Strain-Based and Low Cycle Fatigue Methods to Design Geothermal Well Tubulars

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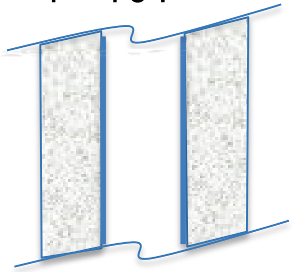
An Example

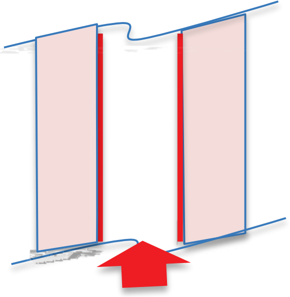
Initial Conditions

T = 70°F



Final Conditions

T = 550°F



- Geothermal Producer with cemented casing heated from 70°F to 550°F.
- Thermal stress $\sigma = \alpha\Delta$
- For a low carbon steel, this is approximately equal to -96,000 psi
- What grade should we select?
- Working Stress Design
  - Traditional basis is to stay within elastic limit, with Design Factor of at least 1.25
  - Requires at least API Q125 grade to satisfy WSD criteria, which may compromise other design considerations
  - Alternative strategies to satisfy WSD
    - Apply pre-tension so that net axial stress is below yield (hurts in quenching load)
    - Use proprietary materials (expensive)
- This problem is prevalent in all thermal service applications- steam injection and geothermal production
- Will K-55 or L-80 grades work?

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The Holliday Approach

- Holliday, G. H., “Calculation of Allowable Maximum Casing Temperature to Prevent Tension Failures in Thermal Wells”, *ASME 69-PET-10, 1969*.
- Examines several casing failures in thermal wells, and concludes that most of the failures occur in tension following compression beyond yield
- Proposes a design approach that *allows* compressive yield but limits resulting tensile stress upon cooldown to be within yield strength
- Considers reduction of yield strength with temperature, and the effect of pressure on stress
- *Represents one of the first strain-based approaches in well engineering thought*

The Holliday Approach

Holliday’s Key Insights

- Pipe is constrained- thermal strain balanced by equal and opposite mechanical strain so net strain is zero
- During heat half-cycle, dominant stress (strain) is compressive, therefore large strains are acceptable
- However, due to plastic strain during compression, we pick up residual tension on cooldown
- This residual tension is responsible for failure, not the compressive strain
- By limiting ur erefore

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Thermal Effects During Cycling

- Thermal deration of yield strength (heat half cycle, considered by Holliday)
- Bauschinger Effect (cool half

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Modified Holliday Approach

- A deterministic High Temperature, Post Yield design approach analogous to WSD, wherein the *extent of post-yield strain* is limited by restricting the allowable stress

- Holliday Stress Ratio $= \frac{\sigma}{\sigma}$

  Where the VME stress includes bending stress from doglegs or buckling of unsupported sections

- Maximum allowable stress ratio is restricted, to conservatively account for all the thermal effects, and limit tensile plasticization
    - SR ≤ 1.4 to 1.5, for L-80
    - SR ≤ 1.6 to 1.7, for K-55
    - Choice of factors and range should be based on Operator experience

- Applicable only to **Thermally Dominated Loads**

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“Strain-

Other Design Considerations

Summary of Modified Holliday Approach

- The use of VME rather than axial stress is conservative, and recommended when using Modified Holliday Approach
- Inclusion of bending stress takes uncemented sections and doglegs into account, thus allowing application to a wider variety of situations
- By limiting the stress ratios according to grade, the cyclic behavior of the materials and thermal effects are being included
- The method should be treated as an evolutionary step from WSD for thermal service tubulars, using familiar calculations and concepts
- Just like WSD, this is a pass/fail approach, and when a tubular “fails” the Modified Holliday Approach, it does not imply failure
- Refinement of the allowable stress ratios to account for material behavior, QA/QC and inspection, and connection qualification is being addressed by ongoing work

