

Investigation of Fatigue-Induced Socket-Weld Joint Failures for Small-Bore Piping Used in Power Plants

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Outline

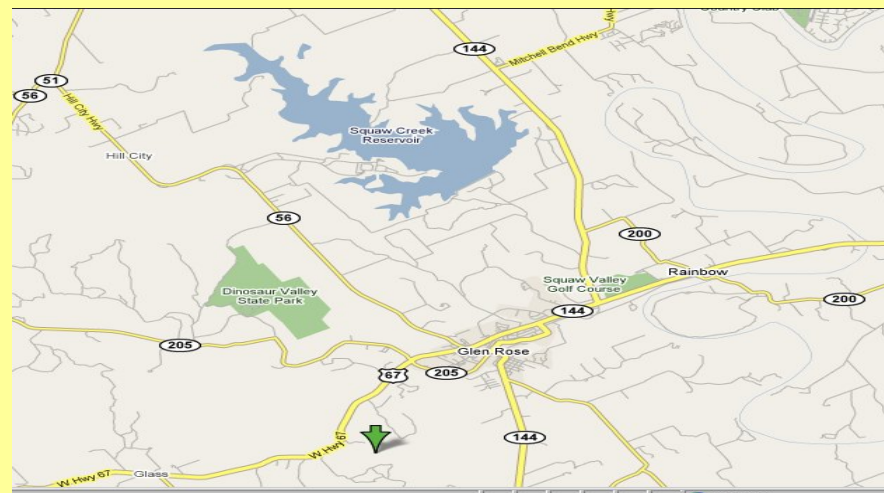
- Introduction
- Statistical Facts
- Design Parameters
- Mechanical Behavior
 - Fatigue
 - Vibration
 - Bending
 - Pressure
- Welding
- Proposed Solutions

