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Why Coiled Tubing Fails and How to Avoid Failure on Your Job ... in Your Well

or

Why Coiled Tubing Works and How to Make Sure it Works on Your Job ... in Your Well

Steven M. Tipton
The University of Tulsa

Society of Petroleum Engineers
Distinguished Lecturer Program
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The Oilfield is a Rough Place
Outline

• Introduction / Mechanics Primer
• CT Fatigue Research
  – TU Coiled Tubing Mechanics Research Consortium
• Surface Defects
• Analytical Modeling
  – FlexorTU5
• Inspection
  – 3D laser imaging
Background

- 1989 - developed CoilLIFE – Schlumberger
- 1994 - JIP to revise CoilLIFE and develop CT test machine
- 1995 - developed coiled tubing fatigue module for NOV-CTES (Achilles)
- 1996 - 2000 University of Tulsa JIP’s to study CT mechanical and fatigue behavior
- 2000 – present: University of Tulsa Coiled Tubing Mechanics Research Consortium
What is “Coiled Tubing”

- Exactly what it sounds like
- Continuously Milled Tubing
- Rolled from Flat Strip
  - Resistance Welded Seam
  - HSLA (High Strength Low Alloy)
    - 55-120 KSI
  - CRA
    - Chrome Alloys, Titanium
- Diameters: 0.75” – 4.5”
- Thicknesses: up to 0.25”
- Lengths > 30k ft
  - 10K – 20k ft most common
Typical CT Rigup

- **Coil Tubing Reel ~ 10-20K ft**
- **"Gooseneck" Guide Arch**
- **Injector**

**What is it used for?**
- Anything "jointed tubulars" are used for!
- **Drilling**
- **Completion**
- **Servicing**

Courtesy ICoTA
Coiled Tubing Units
Coiled Tubing

2009 SAE Baja Vehicle
Bending Strains

Top material in TENSION

Bottom material in COMPRESSION

“Strain” defined as % material stretches in Tension or shortens in Compression
Bending Cycles

spool

strain

straight arch arch spool repeats each trip

spool

hole

straight

strain

time
Bending Strains Lead to

• ULTRA-Low Cycle Fatigue
  – e.g., lives ≈ 10 – 100 cycles to failure
    • Normal Low Cycle >$10^3$ Cycles to Fatigue
    • Engine Parts >$10^6$ Cycles to Fatigue

• Ballooning
  – >30% even when pressure is <50% yield

• Permanent Elongation
  – 6-10 ft per 10,000 ft trip, even for axial loading well below yield
Bending Strains

Huge Cyclic Plastic Strains (>2%!)

Even with pressure below 50% of yield

"Ratcheting"
Incremental diameter growth >30%
Lives < 10 cycles!

Wall Thinning
Permanent Elongation
Bending Strain Distribution

Strain
Bending Strain Distribution

\[ \varepsilon_{x,m} = \frac{r}{R} \]

Strain

r

R
Bending Stress Distribution

\[ -S_y \quad S_y \]

Stress
Bending Stress Distribution

![Bending Stress Distribution Diagram](image_url)
Causes Permanent Elongation

Stress
CT Fatigue Research

CoilLIFE Fatigue Test Machine
CT Fatigue Research

CoiLIFE Fatigue Test Machine
TU CT Fatigue Test Facility
Accelerated CT Fatigue Test Machine
Fatigue Crack Development

NUMBER OF FAILURES

NUMBER OF FAILURES
MOST fatigue cracks initiate at the inner surface. Fatigue behavior of CT defies engineering logic! 

Appears as a “pinhole” failure.
120 ksi, 1.5" x 0.134" x 48"R

CT Life Prediction Routine

50% (mean) prediction

95% confidence prediction
CT Life Prediction

- Factors that influence life:
  - Diameter  Larger diameter – larger bending strains
  - Pressure  Higher pressure – higher tangential stresses
  - Wall Thickness  Thinner walls – higher tangential stresses
  - Bending Radius
    - Spool  Smaller radius – larger bending strains
    - Gooseneck
  - Material Grade  70 – 120 ksi
Effect of Tubing Diameter

90 ksi: 0.156" wall x 48" spool x 72" gooseneck

Trips to Failure

Pressure (psi)

1.5" diameter
1.75" diameter
2" diameter
Gooseneck Radius of Curvature

90 ksi: 1.75" x 0.156" x 48" spool

Graph showing trips to failure vs. pressure (psi) for different gooseneck lengths: 120", 96", and 72". The graph indicates that as the pressure increases, the trips to failure decrease for all gooseneck lengths.
Material Selection

1.75" x 0.156" x 48" spool x 72" gooseneck

Trips to Failure

Pressure (psi)