LCF Approaches

- Non-satisfaction of Holliday criteria does not imply failure.
    - For example, experiments have shown that K-55 tubulars can withstand at least ten cycles with cyclic loading between 70° F and 662° F (350° C)
- *Ultimately, the question is “*

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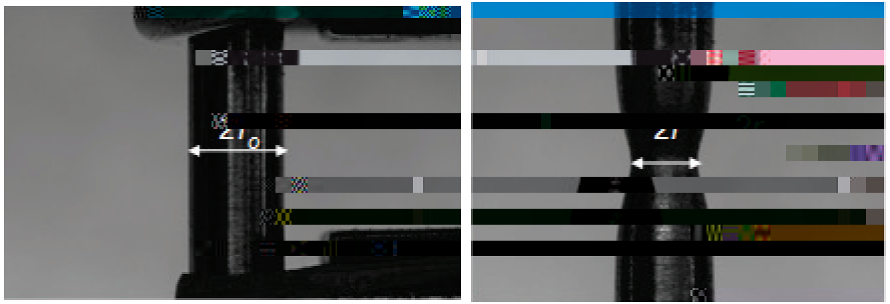
Ductile Failure Damage Indicator

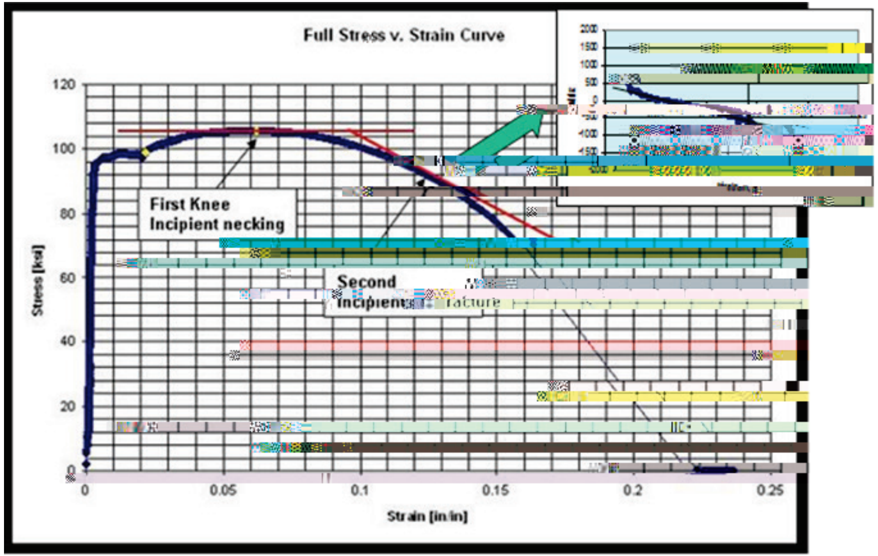
- We use a Ductile Failure Damage Indicator (see Suryanarayana and Krishnamurthy, SPE 178473)
  - Accumulates plastic damage, regardless of mean strain effect
  - Accounts for triaxiality of loading
  - Can be applied to pipe body and connections
  - Can be extended to include impact of environmental conditions

$$= \frac{1}{1.65\varepsilon} \int_0^{\varepsilon} \exp\left(-\frac{3\sigma}{2\sigma} \right) \varepsilon$$

- In above equation, ε_{crit} is the critical strain, a material property (discussed ahead) that is easily measured from uniaxial tension tests

Critical Strain





- Second knee in stress-strain curve beyond necking – from engineering Stress-Strain curve
- Synchronized system measuring load-displacement and specimen images
- Corresponding true strain represents point of crack initiation following coalescence of microvoids
- Used as limiting strain in LCF modeling

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Proposed Approach

- From true stress – true strain tests obtain the Ramberg-Osgood parameters for the material
    - Ideally, we need the stabilized cyclic stress-strain curve
    - In its absence, we use monotonic stress-strain data, conservative for cyclic strain-hardening materials
- Given a starting point of true stress-strain, add strain increment calculated from each loading half cycle, and move to next point, using the Masing hypothesis
- Calculate plastic strain increment and accumulate in DFDI
- Limit is reached when DFDI = 1.0
- In design, we limit DFDI to 0.7 or 0.8

$$\varepsilon \ = \varepsilon \ + \varepsilon \ \ = \frac{\sigma}{\ } + \left(\frac{\sigma}{\ }\right)^{1/}$$

