Report to RTTG Spring 2021 Meeting – May 17, 2021

Liner Behavior Related to Concrete Wall Pre-stressing

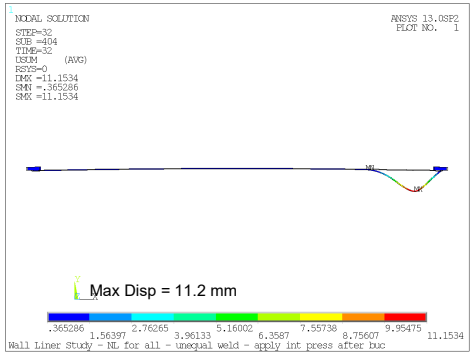
Work done is support of Agenda Item 620-2055

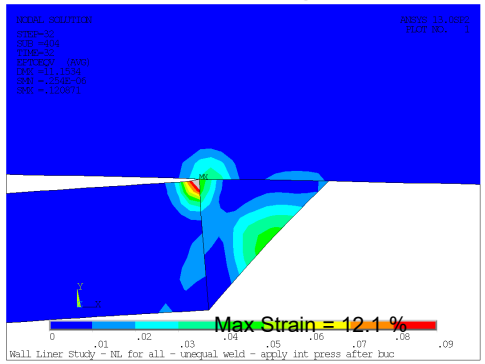
MCDERMOTT

Review of Fall 2020 RTTG Discussion

At F2020 RTTG meeting:

- **David Nadel's 620-2036 addresses sequence of liner NDE relative to inner tank H-test.**
- **Doug Miller noted that sequence of NDE vs. wall prestress is important**
  - The issue Blanchard originally raised
  - Leaking liners have been reported
- **Miller showed a draft agenda item**
  - It called for NDE after prestress for very thin liners <3/16" (5mm)
  - It included an FEM results illustration of the high strains in 3.5mm liner





  - Request from RTTG was to see such results for 5mm liner for comparison

- **Since F20 meeting**
  - Turned out that earlier studies did not have that case run for 5mm
  - Some new studies were done
  - Finding seems to be that 3.5mm vs 5mm probably not the biggest factor

Understand the Sequence of Liner Loading

(when a paste-on liner is used)

