Transmission Workshop

Panel Discussion:
Tubular Steel Arm Designs & Issues

- Need for Improvement in Arm Design?
  Ajay Mallik, P.E., SANPEC, Inc.

- Has Your Arm Connection Design Been Validated?
  Ric Slocum, S.E., P.E., David Nahlen, P.E., Thomas & Betts Corp.

- Wind Induced Vibration Effects on Tubular Steel Arms: Do We Really Understand the Current Issues?
  Wesley J. Oliphant, P.E., ReliaPOLE Inspection Services Company
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Need for Improvement in Arm Design: Consideration for new design approach?

Ajay Mallik, P.E.
President, SANPEC, Inc.
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Date: Sept 12, 2013
Why Arms are Failing?

Several Factors Involved:

- **Design Methodology (Discussion)**
- **Materials (Steel, Welding Electrode)**
- **Manufacturing/Welding process**
- **Assembly & Erection Practices**
- **Wind Induced Vibration**
ASCE/SEI 48-11:

- No Standard Design Method available
- Provides some basic details and layout
- Fabricators responsibility
  - Empirical Formula
  - FEM Method
  - R&D (Full Scale Testing)
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Today’s Challenge:

- Arms are Failing at Job Site
- Projects are Getting Delayed
- Costing Millions of Dollars in Downtime
- Pointing Fingers for the Responsibility:
  - Pole Manufacturers
  - Utility Customers
  - Location of Poles
  (Terrain and Gusting Wind)
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How to Mitigate the Challenges:

- Develop a robust engineering design
- Validate the design with Full Scale Testing
- Consideration of Dynamic/Cyclic Loading
- Follow the best manufacturing process
- Develop Proven Solutions to increase the fatigue life of arms at the weld joints
- Follow the best practices during construction and assembly of steel pole structures
Design Methodology:

- Arm Configuration: Six (6) Sided or Eight (8) Sided or Hex-Elliptical
- Bracket Type: Cold Bend, Hot Bend or Three Piece Brackets
- Factor of Safety (FOS)
- Welding: Full penetration or Partial Penetration
- Design consideration for Fatigue Stress
Arm Design:

- Avoid high Stress concentration at points by changing arm configuration
- Eight sided (8) arm performs better under fatigue stress
- Hex-Elliptical arm with high aspect ratio gives high stress concentration at points
Arm Design (cont.):

- Try to limit the ratio of Arm (F/F) dia and Bracket Ht (H/D) to the range 1.5 - 2 (Max.)
- Limit the % usage at arm base to 70%- 75% (Max.)
- For Galvanized arm, limit the drainage hole size to very minimum
Bracket Design:

- Check Bending Stress
  - Vertical plane (1-1)
  - Horizontal Plane (2-2)
  - Slant Plane (3-3)
- Use the Max. Bending Stress
- Limit the ratio of Yield strength of member and Actual Bending Stress to 1.50 (Min.)
Bracket Design (Cont.):

- **Types of Bracket (U-Shape):**
  - **Cold Bending Bracket**
    - More Leg Spacing due to large inside bend radius
    - High Bending Stress
  - **Hot Bending Bracket**
    - Less Leg Spacing due to small inside bend radius
    - Less Bending Stress
    - Mostly Preferred
Bracket Design (Cont.):

- Three (3) Piece Bracket
- Ideal Preference for bigger arm size
- Option to increase the thick. of face plate
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Welding Preference

- Partial Penetration Weld:
  - Meets the static loading on arms
  - Pole Vendors preference

- Complete Penetration Weld:
  - Meets the static loading on arms
  - Increase the life for fatigue resistance
  - Challenge for small dia arms
Fatigue Stress:

- Cyclic Stresses at arm base
- Conductor Aeolian vibration can produce both vertical and horizontal or combination movements of the tip of the arm
- Static stresses adjacent to weld at base is generally 2 to 3 times higher than predicted by ultimate strength design methods
- Fatigue cracks generally originate from typical weld discontinuities and high stress concentration at corners of arm
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Mitigation Solutions for Fatigue Stress:

