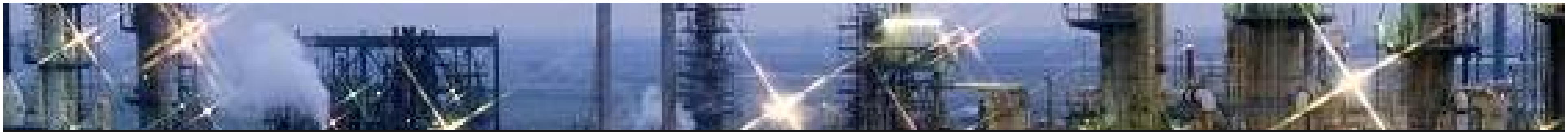

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Experimental Evaluation of the Markl Fatigue Methods and ASME Piping Stress Intensification Factors

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Introduction

Introduction

- **12 new experimental piping fatigue tests have been completed to help examine the Markl fatigue methods.**
  - **10 Girth Butt Welds**
  - **2 Unreinforced Tees**
- **600 butt welds were gathered and compared to the Markl girth mean butt weld fatigue curve.**
- **Although Markl's data points are within scatter band of the reported data, Markl's mean fatigue curve does not agree with the same experimental data.**
- **A new mean girth butt weld is proposed for use with SIF testing (B31.J) and the ASME piping codes.**

Why Perform New Tests?

- **There aren't many low cycle girth butt weld tests.**
- **Some tests indicate that Markl's slope and mean curve may not be representative of larger data sets.**
- **Paulin Research Group's analytical and experimental experience has been that SIF's are often too low – difficult to match Markl's results.**
- **Markl's curve does not follow the expected trends for fatigue of weldments. Slope coefficient of 5.0 vs. 3.0**
- **Several active ASME Technology projects are reevaluating the current SIF's and flexibility factors**
- **Piping codes are being applied beyond simple thermal expansion cases.**
- **Understanding how and why components fail is becoming more important.**

Background

Markl Testing and Stress Intensification Factors

- **Markl & George began fatigue testing piping components in the late 1940's.**
- **The majority of experiments used 4" SCH 40 piping.**
- **End result was a mean fatigue curve for girth butt welded pipe and Stress Intensification Factors (SIF's) for piping components.**
- **SIF rules are base-lined to an SIF of 1.0 which is for girth butt welds.**
- **"Girth butt weld" really pertains most directly to girth butt welds joining weld neck flanges to pipes. In some Markl tests, tapered forgings were used for girth butt weld tests.**
- **Markl's work is the primary basis of ASME B31 piping rules.**

What is an SIF?

- **A Stress Intensification Factor (SIF) is the average nominal bending stress to cause failure in a girth butt weld divided by the nominal stress to cause failure in the component being tested.**

$$i \cdot Sf_{N_f} = 490\,ksi \cdot N_f^{-0.20}$$

$$i = SIF = \frac{490\,ksi \cdot N_f^{-0.20}}{Sf_{N_f}}$$

Markl's Mean Girth Butt Weld Curve

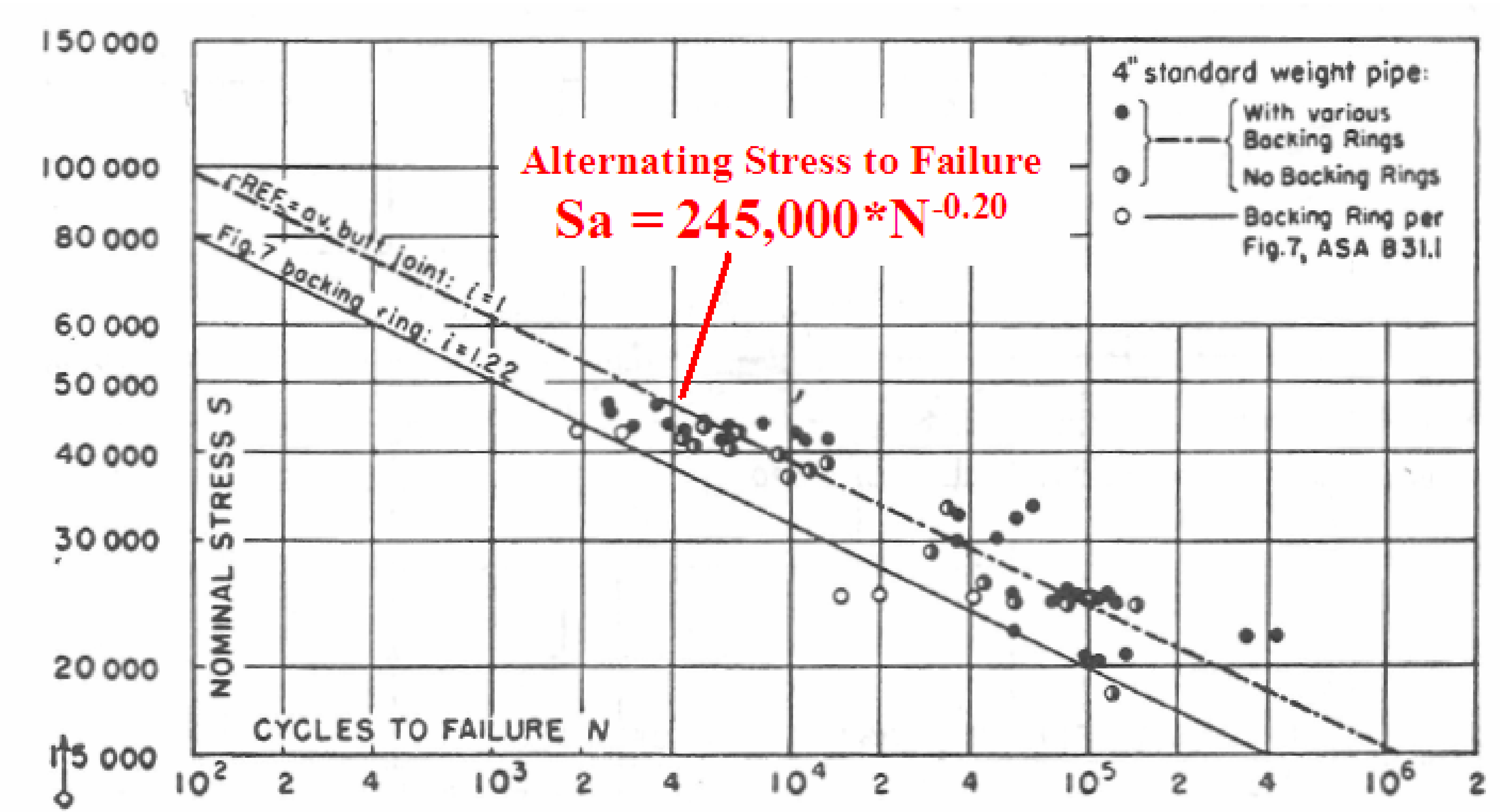
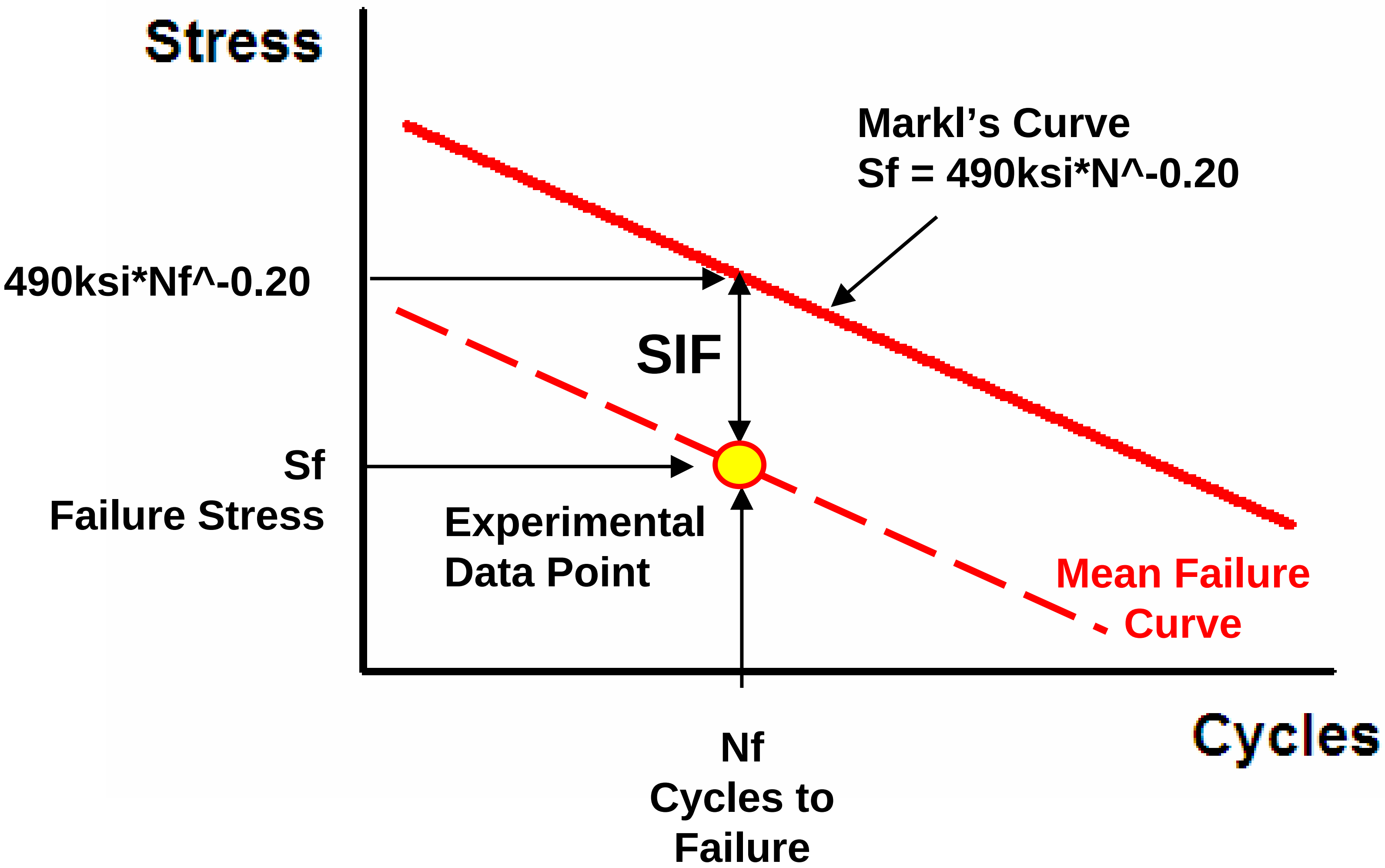


