL OF BRIDGE ENGINEERING JULY/AUGUST 2010

Presentation Goal

- PART 1:
  - Demonstrate how to combine results from multiple NDE methods to estimate remaining service life of reinforced concrete bridge decks

- PART 2:
  - Demonstrate effectiveness of multiple NDE methods to evaluate the condition of reinforced and prestressed concrete beams

NDE Methods

- Visual Inspection (naked eye & microscope)
- Ultrasound
- Magnetic Flux Leakage
- Half Cell Potential
- Impact Hammer
- Chloride Profiles
- pH Profiles

MDOT Funded Research Projects

- Investigating Causes and Determine Repair Needs to Mitigate Falling Concrete from Bridge Decks (completed)
- Evaluating prestressing strands and post-tensioning cables in concrete structures using nondestructive evaluation (NDE) including joint shear wave analysis (active)

Presentation Overview

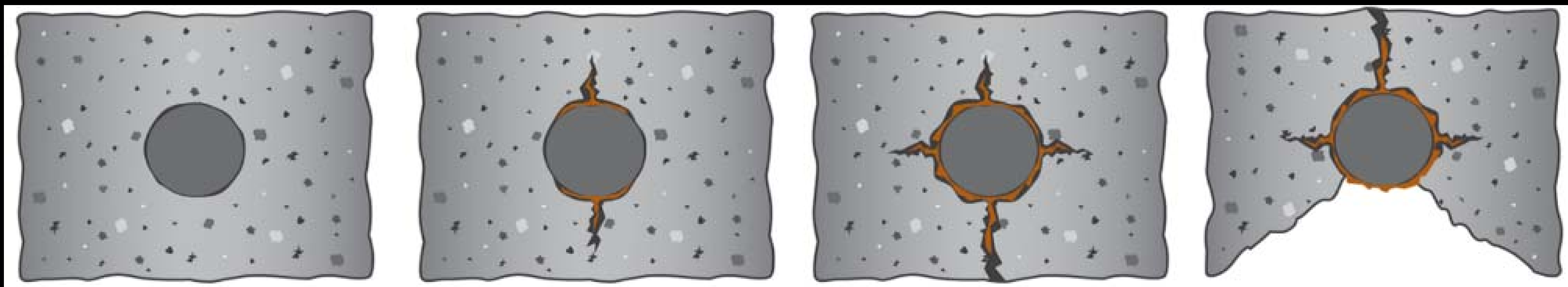
- PART 1:
  - Demonstrate how to combine results from multiple NDE methods to estimate remaining service life of a reinforced concrete bridge decks

Presentation Overview (Part 1)

- To develop performance based thresholds and procedures to identify concrete bridge decks experiencing high risk for falling concrete

- Scope
  - Laboratory investigation to quantify the concrete corrosive environment leading to the development of concrete degradation and steel corrosion
    - freeze-thaw & salt-water exposure
    - repeated loading.
  - Field exploration to quantify in-service degradation of bridge decks

Corrosion Development



- Corrosion rates up to 100 μm/year
- Critical chloride levels in concrete
  - 5 ± 4 lbs/cyd for black steel
  - 8 ± 7 lbs/cyd for epoxy coated steel
- Concrete pH levels < 9.5 corrosion initiates – destruction of passive layer around rebar

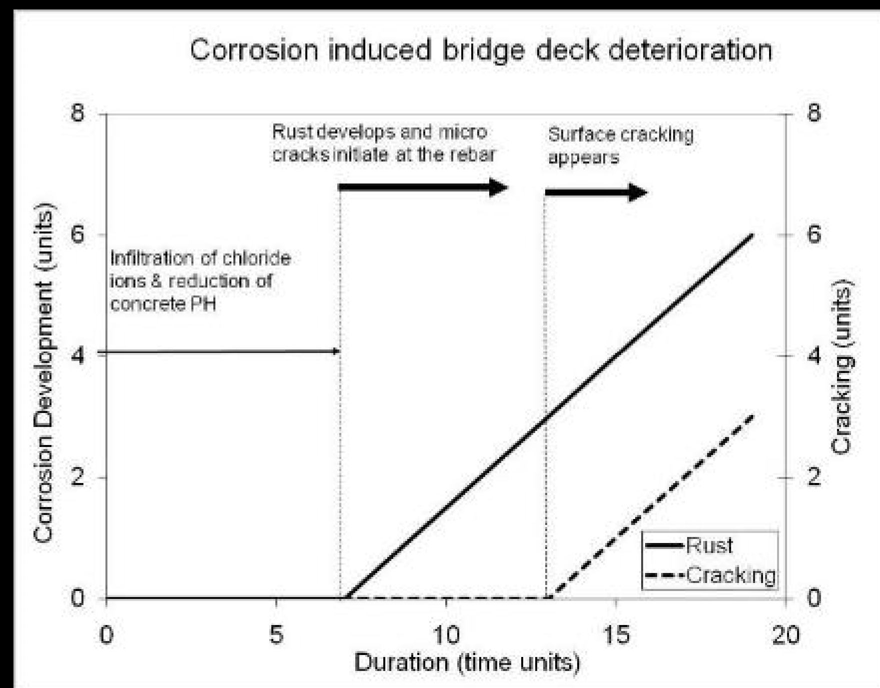
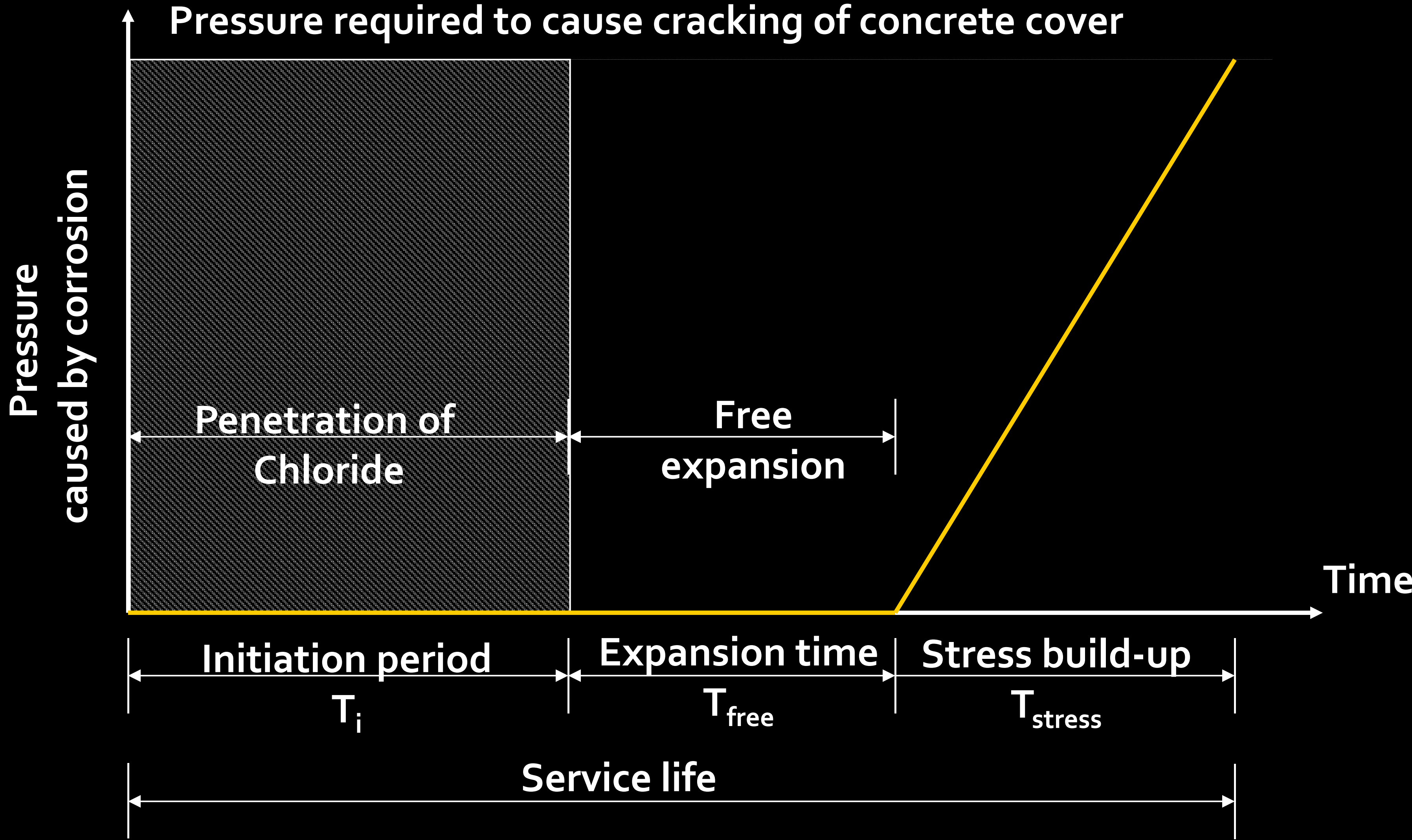


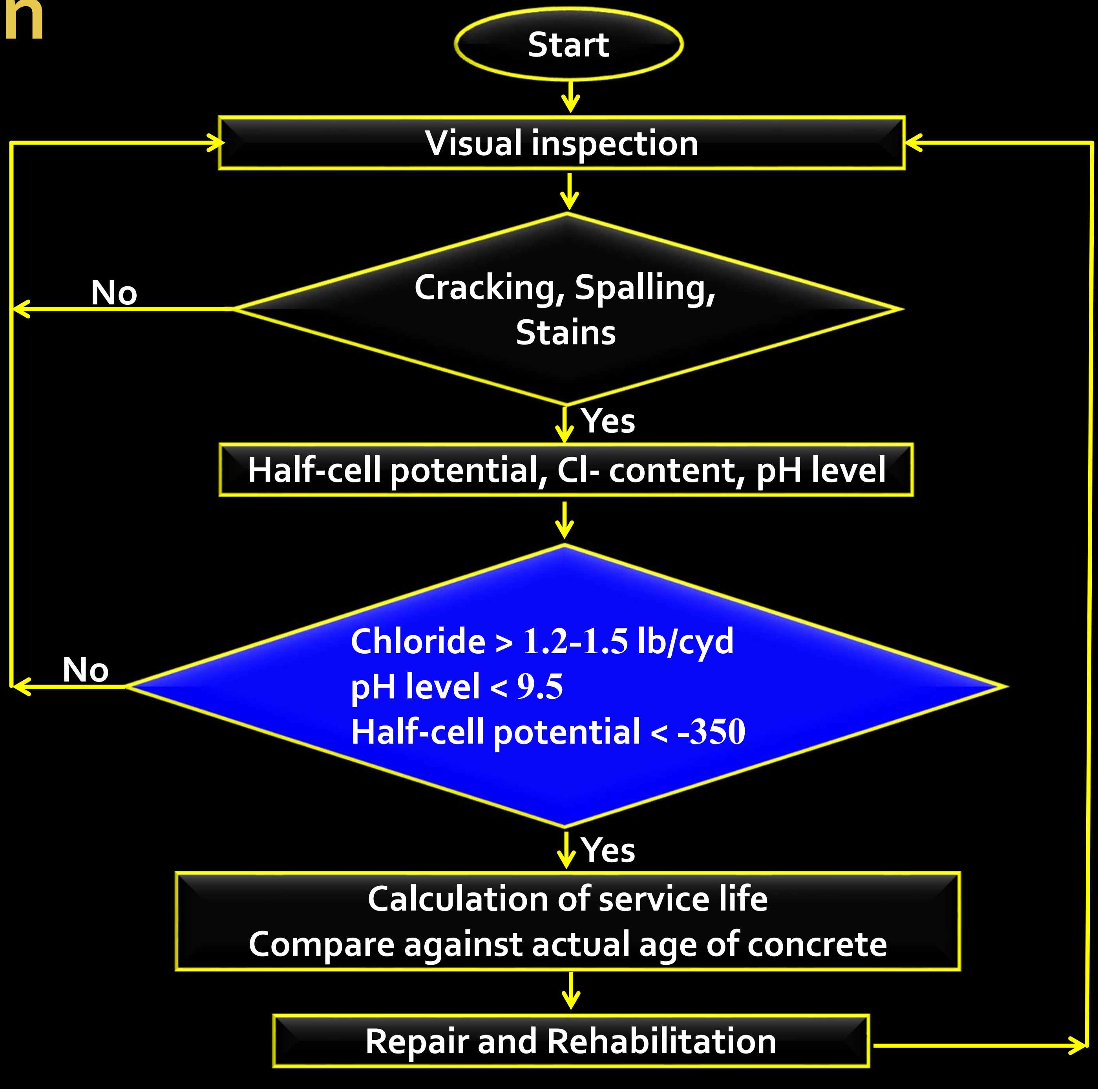
Image adapted from http://frpdistributors.com

Service Life Model of Bridge Deck



Implementation Strategy

- To assess the timing of future maintenance and repair activities



Initiation Time

- Fick's second law of diffusion

Chloride content at a depth of x and time t is given by:

$$C(x,t) = C_i + (C_s - C_i)\,\mathrm{erfc}\frac{x}{\sqrt{4tD}}$$

Initial chloride content (C_i)

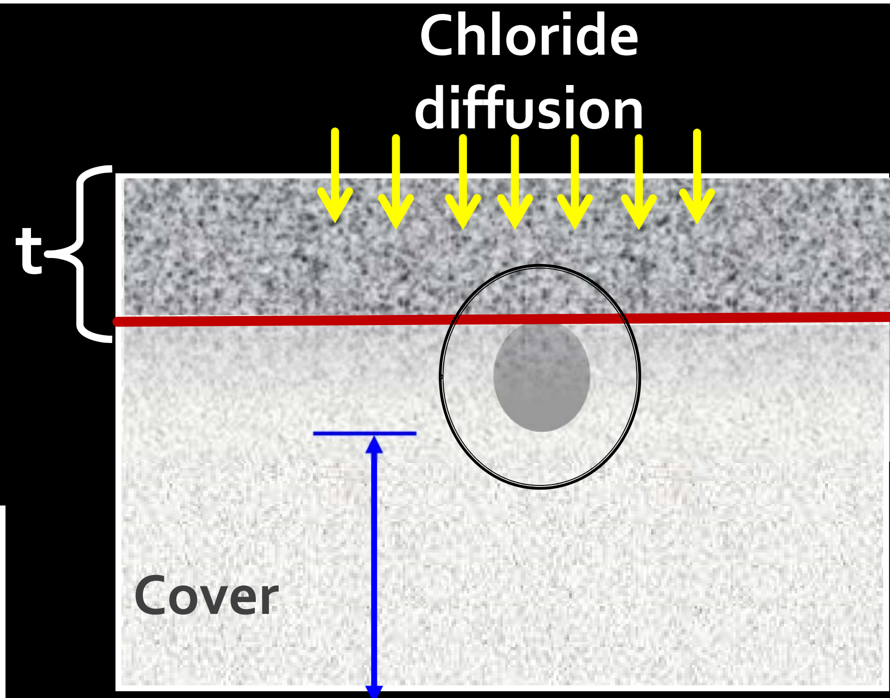
Error function (erfc)

Depth (x)

Chloride content of exposed surface (C_s)

Time (t)

Diffusion coefficient (D)



C_i= 0.2 lb/cyd from regression analysis

Time from Corrosion Initiation to Corrosion Cracking

$$T_{cr} = \left[\frac{7117.5\left(D+2\delta_0\right)\left(1+\nu+\varphi\right)}{iE_{ef}} \right] \left[\frac{2Cf_{ct}}{D} + \frac{2\delta_0 E_{ef}}{\left(1+\nu+\varphi\right)\left(D+2\delta_0\right)} \right]$$

- Diameter of rebar
- Porous zone thickness
- Poisson's ratio
- Concrete effective elastic modulus
- Corrosion current density
- Factor depending on D, C and δ_o
- Concrete cover

T E Maaddawy and K Soudki, **"A model for prediction of time from corrosion initiation to corrosion cracking"**, Cement & Concret Composites 29 (2007) 168–175.