- **Design of Arms:**
  - Increase Bracket Stiffness
  - Three (3) PCS Bracket
  - Full Penetration weld with backing bar
  - Unequal leg fillet overlay weld profile
  - Provision for longer stiffeners, if necessary
  - Proper Bolt tightening procedures to avoid additional stress at toe of the weld
Mitigation Solutions for Fatigue Stress (Cont.):

- **For Loaded Arms:**
  - Install proper damper on conductor
  - String Conductor at lower tension, if possible
- **For Unloaded Arms:**
  - Install suitable weight as per IEC construction guidelines
  - Use Tie-cable to connect the tip of the arm with pole shaft
Mitigation Solutions for Fatigue Stress (Cont.):

- Ultrasonic Impact Treatment (UIT):
  - Increases the fatigue performance (almost doubled) of the welded connection
  - This test is more effective on galvanized steel
  - Suitable for special conditions such as a long arm for river crossing poles
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Mitigation Solutions for Fatigue Stress (Cont.):

- **Consideration for Cyclic Loading:**
  - Min. # of stress cycles in the range of 150,000 – 500,000 based on location and importance of pole structures

- More R&D required
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Project Schedule & Cost Impact Analysis:

- Minimum cost impact to accommodate the new design criteria in the plant
- Need extra time to fabricate
- Huge cost impact to resolve the issue at job site
- Challenges in meeting the project completion date
We can and should **FIX** these issues, or . . .

Thank you for your attention!

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Date: Sept 12, 2013
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Has Your Arm Connection Design Been Validated?

Ric Slocum, S.E., P.E., Director of Engineering, Thomas & Betts
David Nahlen, P.E., Senior Engineer, Thomas & Betts
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Arm and Channel Bracket

Channel Bracket
ASCE 48-11, page 39 – The design stresses for design of connections are applicable only to transmission structures and may deviate from AISC design for building connections.
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ASCE 48-11, Chapter 4 – Loading

• Sect. 4.2.2 Loading considerations – determined by Owner (or owner’s engineer).
  ● Item 7 – Unique Loading (i.e. fatigue, vibration, construction loading)

• Sect. 4.4.2 - The structural designer (usually the fabricator’s engineer) shall be responsible for analysis of connections

• Professional Engineer or supervised by a Professional Engineer
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ASCE 48-11, Sect. 11.3.2 – Bolted Flange Joints
Turn of nut method is industry standard
Snug tight to close gaps – apply additional turn
Pre-tensioned bolts used in some arm connections

Match marking should be used
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ASCE 48-11, C6.4.1 – Slip Joints
- Slip joints should be jacked per Mfg requirements
- Meet Minimum lap length
- No major gaps – greater than 0.25” on 2 adjacent flats.
- ASCE 48-11, page 40 – before stringing contact Mfg to resolve issues

Slip joints, flange and arm connections should be inspected prior to wire stringing.
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ASCE 48-11, Sect. 6.2 – Bolted/Pinned Connections

- Bolt Design
  - Shear
  - Bearing
  - Spacing/Edge Distance
- Connecting Elements
  - Shear - Yielding/Rupture
  - Tension – Yielding/Rupture
  - No equations for bending/stiffness
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ASCE 48-11, Sect. 6.3 – Welded Connections

- T-Joints – 36 ksi max.
- Applies for CJP, PJP or Fillet Welds
- Currently, Sect. 6.3.5 - CJP welds only required for Base Plate and Flange Plate welds
- Should Arm Connections also require CJP?
ASCE 48-11, Sect. 6.5 – Test Verification

- Section 6.5 – Design values other than those prescribed in the standard are permitted, but shall be substantiated by experimental or analytical investigations.
ASCE 48-11, Sect. C6.5 – Commentary on Testing

- “Theoretical methods of analysis for arm connections have not been published. It is recommended that details and practices proven through testing be used.”
- Specifically calls out Arm Connections
- Clearly omits analytical investigations
ASCE 48 – 11 Appendix VIII

“Arm-to-shaft Connection Analysis Considerations”

• Most fabricators use empirical methods including testing (is this true today?)

em·pir·i·cal /emˈpirɪkəl/ Adjective
Based on, concerned with, or verifiable by observation rather than theory or pure logic.
Synonyms = empiric – experimental

• Appendix VIII is “food for thought” and not a complete methodology
Why can’t you use AISC to design arm bracket connections?

