AREVA

SG Tube Burst Test Results

Effect of bending stress on burst pressure of SG tubes with circumferential degradation

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Presentation Outline

- > Purpose
- > Program Description
- > Sample Preparation
- > Test Parameters
- > Test Equipment
- > Test Results
- > Analysis of Results
- > Conclusions

Purpose

The purpose of the EPRI sponsored program is to determine the effect bending loads have on the burst pressure of once-through (straight) and recirculating (U-bend) steam generator tubes with circumferential degradation. As a secondary objective, collapse tests were also conducted.

AREVA

Program Description

The test program consists of clamping U-bend and straight tubes into a test fixture and then applying a deadweight to produce desired moments at a circumferential flaw that has been cut into the tube. The tube is then pressurized and the pressure is increased until burst occurs. Post test exams are made and the results are then analyzed.

Sample Preparation

> **Tube Material:**

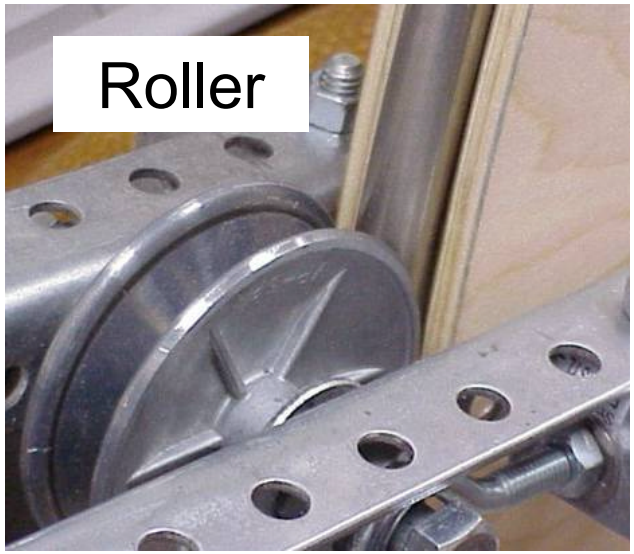
- Used AREVA inventory 5/8” nominal OD OTSG tubing
  - Heat # 92859, Lot # 1818
- Tubing is safety related with applicable CMTR
  - Sy = 47100 psi, Su = 97200 psi
- As measured dimensions
  - OD = 0.6295”, ID = 0.5515”, resulting thickness = 0.039”
- Approximately 550 feet of tubing needed to obtain the desired number of test specimens.

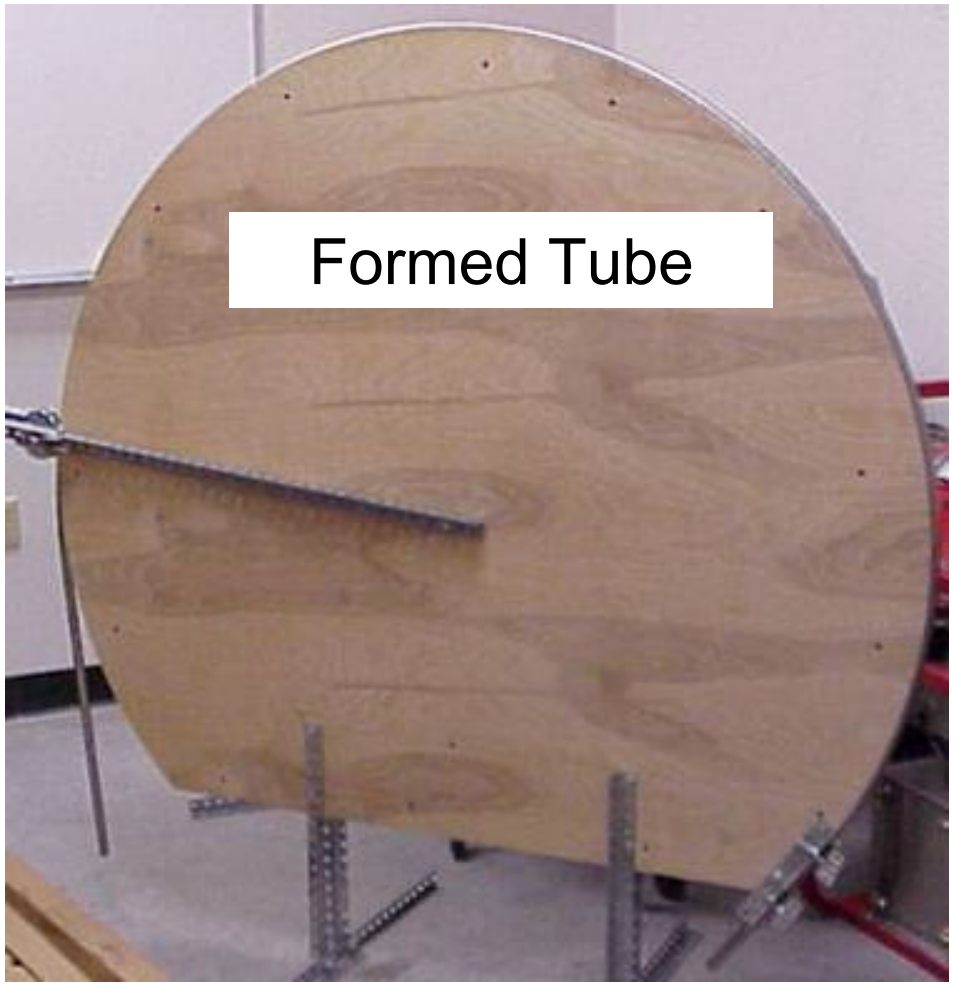
Sample Preparation

> **Forming U-bends:**

- **Compression bending was used to form the U-bends**
- **Two jigs were constructed and the tubes were forced around the jig by a roller**
- **Due to elastic spring back, the tubes were rolled over ~220 degrees to achieve the desired U-bend**
  - **A 28” radius jig resulted in a 36” radius U-bend**
  - **A 14” radius jig resulted in a 16.5” radius U-bend**

Sample Preparation



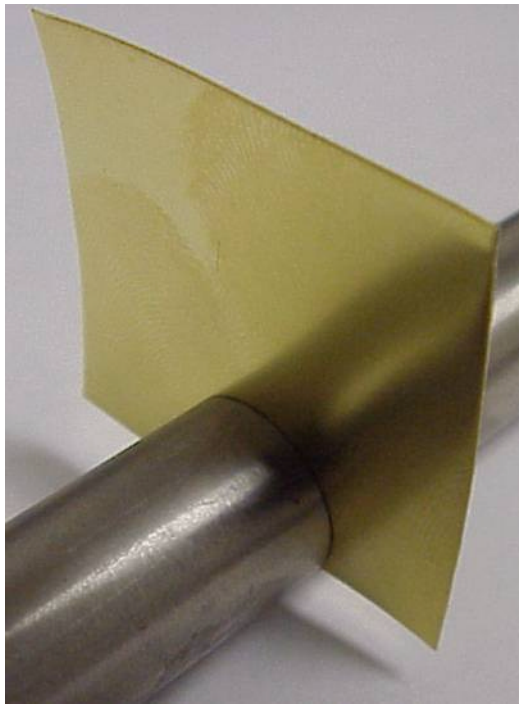


Sample Preparation

Sample Preparation

> EDM Notches:

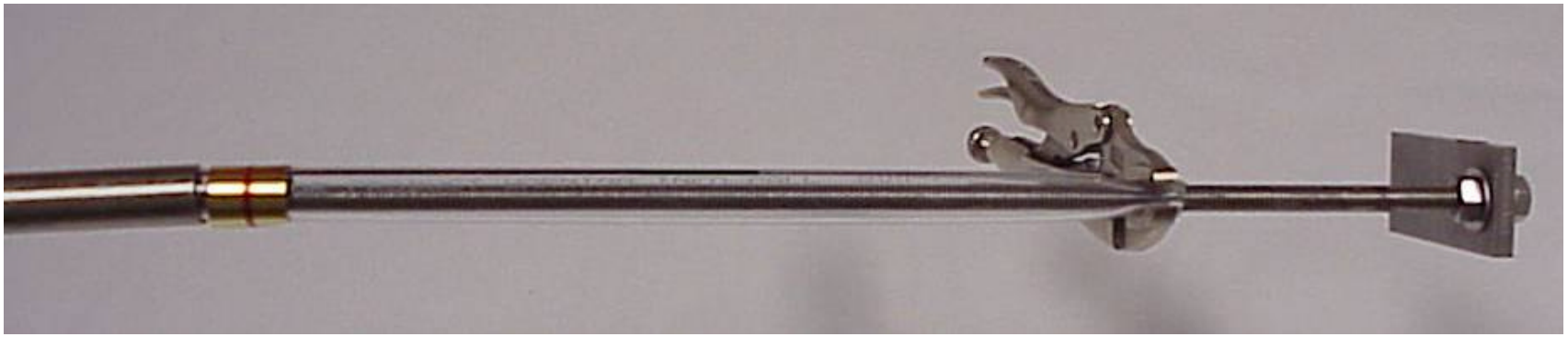
- EDM (wire) was used to create circumferential flaws in the tubes
  - A jig was setup to create consistent flaws
    - Standard test: 100% TW 245 degree flaw (~ 70% degraded area)
    - Supplemental test: 100% TW 180 degree flaw (~ 50% degraded area)
  - Flaws located near point of maximum bending stress
    - 0.25” from fixed end support



Sample Preparation

> **Sealing Tube for Pressurization:**

- **Plastic tubing with brass foil was inserted into flawed tube to seal EDM notch for pressurization**



Test Parameters

- Test geometry was selected to simulate actual SG configurations covering all designs
  - U-bend radius of 36” selected to represent SG outer rows
    - 36” radius 0.625”OD tube = ~ 50” radius 0.875” OD tube
    - also tested 16.5” radius tubes
    - all U-bend tubes were tested with 3” straight leg extension between U-bend and support (fixed)
  - Straight tube of 45.5” used to represent OTSG upper span
    - One end of tube fixed to simulate tubesheet, other supported by use of actual OTSG tube support plate
    - Load displacement test of supported tube was conducted to verify boundary conditions

Test Parameters

- Input from venders defines the maximum design bending moments in the OTSG and RSG result in an outer fiber bending stress of less than 50 ksi.
  - Values elastically calculated for an unflawed tube

- Finite element analysis of the test geometry was used to determine the appropriate loads to apply to achieve the desired stress level.
  - Large U-bend, apex load of 68lbs = 52 ksi bending stress
  - Small U-bend, apex load of 133lbs = 51 ksi bending stress
  - OTSG, center load of 56 lbs = 48 ksi bending stress

Test Equipment

> The test equipment consists of:

