University of Pittsburgh

PITT | IRISE

Prediction of Dowel Corrosion and Effect on Performance of Concrete Pavements

IRISE Annual Meeting

May 22nd, 2025

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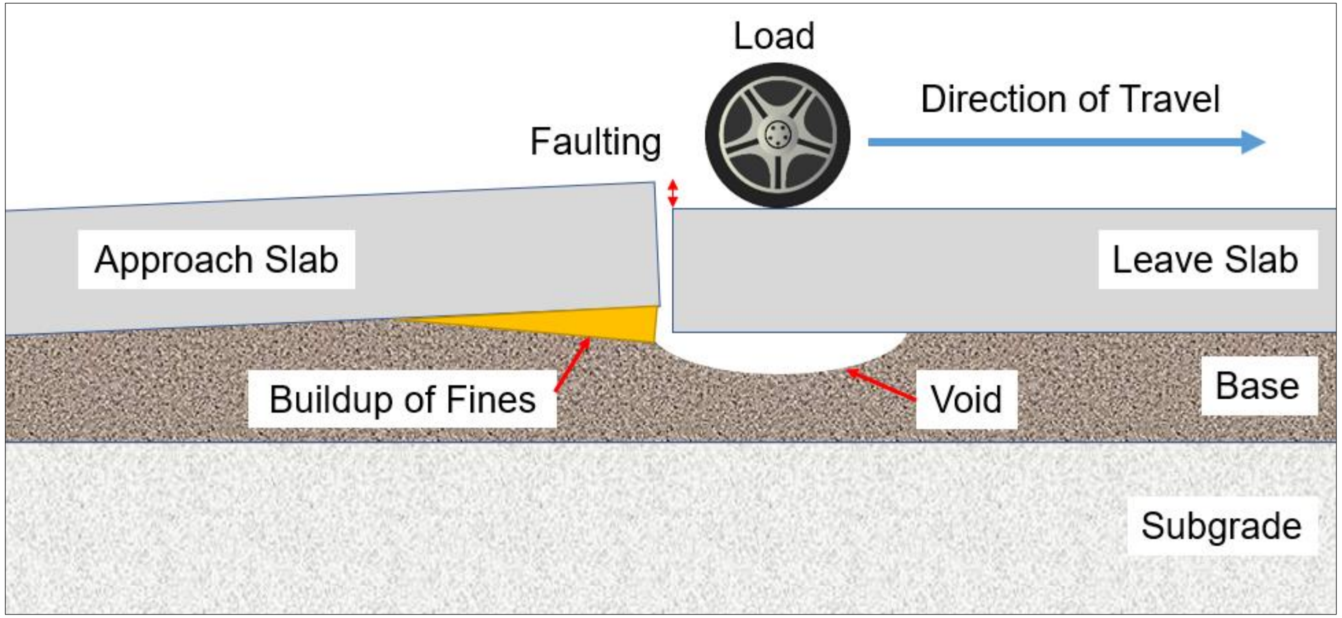
Panel Members

- Matt Blough, Pennsylvania Turnpike
- Chuck Niederriter, Golden Triangle
- Dave Sciullo, Golden Triangle
- Lydia Peddicord, PennDOT
- Jason Molinero, Allegheny County
- Yathi Yatheepan, FHWA

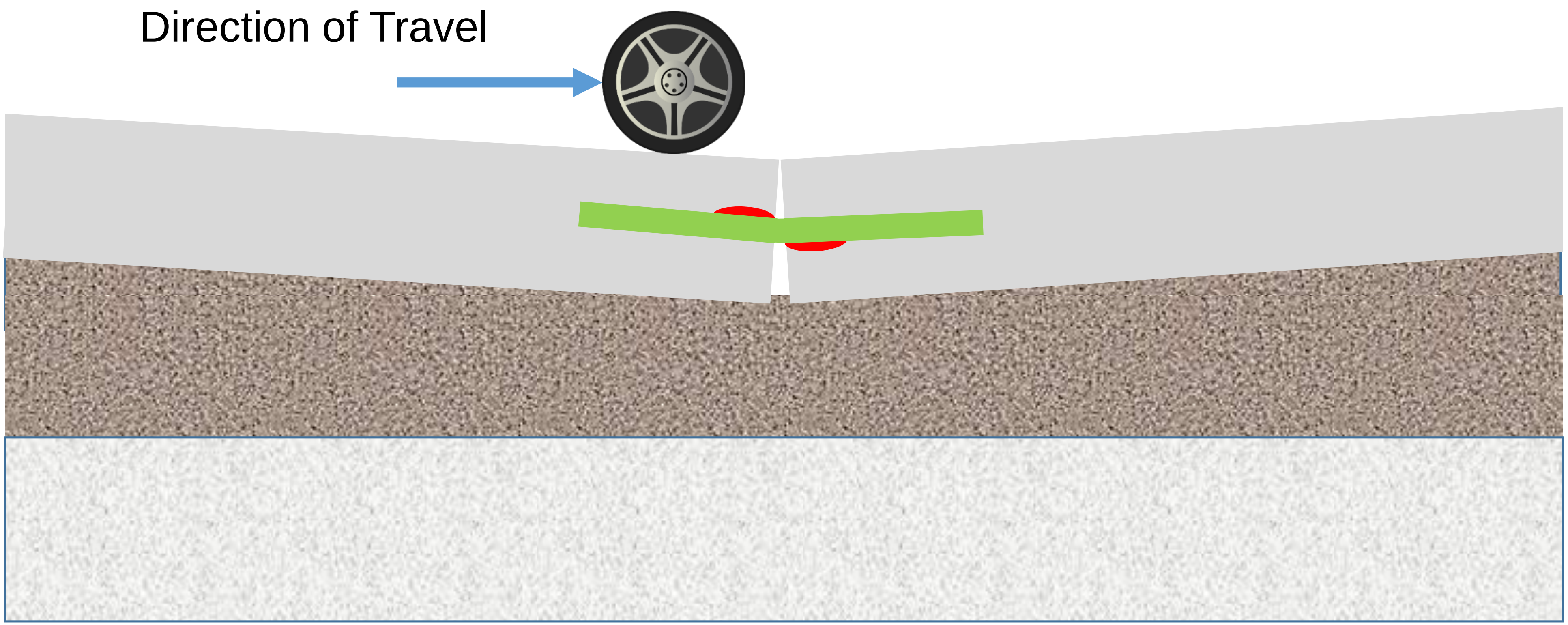
Faulting

Difference in elevation between the approach and leave slabs



Source: pavementinteractive.org

Bearing stress



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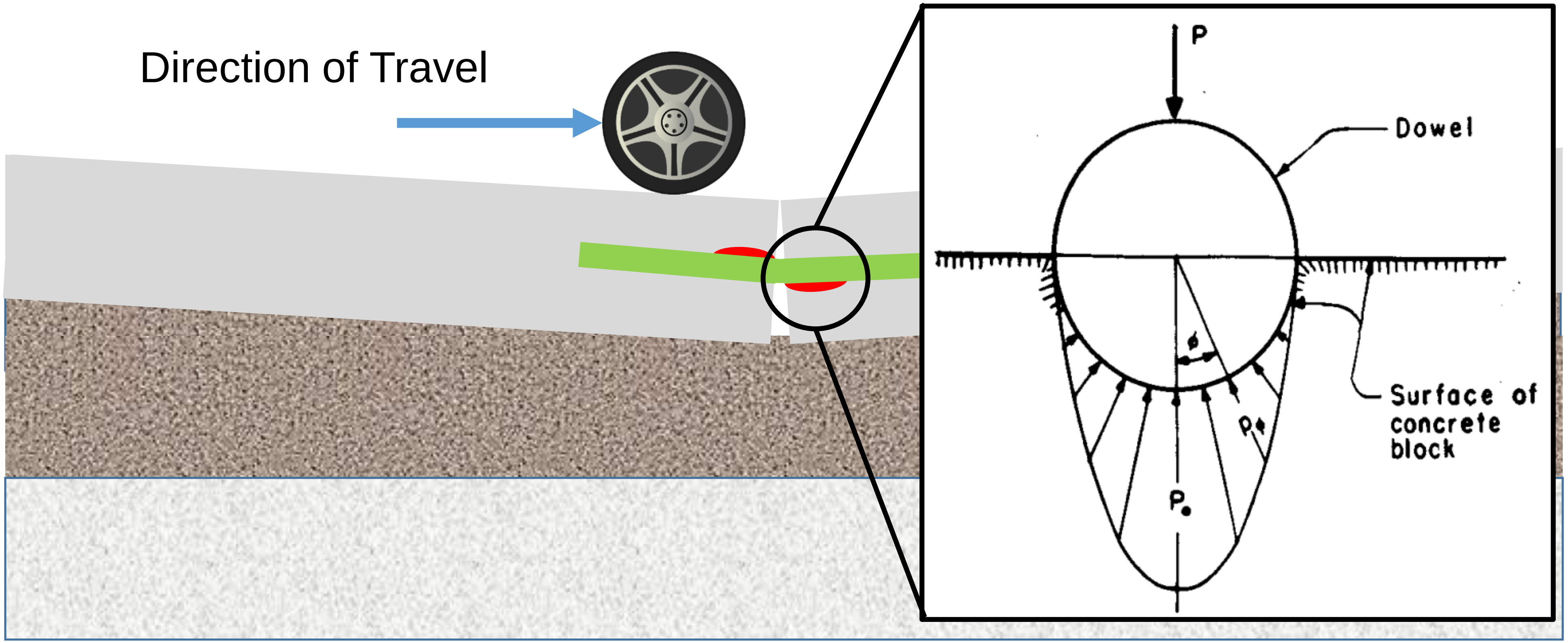
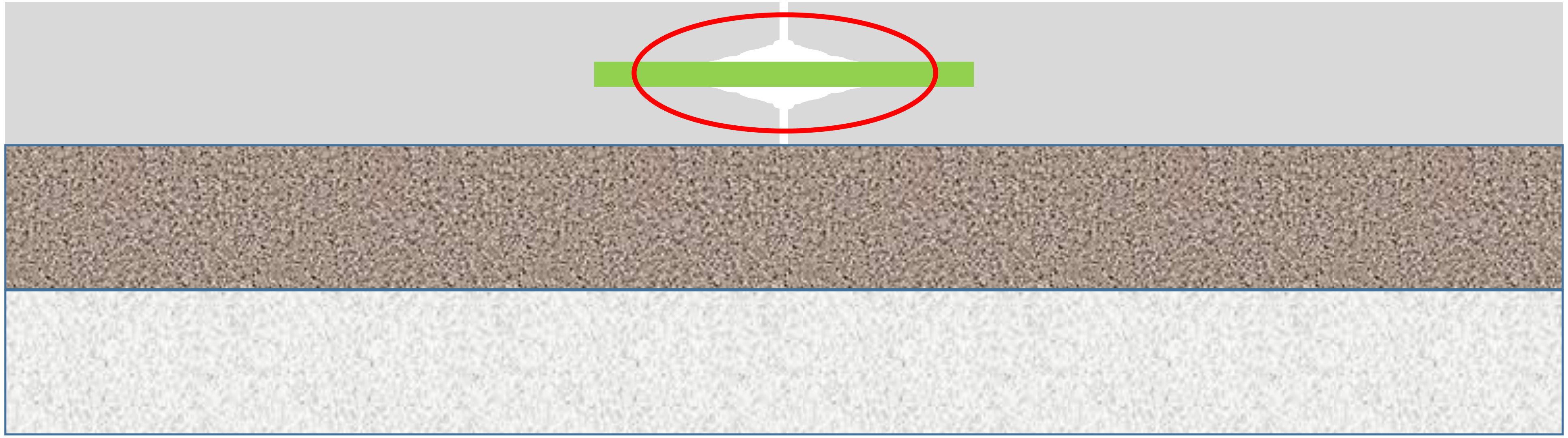


