Fatigue Testing of Welded Flat Head Pressure Vessel Joints

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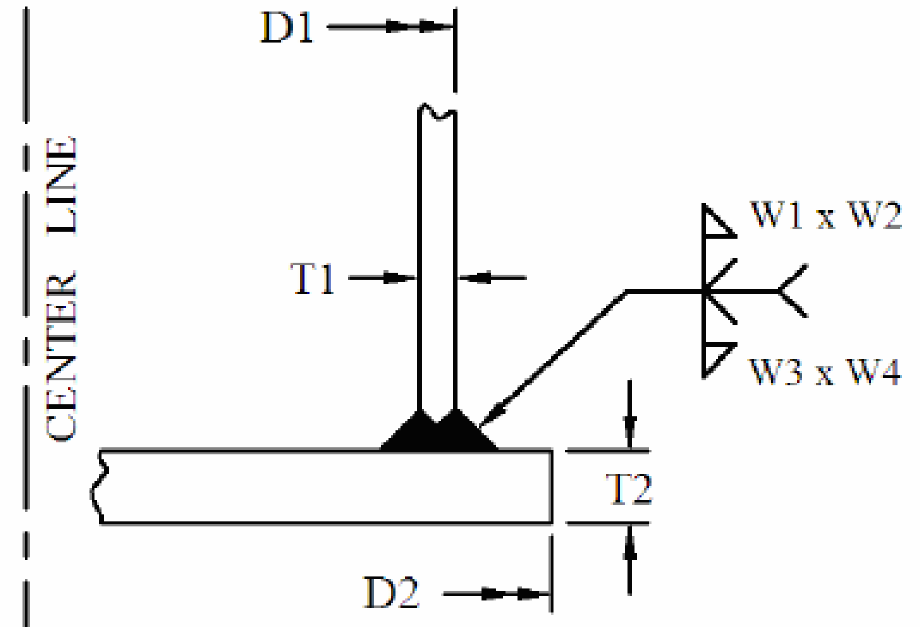
Previous Experimental Work to Date

- **Previous work included 19 failures in 5 test vessels with flat heads. (Hinnant - PVP2006-ICPVT11-93967)**
- **Questions from previous testing:**
    1. **Thickness effects – do very thin plates exhibit much greater fatigue lives?**
    2. **Did testing in tap water adversely affect testing?**

Description of Tests

Test Specimens

- **Cyclic fatigue tests of cylindrical shells with flat heads attached using full penetration welds**
- **Carbon steel used for all new specimens**
- **TIG, GMAW, FCAW welding processes**
- **ASME certified welders and fabrication facilities**



Test Specimens

Two specimens welded together & tested simultaneously

Experimental Procedure

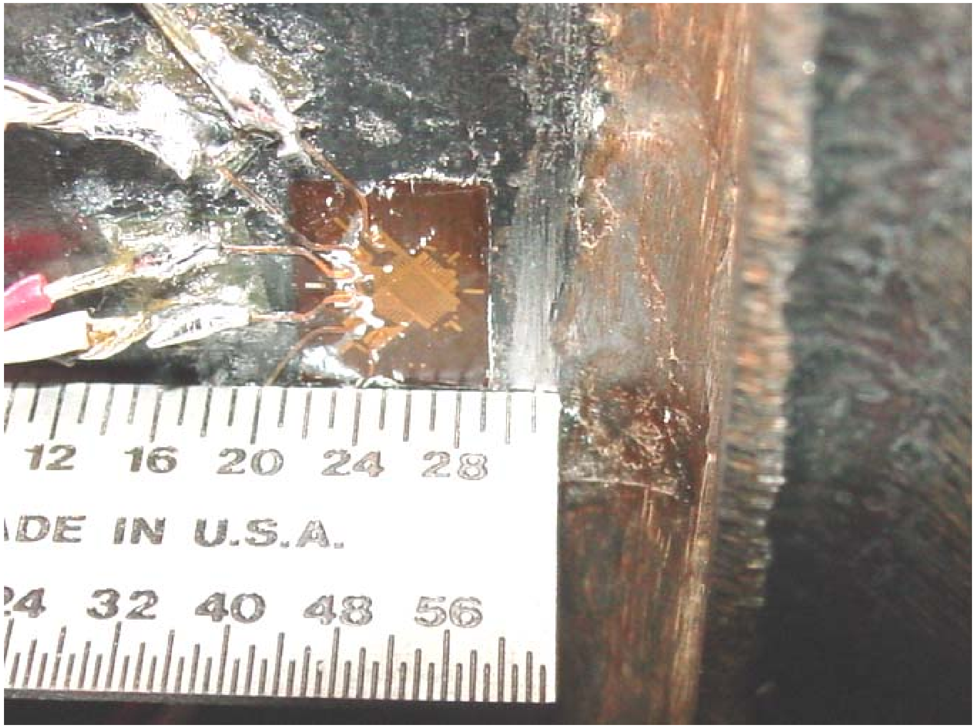
- R=0, cycle between zero and max pressure
- “Thin” test was conducted using water.
- All other tests utilized only compressed air.
- Failures were repaired and testing continued if possible
- Pressure range produces structural stress < 2*Sy

Experimental Procedure – Air Tests

- Concrete castings inserted into test specimens to reduce free air volume and minimize cycle time.
- Air was preheated and filtered to prevent accumulation of condensate.

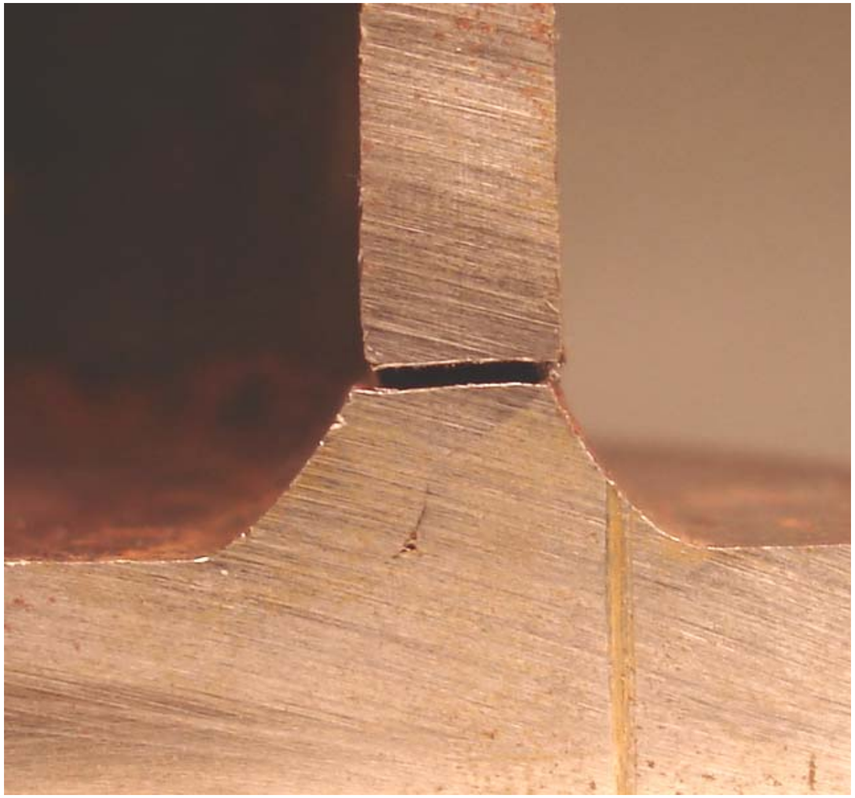
Experimental Procedure

- Strains adjacent to weld toe and displacements at center of flat head were recorded throughout testing
- Measurements used to validate FEA solutions
- Measurements turned out to be an important part of the test procedure



Failure Criteria

- Thru thickness crack with leakage
- Failures originated at weld toe on inside surface and extended to weld toe at outside surface.
- Additional failures which occurred adjacent to fatigue repairs are not included in results.