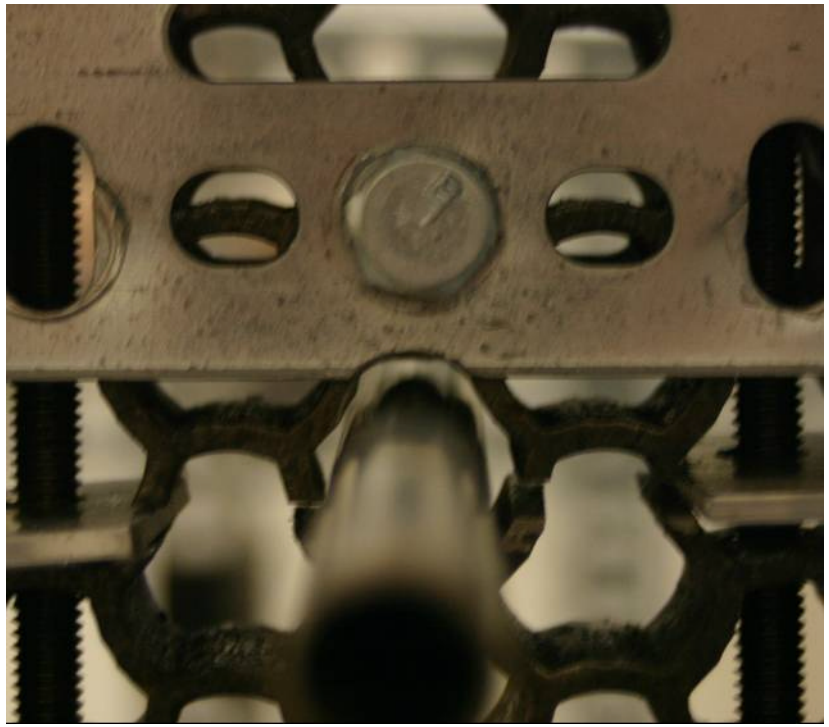
- Test frame for mounting/securing tubes
  - Split block for “fixing” tube
  - OTSG tube support plate for “pinning” tube
  - Eyebolt fixture
- Pressure generator
- Calibrated pressure transducer and recording device
- Camera and recording device
- Various weights and loading apparatus
- Calibrated scales and measuring devices

Test Equipment

Pressure Pump

Camera viewing burst tube and split block

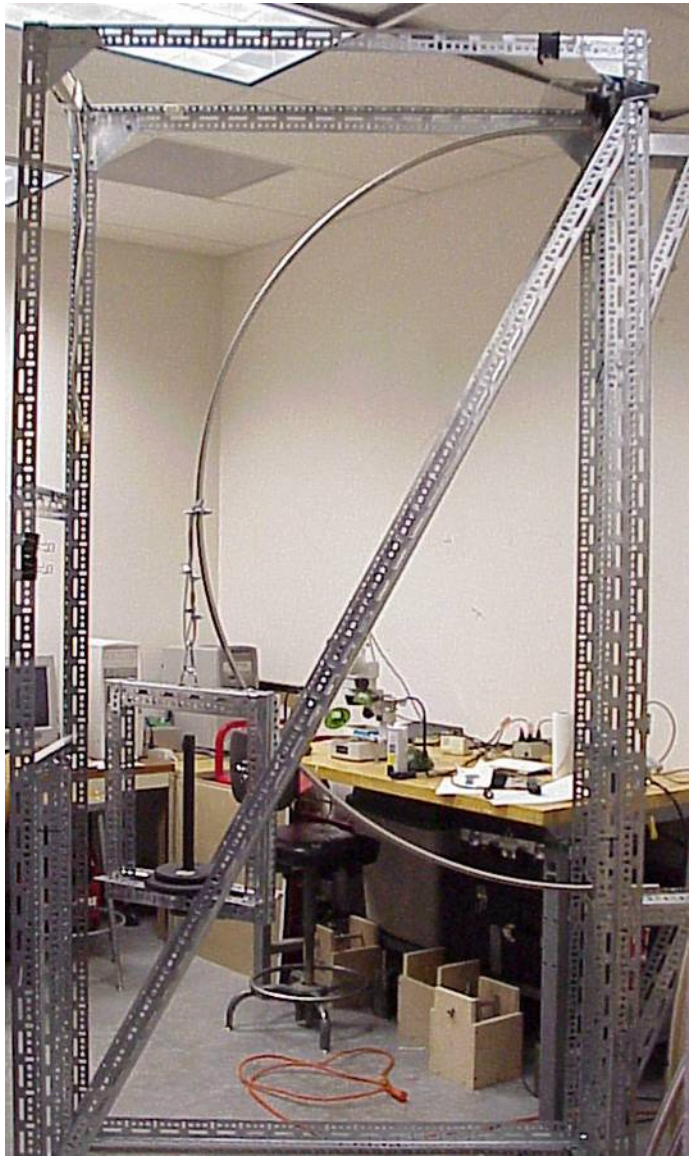
Test Equipment



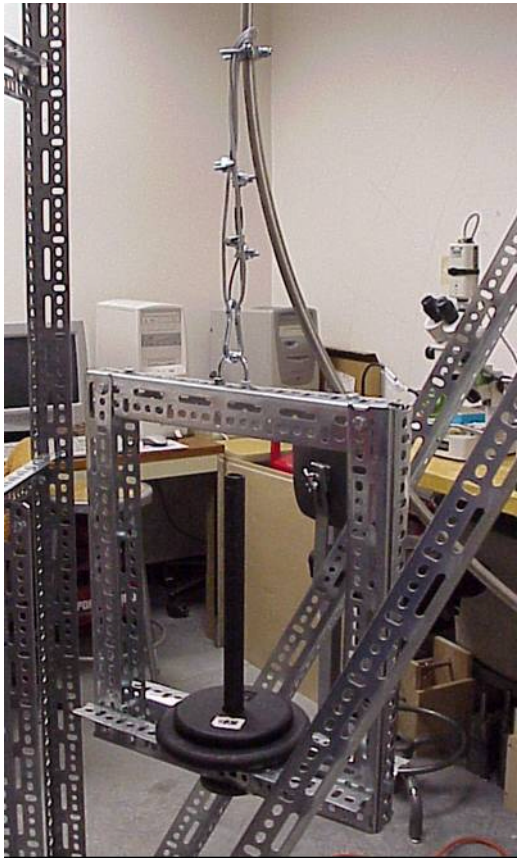
TSP support

Eyebolt support
with load cell

Test Equipment



Test Frame



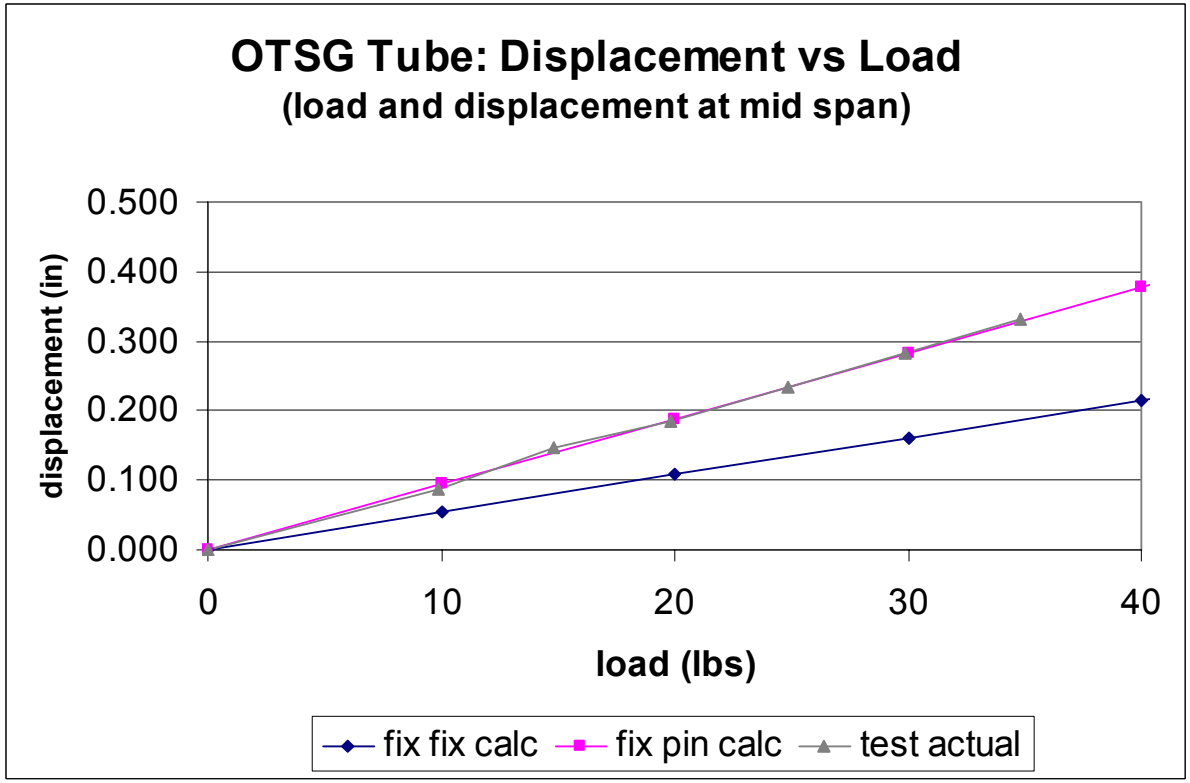
Loading Device

Test Results

- Several different tests were conducted
  - Verification of OTSG TSP boundary condition
    - Load displacement for test configuration
    - Burst test with eyebolt in place of TSP
  - Burst test to verify tube CMTR strengths
    - Burst of 2 unflawed tube samples
  - Collapse test of 36” radius U-bend
    - Both flawed and unflawed tube
  - Collapse test of OTSG tubes
    - Both flawed and unflawed
  - Burst versus moment test
    - 36” radius U-bend
    - 16.5” radius U-bend
    - 45.5” OTSG tube
    - 245 vs. 180 degree flaws

Test Results

Verification of OTSG TSP boundary condition



- Test results compared to calculated values
- Results verify the OTSG TSP behaves as a pinned joint under moderate lateral loading