FIG. 5 BUTT-WELDED JOINTS IN STRAIGHT PIPE

Stress Intensification Factor



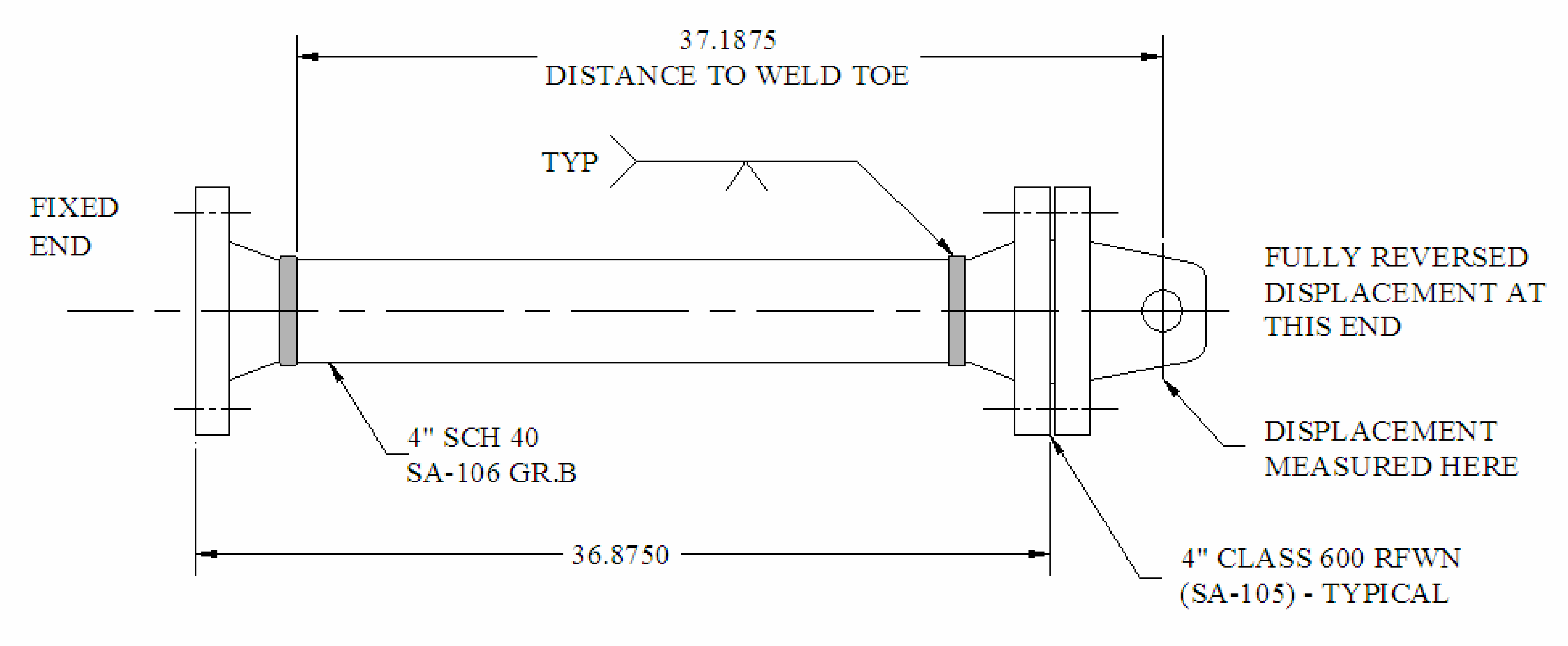
Description of Tests

Girth Butt Weld Specimens

- 4” SCH 40 pipe welded to Class 600 flanges
- SA-106 Grade B material used for all specimens
- Ten girth welds tested – most < 10,000 cycles to failure
- Six welds with GMAW-FCAW welding processes
- Four welds were completed using the SMAW process
  - SMAW welds used electrodes similar to those originally used by Markl & George (Lincoln Fleetweld 5)
  - SMAW welds used to check that weld quality wasn’t responsible for difference between Markl curve and new tests
- Inspected by VT and PT.
- Welds tested in the as-welded condition

Girth Butt Weld Specimens

- **Fully reversed displacement controlled conditions (R = -1.0)**
- **Cantilever fatigue test**



Girth Butt Weld Specimens

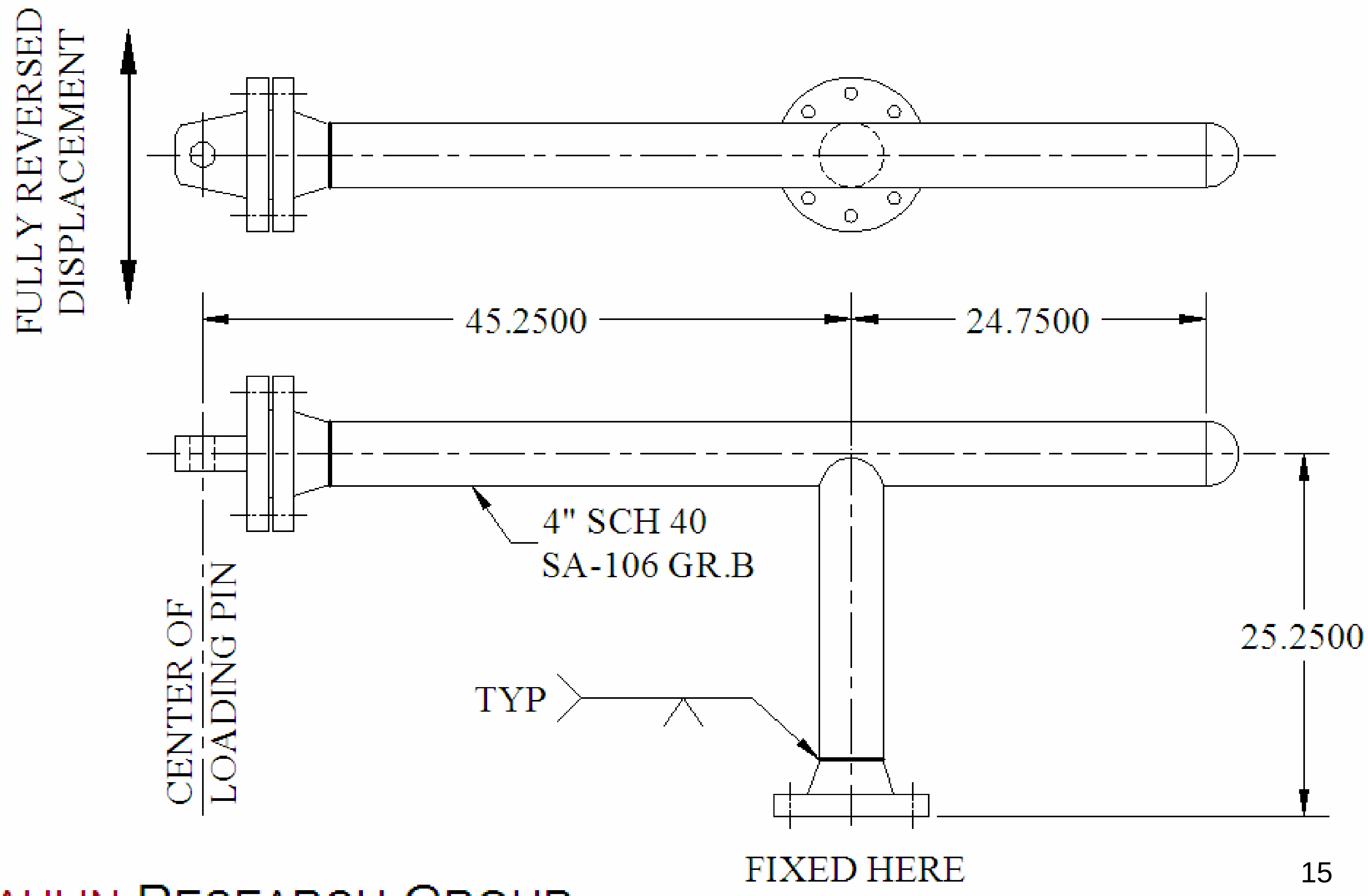
SMAW Weld

GMAW-FCAW Weld

Unreinforced Tee Specimens

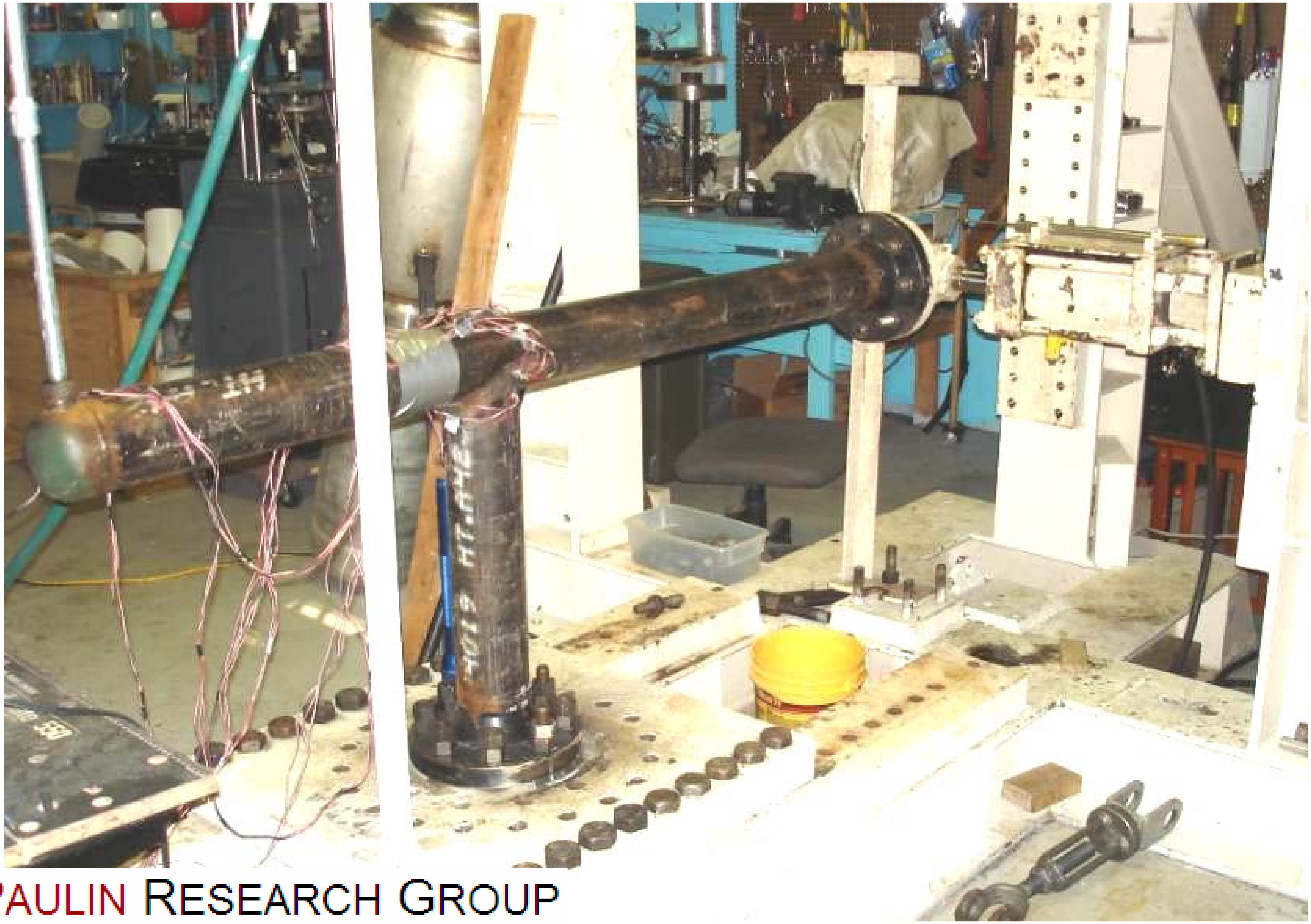
- **Two size-on-size UFT's tested**
- **4" SCH 40 pipe, SA-106 Grade B**
- **GTAW welding process**
- **Out-of-plane loading through the header pipe**
- **Fully reversed displacement controlled conditions**
- **Inspected by VT and PT.**
- **Welds tested in the as-welded condition.**

