Investigating Combined Effects of Corrosion and Hook Cracks on the Structural Integrity of Electric Resistance Welded (ERW) Steel Pipes

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Introduction

- Pipeline installation involves mobilization of material, labor, and machinery to obtain, assemble, install, inspect, and test the pipeline system.

- Underground pipeline installation may seem relatively straightforward:
  1. dig a trench,
  2. lay the pipe in the trench, and
  3. fill the trench back in.

**In reality pipeline installation involves many important engineering and construction considerations**
Advantages of Pipelines

• Economical (in many cases)
• Low energy consumption
• Friendly to environment
• Safe
• Unaffected by weather
• High degree of automation
• High reliability
• Less sensitive to inflation
• Convenience
• Less susceptible to theft
• Efficient land use
• High degree of security

Source: Pipeline Engineering by Henry Liu
Many Factors Impact Life of a Pipeline

Source: O’Day et al., 1986
Detroit Sinkhole

- The sinkhole was caused by a sewer line that burst Sunday under 15 Mile Road. It was estimated Monday to be **30 feet deep**, **60 feet wide** and **160 feet long**.
Massive Hole May Sink Surrounding Businesses
Massive Hole May Sink Surrounding Businesses
Massive Sinkhole Shut Down Traffic

A sinkhole 40-ft in diameter and 16 ft deep, shut down traffic Thursday afternoon, Feb. 7, 2008 on I-25 northbound just south of the 58th Ave exit (exit 215) in Adams County, Colorado.

Source: Mark T. Osler
The Denver Post
Gas Pipeline Explosion

A – Flames go up on November 22, 2011, after a gas pipeline explosion near the Athens-Morgan County line in Southeastern Ohio

Source: Cheryl Powers, Associated Press
San Bruno Gas Pipeline Explosion
Sinkhole appeared on 6/18/04. Picture taken on 6/19/04.
Preventive Maintenance Breakdown
The Problem: Extensive and Deteriorating Networks

More than 3.5 million miles
Existing investment in the trillions of dollars
Poorly documented, neglected
Challenge: Old Guidelines
**Corrosion** = Natural deterioration of a material due to interaction with environment.

**Fatigue** = Process of structural degradation caused by fluctuations or cycles of stress or strain.

Failures in Oil and Gas Pipelines

- **Corrosion**: 33%
- **Fatigue**: 18%
- **Welding Defects**: 10%
- **Fabrication Defects**: 9%
- **Brittle Fracture**: 9%
- **Mechanical Damages**: 14%
- **Others**: 7%

List of Pipeline Accidents/Incidents in the United States in the 21st Century

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>Location</th>
<th>Cause</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Petroleum pipeline failure</td>
<td>Graville, Texas</td>
<td>Loss of pipe coating integrity</td>
<td>Relatively minor</td>
</tr>
<tr>
<td>2001</td>
<td>Crude oil pipeline rupture</td>
<td>Oklahoma</td>
<td>Struck by machine</td>
<td>At least ten persons injured</td>
</tr>
<tr>
<td>2003</td>
<td>Failure on an Enbridge pipeline</td>
<td>Michigan</td>
<td>Site along the company's pipeline</td>
<td>500 barrels of crude oil spilled</td>
</tr>
<tr>
<td>2004</td>
<td>ConocoPhillips oil spill</td>
<td>Texas</td>
<td>Natural gas discharged, but wind helped immensely</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Enbridge pipeline failure</td>
<td>Wisconsin to Whitewater, Wisconsin</td>
<td>Pressure cycle established as the cause</td>
<td>Fault at the pipe maker that failed as pressure cycle was established</td>
</tr>
<tr>
<td>2008</td>
<td>20-inch gas pipeline explosion</td>
<td>Hidalgo County, Texas</td>
<td>Closure of FM 490</td>
<td>Road closure</td>
</tr>
<tr>
<td>2009</td>
<td>Pipeline rupture near Texas City, Texas</td>
<td></td>
<td>Up to 5,000 US gallons of gasoline spilled into Bayou Pierre</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Pipeline rupture near Gilbert, Wyoming</td>
<td></td>
<td>Six-month-old 30-inch natural gas pipeline exploded near Gillette, Wyoming</td>
<td>Construction or installation issues caused the failure</td>
</tr>
<tr>
<td>2011</td>
<td>Cupertino, California condumium gutted</td>
<td></td>
<td>Plastic pipe fitting cracked</td>
<td>More than 50 people killed since 1971, federal government says</td>
</tr>
<tr>
<td>2012</td>
<td>Pipeline carrying heating oil hit by construction workers</td>
<td>East Providence, Rhode Island</td>
<td>Spilled into storm drains, at least 56,000 US gallons of oil spilled</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>Pipeline rupture near Newton County, Texas</td>
<td></td>
<td>September 21, 2013</td>
<td>One person injured</td>
</tr>
</tbody>
</table>