Test Results

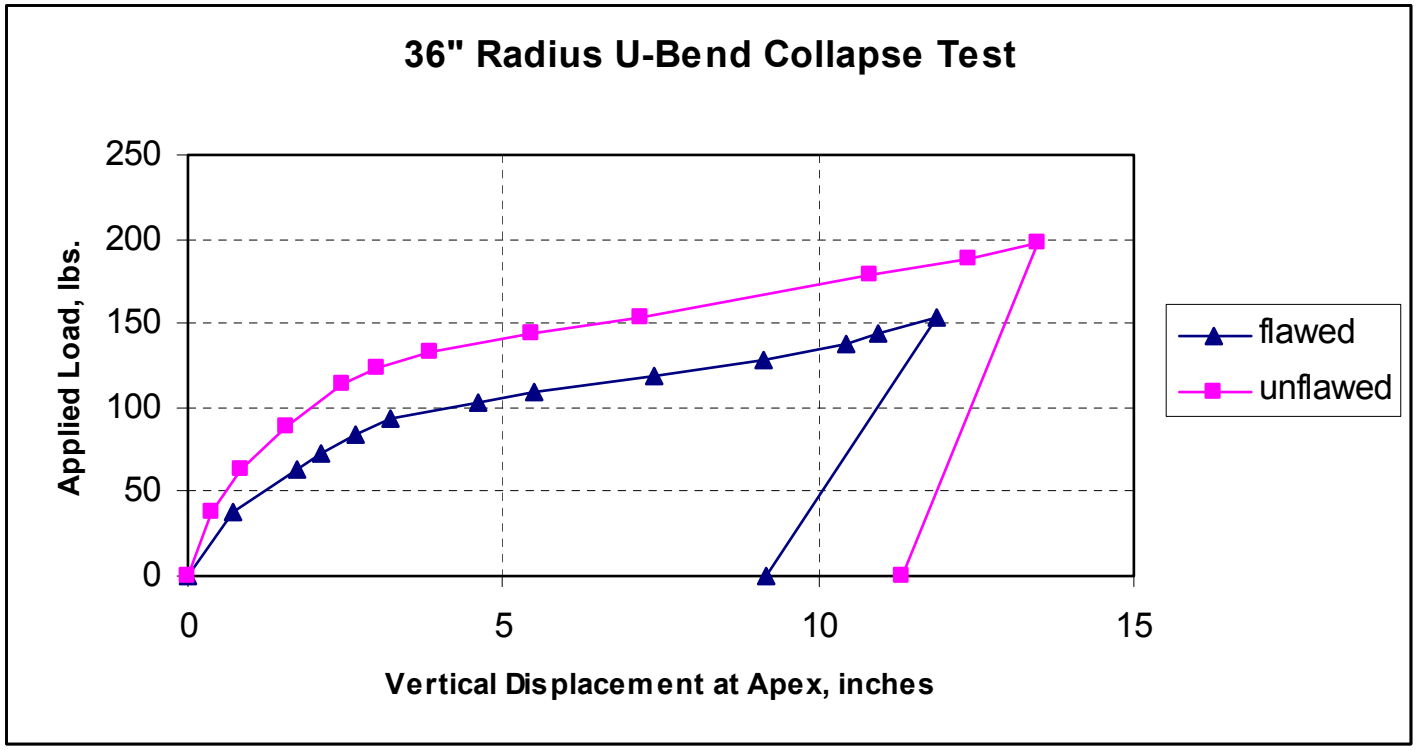
Burst test to verify CMTR strengths

- Unflawed segments of two tubes (U4, U20) were pressurized to burst
  - U4 burst pressure = 11500 psi
  - U20 burst pressure = 11400 psi
- Equation 5-32 of flaw handbook used to calculate burst pressure based on tube geometry and CMTR strengths
  - Calculated burst pressure = 11400 psi
- Test verifies the strength of the tube specimens

Test Results

Collapse Test of 36” radius U-bend Tubes

- Displacements of U-bend apex and both legs near fixed support taken versus applied load
- Tubes did not “collapse” (still had load carrying ability)



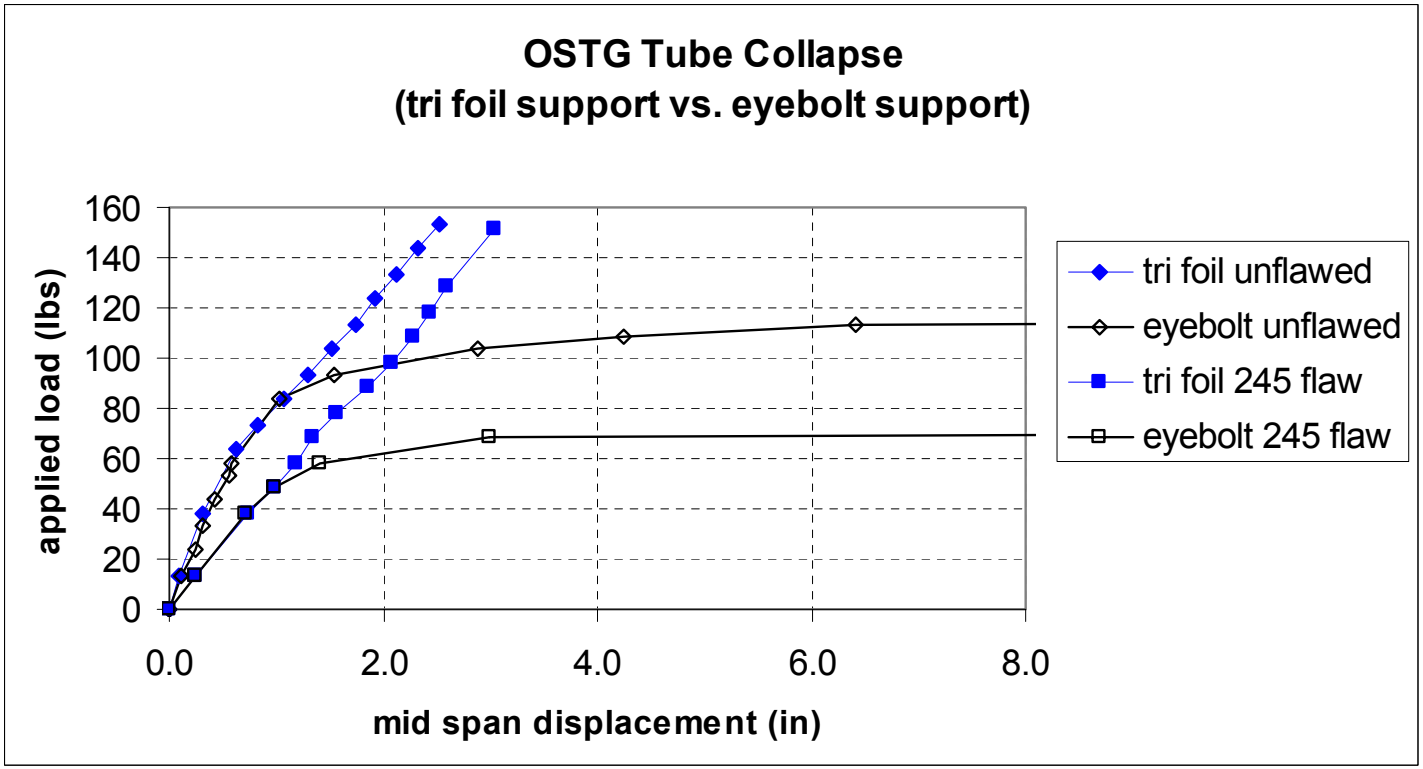
Test Results

Collapse Test of 36” Radius U-bend Tubes

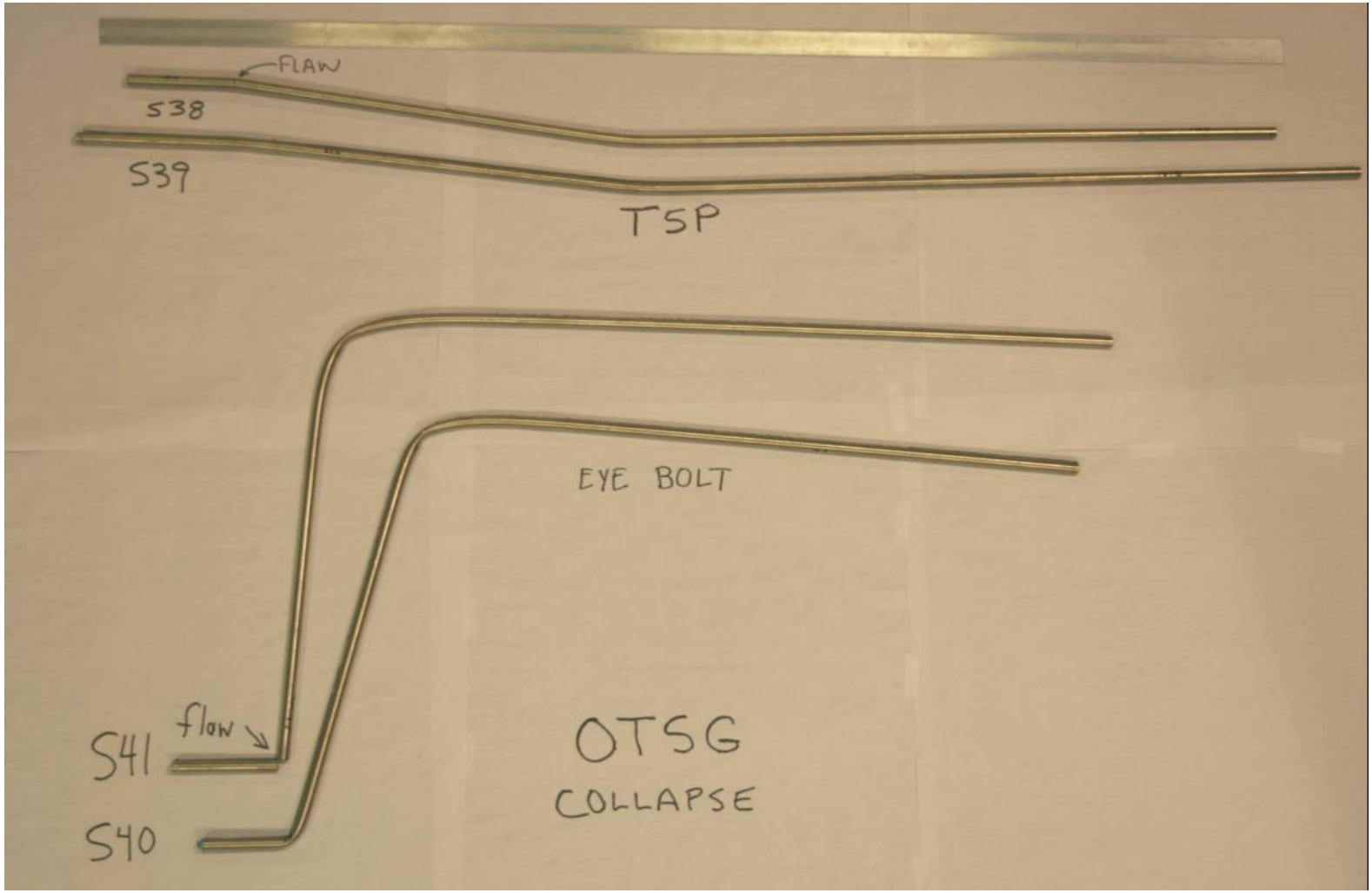
Test Results

Collapse Test of OTSG Tubes

- Both flawed and unflawed tubes tested to collapse
- Displacements at mid span and tube axial movement taken versus applied load