R-O Equation

$$\Delta\varepsilon = \frac{\Delta\sigma}{\ } + 2\left(\frac{\Delta\sigma}{2\ \ '}\right)^{1/\ \ '}$$

Masing Material

Grade	Ramberg-Osgood Parameters	
	n	K (ksi)
K55	0.1982	184.15
L80	0.1844	168.16

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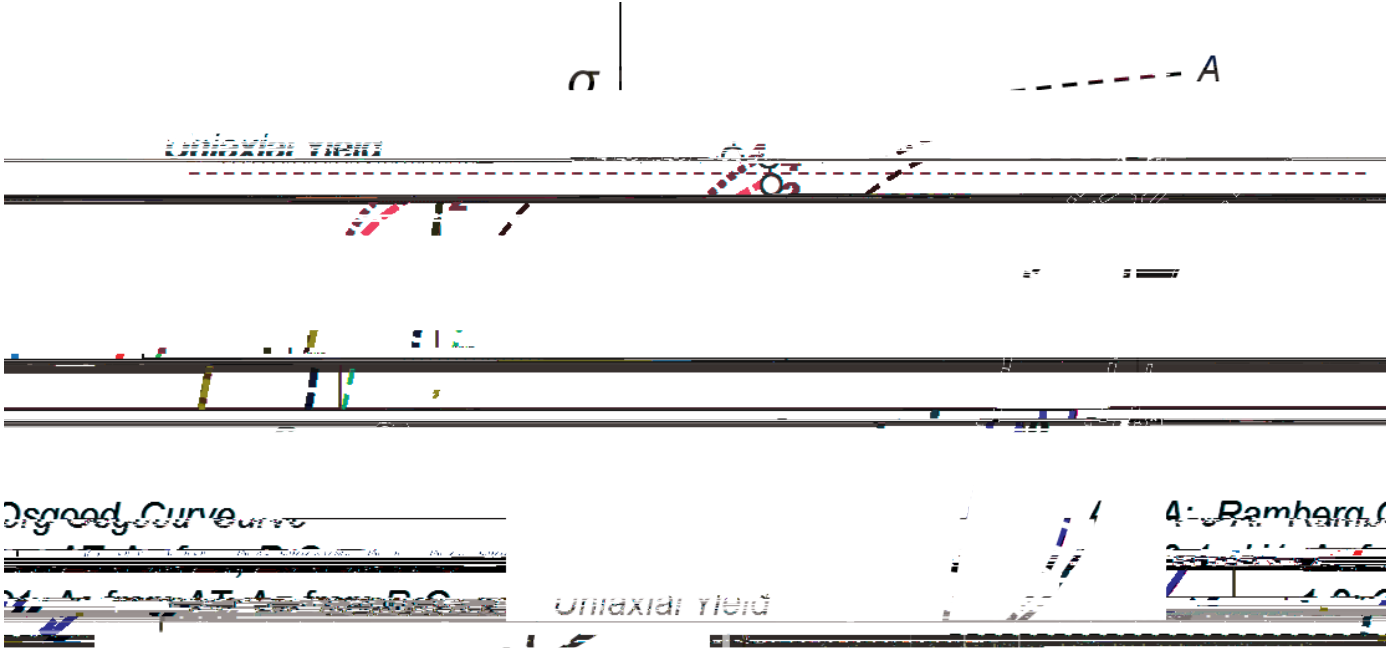
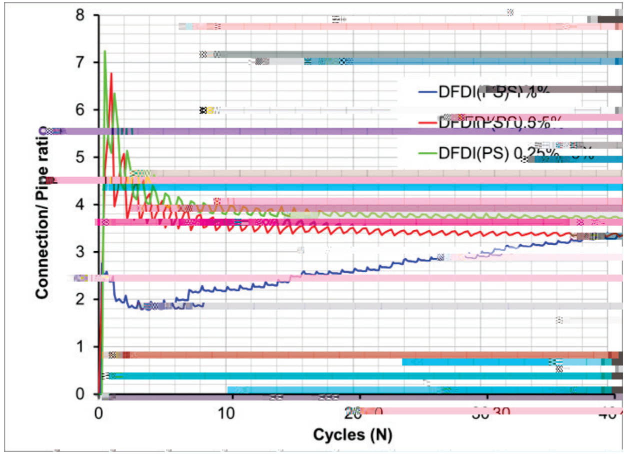
Depiction of Approach



