Observations Related to the Master SN Method in the ASME Division 2 Rewrite Project

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Summary

The following are specific issues related to the implementation of the Master SN method in the ASME Division 2 Rewrite project. These issues illustrate situations where the implementation can lead to non-conservative solutions. In addition, comparisons against other fatigue methods including European as-welded codes is achieved by using fatigue charts based on specified load instead of stress. These charts show that the proposed Div 2 Rewrite SSM method will produce lower lives for high quality weld joints while allowing greater lives for low quality weld joints in comparison to the existing ASME FSRF method. In addition, Neuber's rule is discussed in terms of Code stress limits and analysis methods to illustrate why it is not required in the Div 2 Rewrite project.

Item #1

As the strain due to an applied load increases, the accuracy of the Neuber's correction decreases, potentially resulting in non-conservative design lives.

Test results provided in WRC 433 show that the fatigue failures can occur at less than half of the design life using the -3*STD Master SN design curve when the applied (measured) load is utilized. As shown in Table 1, the proposed ASME Div 2 Rewrite rules may over predict the fatigue life by a factor of 7 or greater (component fails at 1/7 of the design life).

The accuracy of the low cycle adjustment procedure (Neuber correction) diminishes as plasticity increases. In displacement controlled testing, the applied load will change very little once plasticity begins to occur (large increases in displacement are achieved for relatively small increases in applied load). Therefore, the pseudo elastic load based on the extrapolation procedure becomes increasingly greater than the actual applied load.

When the applied load is used to calculate an elastic stress and the low cycle adjustment procedure is used, the resulting pseudo elastic structural stress will be lower than the actual pseudo structural stress based on the linear extrapolation procedure using measured displacement. The problem with under prediction of the real pseudo elastic stress increases as greater levels of stress are applied.

As described in Item #1, the test results shown here illustrate that an upper bound should be applied to the Neuber adjustment such that excessive plasticity is not permitted in the design calculations when applied loads are used in the analysis.

Table 1 – NON-CONSERVATISM of Div 2 Rewrite Rules for recent fatigue tests using measured loads.

Specimen	Description	Applied Force (lbf)	Applied Stress Range (psi)	Cycles to Failure	Allowed Design Cycles -3*STD	Design Margin < 1 implies failure at less than allowed design cycles.
1	CS – No Weld	2468	90165	523	1620	**0.32284**
2	CS – No Weld	2710	99005	285	1068	**0.266854**
3	CS	2468	90165	249	1620	**0.153704**
4	CS	2407	87955	304	1802	**0.168701**

5	CS	2316	84641	615	2120	**0.290094**
6	CS	2649	96795	155	1184	**0.130912**
7	CS	2271	82983	836	2301	**0.36332**
8	CS	2347	85746	461	2008	**0.229582**
9	CS	2286	83536	786	2239	**0.35105**
10	CS	2377	86850	386	1902	**0.202944**
11	CS	2710	99005	183	1068	**0.171348**
12	CS	2528	92375	202	1457	**0.138641**
13	CS	2256	82431	708	2365	**0.299366**
14	CS	2226	81326	791	2499	**0.316527**
15	SS – No Weld	2607	95272	751	1271	**0.590873**
16	SS	2607	95272	595	1271	**0.468135**
17	SS	2878	105152	195	809	**0.241038**
18	SS	2481	90661	1224	1582	**0.773704**
19	SS	2698	98565	478	1090	**0.438532**
20	SS	2788	101859	311	938	**0.331557**

Item #2

The Div 2 Rewrite implementation of Neuber's rule for applied or measured loads is only valid when the applied nominal or structural stress is elastic or only slightly exceeds the material yield stress. If significant plasticity occurs, the Neuber's correction could lead to non-conservative errors.

If the calculated structural stress due to an applied load significantly exceeds yield and plasticity occurs, then the Neuber's hypothesis is no longer valid. This statement is supported by Wetzel's conclusions when he states that Neuber's rule does "*not apply for values of nominal stress which significantly exceed the yield strength of the metal*." To be clear, the stress described is that calculated by using the measured or applied loads. This is the same applied or measured load "Fm" for which Battelle has recommended the Neuber's rule should be used to correct in order to estimate the pseudo elastic load.