Field Investigation

I-75 NB over 14 Mile Rd

1963 Constructed
1970 Lane added
1994 Overlay
ADT 111,000
Deck rating 4 (poor)
Non-epoxy coated bars

I-96 WB over Milford Rd

1957 Constructed
1965 Lane added
1994 Overlay
ADT 101,300
Deck rating 4 (poor)
Non-epoxy coated bars

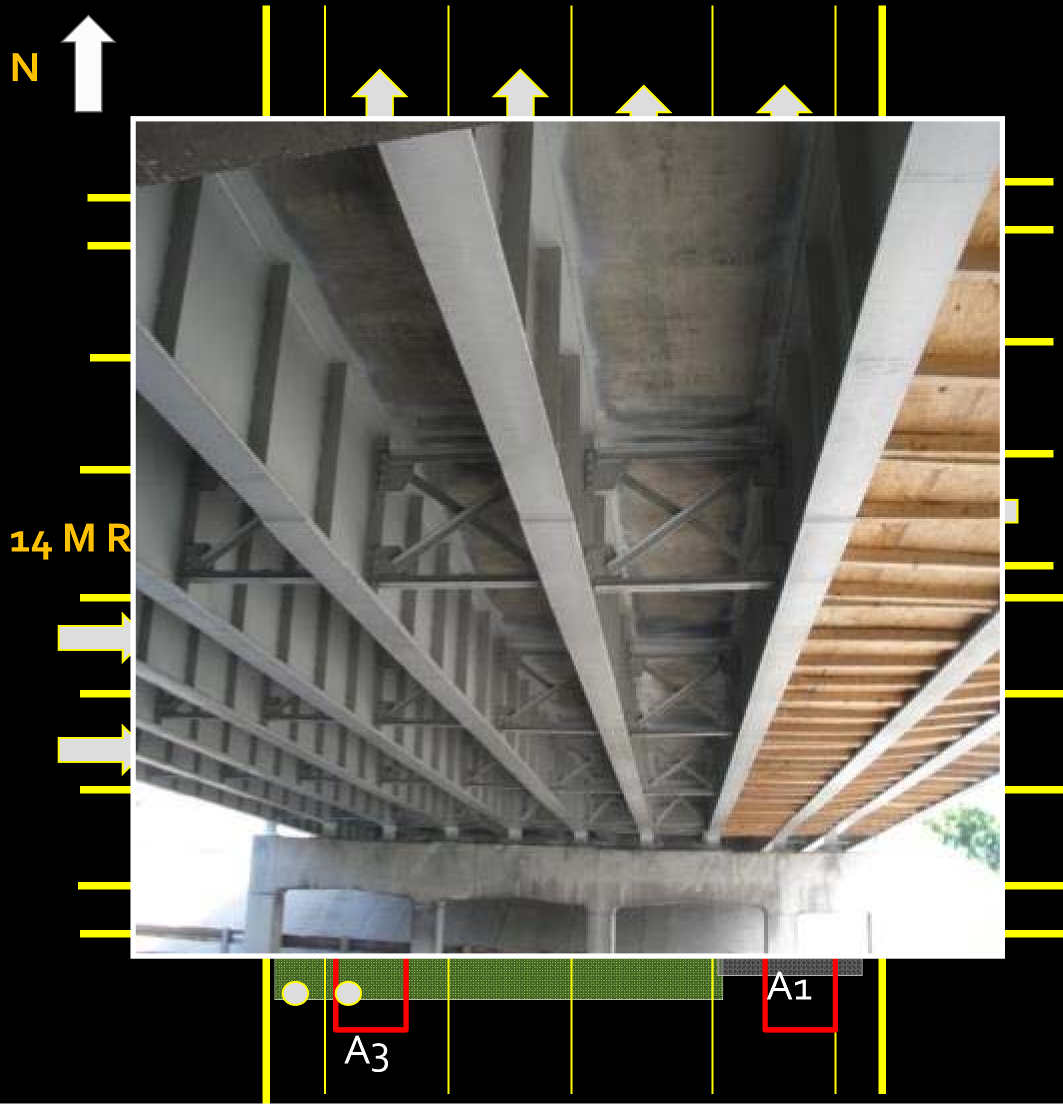
I-96 WB over Kent Lake Rd

1948 Constructed
1967 Lane added
1989 Overlay
ADT 101,300
Deck rating 3 (serious)
Non-epoxy coated bars

I-75 NB over 14 Mile Rd, Troy, MI

Source: Wikimapia.org

63174-S05-1 I-75 NB 14 Mile Rd



LEGEND

A1: NDT over walk path and embankment

A2: NDT over EB 14 Mile Rd

A3 : NDT over walk path and embankment

: Coring location

:Plywood cover & degradation of concrete

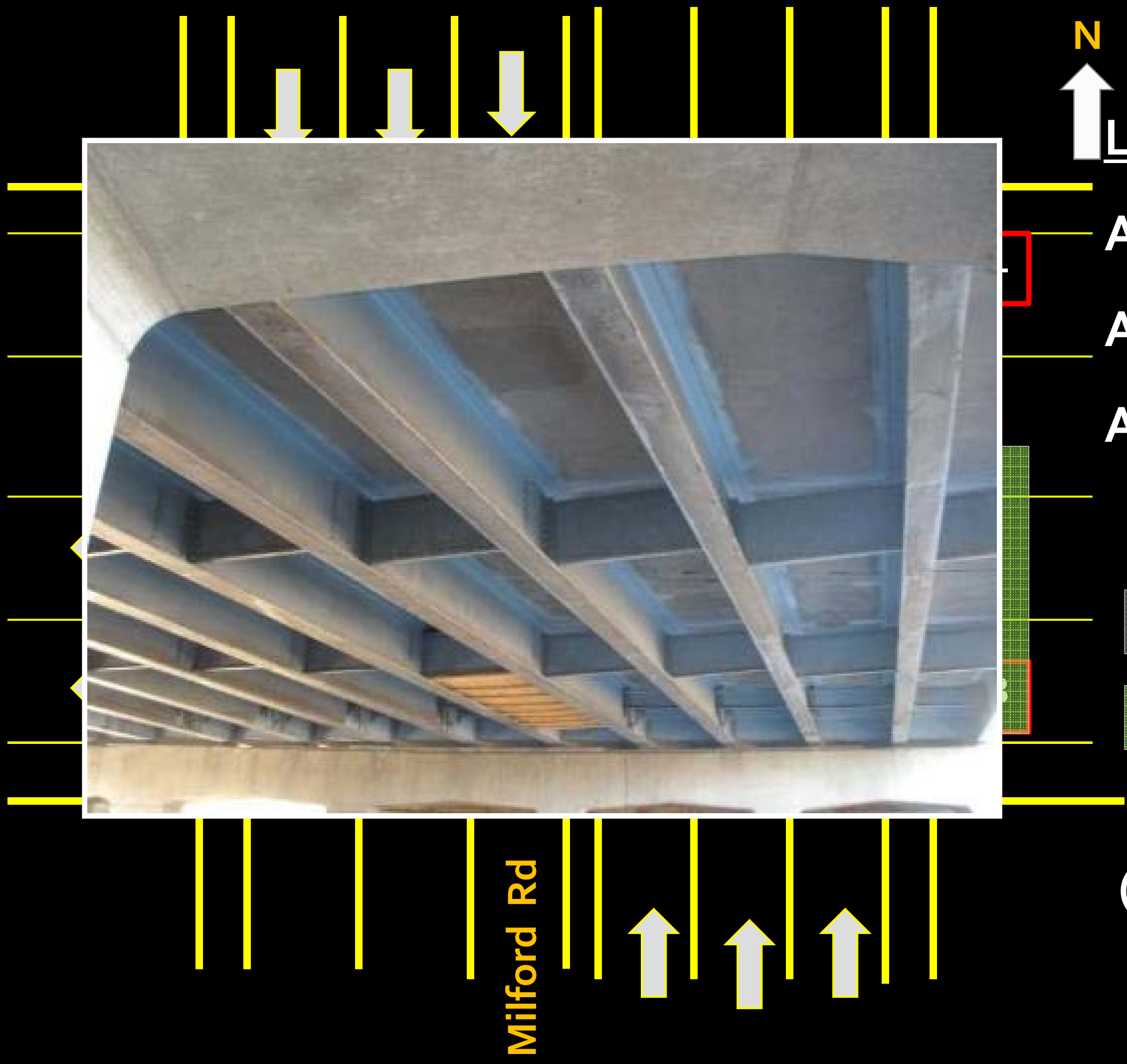
: Good condition of concrete

(Areas A1 and A2 are on outer lane)

I-96 over Milford Rd, East New Hudson, MI

Source: Google maps

3022-S02-3 I-96 WB Milford Rd



LEGEND

A1: NDT over walk path and embankment

A2: NDT over NB Milford Rd

A3 : NDT over walk path and embankment

: Plywood

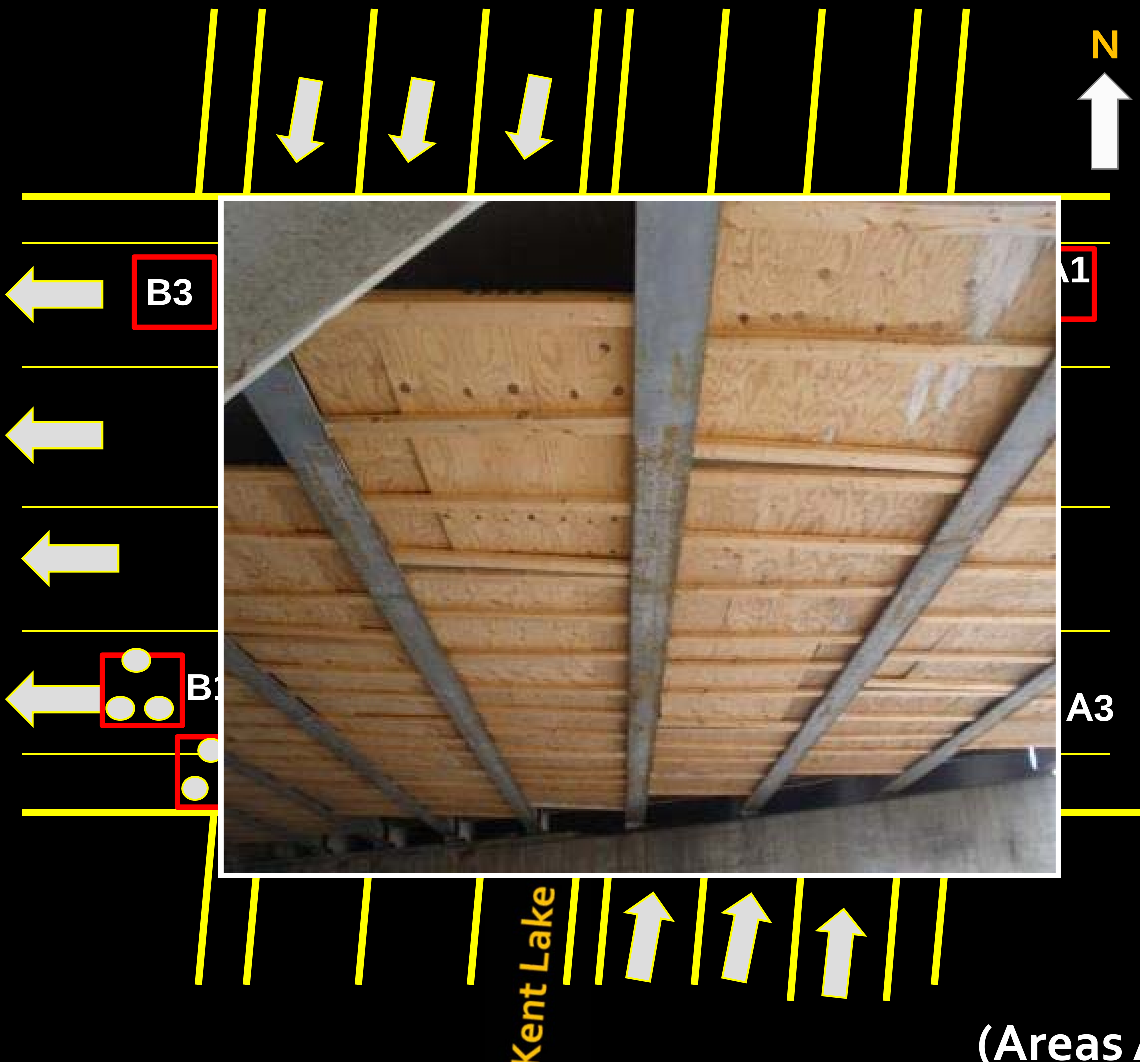
: Good concrete condition

(Areas A1 and A2 are on outer lane)

I-96 over Kent Lake Rd, South Lyon, MI

Source: Google maps

63022-S01 I-96 Kent Lake Rd



LEGEND

A1: NDT over walk path & embankment

A2: NDT over walk path & embankment

A3 : NDT over walk path & embankment

B1 : NDT over walk path & embankment

B2 : NDT over walk path & embankment

B3 : NDT over walk path & embankment

● : Coring location

▩ : Plywood cover, deck in poor condition

(Areas A1 , A2 and B3 are on outer lane)

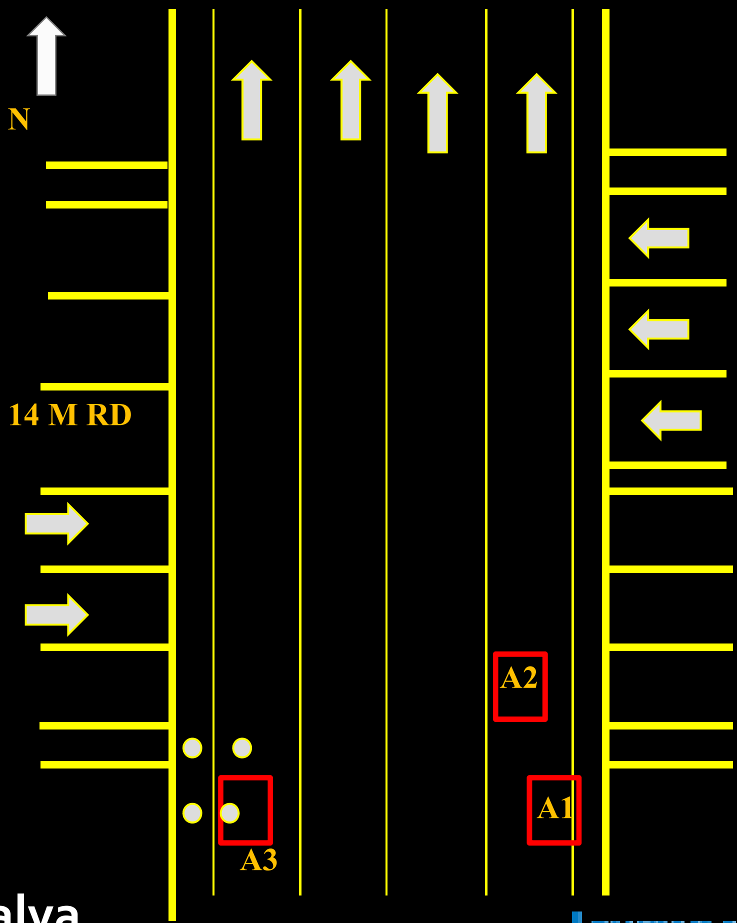
Chance of Corrosion of I-75 NB over 14 Mile Road

Location	A1	A2	A3
Average half-cell potential (mV)	-315	-220	-150
Corrosion rate (µm/year)	78	36	20
COV (%)	13.4	14.4	9.1
Chance of rebar corrosion	50%	50%	5%
# of data points	36	36	36

COV : Coefficient of variation

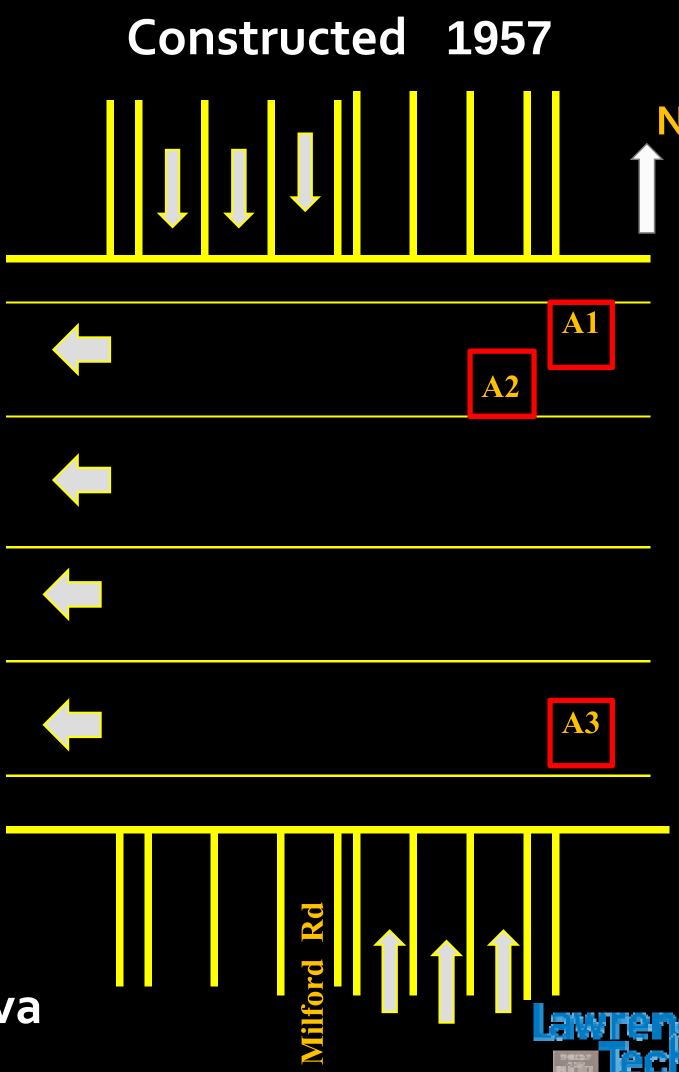
Corrosion rate is based on relationship of CANIN and Galva Pulse obtained from laboratory specimen

Constructed 1963/70



Chance of Corrosion of I-96 WB over Milford Rd

Location	A1	A2	A3
Average half-cell potential (mV)	-405	-400	-368
Corrosion rate (µm/year)	>120	>120	114
COV (%)	4.5	7.6	7.3
Chance of rebar corrosion	95%	95%	95%
# of data points	36	36	36



COV : Coefficient of variation

Corrosion rate is based on relationship of CANIN and Galva Pulse obtained from laboratory specimen

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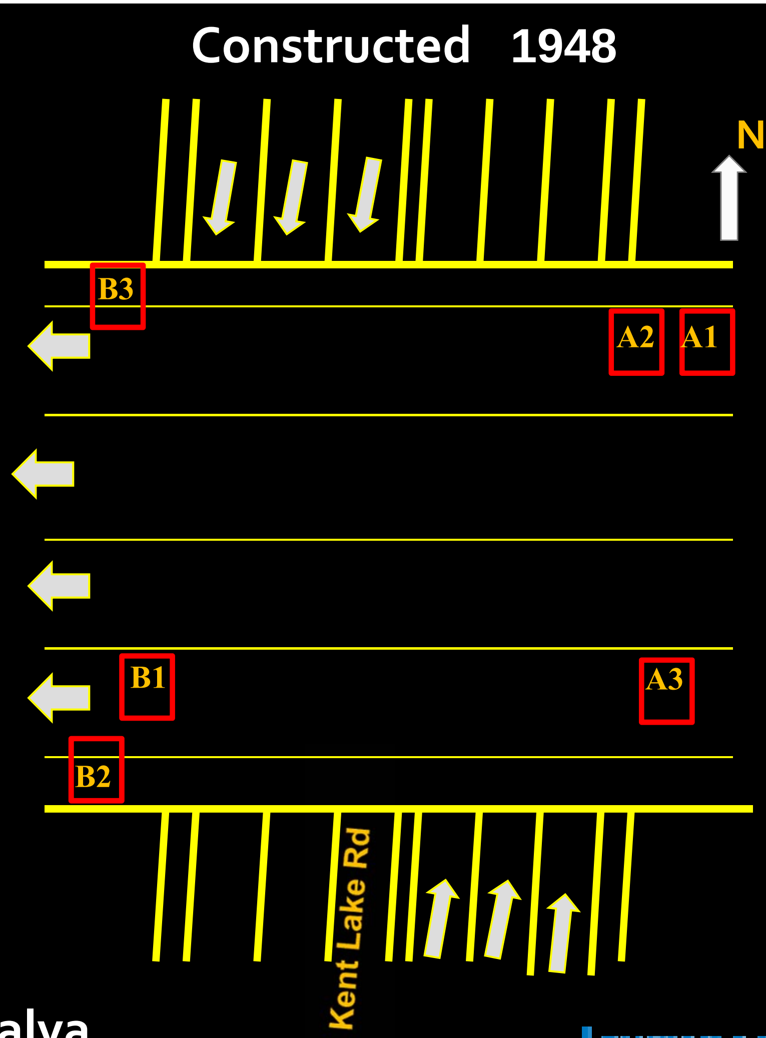
Chance of Corrosion of I-96 WB over Kent Lake Rd

Location	A1	A2	A3	B1	B2	B3
Average half-cell potential (mV)	-411	-406	-344	-207	-397	-547
Corrosion rate (µm/year)	>120	>120	97	42	110	>120
COV (%)	18.1	15.3	12.7	12	15.9	8.7
Chance of rebar corrosion	95%	95%	50%-95%	50%	95%	Visible evidence
# of data points	36	36	36	36	36	36



COV : Coefficient of variation

Corrosion rate is based on relationship of CANIN and Galva Pulse obtained from laboratory specimen