Connections and Materials in LCF

- For connections, we apply cyclic strain in a Finite Element model of the connection
- Track principal stresses and strains in both pipe body and connection
- Calculate DFDI in connection and pipe body
- Ratio of these two is the connection Strain Concentration Factor (or Strain Localization Factor), which is then used in LCF modeling
- Needs to be performed one time per connection, avoids costly testing
- Sour environments and microstructural modifications can also be incorporated here.



Illustrated above is an example of the final result of the FEA, a ratio of DFDI by cycle number. This is for an API BTC connection.

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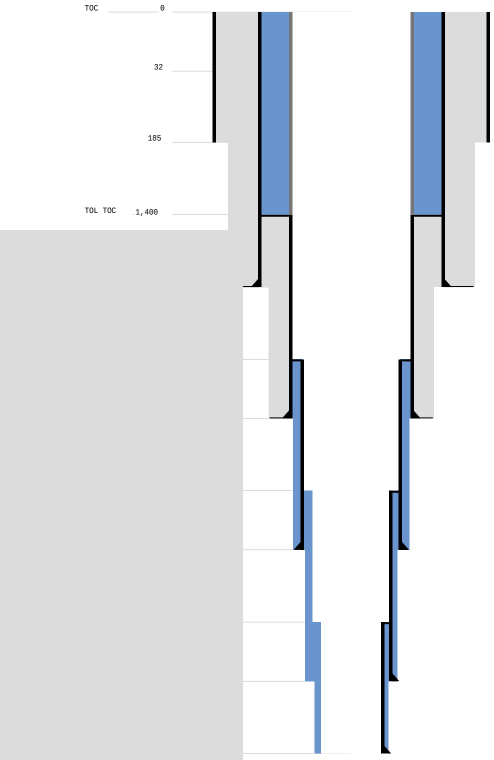
Advantages of Proposed DFDI Approach

- Mean stress (and strain) effects need not explicitly be considered, only plastic strain increments needed
- Connections can be incorporated into design, through (one time) FEA and strain concentration factors
- Triaxiality can be taken into account explicitly in the model – useful for connections and other strain localization effects
- Easy to include other causes of strain, such as geomechanically-induced strain
- Lower experimental burden, fewer parameters needed
- Sour service considerations can be quantitatively incorporated into the DFDI-based LCF model.
- Material property or microstructure enhancements can be quantitatively incorporated into the design using critical strain

Example – 13 3/8” Production Tieback



- We consider a typical geothermal well completed with a 13 3/8” liner/tieback as shown
- Design envelope plot shows that the string satisfies WSD criteria for all loads (including quenching) except for Hot Production (VME SF = 1.03)

