Background on Proposed Revisions to API 653 Appendix B Shell Settlement Evaluation Procedures:

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API Storage Tank Conference

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Outline

• Background on Research Project –
  – Goals
  – Initial Proposal
• Research Study
• Results of Study
• Remaining Work
  – Examine Issues Raised at Spring API meeting
  – Ballot changes
Goals of Work

• Develop an approach that eliminates current Appendix B deficiencies:
  - No differentiation between types of tank roofs
  - Diameter does not matter
  - Can throw out measured data
  - Allowable is function of measurement spacing – better inspection (more closely spaced) means lower allowable
  - $R^2$ may not be the best statistical criterion
  - May have other than single sine/cosine behavior of settlement
  - Consider both stress and out of roundness based criteria
Initial Proposals

- Two provided with API bid documents:
  - Measurement spacing eliminated as a Factor +++
  - Size D and H included +++
  - No Roof Geometry Effect ---
  - Can result in very large permissible settlements at large D (may be too large?) ---

\[
\Delta S_{all} = \frac{\pi^2 D^2 Y}{12EH} \quad \text{(Option 1)}
\]

\[
\Delta S_{all} = \frac{1.7D^2 Y}{EH} \quad \text{(Option 2)}
\]
Research Study

• Determine maximum permissible shell settlement ($S_{\text{max}}$) vs. Key Parameters:
  – Diameter (Size): D
  – Height (Size): H
  – Length settled (somewhat analogous to radius settled in Edge Settlement): $S_{\text{arc}}$
  – Materials: YS and E

• Look at both Open Roof Tanks (external floaters) and Cone Roof Tanks (supported)

• Develop Permissible $S_{\text{max}}$ based on Key Parameters

• Use Criteria similar to Edge Study – strain related
  – 3.0% maximum strain (current B4.2 criteria)
  – 5.0% API 579 Criteria not consistent with API 653

• Look also at Serviceability Criteria: Roundness
Research Study

• API 650 Designed Open Roof with stiffeners, as needed
• API 650 Designed Cone Roof with rafters and columns
• Size examined:
  – D = 50, 80, 120, 180, 240, and 300 ft. (Open)
  – D = 50, 80, 120, and 180 ft. (Cone)
  – H = 40, 48 and 64 ft. (240 and 300 ft. tanks)
• Two materials (CS):
  – YS = 36,000 psi and 50,000 psi (mostly larger tanks)
  – E = 29,000,000 psi for all
• FEA done with Elastic – Plastic Properties (stress–strain curves) from ASME BP&V Sect II
• Examined “Local” and “Fold” patterns, not “Twist”:
  – $S_{arc} = 20, 40, 80$ ft. ... Half Circumference
• TOTAL: 22 Geometries, > 2500 Settlement Cases
Research Study

- Parameters examined
  - Many have a basis in bending or other elastic theory
  - Many are dimensionless or dimensionally correct:

\[
\begin{align*}
S_{\text{max}} & \text{ vs. } \frac{S_{\text{arc}}}{D} \\
S_{\text{max}} & \text{ vs. } \frac{S_{\text{arc}}}{D} \left( \frac{YS}{E} \right) \\
S_{\text{max}} & \text{ vs. } \frac{S_{\text{arc}}^2}{D} \\
S_{\text{max}} & \text{ vs. } \frac{S_{\text{arc}}}{D} \left( \frac{YS}{E} \right) \\
S_{\text{max}} & \text{ vs. } \frac{S_{\text{arc}}}{H} \left( \frac{YS}{E} \right) \\
S_{\text{max}} & \text{ vs. } \frac{S_{\text{arc}}}{H} D
\end{align*}
\]
Research Study

- FEA Models:
Research Study

• Applied local shell settlement over varying arcs
  – smooth settlement profile
  – tangent at ends to rest of shell
  – On shell area with no low nozzles
• Cases run until > 3% strain or some out-of-roundness (OOR) value was reached
• OOR = 3, 6, 9, 12, and 18 inches considered
  – Would be a function of roof design
• Few cases where OOR would be >> 2 feet before 3.0% reached and analysis was stopped
Results

• FEA Results:
  - Strains high at bottom corner of shell, top corner, stiffener – dependent on geometry
Results

