# Analysis and Evaluation of Reinforced Concrete Bridges with Flexural Cutoffs at Diagonal Crack Locations

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Western Bridge Engineer's Seminar

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# Outline

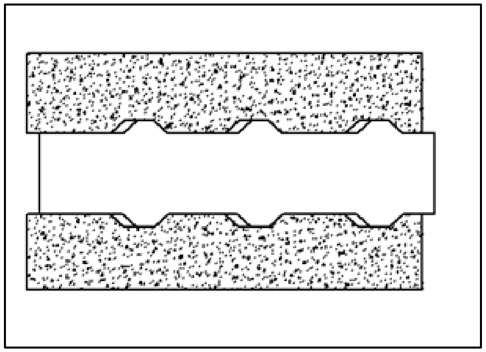
- Introduction and Objective
- Test Program
- Experimental Results
- Analysis
- Conclusions



# Introduction

# What is Anchorage?

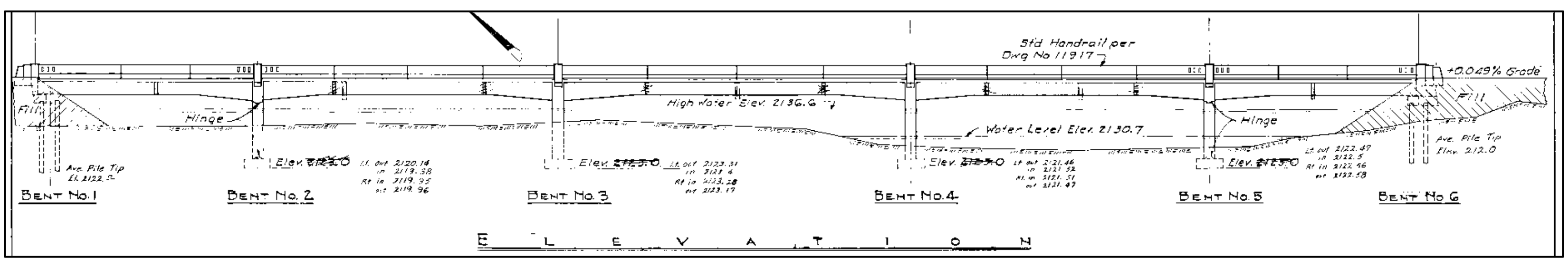
- Anchorage is the result of the development of bond between reinforcing bars and surrounding concrete.
- Loads applied to a bridge girder affect the strain and corresponding bond demand on reinforcing bars.
- Anchorage slip occurs when demand exceeds available anchorage capacities.
- Currently, design specifications are used to determine sufficient anchorage lengths.



-Triska, 2010-

# Anchorage in Vintage Bridges

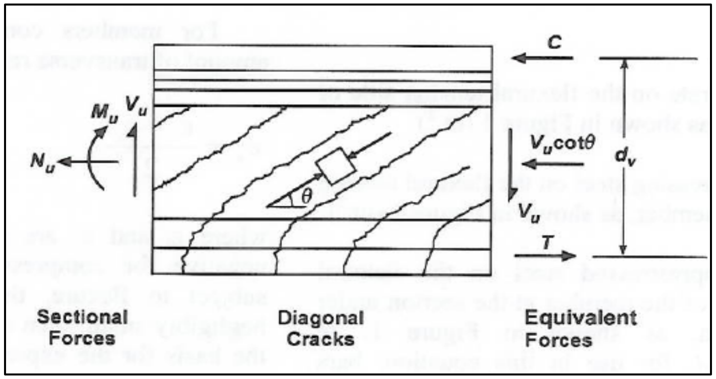
- Cutoff details in 1950s and 60s reinforced concrete deck girder (RCDG) bridges
- Load-induced diagonal cracking bisects cutoff reinforcement
- Diagonal cracking may affect anchorage development
- Concerns in predicting failure mode




Malheur River Bridge
-ODOT Bridge Inventory-

# Current Anchorage Pitfalls

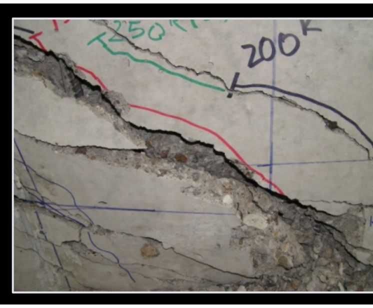
- Current load ratings use design specifications
- Design specifications are conservative and may under-predict tensile capacity
- May lead to erroneous repair and replacement prioritization