Comanche Peak Steam Electric Station

- Location
 - Glen Rose, TX



- Water Source – Squaw Creek Reservoir



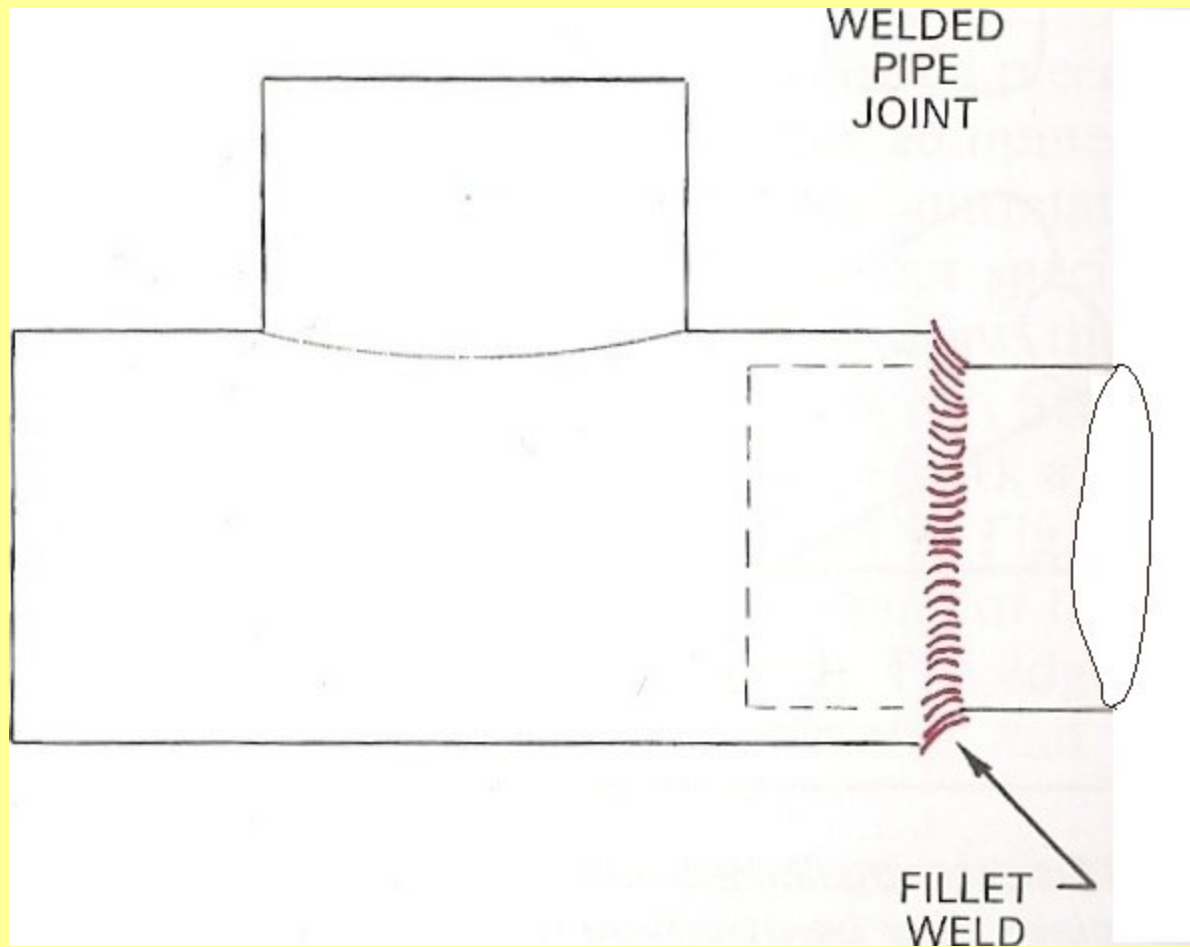
Introduction

- Nuclear power plants experience 2 or 3 high-cycle fatigue failures of stainless steel socket welded connections each plant year of operation.
- High cycle fatigue is invisible during initial phase of crack growth.
- When fatigue cracks grow large enough to be visible, it is too late for inspection and leads to failure.

Statistical Facts

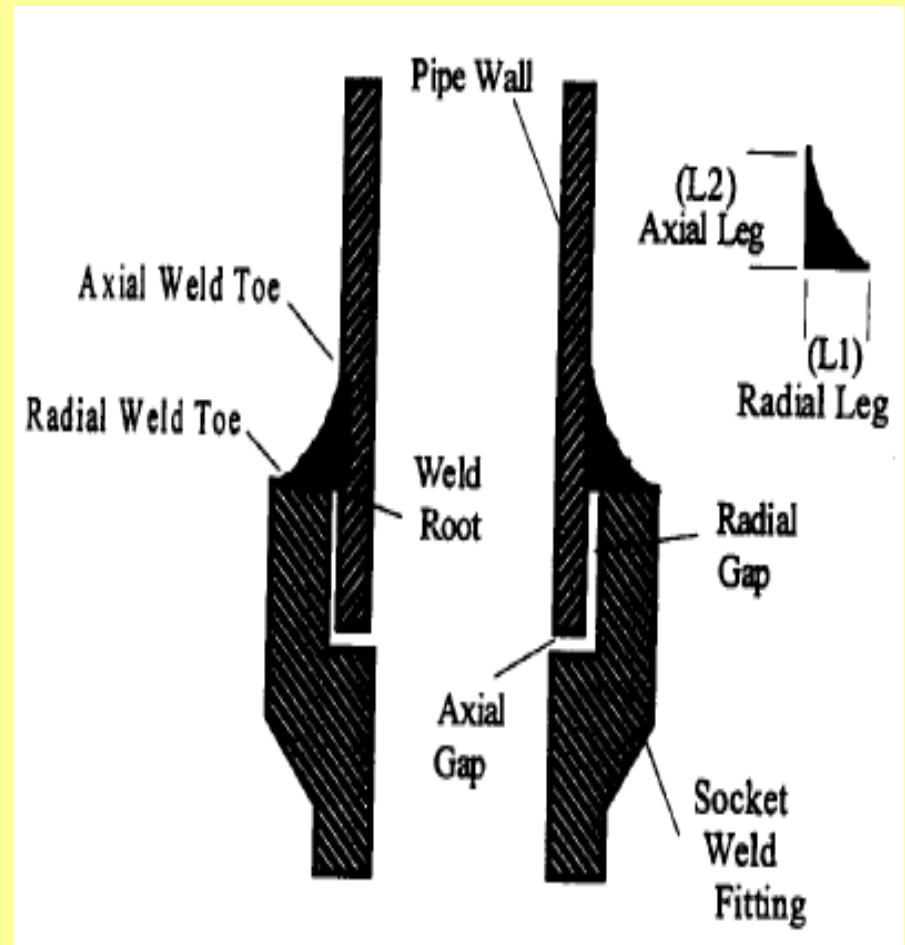
- Difficult to know the next failure if there are over 100,000 socket-welded joints
- 80% of fatigue failures relate to high cycle vibration fatigue of socket welded connections
- Maintenance check at Comanche Peak Steam Electric Station for suspected fatigue induced failures occurred between March 1990-1998
 - 28 leaks considered likely to have been caused by fatigue in this eight year period
 - Failures occurred in socket welded fittings