Build Concrete Wall including its embeds

Fit and Weld liner to embeds with lap welds

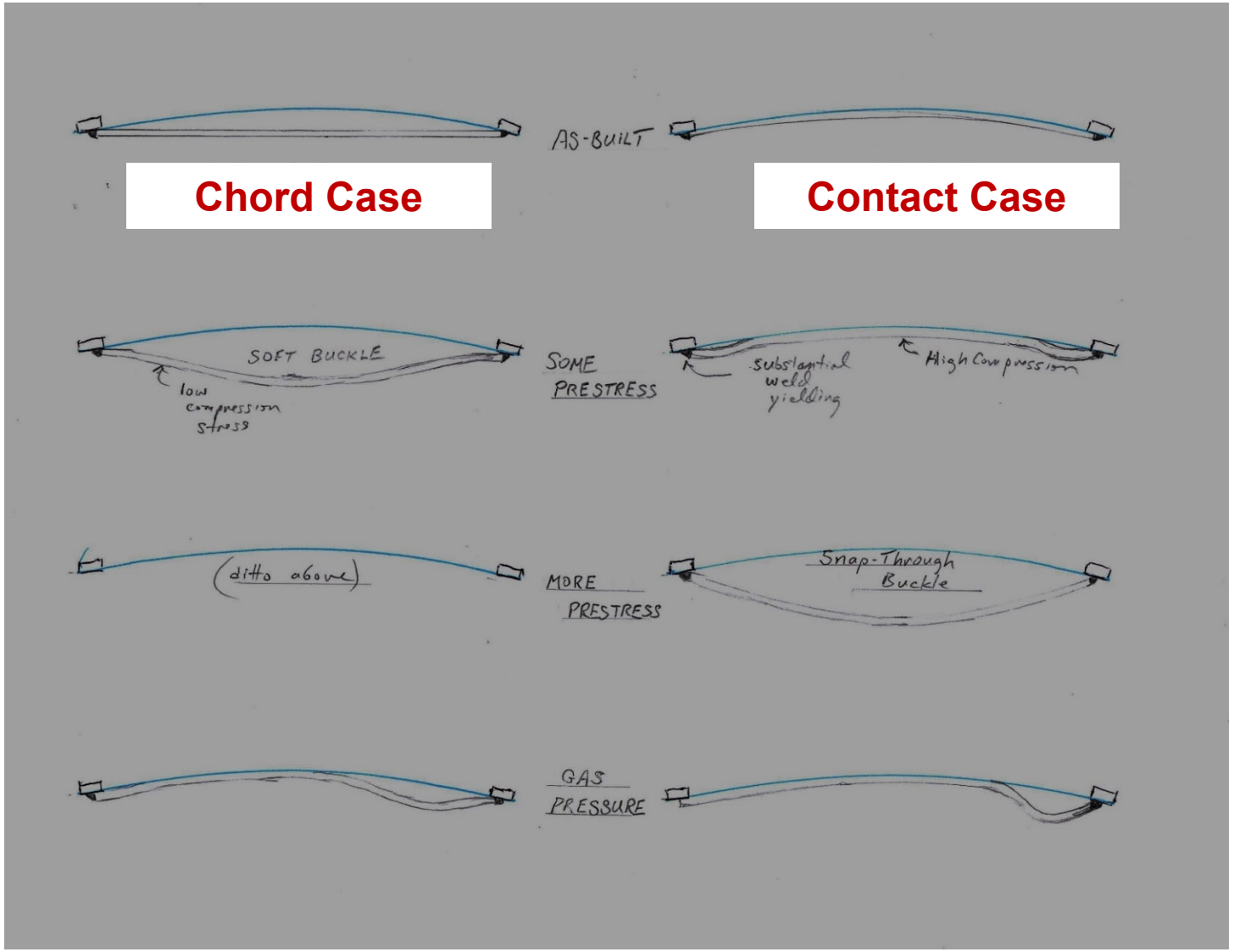
Vacuum Box check the lap welds

Prestress the wall, compressing the liner, and potentially buckling it.

Concrete creep & shrinkage, added liner compression, Buckling pretty certain.

Tank goes into service. At times, pressure tries to push liner against wall.

Two Modeled Cases of Liner Behavior



Actual initial shapes will not be exactly either of these,
but will initially drive the liner either towards or away from the wall.

Factors Guiding the Type of Behavior that Will Occur at Prestress

- **A "Chord Case" leads to a soft buckle and produces low stresses and strains**
- **A "Contact Case" leads to a snap through buckle with high stresses and strains.**
- **Which will occur???**
- **Here are some Factors**

Factor	Promotes Soft Buckle	Promotes Hard Buckle
Liner plate bow from mill	Away from wall	Towards wall
Liner fit up	Not Tight to Wall	Tight to Wall
Eccentric weld	Promotes Soft	---
Recessed embeds	Promotes Soft	---

- Possibly some panels will be each way in a given tank

Other Factors that also would promote Liner Leaks

- **Single Pass Welds (vs 2-pass)**
- **Poor or Undersized Welds**
- **Recessed Embeds promoting less than full fillet**
- **Flexing of the Welds (both statically and cyclically)**

Facts and Figures on Cases Studied and FEM modeled

Liner thicknesses = 3.5mm and 5mm

Wall Diameter = 90.8 meters

Embed Spacing = 1900 mm

Wall prestressing strain in FEM ran from 0 to 1.0 mm/M (i.e 0 to 0.1% wall strain)

- Typically final wall prestress strains end up around 0.8 – 1.0 mm/M

Versine = 9.9mm (computed from spacing and radius)

Perspective Facts:

- ASTM A20 out of flat tolerance is 35 mm for 5mm thick x 1900mm wide plate.
- Liner thickness < **Versine** < Liner plate natural bow

Disclaimers on FEM results:

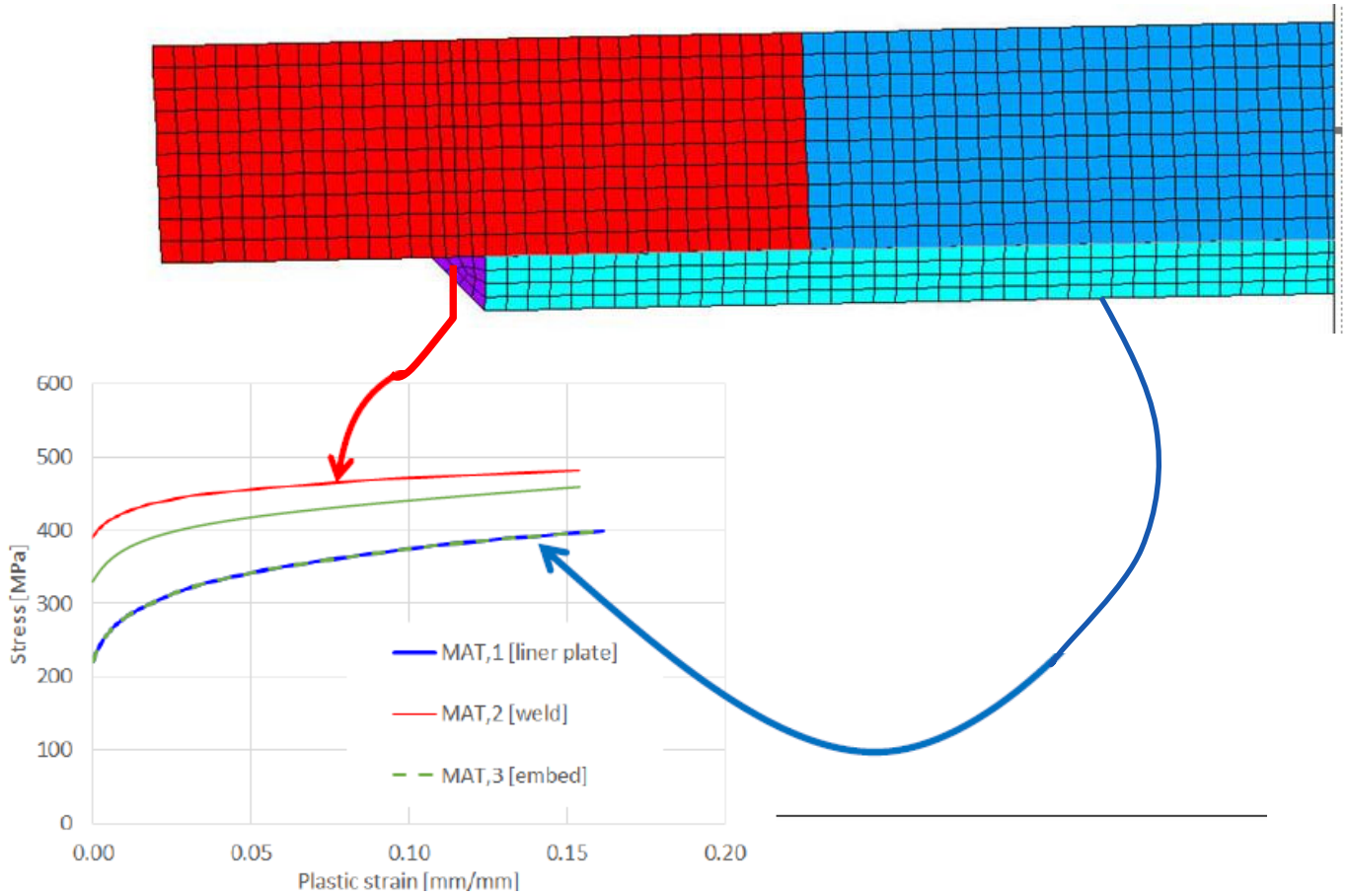
1. **Results and especially result comparisons between thickness may differ as the model inputs vary. So the model comparisons may not represent universal truths.**
2. **Buckling (especially snap-through) is very sensitive to initial conditions. So don't view numbers as anything like exact.**
3. **Focus on big differences seen between models in order to understand general issues.**

Factors and Figures on Case Studied and FEM modeled

Materials

Mild Steel liner
(YS = 221 MPa)

with somewhat
overmatching
weld metal
(YS = 390 MPa)



FEM Results for Soft Buckling Case (p1/2)

Step 1: As-built

Step 2: Apply 1.0 mm/M wall strain

Step 3: apply a fraction (10% of total) of the pressure

1.0p

Step 4: apply remaining pressure

FEM Results for Soft Buckling Case (p2/2)