AASHTO-LRFD Figure 5.8.3.4.2-1

# Research Objectives

- Experimentally asses the role of diagonal cracks on cutoff reinforcement bond development in vintage RC girders.
- Using test data, provide rating engineers and inspectors with enhanced methods of rating and inspecting bridges with flexural anchorage cutoffs

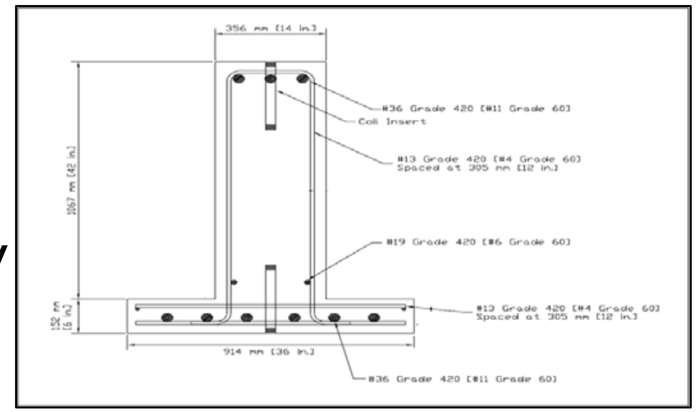




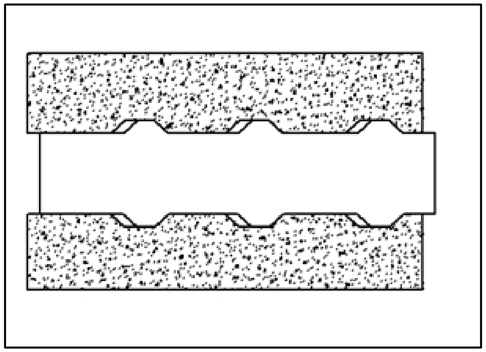
# Test Program

# Specimens

- 4 Inverted-T (IT) Girders
  - IT.45.Ld2(6)
  - IT.45.Ld2(5)
  - IT.60.Ld2(6)
  - IT.60.Ld2(5+19)
- Pre-defined initial crack geometry
- Longitudinal reinforcement
  - 2 bars cutoff
  - Remaining bars extend beyond supports
- 10″-12″ stirrup spacing
- One side over-reinforced – 6″ stirrup spacing
- Additional data from SPR 350 specimens



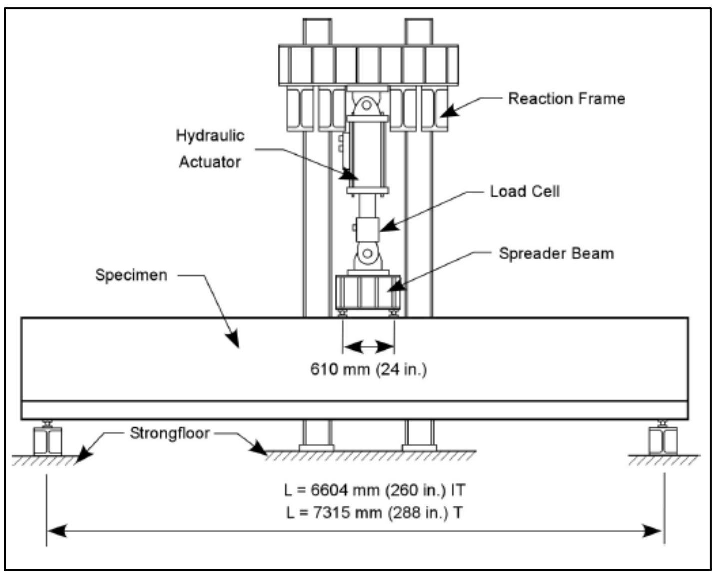
# Materials



- Reinforcing Steel
  - 40 ksi stirrups
  - 60 ksi longitudinal bars
    - Anchorage due to mechanical interlock
- Concrete Mix
  - Class "A" AASHO
  - Specified 28-day strength of 3300 psi
- Pre-formed Crack
  - 1/16" polycarbonate sheet
  - Installed at pre-specified angles