• Cone Roof
  – OOR max. at about two-thirds of height
  – OOR less than open roof tanks
  – 3.0% Strain generally reached before 6 inches of OOR
  – 1.0 to 2.0 inches of OOP settlement for 3.0% strain in under 80 foot cone roofs
  – Upwards of 4.0 inches of OOP settlement for 3.0% strain in 180 foot cone roofs

• Open Roof
  – OOR max. at top
  – 3.0% Strain reached generally before 18 inches OOR
  – 3.0 to 4.0 inches OOP settlement for 3.0% strain in 50 to 180 foot open roofs
  – 4.0 to 5.0 inches of OOP settlement for 3.0% strain in over 240 foot, but a few points upwards of 8.0 or 9.0 inches
  – Nothing in 10 to 20 inch range earlier proposals would allow
Results

- EXAMPLE Tabulated Results (3.0% occurs with 7.0 inches OOR)

<table>
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<tr>
<th>D (ft)</th>
<th>H (ft)</th>
<th>( S_{\text{arc}} ) (ft)</th>
<th>( S_{\text{max}} ) (1), (in)</th>
<th>( \varepsilon_{\text{max}} )</th>
<th>OOR(_{\text{max}}) (in)</th>
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Open Roof Results

- Developed Envelope of All Open Tank Data versus All Parameters – Determined best fit
Open Roof Results

- Best fit also used to develop Curves as a function of D
- Best fit parameter:

\[ S_{\text{max}} \text{ vs. } k \frac{S_{\text{arc}}}{H} D \left( \frac{Y_S}{E} \right) \]

[Graph showing strain criteria by diameter with S vs. \( S_{\text{arc}} D / H (Y_S / E) \)]
Cone Roof Results

- Similarly, Developed Best Fit Envelope of Cone Tank Data
  - Much more scatter (design jumps with number of columns, etc)
Cone Roof Results

- Developed Curves of Cone Tank Data by D
- Best Fit Same Equation

Strain Criteria - By Diameter
$S_{\text{max}}$ vs. $a + k \frac{S_{\text{arc}} \cdot D \cdot (\frac{YS}{E})}{H}$

![Graph showing strain criteria by diameter with fitted equations for different fit types and tank diameters.](image)
OOR Results

- Developed Best Fit Envelopes for OOR
  - Function of permissible OOR for type of floating roof or other operability concern as determined by roof designer, manufacturer, etc.

\[
S_{OOR} = k \times OOR_{allow} \times \frac{S_{arc}^2}{D} \left( \frac{YS}{E} \right)
\]
Proposed Procedure

- Take measurements and plot data
- Measure still at maximum of 32 feet \((10\pi)\), but at least 8 points, around shell, even number of points, same locations over time
- Determine if cosine fit behavior is adequate and meets current procedure
- Otherwise determine allowable from new procedure
Proposed Procedure

- $S_{arc}$ and maximum OOP from plot of data
- Determine appropriate $S_{max}$ equation for roof construction and size
- Check new strain–based criteria
- Check OOR criteria
- Make a “Run / Repair / Replace” decision

$S_{max,i}$=maximum out-of-plane settlement measured from indicated plane
$S_{arc,i}$=settlement arc corresponding to $S_{max,i}$
$S_{unif}$ has been eliminated from all measurements
Ballot on Procedure

• New measurement language 12.5.1, B2.1: similar to any inspection:
  – Use appropriate equipment and personnel for the job
  – Use same location each time (TML)
  – Interval based on design, settlement rate (similar to corrosion rate), etc.
  – Preserve all Data

• FFS procedure in B3.2: Similar to 3 Level API 579 to make a Run–Repair Decision:
  – Level 1: Tanks that fit current procedure (with other than R² requirement?)
  – Level 2: Tanks examined to new procedure
  – Level 3: Tanks that require more rigorous look

• Use both Strain and OOR Criteria

• LIMITATIONS
  – No Twisting Patterns
  – Smooth profile: no sharp breaks, step changes
  – Did not consider nozzles and attachments in regions of high strain
Wrap Up Work

- Evaluating shell settlement patterns with concurrent full hydrostatic load (bridging a “weakened” foundation area)
- Evaluating any need for penalty for strain occurring inward from corner (in bottom lap) joint
  - Similar to what is done on weld orientation in edge settlement curves
  - Evaluating coincident edge settlement and shell settlement
- Evaluating $R^2$ replacement
- Develop Examples for Final Procedures
- Formal Ballot to API PVT