Small-Bore Piping Weld Joint



Design parameters contribute to failure

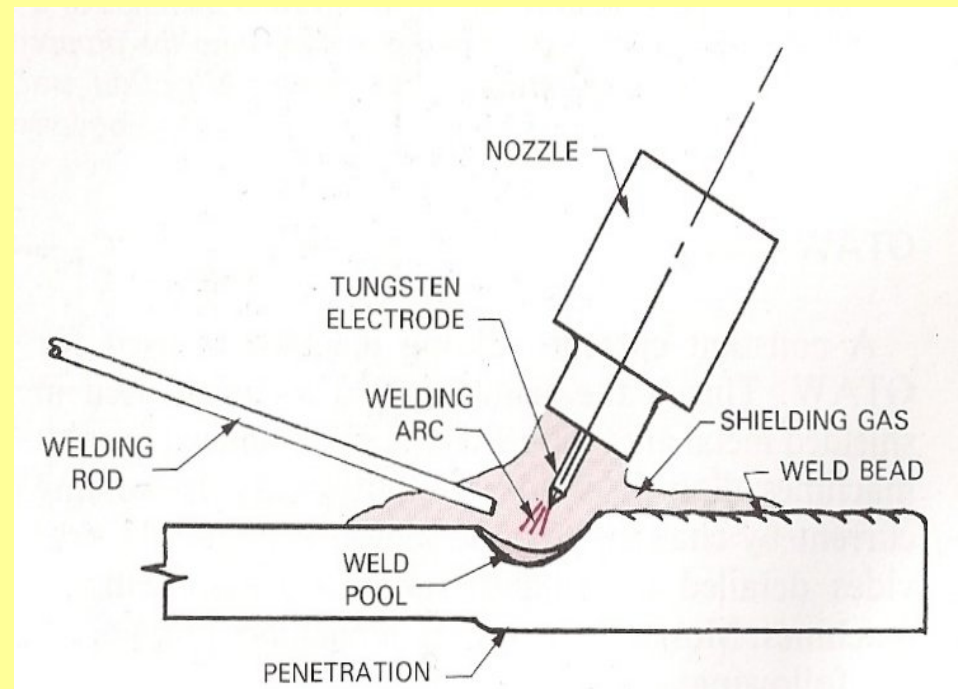
- Gap forms when pipe is inserted into the fitting.
- Creates stress at the weld root.
- Forms a crevice where corrosive fluid comes into contact with the weld root.
- Crack initiation starts at the weld root.
- Environmental Corrosion