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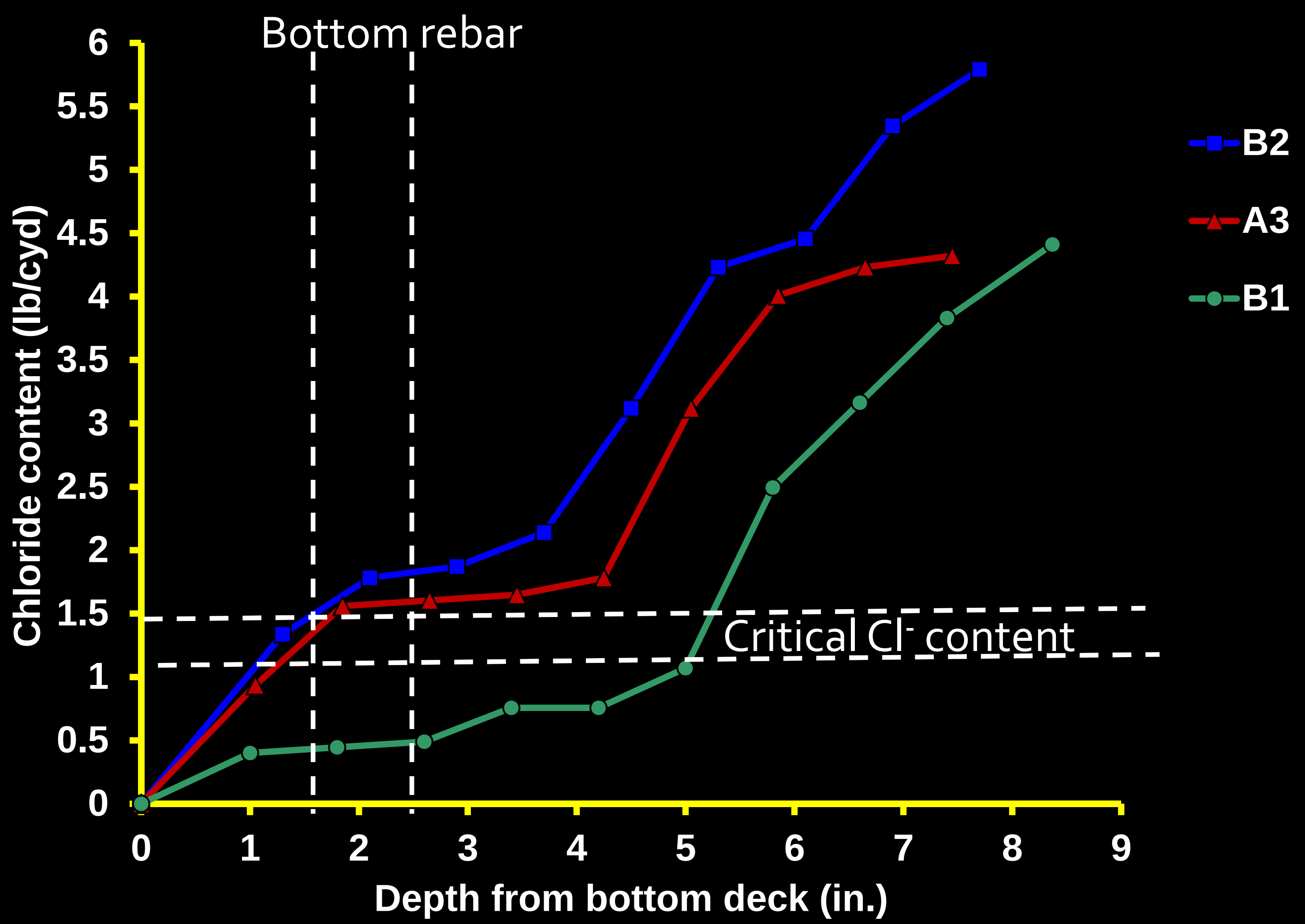
Chloride Content of I-96 WB over Kent Lake Rd (Cores)



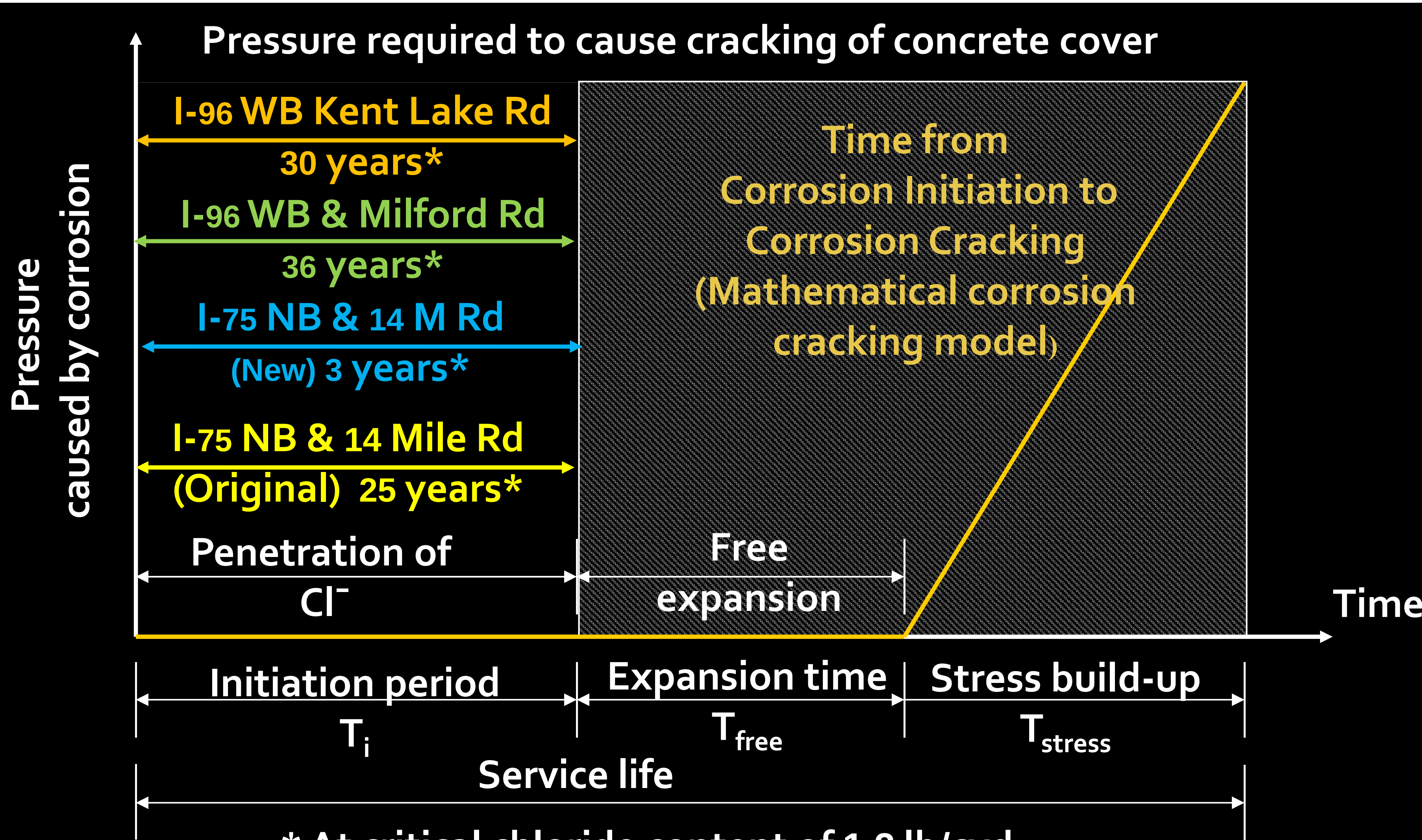
Exposed Surface Chloride Content

Bridge	Area	Chloride content (%) by weight	Surface chloride content (lb/cyd)
I-75 NB over 14 Mile Road (most left lane)	A3	0.613	2.5
I-96 WB over Kent Lake Road (most left lane)	B1	0.114	4.6
I-96 WB over Kent Lake Road (inside shoulder)	B2	0.143	5.8
I-96 WB over Kent Lake Road (most left lane)	A3	0.109	4.4

Average Diffusion Coefficient (from Exposure to Sampling Duration)

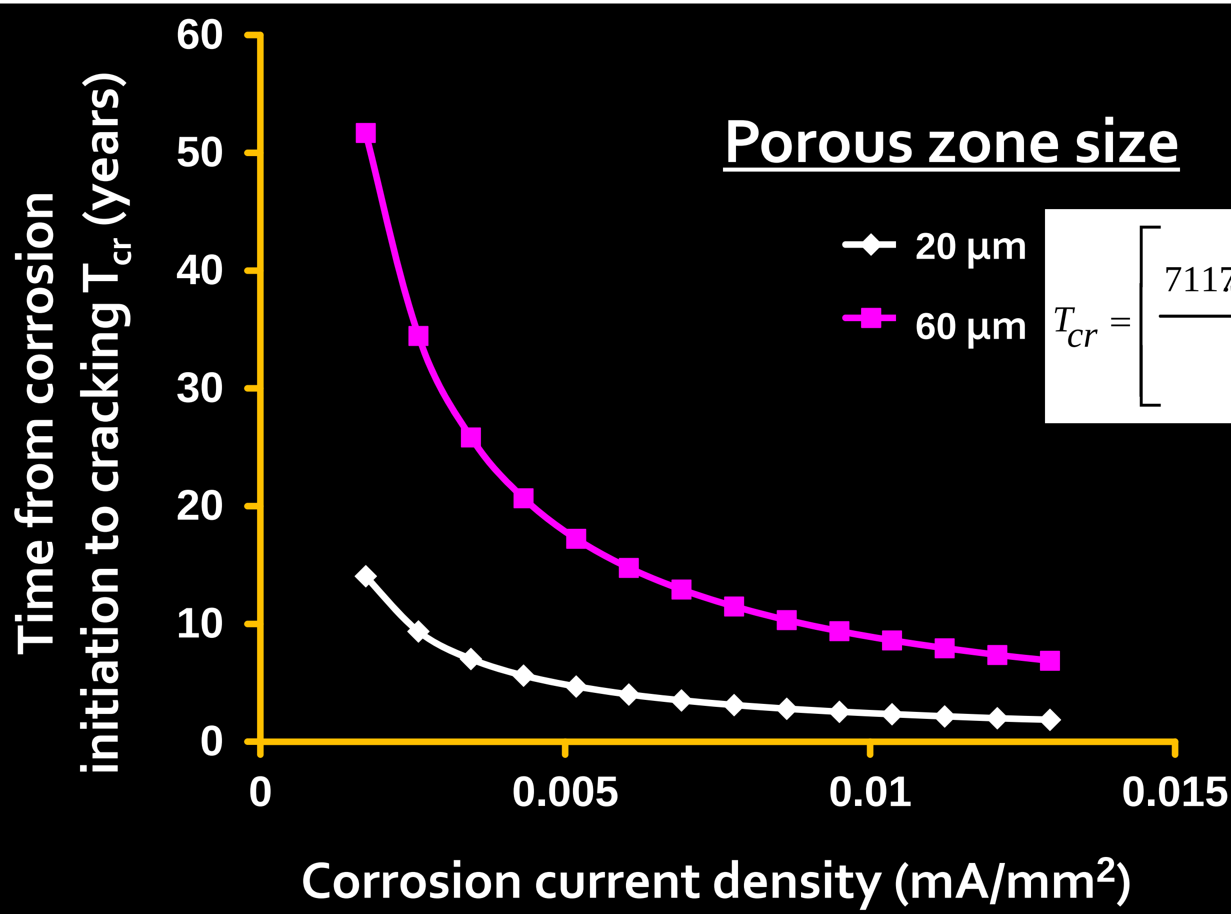
Bridge	Area	Average D (mm^2/s)	Ti (years) for 1.2 lb/cyd
I-75 NB over 14 Mile Road	A1	1.32×10^{-04}	3.0
	A2	1.59×10^{-05}	25.5
	A3	1.65×10^{-05}	24.5
I-96 WB over Milford Road	A1	1.51×10^{-05}	27.0
	A2	9.79×10^{-06}	42.0
	A3	1.04×10^{-05}	39.0
I-96 WB over Kent Lake Road	A1	1.33×10^{-05}	31.0
	A2	7.59×10^{-06}	44.0
	A3	8.64×10^{-06}	38.5
	B1 (core)	8.02×10^{-06}	41.5
	B2 (core)	3.3×10^{-05}	12.5

Corrosion Initiation Time Summary



* At critical chloride content of 1.2 lb/cyd

Relationship between Corrosion Current Density & Time from Corrosion Initiation to Cracking



$$T_{cr} = \left[\frac{7117.5 \left(D + 2\delta_0\right)\left(1 + \nu + \varphi\right)}{iE_{ef}} \right] \left[\frac{2Cf_{ct}}{D} + \frac{2\delta_0 E_{ef}}{\left(1 + \nu + \varphi\right)\left(D + 2\delta_0\right)} \right]$$

Parameters

Dia of rebar = 16 mm

Cover = 38 mm

E of concrete = 29,000 MPa

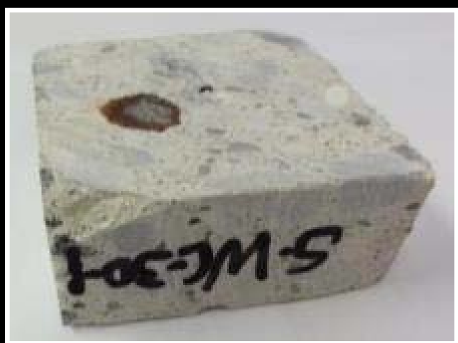
Poisson's ratio = 0.2

Tensile strength = 5 MPa

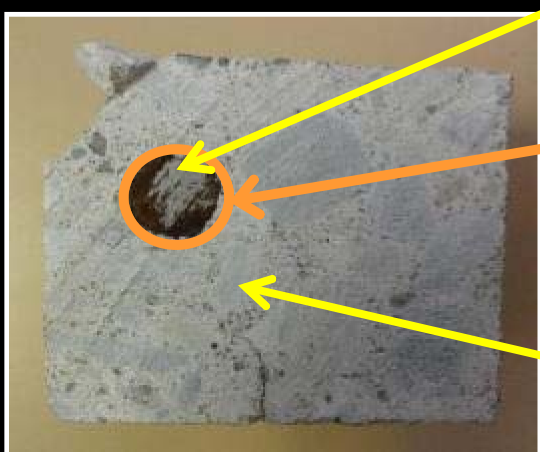
Density of steel = 7.85 g/cc

Density of rust = 5.2 g/cc

Porous Zone Size



3.0″ x 3.0″ x 1.5″
Sample cut

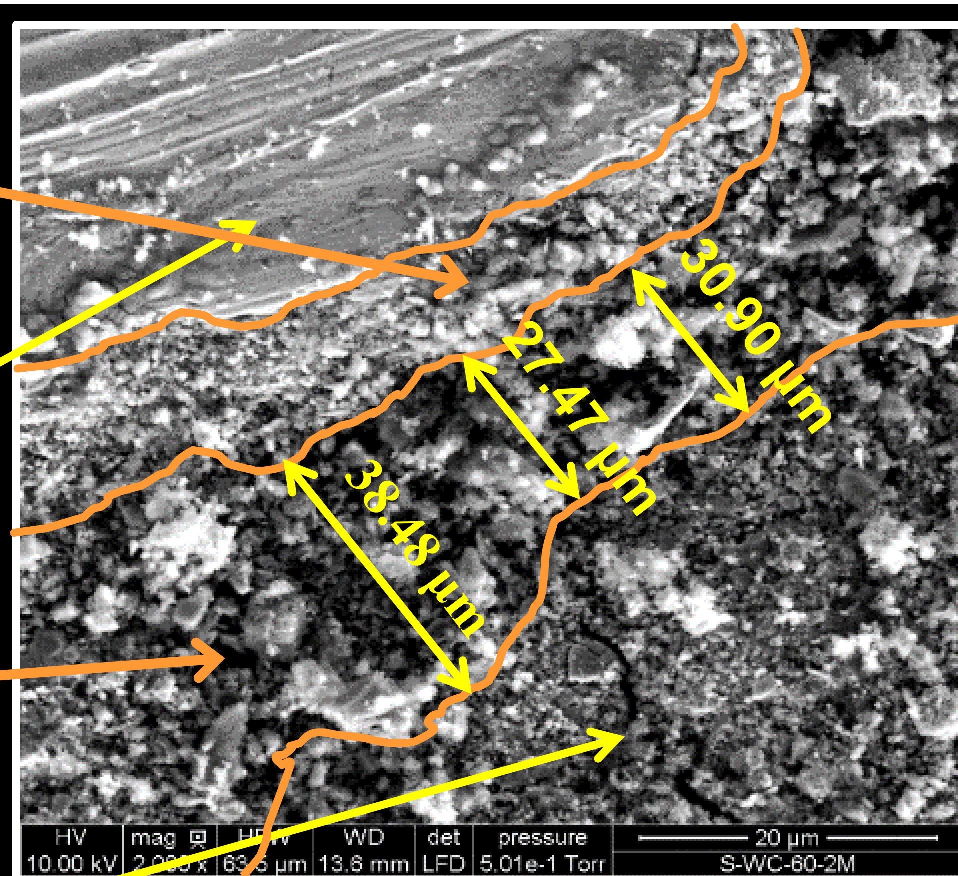


Corrosion products

Rebar

Porous zone (at interfacial)