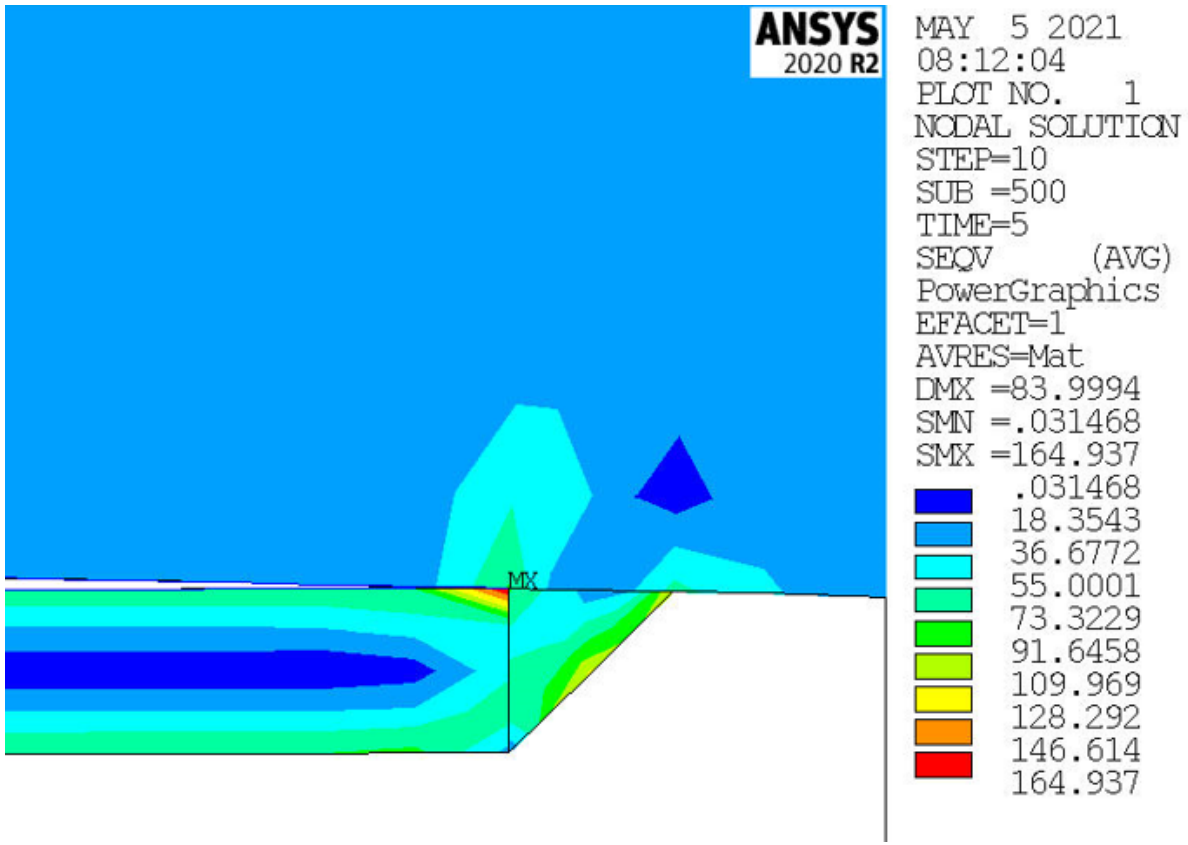
This is for 3.5 mm thickness.

This is the full 1.0 mm/M wall prestress, but no pressure.

Liner membrane stress looks to be <= 20 Mpa based on dark blue at liner centerline.

Stress in weld is less than 150 MPa in most of the weld. Well below YS.

Because of the below yield weld stresses, the rotation and strains never get high in the welds.



FEM Results for Hard Buckling Case (p1/3)

This is for 5 mm thickness.

Just before snap-through. That's when forces are greatest.