Socket Welded Joint Configuration

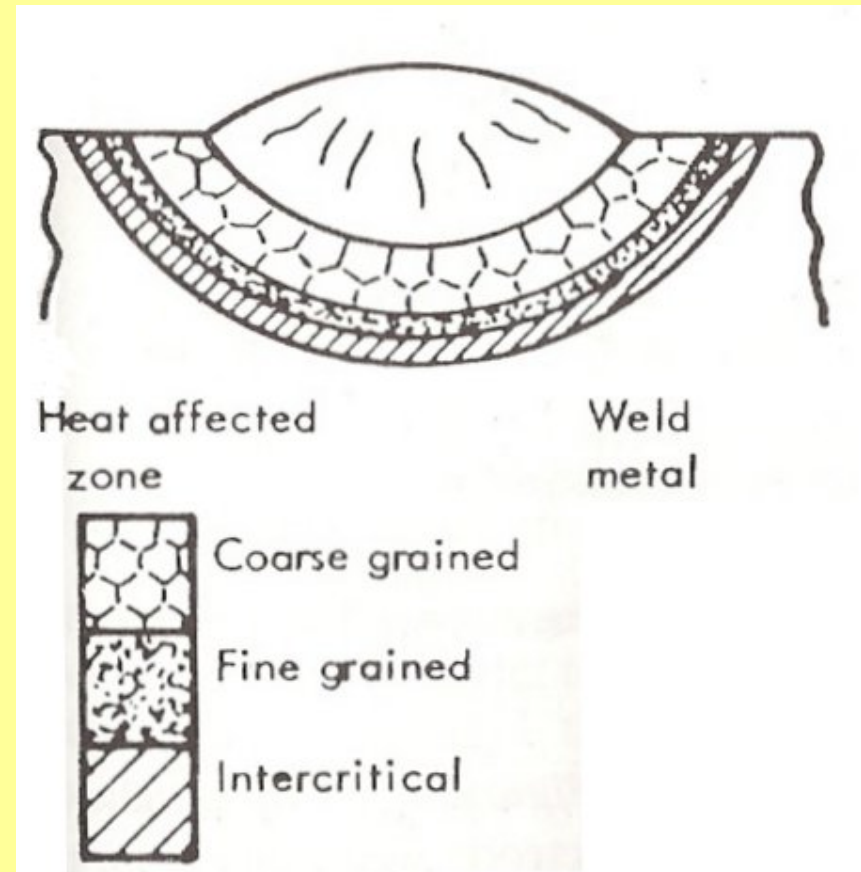
Gas Tungsten Arc Welding

- Heat causes compressive and tensile stresses
- Phase transformations create strain in the lattice
- Absorption of O and CO cause porosity and cracking



Grain Growth in the HAZ

- Grain growth occurs in the heat affected zone (HAZ)



Fatigue

- Fatigue is a form of failure that occurs in the structures subjected to dynamic and fluctuating stress or strain.
- Failure to occur at a stress level considerably lower than the tensile or yield stress for a static load.
- Fracture surface is perpendicular to the direction of an applied tensile stress.