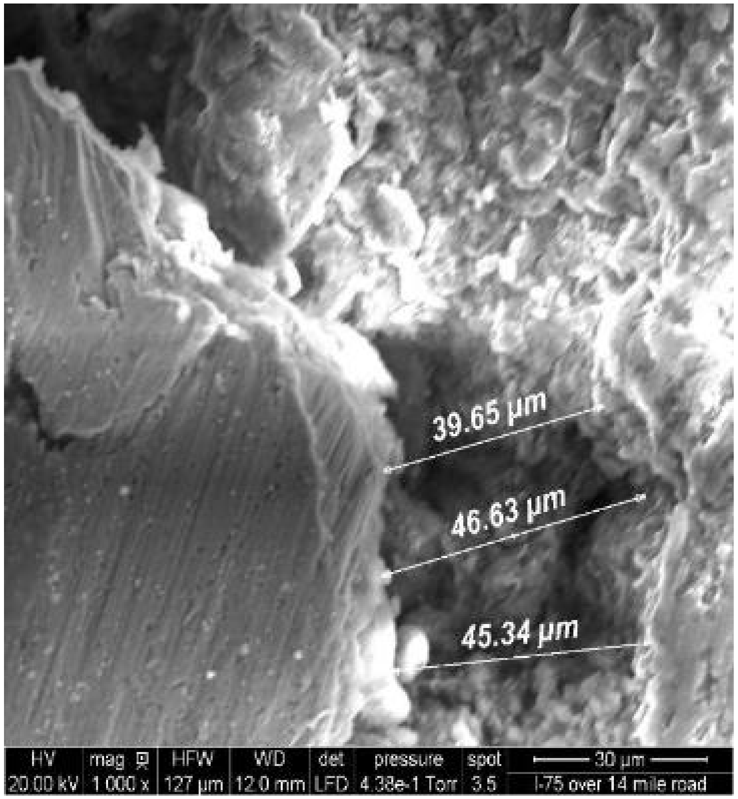
Concrete



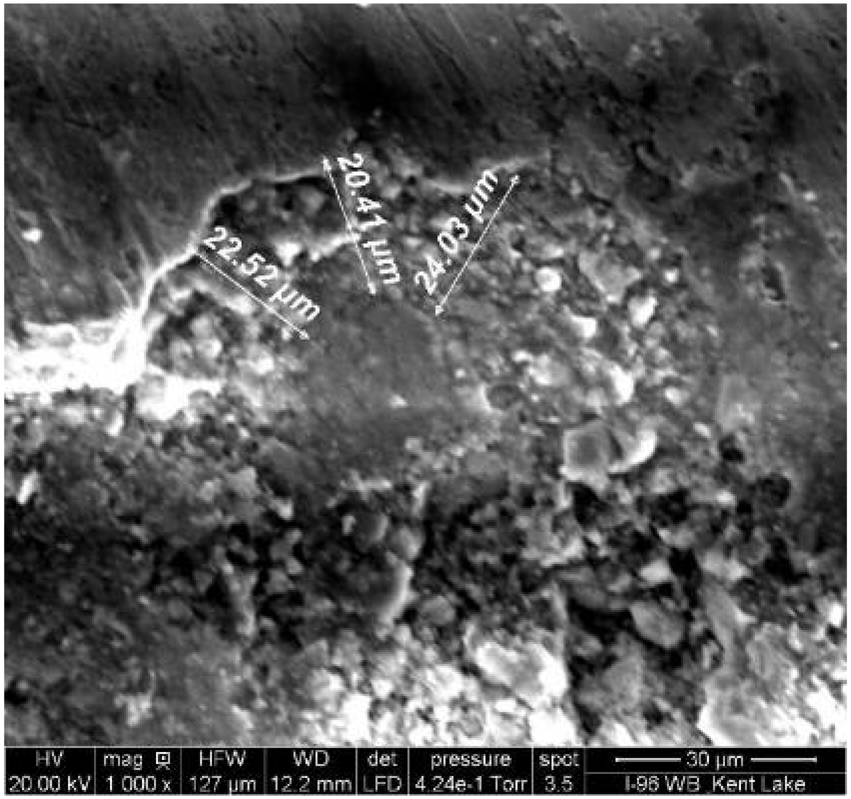
2,000X magnified & examined using Environmental Scanning Electron Microscope

The thickness of the porous zone is typically considered in the range of 10-60 µm

Porous Zone Size for Field Investigated Bridges



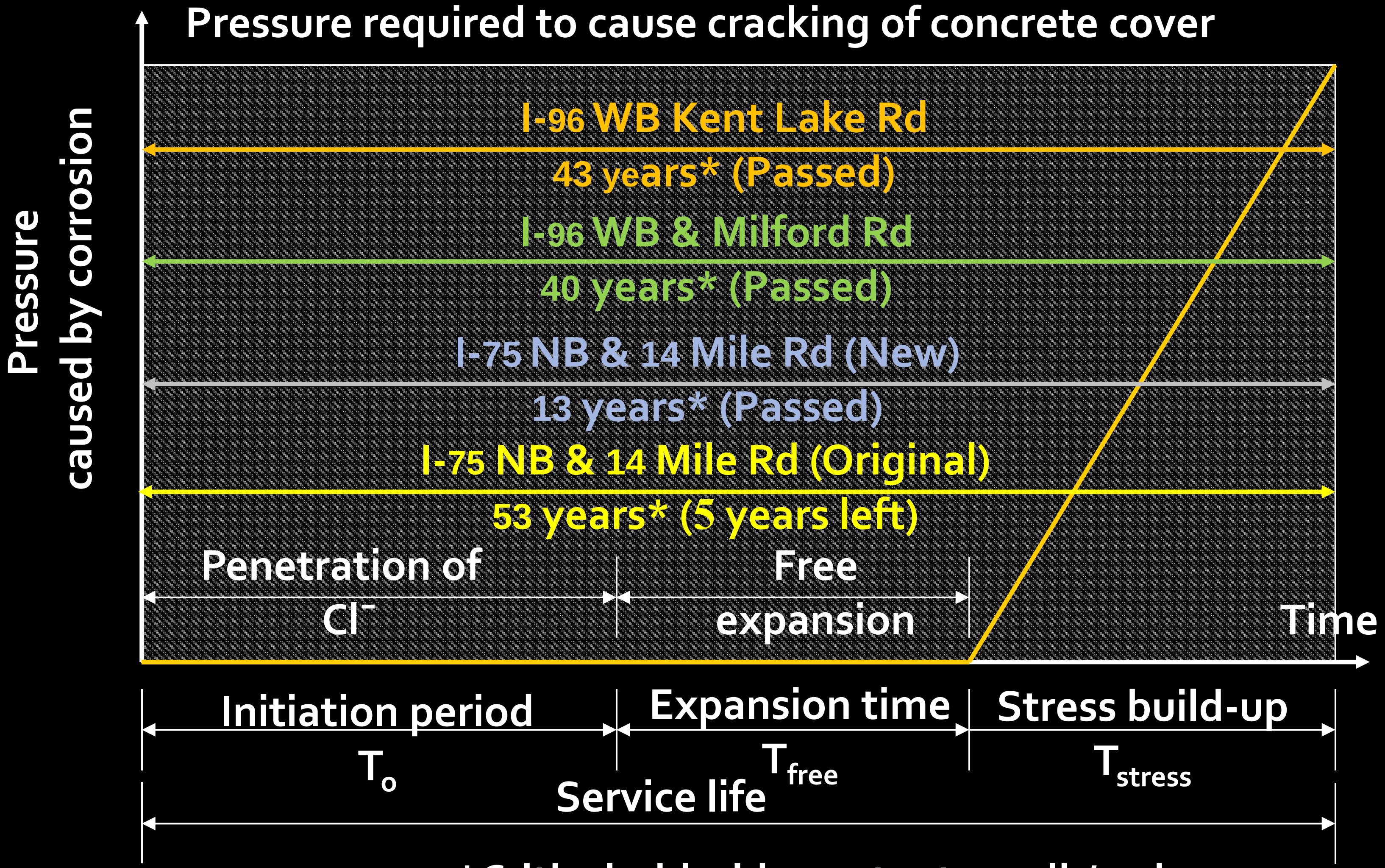
I-75 NB over 14 Mile Road
(43 µm)



I-96 WB over Kent Lake Road
(22 µm)

- A porous zone range of 20-40 µm (30 µm on average) recommended to be used for field bridges

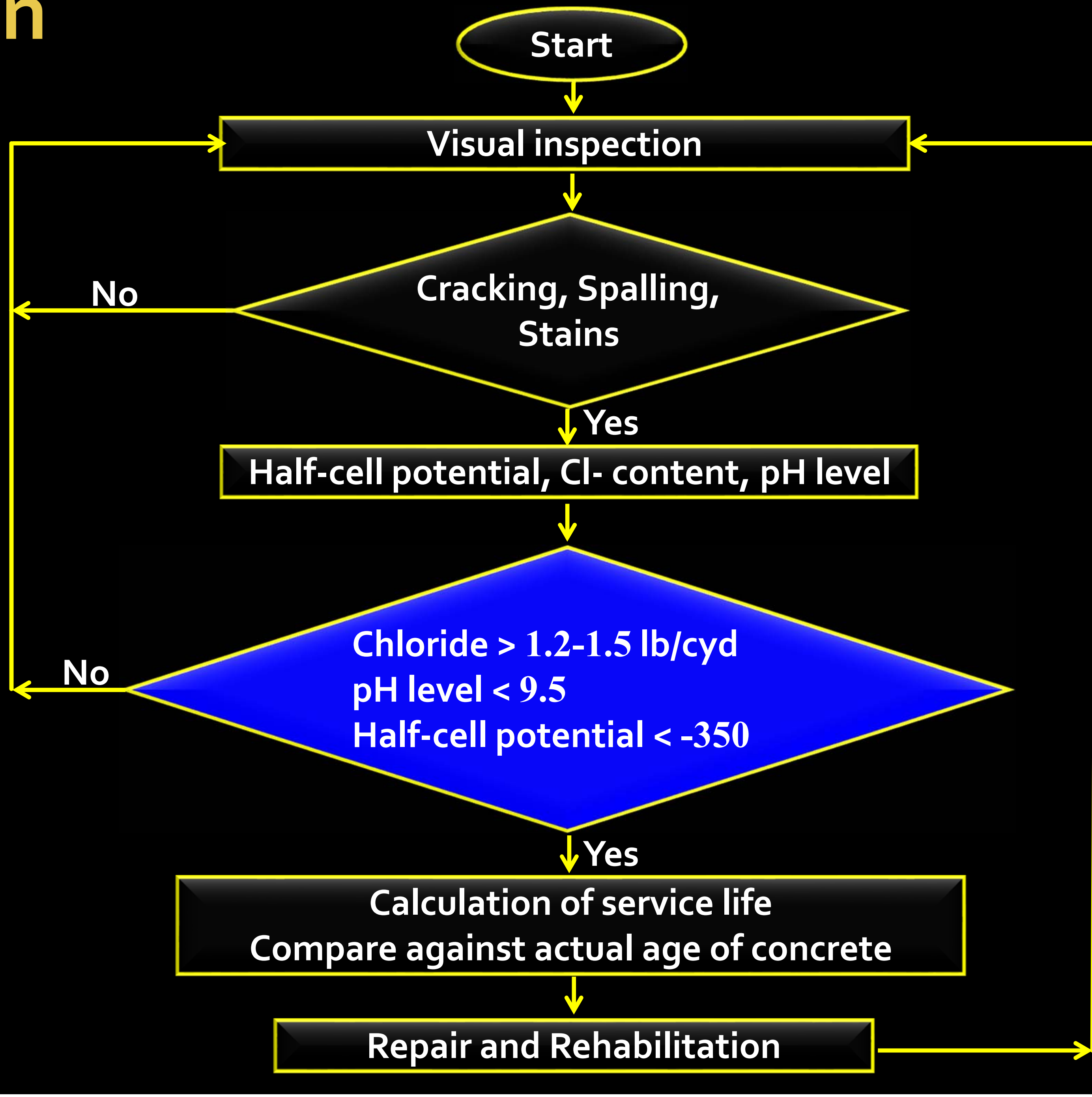
Service Life Summary



*Critical chloride content =1.2 lb/cyd

Implementation Strategy

➢ To assess the timing of future maintenance and repair activities



Active research project (Part 2)

- Evaluate effectiveness of multiple NDE methods to evaluate the condition of reinforced and prestressed concrete beams

- Scope
  - Laboratory calibration for detection and quantification of defects associated with corrosion of steel reinforcement and grout defects in post-tensioning applications
  - Field investigation to evaluate the effectiveness of selected NDE methods to detect and quantify deterioration


91753

Overview of Plainfield Bridge #6, Chidsdale Avenue

Plainfield Bridge #6 in Chidsdale Avenue before decommission. Wearing surface in Fair condition according to MDOT inspection rating.

Overview of Plainfield Bridge #6, Chidsdale Avenue

Box beams showing signs of deterioration. Exterior box beam showing spalling and exposed bottom strand.

Overview of Plainfield Bridge #6, Chidsdale Avenue

Exterior box beam showing spalling and exposed transverse reinforcement.

Overview of Plainfield Bridge #6, Chidsdale Avenue

Underside of box beams showing spalling and exposed bottom strands and transverse reinforcement.

Decommissioning Plainfield Bridge #6, Chidsdale Avenue.

Exterior box beam being decommissioned

Decommissioning Plainfield Bridge #6, Chidsdale Avenue.

Interior box beam being decommissioned

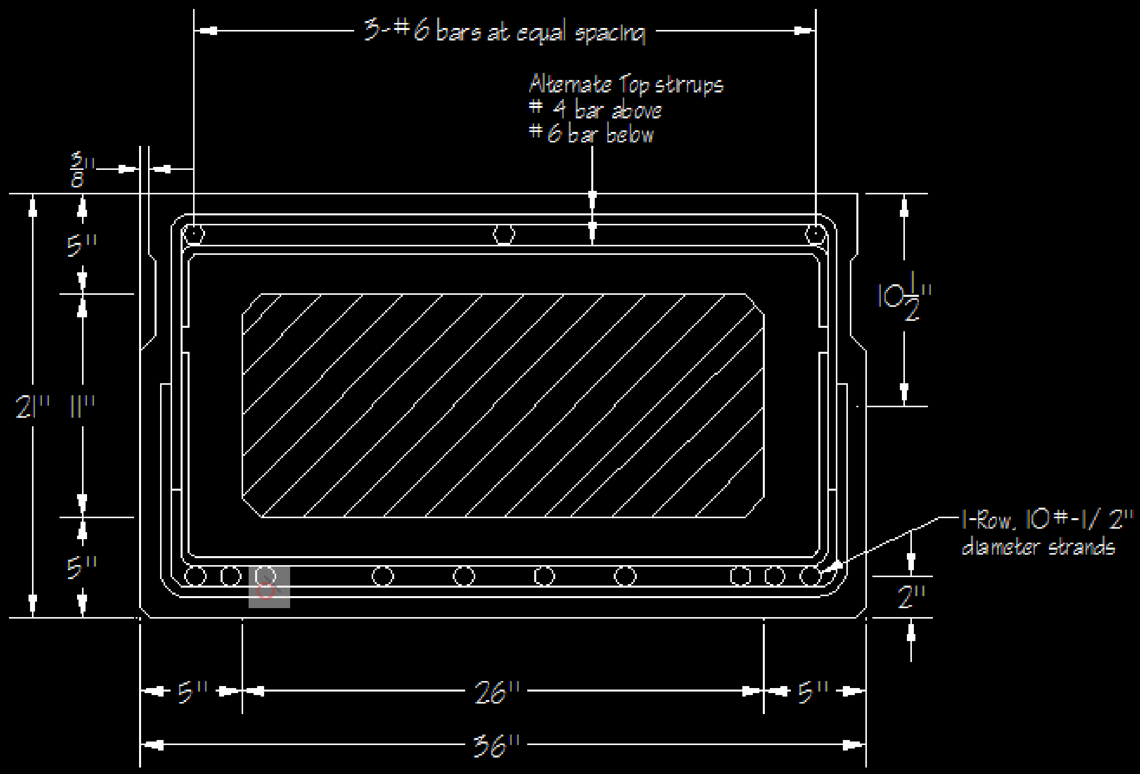
Transporting Salvaged Beams from Storage Site in Kent County to LTU.

Salvaged box beam being loaded to be transported to LTU.

Transporting Salvaged Beams to Storage Site in Kent County.

Another load

MDOT Salvaged Beam Configuration



Typical Cross-section

General Dimensions:

- 43'-8" long
- 36" wide, and
- 21" deep

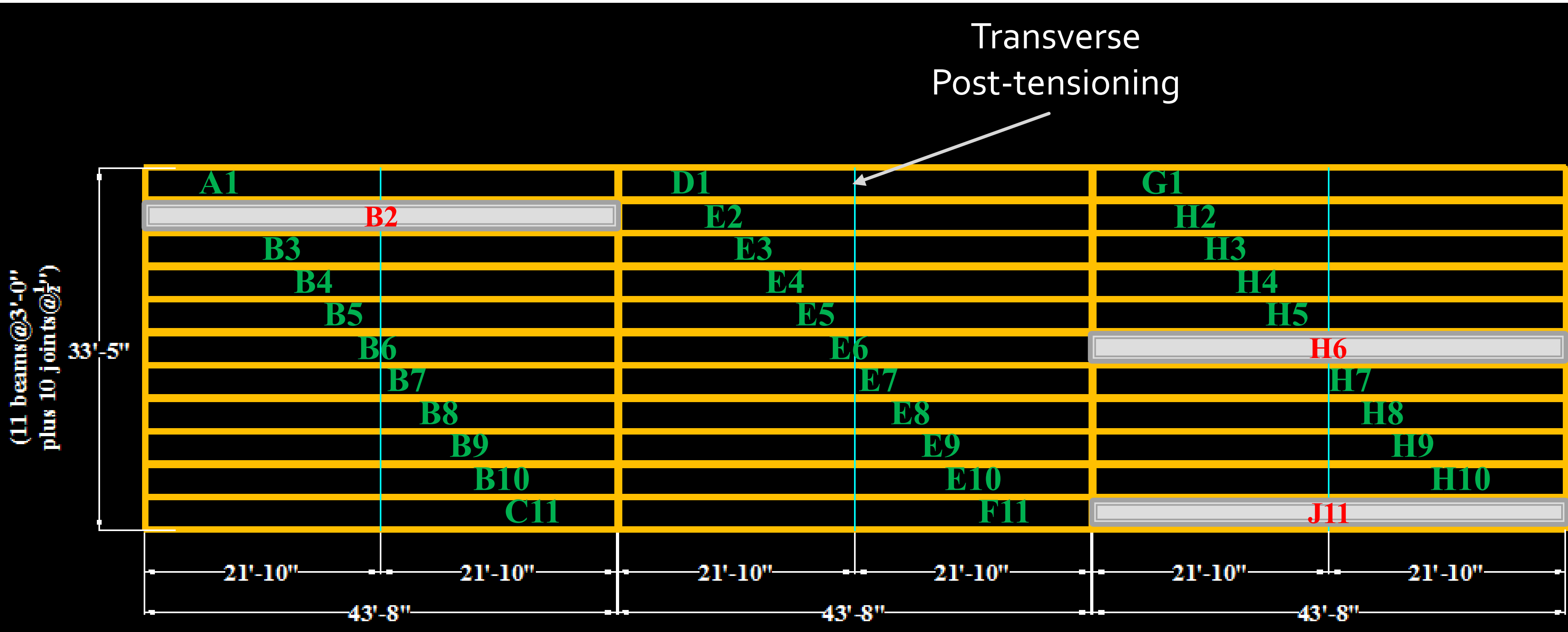
Selected beams:

- 1 exterior
- 2 interior

Other details:

- 35 years in service

Layout of Kent County Bridge



Plan View of Bridge

Deployed Nondestructive Methods for Assessment of MDOT Salvaged Box Beams

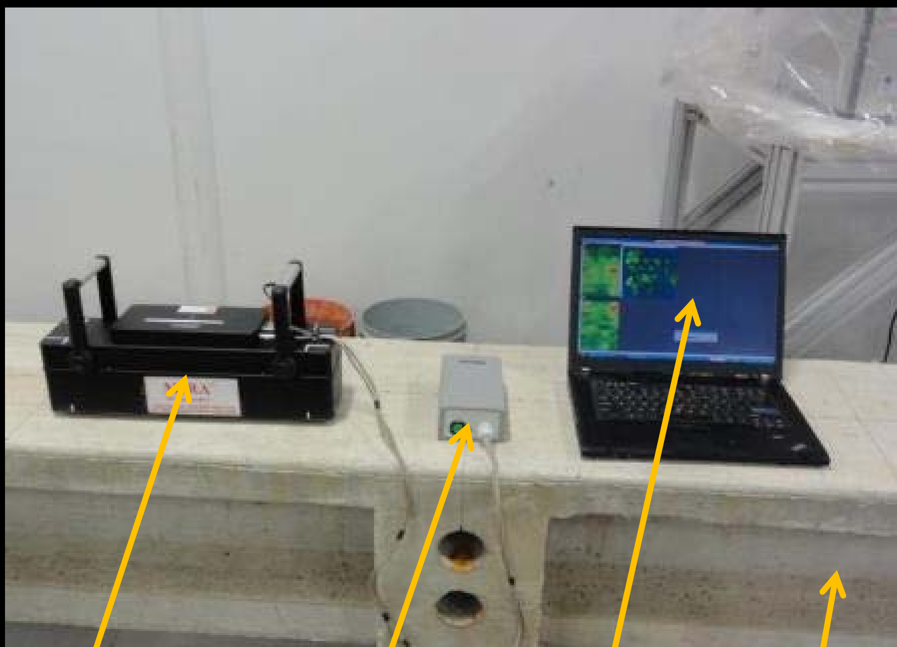
(i) ultrasonic assessment for delamination and void detection;

(ii) electro-chemical half-cell assessment for detecting corrosive environment;

(iii) impact hammer assessment of surfaces to detect variations and potential delamination;

(iv) magnetic flux leakage to determine loss of cross sectional area of rebar and strands.