- Blue line: 80 ksi
- Pink line: 90 ksi
- Green line: 100 ksi
Fatigue Life Estimation

MATERIAL DATA SET

- LCF Data
  - $\sigma_f'$, $b$, $\varepsilon_f'$, $E'$, $K'$, $n'$

- Coil Tubing Parameter
  - $S=f(\sigma_h, S_y', \Delta \varepsilon_x)$

**LCF Testing** to **Fitting Routine**

**Constant Pressure Fixture Testing** to **Plasticity / Fitting Routine**

**Complex Field Loading**

- $\varepsilon_x$
- $\varepsilon_x$
- $P$

**CT Fatigue Model**

- $D$
- time

input

output

input
CT Life Prediction

- Implemented with String Management Software:
  - CT Life Prediction
  - Fatigue eliminated as a primary failure mode!
What About Defects?
Means of Imposition

- Milling (cut into surface)
- Impressing
- Corrosion Pits (chemical milling)
- EDM – Different shapes possible
Means of Imposition

Milled Ball

Impressed Ball
Influence of Surface Defects

Low Pressure Impressed vs Milled 1/8" Balls
2.375" 80 ksi tubing, tested on 72" radius fixture
Repairing Defects

• What happens after a defect is discovered?
  – Scrap / Replace string (expensive)
  – Cut and splice (welding – expensive)
  – Grind repair
Repairing Defects
One Option: Butt Welding
Butt Welding Fatigue Data

- Manual Welds: average = 38%, std. dev = 18%
- Orbital Welds: average = 41%, std. dev = 11%

Manual Average

Orbital Average
Grind Repairing

Replacing abrupt, localized discontinuities with smooth, gradual thickness change.

Technique is important and guidelines have been developed.
Fatigue Life Predictive Model

No defect: 229
Cut defect: 76
Repaired: 129
Impressed: 214
Defects Must be FOUND

• Visual Inspection
• Magnetic Flux Leakage
  – Most popular approach for CT inspection
  – MFL can only DETECT defects
  – Can’t provide any information about defect size or severity
• 3D Laser Imaging for NDE
  – Complete geometry of defect is captured digitally
3D Laser Imaging System
(Low-Cost)

Longitudinal Milled Defect
Commercial Laser System

Sawcut
Milled ball

Impressed ball
Milled Cylinder
Color-coded Digital Data

Impressed ball

Machined ball
Automated Defect Measurements

\[ d \]
\[ r_{\text{max}} \]
\[ r_{\text{min}} \]
\[ A_p \]
\[ w \]
Color-coded Digital Data & Photographic Image

Useful to distinguish cut or impressed
Sour and Corrosive Environments

• Similar effects: CT to Pipe
  • H2S
    • HIC (Hydrogen Induced Cracking)
    • SSC (Sulfide Stress Cracking)
  • SCC (Stress Corrosion Cracking)

• Residual Stresses
  • Accelerates Corrosion
Manufacturing and Materials defects/flaws

- From 7 to 20 reels per 1,000 reels (~last 3 yrs)
  - 0.7 to 2%
  - Only Those Reported

- Failures occur that are not fully investigated
  - Especially later in CT Life

'Cold' Weld
Conclusions

• Fatigue is inherent to the use of CT
• Large CT Bending Strains Cause
  – Fatigue, diameter growth, elongation
• Scatter is Associated with Fatigue Data
• Fatigue Software can Predict Influence of
  – Material, diameter, wall thickness, bending radius, internal pressure, statistical scatter, defects, grind repairs
• Field Monitoring Software used to Assess Every Section of Tubing Along the Entire String – Avoids failures in the field
Conclusions

• Defects can have first order influence (cut)
  – Or negligible influence (impressed)
• Repairing by Grinding is a viable option
• Software helps to quantify defect severity
  (and effectiveness of a grind repair )
• 3D Laser Scanning
  – Holds the potential to detect defects
  – Capable of measuring every detail about their geometry
Conclusions
To Avoid Failures on Your Job
.... or In Your well:

• Control the Factors that Contribute to Fatigue Damage Accumulation
  – Minimize tubing diameter
  – Maximize spool and gooseneck sizes
  – Select material most suited for application
  – Minimize tripping
  – Minimize tubing movement with high pressure
Conclusions

• Avoid Defects
  – Eliminate sources of defects - handling, injector debris…
  – Monitor/Inspect
  – Environmentally Induced Cracking
    • Storage corrosion
  – Repair shallow defect using grind repair techniques
Why Coiled Tubing Succeeds and How to Assure Success on Your Job... in Your Well

Steven M. Tipton
The University of Tulsa

smt@utulsa.edu
918-850-0252
www.coiledtubingutulsa.org
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