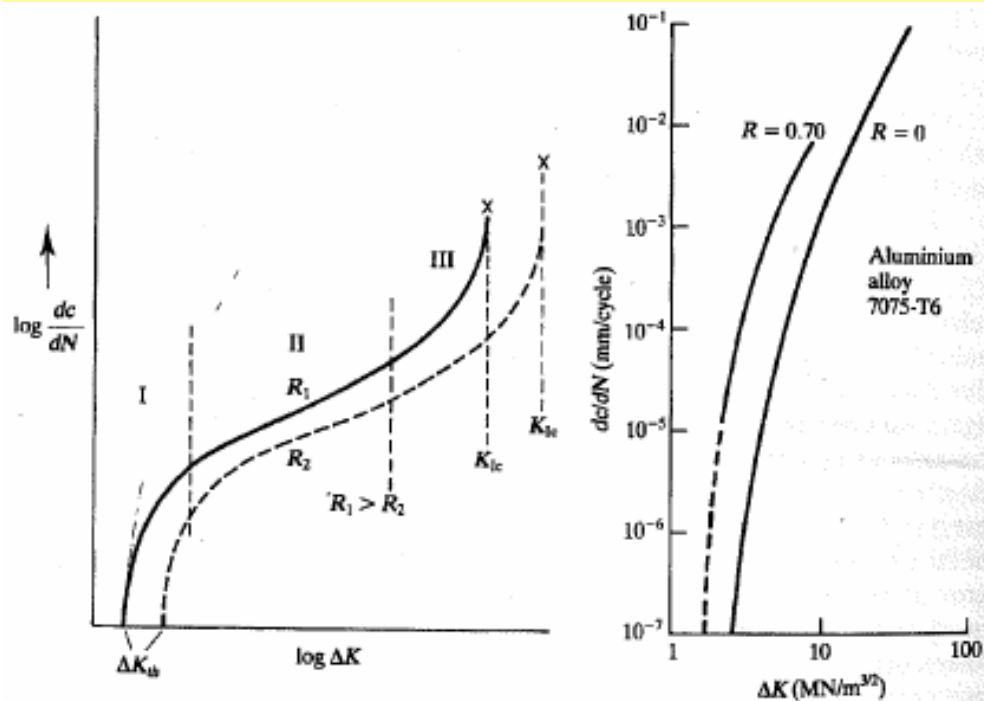
Fatigue

- The stress intensity factor K can be defined as the severity of the crack propagation which is affected by crack size, stress, and geometry.
 - K depend on remotely applied stress S and crack length c . As the cyclic pressure continues to be applied on the crack, the crack grows and propagates.

$$\Delta K = \Delta \sigma \left(\sqrt{\pi c} \right)$$

Fatigue and Cyclic Loading

- As stress ratio (R) increases the crack growth rate increase within Regions I and III



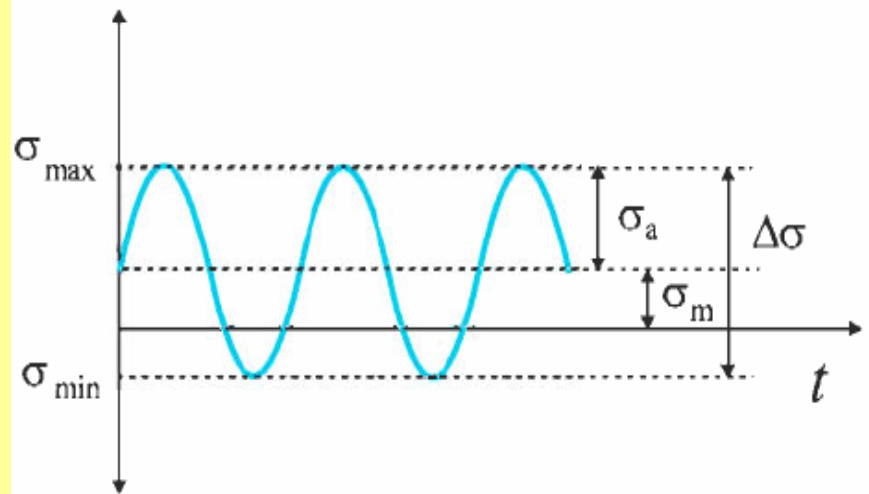
Stress Range: $\Delta\sigma = \sigma_{\max} - \sigma_{\min}$