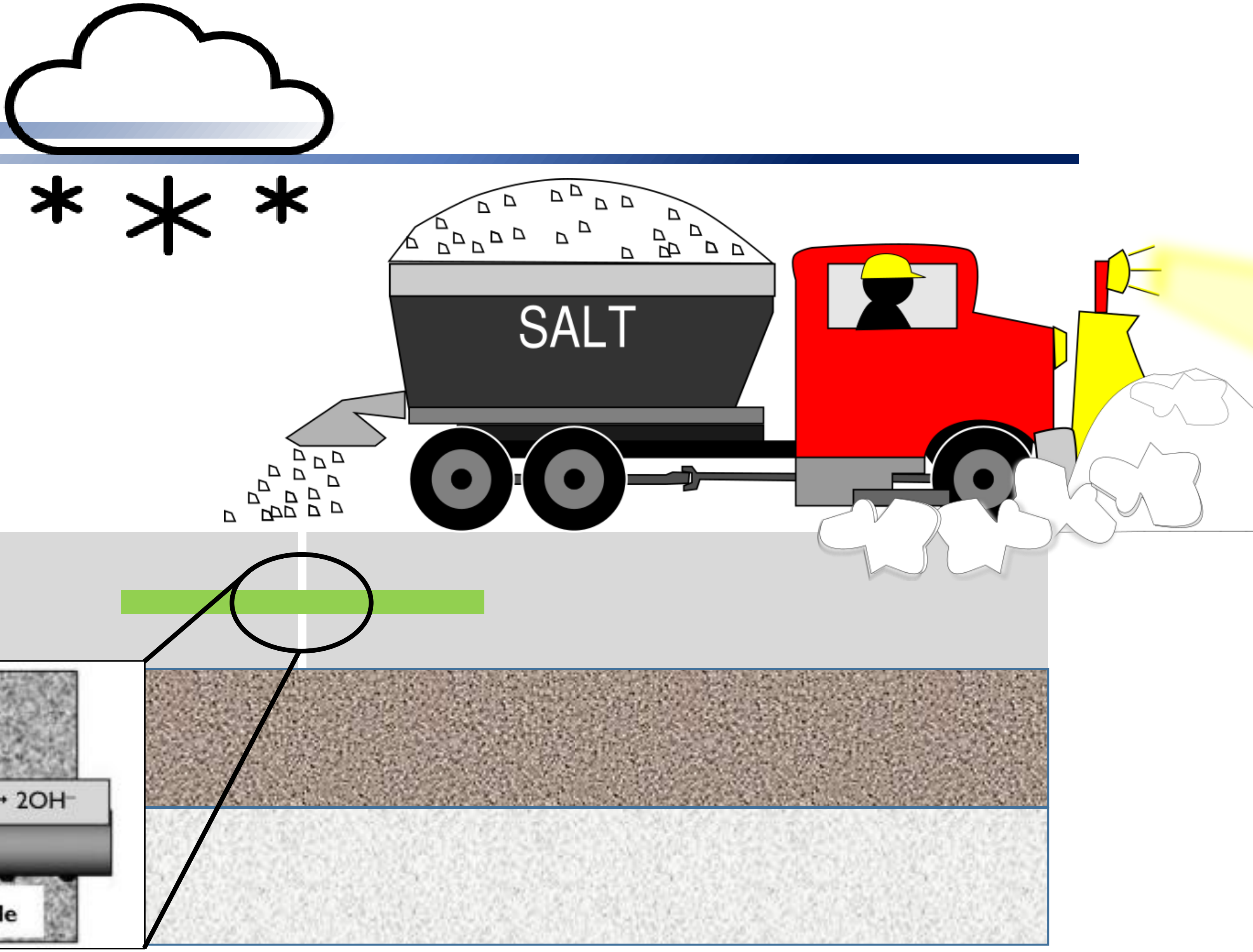
Marcus, Henri. "Load carrying capacity of dowels at transverse pavement joints." ACI Journal Proceedings. Vol. 48. No. 10. 1951.

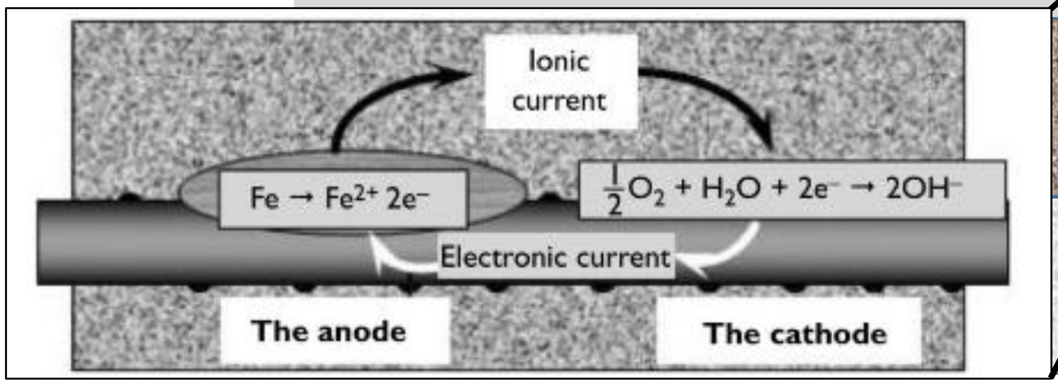
Looseness

Bearing stresses damage concrete around dowel



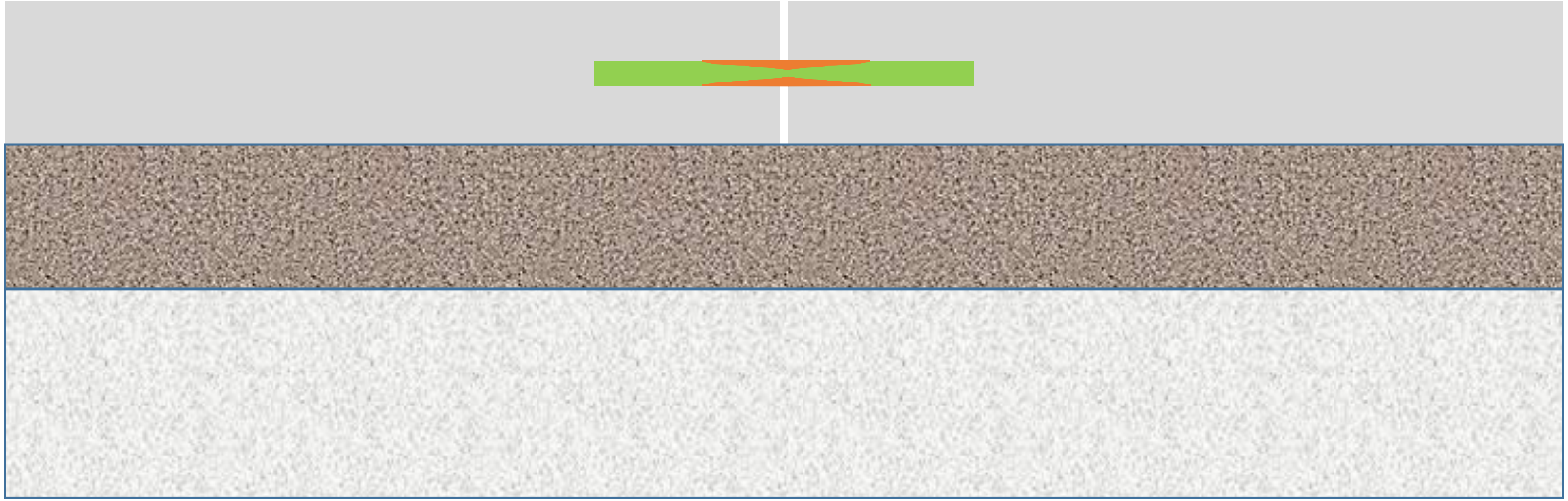
Corrosion


SALT


Ionic current
$Fe \rightarrow Fe^{2+} 2e^-$
$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$
Electronic current
The anode
The cathode

Corrosion

Corrosion causes decreases dowel diameter at joint



Objectives

Account for the following in faulting prediction models

1. Load damage (Decouple doweled and undoweled jts in calibration)
2. Incorporate non-standard dowel designs
3. Corrosion for both standard epoxy coated steel and long-life dowels