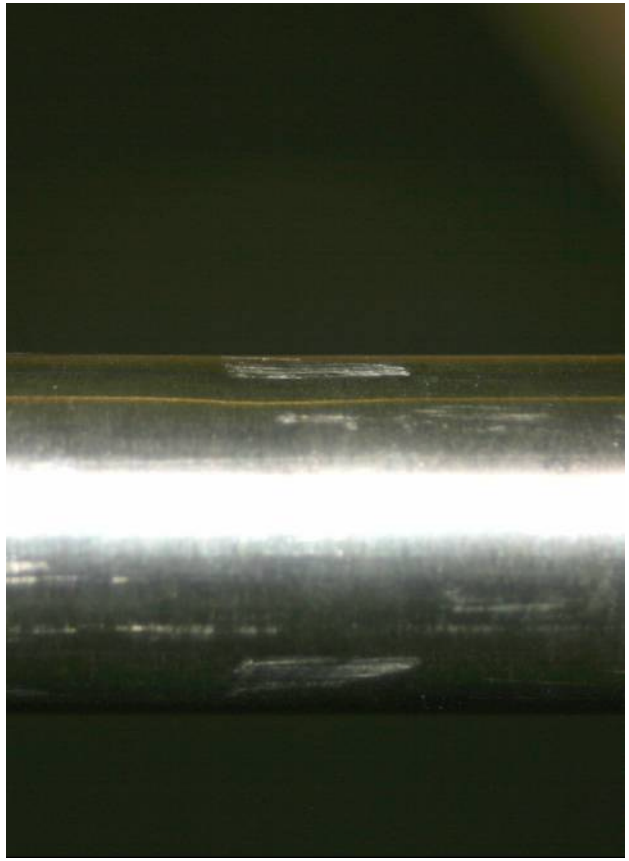


Collapse Test of OTSG Tubes



Test Results

Collapse Test of OTSG Tubes



Gouges in tube from contact with TSP due to bending

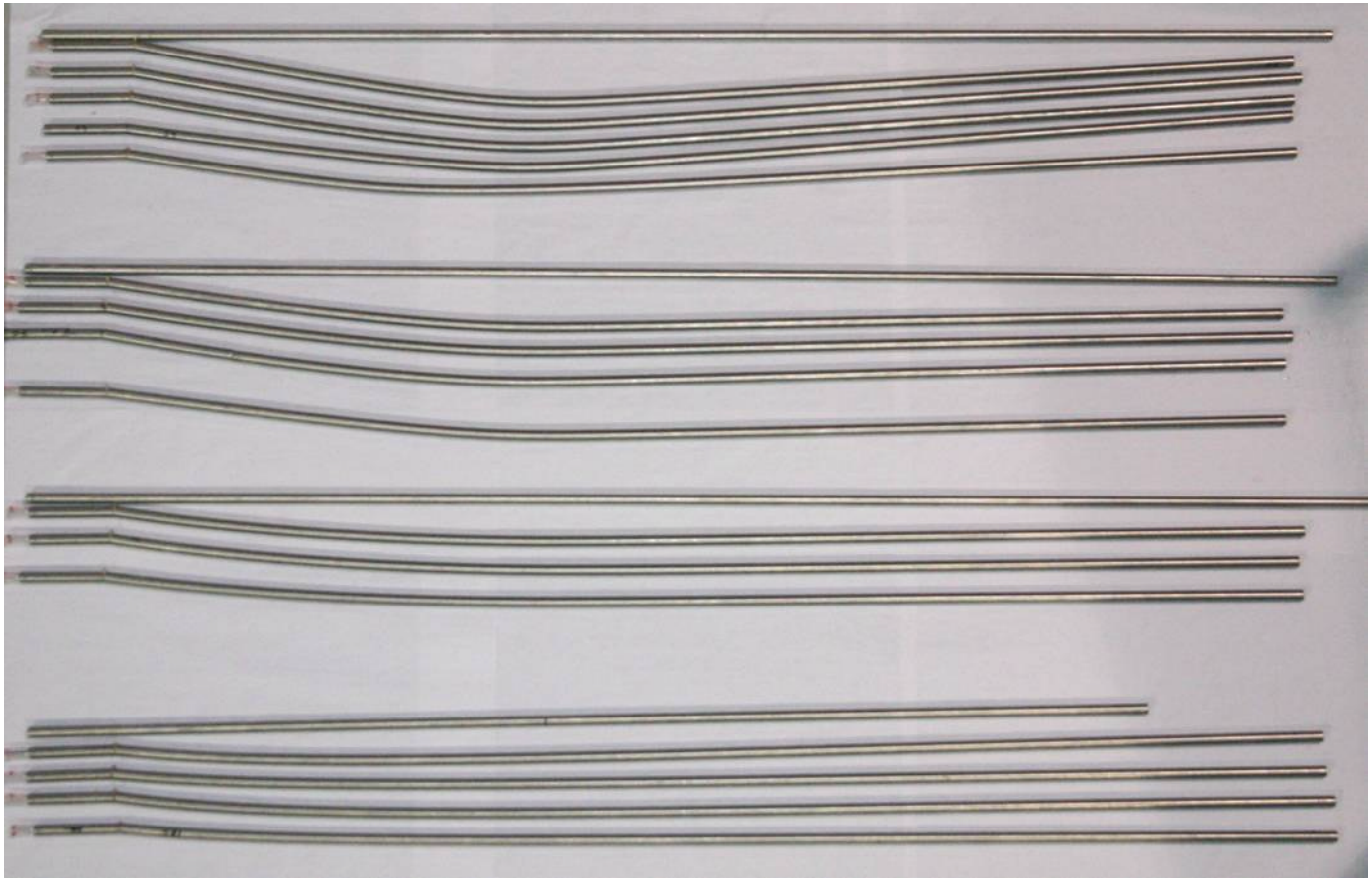
Test Results

- **Burst pressure vs. moment**
  - **Both U-bend and straight tubes tested**
    - **Configuration to simulate actual SG geometry**
  - **Performed test under various moment loadings**
    - **Maximum moment to simulate actual SG maximums**
  - **Tested two different flaw sizes**

Test Results

Straight tubes as burst (with reference tubes)

High load: ~50 ksi



Low load: ~0 ksi

Test Results

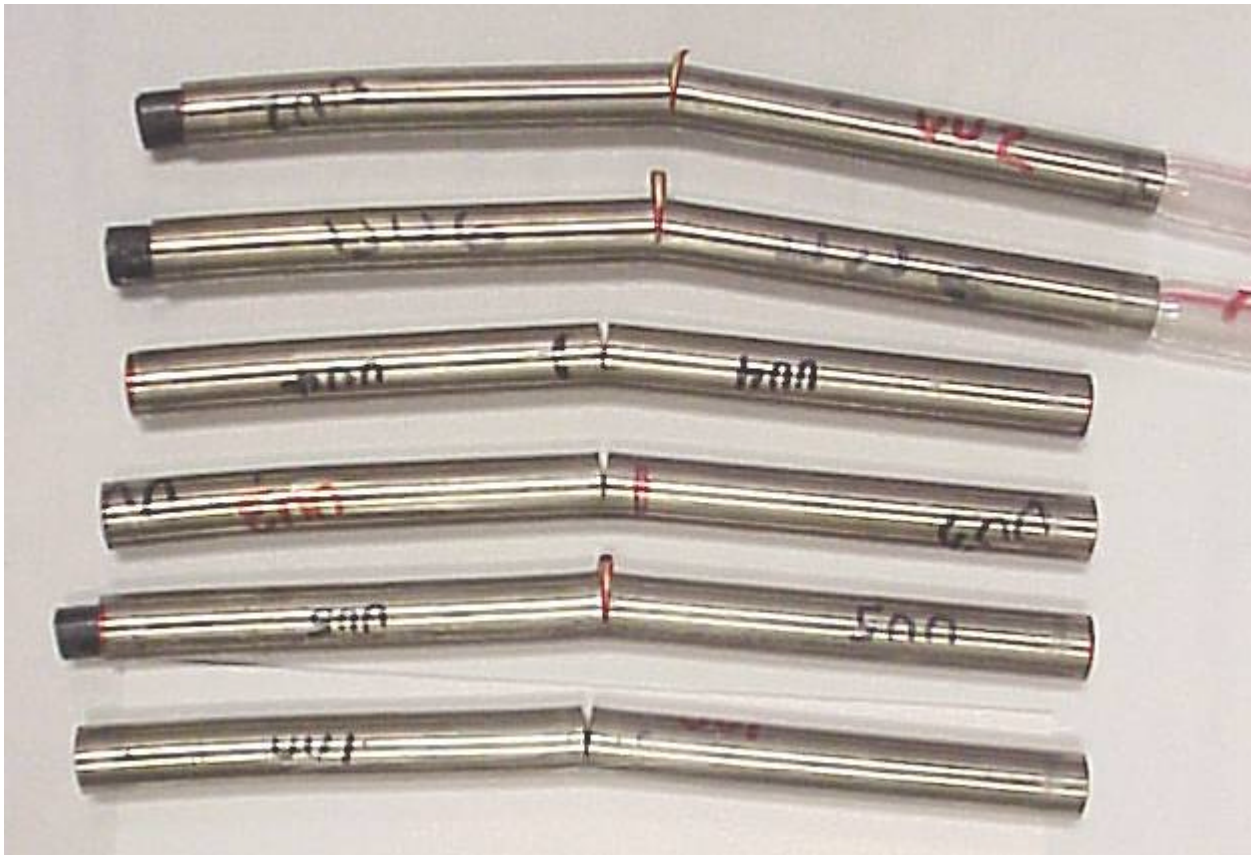
Large U-bend tube ends as burst

High load: ~50 ksi

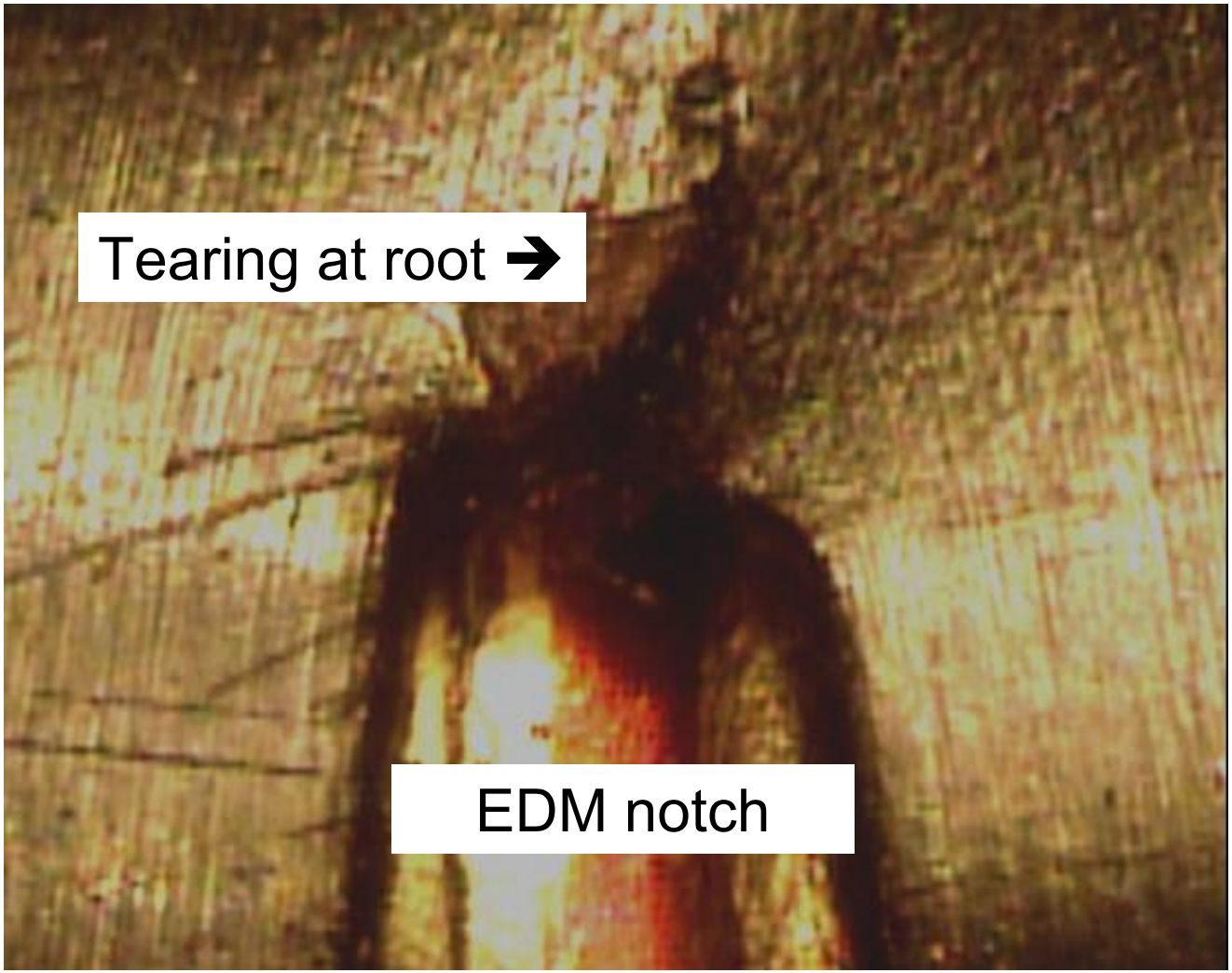
Low load: ~0 ksi

Test Results

Small U-bend tube ends as burst



Post Burst Tearing at Root of Flaw (U5)