# Test Setup

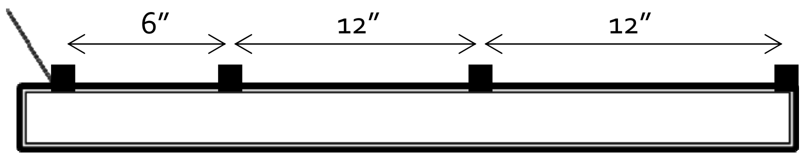
- Four-point cyclic loading
- Closed-loop, servo-hydraulic
- Load control 1k/s - 500k capacity




| Load Step | |
|---|---|
| (kN) | (kip) |
| 0-111.2 | 0-25 |
| 22.2-222.4 | 5-50 |
| 22.2-333.6 | 5-75 |
| 22.2-444.8 | 5-100 |
| 22.2-667.2 | 5-150 |
| 22.2-889.6 | 5-200 |
| 22.2-1112.0 | 5-250 |
| 22.2-1334.4 | 5-300 |
| 22.4-1556.8 | 5-350 |
| 22.4-1779.2 | 5-400 |
| 22.4-2001.6 | 5-450 |

# Instrumentation

- Midspan Displacement
- Reinforcing Bar Strain
- Cutoff Bar Slip




Test Program



# Experimental Results

# Specimen Faliure

- Failure Load

| Specimen | Applied Failure Load [kip] | Net Applied Shear [kip] | Self-Weight Shear [kip] | Total Shear at Failure [kip] |
|---|---|---|---|---|
| IT.45.Ld2(6) | [450] | [225] | [3.4] | [229] |
| IT.60.Ld2(6) | [351] | [175] | [7.6] | [183] |
| IT.45.Ld2(5) | [359] | [179] | [4.8] | [186] |
| IT.60.Ld2(5+19) | [364] | [182] | [4.8] | [187] |

- Failure Type

| Specimen | Failure Mode | Failure Crack Angle (degrees) | Midspan Deflection [in] |
|---|---|---|---|
| IT.45.Ld2(6) | Shear-Compression | 32 | [0.97] |
| IT.60.Ld2(6) | Shear-Compression | 60 | [0.69] |
| IT.45.Ld2(5) | Shear-Anchorage | 44 | [0.98] |
| IT.60.Ld2(5+19) | Shear-Anchorage | 45 | [1.05] |