The conclusion that Neuber's rule is not applicable when the structural stress calculated from measured loads exceeds yield is also supported by the fatigue tests provided by Scavuzzo in which the structural stress exceeds the yield strength of the material. In Scavuzzo's case, the Neuber's adjustments lead to over predictions of the fatigue life resulting in non-conservative designs lives (failure occurs at lower cycles than predicted). See Item #1 for additional explanation.

Based on the above conclusions it would seem reasonable to limit fatigue designs using Neuber's rule to cases where the calculated structural stresses only slightly exceed the yield strength of the material.

Item #3

In comparison to current the current ASME rules with WRC 432 FSRFs, the Master SN method implemented in the Div 2 Rewrite will result in reduced design lives for simple welded joints with higher quality while permitting increased design lives for more complex welded joints where quality has historically been difficult to deliver.

As shown in the following figures, relative to the existing FSRF based ASME methods, the Master SN method will result in decreased design lives for simpler joints such as girth butt welds, but increased fatigue lives for more complex joints such fillet welds with throat failure.

For example, double sided girth welds designed to the current ASME rules with a required design life of 10,000 cycles would need to be almost 2.5 times thicker or be placed into service with a reduction of approximately 7.5 times on life using the Master SN method.

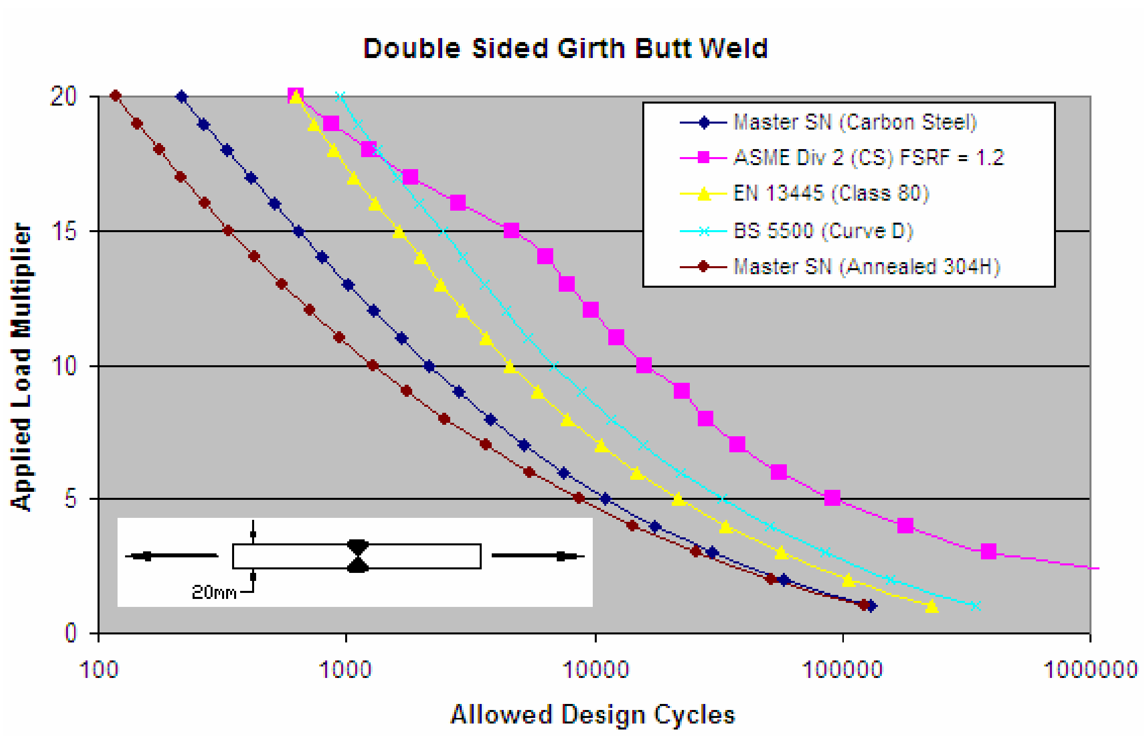
On the other hand, fillet welds where root failure dominates would be designed to 10,000 cycles with the existing FSRF methodology, yet the same detail designed with the Master SN method would be permitted a design life of nearly 80,000 cycles.