Unreinforced Tee Specimens



Unreinforced Tee Specimens

Unreinforced Tee Specimens



Experimental Procedure

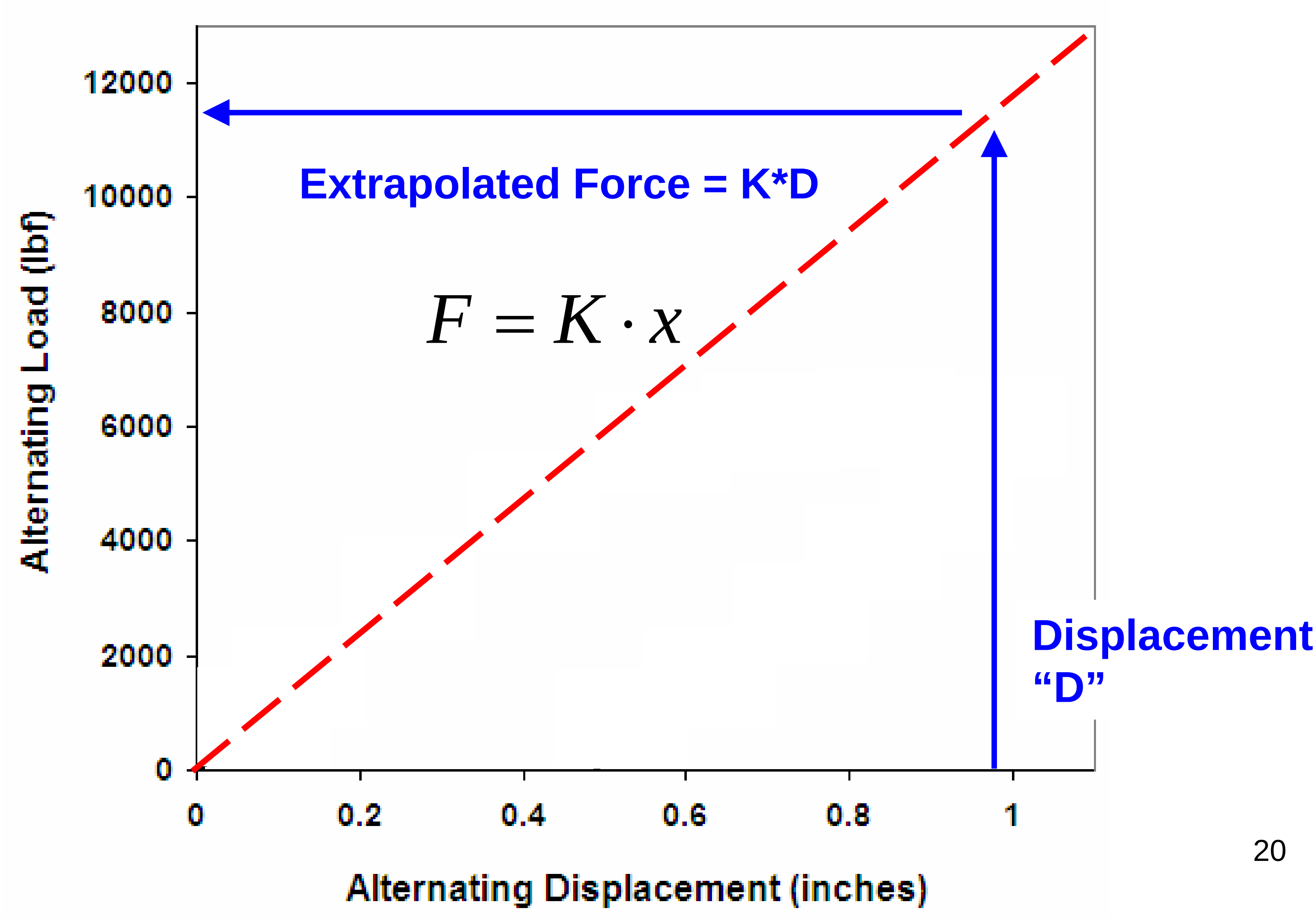
Experimental Procedure

General "Markl" Procedure:

- **Step 1 – Apply strain gauges**
- **Step 2 – Mount specimen to fatigue test machine**
- **Step 3 – Fill specimens with room temperature water**
- **Step 4 – Generate a load-deflection curve**
- **Step 5 – Select a displacement range for fatigue test**
- **Step 6 – Run test until visible leakage occurs**
- **Step 7 – Record the cycles to failure, stress is based on extrapolation of the elastic stiffness from Step #4**

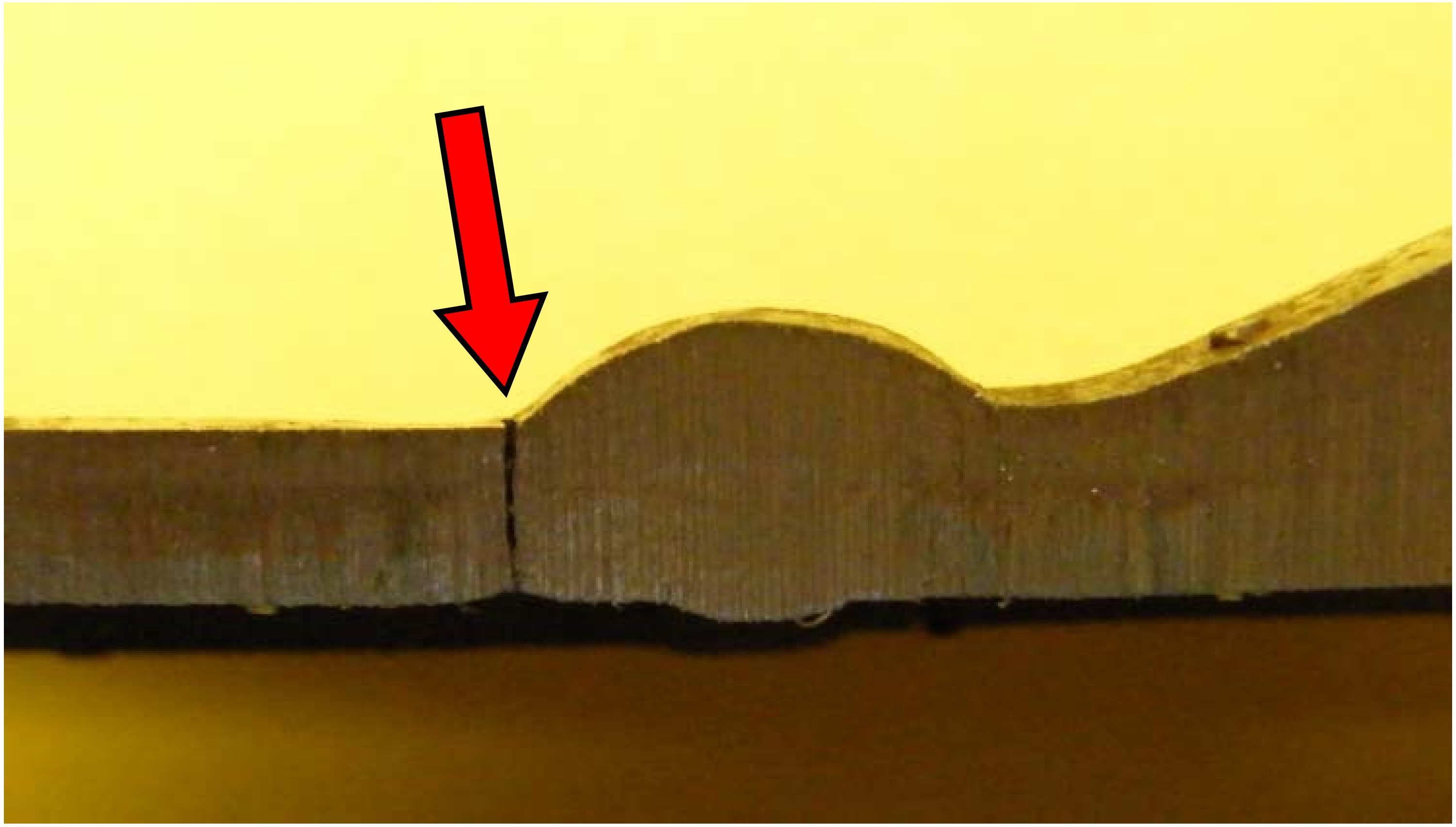
Experimental Procedure

Example use of Load-Deflection curve for piping fatigue tests



Failure Criteria

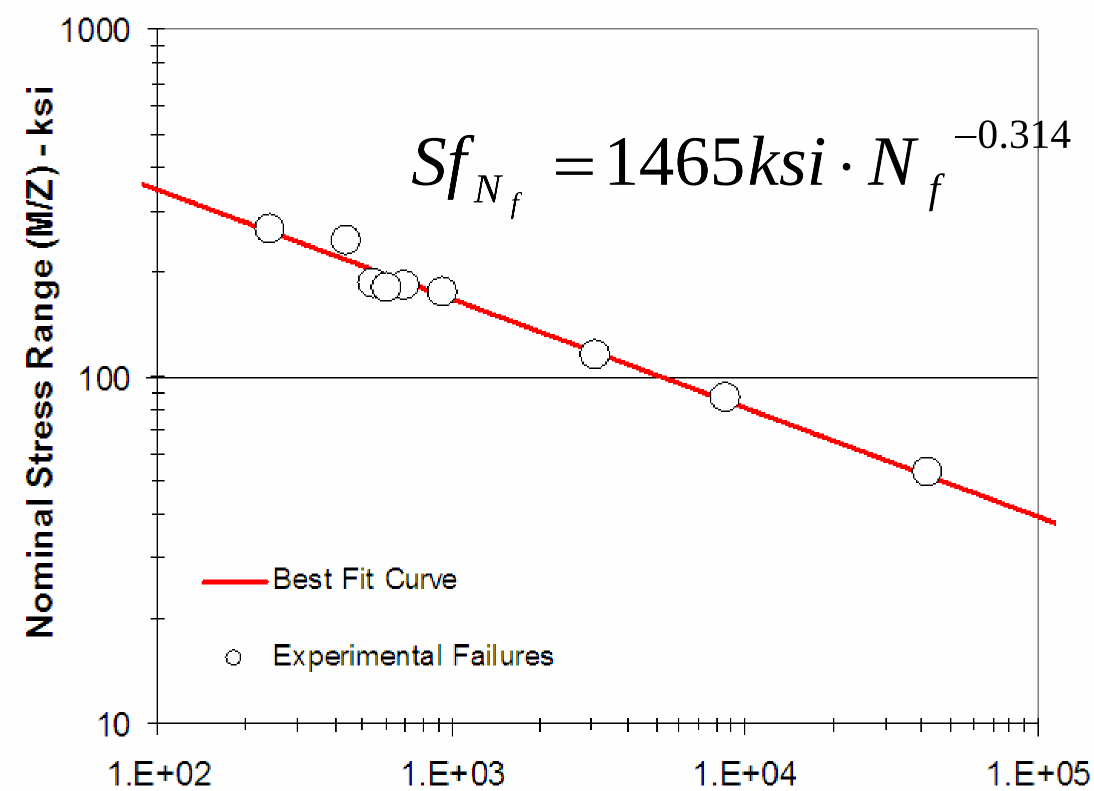
Thru thickness fatigue crack resulting in visible leakage