K-Range: $\Delta K = K_{\max} - K_{\min}$

Stress amplitude: $\sigma_a = \frac{1}{2} (\sigma_{\max} - \sigma_{\min})$

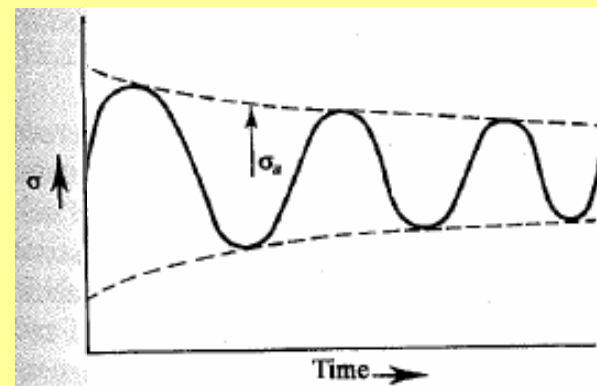
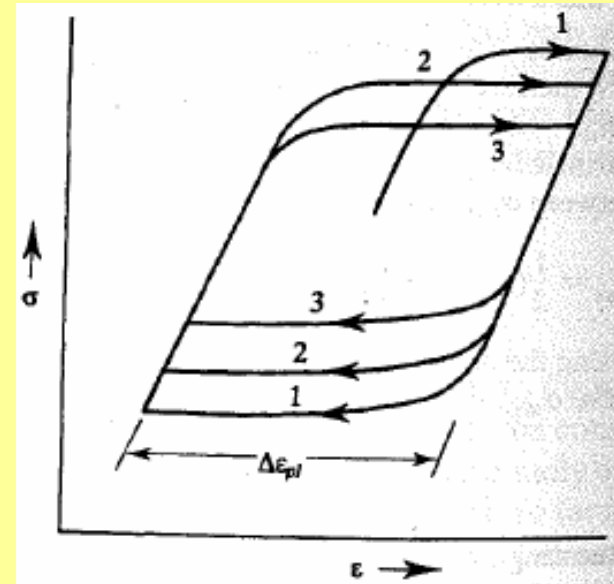
Mean stress: $\sigma_m = \frac{1}{2} (\sigma_{\max} + \sigma_{\min})$

Load ratio: $R = \frac{\sigma_{\min}}{\sigma_{\max}} = \frac{K_{\min}}{K_{\max}}$