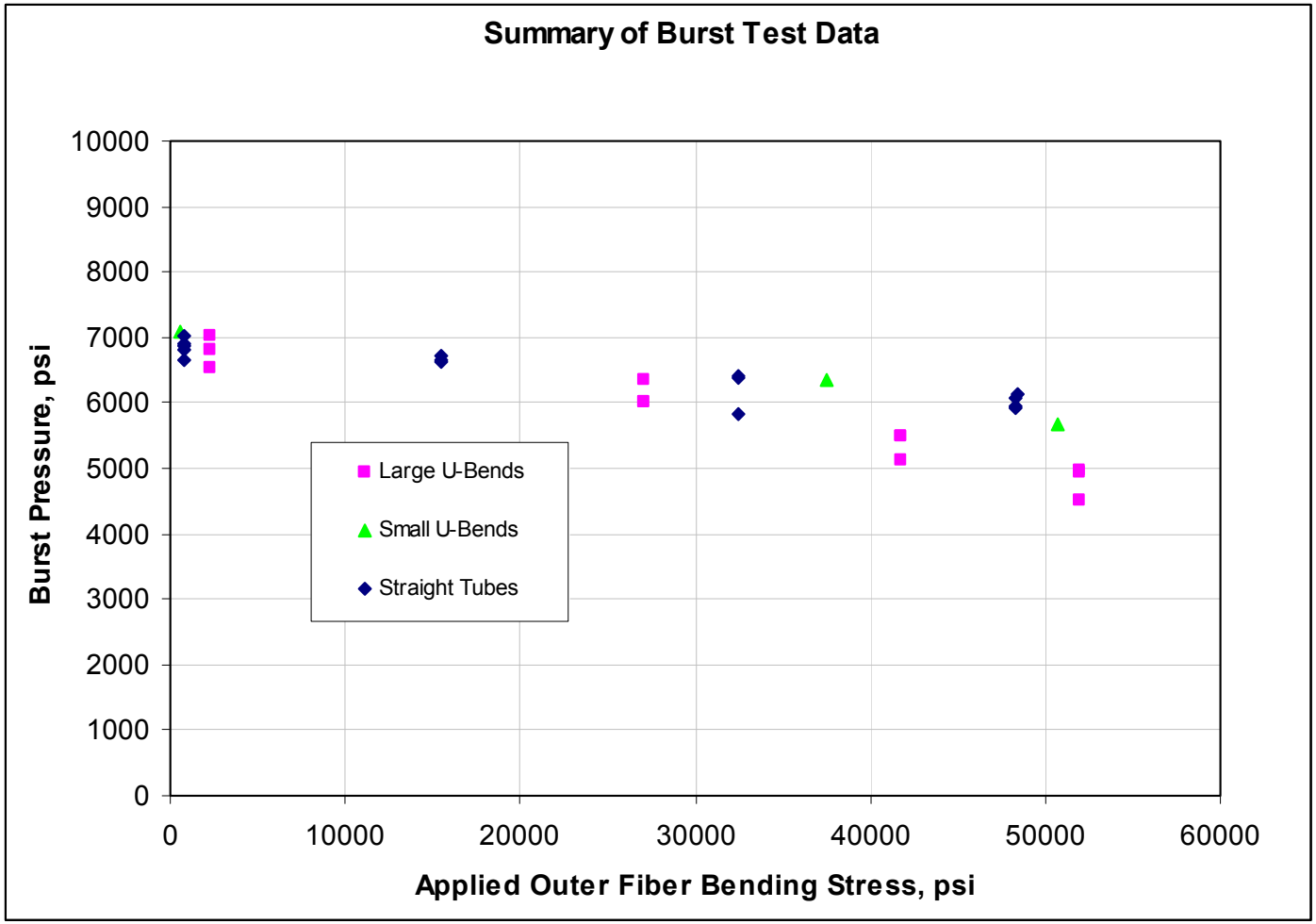
Test Results

> **Burst pressure vs. bending stress**

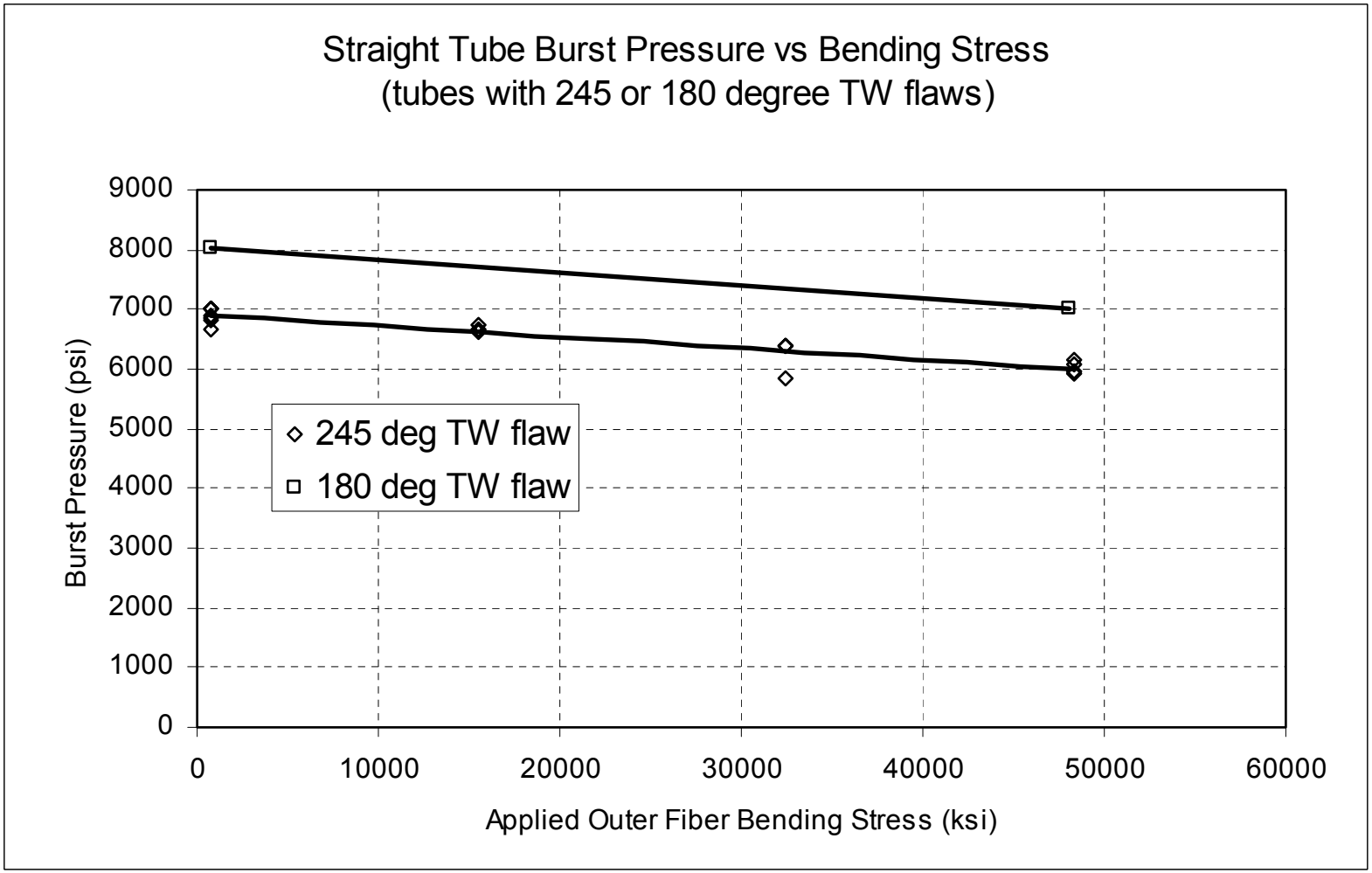
- **As previously stated, burst pressure determined for range of applied bending stress**
  - **Bending stress based on elastic analysis of unflawed tube**
- **Plots made of burst pressure vs. outer fiber stress**

Test Results

> **Burst pressure vs. outer fiber bending stress**
  - **stress from elastic analysis of unflawed tube with same applied load**