Experimental Results

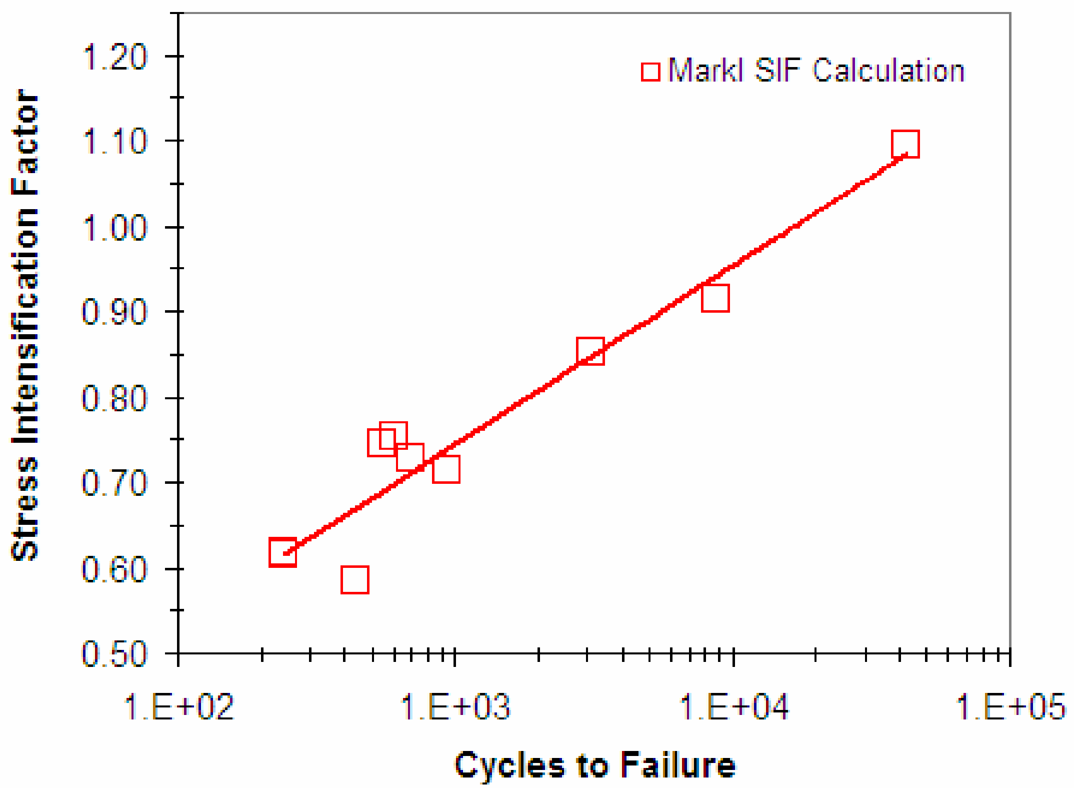
Girth Butt Weld Tests

- **Results of 10 new girth butt weld tests are shown below.**
- **Standard deviation of Log(N) with best-fit curve 0.082**
- **Standard deviation about Markl's mean curve is 0.78**



Girth Butt Weld Tests

- SIF's calculated using Markl's mean girth weld equation show a strong variation as a function of cycles to failure.
- If the basis for the SIF calculation is parallel to the test data, the SIF should not be a function of cycles to failure.



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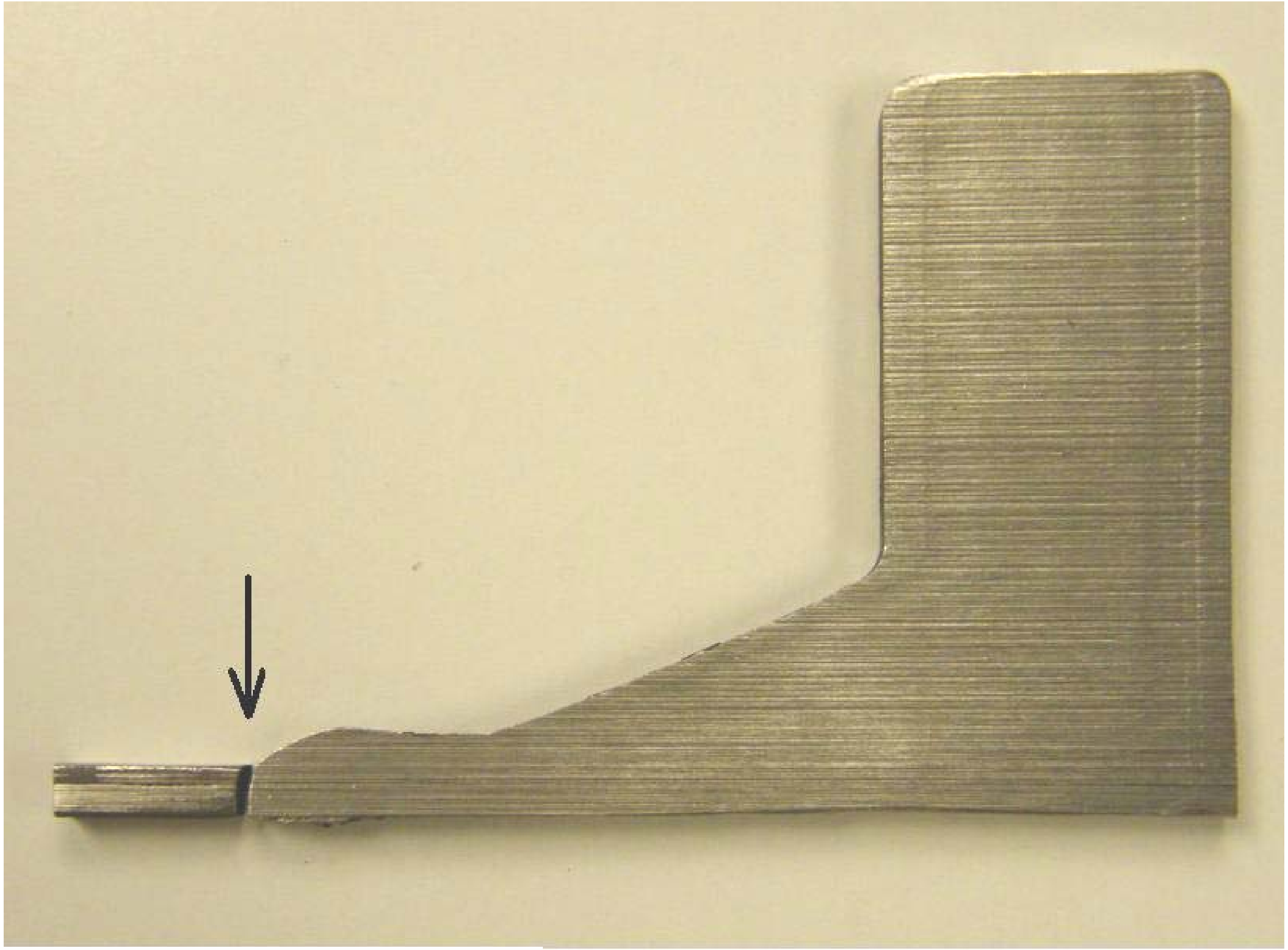
Girth Butt Weld Tests

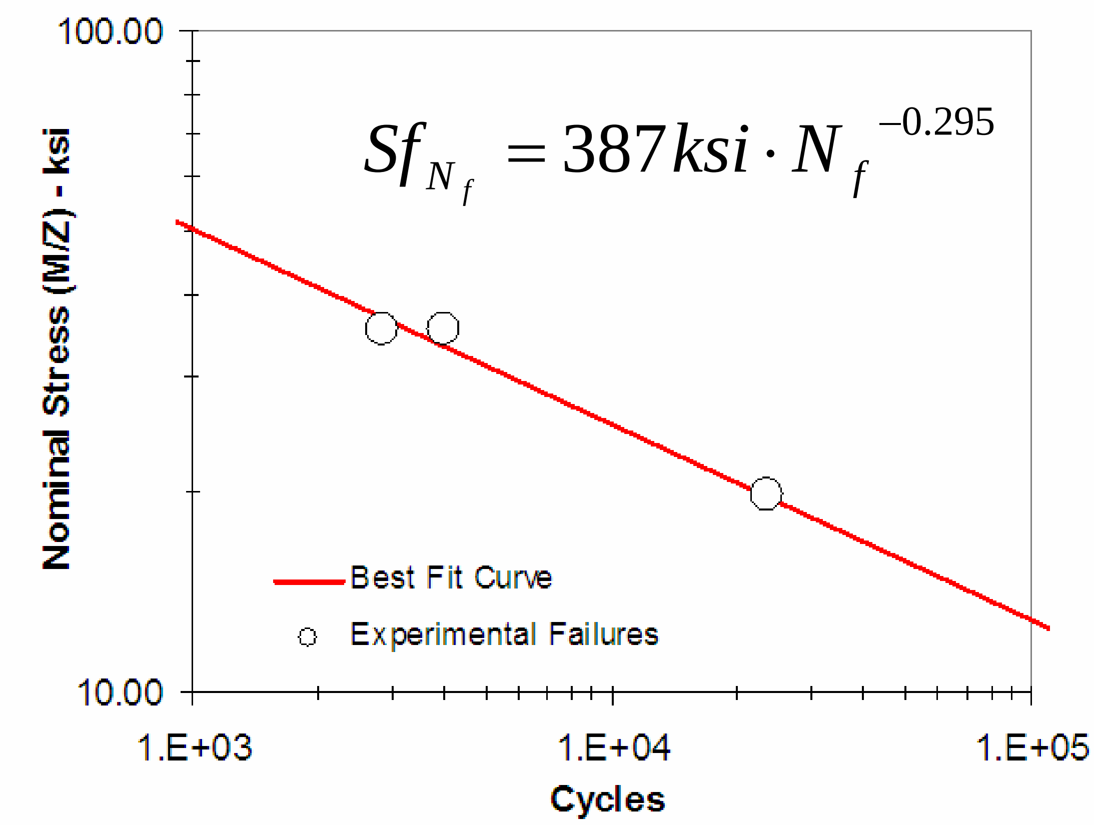
- **Failures originated at the outside surface along the weld toe**



Typical Girth Butt Weld Failure

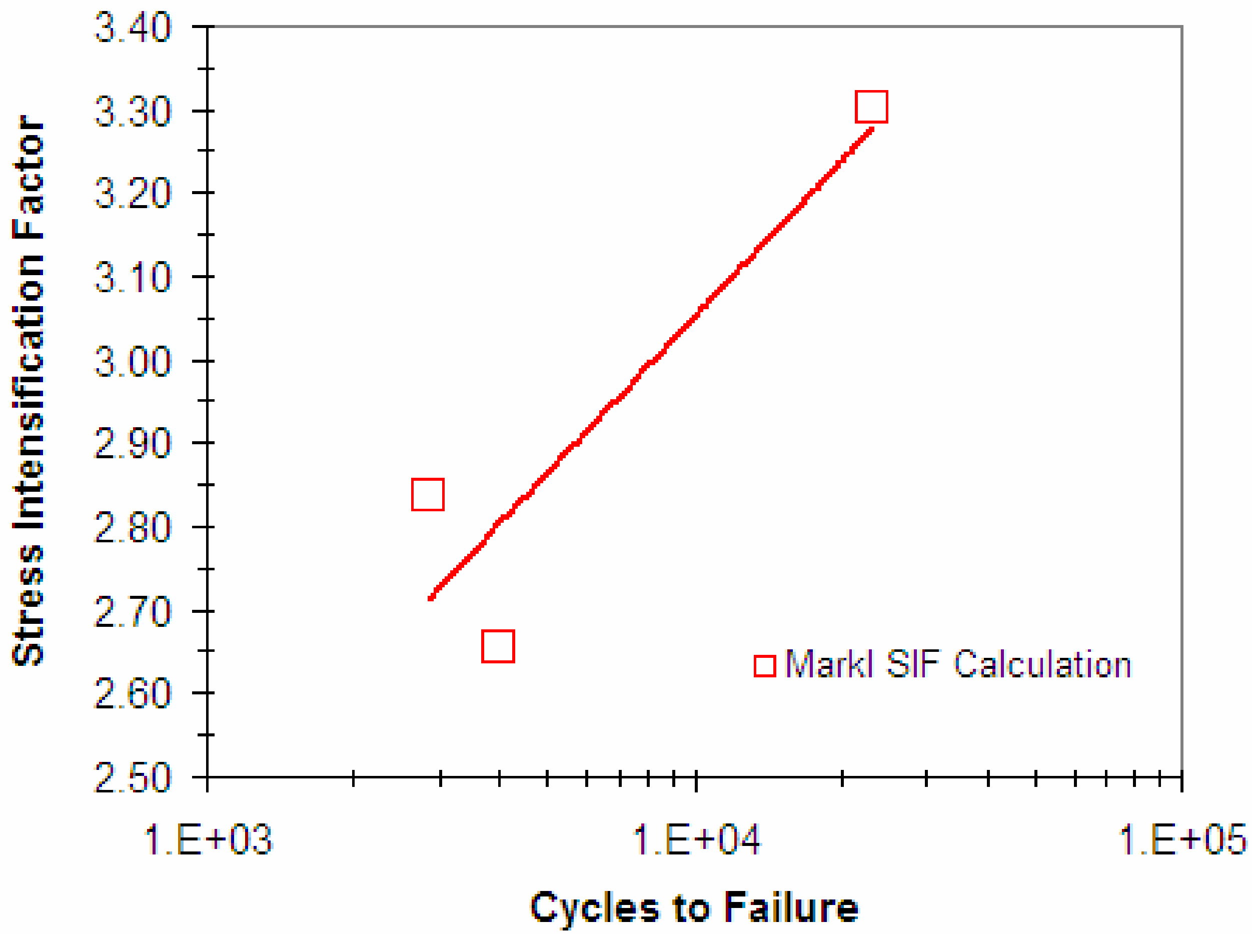
Unreinforced Tee Results

- **Results of 2 new girth butt weld tests shown below.**
- **Three failures sites in the two samples.**
- **Best-Fit equation slope is close to m = -1/3 (not -1/5 like Markl)**



Unreinforced Tee Results

Stress Intensification Factors for new UFT Tests using Markl's mean girth butt weld curve.