Fatigue Design Methods

Fatigue Design Methods

Experimental results compared with:

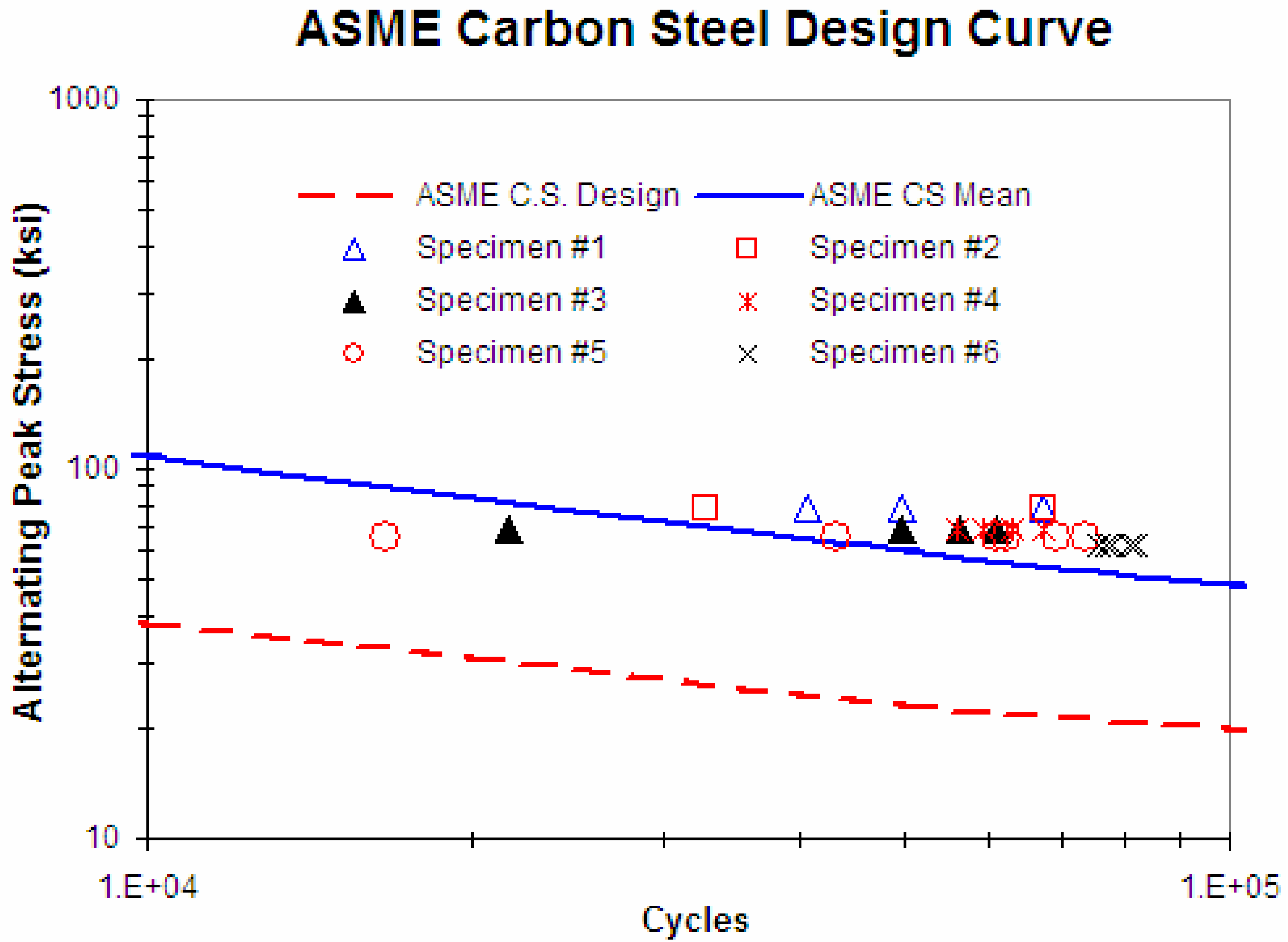
- **ASME Section VIII, Division 2, Appendix 5 using FSRF methodology**
- **Battelle Master S-N Method**
- **EN 13445 – FAT 71**

- **API 579 – Class 63**
- **PD 5500 – Class F**

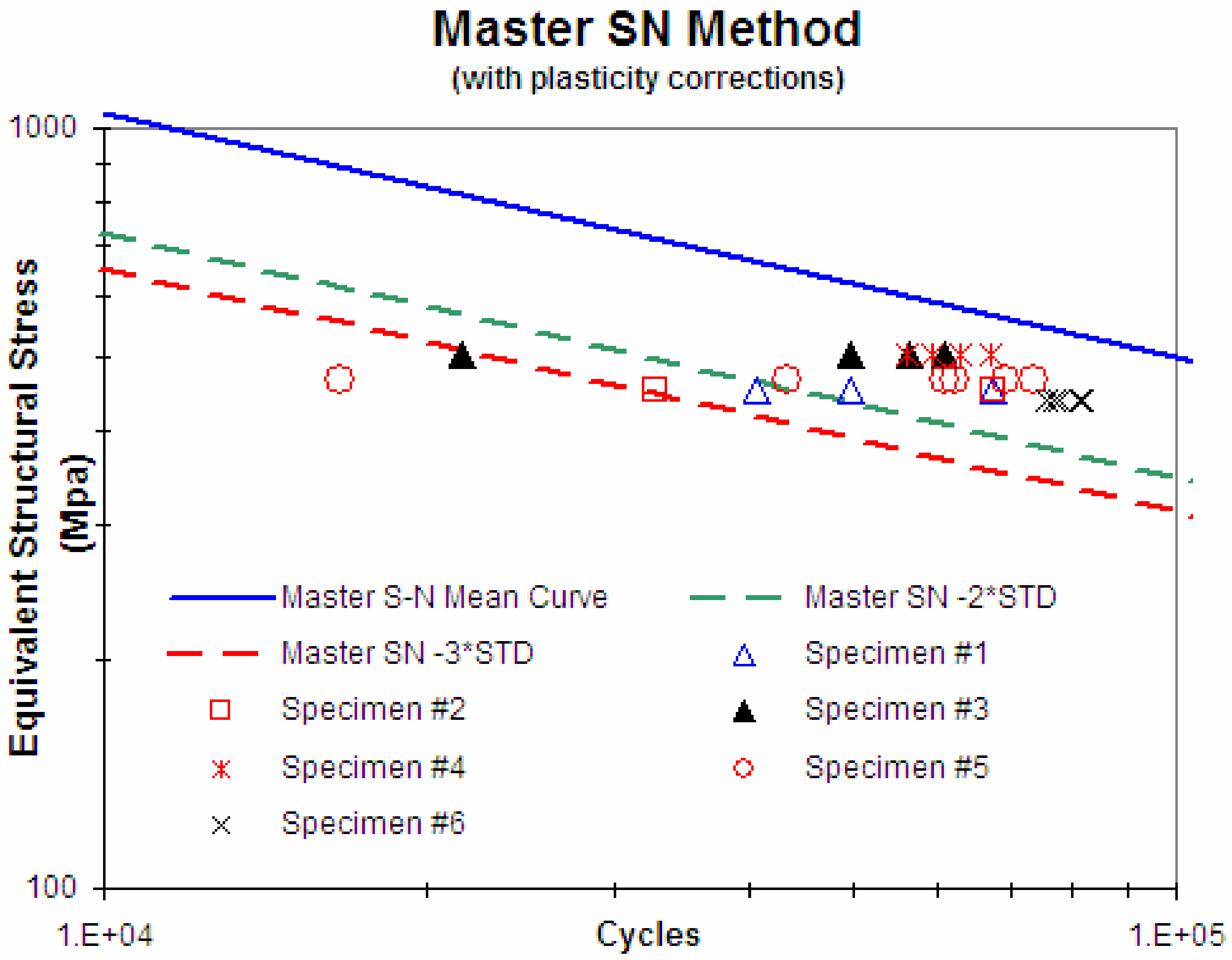
Fatigue Design Methods

- Axisymmetric models used to determine stresses
- Linear elastic FEA used for all tests.
- To account for geometric stiffening, large displacement theory was used to analyze specimens #3 & #4
- As-built dimensions were used in all calculations.