Dowel load damage model

Nonstandard dowels

Dowel corrosion model

Research approach

Laboratory analysis

Accelerated loading test

Characterize damage from vehicle loading

Accelerated corrosion test

Characterize damage from corrosion

Revise dowel damage model in faulting framework

Field data analysis

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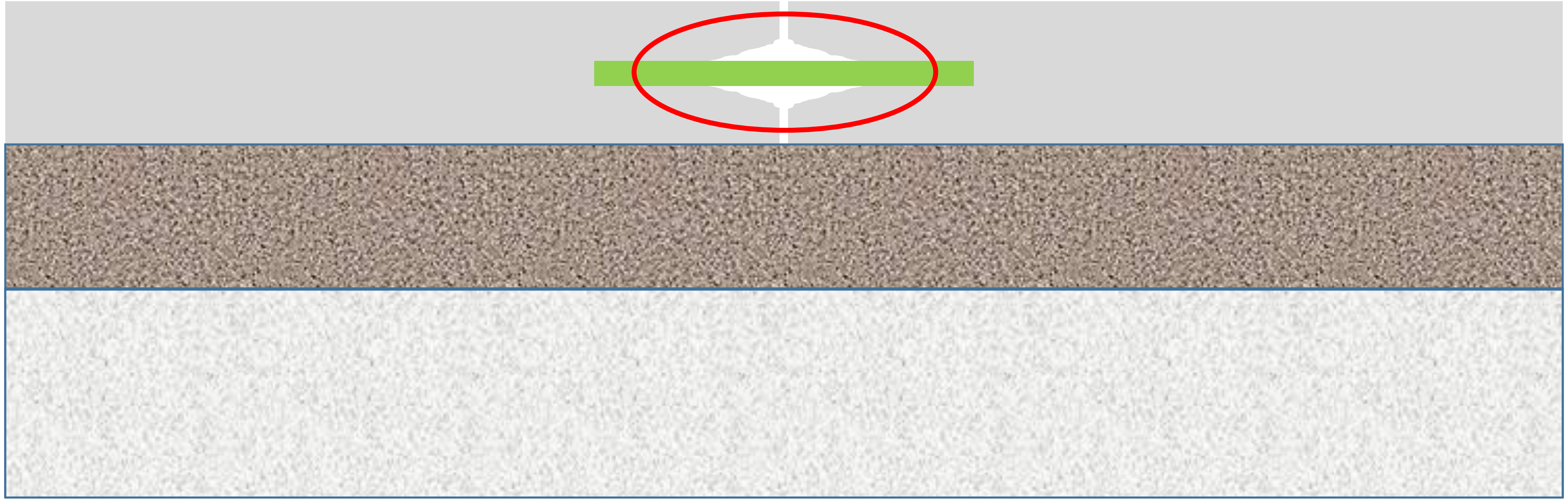
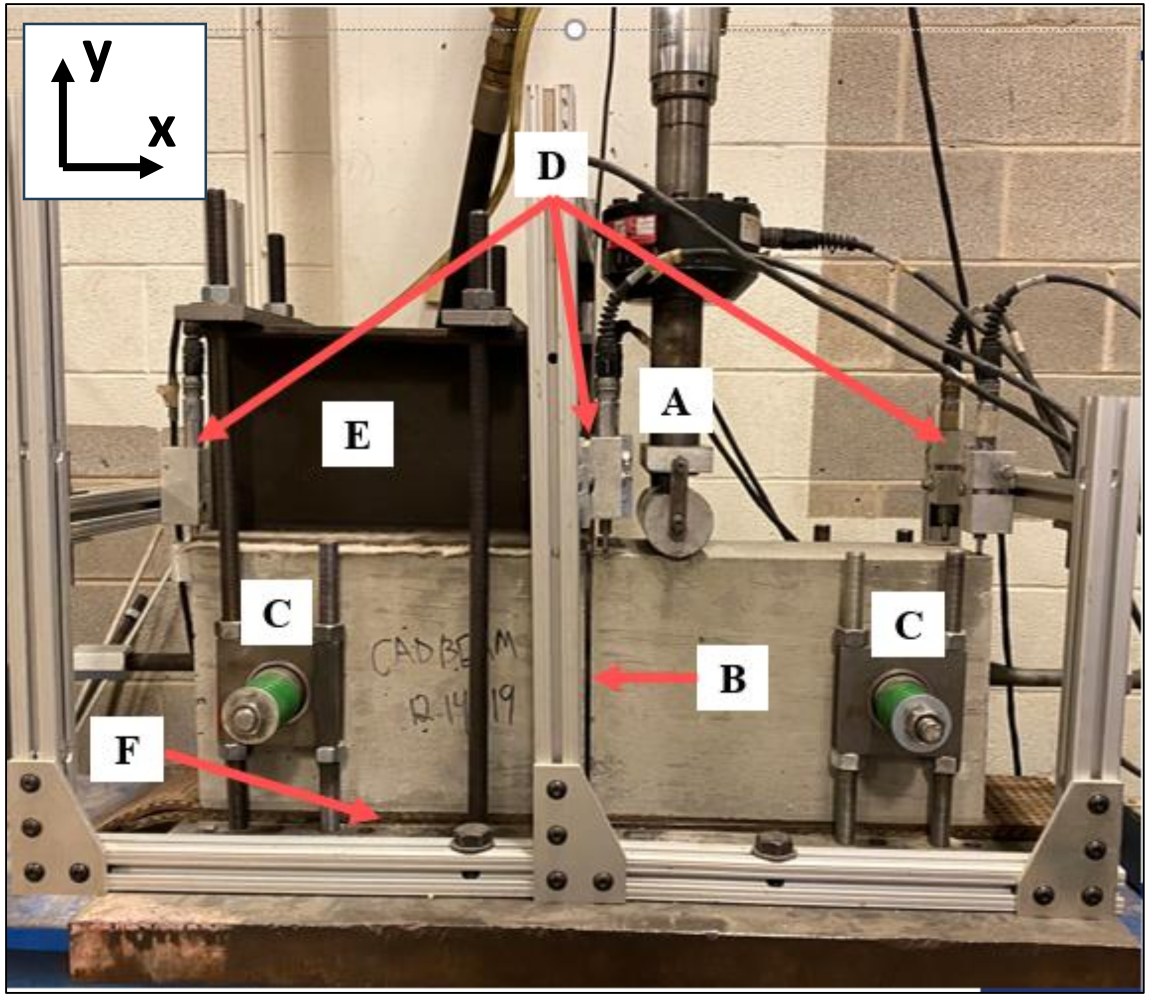
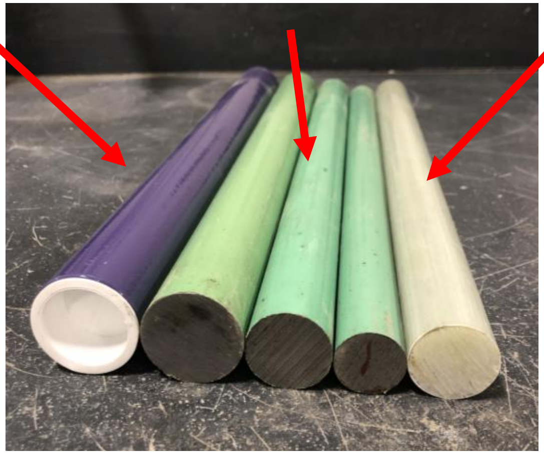


Laboratory setup



A – load head
B – joint
C – bearings
D – sensors
E – clamp
F – simulated base
k = 200 psi/in

Experimental design



$$B = \frac{E * I}{d}$$

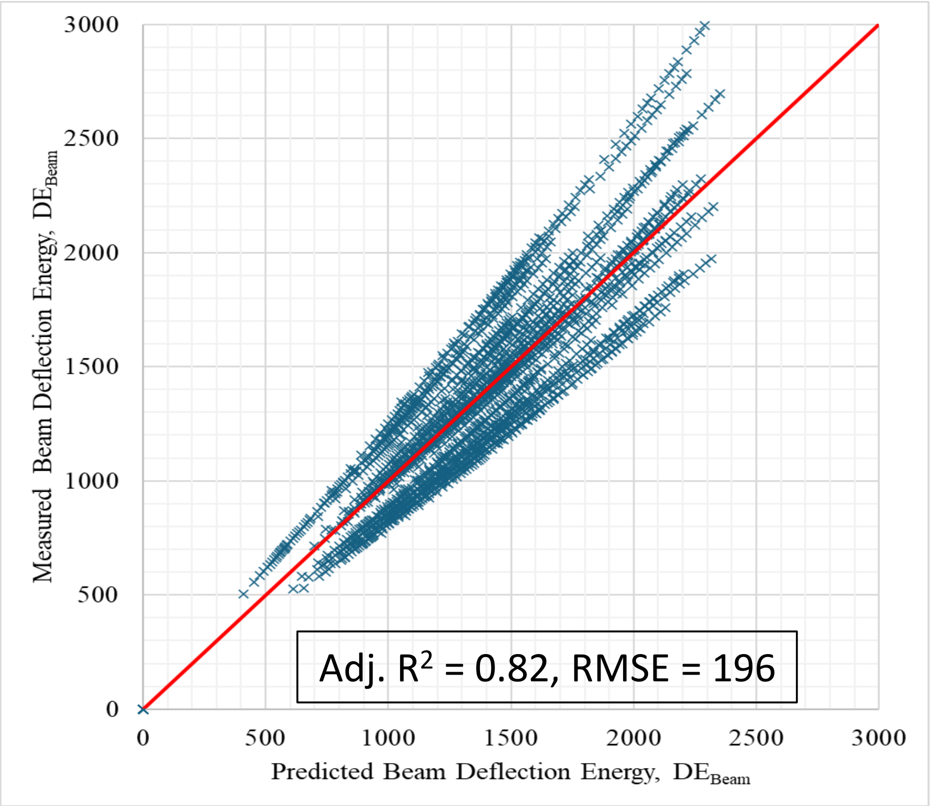
B = dowel stiffness
E = dowel elastic modulus
I = dowel moment of inertia
d = dowel diameter

		Dowel Diameter (in)					
		Low stiffness (7.5 – 1.4x10^5 lb·in)		Medium stiffness (2.8 – 3.2x10^6 lb·in)		High stiffness (4.1 – 5.0 x10^6 lb·in)	
Beam thickness (in)	Load	1	1.25	1.25	1.375	1.625	1.5
6	Low						
	Medium	EC	FRP	EC			
	High						
8	Low			EC			
	Medium	EC		EC	ET		
	High			EC			
10	Low						
	Medium			EC		ET	EC
	High			EC			EC

DE_{Beam} model

$$DE_{Beam} = \alpha_1 * \log(x+1) + \alpha_2 * \log(x+1) * \frac{\log(Load)}{\beta} + \alpha_3 * \frac{\log(x+1)}{\beta}$$

x = number of load cycles,
Load = applied load (lb),
$\beta = \sqrt[4]{\frac{K*d}{4*E_{dowel}*I}}$,
$K = \frac{E_{PCC}}{h_{PCC}}$ = modulus of dowel-concrete reaction (psi)
E_{PCC} = concrete elastic modulus (psi),
h_{PCC} = PCC thickness (in)
d = dowel diameter (in),
E_{Dowel}= dowel elastic modulus (psi),
I = moment of inertia (in^4),
C_8 = calibration coefficient
α_1 = 592.8, α_2 = 353.3, α_3 = -1256.5,



Research approach

Laboratory analysis

Accelerated loading test

Characterize damage from vehicle loading

Accelerated corrosion test

Characterize damage from corrosion

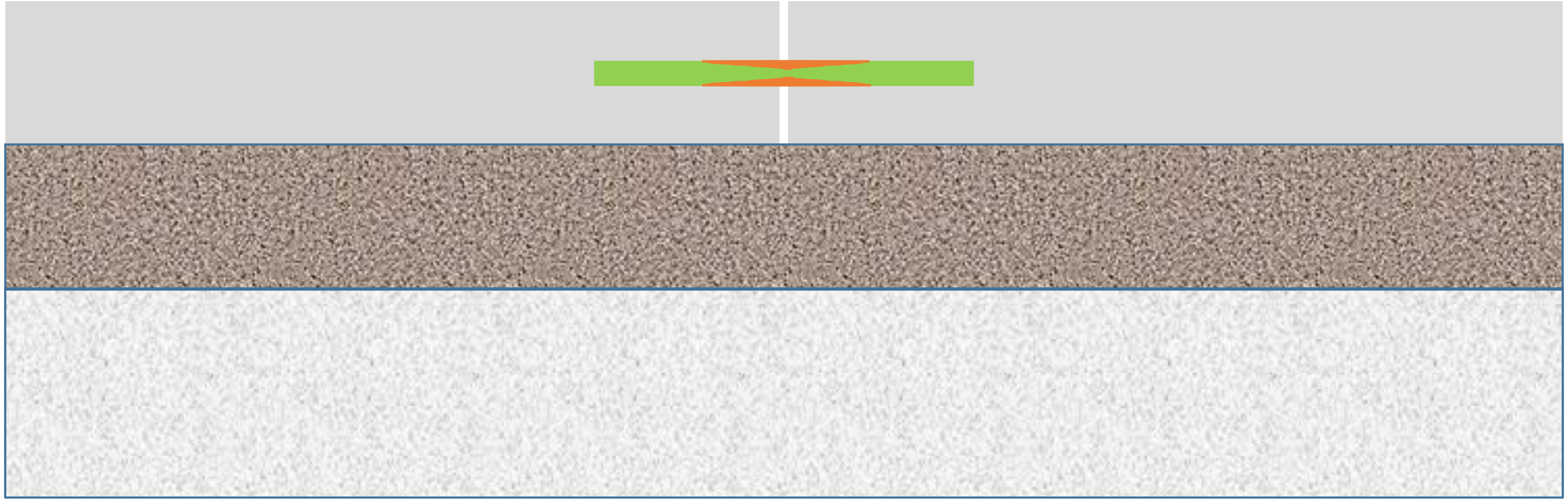
Revise dowel damage model in faulting framework