Typical UFT Failure

Validation of Results and Markl Comparisons

Girth Butt Weld Validation

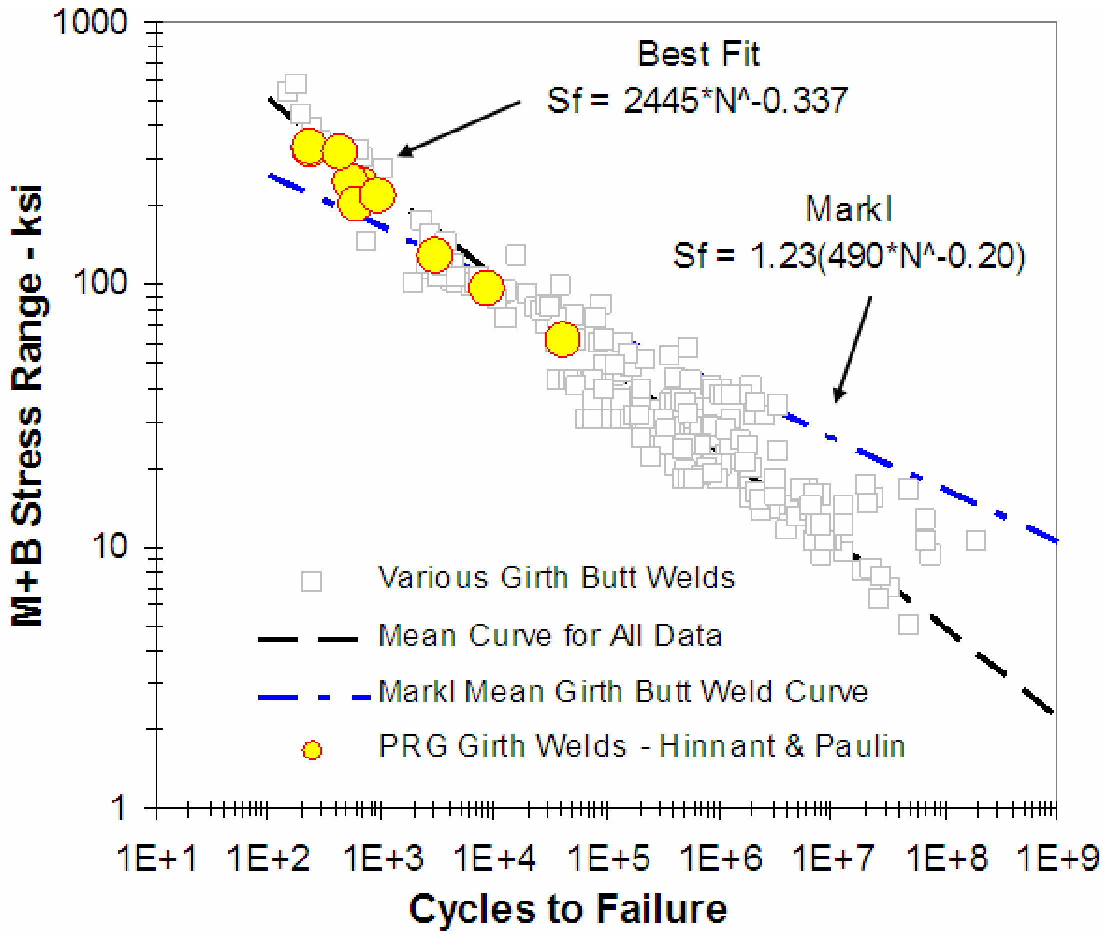
A limited number of tests were performed. Therefore, those results require validation to determine their significance.

1. **Compare with other girth butt weld tests (236 total)**
2. **Compare with other butt welded plate tests (365 total)**
3. **Compare with mean curves for similar geometries in other fatigue design Codes.**

- **Membrane plus Bending stresses are used for the validation case. M+B stresses are used since the membrane stress alone does not characterize the complete stress state causing damage to the weldment.**
- **Mismatched thicknesses or local tapers (flange taper) cause local secondary bending stresses. For the same nominal bending stress, these local bending stresses result in a shorter fatigue life in comparison to joints where local bending stresses are not present. Compare a straight pipe to a weld at a taper. The nominal bending stress in the pipe is the same in both cases, but the M+B stress is higher in the case with a taper.**

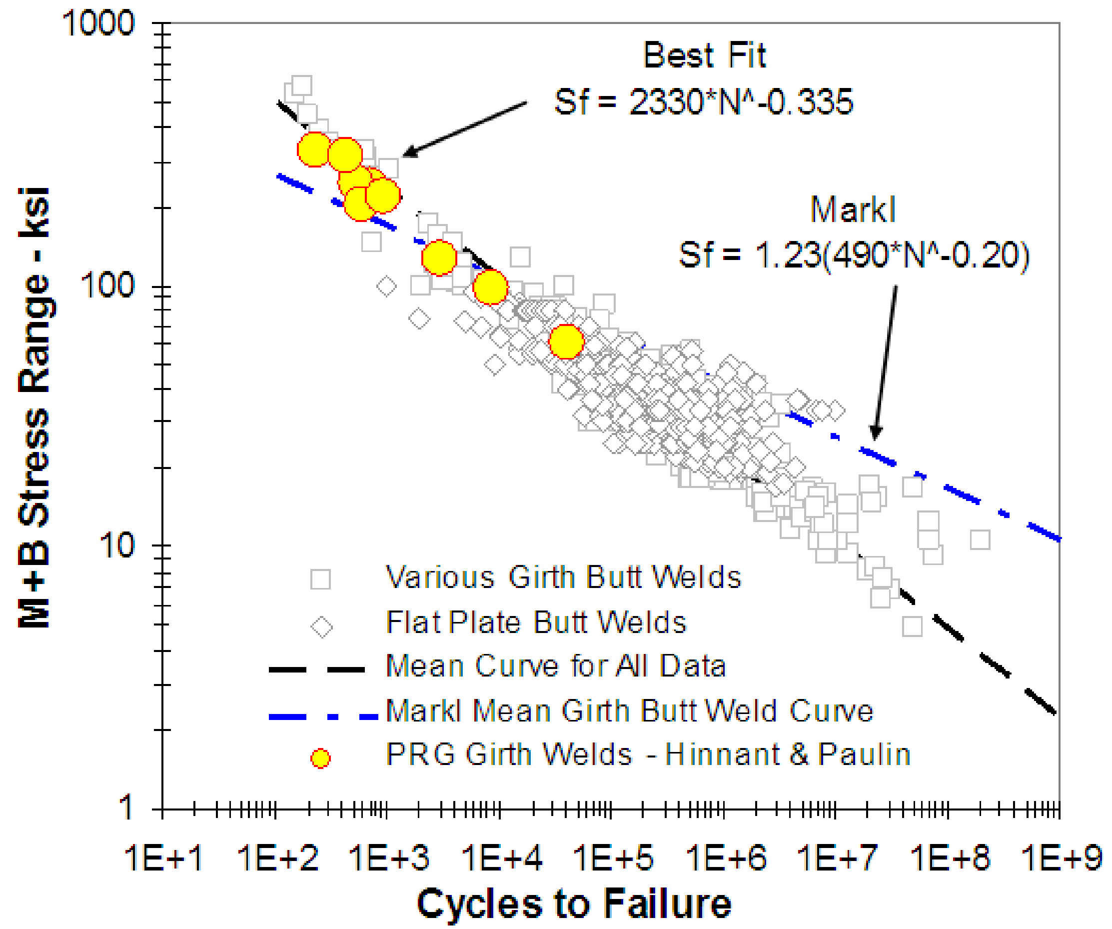
Girth Butt Validation

- **PRG girth butt weld test validation with 236 girth butt welds**
- **Note difference between the mean data curve and Markl's curve.**



Girth Butt Validation

- **236 girth welds and 365 flat plate butt welds**
- **Poor comparison between “Best Fit” curve and Markl’s curve.**



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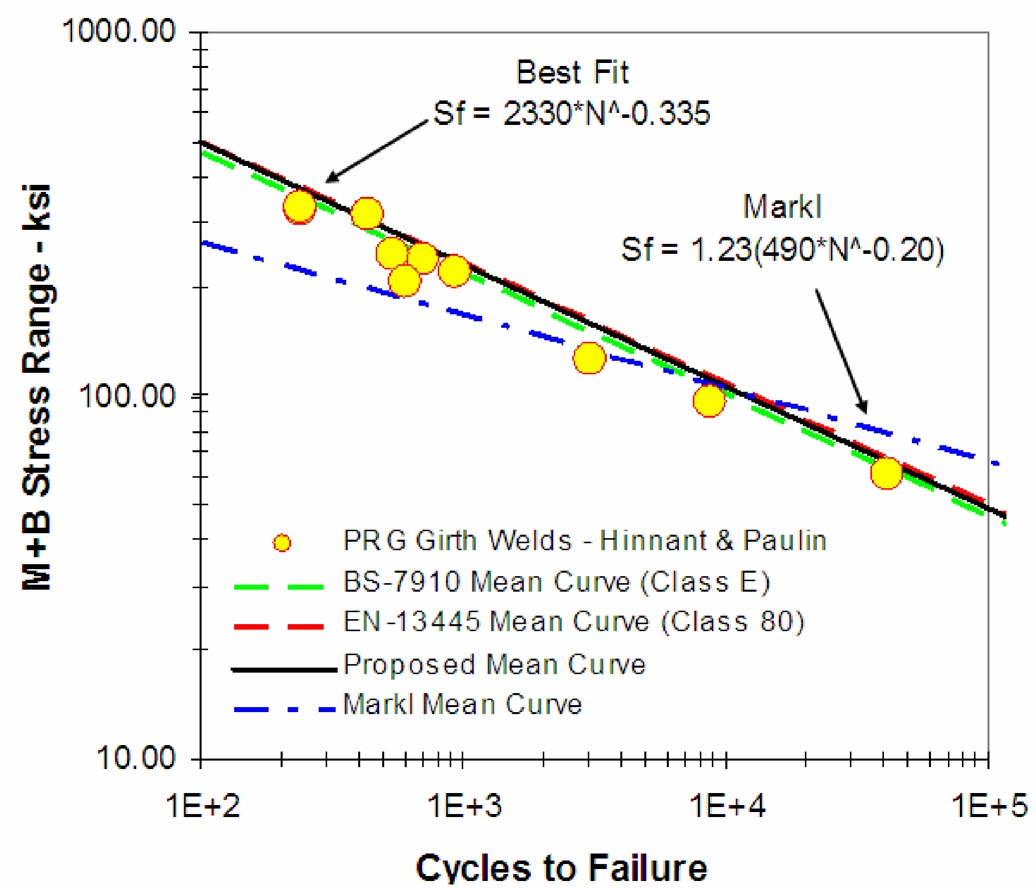
Girth Butt Validation