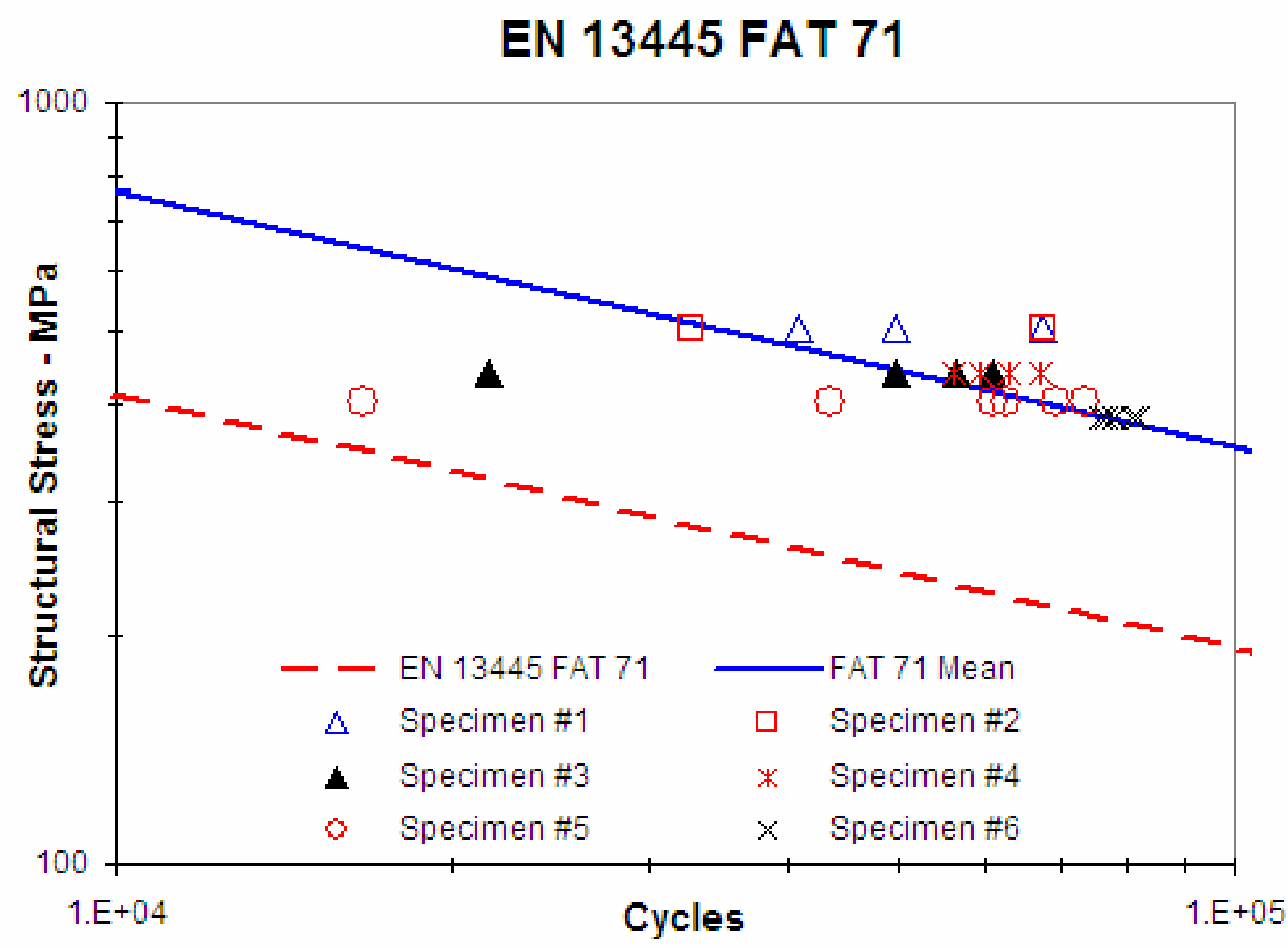
Fatigue Design Methods – ASME VIII-2 (FSRF = 2.15)



Fatigue Design Methods – Battelle Master S-N



Fatigue Design Methods – EN 13445 (FAT 71)