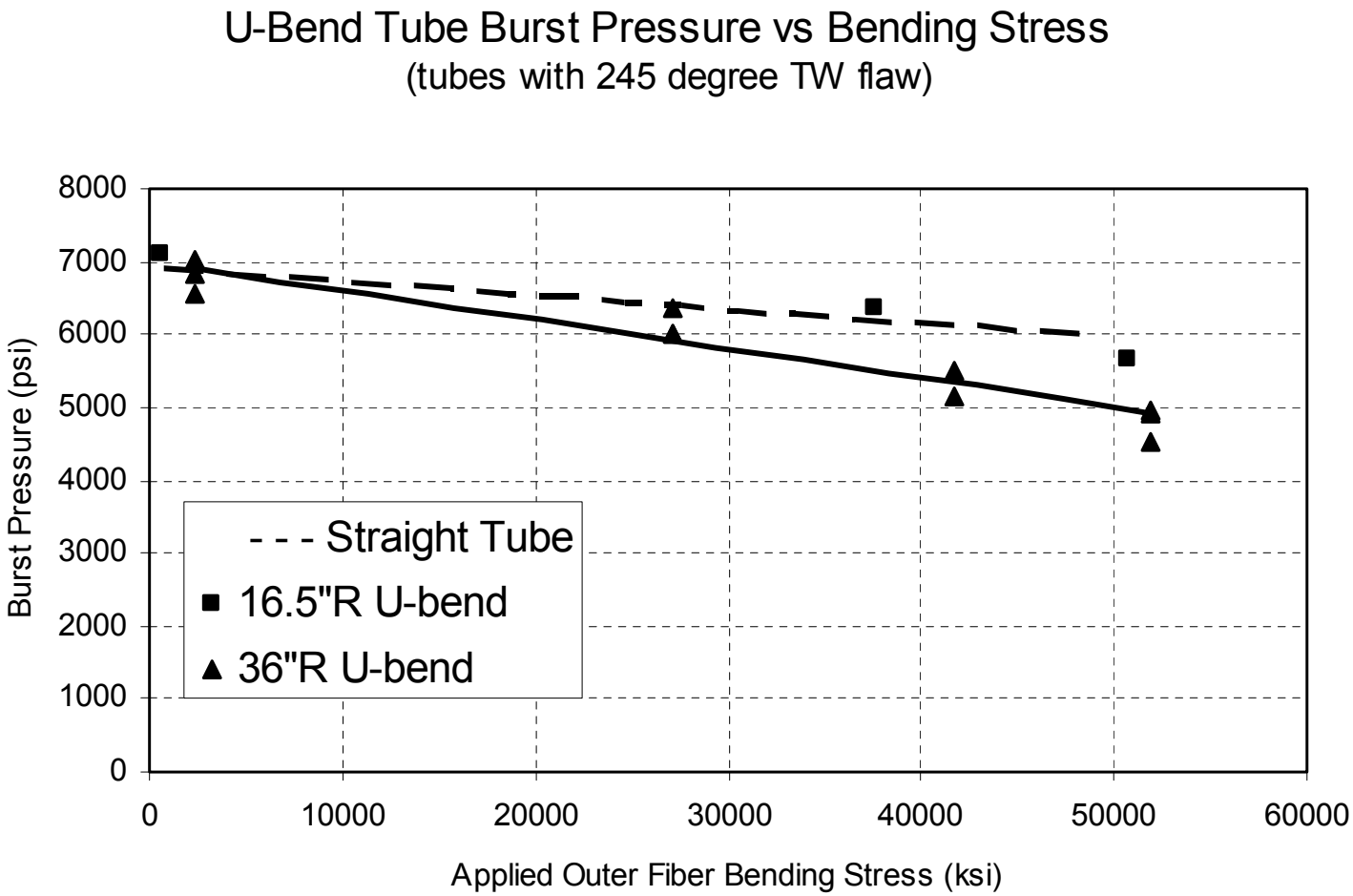
Test Results



Test Results

- **Straight tube burst test results**
  - **The results are conservative relative to actual straight tube geometry**
    - **Actual geometry provides axial constraint for tube**
    - **Tested geometry allows for more tube rotation and therefore lower burst pressure**
  - **The burst pressure with maximum outer fiber bending stress is well above the normal 3?P value of ~ 4000 psi**
  - **The reduction in burst pressure due to moment loading is the same for the 245 degree flaw and 180 degree flaw**

Test Results



Test Results

> **U-bend tube burst test results**

- **The burst pressure with maximum outer fiber bending stress is well above the normal 3?P value of ~ 4000 psi**
- **The reduction in burst pressure due to moment loading is affected by the U-bend radius**
- **The reduction in burst pressure for the small U-bend is similar to that of the straight tube**

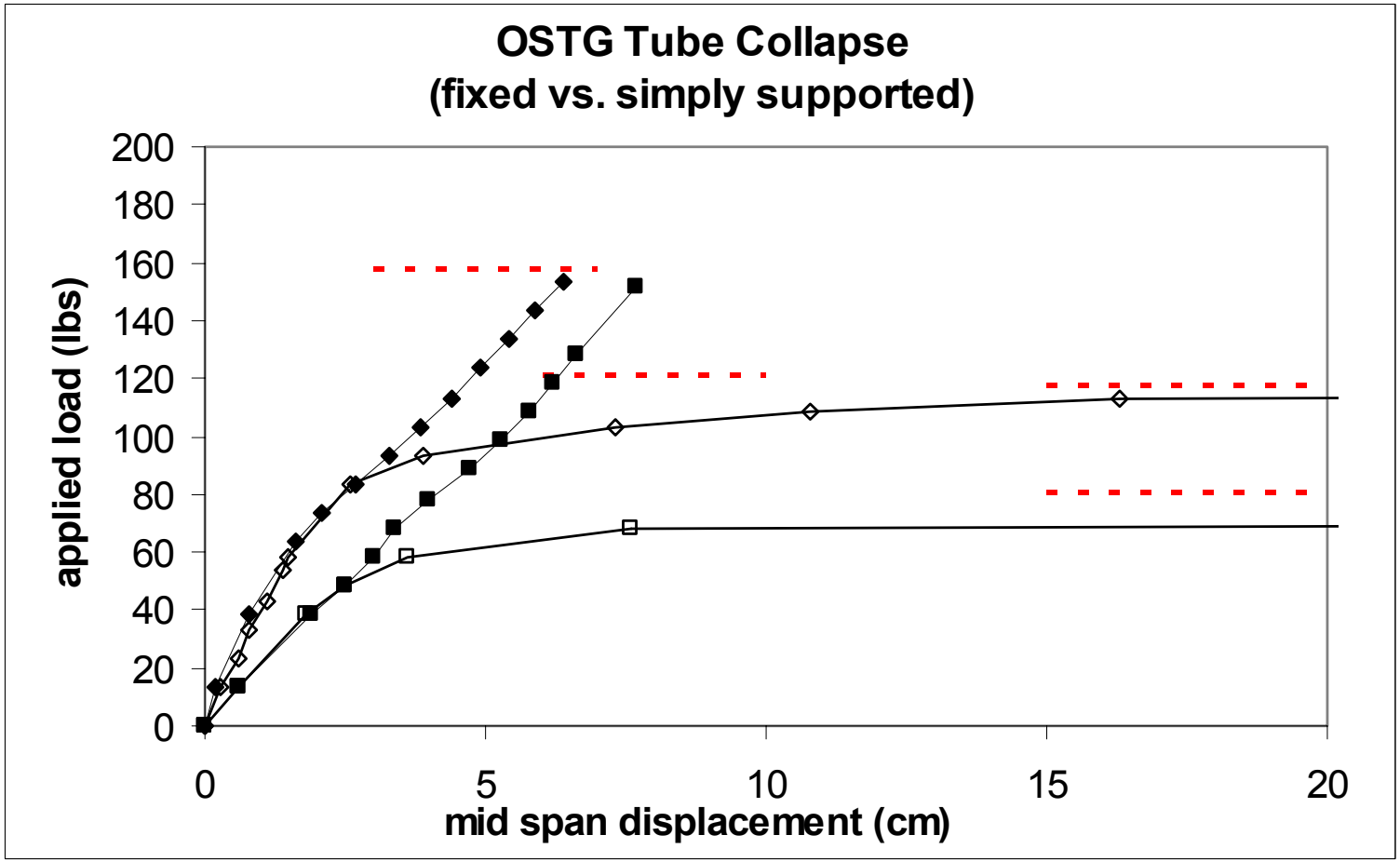
Analysis of Test Results

> **Analysis Results Include:**

- **Lateral Load Plastic Collapse Analysis of U-Bends and Straight Lengths of Tubing (Plastic Hinge Formation)**
- **Comparison of a modified Hernalsteen equation to test data**
- **Scaling of test results to all steam generator tubing sizes and materials**

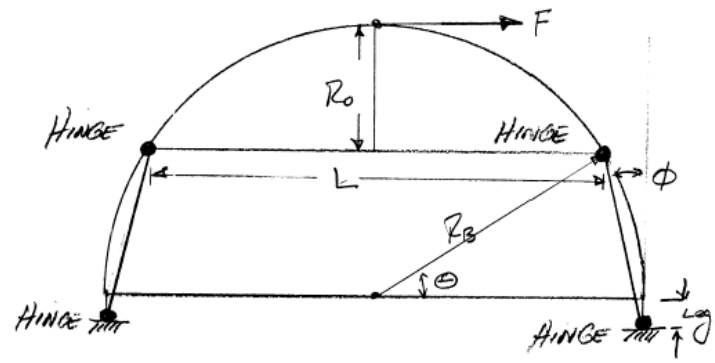
Analysis of Test Results

Plastic Collapse Calculations for Flawed and Unflawed Tubes as a Function of Support Conditions



Analysis of Test Results

Four Hinge Mechanism for In Plane Plastic Collapse of U-Bends



M_L = LIMIT MOMENT OF TUBE CROSSECTION

$$F_L = \frac{2M_L + 2M_L\left(1 + \frac{2R}{L}\sin\phi\right)}{R\cos\phi - 2R_0\frac{R}{L}\sin\phi}$$