Field data analysis

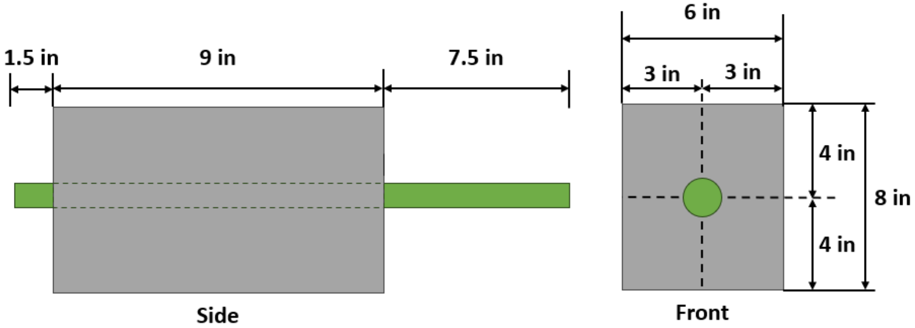
Calibrated faulting model

Corrosion

Corrosion causes decreases dowel diameter at joint



Experimental design

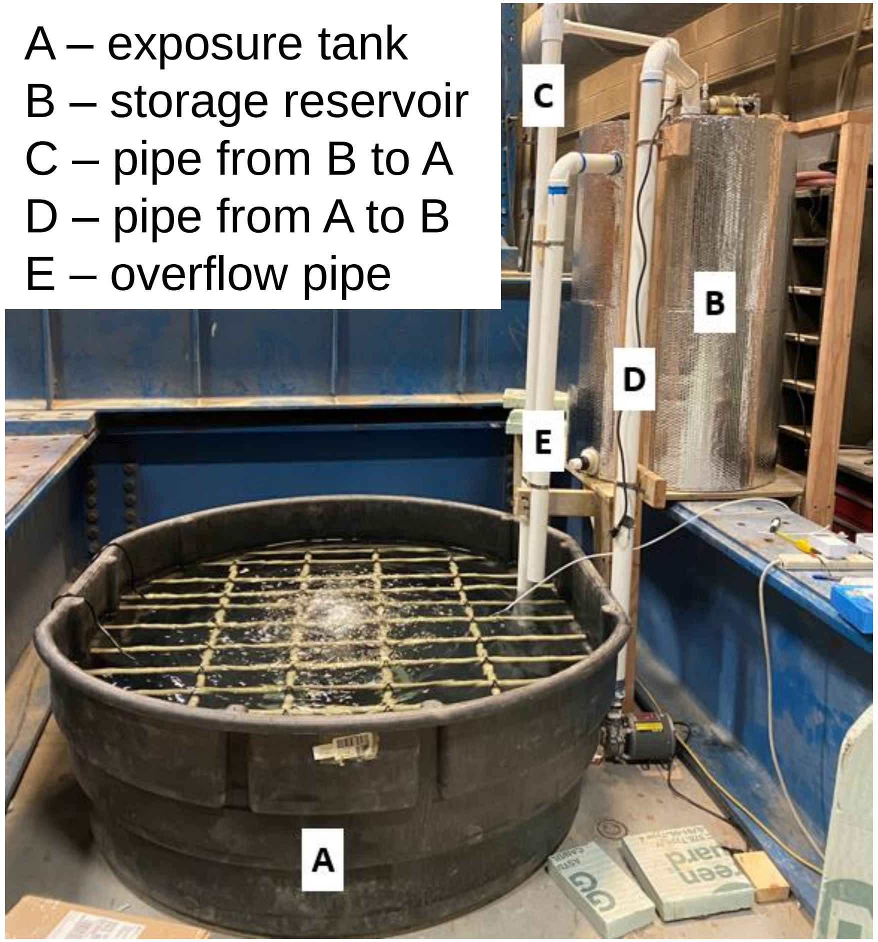


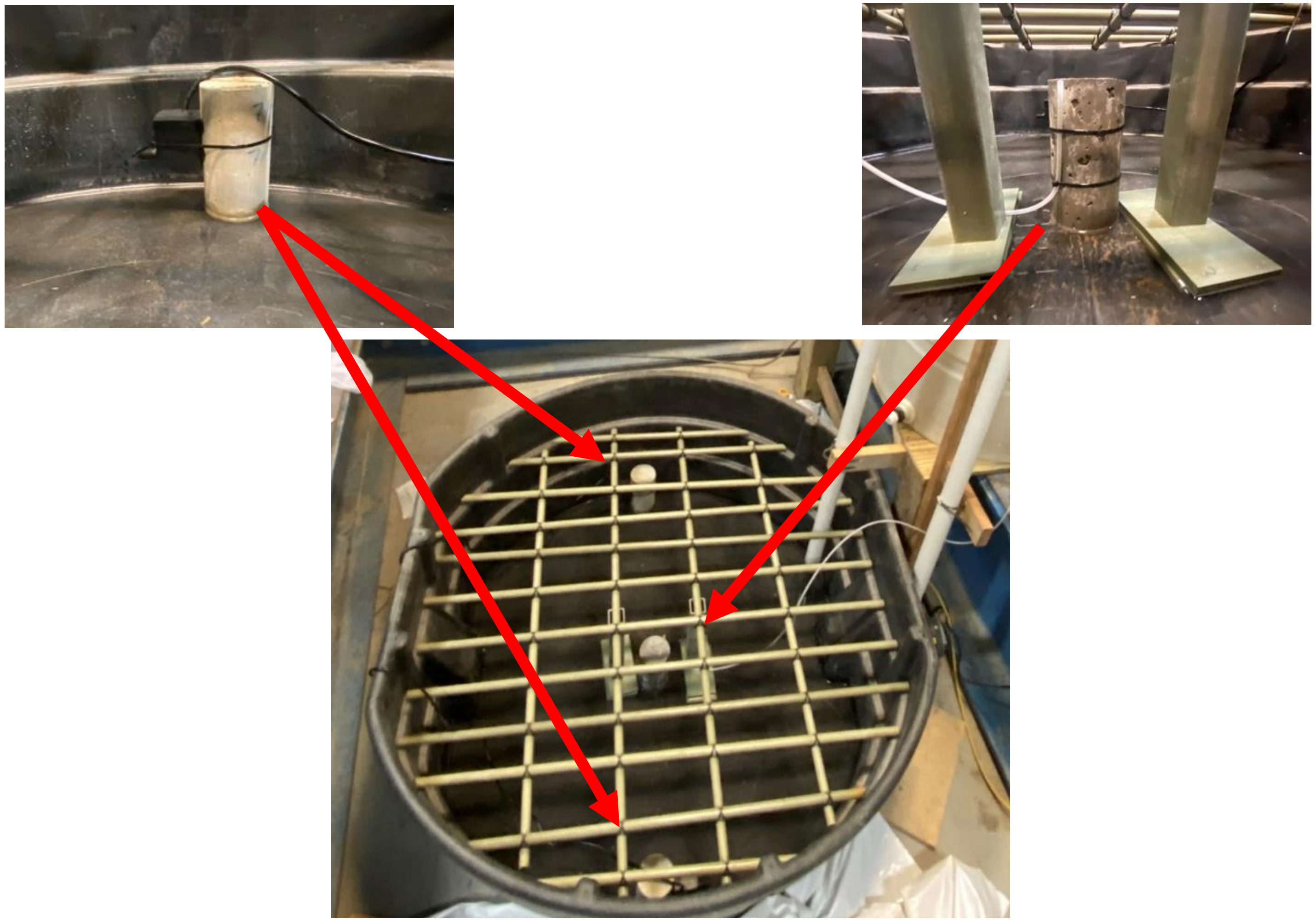
Three replicates per dowel, 21 total specimens

Dowel ID	Core material	Coating material	Approx. coating thickness (mil)	Dowel diameter (in)
C2G	Solid carbon steel	A775 (green) epoxy coating	20	1.25
C2P	Solid carbon steel	A934 (purple) epoxy coating	20	1.25
G1G	Tubular carbon steel with hot-dip zinc galvanized coating	A775 (green) epoxy coating	10	1.34
G1P	Tubular carbon steel with hot-dip zinc galvanized coating	A934 (purple) epoxy coating	10	1.34
C4Z	Tubular carbon steel	Mechanically bonded zinc cladding	40	1.70
SN	Tubular type 316L stainless steel	No coating	-	1.90
FN	Solid fiber-reinforced polymer (FRP)	No coating	-	1.25

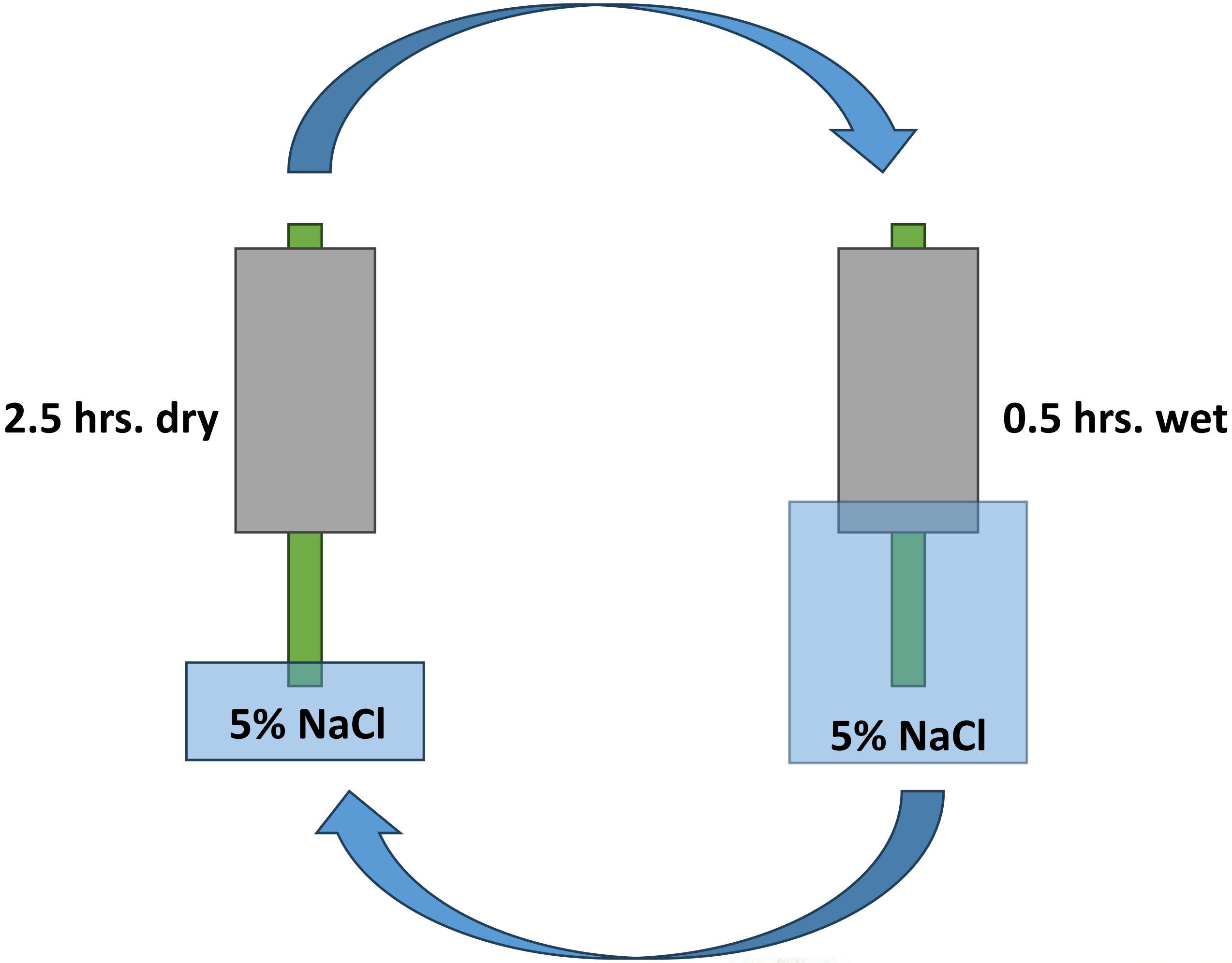
Corrosion setup

A – exposure tank
B – storage reservoir
C – pipe from B to A
D – pipe from A to B
E – overflow pipe