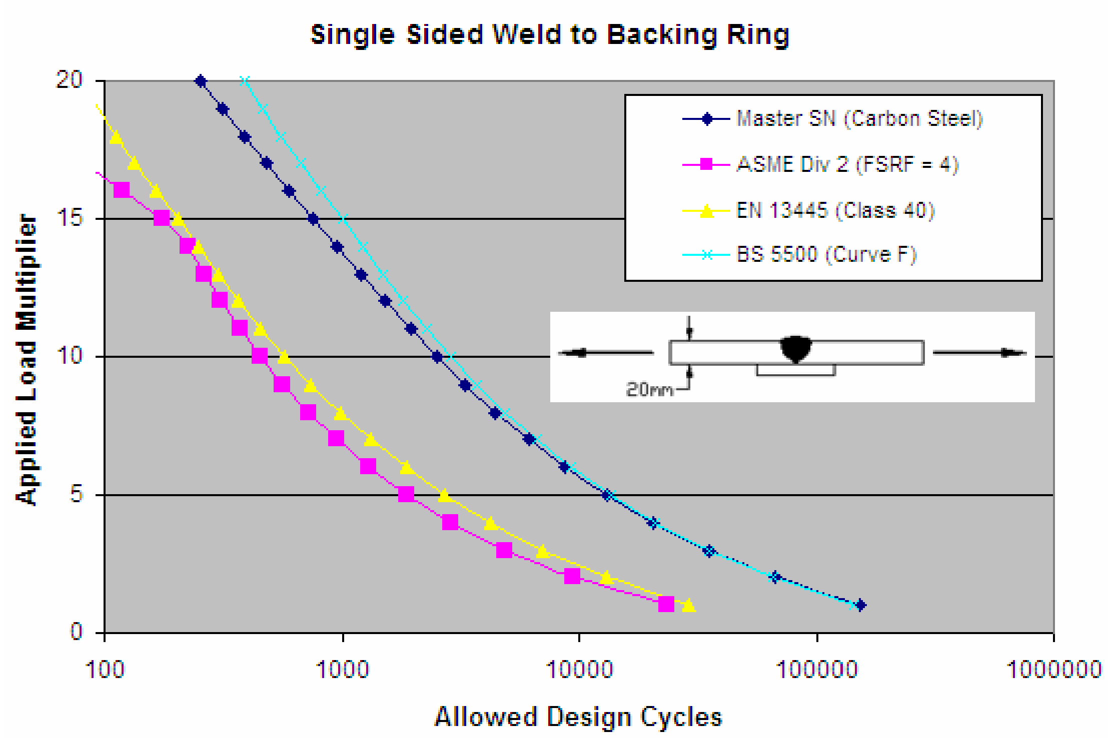
Note that the following are not fatigue curves in the traditional sense. The curves are generated for an applied load multiplier instead of stress. For each unit load, the appropriate stress has been calculated as required by each Code. Therefore, the curves are directly comparable since they represent the permitted cycles for a given load, not for a single stress definition.

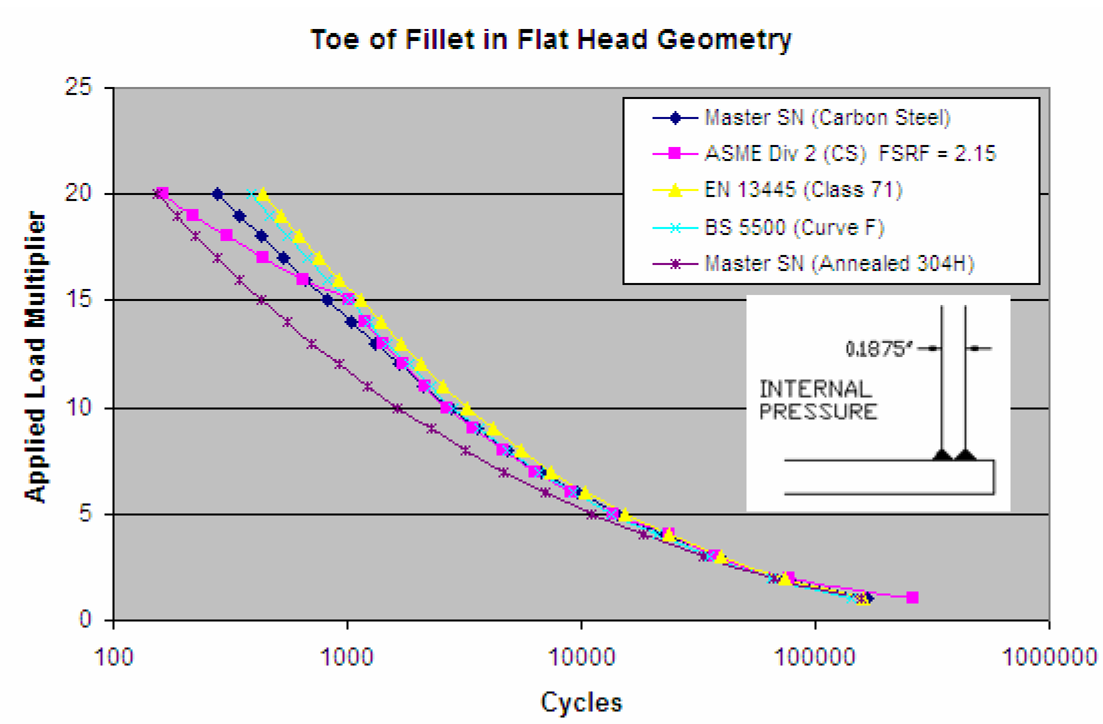
The stresses calculated for each unit load for the various fatigue methods are:

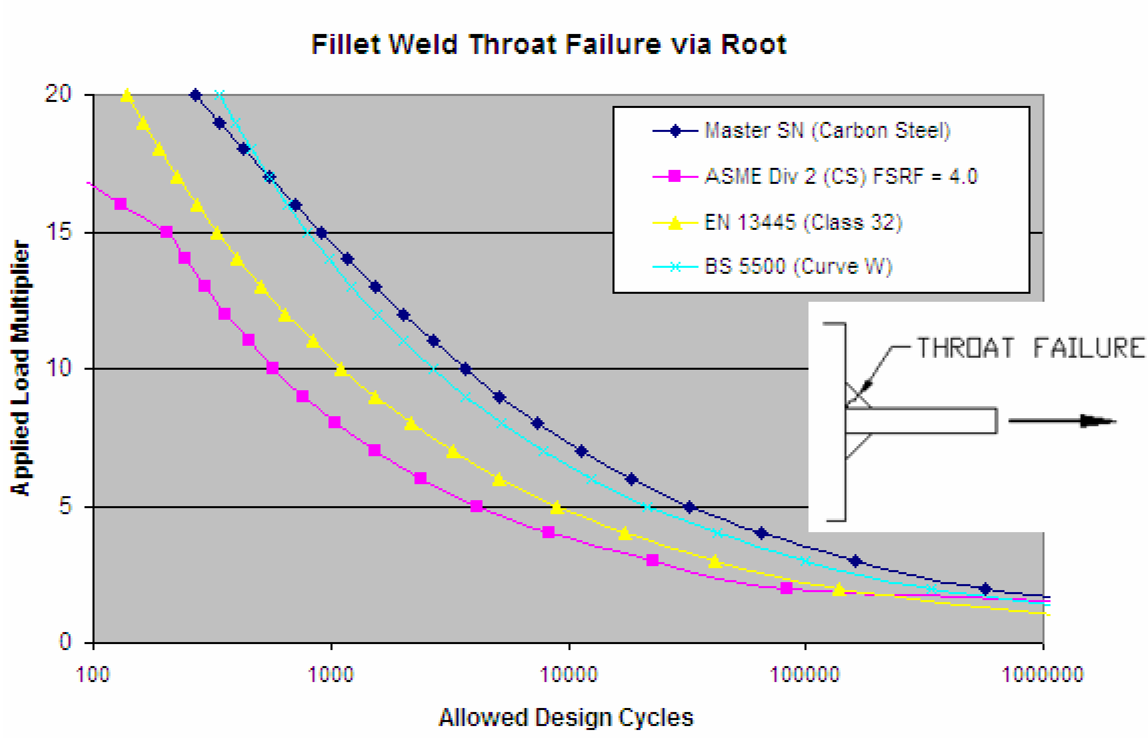
1. Master SN – equivalent pseudo elastic stress
2. ASME Smooth Bar – peak alternating stress intensity
3. BS 5500 – maximum direct stress acting at the failure site
4. EN 13445 – hot spot stress (extrapolated stress)

Note that these comparisons only provide a comparison between various fatigue methods. These are not intended, nor do they imply that one method provides better predictions against actual failure life over another method.