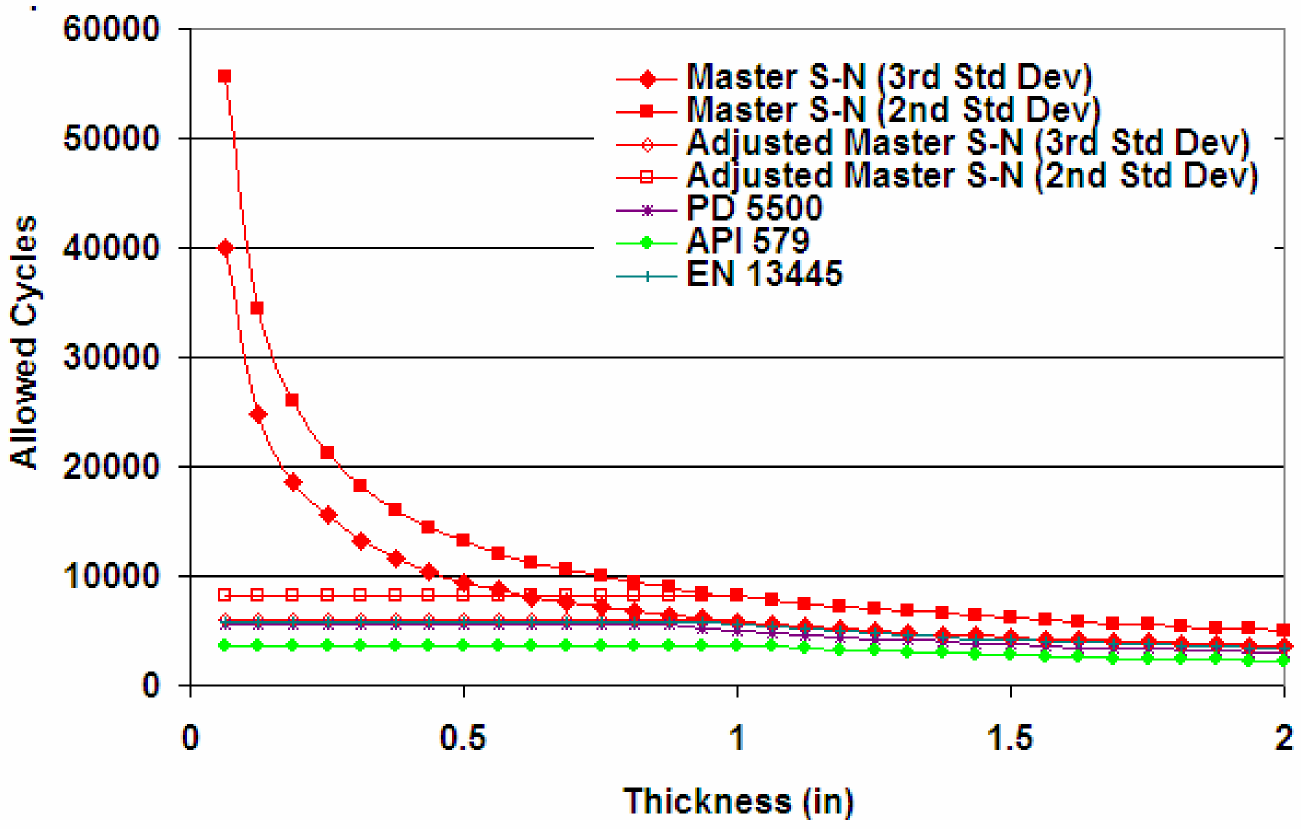
Some notes on fatigue calculations

- **Success of ASME FSRF method is dependent upon selection of an accurate FSRF**
- **Excluding Master S-N Method, plasticity correction factors are not used since structural stress range < 2*Sy**
- **For the Battelle Master S-N method, plasticity correction factors are applied for structural stress > 1.0*Sy**
- **Tests #1 & #2 (thin plate) were corrected for tap water environment by a factor of 1.35 on life.**

Thickness Effects

Thickness Effects

- Nearly all PRG data is below Battelle mean curve – could be improved by adjustment of thickness correction factor.
- Master S-N Method's thickness correction factor provides significantly increased fatigue lives for very thin plates.



Thickness Effects

- Test specimens #1 & #2 were constructed with 0.055” (1.4 mm) thick plate to evaluate thickness effect.
- Test showed that the thickness correction factor is over estimated for “thin” test specimens #1 & #2.
- Actual fatigue life increase = 174%
- Master S-N predicted life increase = 247%

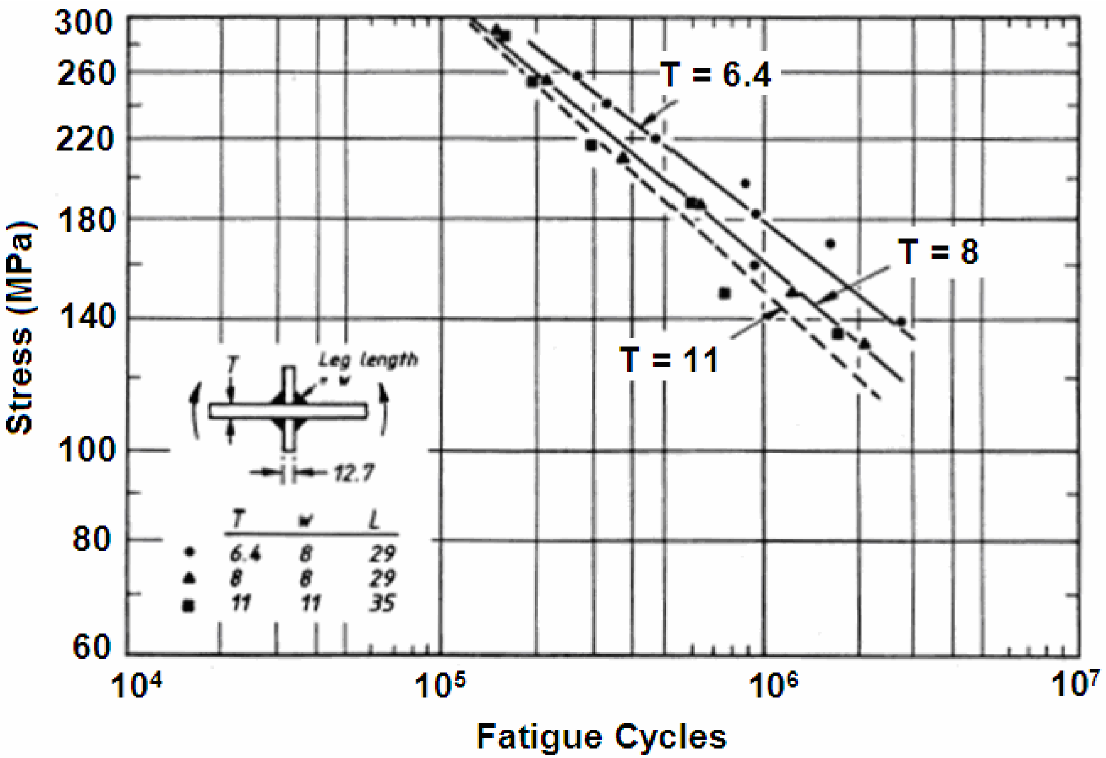
- Not a closed issue – further investigations planned

Thickness Effects – Other results…

- Branco, et.al. tested similar thicknesses and concluded that a part of the fatigue life increase is attributed to better quality welds (TIG vs. MIG)
- They also reported over prediction of thin plates using a similar thickness correction method.

Thickness Effects – other results…

- DeJesus tests suggest thickness effects are less significant in thin plate failing at low cycles.
- Research by Gurney suggest thickness correction extends into lower thicknesses, but a limit does exist.
- Thickness effect may collapse at high stress levels in bending dominant stress fields.