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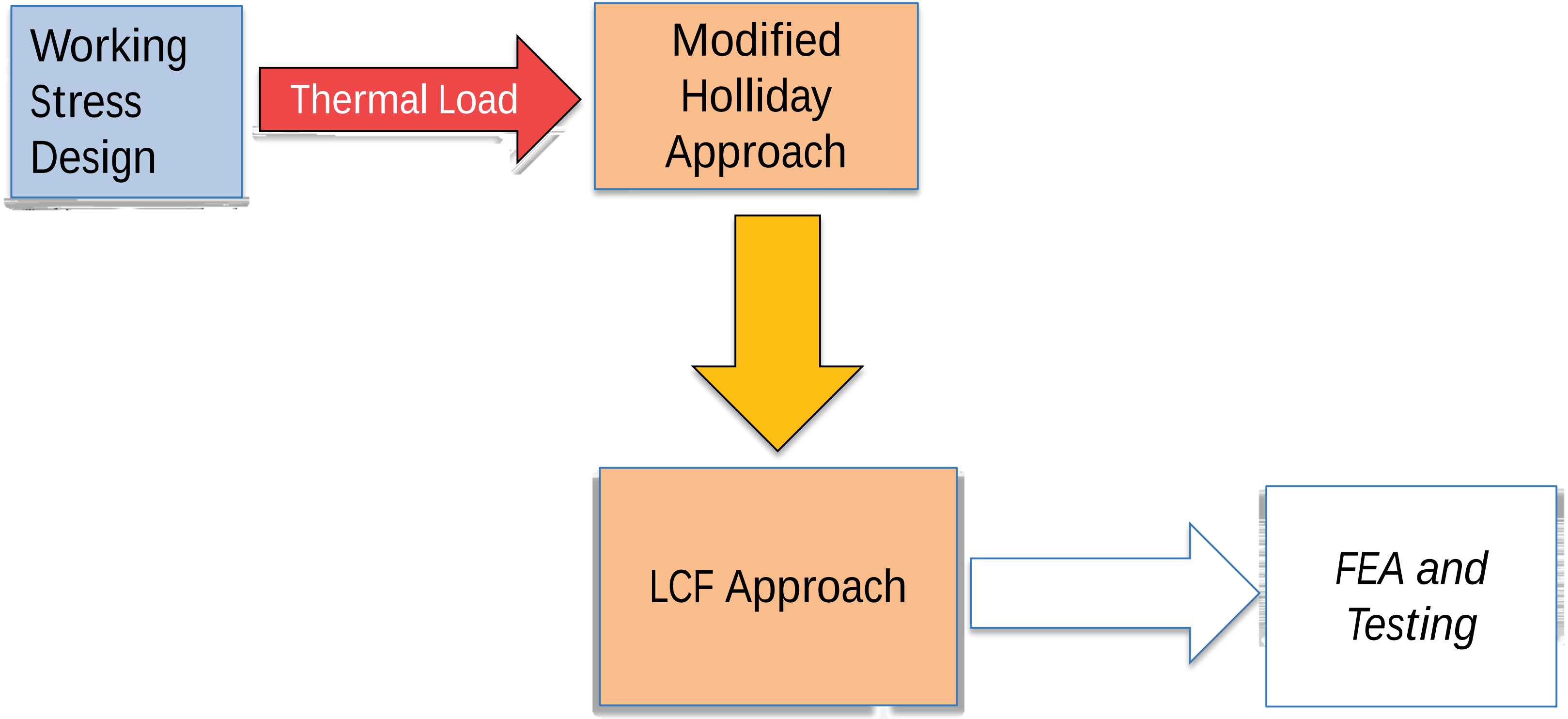
Design Using MHA and LCF

- Using Modified Holliday Approach
  - VME Stress = 67,900 psi.
  - Holliday Stress Ratio (L80) = 0.87
  - Holliday Stress Ratio (K55) = 1.23
  - *Even K55 is an option according to MHA!*
- Using LCF Approach
  -

Proposed Design Process



Working Stress Design

Thermal Load

Modified Holliday Approach

LCF Approach

FEA and Testing

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Concluding Remarks

- A strain-based design approach, based on Holliday’s original thermal tubular design approach, has been proposed
  - The method accounts for thermal effects not previously considered by Holliday
  - It can be easily implemented, using existing working stress design tools
  - Recommended stress ratio criteria can be refined to further improve the method
- A new Low Cycle Fatigue design approach, based on the concepts of critical strain and DFDI, has also been presented
  - The method provides life estimates for thermally cycled tubulars
  - It can take multi-axial loading, connections, other strain sources, and material selection into account
  - The method can form the basis for design of demanding thermal service wells
- The design procedure progresses from Working Stress Design, to Modified Holliday Approach, and finally to Low Cycle Fatigue approach, with FEA and Testing as needed

Thank You For Your Attention

Questions?

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