# Specimen Faliure

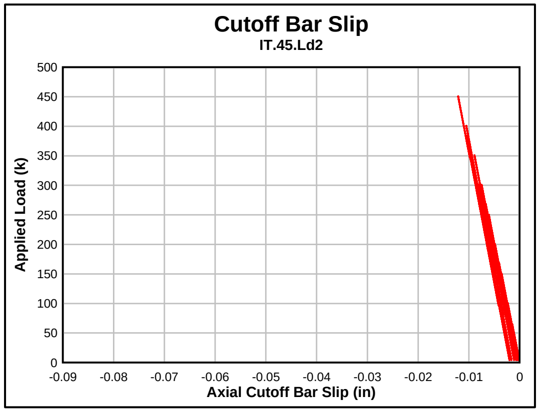
- Failure Photos

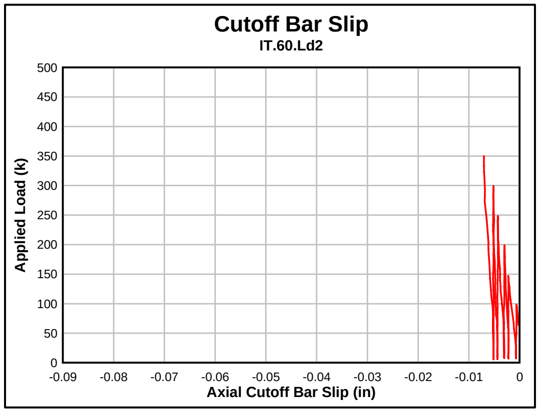


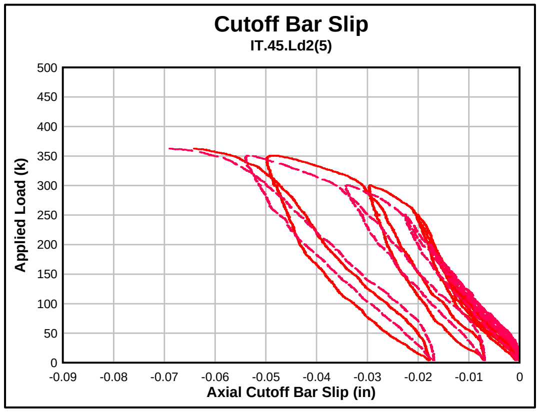

- Shear-Compression
- Shear-Anchorage

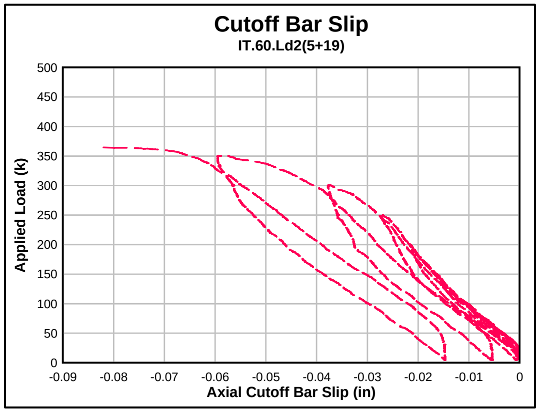
# Anchorage – Bar Slip

- Average Cutoff Bar Slip




- Shear-compression failures: negligible bar slip

- Shear-anchorage failures: noticeable, permanent bar slip

# Anchorage – Bond

- Measured Maximum Average Bond Strength

| Specimen | Cutoff Bars | Well Anchored Bars |
|---|---|---|
| | Average Bond Strength [psi] | |
| IT.45.Ld2(6) | [405] | [345] |
| IT.60.Ld2(6) | [459] | [374] |
| IT.45.Ld2(5) | [648] | [396] |
| IT.60.Ld2(5+19) | [634] | [396] |

- Maximum average bond strength
  - Anchorage Failure – 642 psi
  - Well Anchored Bars – 378 psi

# Anchorage – Tensile Development

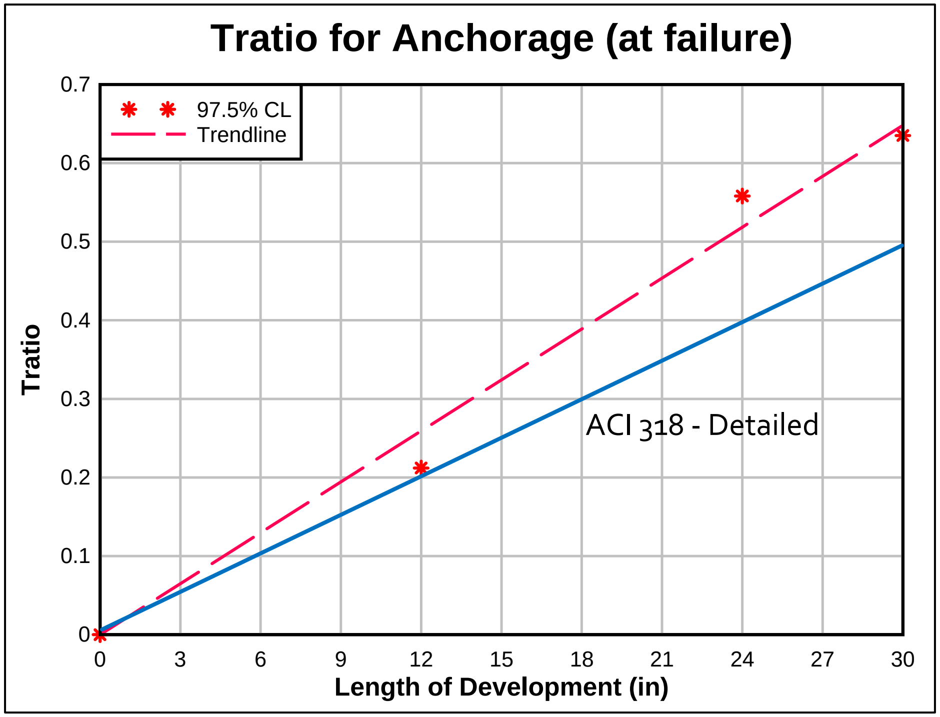
- Comparison of tensile demand in cutoff vs. anchored bars