$$\phi = \tan^{-1}\left(\frac{R_B - R_B\cos\theta}{L_g + R_B\sin\theta}\right)$$

$$R = \left[(R_B - R_B\cos\theta)^2 + (L_g + R_B\sin\theta)^2\right]^{1/2}$$

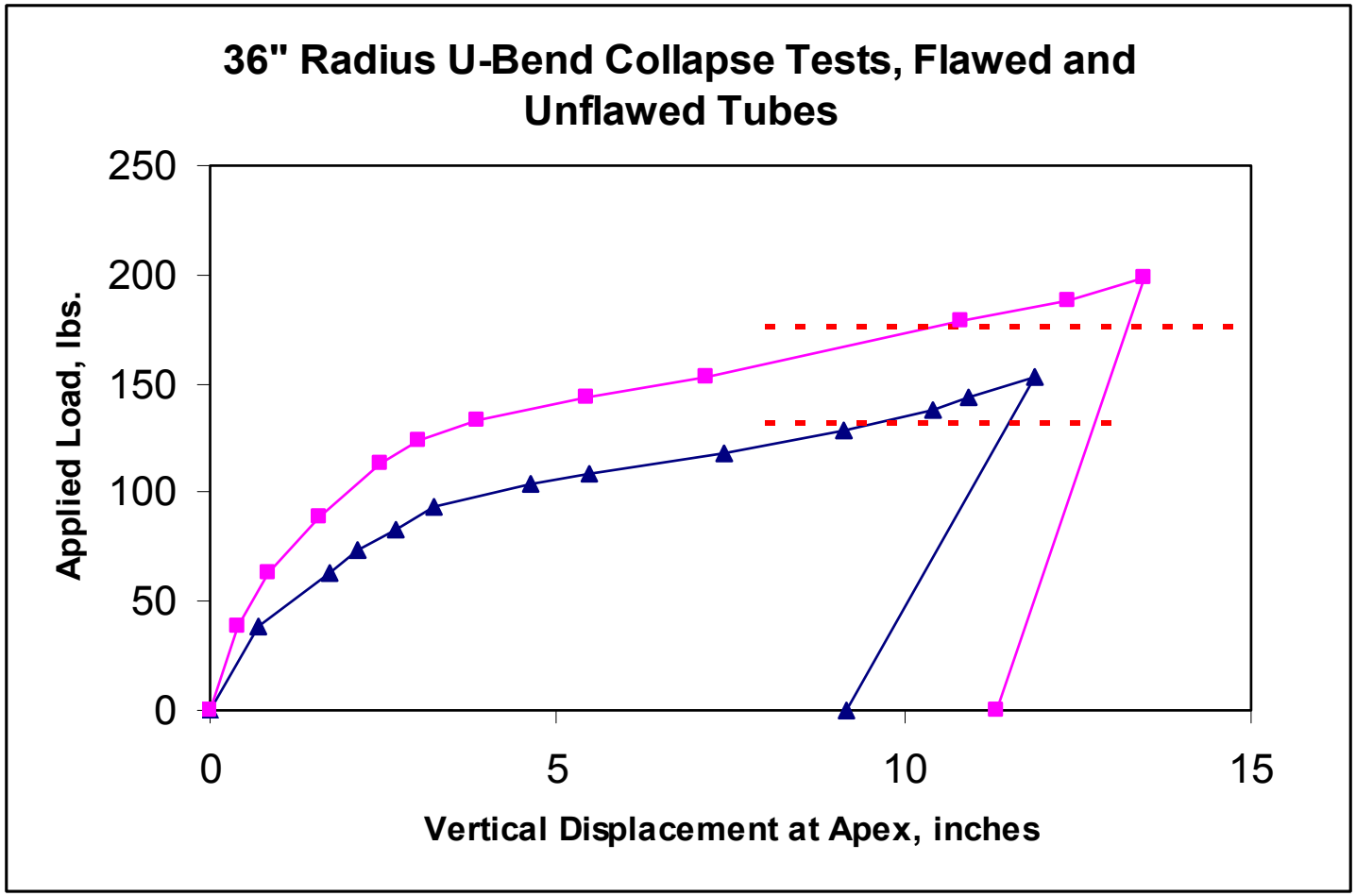
$$R_0 = R_B - R_B\sin\theta$$

$$L = 2R_B\cos\theta$$

MINIMIZE F_L BY VARYING θ WHICH CHANGES THE HINGE LOCATIONS

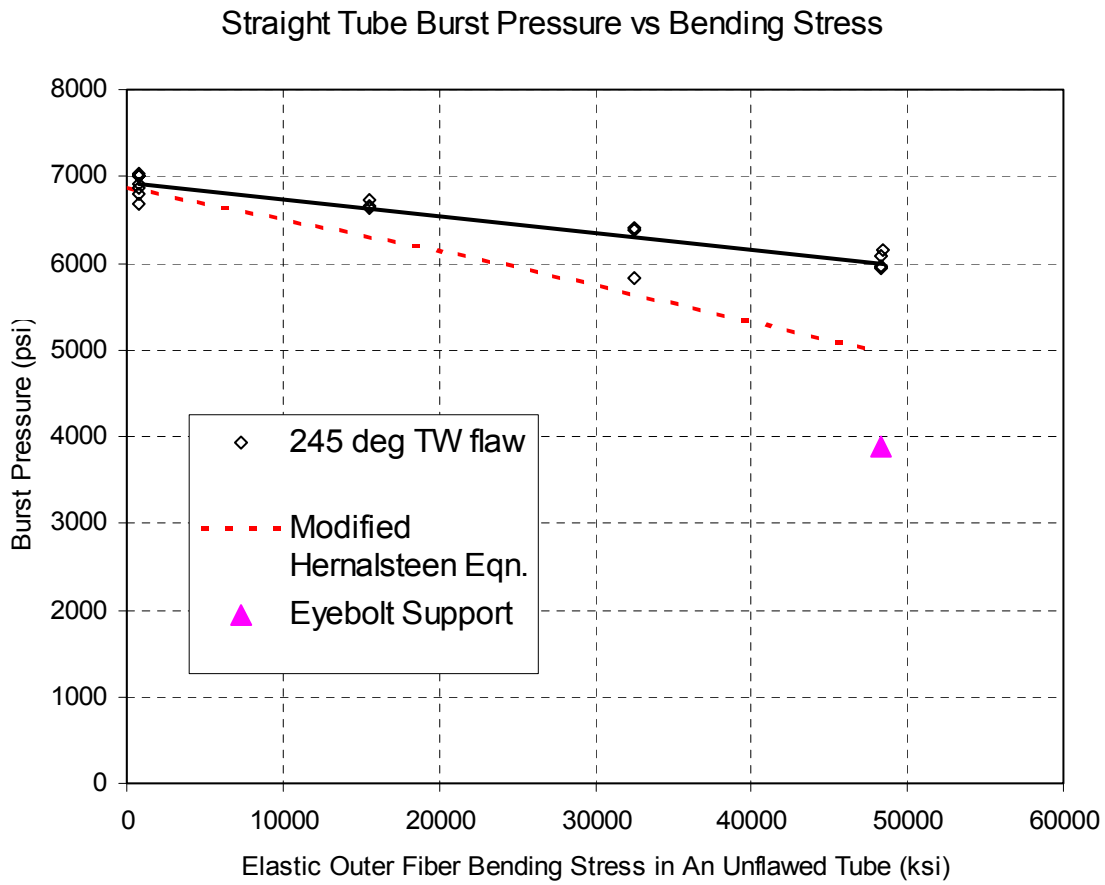
Analysis of Test Results

In Plane Bending Collapse of Flawed and Unflawed U-Bends, Four Hinge Mechanism



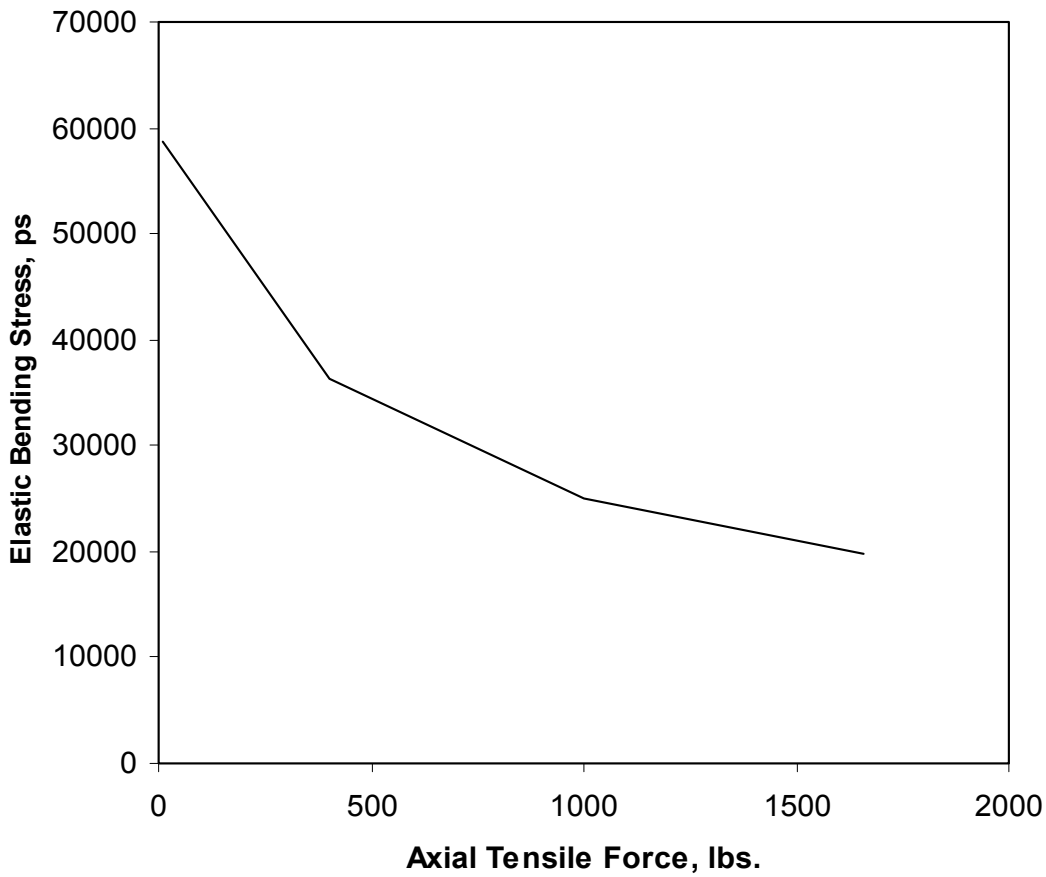
Analysis of Test Results

If Axial Force Effects On Bending Stresses are Considered, A Modified Hernalsteen Equation is a Reasonable Lower Bound to Straight Tube Test Data



