Aluminum Orthotropic Deck Research UPDATE
Florida Department of Transportation

AASHTO Bridge Subcommittee Meetings
T-8 Movable Bridges
June 13, 2017

Presented by: George Patton, PE
Principal Associate
Hardesty & Hanover, LLC
Topics Discussed

- Update on FDOT Research Program (2011-17)
- Latest Deck System Features
- FSW
- Wearing/Friction Course
- Deck to Steel Framing Details (ABC)
- Analysis/Design Methodology
- Thermal Effects
- Corrosion Resistance
- Laboratory Testing Program
- Continuing Developments
Aluminum Orthotropic Deck

- Advantages
  - Weight Neutral Solution
  - Solid Surface with Friction Course
  - Durability and Service Life
  - Adaptable
  - Available AASHTO LRFD Design Specifications
  - Material Familiarity and Predictability
  - Significant History/Previous Testing and Research
  - North American Installations
  - Similar Applications
Aluminum Orthotropic Deck

- Challenges (No Perfect Lightweight Deck System)
  - Relatively High Initial Cost
  - Coefficient of Thermal Expansion
  - Wearing/Friction Course
  - Galvanic Corrosion
  - Limitations on Panel Sizes
  - Deck Drainage
  - Hollow Profiles Complicate Attachment
  - Proprietary Product

AlumaBridge Gen II Panel
Initial Developments/Refinements

- Generation I
  - Not Initially Available, Development Req’d
  - FEA Analysis Performed
  - Trial Extrusions, FSW and Panel

- Generation II
  - Lessons Learned from Generation I
  - New Extrusion Supplier
    - Longer/Wider Extrusions
    - Reduced Number of Joints
    - Achieve Better Tolerances (No Roll Correction)
  - Collaboration with FSW Provider
    - More Efficient Welding
    - Single Sided FSW Joints
    - Matched Top and Bottom Weld Thickness
  - Improved Tolerances/Fit-up/Flatness
  - Cost Reduction: $150/sf → $120/sf
Aluminum Orthotropic Deck – Generation II Extrusions

- 6063-T6 Aluminum Alloy for Improved Extrudability
- 40-foot Max. Extrusion Lengths
- Main Extrusions
  - 5-inch Deep x 18-inch or 13½-inch Wide Main Extrusions
  - Vertical Web with Seats (Top & Bott.) - Built-in Backing for Single-Sided FSW Joints
  - Male-Female and Male-Male Extrusions
Aluminum Orthotropic Deck – Generation II Extrusions

- End Extrusions
  - 5-inch Deep x 13½-inch Wide End Extrusions
  - Lip at Deck Top to Retain Wearing Surface
  - Lip at Ends to Retain Joint Sealant
  - Trim Top & Bottom Plates for Variable Width Panels
Aluminum Orthotropic Deck – Panels

- Extrusions Welded into Panels using FSW
- Infinite Range of Panel Widths
  - Main Extrusions Multiple of 4½ inches
  - Trim End Extrusion Flanges Up to 2¼ inches Each
- 14-foot Maximum Panel Width
  - Restricted by FSW Machine
- 40-foot Maximum Panel Length
  - Restricted by Extrusion Length

Friction Stir Welding Set-up

Typical Deck Panels with Varying Length
# Aluminum Orthotropic Deck – Unit Weight

<table>
<thead>
<tr>
<th>Unit Weight</th>
<th>Wearing Surface</th>
</tr>
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<tbody>
<tr>
<td>17.4 psf</td>
<td>None</td>
</tr>
<tr>
<td>20.9 psf*</td>
<td>1/4-inch Two Layer</td>
</tr>
<tr>
<td>22.7 psf</td>
<td>3/8-inch Three Layer</td>
</tr>
</tbody>
</table>

* Nearly Weight Neutral to Hot Dip Galvanized
5-inch 4-Way Steel Open Grid Deck (20 – 21 psf)