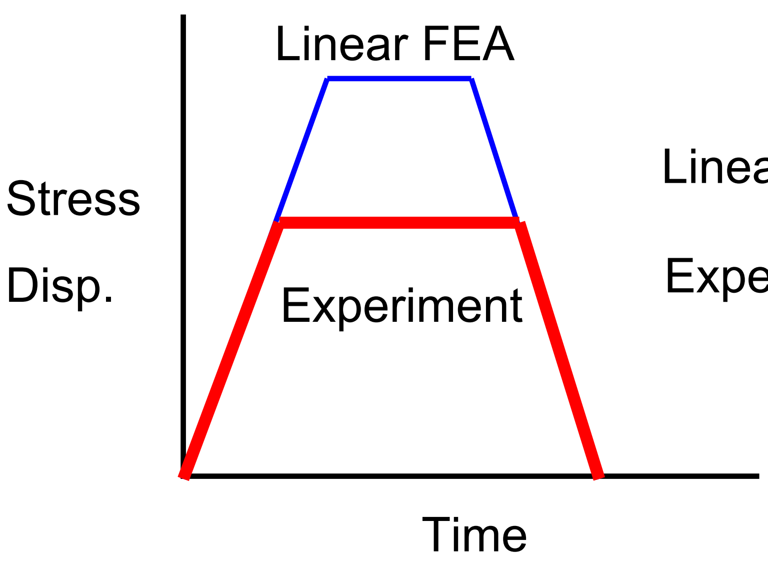
Geometric Effects

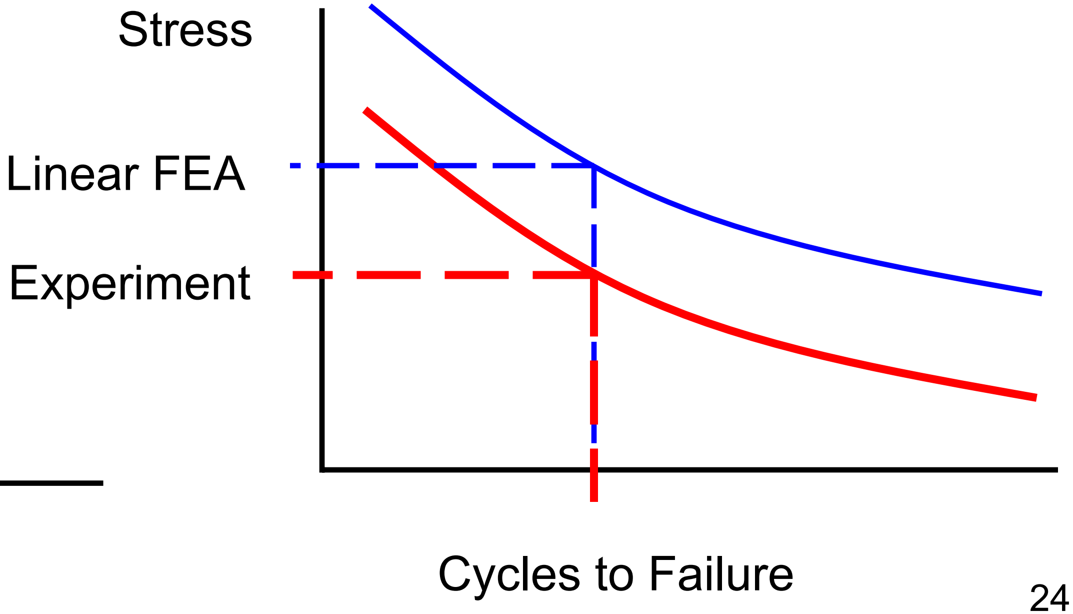
Geometric Effects

- **For specimens #3 & #4, a slightly thinner flat head was used.**
- **The flat head was sufficiently thin to induce geometric stiffening to occur.**
- **As a result, the stress range and displacement was less than would be predicted by small displacement theory.**
- **For an “apples to apples” comparison, we need the actual elastic stress range experienced by the weld joint during testing.**
- **It would be incorrect to use the results for a linear elastic FEA solution with small displacement theory.**

Geometric Effects

- **Geometric stiffening results in decreased displacement and decreased stress range for the same load**
- **Linear elastic FEA over estimates the stress range, resulting in development of non-conservative fatigue <u>design</u> curves.**





Geometric Effects

- Measured stress is over predicted by 21%
- Displacement is over predicted 46%

	Stress Value	vs. Measured
Strain Measurements	52,740 psi	
FEA Large Displacement Theory	50,340 psi	95%
FEA Small Displacement Theory	63,920 psi	121%

	Displacement	vs. Measured
Measurements	0.165”	
FEA Large Displacement Theory	0.1936”	117%
FEA Small Displacement Theory	0.2426”	146%

Environmental Effects

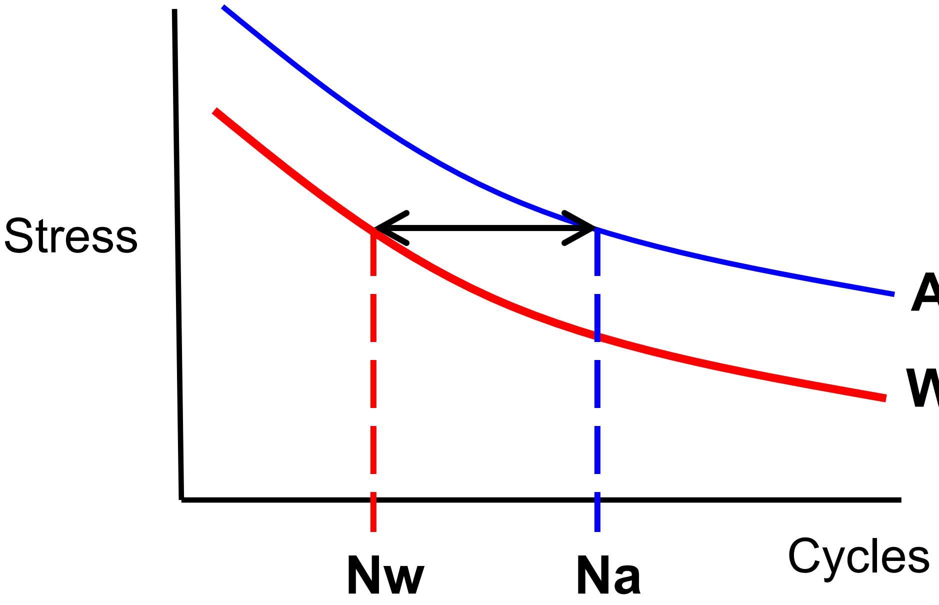
Environmental Effects

- **All 2006 tests and two new tests were conducted using Houston tap water.**
- **PVP 2006 - It was hypothesized that environmental effects were responsible for the test data consistently falling below Master S-N mean curve.**
- **Four additional tests were completed and tested in air to determine the environmental factor.**
- **NOTE - Environmental factor is only applicable to room temperature tap water at PRG lab in Houston, TX.**

Environmental Effects

The environmental effect is estimated by:

1. **Determine mean curve for tests conducted in water.**
2. **Determine mean curve for tests conducted in air.**
3. **Environmental effect is the ratio of the lives for a specified stress level**



$$\boxed{Fen = \frac{Na}{Nw}}$$

Environmental Effects

Four environmental factors were calculated…

- **Two stress methods were used: Structural Stress and Equivalent Structural Stress.**
- **Two approaches were used to bound the possible range of environmental factors: “strict” and “relaxed”.**
- **“Strict” compares only welds and tests that are very similar.**
- **“Relaxed” compares most all results.**

Observed Environmental Effects

Conclusion – environmental effects for room temperature Houston tap water are minimal.

Case	Stress Method	Fen
Strict	Structural Stress	1.356
Strict	Equivalent Structural Stress	1.302
Relaxed	Structural Stress	1.136
Relaxed	Equivalent Structural Stress	1.308

Summary of Testing

Summary of Testing

A total of 43 unique failures in 11 pressure vessels

Mean curve for structural stress definition :

(STD DEV = 0.217)

$$S = (16960.29\ MPa)(N^{-\frac{1}{3}})$$

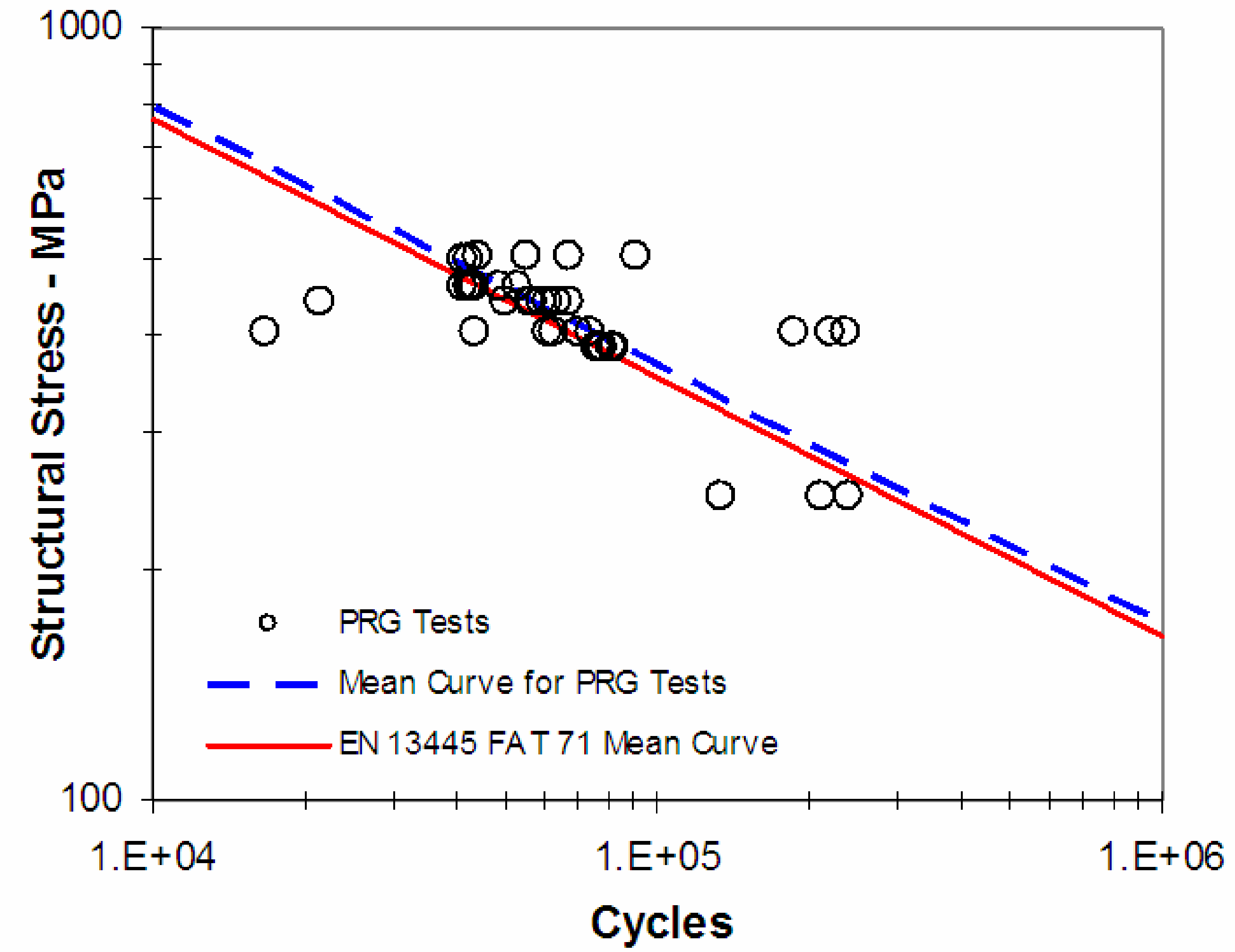
Mean curve for Master S-N Equivalent Structural Stress :