Ultrasonic Test Equipment



Antenna

Power supply

Captured images

Example test beam

Measurement on deck
RC-1567, I-96 over Kent Lake

Overview of Ultrasonic Method

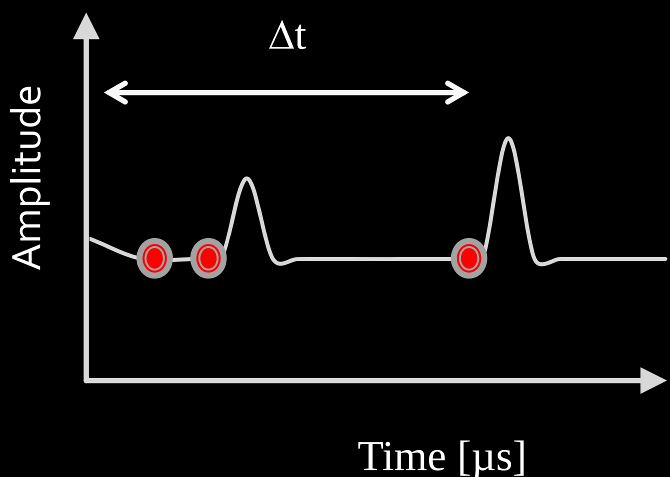
- Mechanical sound waves generated to assess structural integrity and to make material property measurements (> 20 kHz)
- The sound wave causes each material point to cycle around it's equilibrium at the impact frequency

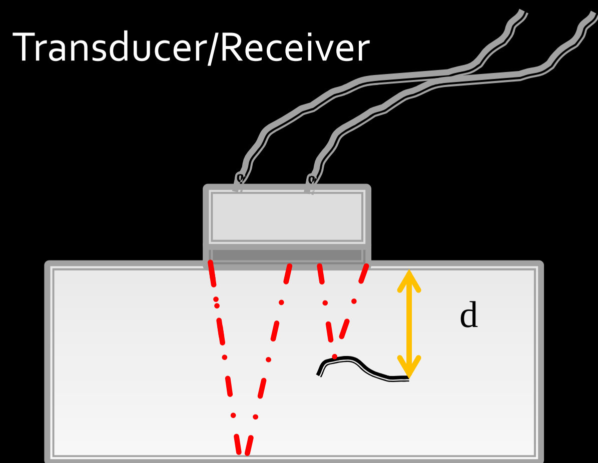
Compression wave

Shear Wave

Longitudinal waves are affected more by geometry (edges) than shear waves

Overview of Ultrasonic Method - Indirect Measurements





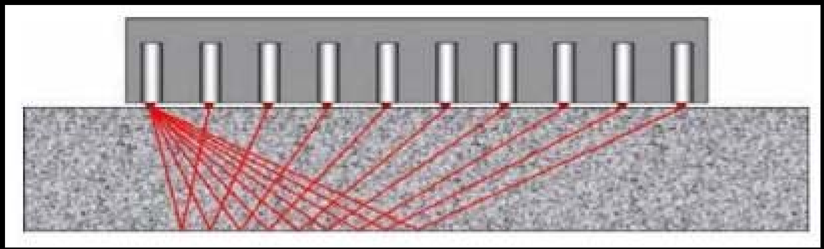
$$d = C\frac{\Delta t}{2}$$

C: shear wave speed of material [m/s]

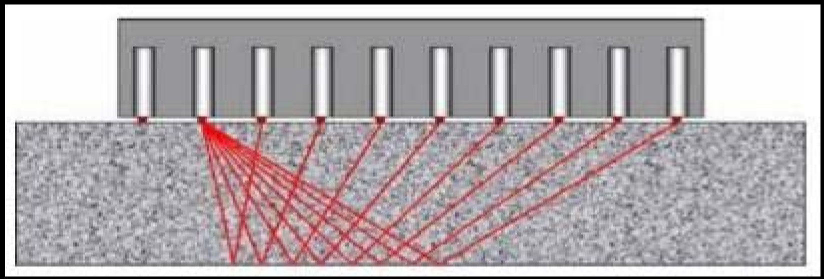
$$C = \sqrt{\frac{E}{\rho}\frac{1-\mu}{2(1+\mu)}} = \sqrt{\frac{G}{\rho}}$$

E [MPa], G [MPa], μ[-] are elastic properties and ρ is the density [kg/m^3]

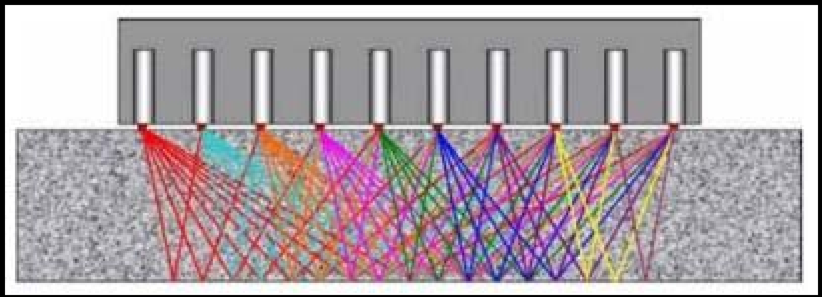
Antenna Process



First row transmits,
the 9 remaining receive



Second row transmits,
the 8 remaining receive



All phases, illustrated yielding 45 arrays
(4 sensors in each row)

Detecting Reflective Surfaces

Rule of thumb:
Discontinuity must > ½ of wavelength to stand a reasonable chance of being detected

$$\lambda = \frac{v}{f}$$

where λ : wavelength
v : velocity (shear wave)
f : frequency

Typically low frequency impacts are used in concrete such as 30 kHz < f < 100 kHz

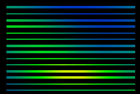
$$\lambda = \frac{2500\ m/s}{50\ kHz} = 0.05m$$

Laboratory Testing for MDOT Box Beam(Cont.)

Intensity of reflections are related to the magnitude of the change in material properties such as density, as shear wave propagates through the material

Color code for this presentation:

no change in shear wave reflection

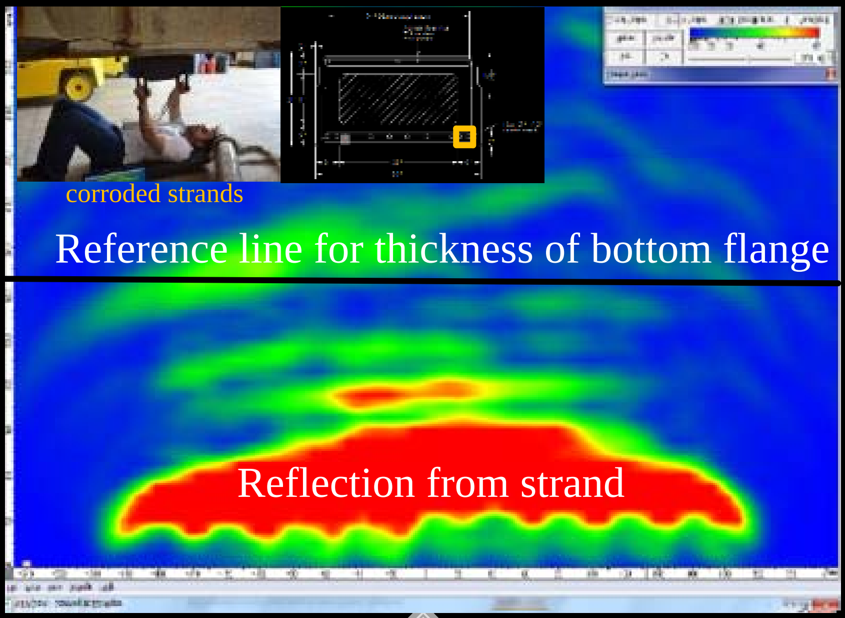


medium change in shear wave reflection

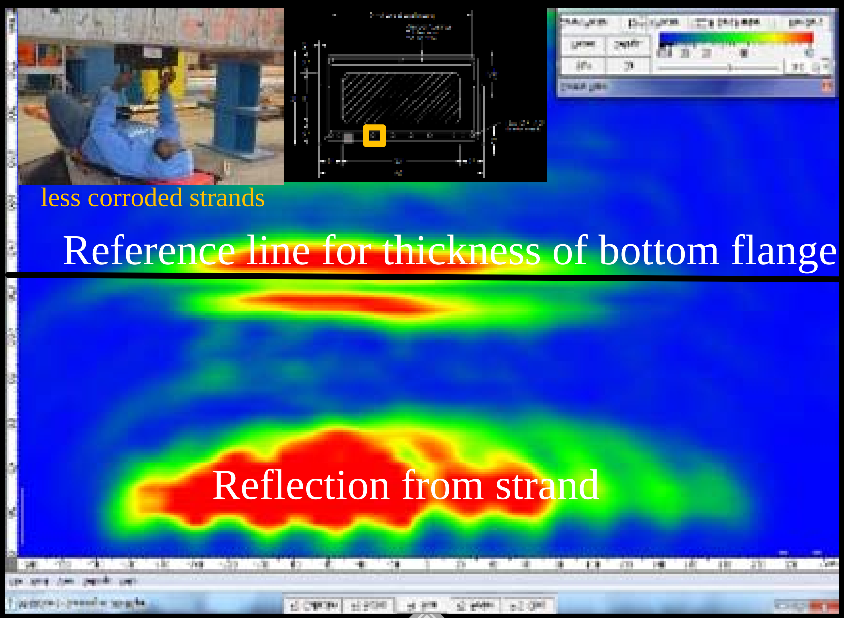
high change in shear wave reflection

Typical scans on various embedment in MDOT box beams have been shown on the subsequent slide

Scanning on Corroded & Less Corroded Strands Locations along Salvaged Beams



Scanning at 100 kHz



Scanning at 100 kHz

Half-Cell Potential Testing on MDOT Salvaged Beam

Measurement in grids of 6”x6” on the bottom of the box beams (742 readings)

Rod electrode
(CuSO4 solution)

Rebar located by Profometer

Rebar exposed by hammer drill

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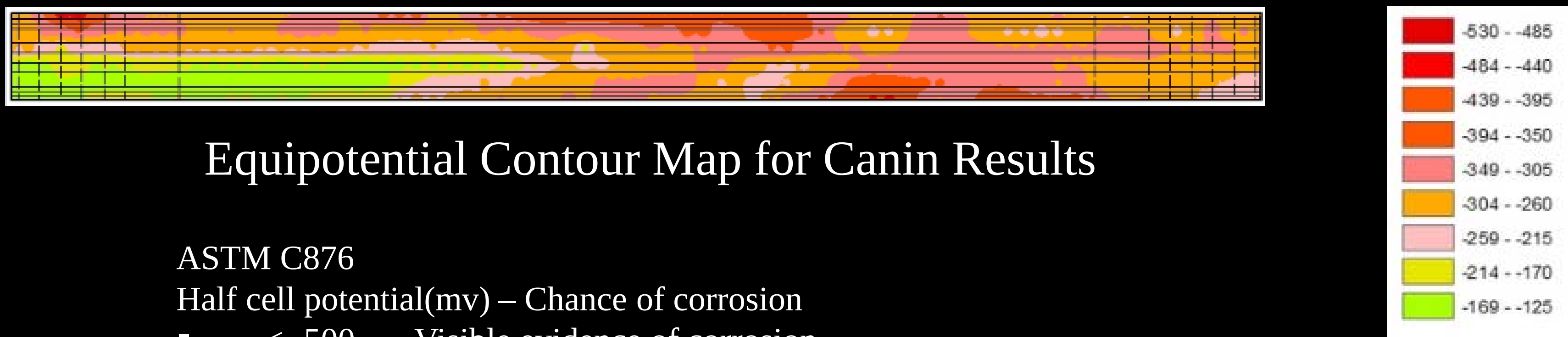
Half-cell Potential & Impact Hammer Results for MDOT Salvaged Beam

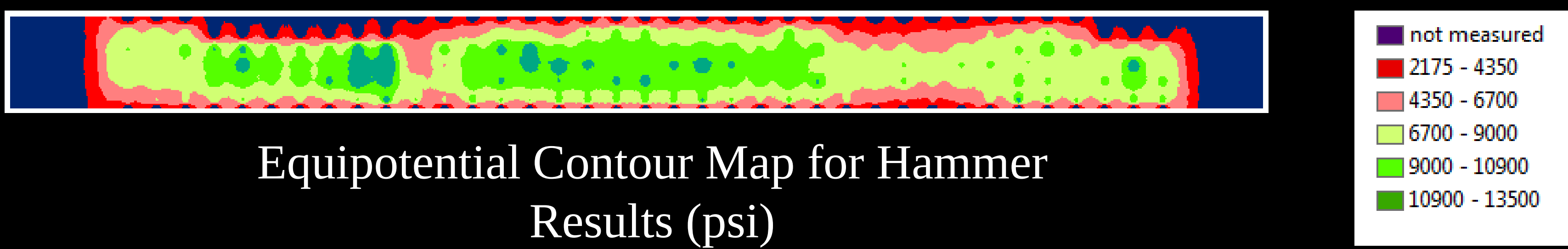


Equipotential Contour Map for Canin Results

ASTM C876

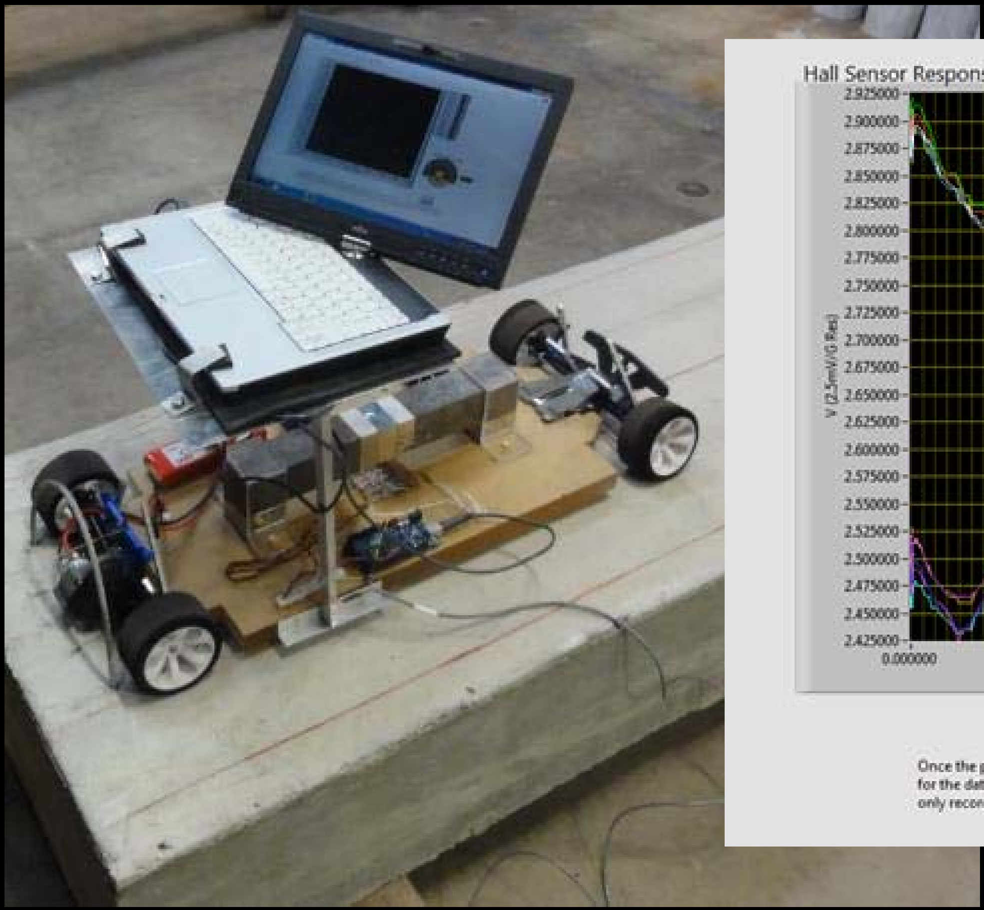
Half cell potential(mv) – Chance of corrosion