<table>
<thead>
<tr>
<th>Aluminum Density</th>
<th>Steel Density</th>
</tr>
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<tbody>
<tr>
<td>175 pcf</td>
<td>490 pcf</td>
</tr>
</tbody>
</table>

Aluminum = 0.36 x Steel
Section Properties

- Nearly Isotropic
- Moment of Inertia/Section Modulus - Secondary Direction
  Approximately 90% of Primary Direction

Deck Section Properties
Stiffness vs. Steel Open Grid Deck

- 2 x Stiffer than Steel Open Grid Deck
- Despite Lower Modulus of Elasticity
- More Efficient Use of Material
- Allows Deck to Span Greater Distances, Re-spacing of Stringers
- Stiff Deck Optimal for Epoxy Polymer Based Friction/Wearing Course
  - Greater Wear Resistance
  - Reduced Risk of Debonding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Alum Orthotropic</th>
<th>Steel Open Grid</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness, EI</td>
<td>586,700 kip-in²/ft</td>
<td>284,500 kip-in²/ft</td>
<td>2.06</td>
</tr>
<tr>
<td>Modulus of Elasticity, E</td>
<td>10,100 ksi</td>
<td>29,000 ksi</td>
<td>0.35</td>
</tr>
<tr>
<td>Moment of Inertia, I</td>
<td>58.09 in⁴/ft</td>
<td>9.81 in⁴/ft</td>
<td>5.92</td>
</tr>
</tbody>
</table>
Friction Stir Welding (FSW)

- Renewed Interest in Aluminum Deck
- Previously Welded using Metal Inert Gas (MIG)
- Developed by The Welding Institute, UK, 1991
- Solid-State, Hot Shear Joining Process
  1. Rigidly Clamped Plates
  2. Tool with Profiled Pin Plunges into Material at Joint
  3. Tool Shoulder Bears in Firm Contact with Surface
  4. Tool Rotates Rapidly, Advances along Joint
  5. Friction Generates Heat, Softens Material
  6. Produces Plastic Deformation and Flow
  7. Material Re-deposited from Front to Trailing Edge
  8. Material Forges into Solid-state as it Cools
Friction Stir Welding (FSW)

- Complex Thermo-Mechanical Process
  - Low Temperature (0.7 to 0.9 x Melting Point)
- Produces Different Zones and Microstructures
  - Weld Nugget (Fine Grained)
  - Thermo-Mechanically Effected Zone
  - Heat Effected Zone
- Slightly Asymmetric Profile

- FSW is Higher Quality than MIG Welding
  - Lower Heat Input Yields Lower Distortion and Residual Stress
  - Improved Fatigue Resistance
  - Produces Softening Zone Like MIG Welding with Reduced Strength at Welds (Within 1-inch)
    - Addressed with Deck Design
Friction Stir Welding (FSW)

FSW Upper Set-up

FSW Lower Set-up
Friction Stir Welding (FSW)

- Despite Higher Quality, Flaws still Possible
  - Voids, Lack of Fusion, Lack of Penetration, Faying Surface Defects, Entrapped Oxides

- Quality Influenced by
  - Tooling (Shoulder Size, Probe Size, Depth and Thread Details)
  - Support (Alignment, Clamping Force)
  - Process (Rotation/Advancement Speed, Force, Inclination Angle)
  - Welding Trials Useful

- Quality Control/Weld Inspection
  - AWS D1.2 Structural Welding Code – Aluminum (2014)
  - WPS, WPQR Required
  - Bend and Macroetch Tests (Weld Tabs)
  - Visual Inspection
  - RT/UT