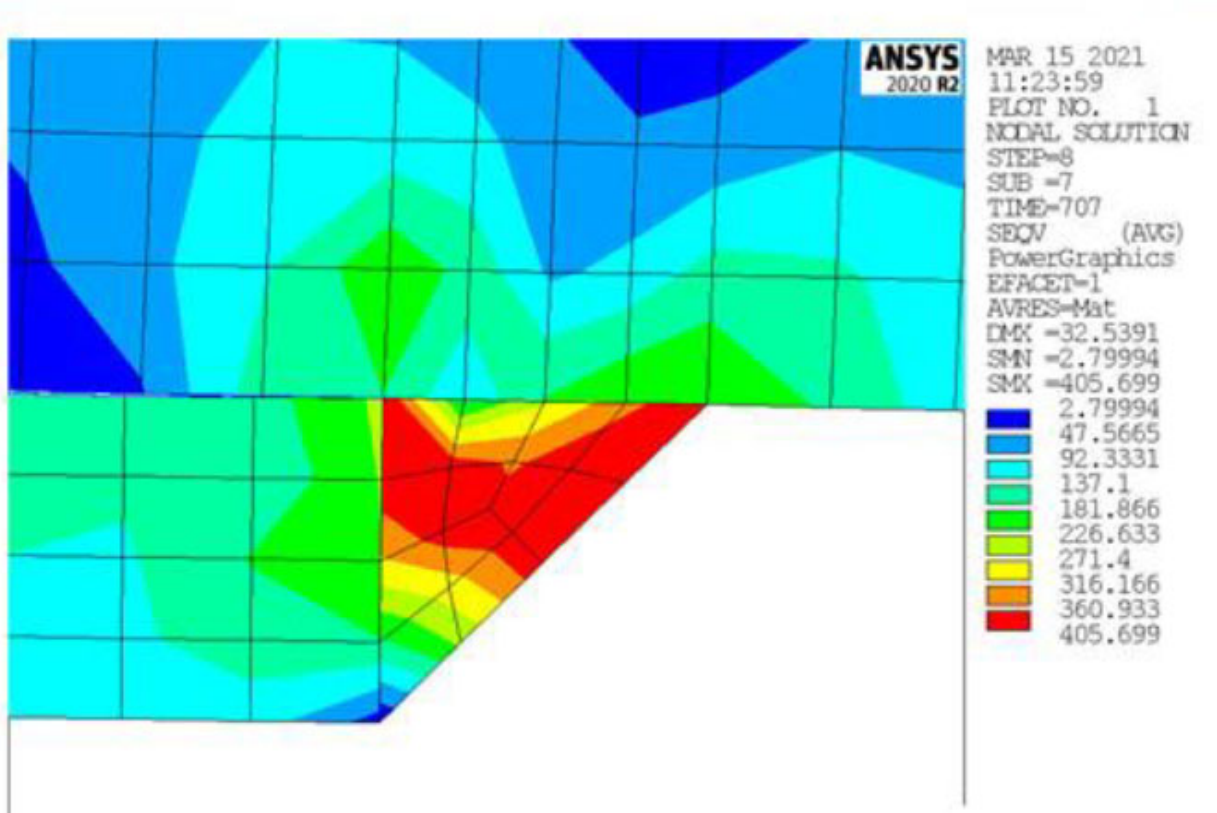
Liner membrane stress looks to be around 165 Mpa

Stress in weld is around 360 to 405 Mpa (Large red zone).

So stress is mostly beyond yield (390 MPa) through the complete throat of the weld.

Stresses in adjacent liner plate are lower because the liner plate has lower YS,

Note the model is something of an upper bound since imperfect initial wall contact will trigger buckling sooner (at smaller wall strain)