Corrosion program

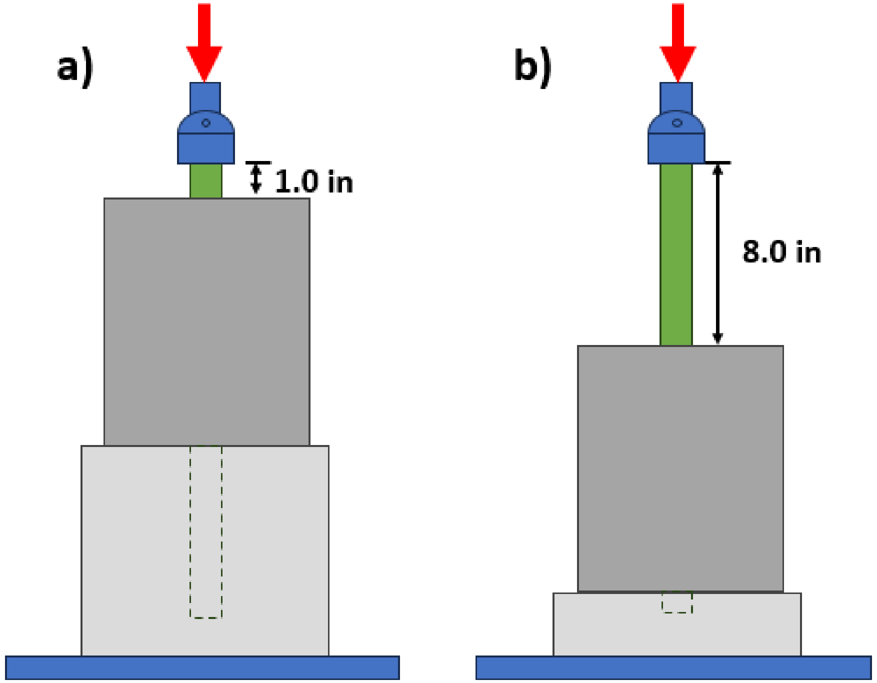


Simulated joint opening/closing

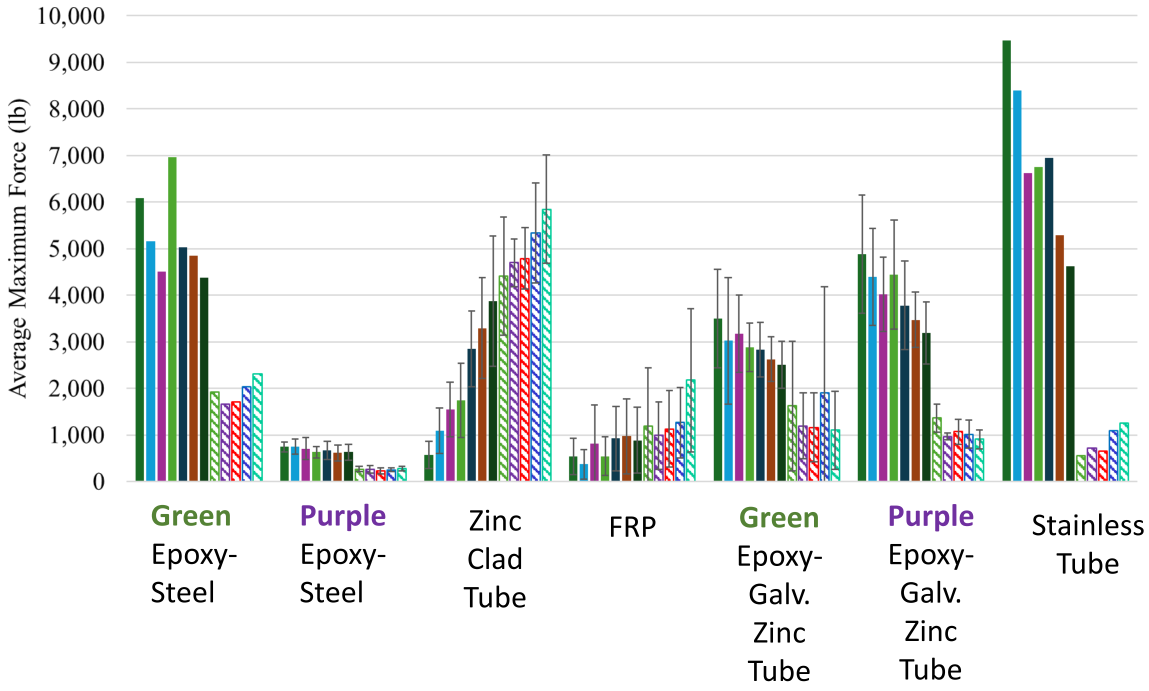
Objective:

Mobilize dowel

Evaluate potential for seizing

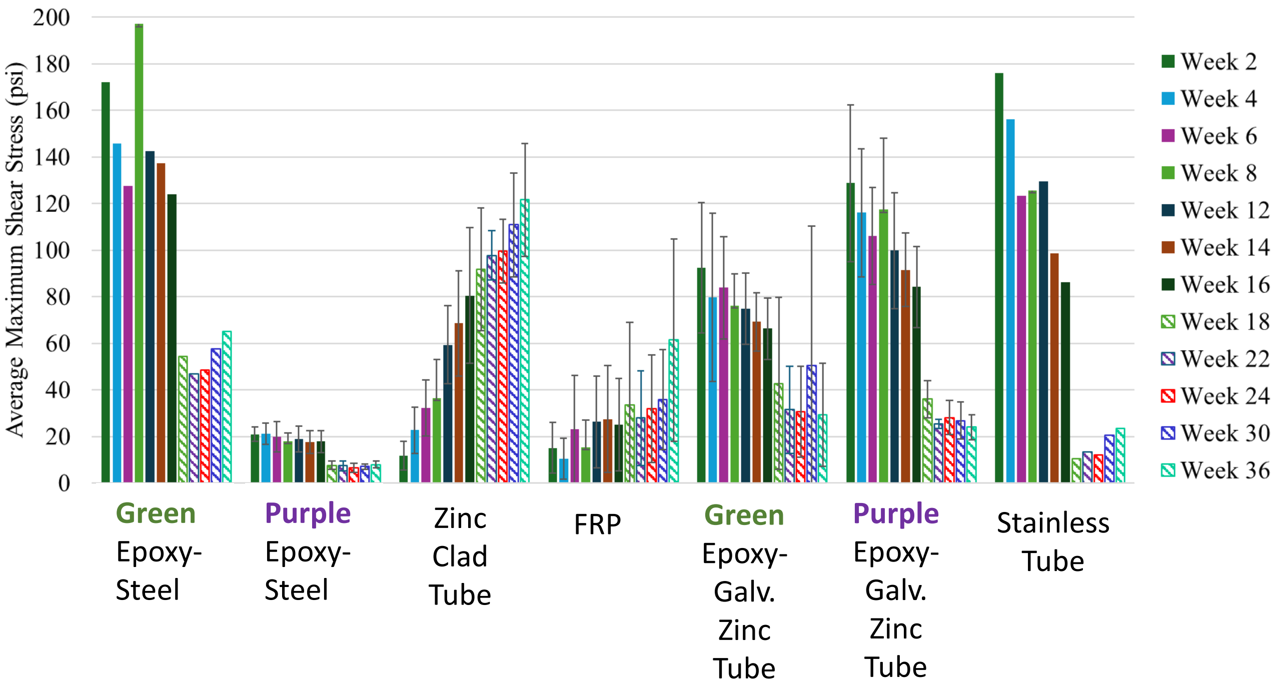


Simulated joint opening/closing



Average maximum force for joint opening/closing

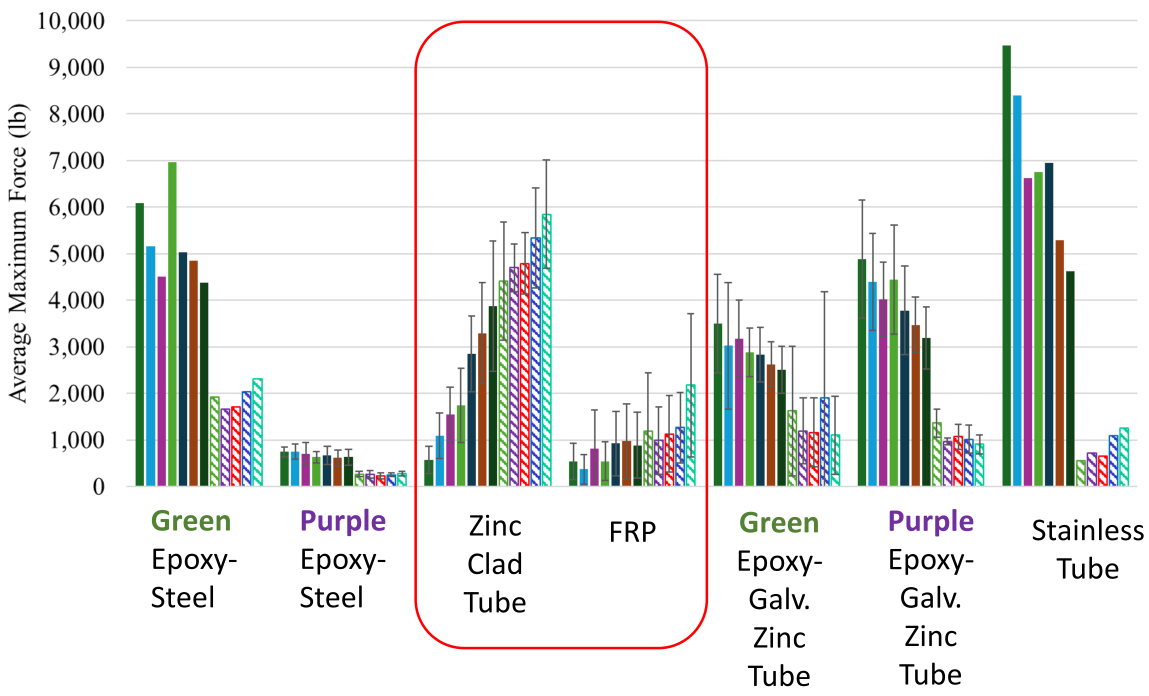
Dowel diameter and coating



Average maximum shear stress for joint opening/closing

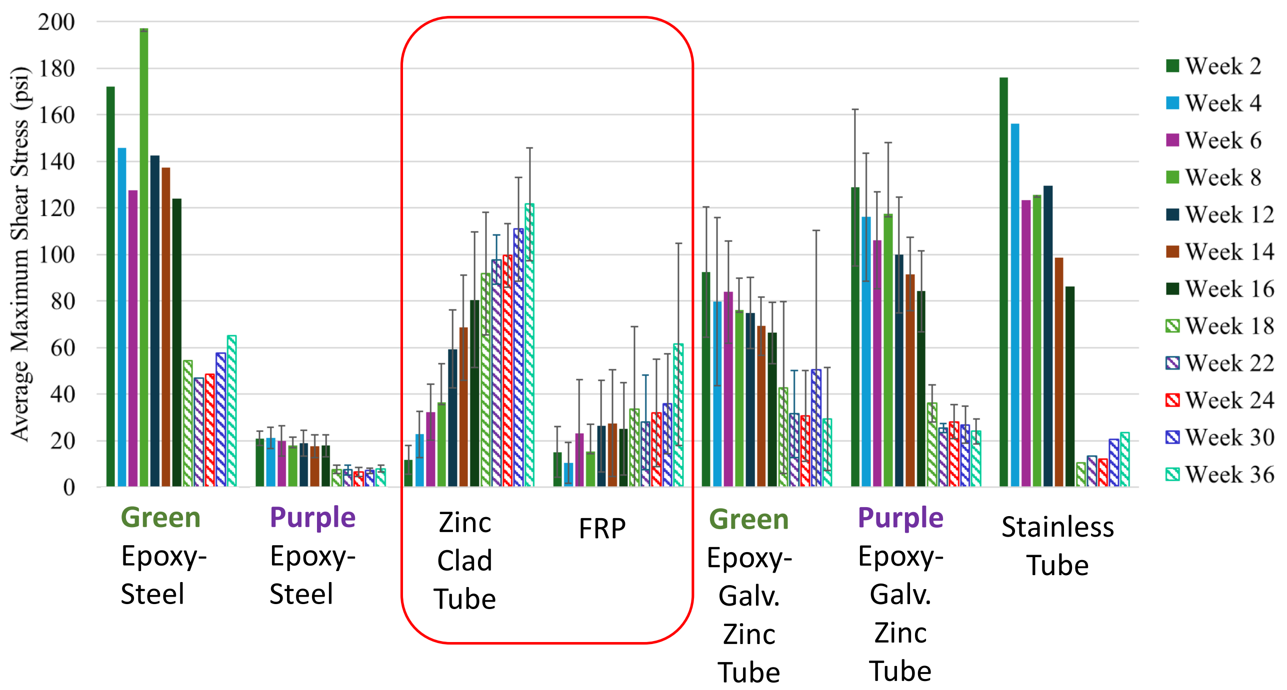
Coating

Simulated joint opening/closing: FRP? & Zinc clad



Average maximum force for joint opening/closing

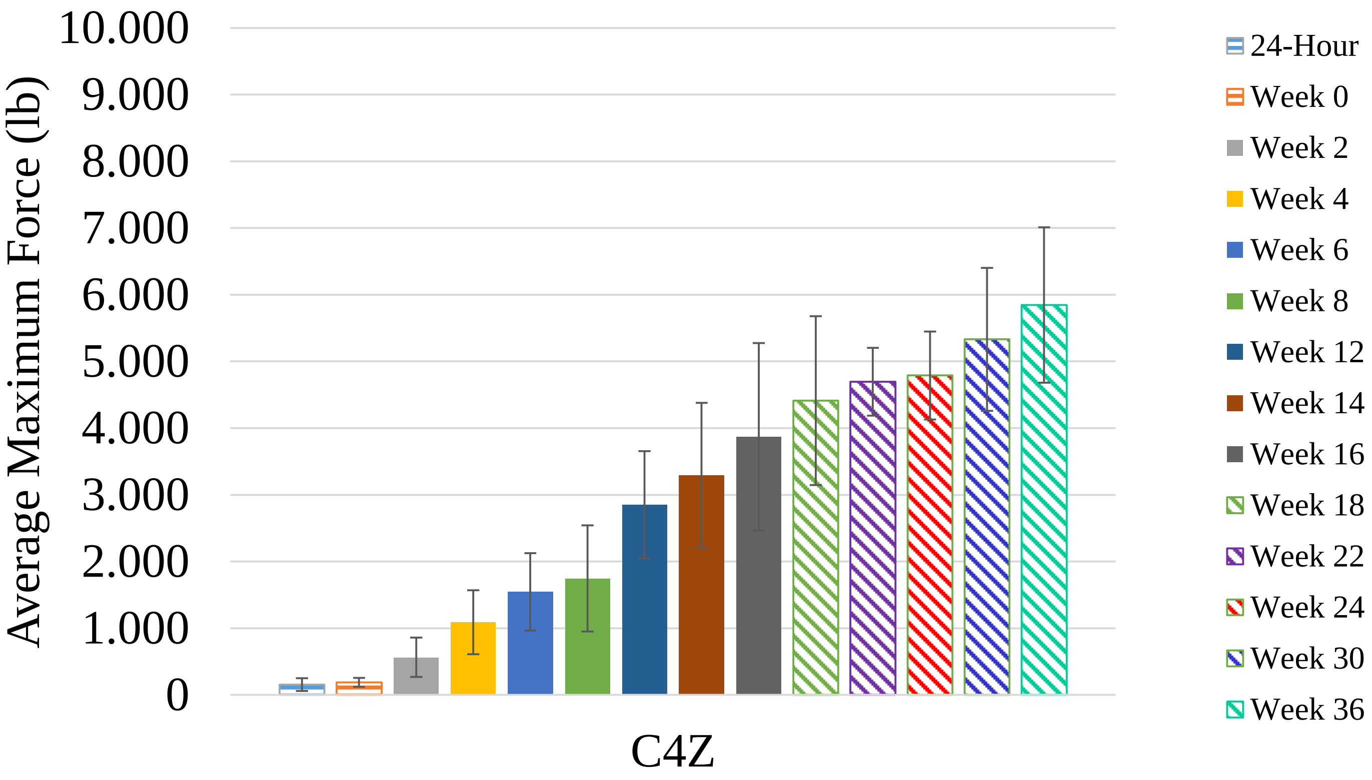
Dowel diameter and coating



Average maximum shear stress for joint opening/closing

Coating

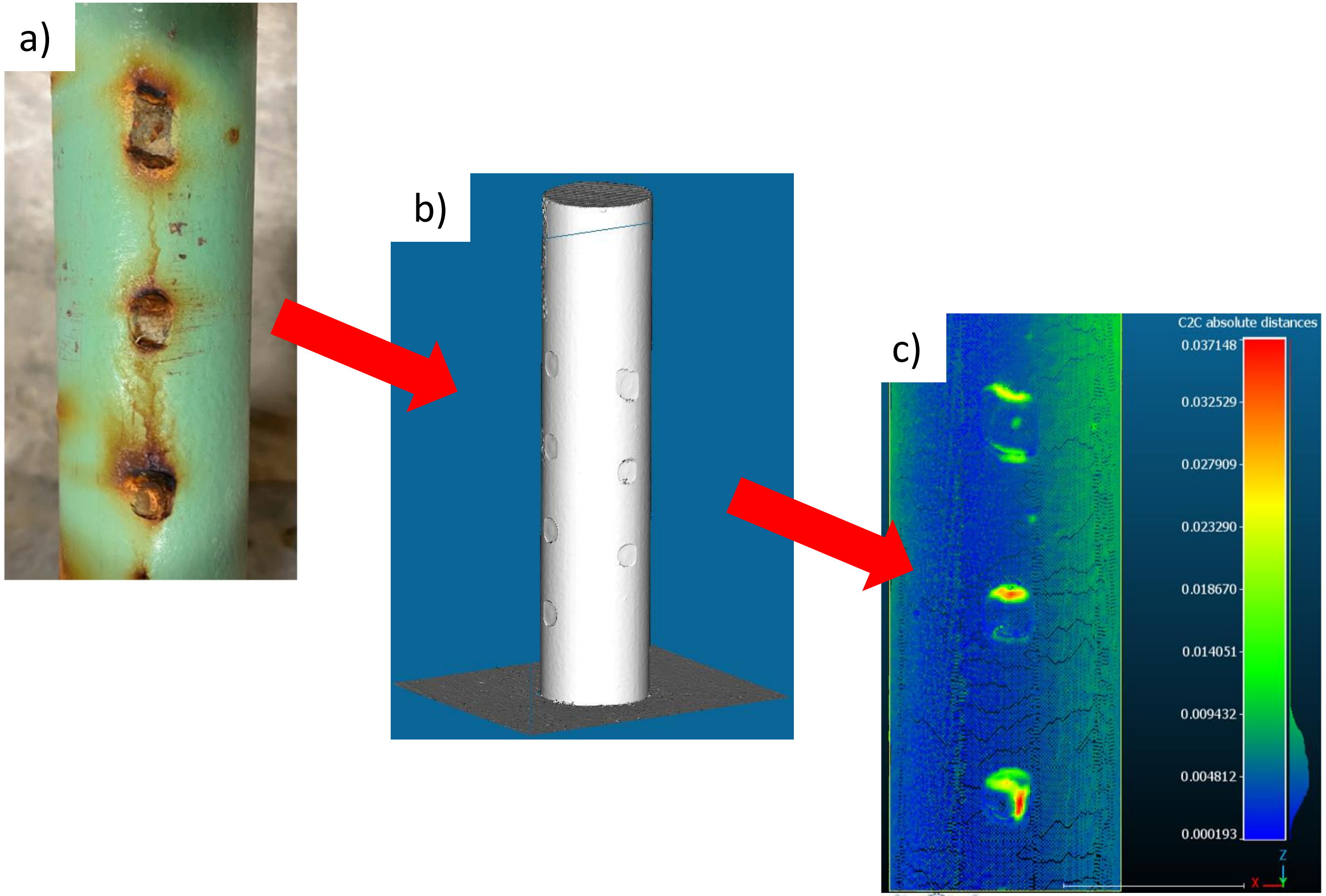
Simulated joint opening/closing



Zinc-clad dowel (C4Z)