FSW Tool
Wearing/Friction Course

- Euclid Flexolith (Low Modulus Epoxy Coating w/ Broadcast Overlay)
- Skid/Wear Resistance (Basalt/Aluminum Oxide Aggregate Blend)
- Two or Three Layers (Each Layer 1/8” Thick, 1.5 to 2.0 psf Unit Weight)
- QC - Adhesion/Cohesion Bond Strength
  - Environmental Factors (Temperature, Humidity, Oxidation)
  - Surface Preparation (Anchor Profile, Chemical Treatment, Cleaning)
  - Bond Strength Tests
- Service Life
  - Two-Layers: 10 to 15 Year Service Life
  - Three-Layers: 15 to 20 Year Service Life
- Resurface (before Aluminum Exposed)
  - Simplify Surface Preparation
  - Avoids Field Applied Chemical Treatment
Deck Design – Stringer Spacing

- Deck Spans Transversely across Stringers
  - Steel Open Grid Deck
    - 3.5 to 4.5 feet
  - Aluminum Deck
    - 6.0 feet Maximum Span
    - 2.0 feet Maximum Cantilever
Deck Design – Accelerated Bridge Construction (ABC)

- Shop Bolt Deck Panels to New Stringers
  - Facilitate Alignment, Minimize Field Work
- Stringer Ends Detailed to Clear Floorbeam Flange
  - Tee Connection Stiffeners Bolted to Floorbeam Webs, Offset from Existing Stringers, Installed in Advance
  - Splice Type Connections
  - Slotted Holes in Select Locations, Facilitates Alignment
- Overnight Replacement of Deck
- Phased Construction with Longitudinal Joint

Part Longitudinal Section Thru Bascule Leaf
Deck Design – Thermal Effects

- Coefficient of Thermal Expansion
  - $\alpha_{\text{alum}} = 12.8 \times 10^{-6} / \text{deg F}$ vs. $\alpha_{\text{steel}} = 6.5 \times 10^{-6} / \text{deg F}$

- Very Large Thermal Restraint Forces
  - $F = E_{\text{alum}} A_{\text{deck}} (\alpha_{\text{alum}} - \alpha_{\text{steel}}) \Delta T$

- Large Deck Cross Sectional Area

- Permit Connections to Slip from Temperature Changes

- Small Thermal Movements
  - $\Delta L = L (\alpha_{\text{alum}} - \alpha_{\text{steel}}) \Delta T$

<table>
<thead>
<tr>
<th>Case</th>
<th>Temperature Range, $\Delta T$</th>
<th>Restraint Force, $F$</th>
<th>Movement, $\Delta L$**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Range (Moderate)*</td>
<td>0 to 120 deg F</td>
<td>393 kips</td>
<td>0.038”  0.111”</td>
</tr>
<tr>
<td>Full Range (Cold)*</td>
<td>-30 to 120 deg F</td>
<td>491 kips</td>
<td>0.048”  0.136”</td>
</tr>
<tr>
<td>Daily (Diurnal)</td>
<td>15 deg</td>
<td>82 kips</td>
<td>0.005”  0.015”</td>
</tr>
</tbody>
</table>

* Computed using $0.6 \times \Delta T$, ** Max. Width 14 feet, Max Length 40 feet
Deck Design – Panel Joints

- Accommodate Thermal Movement and Panel Tolerances
- Locate over Floorbeams and Mid Span
- Sealant Types
  - WABO Evazote UV Seal (1” Joint) – FDOT Initial Preference
  - Ultra Low Modulus Silicone Sealant (1/2” Joint)
Deck Design – Deck to Steel Framing Connections

- Designed as Slip Resistant
- Non-Composite for Stringer Design (Conservative)
- Composite Behavior for Connection Design
- Certified Class ‘B’ Surface Condition
  - Abrasion Blast Aluminum Surface
  - Steel with Hot Dip Galvanized or Inorganic Zinc Primer Coatings
- 3/4” Dia. ASTM A325 Bolt
- No Slip from Live Load
  - High Number of Cycles ($1 \times 10^7$)
  - Prevent Fretting (Premature Coating Wear)
- Allow Slip from Thermal Load
  - Forces Relieved after Slip Occurs
  - Low Number of Cycles ($1 \times 10^4$)
Deck Design – Conventional Fasteners