Single Sided Weld to Backing Ring
Master SN (Carbon Steel)
ASME Div 2 (FSRF = 4)
EN 13445 (Class 40)
BS 5500 (Curve F)
20mm
Applied Load Multiplier
Allowed Design Cycles
0
5
10
15
20
100
1000
10000
100000
1000000


Toe of Fillet in Flat Head Geometry
Master SN (Carbon Steel)
ASME Div 2 (CS) FSRF = 2.15
EN 13445 (Class 71)
BS 5500 (Curve F)
Master SN (Annealed 304H)
0.1875"
INTERNAL
PRESSURE
Applied Load Multiplier
Cycles
0
5
10
15
20
25
100
1000
10000
100000
1000000



<u>Item #4</u>

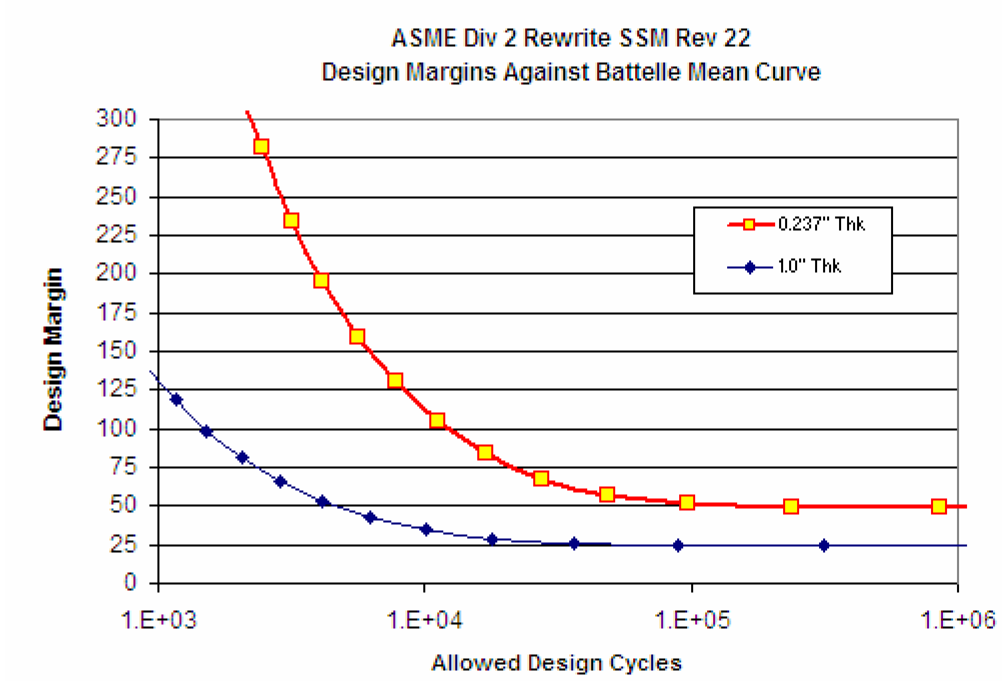
The implementation of the Master SN method in the Division 2 Rewrite project can result in unduly large design margins against the Battelle database mean curve.

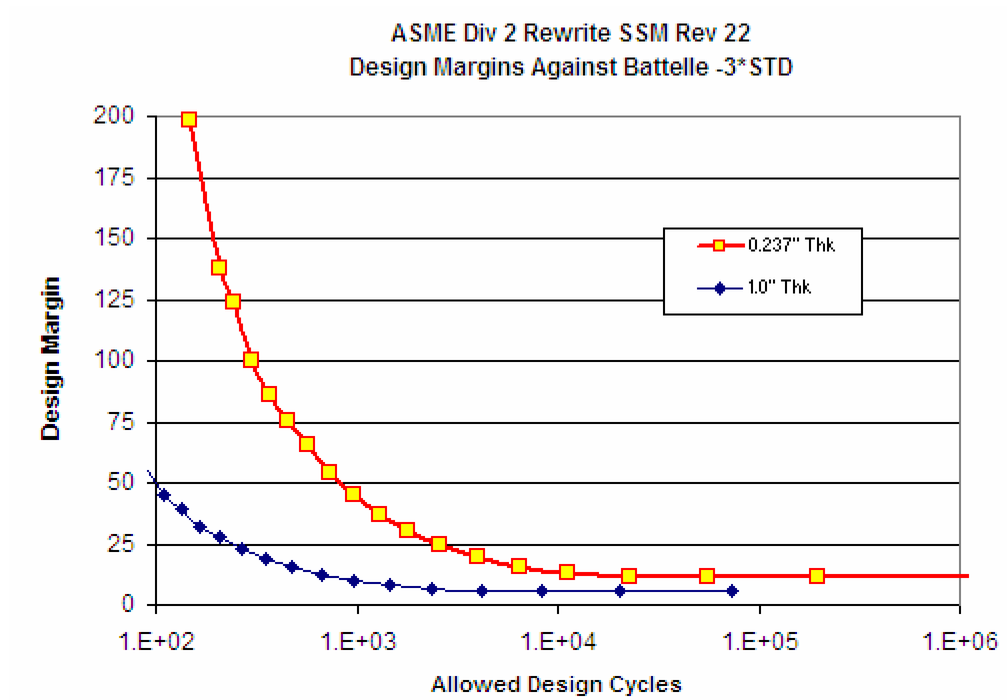
In regions where plasticity is not significant, the Division 2 Rewrite margin against the Battelle database's mean curve is approximately 50 for 4" SCH 40 pipes which have been the majority of PVP validation samples in the mid to low cycle range. In the low cycle region this margin dramatically increases due to the Neuber correction. At 10,000 cycles the design margin is over 100. Against the -3*STD curve, the Division 2 Rewrite provides a margin of approximately 11 against similar 4" SCH 40 pipe geometries.