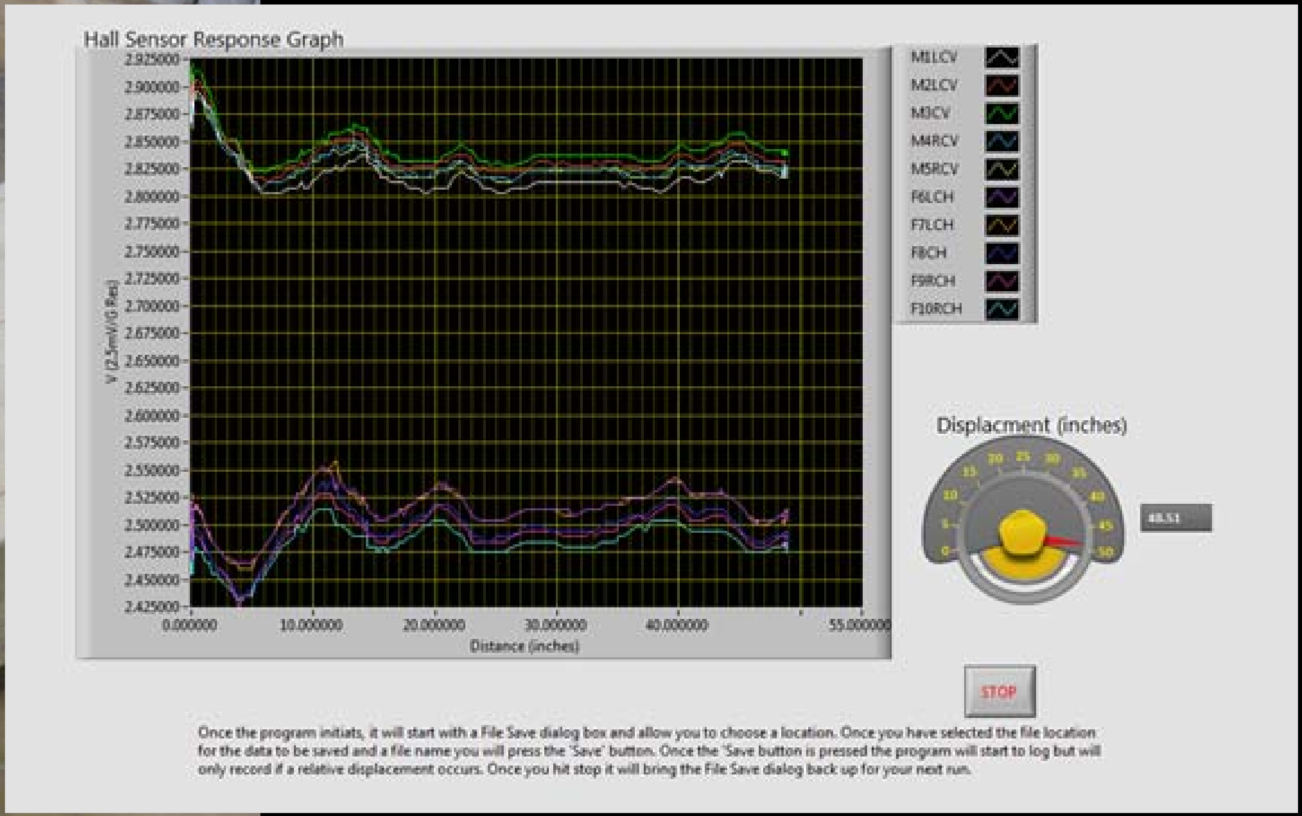
- < -500 – Visible evidence of corrosion
- -350 - -500 - 95%
- -200 - -350 - 50%
- > -200 - 5%



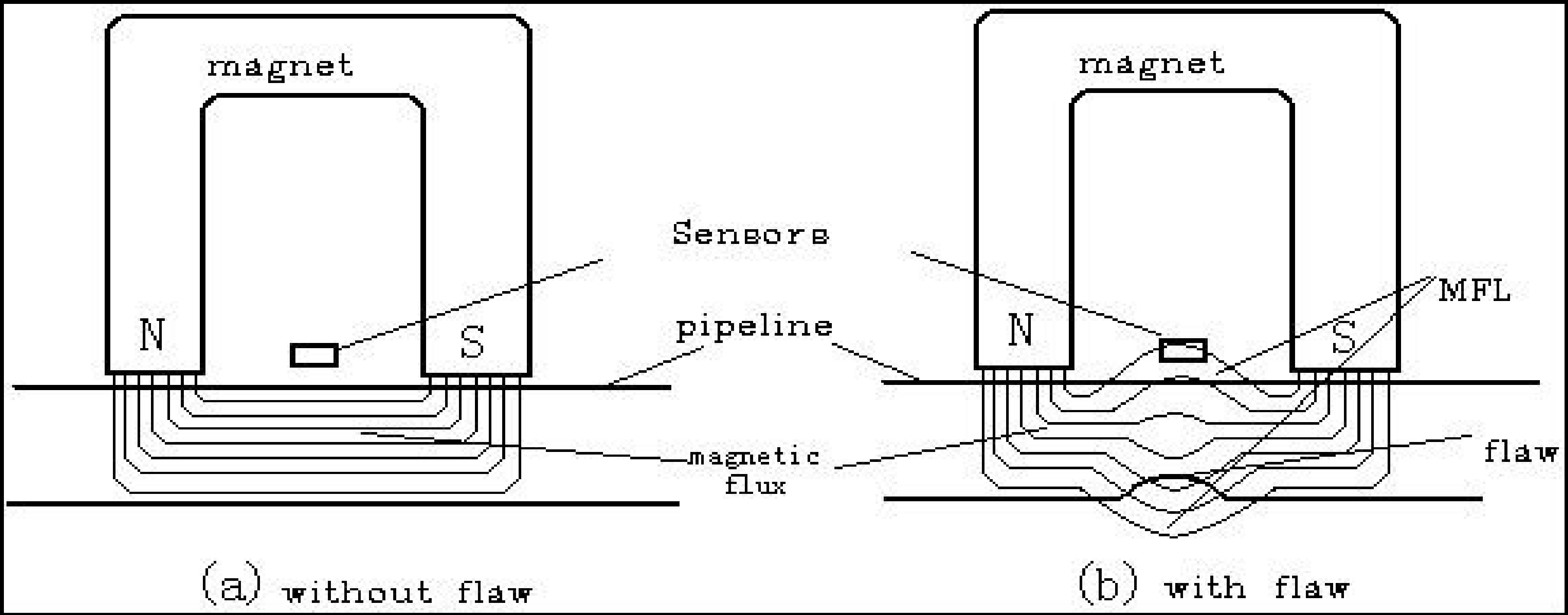
Equipotential Contour Map for Hammer Results (psi)

Magnetic Flux Leakage



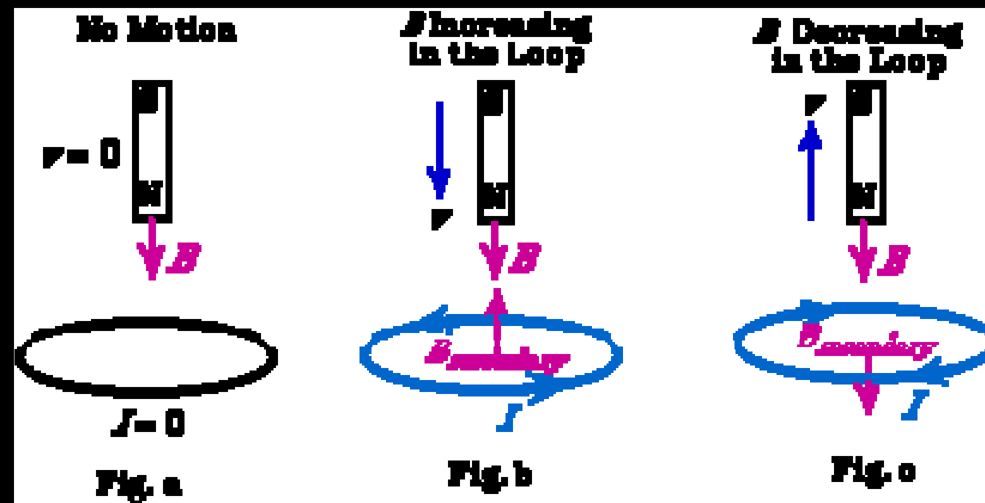


Magnetic Flux & Magnetic Flux Leakage

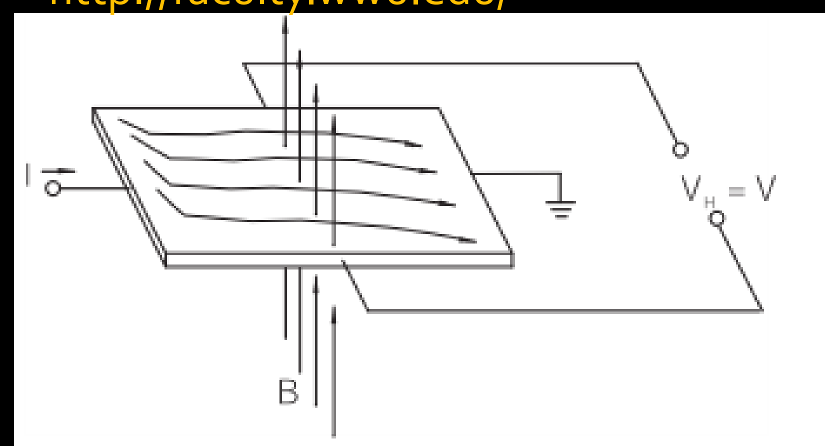


Measuring Magnetic Flux

- A coil experiences an induced current when the magnetic field passing through it varies
- Voltage generated by the interaction between the magnetic field and electric current (**Hall Effect**).
- The voltage can be measured through sensors and related to the magnetic flux (**Hall Effect Sensors**).



http://faculty.wwu.edu/



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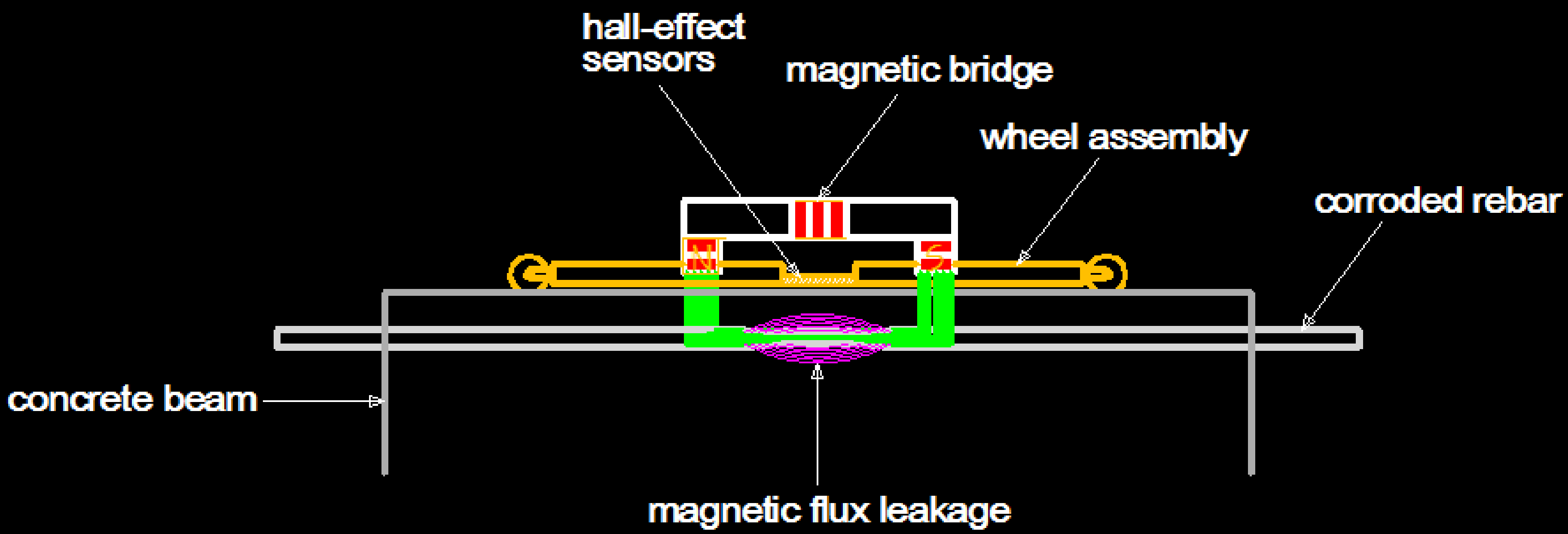
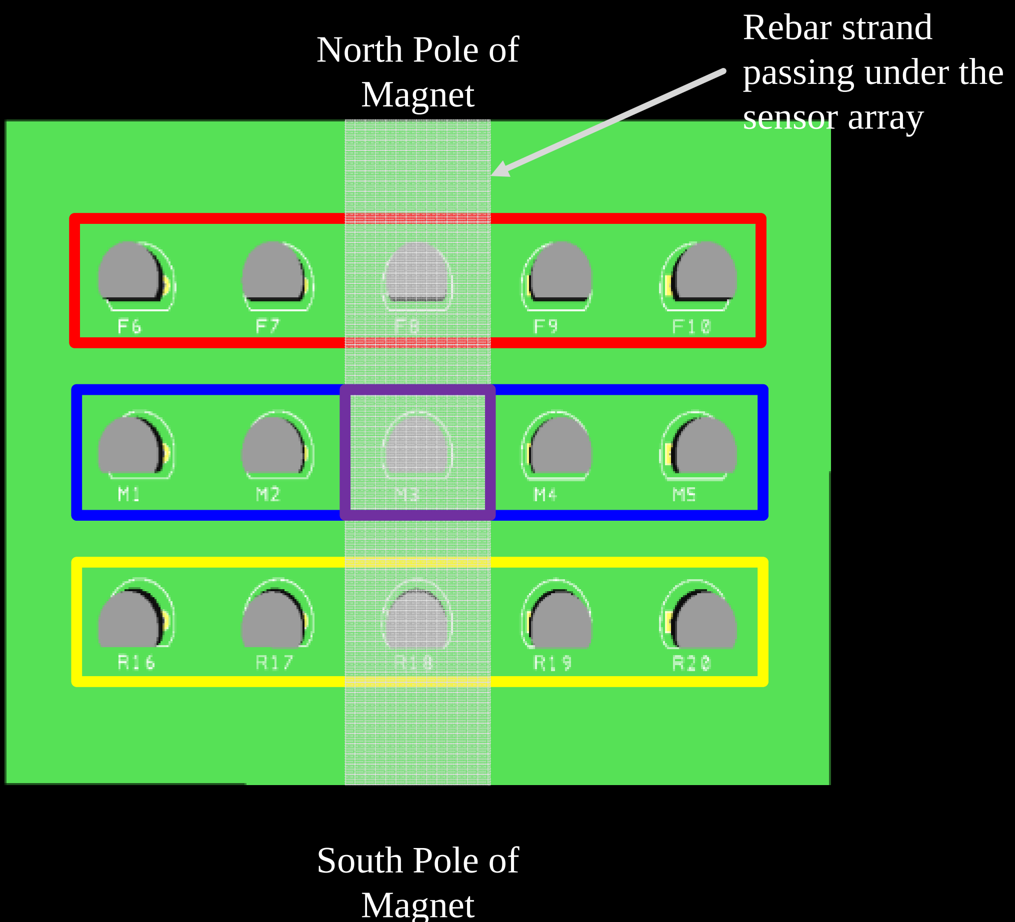
Magnetic Flux Field for Rebar with/without Loss of Cross-Sectional Area



MFL Hall Effect Sensor Array



Front Hall sensors, labeled F6 to F10, are aligned orthogonal to the magnetic flux field

Middle Hall Sensors, labeled M1 to M5, are aligned parallel to the magnetic flux field

Rear Hall Sensors, labeled R11-R15, are aligned orthogonal to the magnetic flux field

M3 has been primarily used for calibration

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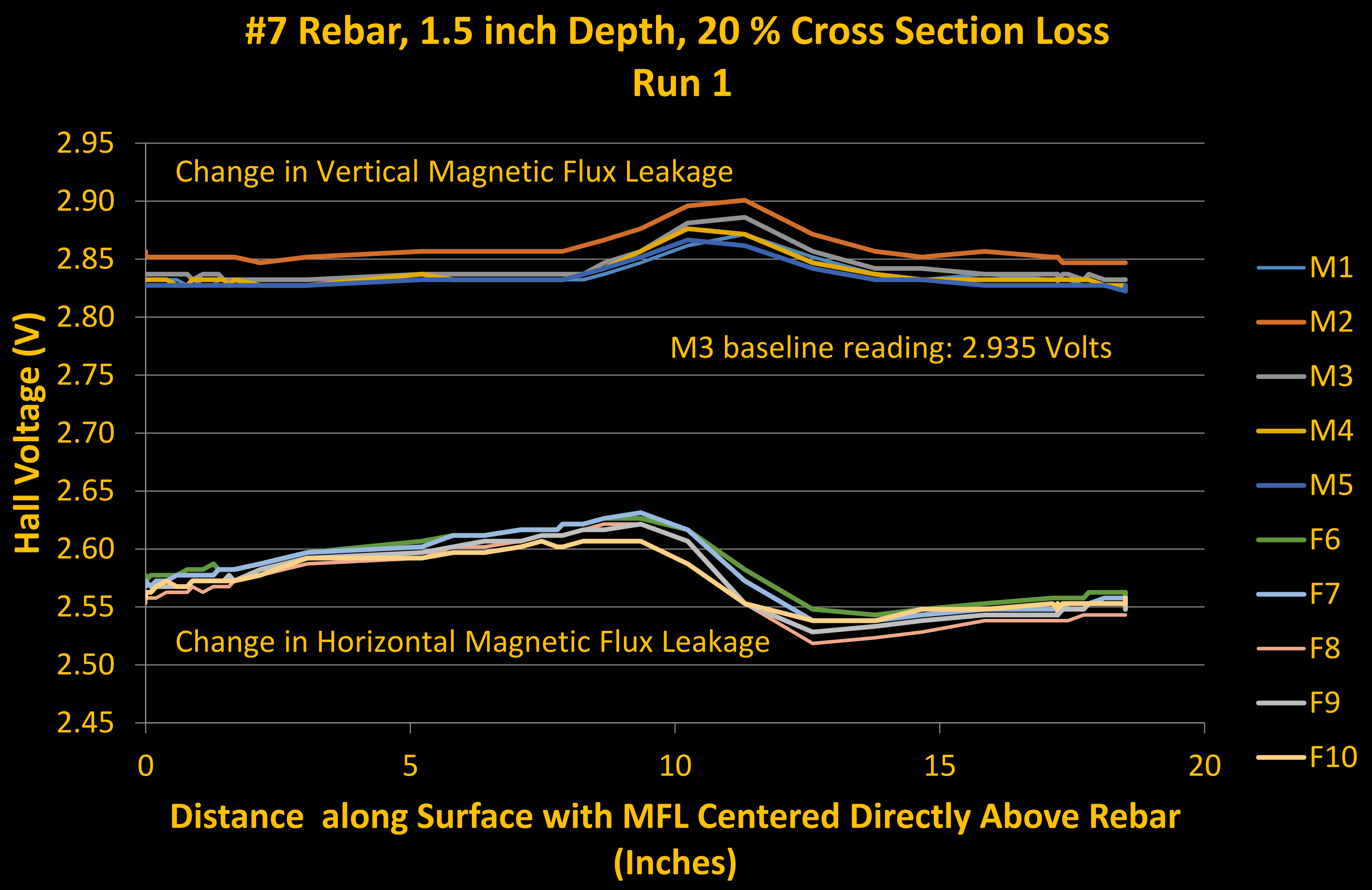
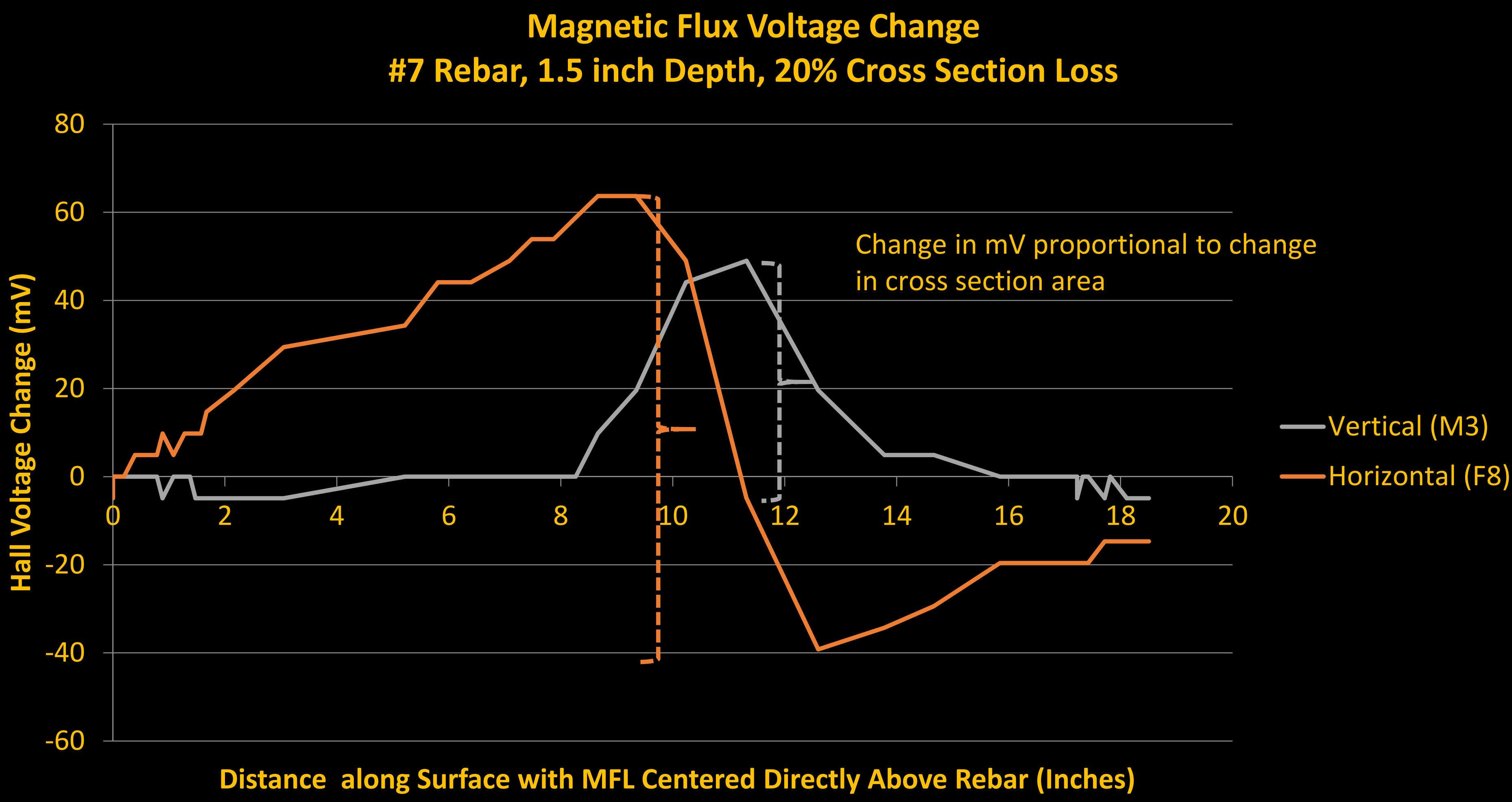
Magnetic Flux Leakage (MFL) System