- ASTM A325 Bolts (3/4” Dia.) – RECOMMENDED
  - Heavy Hex
  - Tension Control Bolts (Preferred)
- Hollow Profile Installation Challenges
  - Special Tools

Bolt Drilling

Tension Control Bolts

Bolt Installation
Deck Design – Blind Type Fasteners

- Böllhoff Rivnuts – NOT RECOMMENDED
- Lindapter Hollo-Bolts – NOT RECOMMENDED
- Not Recommended as Primary Fastener
  - Limited Pre-load Capability
  - Possible Loosening Under Vibrations
Deck Design – AASHTO LRFD Bridge Design Specifications

- Section 7 (Aluminum Structures) & Article 9.8.4 (Orthotropic Aluminum Decks)
- Analysis Similar to Steel Orthotropic Decks
- Wheel Load Distribution Similar to Concrete Decks
- Current Provisions with Stiffening Ribs Parallel to Traffic
- New Provisions for Stiffening Ribs Perpendicular to Traffic
  - Address Shear Lag Effects
- HL-93 Design Truck and Tandem
- Design Limit States
  - Service I (Deflections)
  - Service II (Bolted Connections)
  - Strength I
  - Strength II (Overload Permitting)
  - Fatigue I (Infinite Life)
Deck Design – Orthotropic Analysis

- System 1
  - Deck Longitudinal Forces (Axial and Flexure) from Stringer Flexure with Composite Deck

- System 2
  - Deck Transverse Forces (Flexure) from Loading between Stringers
  - Positive, Negative and Cantilever Flexure

- System 3
  - Localized Flexure of Deck from Wheel Patch Loading
  - Hollow Profiles behave as Rigid Frames

- Combine Stresses where Coincident
Deck Design – Finite Element Analysis

- System 2 – Load Distribution – 3D Plate and Shell FEA
- Performed on Generation I Design Only
- Results Similar for Generation II (Equivalent Section Properties)

Deck Top Stress (Positive Moment – Tandem Loading)
Section thru between Stringers
Deck Design – Finite Element Analysis

- System 2 – Load Distribution – 3D Plate and Shell FEA

Deck Top Stress (Positive Moment – Truck Loading)
Section thru Deck between Stringers
Deck Design – Simple Closed Form Equations

- Equivalent Strip Width, $b_e$
  - Simplified Analysis/Avoids FEA for Each Design
- Wheel Distribution Similar to Concrete Decks
- Wheel(s) at Edge of Panel Controls

- Shear Lag Effects
  - Multiplier from FEA
  - 20% Increase in System 2 Stress (Top of Panel)
  - 9% Increase in System 2 Stress (Bottom of Panel)

- Combined Effects
  - System 2 (Global Flexure) x Shear Lag Multiplier + System 3 (Local Wheel Patch)
  - System 1 (Composite Flexure) + System 3 (Local Wheel Patch)
Deck Design – Flexural Resistance

- AASHTO LRFD – Chapter 7 (Aluminum Structures)
- Section Proportioned with Non-slender Elements (No Local Buckling)
- Secondary Direction Resistance = $\frac{1}{3}$ Primary Direction Resistance

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Nominal Unwelded Flexural Resistance</td>
<td>$F_{nbo} = 32.5$ ksi</td>
</tr>
<tr>
<td>Nominal Welded Flexural Resistance</td>
<td>$F_{nbw} = 10.4$ ksil (Within 1-inch of Welded Joint)</td>
</tr>
<tr>
<td>$F_{nb} = F_{nbo}(1 - A_{wz}/A_g) + F_{nbw}(A_{wz}/A_g)$</td>
<td>$A_g$ denotes Gross Area, $A_{wz}$ denotes Welded Area</td>
</tr>
<tr>
<td>Resistance Factor</td>
<td>$\phi_f = 0.90$</td>
</tr>
<tr>
<td>Design Resistance Primary Direction</td>
<td>$\phi_f F_{nb} = 26.3$ ksi (15% Gross Area Welded)</td>
</tr>
<tr>
<td>Design Resistance in Secondary Direction</td>
<td>$\phi_f F_{nb} = 9.4$ ksi (100% Gross Area Welded)</td>
</tr>
</tbody>
</table>