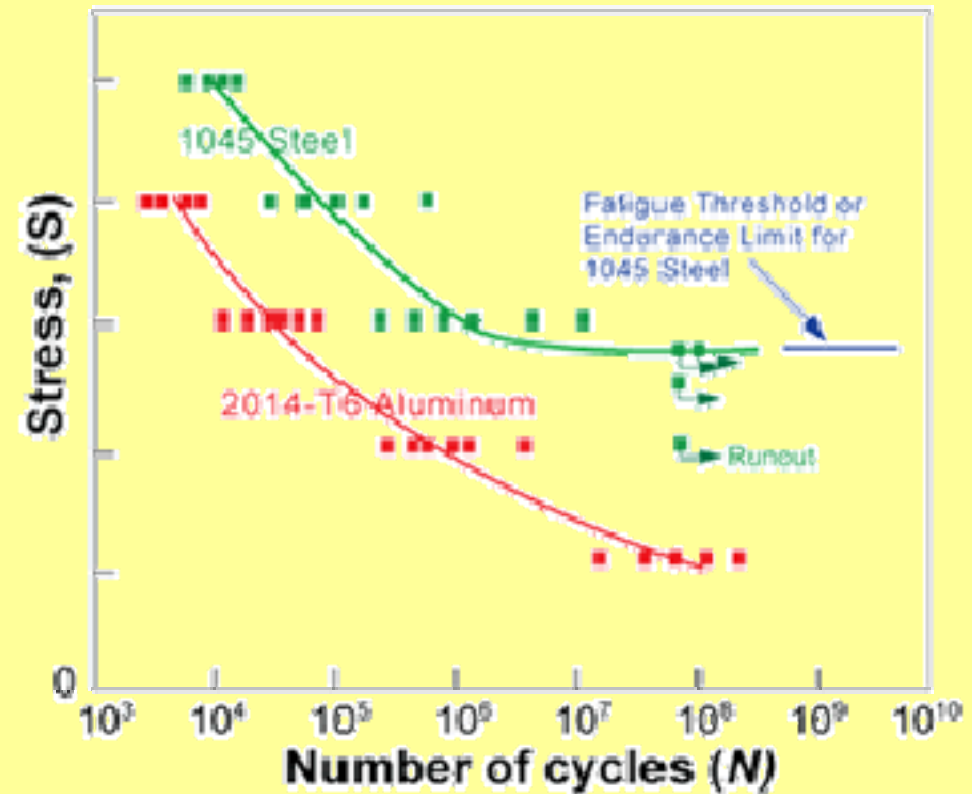
Vibrations

- Results of vibrations :
 - Shear on the cracks
 - Dislocation separation
- Hysteresis cycle.
- Stress amplitude decrease with increased number of cycles.
 - The welded joint become softer
 - Crack propagates



S-N Curve

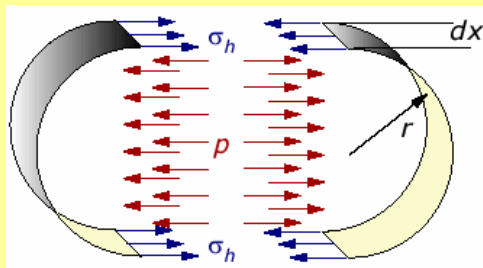
- The S-N curve gives a method to predict the fatigue limit and fatigue life of a material.
- The S-N curve becomes horizontal at higher N value (fatigue limit).



S-N Curve

Pressure

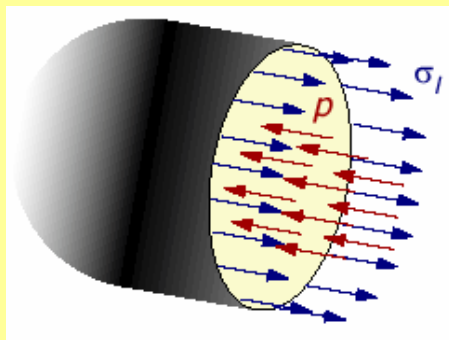
- The pressure serves as a cyclic tension-compression load inside of the pipe.
 - The cyclic pressure at weld root creates stress concentration and initiates a sharp crack.
- Pressure Vessel Laws for cylinder
 - Hoop stress :



$$\sigma_h * 2t * dx = p * 2r * dx$$

$$\sigma_h = \frac{pr}{t}$$

- Axial stress:



$$\sigma_l * t * 2\pi r = p * \pi r^2$$

$$\sigma_l = \frac{pr}{2t}$$

Where p = pressure
 r = radius
 t = wall thickness

Bending Force

- The bending force acting on the welded joint causes a bending moment at weld toe.