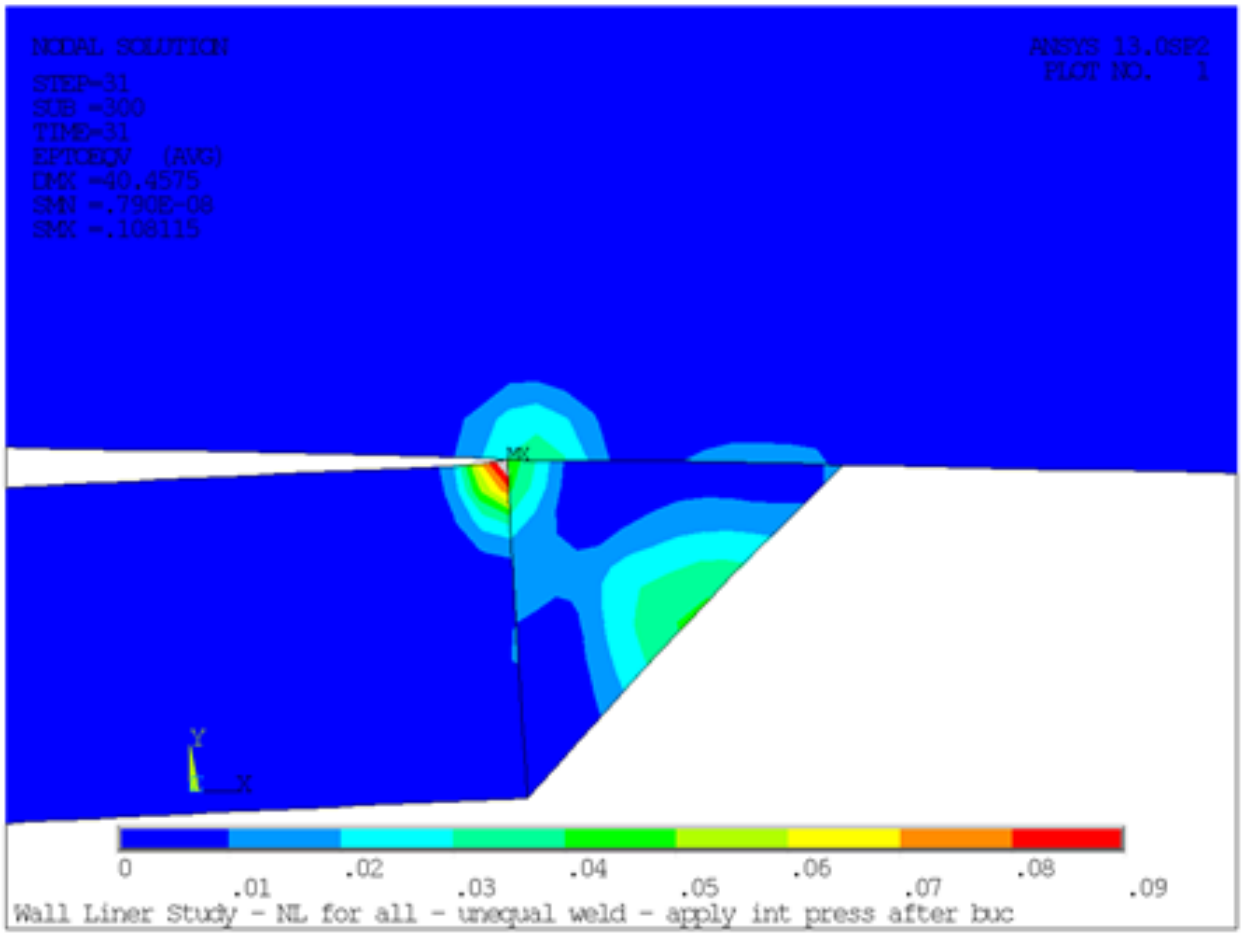
(b) 5 mm plate; singular stress in weld just before instability; plastic material, $\sigma_{eqv,max}$ = 406 MPa

FEM Results for Hard Buckling Case (p2/3)

This is from a 3.5 mm case.

This is after snap-through and at wall strain at 0.7 mm/M.

Strains are much higher after snap through



FEM Results for Hard Buckling Case (p3/3)