Welded Areas
# Deck Design – Results

## SYSTEM 2 POSITIVE FLEXURE MAXIMUM STRESSES AND DEFLECTIONS

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Loading</th>
<th>Max. Stress (ksi)</th>
<th>Max. Deflection (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tension (Bottom)</td>
<td>Compression (Top)</td>
</tr>
<tr>
<td>Service I</td>
<td>HL-93 Design Truck</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>HL-93 Design Tandem</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Strength I</td>
<td>HL-93 Design Truck</td>
<td>11.1</td>
<td>11.7</td>
</tr>
<tr>
<td></td>
<td>HL-93 Design Tandem</td>
<td>9.7</td>
<td>10.0</td>
</tr>
<tr>
<td>Strength II</td>
<td>FL-120 Permit Truck</td>
<td>14.3</td>
<td>15.0</td>
</tr>
<tr>
<td>Limits</td>
<td></td>
<td>$\Phi_fF_{nb}$</td>
<td>$\Phi_fF_{nb}$</td>
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</tbody>
</table>

## SYSTEM 2 NEGATIVE FLEXURE MAXIMUM STRESSES AND DEFLECTIONS

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Loading</th>
<th>Max. Stress (ksi)</th>
<th>Max. Deflection (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tension (Top)</td>
<td>Compression (Bottom)</td>
</tr>
<tr>
<td>Service I</td>
<td>HL-93 Design Truck</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>HL-93 Design Tandem</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Strength I</td>
<td>HL-93 Design Truck</td>
<td>11.0</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>HL-93 Design Tandem</td>
<td>8.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Strength II</td>
<td>FL-120 Permit Truck</td>
<td>14.2</td>
<td>19.5</td>
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<tr>
<td>Limits</td>
<td></td>
<td>$\Phi_fF_{nl}$</td>
<td>$\Phi_fF_{nl}$</td>
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## SYSTEM 2 CANTILEVER NEGATIVE FLEXURE MAXIMUM STRESSES AND DEFLECTIONS

<table>
<thead>
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<th>Limit State</th>
<th>Loading</th>
<th>Max. Stress (ksi)</th>
<th>Max. Deflection (in)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tension (Top)</td>
<td>Compression (Bottom)</td>
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<tr>
<td>Service I</td>
<td>HL-93 Design Truck</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>HL-93 Design Tandem</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Strength I</td>
<td>HL-93 Design Truck</td>
<td>10.0</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>HL-93 Design Tandem</td>
<td>8.1</td>
<td>11.9</td>
</tr>
<tr>
<td>Strength II</td>
<td>FL-120 Permit Truck</td>
<td>12.9</td>
<td>18.3</td>
</tr>
<tr>
<td>Limits</td>
<td></td>
<td>$\Phi_fF_{nl}$</td>
<td>$\Phi_fF_{nl}$</td>
</tr>
</tbody>
</table>

C/D Ratio = 0.57
C/D Ratio = 0.74
C/D Ratio = 0.70
Deck Design – FEA Fatigue Analysis

- System 3 Fatigue Analysis with Plain Strain FEA
- Stress Range from Moving Wheel Patch
- Same for All Designs (No Need to Revisit)

Magnified Results at Top Plate/Inclined Webs

Magnified Results at Weld Backer Seam

Moving Wheel Patch Loading

Fatigue I System 3 Stress Range
Deck Design – Fatigue Resistance

- AASHTO LRFD – Chapter 7 (Aluminum Structures)
- Fatigue I Limit State (Infinite Fatigue Life)
- Fatigue Provisions Based on MIG Welding
- Fatigue Testing of FSW 6063-T6 Aluminum Alloy
  - Welded Joints with Greater Fatigue Resistant than Base Metal