- **Comparison with various mean fatigue curves for other codes.**
- **BS-7910 and EN-13445 mean curves match new tests.**
- **Markl curve is not parallel to test data or other codes.**



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Girth Butt Weld Validation

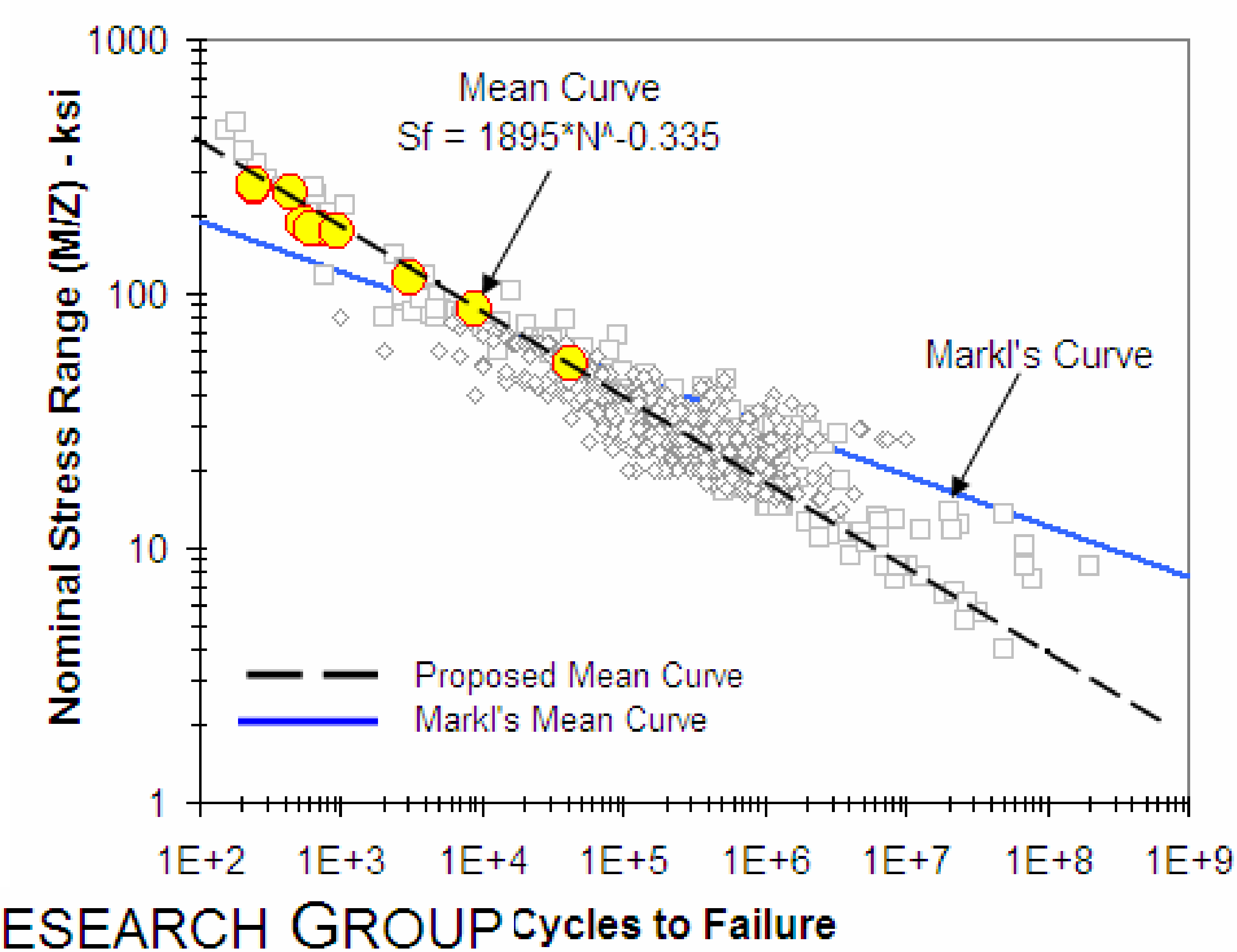
Summary of girth butt weld validation:

1. **Approximately 600 butt weld tests have been reviewed.**
2. **New PRG tests match existing pipe and plate data.**
3. **Markl's mean curve differs from the mean curve for the data collected in this work.**
4. **Markl's mean curve is not parallel to the data collected.**

Proposed Mean Girth Butt Weld Equation

Based on the validation data, we propose a mean girth butt weld curve with the following equation:

$$Sf = 1895\, ksi \cdot N^{-0.335} \quad (Range)$$



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Significance to the Piping Codes

Significance to the Piping Codes

- **Markl's mean butt weld curve is not consistent with the new PRG tests, other data collected, and other fatigue codes.**
- **Potential issues affect any piping rules that rely on the Markl methodologies (for example B31.1, B31.3, Section III Class 2/3)**
- **Most apparent discrepancy is the difference in slope coefficients**
    - **Markl's equation uses -1/5, test data suggests -1/3**

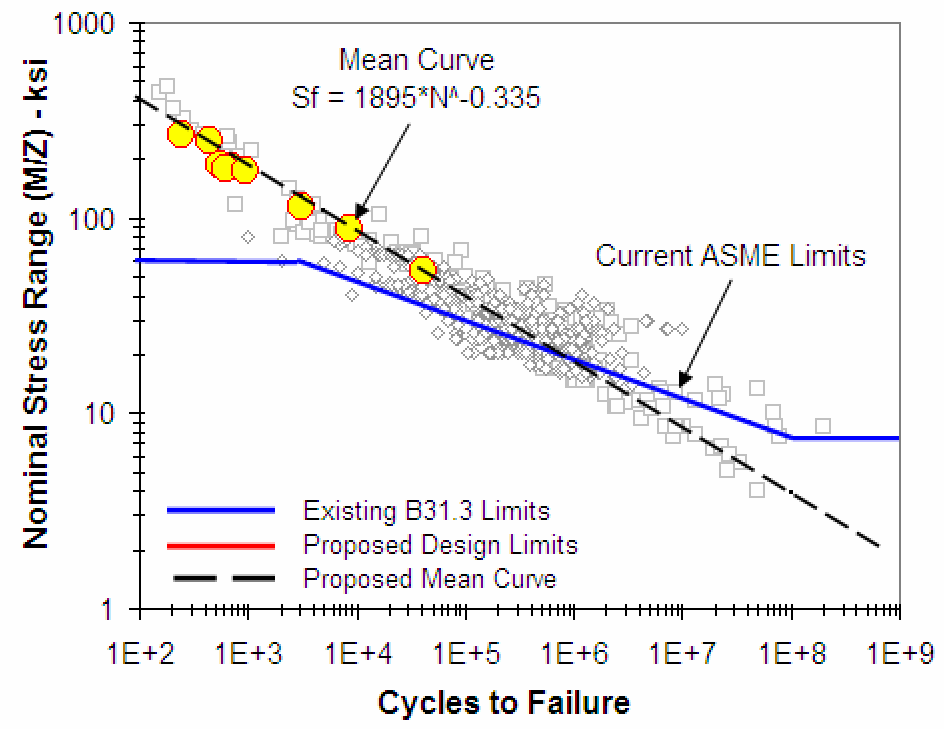
There are three areas of importance relative to the Codes:

1. **An errant slope produces a variable design margin.**
2. **Low cycle SIF testing with Markl's curve may lead to inappropriately low SIF's. This is important for B31.J.**
3. **High cycle design with rules derived from Markl's tests may over predict the fatigue life.**

Item #1 - Variable Design Margin

For basic conditions with carbon steel material:

- **ASME B31.3 provides a design margin of 1.63 on stress for the fatigue life of girth butt welds (11.5 on cycles)**
- **Data here shows that the B31.3 margin of 1.63 is maintained up to 22,790 cycles.**
- **Above 22,790 cycles, the design margin relative to the presented data continues to decrease.**
- **At 850,000 cycles the B31.3 design life equals the mean life to failure for the data presented here (design margin is zero).**
- **Above 850,000 cycles, the B31.3 Code permits design lives in excess of the average failure life.**



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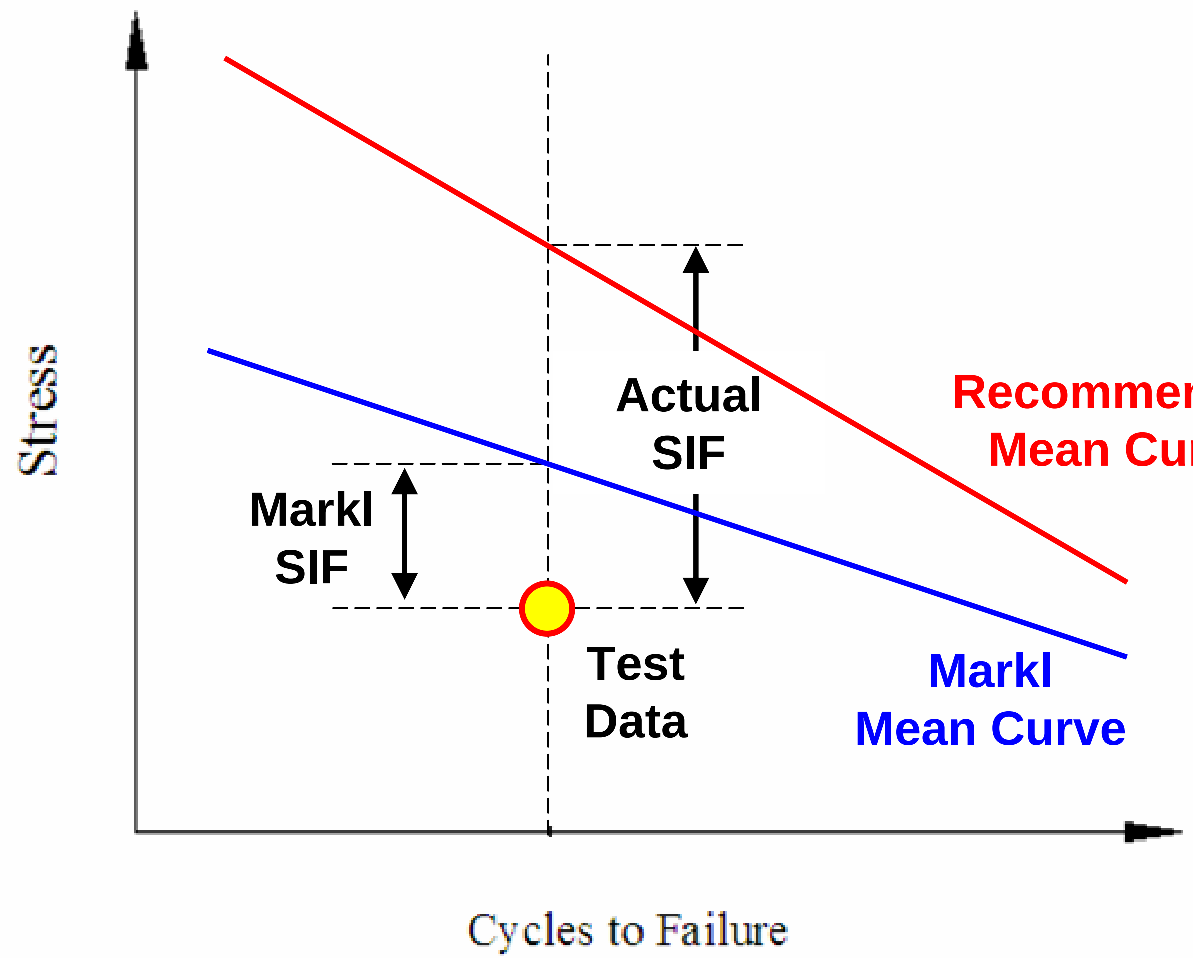
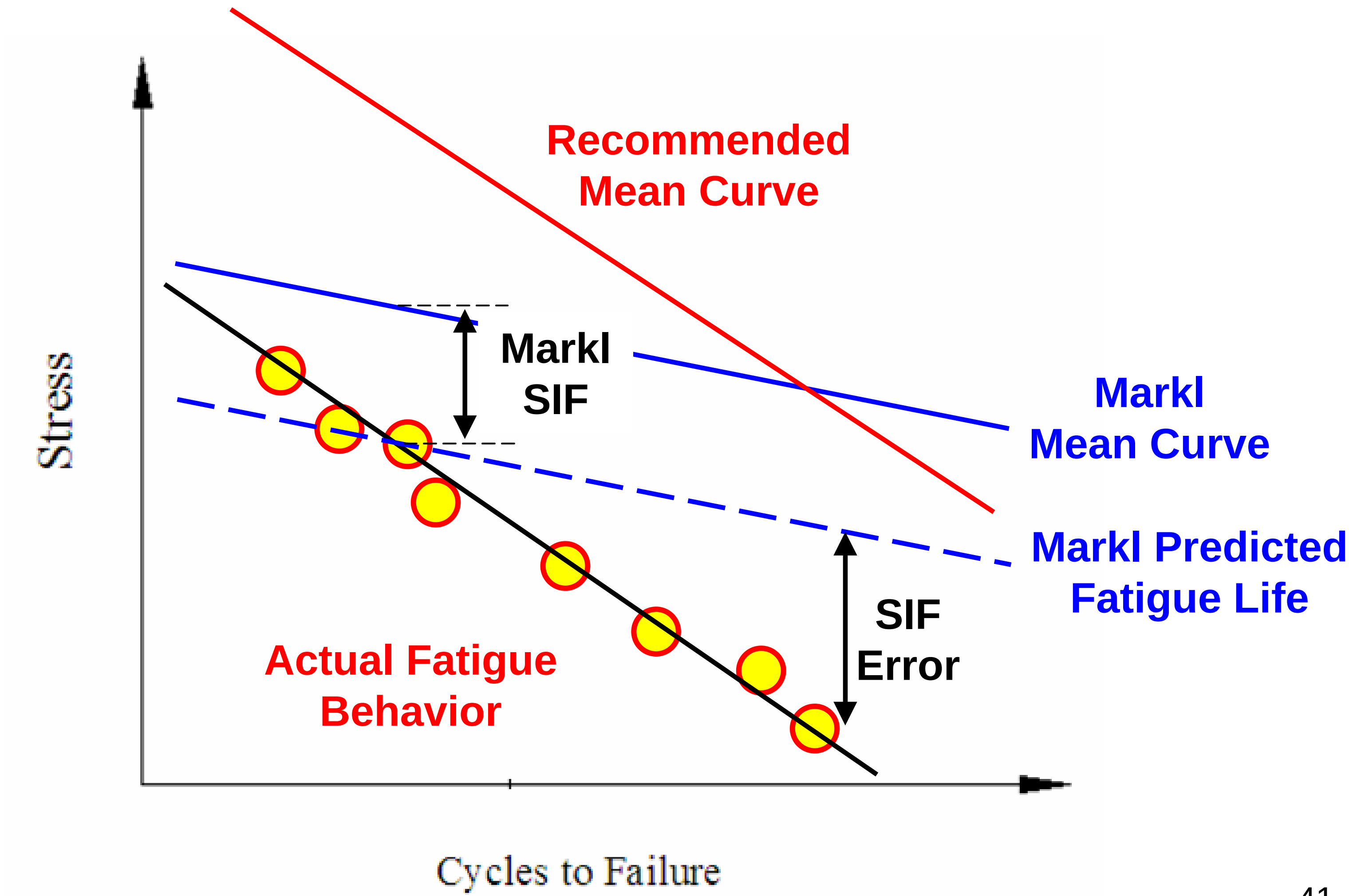
Item #2 - Errors in Low Cycle SIF Testing