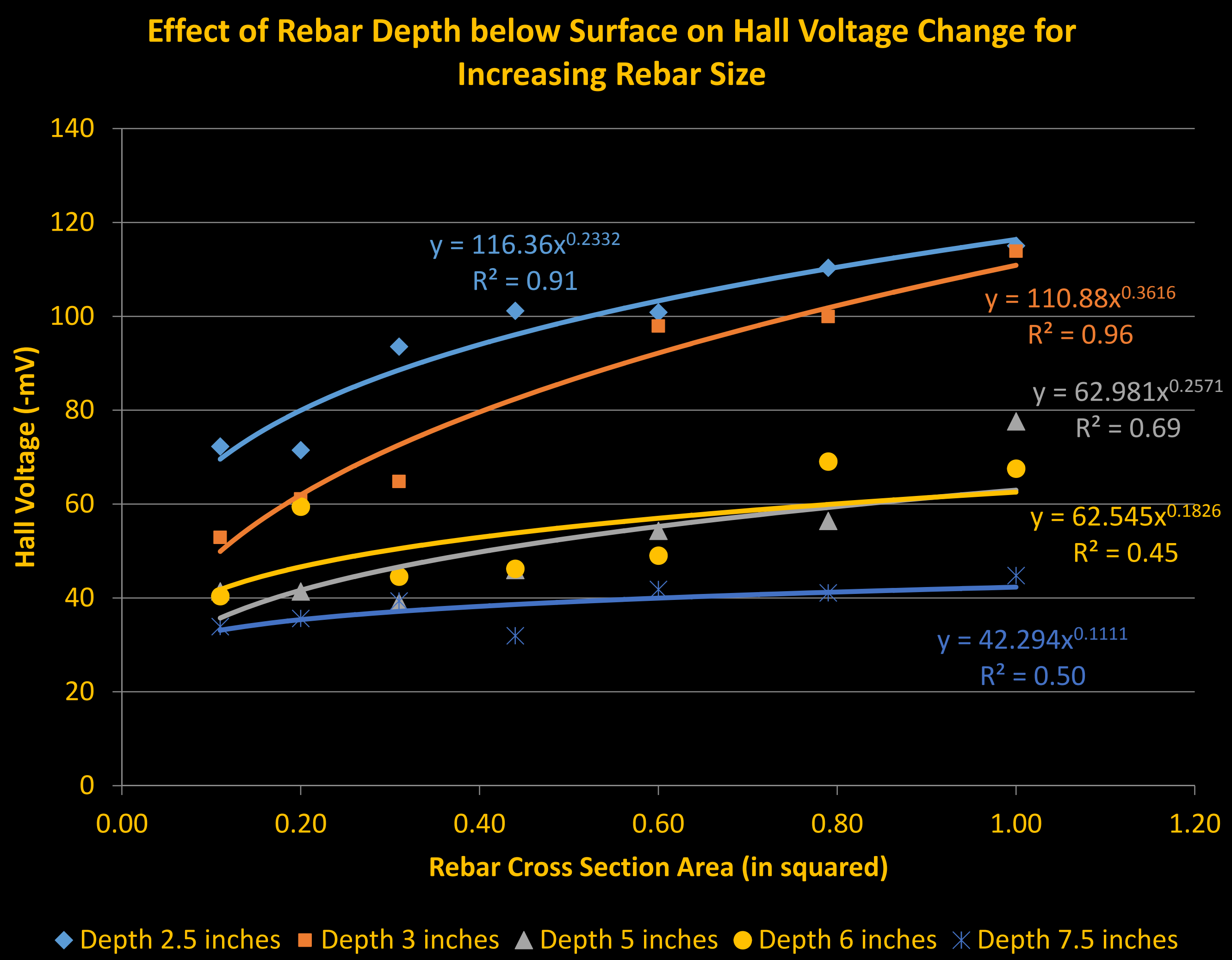
Rebar at 1.5 Inch Depth with 20% Cross Section Loss – Raw Data without Amplification



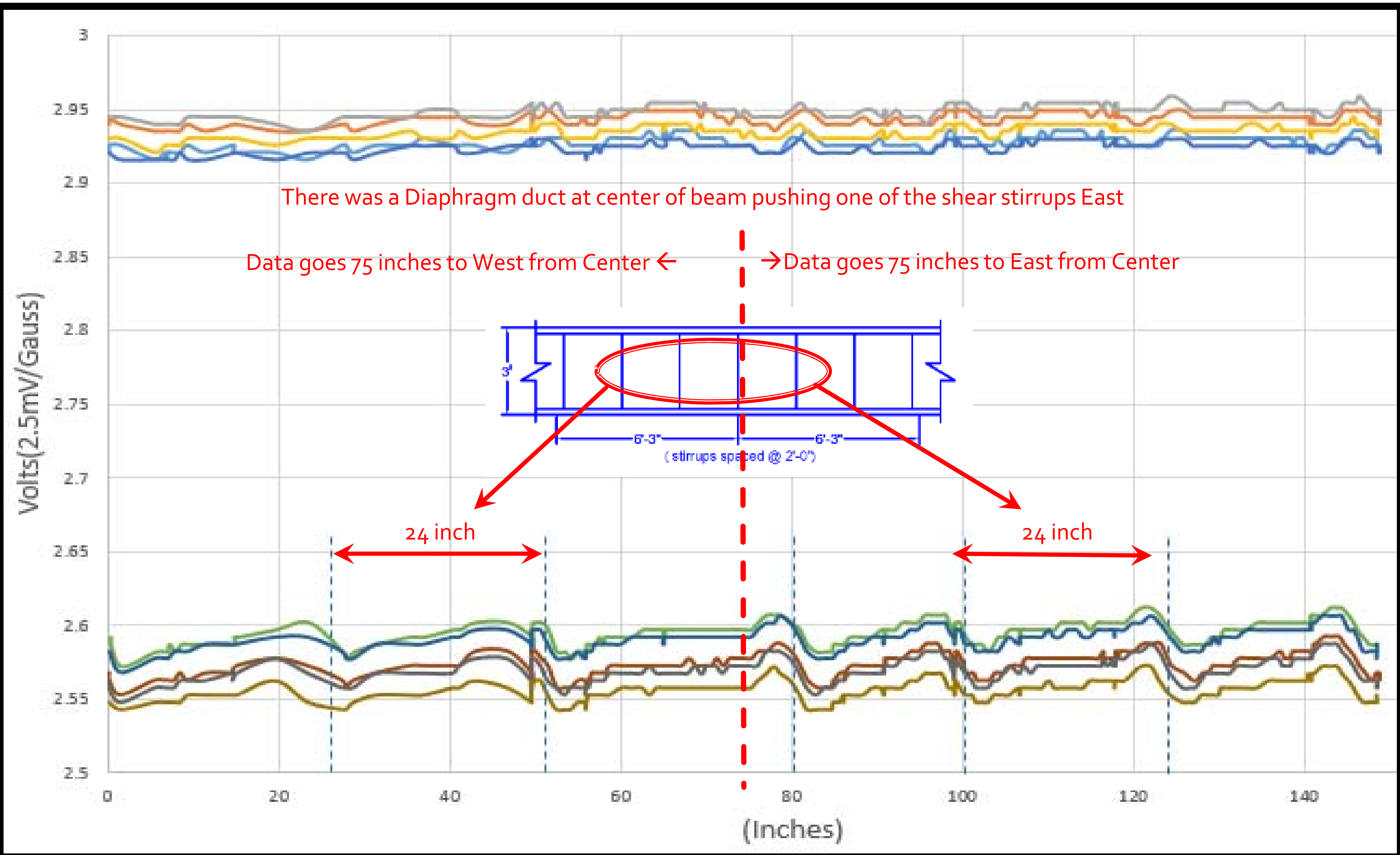
Magnetic Flux Voltage Change



Effect of Rebar Depth below Surface of Hall Voltage Change for Increasing Rebar Size



Preliminary Results of Magnetic Flux Leakage Data from Salvaged Beam



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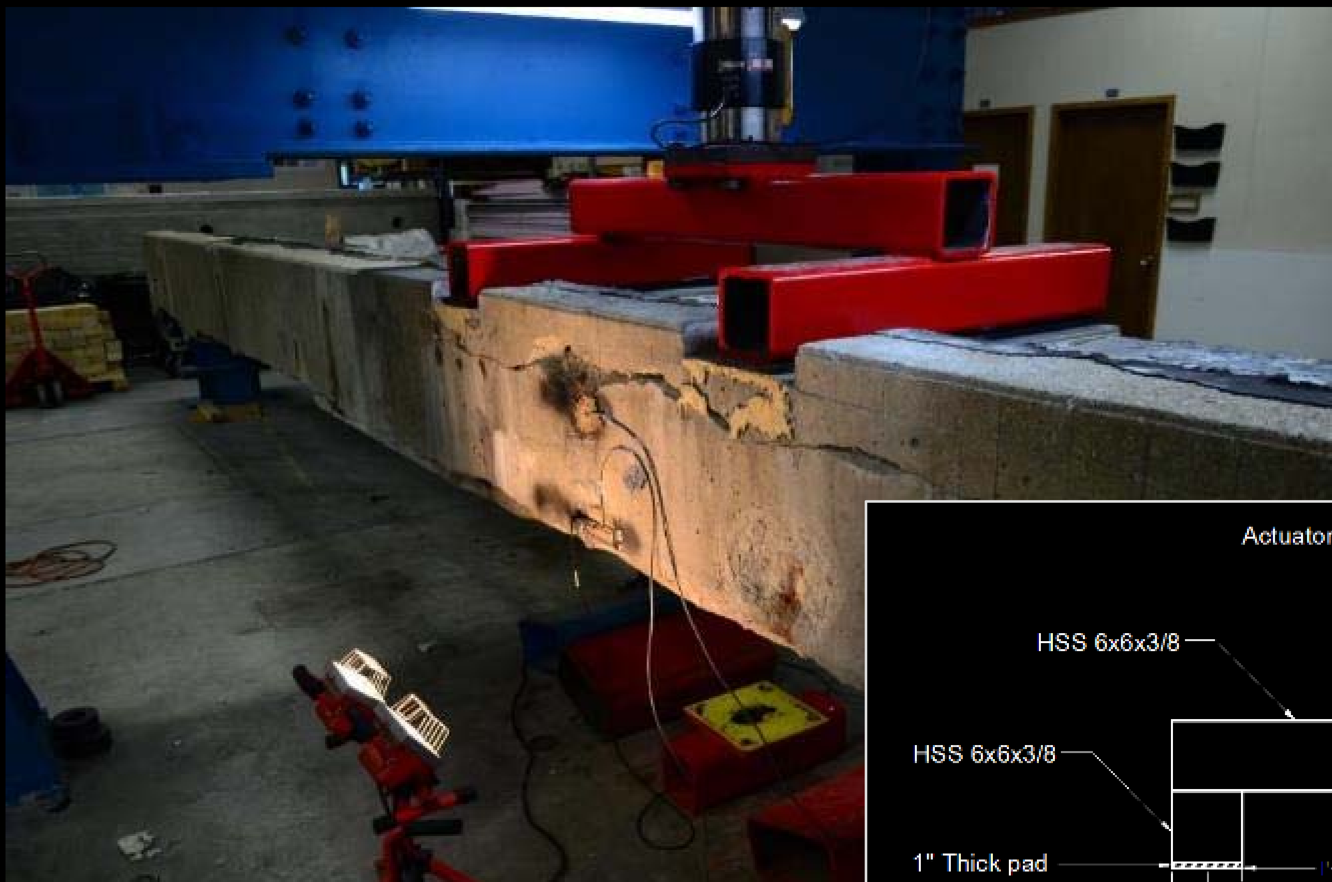
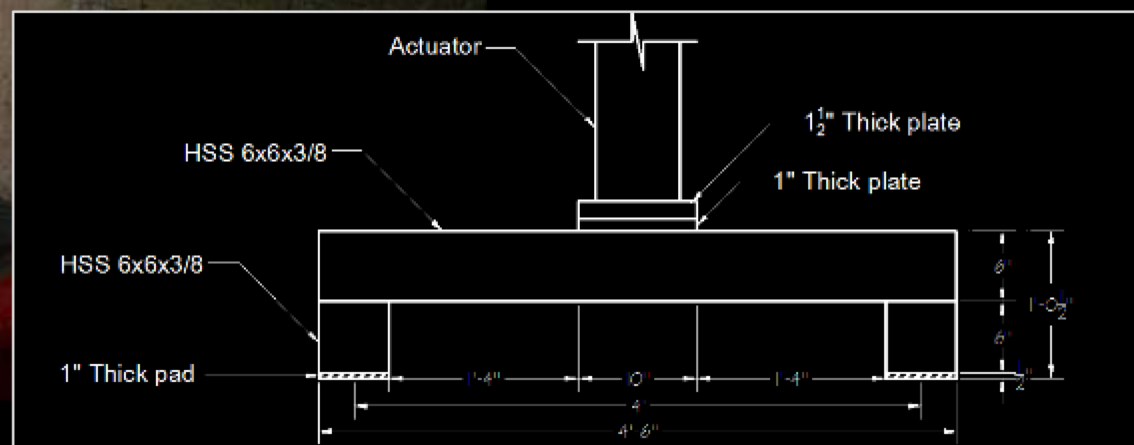
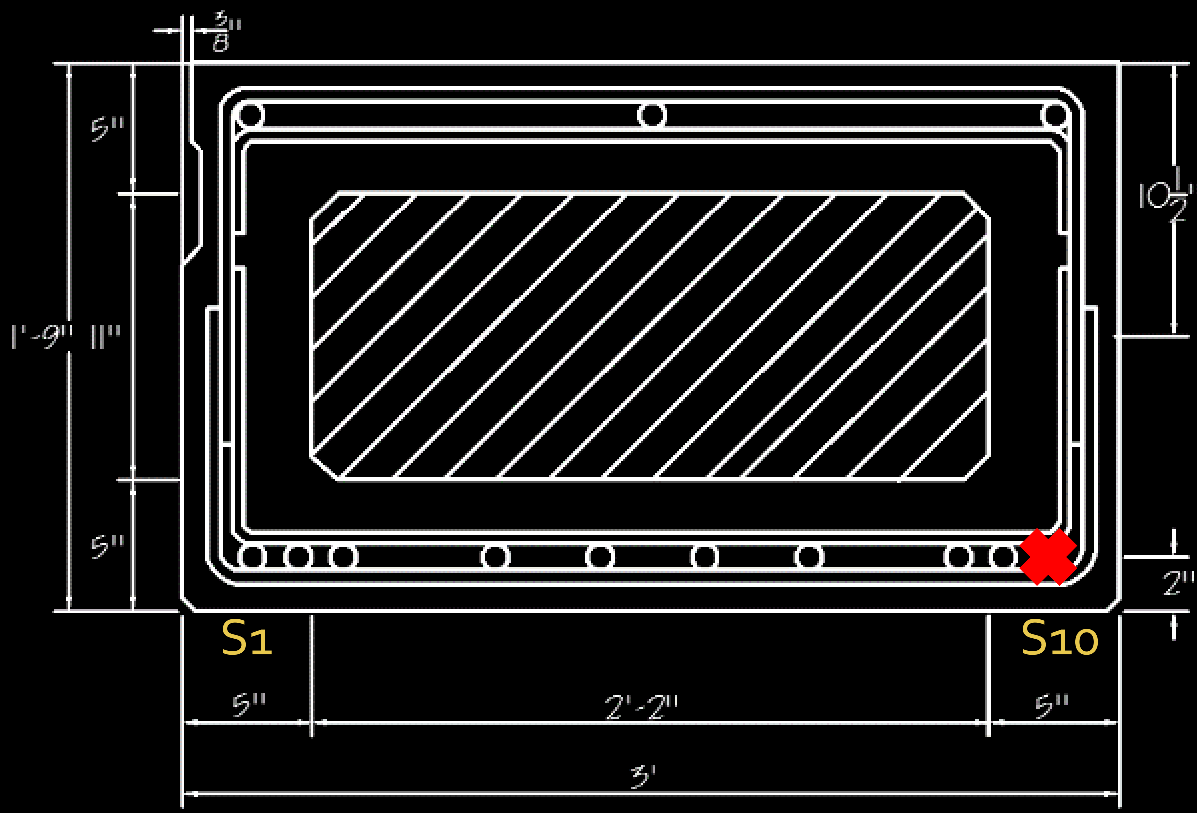
Residual Flexural Test Set-up