<table>
<thead>
<tr>
<th>Location – Detail</th>
<th>Category</th>
<th>(ΔF)$_{TH}$</th>
<th>(Δf)</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Metal</td>
<td>A</td>
<td>10.2 ksi</td>
<td>3.85 ksi</td>
<td>(Primary)</td>
</tr>
<tr>
<td>Longitudinally Loaded FSW Joints</td>
<td>B</td>
<td>5.4 ksi</td>
<td>3.85 ksi</td>
<td>(Primary)</td>
</tr>
<tr>
<td>Base Metal</td>
<td>A</td>
<td>10.2 ksi</td>
<td>4.25 ksi</td>
<td>(Secondary)</td>
</tr>
<tr>
<td>Transversely Loaded FSW Joints</td>
<td>E</td>
<td>1.8 ksi</td>
<td>0.63 ksi</td>
<td>(Secondary)</td>
</tr>
<tr>
<td>Steel Open Grid Welds</td>
<td>E’</td>
<td>2.6 ksi</td>
<td>--</td>
<td>(Primary)</td>
</tr>
</tbody>
</table>

$C/D$ Ratio = 0.35 to 0.70
Deck Design – Deck to Steel Framing Connections

- Compute Fastener Pitch for Composite Behavior
  - Live Load Shear Flow
    - $q = \frac{VQ}{I}$ Not Applicable, $Q$ and $I$ Vary Along Length
  - Rate of Change in Compression
  - Composite Section Properties Influenced by Shear Lag
    - Bottom Plate Fully Connected to Stringer Top Flange
    - Top Plate Attached to Bottom Plate with Inclined Webs
  - Shear Flow “Spike” at Mid-Span Discontinuity
Test Program – FDOT Structures Research Center

- Test Panels – Verify Constructability
  - (2) 8 feet x 14 feet Deck Panels - Generation I and II
  - Bolted to Three Steel Stringers, Special Tools to Install TC Bolts
  - Future Installation, Specific Location on a Bascule Bridge
  - No Construction Related Issues

Surface Preparation  | Hole Drilling  | Bolt Installation/Tightening
Completed Test Panel | Shipment
Test Program – FDOT Structures Research Center

- Thorough Testing – Acceptable to Place Test Panels into Service
  - Visual/Tactile Inspection
  - Structural Testing
  - Heavy Vehicle Simulation (HVS) with Heavy Moving Wheel
  - Wearing Surface
  - Accelerated Corrosion Testing
Test Program – FDOT Structures Research Center

- Visual Inspection
  - Photographic Inventory (182 Picture Locations)
    - Before Testing (Baseline),
    - After Structural Testing
    - After HVS Testing
- General Conditions
  - No Signs of Degradation after Load Testing

Documentation Locations
Test Program – FDOT Structures Research Center

- FSW Joint Seams
  - Generation II – Built-in Backer for Single Sided Welds
  - Incomplete Fusion Inherent in Weld Detail
  - Measured with Feeler Gages/Machinist Scale (Panel Ends Only)
  - No Growth of Seams after Testing
    - Residual Precompression across Crack Tip
    - Low Calculated Tensile Stresses at Crack Tip

Magnified 20 x

Joint Section
Test Program – FDOT Structures Research Center

- Structural Load Testing – Single Position Static/Cyclic Loading
  - Verify Performance
    - Compare with FEA Results
    - Verify Strain/Stress Results Conservatively below Design Limits
    - Verify Fatigue Stress Range below Nominal Fatigue Resistance
    - Deck Not Loaded to Failure (Ultimate Strength) – Test Panel Reused
  - (9) Static and (1) Cyclic Loading Scenarios