- AISC equations/coefficients are based on research and testing for the types of connections shown in AISC.
- AISC Manual “Specification for Structural Steel Buildings” and other structures with characteristics similar to buildings – “building-like structures”
- Transmission structures are not “building-like structures”
- Try finding a U-Bracket or Wrap Connection in AISC.
- Long knife plates (thru vangs)? Localized areas of high stress (stress risers) can cause cracking. Not the same as HSS connections (max tube size is 16 x 16).
- How do you check bending?
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Why the issue with Bracket Bending?

- An experienced engineer can develop the bending plane assumptions, yield line theory, etc…right?
- Without testing to validate – can and should an engineer really do this?
  - ASCE 48-11 C6.5 says that any design assumptions should be proven through testing
- Designing a Bracket and Arm separately, without testing, may not accurately predict behavior.
- Once welded, the arm and bracket act as a single member.
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Unless your design method has been validated by testing
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Research and Testing at T&B

• Fatigue Testing
• Research on Dampening Effects
• Full Scale Arm Connection Test
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Fatigue Susceptibility of 3 Different Shaft to Plate Weld Joints

- Fillet Weld
- Partial Penetration Weld
- Full Penetration Weld
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Comparison of Arm Shaft to Arm Bracket Weld Details - 1987

Cycles to Failure

- Fillet
- Partial Penetration
- Full Penetration

Cycles to Failure
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Damping Effect of ~ 50 lbs. Drop Bracket

Installing drop bracket reduced amplitude to 30% of its original value.
Arm connections can require more capacity than small engineered poles:
Arm Test - Design

- Static Calculations
  - Initial design phase

- Finite Element Analysis
  - Refined Design for testing

- Full Scale Test
  - Validate design
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The Unexpected Result
Conclusion:

Arm Connection Designs Should be Validated with Full Scale Testing
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THANK YOU!

Ric Slocum, SE, PE – Director of Engineering
David Nahlen, PE – Sr. Engineer
Wind Induced Vibration Effects on Tubular Steel Arms: Do We Really Understand the Current Issues?

Wesley J. Oliphant, P.E., AWS-CWI, F.SEI, F.ASCE
President, ReliaPOLE Inspection Services Company
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It is not a new discovery that wind induced oscillation (vibration) forces . . . . . .

Consisting of:

1. Horizontal forces (wind on projected area)
2. Vertical downward forces (from vortex motion)
3. Vertical upward forces (from vortex motion)
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... can contribute to fatigue related cracking in tubular steel arms.
So why has there been a **sharp and significant rise** in fatigue related weld cracking in **newly installed**, tubular steel arms?
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Do we really understand the issues?

What other contributing factors are combining with the wind induced oscillation cycles?
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Or, do we simply want to believe Bob Dylan:

“The answer, my friend, is blowin’ in the wind”,

The answer, my friend, is blowin’ in the wind,
“This is the way we have always done it, and nothing has changed.”

From a Paper: “Powerline Tower Arm Failure Analysis”, Authored by Dr. Wayne Reitz, Ph.D., PE
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But... Sometimes changes are rather subtle.
If we remember:

- **Low cycle fatigue:** typically infers low cycles combined with high stress
- **High cycle fatigue:** typically infers high cycles combined with low stress

And, we typically characterize weld and base metal cracking from wind induced vibration as **low cycle fatigue**,.

**The question that must be asked becomes:**

*Where does the high stress generally associated with low cycle fatigue come from?*
In my investigations I have observed subtle, but significant changes in:

- Design
- Materials (Steel)
- Manufacturing/Welding
- Assembly & Erection Practices
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Subtle changes in...

**Steel (raw materials):**

- Constantly changing percentages of Alloying elements (a result of continuous casting techniques with higher scrap % used)

- Higher ratios of Yield Strength to Tensile Strength ($F_y / F_{uts}$)
  - $65 \text{ ksi} / 80 \text{ ksi} = 0.81$  ASTM minimum values
  - $79 \text{ ksi} / 86 \text{ ksi} = 0.92$  (recent typical MTR)

- Higher Carbon Equivalencies
  - Not uncommon today to see CE’s in the 0.48-0.55 range

\[ CE = %C + \left( \frac{%Mn + %Si}{6} \right) + \left( \frac{%Cr + %Mo + %V}{5} \right) + \left( \frac{%Cu + %Ni}{15} \right) \]
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Subtle changes in . . . .