(STD DEV = 0.212)

$$S = (16449.77\ MPa)(N^{-0.32})$$

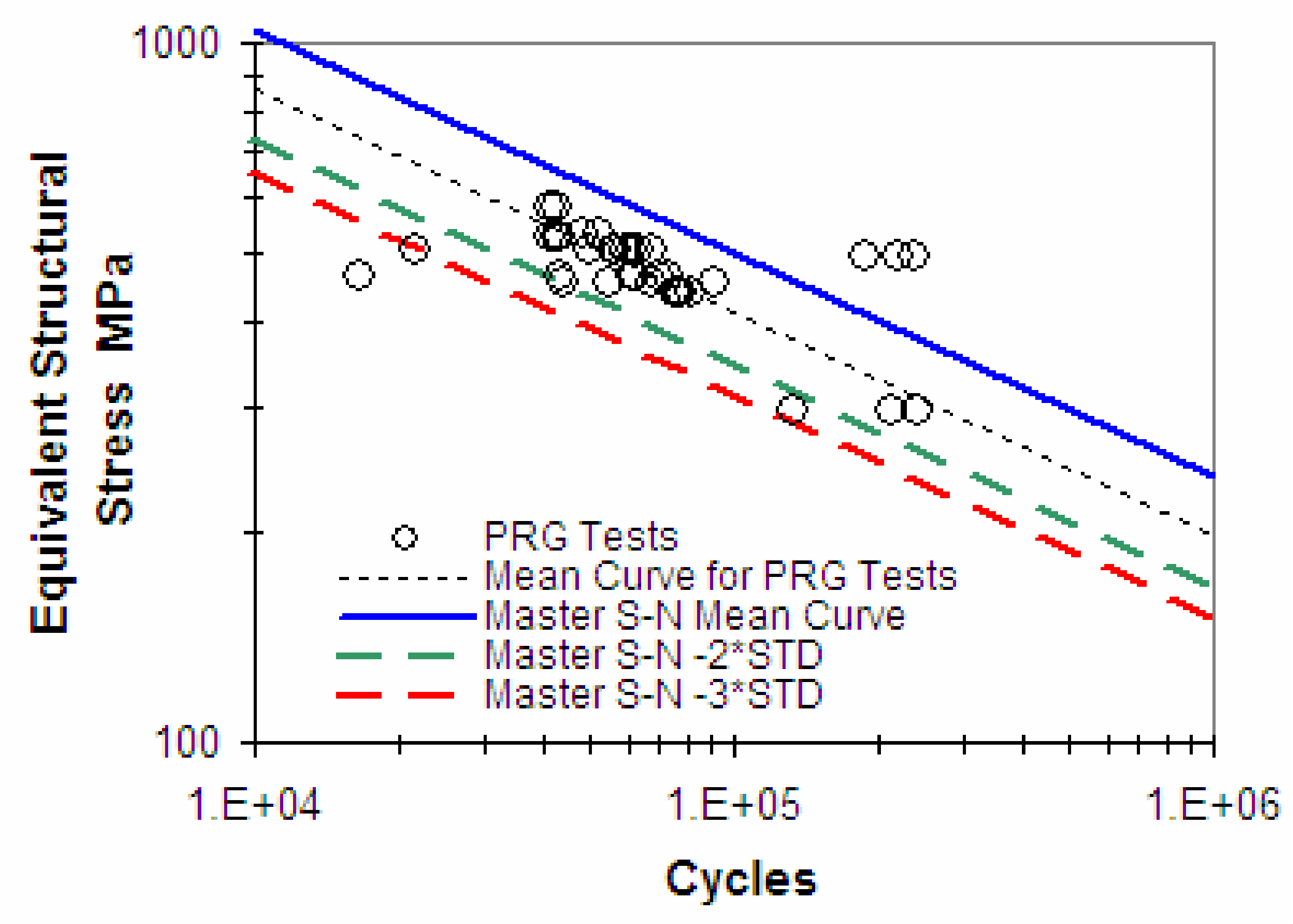
Summary of Testing

Best fit for experimental data is FAT 82, slightly higher than the designated FAT 71 in EN 13445