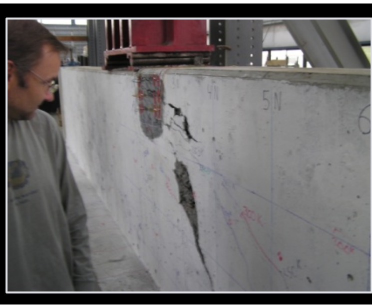
$$T_{ratio} = \frac{T_{cutoff}}{T_{anchored}}$$

$$T = 0.0216 l_{em} A_s f_y$$

$$R^2 = 0.9851$$

Max. average bond strength = 545 psi





# Analysis

# Analysis – Development Length

- Development length prediction

| Method | Development Length - Straight Bars [in] | Development Length - Hooked Bars [in] | Max. Avg. Bond Strength [ksi] |
|---|---|---|---|
| AASHTO-LRFD | [72.7] | [18.3] | [0.348] |
| ACI 318 Simplified | [83.1] | N/A | [0.304] |
| ACI 318 Detailed | [60.9] | [18.3] | [0.441] |
| Test Results (97.5% CL) | [46.3] | N/A | [0.545] |

- ACI 318 detailed process is the least conservative specification method
- Test results predict lower bound of actual development length equal to 80% of smallest design development length

# Analysis – Tensile Comparison

- Relationship between test results and AASHTO-LRFD equation 5.8.3.5-1

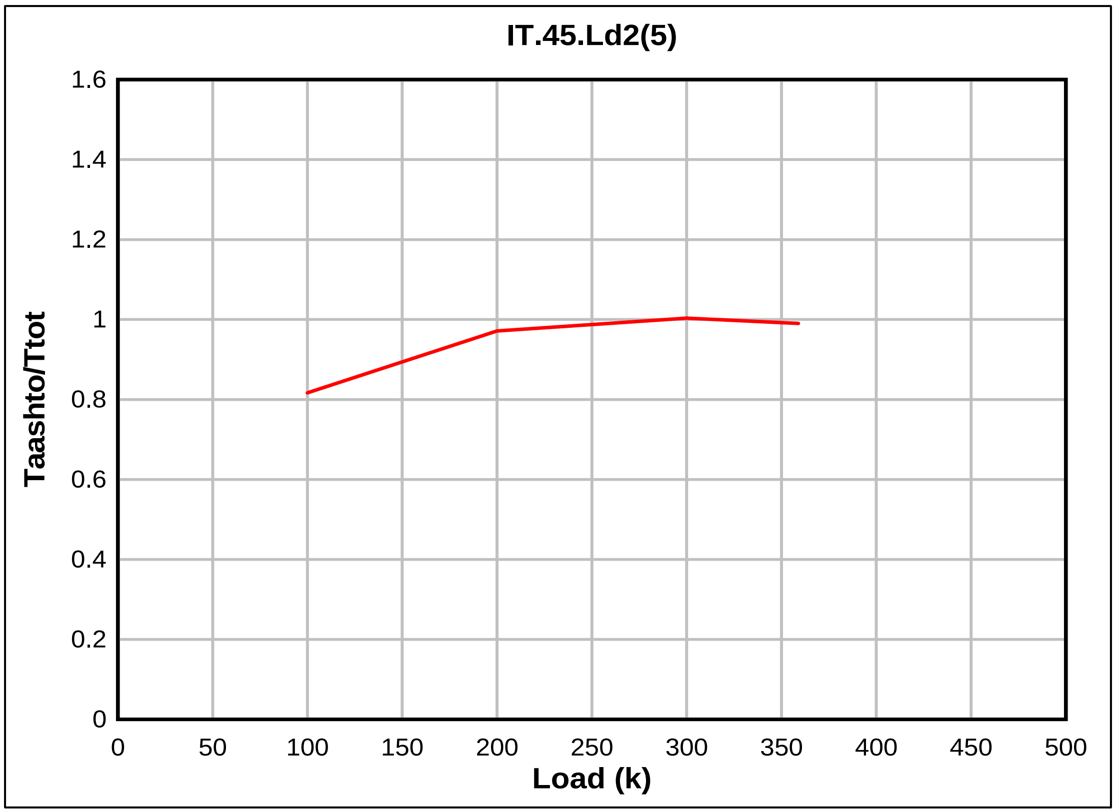
$$T = \frac{M_u}{d_v} + 0.5N_u + (V_u - 0.5V_s - V_p)\cot\theta$$

- Tensile demand at failure

| Specimen | AAHSTO-LRFD Prediction [k] | Measured Tensile Demand [k] | % Difference |
|---|---|---|---|
| IT.45.Ld2(6) | [638.7] | N/A | N/A |
| IT.60.Ld2(6) | [473.9] | [461.4] | 2.70% |
| IT.45.Ld2(5) | [446.6] | [437.4] | 2.09% |
| IT.60.Ld2(5+19) | [470.1] | [461.0] | 1.96% |