Visualized corrosion progression

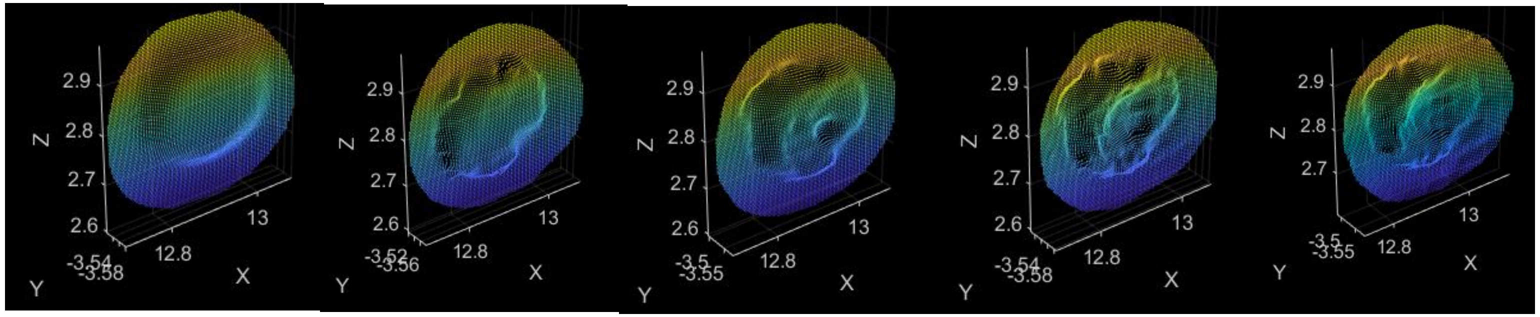
Quantum Max FaroArm®



Visualized corrosion progression

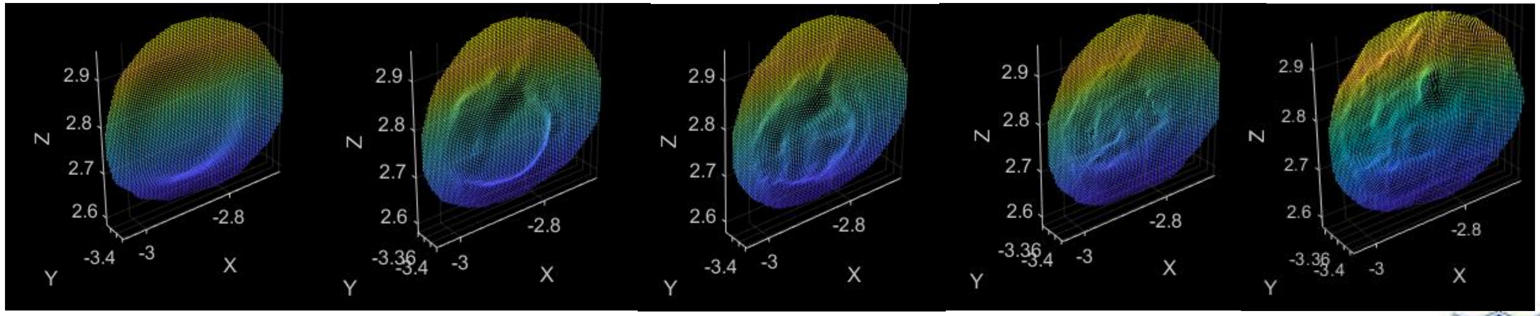
Carbon steel with green epoxy coating dowel (C2G)

Week 0 Week 4 Week 8 Week 16 Week 36

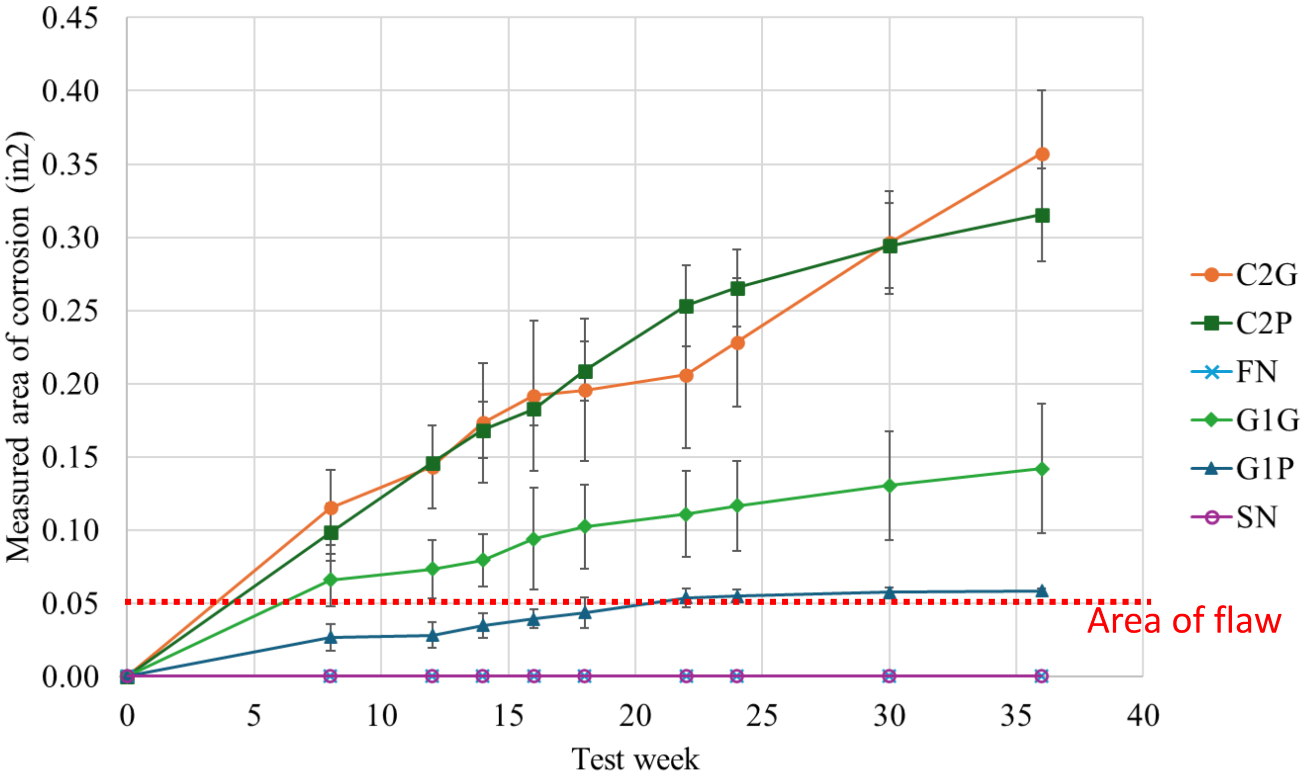


Carbon steel with purple epoxy coating dowel (C2P)

Week 0 Week 4 Week 8 Week 16 Week 36



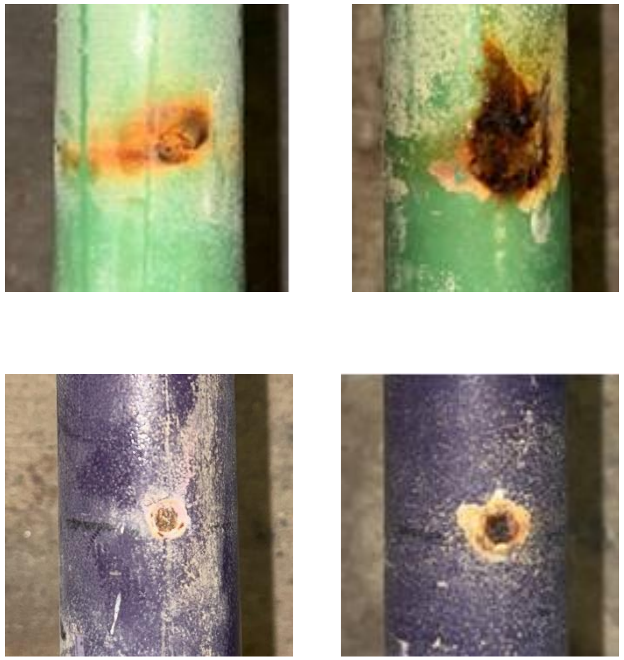
Corrosion area



Week 8 | Week 36

C2G

G1P



Progressive increase in surface area that corroded was estimated using ImageJ

Steel vs galvanized dowels

Corrosion rates (in^2/wk):

Purple vs Green steel:

C2G** approx. = **C2P

Purple vs Green galvanized:

C2G is **2.5x** faster than **G1P**

Steel vs galvanized

Green: **C2G & C2P** is **3x** faster than **G1G**

Purple: **C2G & C2P** is **7x** faster than **G1P**

- Galvanized layer reduces probability of corrosion development with double barrier system

Galvanized (G1P)

Carbon steel (C2P)

Purple vs green epoxy

- Pliable green epoxy coating tended to **bunch up and peel** during the joint opening/closing simulation
- Area of corrosion on the **G1G** dowels is **2.4x** greater than **G1P** dowels

C2G3

Zinc clad vs zinc galvanized

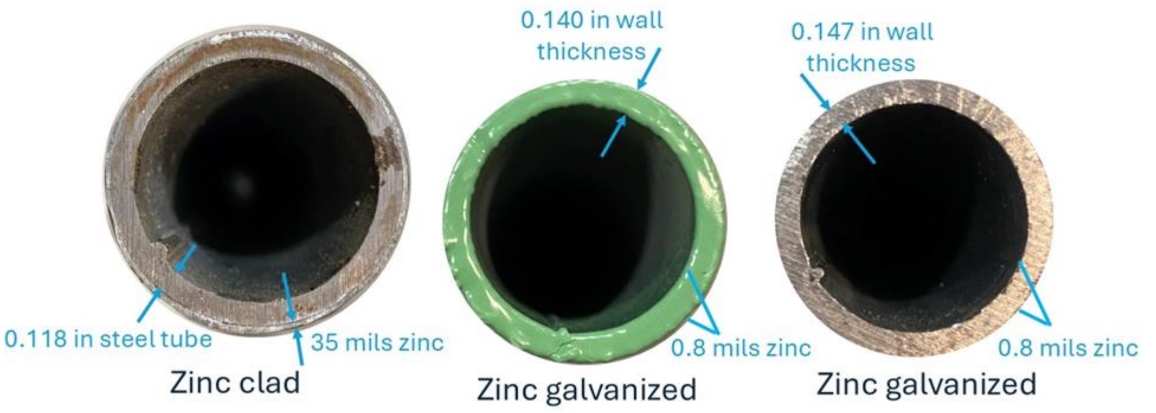
Degradation Process: depassivation **->** galvanized layer is dissolved **->** surrounding zinc is depleted **->** corrosion of the steel.

Zinc galvanized

- Dowel protected by epoxy coating then thin zinc galvanized layer

Zinc clad

- More pure zinc to react (35 mils vs 0.8 mils) = more zinc oxide produced
- Corrosion resistant but increased potential for spalling and joint lock-up



Zinc Galvanized

Zinc Clad

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Characterize damage from vehicle loading

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Characterize damage from corrosion

Revise dowel damage model in faulting framework

Calibrated faulting model

Field data analysis

Faulting model framework

$$FMAX_0 = (C_1 + C_2 * FR^{0.25}) * \delta_{curl} * \left[Log(1 + C_5 * 5^{EROD}) * Log\left(\frac{P_{200} * WetDays}{p_s}\right)\right]^{C_6}$$

$$FMAX_i = FMAX_{i-1} + C_7 * DE_i * [Log(1 + C_5 * 5^{EROD})]^{C_6}$$

$$\Delta Fault_i = (C_3 + C_4 * FR^{0.25}) * (FMAX_{i-1} - Fault_{i-1})^2 * DE_i$$

$$Fault_i = Fault_{i-1} + \Delta Fault_i$$

$FMAX_0$ = Initial maximum mean transverse joint faulting (in.),
FR = Base freezing index defined at the percentage of the time that the top of the base is below freezing,
δ_{curl} = Maximum mean monthly PCC upward slab corner deflection due to temperature curling and moisture warping,
EROD = Base/subbase erodibility index (Integer between 1 and 5),
P_{200} = Percent of the subgrade soil passing No. 200 sieve,
WetDays = Average number of annual wet days (> 0.1 in. of rainfall),
p_s = overburden on subgrade (psi),
$FMAX_i$ =Maximum mean transverse joint faulting for month i (in.),
$FMAX_{i-1}$ =Maximum mean transverse joint faulting for month i-1 (in.) (If i =1, $FMAX_{i-1} = FMAX_0$),
DE_i = Differential energy density of subgrade accumulated during month i,
$\Delta Fault_i$ = Incremental monthly change in mean transverse joint faulting during month i (in.),
FR = Base freezing index defined at the percentage of the time that the top of the base is below freezing (<32 ^{o}F),
$Fault_{i-1}$ = Mean joint faulting at the beginning of month i (in.) (0 if i = 1),
$C_1 \ldots C_7$ = Calibration coefficients.