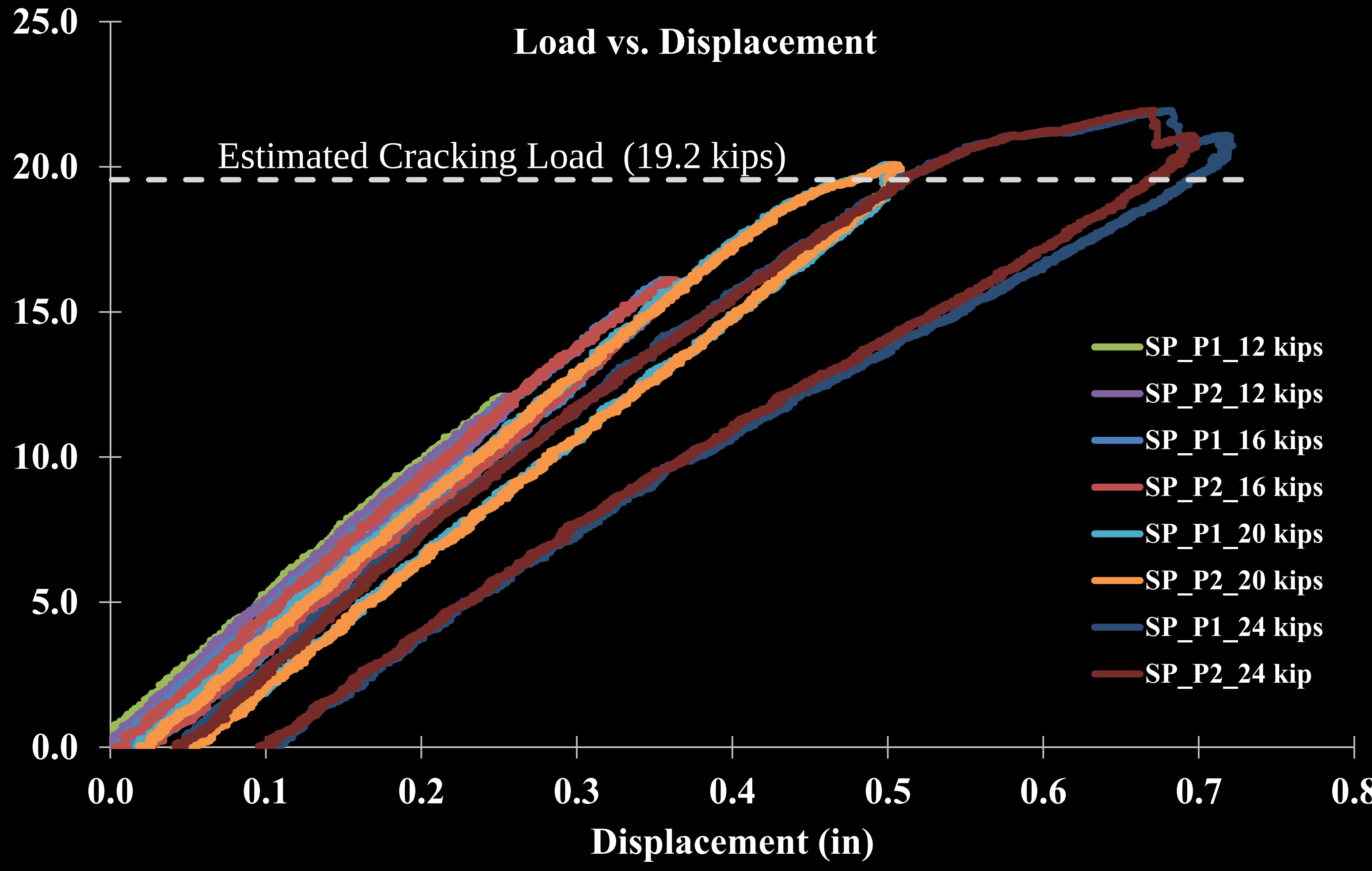
Assumptions (Salvaged Beam)

- 6000 psi concrete
- Strand #10 broken (corroded)
- Remaining strands with 20% loss of cross section area
- Section considered homogeneous before flexural cracking occur



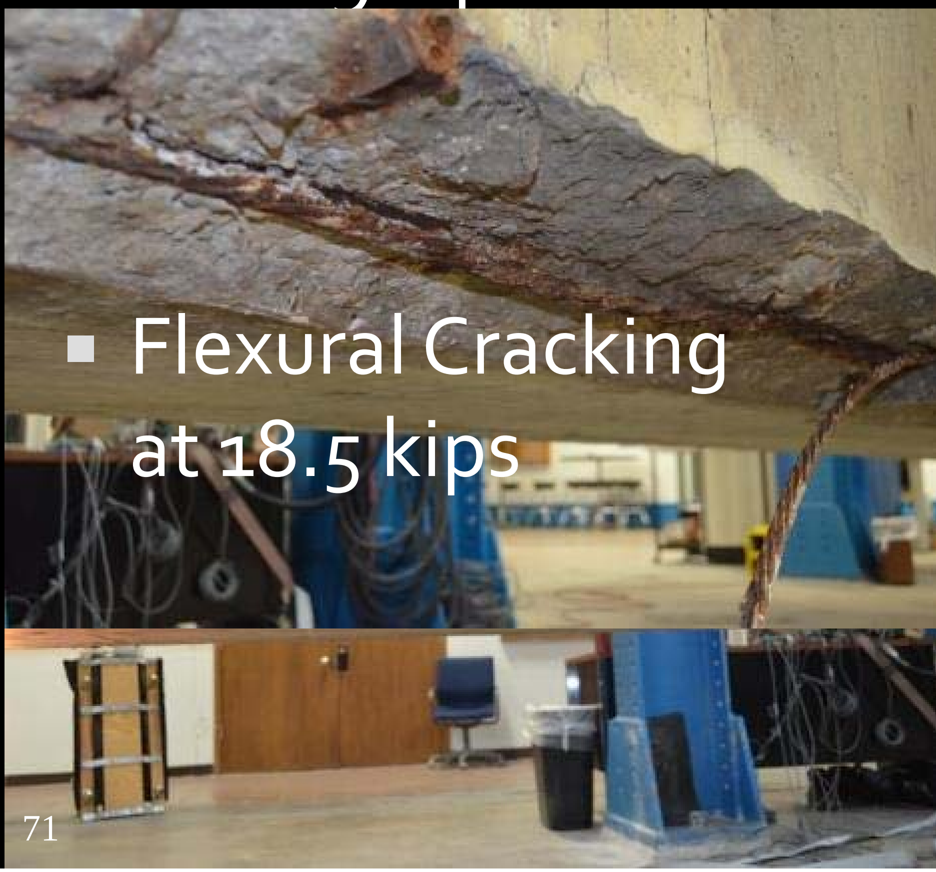
S1 is Located at the Interior Face of the Beam
S10 is Located at the Fascia of the Beam

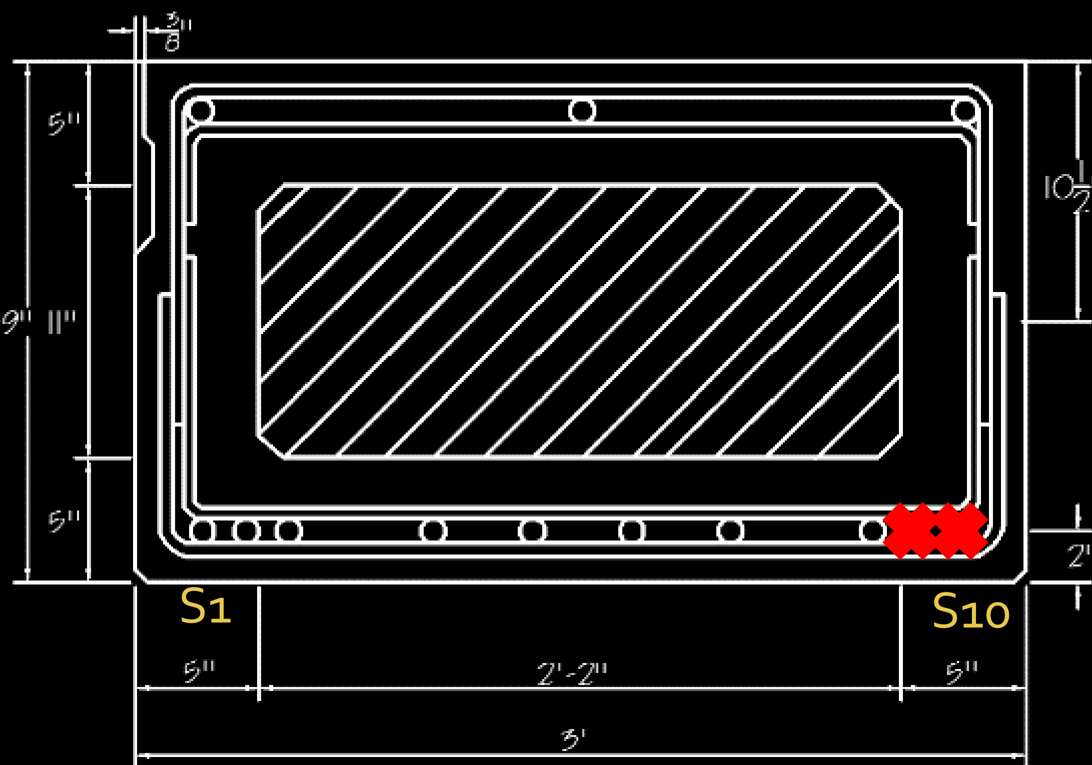
Experimental Results of Residual Flexural Testing of Salvaged Beam, J11



24 kip Load Cycle

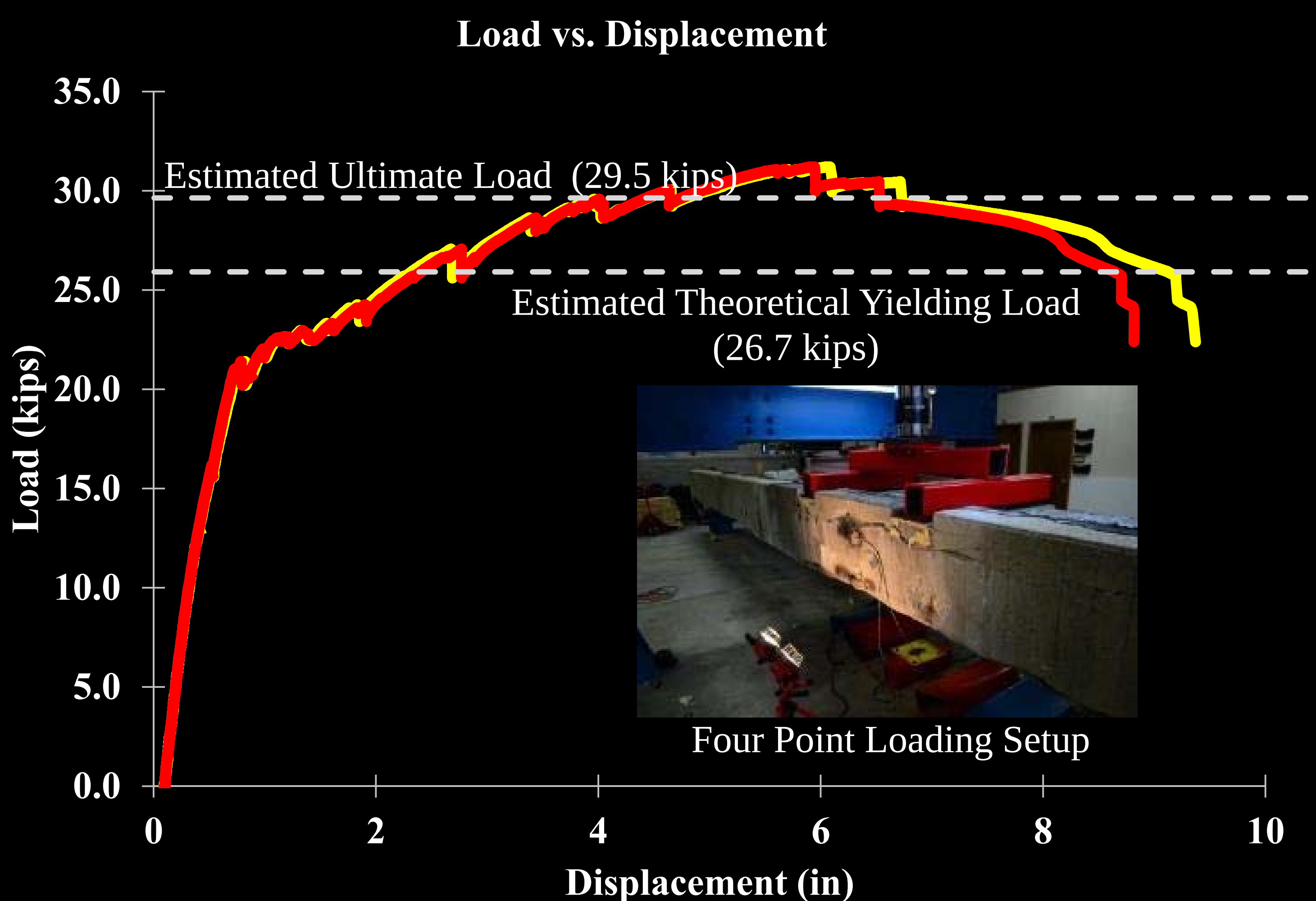
- Strand #9 Rupture at 21.9 kips
- Flexural Cracking at 18.5 kips



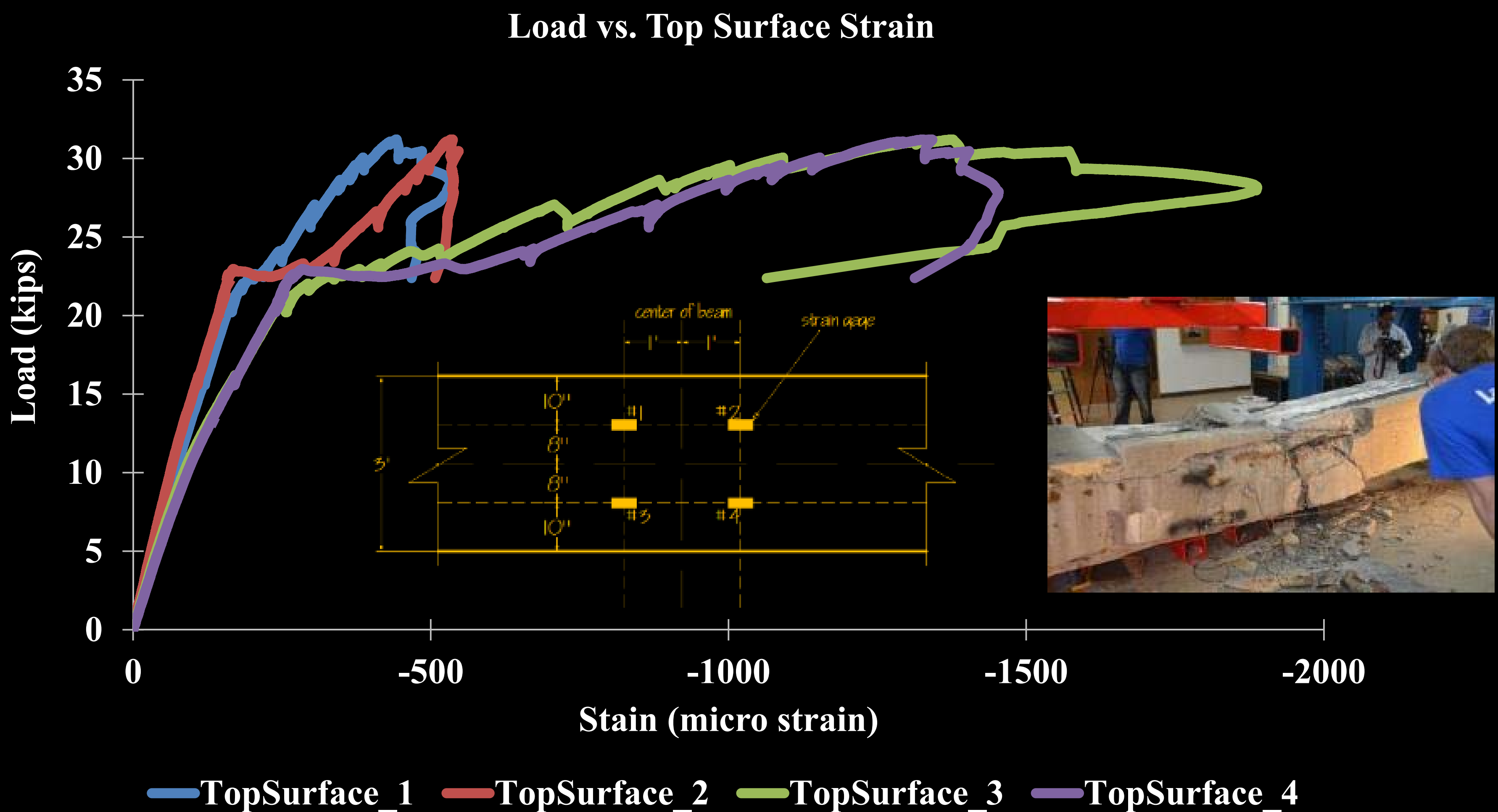


S1 is Located at the Interior Face of the Beam
S10 is Located at the Fascia of the Beam

Residual Flexural Testing of Salvaged Beam, J11



Experimental Results of Residual Flexural Testing of Salvaged Beam, J11



Failed MDOT Salvaged Beam

Summary (preliminary)

- Ultrasonic 3D Tomography method detects defects such as delamination.
  - The method appears not to detect small defects such as beginning corrosion.
  - The impact hammer results correlate well with areas of delamination

- The half-cell potential method detects area with chance of corrosion.
  - The areas of high chance of corrosion correlates well with the areas detected with ultrasonic 3D tomography as having defects

Summary (preliminary)

- The flexural beam failure progressed as expected with the assumption of 20 % average loss of cross section area and 2 of 10 strands broken.
  - The fracture was a brittle shear failure

- Analysis of MFL data as well as visual (microscope) quantification of loss of cross section of the strands will provide further calibration of the MFL method to detect and quantify corrosion

Salvaged Beam Failure Video

Thank You!

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