List of Pipeline Accidents/Incidents in the United States in 2013

- On January 15, a utility crew struck & ruptured a 4 inch gas pipeline in Lewisville, Texas, causing a nearby home to explode later on. The explosion killed a man.
- An independent contractor installing fiber-optic cable for a company in Kansas City, Missouri inadvertently struck an underground gas line on February 19. Gas later caught fire, and created an explosion that destroyed a popular local restaurant, killing one of the workers there, and injuring about 15 others near the scene.
- A tug towing a barge struck and ruptured a Chevron LPG pipeline near Bayou Perot, Louisiana on March 12. The tug Captain was severely burned when the escaping gas ignited, and died several weeks later from those injuries.
- On March 18, a 8 inch petroleum products pipeline ruptured along a seam, spilling diesel fuel into Willard Bay State Park near Ogden, Utah. Wildlife was coated with diesel, but, the fuel was prevented from entering into water supply intakes. About 25,000 gallons of diesel were spilled.
- A Williams Companies 24 inch gas gathering pipeline failed in Marshall County, West Virginia on March 22. There were no injuries.
- Mayflower oil spill occurred when ExxonMobil's 20 inch Pegasus crude oil pipeline spilled near Mayflower, Arkansas on March 29, causing crude to flow through yards and gutters, and towards Lake Conway. Wildlife was coated in some places.
- On April 4, an explosion & fire occurred at a gas compressor station near Guthrie, Oklahoma. Nearby homes were evacuated. There were no injuries reported.
- A fire at a pipeline gas compressor station broke out when natural gas liquids ignited in Tyler County, West Virginia on April 11, seriously burning 3 workers, two of whom later died. The workers were performing pipeline pigging operations.
- A 12 inch gas transmission pipeline failed near Torrington, Wyoming on June 13. LF-ERW seam failure was identified as causes of the failure.
- On May 9, diesel fuel was detected to be leaking from a Marathon pipeline in Indianapolis, Indiana. Over 20,000 gallons of diesel leaked, at a slow rate that was not detected by SCADA systems. Cleanup cause a nearby major road to be shut down for 5 days. There were no injuries reported.
- Late night on May 14, an explosion & fire hit a Williams Companies gas compressor station near Brooklyn Township, Pennsylvania. There were no reported injuries.
- On May 30, 2 construction workers were injured, when a fire erupted during welding at a Williams Companies natural gas facility in Hunterdon County, New Jersey.
- A farmer near Tioga, North Dakota smelled oil for several days before discovering a leaking 6 inch 20 year old Tesoro pipeline under his wheat field on September 29. Crews tried to burn off the oil at first. The spill size was estimated at 865,000 gallons, and covered over 7 acres. There were no injuries.
- On July 4, a fire involved a gas compressor and a nearby ruptured 2 inch gas pipeline in Gilmore Township, Pennsylvania. There were no injuries.
- On October 14, a 30 inch natural gas pipeline was cut by a construction crew in Oklahoma City, Oklahoma. There were no injuries.
- A leak developed on a valve on the Longhorn Pipeline in Austin, Texas during maintenance on August 14, spilling about 300 gallons of crude oil. There were no evacuations.
- Atmos Energy crews dug into a 4 inch gas pipeline in Overland Park, Kansas on September 2, causing an explosion and fire. There was no major damage or injuries.
- A 30 inch gas gathering pipeline ruptured & burned in Newton County, Texas on September 21. About a dozen people from nearby homes were evacuated for a time. There were no injuries.
- On September 24, a Denton TX city water utility worker ruptured a 1/2 inch gas pipeline in Denton, Texas, which immediately caused a fire that gave the worker minor burns. There was no other significant damage.
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Possible Impacts of Pipeline Failures

• Injury and death
• Damage to property
• Disruption of service
• Environmental damage
• High costs of emergency repairs
• Loss of business
• Social costs
Electric Resistance Welded Pipes (ERW)

- Manufactured by cold-forming a sheet of steel into a cylindrical shape.
- Current is passed between the two edges of the steel to heat the steel to a point at which the edges are forced together to form a bond without the use of welding filler material.
- From 1920’s to 1970 used low frequency A.C. current to heat the edges.
- In 1970, the low frequency process was superseded by a high frequency ERW process which produced a higher quality weld.
- Over time, the welds of low frequency ERW pipe was found to be susceptible to seam corrosion, hook cracks, and inadequate bonding of the seams.
- The high frequency process is still being used to manufacture pipe for use in new pipeline construction.

Source: PHMSA
Residual Stresses

• Residual Stresses at crown are main causes of several failures in ERW pipes.