- **SIF's may be underestimated by using Markl's mean curve in the low cycle regime.**



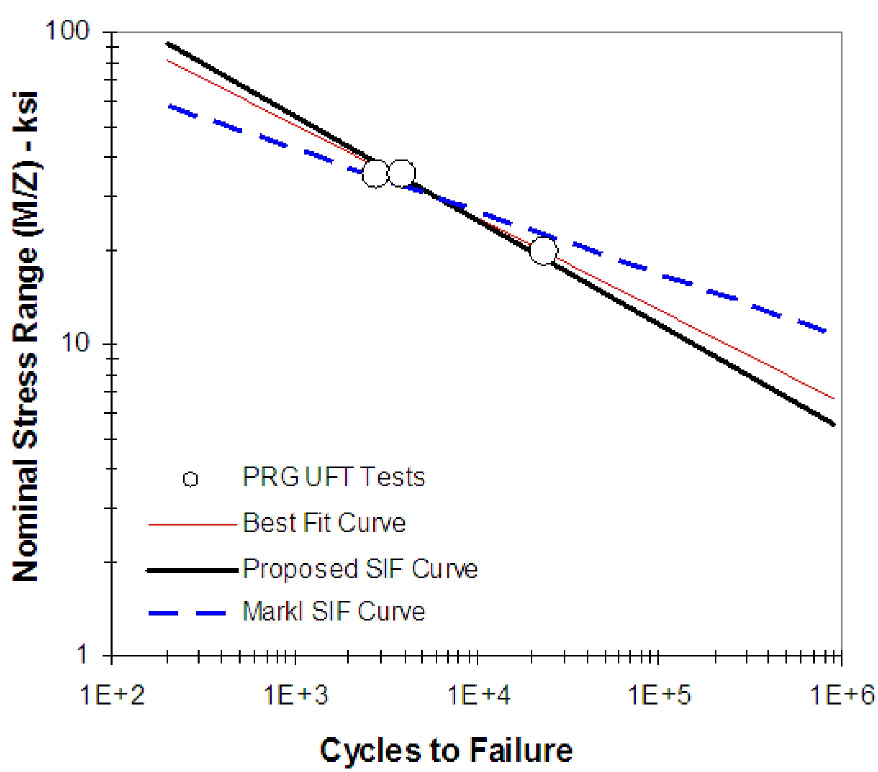
Item #2 - Errors in Low Cycle SIF Testing

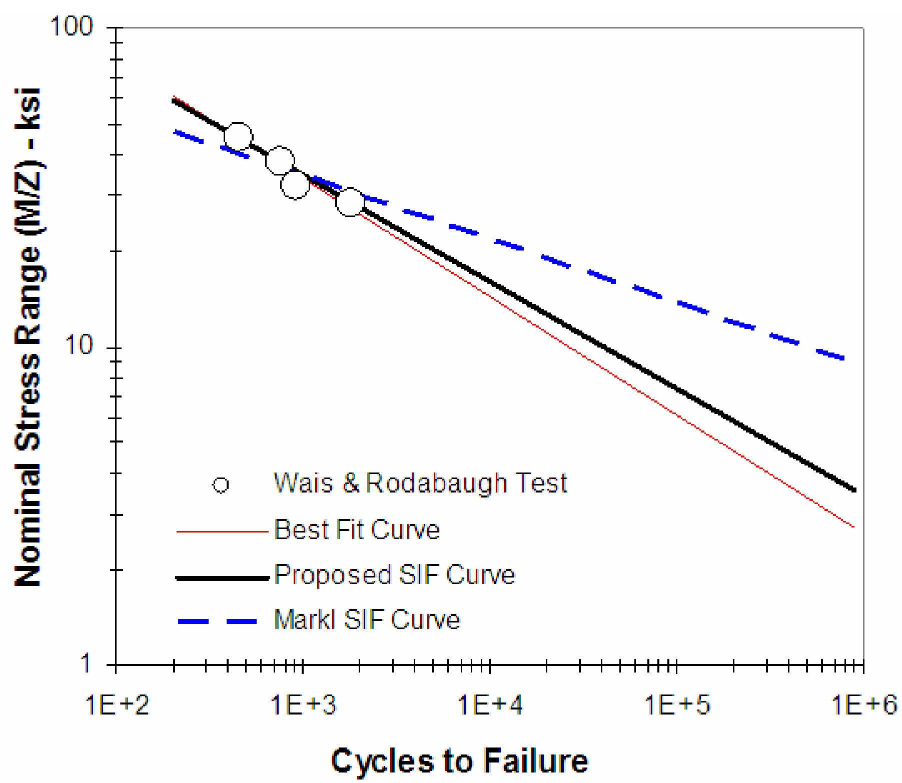
Using a low cycle SIF may result in reduced margins at higher design lives.



Item #2 - Errors in Low Cycle SIF Testing

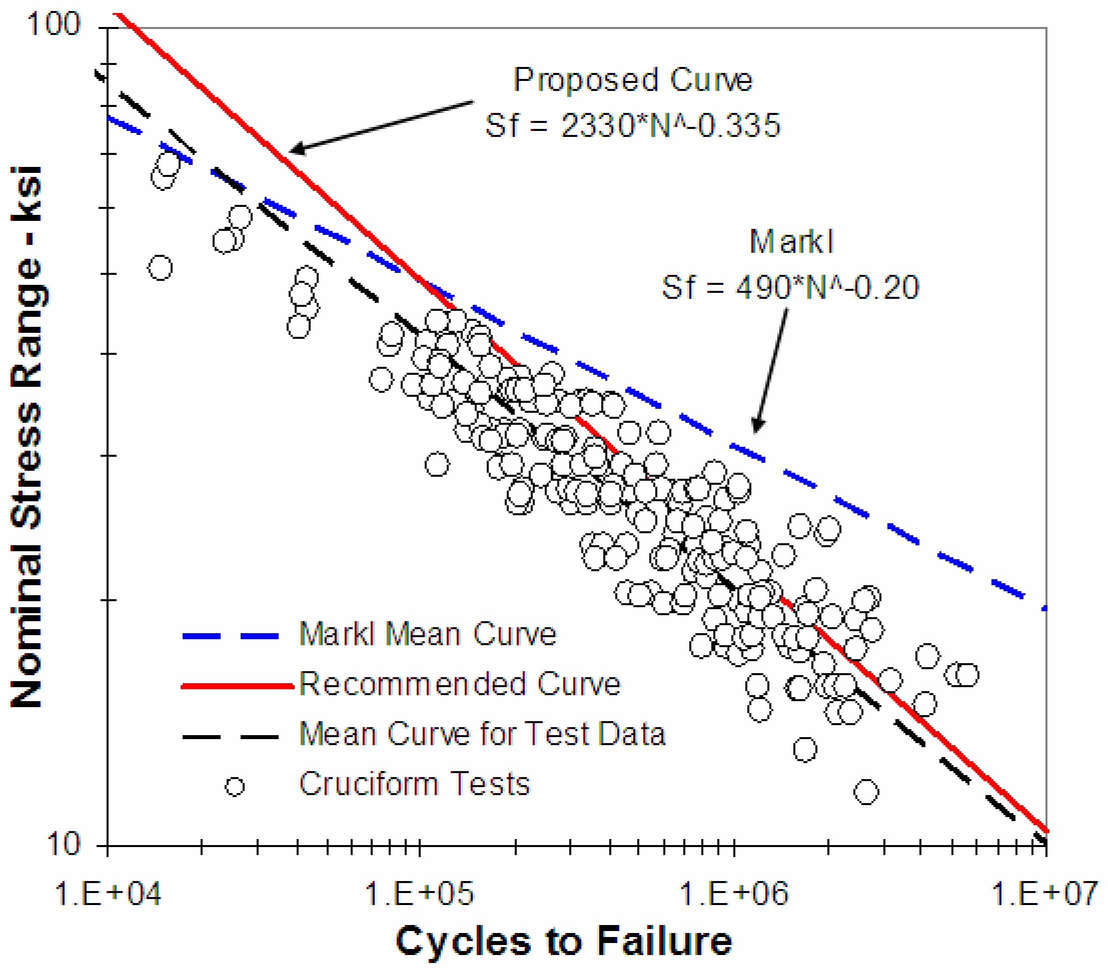
- **Is this trend only for butt welds? NO –all geometries are affected.**
- **UFT tests by PRG and Wais & Rodabaugh suggest that Markl's slope does not fit the experimental data.**