<table>
<thead>
<tr>
<th>AASHTO Load Combination</th>
<th>Wheel (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Truck</td>
</tr>
<tr>
<td>Service I</td>
<td>25.6</td>
</tr>
<tr>
<td>Service II</td>
<td>33.2</td>
</tr>
<tr>
<td>Strength I</td>
<td>44.7</td>
</tr>
<tr>
<td>Strength II</td>
<td>57.5</td>
</tr>
<tr>
<td>Fatigue I</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Includes Load Factors, Multiple Presence Factor, and Dynamic Load Allowance Factor
Test Program – FDOT Structures Research Center

- Test Set Up
  - Boundary Conditions (Enveloped)
    - Stringers Rigidly Anchored to Floor – 5 Static Tests
    - Stringers on Neoprene Bearings – 4 Static Tests, 1 Cyclic Test
  - Neoprene Pads with Spreader Beams (Multiple Wheels)

- Instrumentation
  - 92 Bi-axial Strain Gages
  - 20 Deflection Gages
Test Program – FDOT Structures Research Center

- Static Position Static Load Test Results
  - **Stress Results Conservatively below Limits**
  - **Deflection Results Minimally Above Limit (0.02 in), Max. Recommended Span Used**

<table>
<thead>
<tr>
<th>STRESS (ksi)</th>
<th>Measured</th>
<th>Limit</th>
<th>C/D Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>17.6</td>
<td>26.3</td>
<td>0.67</td>
</tr>
<tr>
<td>Compression</td>
<td>15.0</td>
<td>26.3</td>
<td>0.57</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEFLECTION (in)</th>
<th>Measured</th>
<th>Limit (L/800)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection</td>
<td>0.11</td>
<td>0.09</td>
</tr>
</tbody>
</table>
Test Program – FDOT Structures Research Center

- Static Position Cyclic Load Test Results
  - Fatigue Stress Range
  - Maximum Values at Deck Top, Near Edge of Panel at Welded Joint
  - Results within Margin of Error
  - Max. Recommended Span Used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured</th>
<th>Limit</th>
<th>C/D Ratio</th>
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<td>Stress Range</td>
<td>1.82 ksi</td>
<td>1.80 ksi</td>
<td>1.01</td>
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</tbody>
</table>
Test Program – FDOT Structures Research Center

- Heavy Vehicle Simulator Testing (Heavy Moving Wheel)
  - Dynatest HVS-A Mark V
  - 11 kip Single Wheel (Tire Limits Loading)
  - 600,000 Total Cycles
    - 300,000 Cycles at 100 to 120 deg F Temperature (Heaters/Enclosure)
    - 300,000 Cycles at 75 deg F Ambient Temperature with Water

- Test Set Up
  - Test Panel plus Steel Open Grid Panels at Each End

- Instrumentation
  - 38 Bi-axial Strain Gages
  - 13 Position Transducers
  - 2 Linear Motion Potentiometers
Test Program – FDOT Structures Research Center

- HVS Testing Results
  - Results Consistent with Static Position Loading
  - Measures Stress Reversal from Moving Wheel (Only Possible with HVS Testing)
  - No Structural or Wearing Surface Degradation
  - No Slip between Deck and Stringers
    - Temperature Differential (45 deg F), Live Load, and Combination
Test Program – FDOT Structures Research Center

- **Wearing Surface Evaluation**
  - Friction (ASTM E1911, ASTM E2157, and ISO 13473)
  - Before, Intermediate, and After HVS Testing
  - Results Better than In Service Concrete Pavement (Long. Diamond Ground and Trans. Grooved) after Testing
  - Dynamic Friction Test (0.65 to 0.72) > 0.55
  - Mean Profile Depth (1.66) > 1.30
- **Bond Testing (ASTM C1583)**
  - PosiTest AT Adhesion Tester
  - Before and After HVS Testing
  - 17 on Test Panel, 10 on Small Test Samples
  - Ambient (75 deg F) and Heated (120 deg F) Conditions
  - Greater than Target 250 psi Bond Strength
General Aluminum Corrosion