• Residual Stresses are due to:
  – Welding
  – Heating Process

http://www.treehugger.com/energy-disasters/dilbit-could-have-caused-pegasus-pipeline-oil-spill.html
Computational Modeling of ERW

- Discretize pipe to small elements (Finite Elements)
- Provide equilibrium and continuity on adjacent element’s nodes
- Extrapolate displacements within the pipe based on nodal displacements
eXtended Finite Element Method (XFEM) Enrichments

Element Enrichment for Cracks

\[ u(\xi, \eta, \zeta) = \sum_i N_i(\xi, \eta, \zeta)U_i + \sum_i N_i(\xi, \eta, \zeta)U_i H(\xi, \eta, \zeta)b_i \]

Elements completely crossed by a crack are enriched with the heavy side step function.
XFEM Enrichments

Element Enrichment for Cracks

\[ u(\xi, \eta, \zeta) = \sum_i N_i(\xi, \eta, \zeta)U_i + \sum_i N_i(\xi, \eta, \zeta)U_iH(\xi, \eta, \zeta)b_i + \sum_i N_i(\xi, \eta, \zeta)\left( \sum_j \psi_j(r, \theta)c_{ji} \right) \]

Elements that contain a crack front (tip) are enriched with \( \psi_j \) function

Nonlinear FEM was Used to Evaluate:

– Crack initiation and propagation
– Failure pressure
– Stresses at failure
– Size of the failure zone
Case Study

Sample Pipe Buried in 3 feet deep sandy clay soil

<table>
<thead>
<tr>
<th>Input Properties</th>
<th>D</th>
<th>20 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Diameter</td>
<td>t</td>
<td>0.312 in.</td>
</tr>
<tr>
<td>Pipe Wall Thickness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td>Grade 42</td>
</tr>
<tr>
<td>Pipe Length</td>
<td></td>
<td>50 ft</td>
</tr>
</tbody>
</table>
Creating the FEA Model

A rate-independent plasticity model using the von Mises yield criterion and isotropic hardening rule

Soil-structure Interaction is Important!

Nonlinear Analysis:
Material nonlinearity:
  stress-strain relationship
Geometry nonlinearity:
  large deformations and crack

Mesh density increased towards the defect area
Soil-Pipe Interaction (SPI):

Soil-pipe interaction is more flexible than a corresponding rigid structure.

SPI increases the effective damping ratio of the system.

1. Water Level was considered
2. Stresses change in the border of dry and saturated soil
Defects Considered in the Pipe

Corrosion
Wall loss thickness: 7%
Corroded zone length: 32 feet
Defects Considered in the Pipe

Hook Crack

24 inch Length
0.15 inch depth
In the field, cracking at the ruptured pipe displays a straight, linear crack over a length of **34 feet** at approximately at the **12:00 o’clock** position.
Displacement in the Pipe
## Results

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Failure Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Corrosion No Crack</td>
<td>1,408 psi</td>
</tr>
<tr>
<td>With Corrosion No Crack (7%)</td>
<td>1,360 psi</td>
</tr>
<tr>
<td><strong>With Corrosion With Crack</strong></td>
<td><strong>733 psi</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Max Stress in the pipe</th>
<th>Max Principal Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Corrosion No Crack</td>
<td>45,430 psi</td>
<td>46,060 psi</td>
</tr>
<tr>
<td>Increase %</td>
<td>87%</td>
<td>140%</td>
</tr>
</tbody>
</table>
Conclusions

✓ Our FEA results show that for this specific case Hook Cracks are the main reason of failure in the ERW 20-inch steel oil pipe which caused about 50% reduction in Failure pressure.

✓ Our FEA results show that in this study 7% Corrosion is NOT the main reason of failure in the ERW 20-inch steel oil pipe which caused about 3.5% reduction in Failure pressure.

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Failure Pressure</th>
<th>Strength Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Corrosion No Crack</td>
<td>1408 psi</td>
<td></td>
</tr>
<tr>
<td>With Corrosion No Crack</td>
<td>1360 psi</td>
<td>3.5%</td>
</tr>
<tr>
<td>With Corrosion With Hook Cracking</td>
<td>733 psi</td>
<td>50%</td>
</tr>
</tbody>
</table>
Recommendations for Future Works

• FEA Modeling of Residual Stresses due to Welding and Heat Process in ERW Pipes.
• Fatigue Simulation in Gas and Oil Pipeline Systems Using FEM.
• Performance Curves for Corroded Steel Oil and Gas Pipes to *Predict their Remaining Useful Life*
• Fracture Analysis and Failure Modeling for Forensic Evaluation of Steel Pipes.
• XFEM Method for Crack Growth and Crack Propagation Modeling is applicable to other types of pipes such as Cast Iron and Ductile Iron Pipes.
Questions?

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