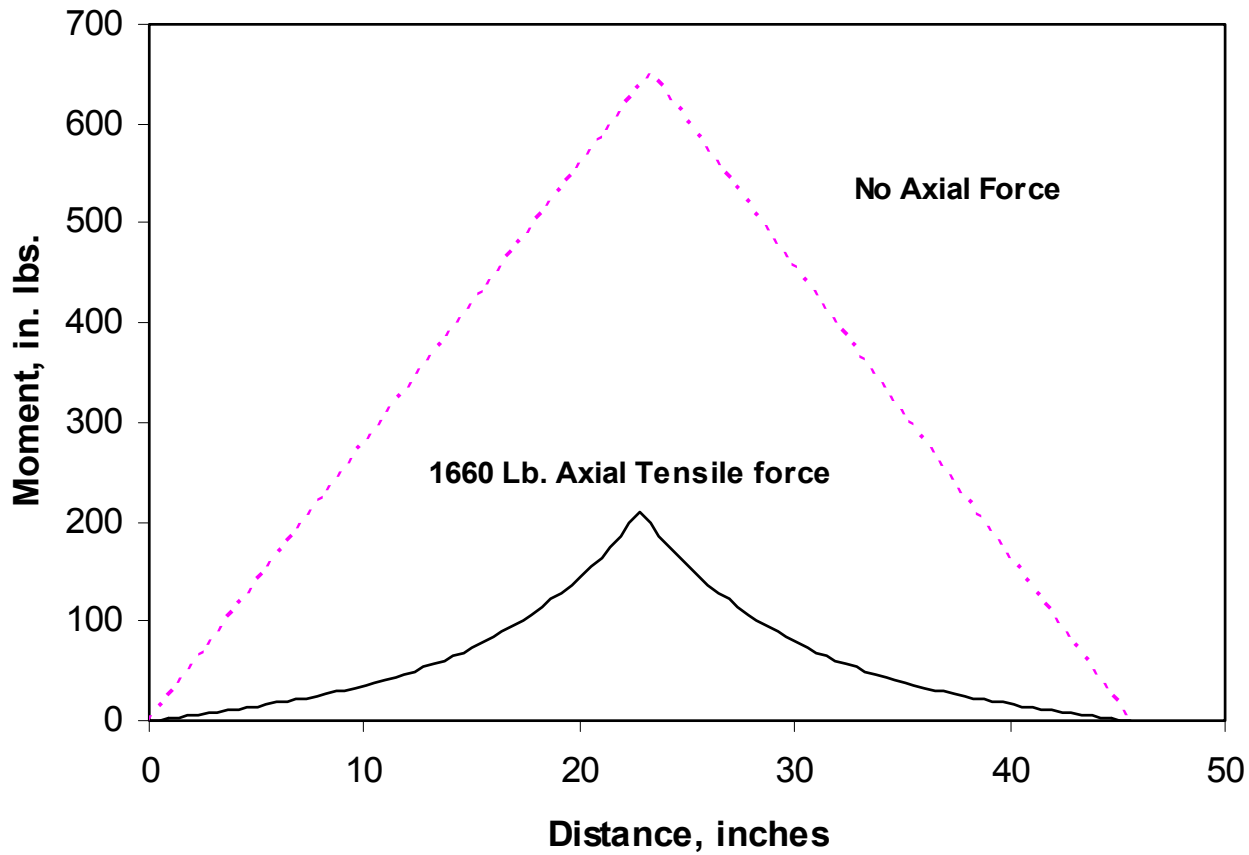
Analysis of Test Results

Simply Supported Beam with Lateral Load at Mid Span and Axial Tensile Load



Analysis of Test Results

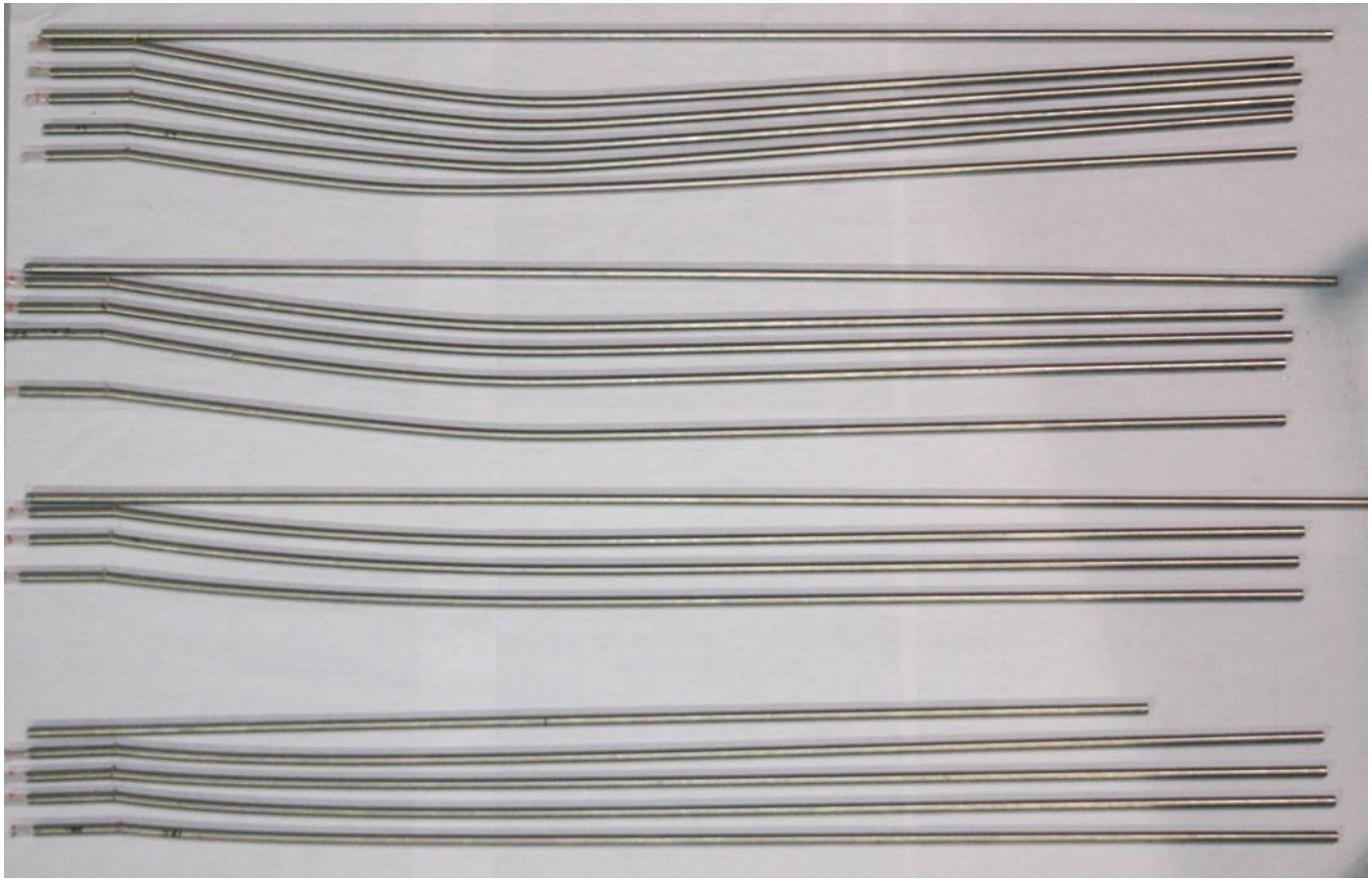
Effect of axial load on moment diagram of simply supported beam



Test Results

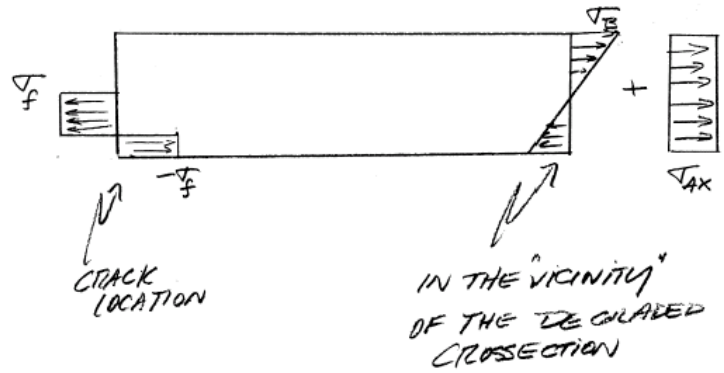
Straight tubes as burst (with reference tubes)

High load: ~50 ksi



Low load: ~0 ksi

Analysis of Test Results



$$\sigma_B + \sigma_{AX} = k\,\sigma_{yp}$$

$k \approx 1$ OR SLIGHTLY LARGER

- THE NET SECTION AT THE CRACK LOCATION IS FULLY PLASTIC

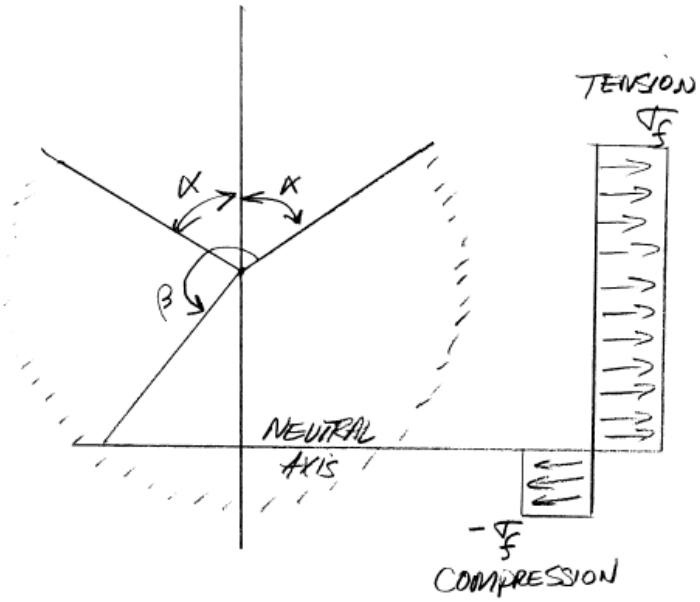
$$M_c = 2\left(2\sin\beta - \sin\alpha\right) R_m^2\, t\, \sigma_f$$

- CLOSE TO THE CRACKED SECTION BUT AT AN UNFLAWED LOCATION, THE OUTER FIBER STRESS $(\sigma_B + \sigma_{AX})$ IS AT OR SOMEWHAT ABOVE THE YIELD POINT

$$\sigma_B + \sigma_{AX} = k\,\sigma_{yp}$$

$$M_B = \pi R_m^2\, t\, \sigma_B = \pi R_m^2\, t\left(k\,\sigma_{yp} - \sigma_{AX}\right)$$

Analysis of Test Results



END CAP PRESSURE LOAD

$2\pi R_m t \sigma_{Ax}$

$\left(\sigma_{Ax} = \frac{p R_m}{2t}\right)$

=

SUM OF AXIAL STRESSES ON NET SECTION

$2(2\beta - \alpha - \pi) R_m t \sigma_f$

MOMENT RESTRAINT OF UNFLAWED TUBE SECTION

$\pi R_m^2 (k \sigma_{yp} - \sigma_{Ax})$

=

LIMIT MOMENT OF CRACKED SECTION UNDER SPECIFIED AXIAL FORCE

$2(2\sin\beta - \sin\alpha) R_m^2 t \sigma_f$

Analysis of Test Results

Scaling of Test Results

- Steam Generator Tubing in the U.S. is Geometrically Similar Within + or – 6%

- If "m" is a Scaling Factor from $Size_1$ to $Size_2$ such that

$$Size_2 = m\ Size_1$$

then normalized load versus normalized displacement is given by:

$$Load/m^2 \quad \text{versus} \quad Displacement/m$$

Analysis of Test Results

Scaling of Test Results cont.

- Load Displacement Plots can be Converted from One Tubing Size to Another
- Elasticity and Plasticity Scale in the Same Manner
- Stress Strain Curve are Essentially Equivalent for Alloy 600 and Alloy 690
- Fracture Scales According to the Fracture Criteria
- A Critical CTOD Criteria is Appropriate for Steam Generator Tubing.
- The Critical CTOD Value Scales Directly with Wall Thickness, the scaling factor is “m”
- Test Results for Burst Pressure as Affected by Bending Stress Can Be Scaled for All Tubing Sizes

Analysis of Test Results

Burst Model Development

- **Linear Decrease in Burst Pressure as Applied Bending Stress Increases**

- **Burst Pressure Decrease = 0.134*Bending Stress* t / Rm**
  - **Applies to Straight Tubes**
  - **Applies to U-Bends up to Row 18 in Model 51 SG's**
  - **For Rows 18 and Higher, Increase Constant Linearly up to 0.27 for Row 46**
  - **Apply to Bending Dominant Region of Burst Pressure Versus PDA Curve**
  - **Bending Stress is Outer Fiber Bending Stress Without Consideration of Deformed Geometry**
  - **Do Not Apply Bending Stress Effect for PDA Values Less Than 25**

- **Typically, 3ΔP will be Limiting**
  - **At a Bending Stress of 25,000 psi, the Burst Pressure Decrease is about 500 psi.**
  - **1.4 SLB is about 3580, therefore for a 3ΔP Value of 4080 psi, 3ΔP Would Be Limiting**

Conclusions

- Effects of bending stresses on the burst pressure of tubing with circumferential degradation can be determined for all domestic tubing sizes and tubing alloys by the direct scaling of present burst test data.

- A simple equation has been developed that provides the burst pressure decrease as a function of external moment in an unflawed tube. This burst pressure decrease is independent of flaw size.

- Test results indicate bending moment required to collapse a tube significantly exceeds design-basis bending moments.