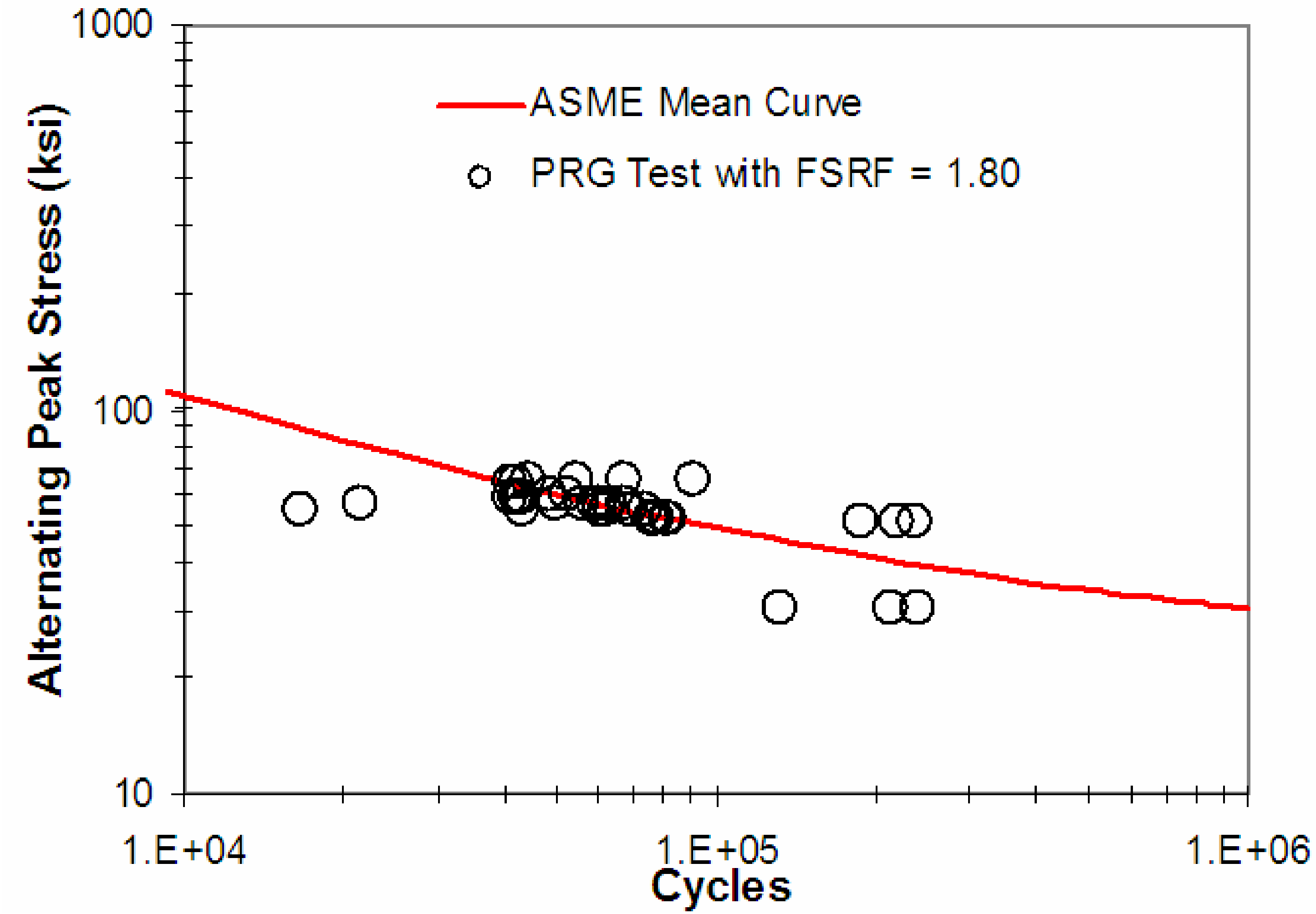
Summary of Testing to Date

Experimental mean curve is approximately one standard deviation below Battelle Master S-N mean curve.



Summary of Testing

- **Best fit FSRF for all PRG tests is 1.80.**
- **Less than 2.0 as per WRC 432 & 2007 ASME VIII-2**



2007 ASME VIII-2

Welded Fatigue Method

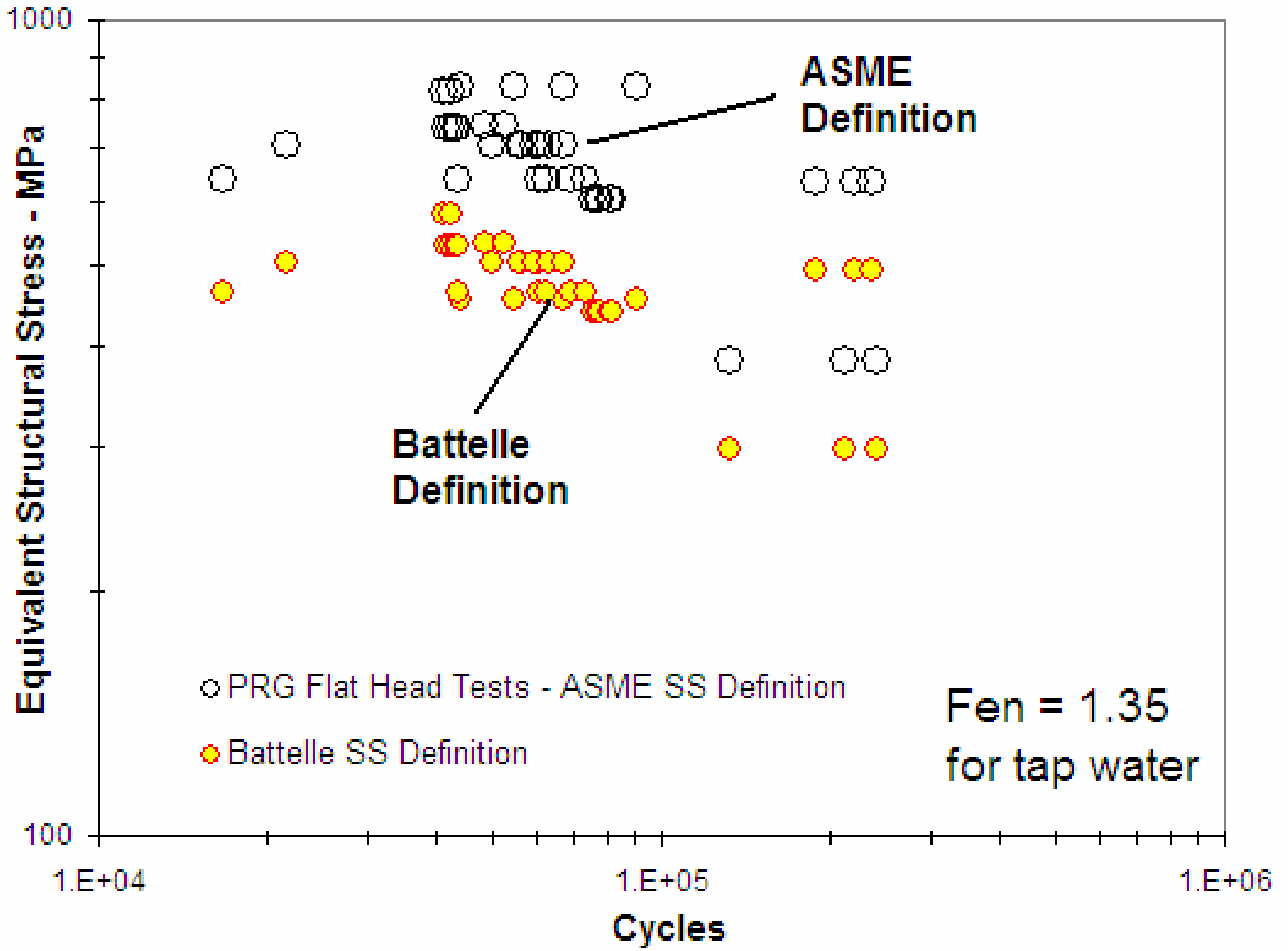
2007 ASME Section VIII-2 Welded Fatigue Method

2007 ASME Section VIII Division 2 rules differ slightly from stress definition used in Battelle database:

- **Thickness cut-off to eliminate increased life below 16 mm (0.625")**
- **Mean stress correction**
- **Requires that operating environment be considered**