**Design:**

- Pressures to “save weight” by reducing plate thicknesses and overall dimensions in arm mounting brackets.

- Unanticipated effects of larger cutouts in arm mounting brackets to improve galvanizing drainage.

- Unaccounted for (or underestimated) bolt tightening stresses in arm mounting brackets.

- Design weld details (bigger is not always better in welding).
In adjacent spans, on the same line, arms from supplier “A” did NOT suffer fatigue cracking, arms from supplier “B” did. What were the differences?

<table>
<thead>
<tr>
<th>Supplier A</th>
<th>Supplier B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length:</td>
<td>16’-6”</td>
</tr>
<tr>
<td>Shape/size:</td>
<td>Octagonal</td>
</tr>
<tr>
<td>Arm Shaft Thickness:</td>
<td>0.1875”</td>
</tr>
<tr>
<td>Arm shaft to bkt weld</td>
<td>CJP (100%)</td>
</tr>
<tr>
<td>Bracket thickness:</td>
<td>1.0” Thick</td>
</tr>
<tr>
<td>Bracket Height:</td>
<td>21.0” Tall</td>
</tr>
</tbody>
</table>
Subtle changes in . . . .

Residual stresses (thermal and mechanical effects):

- From effects of welding on or near strain hardened formed bends in the arm brackets.
- From the heating/cooling distortion of the thin arm shaft material from welding?
- From galvanizing (similar to post galv. toe cracks on pole shaft to base plate welds).

Remember: *Residual stress* is defined as: “the stress resident inside a material after all applied forces have been removed.”
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TOTAL STRESS = RESIDUAL STRESS + APPLIED STRESS

(Compressive residual stress can be beneficial; Tensile residual stress is not!)
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Subtle changes in . . . . .

*Manufacturing:*

- changes in welding processes (SMAW, FCAW, GMAW, SAW).
- changes in welding consumables (Wire, Shielding Gas).
- consistent over-welding (more is not always better because of heat inputs from welding)
The effects of over-welding:

Dimensions shown are the actual weld detail as reflected on the design drawing for this part.

- Groove Weld Depth: 0.19"
- Bevel 45°
- 0.25" thk
- 0.45" gap
- 0.45"
- 0.19" Req'd Groove Depth

The effects of over-welding:

Dimensions shown are the actual weld detail as reflected on the design drawing for this part.
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Manufacturing (continued):

- Weld Procedures Specifications (WPS’s) parameter ranges too wide
- Weld Procedure Qualification Records (PQR’s) not reflective of Joint being welded (2 plates welded together vs. highly restrained tubular joint welded together)
- General weld quality (undercut, cold lap, buckshot, all – stress risers, stress concentrations)
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Anyone see this as a fatigue resistant arm shaft weld?
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Subtle changes in. . . . . .

**Assembly & Erection:**

- Do we have non-ambiguous instructions for dampening of arms during erection (if the arms are determined to be susceptible to wind induced vibration)?
  - hang weights – how much weight? Insulator weight ok?
  - Tie downs – tie down to what and what tie down tension?)

  and, are those instructions being followed.

- Do we also consider blocking up tip of arms if assembled on the ground and left cantilevered out from horizontal pole shaft?

- Are we following the specified bolt tightening procedures?
Assembly & Erection:

- Are there instructions for bolt tightening sequencing?

Tightening top bolts before tightening bottom bolts may cause all of the "fit-up" gap to be shifted to one leg of the bracket.

Tightening bolts, can cause bending and significant stress at toe of weld.
My Summary Thoughts:

Subtle, but significant changes have been observed in:

- Design
- Materials (Steel)
- Manufacturing/Welding
- Assembly & Erection Practices

In my opinion, the significant increase in fatigue related failures are due in part to the combined effects of these subtle changes.
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We can and should **FIX** these issues, or. . . .

Thank you for your attention!
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Open Panel Discussion

Ajay Mallik, P.E.
Ric Slocum, P.E.
David Nahlen, P.E.
Wes Oliphant, P.E.
Erik Ruggeri, P.E.