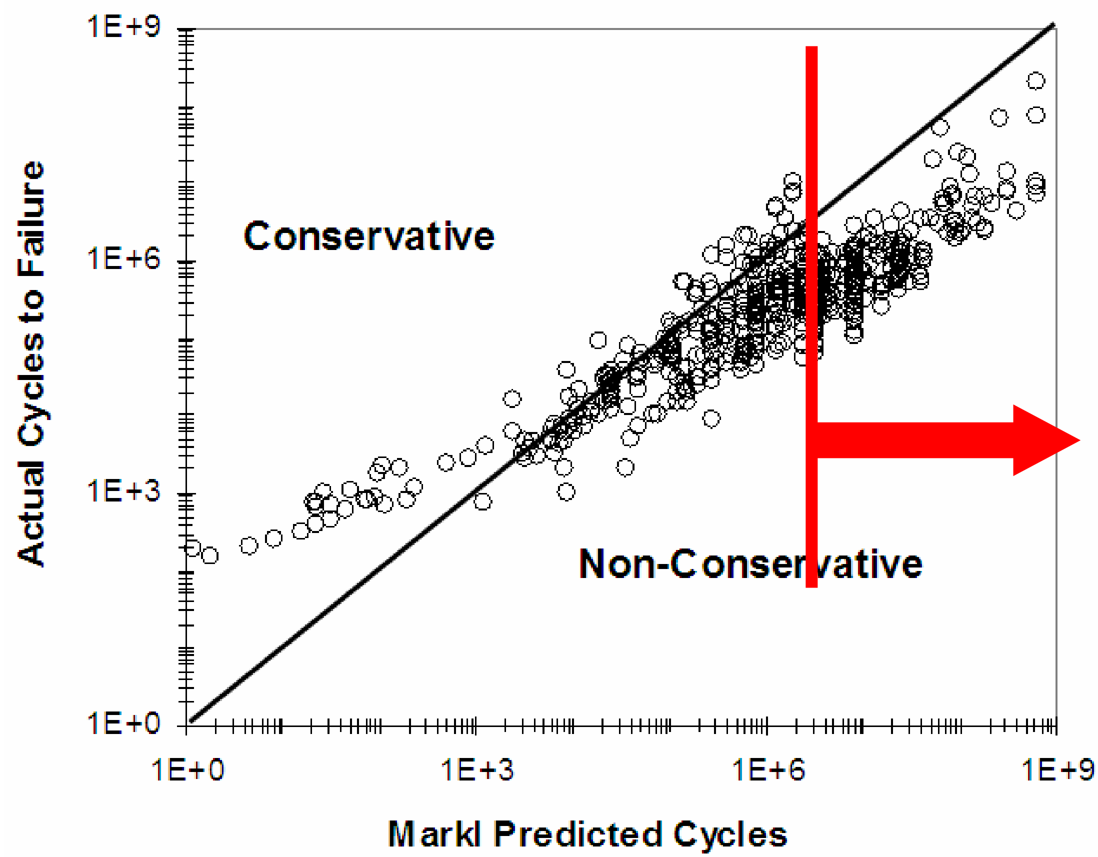
Item #2 - Errors in Low Cycle SIF Testing

- **For example, consider developing SIF's for clips\lugs using experimental data for cruciform samples.**



Item #3 - High Cycle Fatigue Design

- **Large discrepancy in the high cycle regime.**
- **Essentially no data is "conservative" above 1e6 cycles to failure. In general, more data is "Non-Conservative" than "Conservative"**



Recommendations

Recommendations

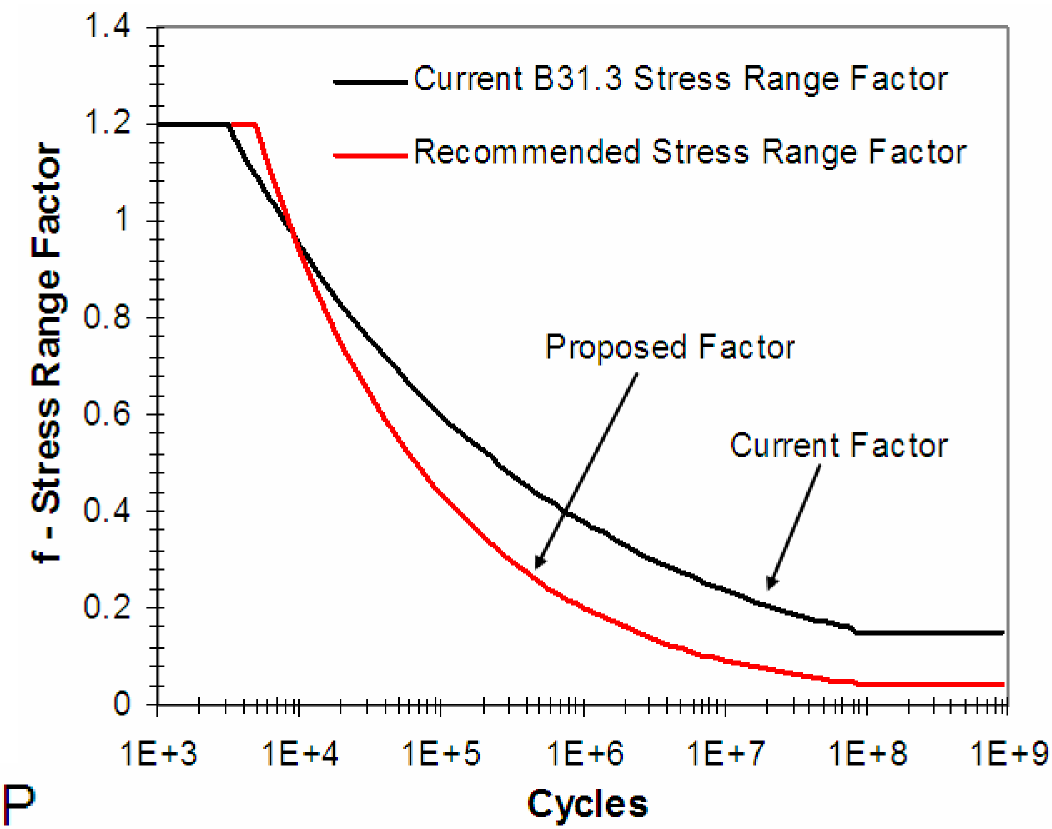
- **Consider use of recommended girth butt weld equation for SIF development and possible implementation into the B31 Codes**
- **The proposed equation has several benefits in light of the test data reviewed to date:**
  1. **Increased low cycle design lives**
  2. **Better correlation with other fatigue methods and state-of-the-art today**
  3. **Improved predictions in the high cycle regime**
  4. **More consistent design margins for all portions of the SN design curves**
  5. **An opportunity for alignment to harmonize with other ASME fatigue methods.**

Recommendations

- In B31.3, the proposed design equation could be implemented by modifying the existing stress range factor “f”
- The proposed design equation is based on two standard deviations below the mean failure curve.
- Provides a consistent design margin of 1.84 on mean failure stress

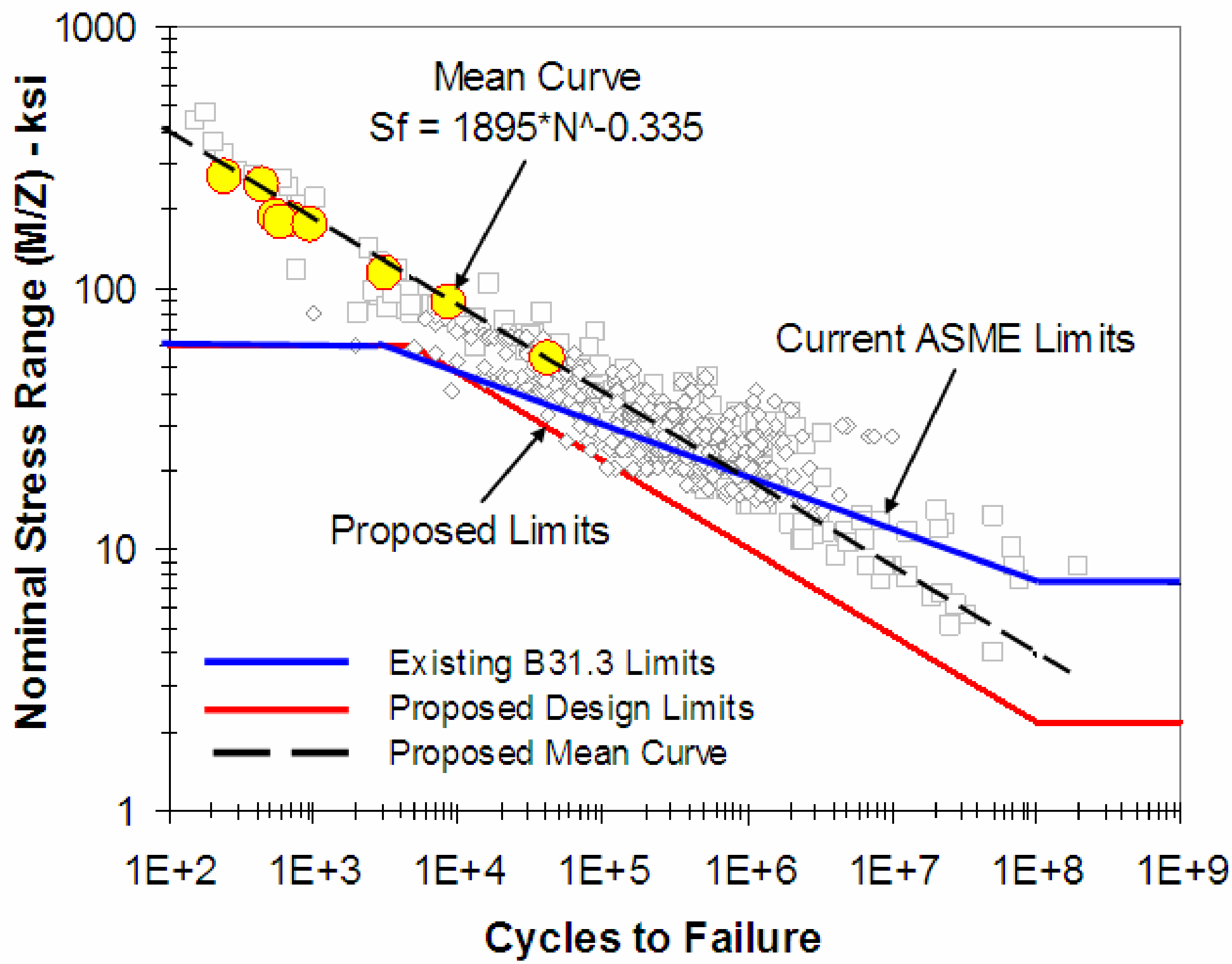
Proposed Stress Range Factor

$$f = 20.6 \cdot N^{-0.335}$$



Proposed Limits vs. Existing Limits

- **As shown below, the proposed limits provide an improve fit to the test data and a consistent design margin throughout a wide range of cycles.**



Conclusions

- **New test results presented here suggest amendments to the Markl piping methods are warranted. These conclusions are supported by other experimental references and design codes.**
- **The fatigue curve slope used by Markl's equations does not match results for existing test data.**
- **Current B31.3 code rules do not provide a consistent design margin for the reported tests. Above 850,000 cycles, the rules may allow design lives in excess of the mean failure life.**
- **Markl's mean girth weld equation may lead to inconsistent SIF's. SIF's tested within the low cycle regime may be under predicted.**
- **High cycle fatigue strength appears to be over estimated by Markl's curve.**
- **A new girth butt weld equation has been proposed that fits a large population of data and agrees with other fatigue design methods.**

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