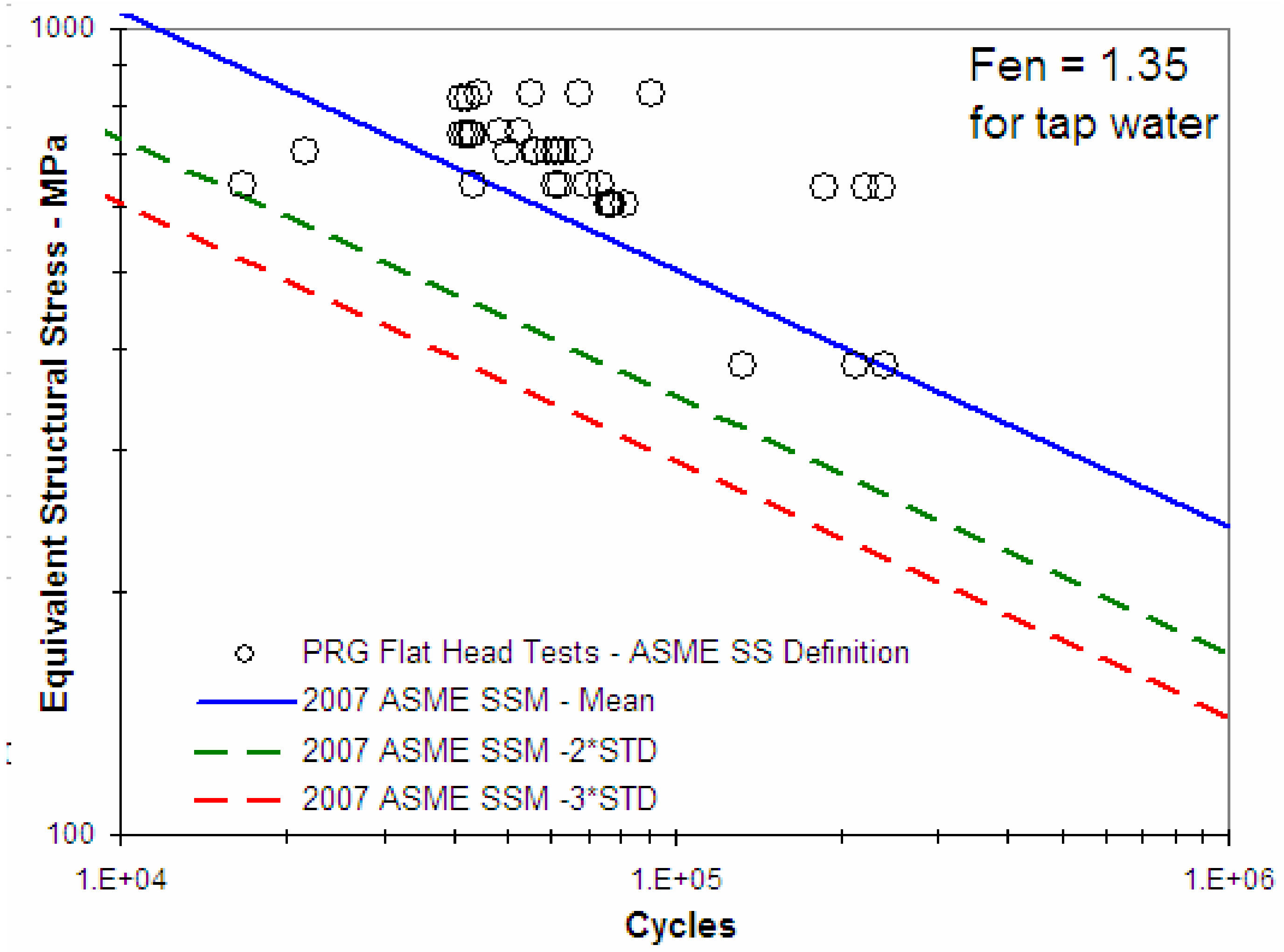
2007 ASME Section VIII-2 Welded Fatigue Method

- **The following illustrates the difference in the stress definition between Battelle EQ. SS and 2007 ASME VIII-2**
- **2007 ASME increases stress range from 28% to 40%.**



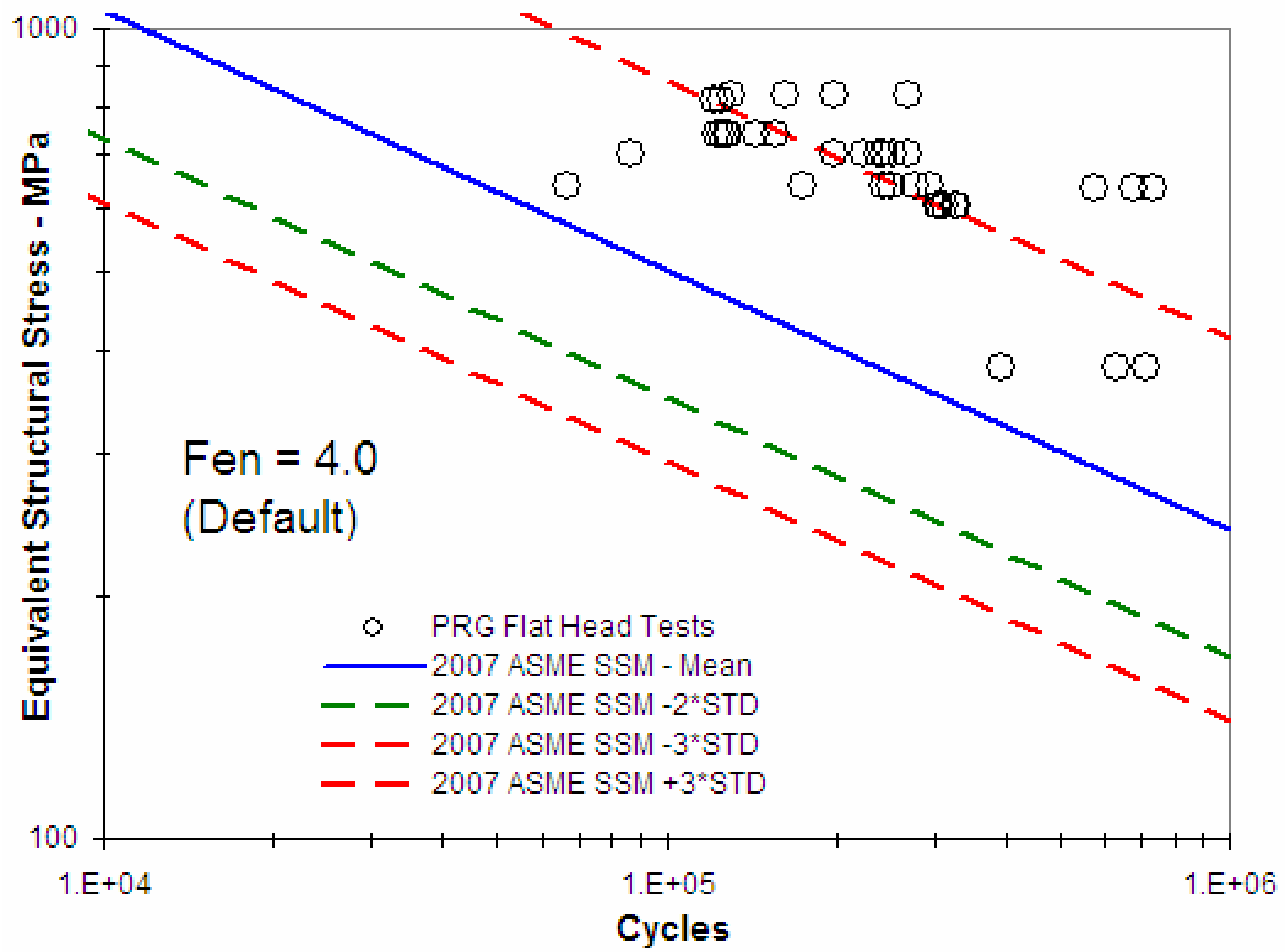
2007 ASME Section VIII-2 Welded Fatigue Method

The following are the experimental failures with an Fen of 1.35 applied to tests using tap water



2007 ASME Section VIII-2 Welded Fatigue Method

The following are the experimental failures with an Fen of 4.0 applied to all data points (default per 2007 VIII-2).



Conclusions

Testing Considerations

- **PVP 2006 tests agree with recent tests reported here.**
- **43 failures have been documented and reported.**
- **Mean curve shows EN & ASME FSRF to be conservative.**
- **Mean curve of test data is one standard deviation below mean curve of Master S-N Method.**
- **Geometric effects in testing must be properly addressed.**
- **Environmental effects of Houston tap water are minimal.**
- **Master S-N thickness correction factor over predicted fatigue life of very thin plate**
    - **2007 ASME VIII-2 includes a lower limit on the correction factor**

Questions?

Available for download at:

www.paulin.com