Dowel damage model

$$J_d = J^*{}_d + (J_0 - J^*{}_d)\exp(-DAM_{dowels})$$

$$\Delta DOWDAM = C_8 * \frac{J_d * (\delta_L - \delta_{UL}) * DowelSpace}{d\ f^*{}_c}$$

J_d = nondimensional dowel stiffness
$J^*{}_d$ = critical nondimensional dowel stiffness
J_0 = initial nondimensional dowel stiffness
DAM_{dowels} = damage from past loading at the doweled joints
$\Delta DOWDAM$ = incremental change in dowel damage for current month
δ_L = deflection of the loaded slab, in
δ_{UL} = deflection of the unloaded slab, in
C_8 = Calibration constant
DowelSpace = Dowel spacing, in
$f^*{}_c$ = Concrete compressive strength

Proposed damage model

$$DOWDAM = \begin{cases} C_{Corr} * \sum [\, \alpha_1 * log(x_i + 1) + \alpha_2 * log(x_i + 1) * \frac{log(Load_i)}{\beta} + \alpha_3 * \frac{log(x_i + 1)}{\beta}] & if\ Load_i \geq 900 \\ C_{Corr} * \sum \frac{Load_i}{900} * [\, \alpha_1 * log(x_i + 1) + \alpha_2 * log(x_i + 1) * \frac{log(900)}{\beta} + \alpha_3 * \frac{log(x_i + 1)}{\beta}] & if\ Load_i < 900 \end{cases}$$

x = number of load cycles,
Load = applied load (lb),
Beta = $\sqrt[4]{\frac{K*d}{4*E_{dowel}*I}}$,
$K = \frac{E_{PCC}}{h_{PCC}}$ = modulus of dowel-concrete reaction (psi)
E_{PCC} = concrete elastic modulus (psi),
h_{PCC} = PCC thickness (in)
d = dowel diameter (in),
E_{Dowel}= dowel elastic modulus (psi),
I = moment of inertia (in^4),
α_1 = 592.8, α_2 = 353.3, α_3 = -1256.6,
C_8 = calibration coefficient,
t = pavement age (months),
C_{EXP} = exposure rating,
$C_{Coating}$ = coating rating, and
jw = joint width (in)

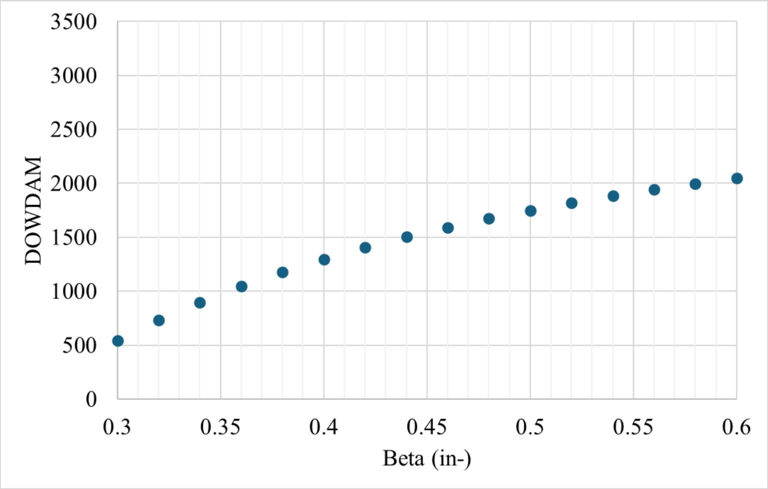
$$C_{Corr} = C_8 * t^{C_{EXP} * C_{Coating}}$$

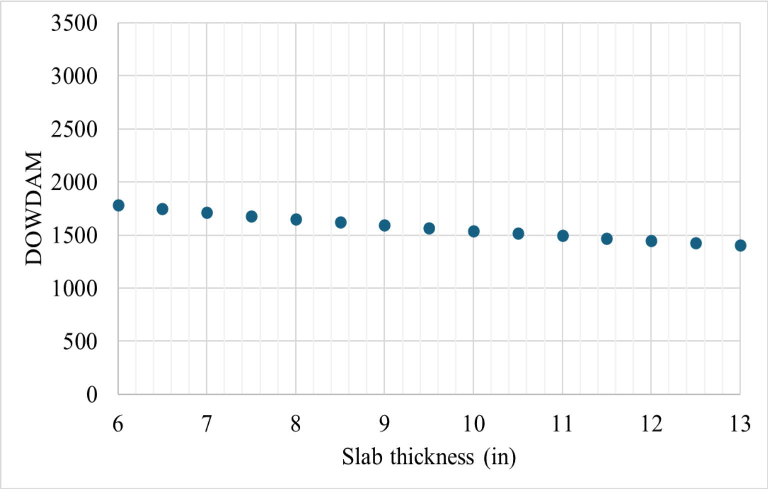
Freezing index (°F day)	C_{EXP}
< 100	0
100 - 400	0.15
400 - 600	0.2
600 - 1000	0.25
> 1000	0.25

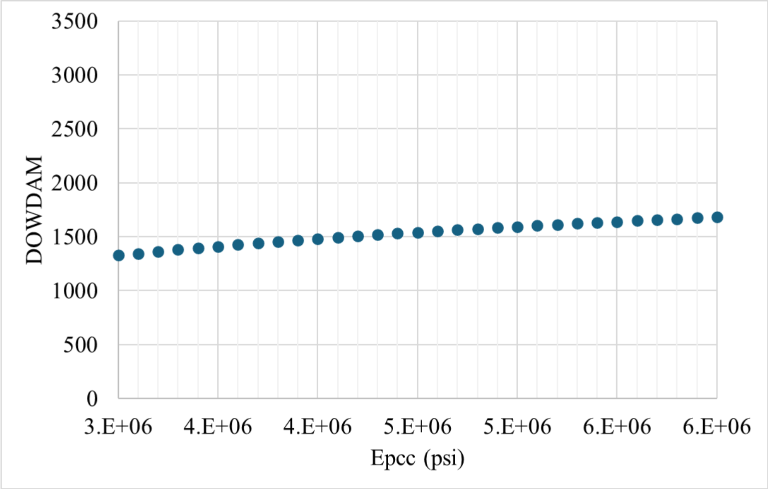
$$C_{Coating} = \alpha * (\pi * d) * jw$$

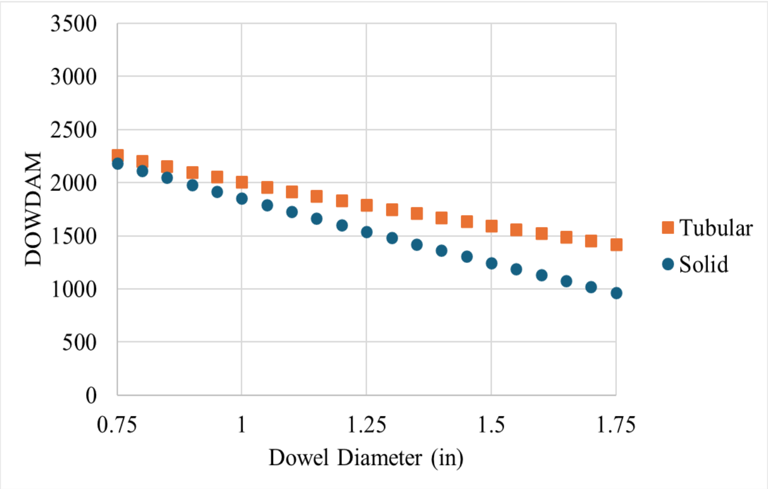
Dowel coating and material type	α
Epoxy-coated steel	0.15 (20 yrs;1x))
Green galvanized	0.075 (40 yrs; 3x)
Purple galvanized	0.01 (50 yrs; 7x)
Non-corrodible bars (FRP & stainless steel)	0 (never)

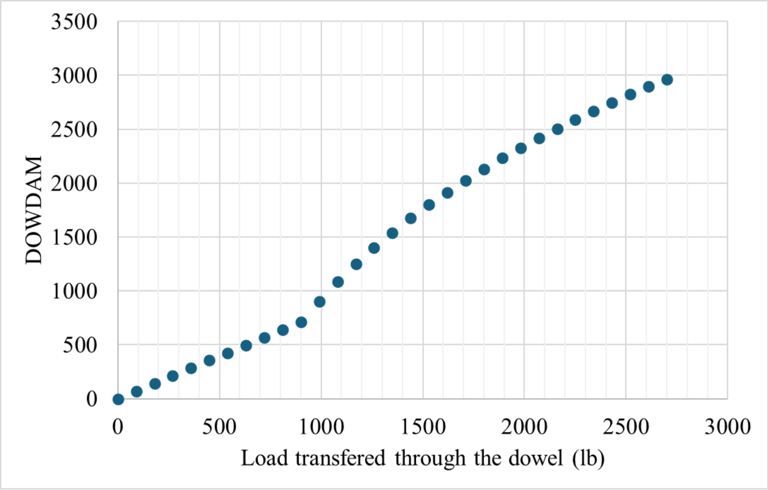
DOWDAM sensitivity

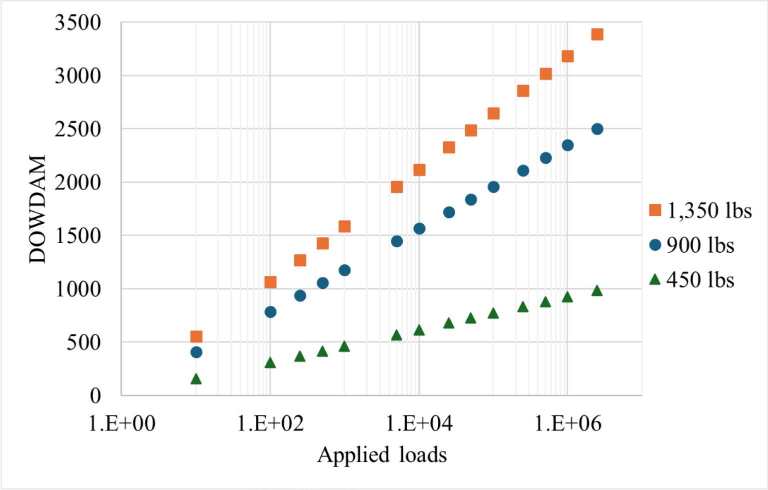












Conclusions

- Abrasion and impact resistance testing – **All passed**
  - Majority of dowels pass performance requirements
- Corrosion not correlated to dowel mobilization force for epoxy coated and stainless
  - Application of bond breaker is imperative
  - Zinc clad oxidizes -> increasing pushout force
- Epoxy galvanized steel developed less corrosion than epoxy carbon steel
- Epoxy coating effective in preventing corrosion if coating is undamaged
- Green epoxy more susceptible to peeling on carbon steel bars
- Improved faulting model developed
  - Supplement to PavementME Design procedure
  - Corrosion and vehicular loading damage accounted for (calibrated separate from undoweled pavements)
  - App developed to assist with implementation

Acknowledgements

CAWP
Constructors Association of Western Pennsylvania

CDR | MAGUIRE ENGINEERING

PITT | IRISE
ALLEGHENY COUNTY
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Federal Highway Administration

CMC

O-DOWEL

Thank you!

Questions?