- 6063-T6 Alloy – Excellent Corrosion Resistance
  - Tightly Bonded Aluminum Oxide Film
- Experiences Superficial Pitting Only
  - Maximum Pit Depth is Fraction of Material Thickness
- Avoid Standing Water
  - Wetness from Condensation - Limited Duration
  - Rainwater Runoff through Joints/Edges
  - Seal Openings in Hollow Extrusions or Provide Drain Holes
Galvanic Corrosion

- Dissimilar Metals (Galvanic Series)
- Less Noble (Anodic) Material Sacrifices to Protect More Noble (Cathodic) Material
- Galvanized Steel Bolts/Stringers
  - Zinc Less Noble than Aluminum
  - Zinc Sacrifices to Protect Aluminum
  - Maximize Zinc in Coatings
- After Zinc Material Spent
  - Aluminum Less Noble than Uncoated Steel
  - Aluminum Deck Corrodes to Protect Steel
  - Corrosion Rate Slow
  - Low Current Density
  - Surface Area of Bolts/Stringer Flange Significantly Less than Surface Area of Aluminum Deck
Test Program – FDOT Materials Office Corrosion Research Laboratory

- Accelerated Corrosion Testing
  - Immersion in Salt Solution (80 days)
    - Deck Extrusions Capped, Voids Filled With Saltwater
    - Lindapter Hollo-Bolts Tested
  - Test 1 – Bolts Suspended in Saltwater, No Direct Contact with Deck
  - Test 2 – Bolts Installed into Deck, Tensioned (Plastically Deformed)
  - Measure Current between Aluminum and Galvanized Steel Bolts

- Results
  - Initial Zinc Corrosion (Negative Current) – First 40 days
  - Followed by Aluminum Corrosion (Positive Current) – Last 40 days
  - Greater Corrosion of Deformed Hollo-bolt Sleeves
  - Minimal Corrosion of Galvanized Threaded Bolt and Deck

- Preliminary Results (Testing Ongoing)
Test Program – Field Installation/In Service Testing

- Install Test Panel on Existing Bascule Bridge - North Causeway, Ft. Pierce, FL
- Reuse Panels/Stringers from Laboratory Testing
- One Floorbeam Bay, Half Roadway Width

Transverse Section thru Bascule Leaf
Showing Test Panel Installation
Prototype Panel for TBTA Marine Parkway Bridge, New York

- Design Demonstrates Flexibility of Aluminum Orthotropic Deck
- 5-inch Alum. Deck with 6-inch Alum. Purlins Replaces 4-inch Steel Open Grid Deck with 7-inch Steel Purlins
- Through Truss Spans of Vertical Lift Bridge
- 100,000 Vehicles per Day, Bridge Closures Only from 9 P – 5 A (8 hours)
- Collaboration with TBTA, AlumaBridge, LB Foster, and Kiska (Contractor)
Prototype Panel for TBTA Marine Parkway Bridge, New York

- Panel for (1) Floorbeam Bay, Half Width
  - (2) 38.5 feet Long x 12.75 feet Wide Panels
- Aluminum Purlins (6-inch Tees) Welded to Deck Underside, Bolt to Existing Stringers
- Eliminates Blind Connections
- Longitudinal Deck Span
- Parabolic Crowned Roadway
  - Deck Panels Deflected
  - Locked-in Forces Accounted for in Design
- Traffic Barrier Supported on Purlin Extensions
- Accelerated Bridge Construction
  - Deck Replaced in (2) 8 hour Overnight Periods
- Testing (2) Wearing/Friction Courses
  - Flexolith (Epoxy Polymer)
  - Bridgemaster (Methyl methacrylate Polymer)
- FEA/Manual Calculations

Transverse Section thru Through Truss Spans
Questions/Discussion?

http://www.fdot.gov/structures/structuresresearchcenter/CompletedResearch.shtml

- Aluminum Lightweight Orthotropic Deck Evaluation Project
  Christina Freeman dated 2/17/2017

- Bascule Bridge Lightweight Solid Deck Retrofit
  George Patton dated 12/31/2015