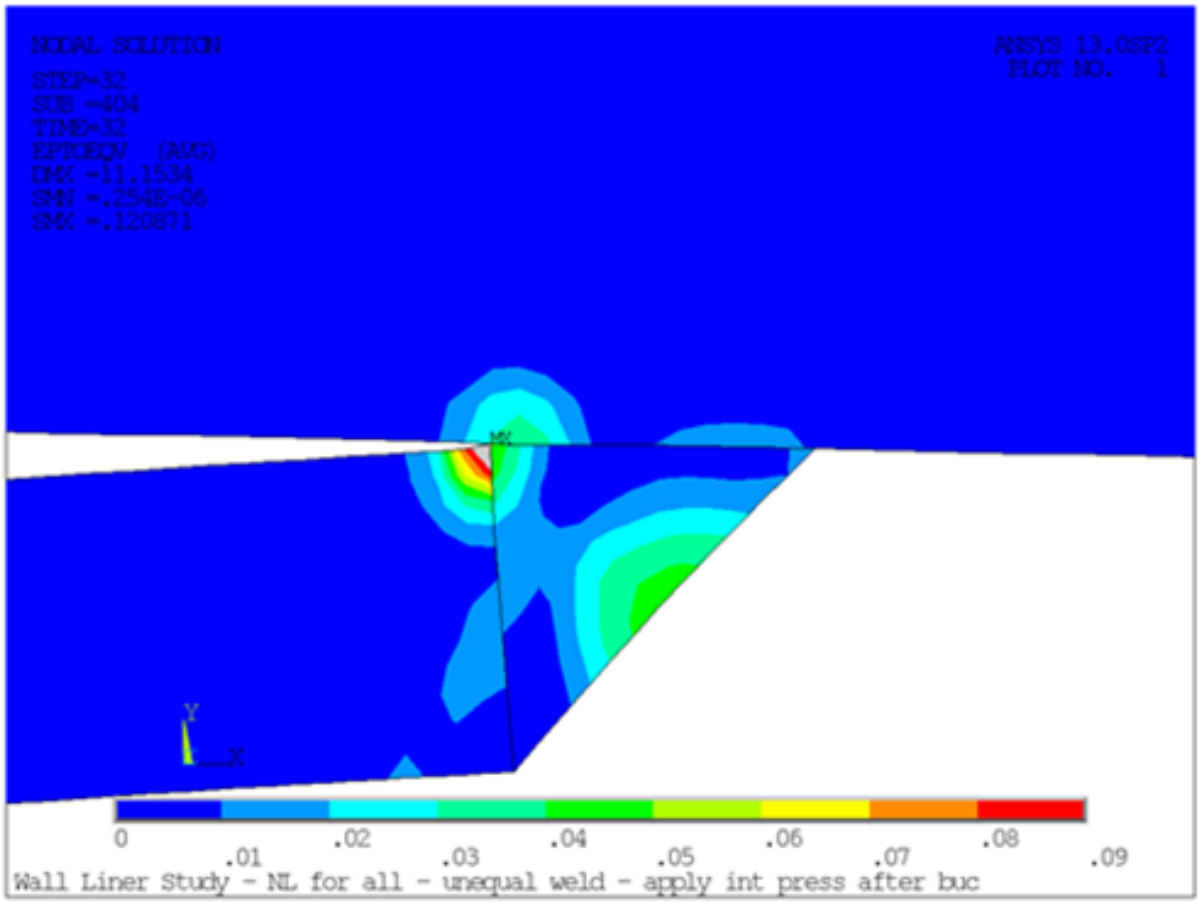
This is from a 3.5 mm case.

This is after snap-through and at wall strain at 0.7 mm/M, but now with pressure added.

Strains in most of weld are around 2% with higher peaks at weld root.

Strains will increase some more when pressure is applied.

NOTE: This is plot that was included in draft 620-2005 shown at F20 RRTG mtg.



Comparing As-Modeled Contact and Chord Case Results

Initial Liner Condition	Stage of Loading	Liner Membrane Stress	Weld Stress Situation
Full contact with wall (Any contact with wall will produce a hard buckle)	Wall prestress, Just before snapthrough, No pressure	165 MPa	Large zone around 400 MPa (so yielded across most of the section)
Chord case (Various non-contract cases will produce a soft buckle)	100% wall prestress, No pressure	Around 20 MPa	Mostly < 150 MPa

Further Work that could be Done

- Pressure cases including cyclic pressure loading
- Effects of weld eccentricity, embed recess, unsymmetrical wall shape
- Effects of varying weld and plate relative yield strengths
- Laser scanning of liner before and after prestressing
- Other?

Future API 620 Provisions that could be Considered

Possible code provisions that could be considered:

- NDE and its timing.
  - *NDE after prestress could catch tears from buckles during initial prestress.*
  - *But more snap-through buckles might occur later after shrinkage and creep.*
- Multi-pass requirement with resulting thickness limitation
  - *If we view single-pass, 3.5 mm as worse.*
- Weld detail limitations for paste-on liners.
  - *Butt welds have advantages*
- Shape tolerance criteria.
  - *Try to preclude hard snap-throughs?*
- Other ideas?