$$S = \frac{Mc}{I}$$

S = Stress

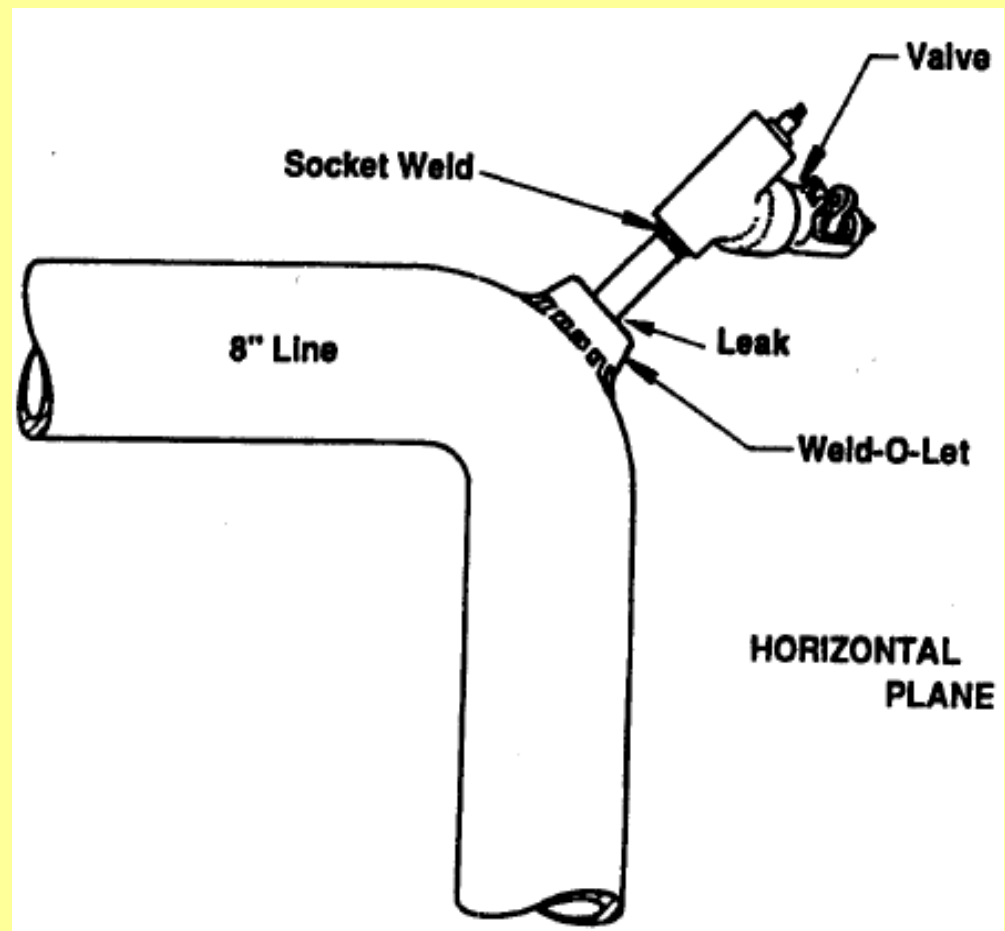
M = bending moment

c = distance from void to surface

I = area moment inertia about the bending axis

Bending: “Lollipop” structure

- Crack morphology seen when small pipe provides mechanical support for massive object.
- Only small amounts of vibrational energy are needed to induce ***cyclic bending forces*** – these exceed the pipe’s ability to support the object.



Axial Weld Toe Cracks Caused by Bending

- Symmetric bending stresses typically cause 2 simultaneous fatigue cracks that initiate at the outer diameter surface.
- Inadequately supported free spans of pipe oscillate during operation.
- The pipe can be subjected to a bending moment if the supports are too rigid.
- Results: higher mean stress on one side of the weld ~ susceptibility to fatigue.

Solutions from TU Electric

- Detect cracks through nondestructive inspection methods such as dye penetration or visual examination.
- Shortening time interval between visual inspection.

Solutions from TU Electric-Control of Mechanical Vibrations

- Reducing vibration energy and frequency (i.e. stabilizing the pipe and increasing wall thickness)
- Modifying system design (i.e. reroute pipe, eliminate lollipops)
- Isolating vibration energy (i.e. install flexible hose).

Materials Composition-Austenitic Stainless Steel

- Carbon <0.03 wt%
- Manganese <2.0 wt%
- Silicon <1.0 wt%
- Chromium 18-20 wt%
- Nickel 8-12 wt%
- Phosphorous <0.045 wt%
- Sulfur <0.03 wt%

Proposed Solutions

- Material
 - SST 304N
 - Solid Solution Strengthening
 - Each 0.01 wt% Nitrogen added increases yield strength by 5.5 – 7 MPa
- Flexible stainless steel tubing¹
 - PVC coating
 - Sufficient pressure resistance
 - Satisfactory bending characteristic and weather resistance

Summary

- Stress concentration causes failure by the means of :
 - Fatigue
 - Vibration
 - Bending
 - Pressure
- Welding :
 - Heat : contraction and expansion
 - Phase transformation : Lattice Strain
 - Absorption of gases : Voids and Cracking
- Solutions :
 - Design
 - Materials