# Analysis – Tensile Comparison

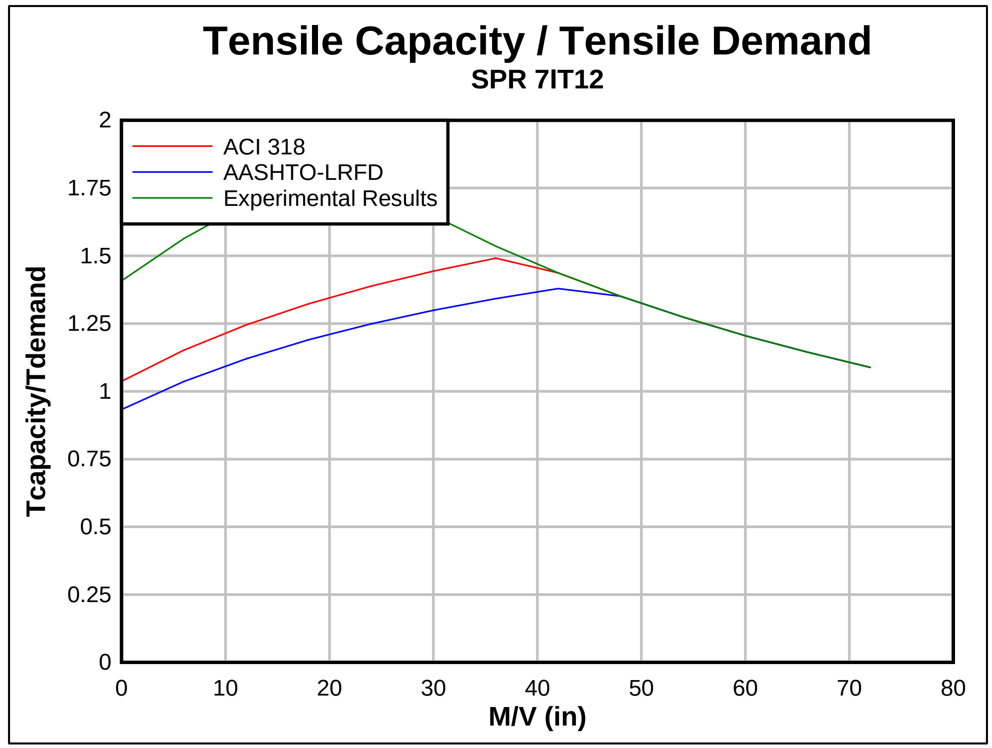
- Measured vs. Predicted tensile demand throughout test




- Poor correlation at low loads
- Failure crack propagates at higher load levels

# Analysis – SPR 350 Comparison

- Use described analysis procedure to predict failure mode for sample SPR 350 specimens
  - AASHTO-LRFD tensile demand prediction
  - Tensile capacity predicted using specifications and test results
  - All straight longitudinal anchorage details



# Analysis – SPR 350 Comparison

- Experimentally derived bond capacities produce most accurate prediction of specimen behavior

| Specimen | Failure Mode Prediction | | | |
|---|---|---|---|---|
| | Actual Failure Mode | ACI 318 | AASHTO-LRFD | Experimental Results |
| SPR 2IT10 | Shear-Anchorage | Correct | Correct | Correct |
| SPR 2IT12 | Shear-Anchorage | Correct | Correct | Correct |
| SPR 5IT12-B4 | Shear-Compression | Correct | Incorrect | Correct |
| SPR 7IT12 | Shear-Compression | Correct | Incorrect | Correct |
| SPR 8IT12 | Shear-Compression | Incorrect | Incorrect | Correct |

SPR 7IT12 Failure
-SPR 350, Higgins et.al-



# Conclusions

# Conclusions – Bond and Anchorage

- Initial observed diagonal cracking not necessarily indicative of failure angle
- Development lengths predicted by specifications are conservative compared to experimental results
- Design development lengths may mistakenly identify anchorage failures
- Anchorage failures predicated by wedge cracking near slip location

# Conclusions – Recommendations

- AASHTO-LRFD 5.8.3.2-1 reliably predicts tensile demand as specimen approaches failure
- Minimum development length may be calculated based on increased bond stress
- Inspectors should pay special attention to chevron cracking near cutoff locations


# Questions?


## Thank You:

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