Note that these large margins for thinner geometries are primarily a result of the thickness factor cut-off limit which was implemented in the Div 2 Rewrite rules, but not in the Battelle database.

The margin is less drastic for thicker geometries (approximately 25 against the Battelle mean curve in the mid to high cycle regime). The Battelle lower third standard deviation is approximately a factor of 4 to 5 below the mean curve. Therefore, the Div 2 Rewrite is approximately five times greater than the 99% prediction intervals.

It is interesting that these large margins are required given the fact that the Battelle database and third standard deviation curves already contains 99% of the test data. Other PVP as-welded fatigue codes utilize their statistical databases directly without large margins, yet are still able to provide "safe" design lives.


ASME Div 2 Rewrite SSM Rev 22
Design Margins Against Battelle Mean Curve
Design Margin
300
275
250
225
200
175
150
125
100
75
50
25
0
0.237" Thk
1.0" Thk
1.E+03
1.E+04
1.E+05
1.E+06
Allowed Design Cycles


ASME Div 2 Rewrite SSM Rev 22
Design Margins Against Battelle -3*STD
Design Margin
200
175
150
125
100
75
50
25
0
0.237" Thk
1.0" Thk
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
Allowed Design Cycles

Item #5

If the Neuber's correction is intended to modify structural stresses, then it does not apply for stress ranges less than 2*Sy since these PVP cases shake down to purely elastic action after a few cycles and don't require a plastic correction term.

Theory utilized in the ASME codes says that for structural stresses (membrane plus bending), the stresses will shake down to elastic action for stress ranges less than 2*Sy. This is a conservative approach and based on elastic-perfectly-plastic material assumptions. However, using the current Div 2 Rewrite Design Rules, the Neuber correction will reduce the fatigue life by up to 35% even when the stress range is within 2*Sy. This seems to be an unnecessary penalty given the fact the stresses will be elastic within this stress range.

Item #6

The Neuber's adjustment as implemented in the Division 2 Rewrite should not be applied to stresses resulting from thermal loadings or applied displacements as these are already equivalent to the pseudo elastic definition required for use in the Master SN method. Applying the Neuber's adjustment to such data will result in "double dipping" and excessive error in the calculations.

If thermal loadings (i.e. thermal distributions resulting is thermal strains) or applied displacements are specified in an elastic FE analysis, the resulting loads and stresses are always the pseudo elastic loads and stresses required by the Master SN methodology. Therefore, there is no need to perform any adjustments.

A similar approach is utilized in the ASME piping codes where thermal analysis and fatigue design does not require a plasticity adjustment. As Rodabaugh describes in NUREG 3243, the thermal analysis is analogous to the displacement controlled conditions which were used to develop the fatigue curves. Since the analysis matches the testing methodology by using controlled displacements, no adjustment is necessary.

From NUREG 3243 (Rodabaugh)

> The test method is consistent with an elastic analysis of a piping system, even though calculated stresses may be above the material yield strength and some plastic deformation may occur. Accordingly, an adjustment analogous to the K_e used in Code 1 is not needed.

Pingsha Dong, developer of the Master SN method, also provides support for the idea that the Neuber correction is not required when displacement controlled conditions are analyzed. The following statement is taken from the special ASME Fatigue Forum in Columbus, OH (Dec. 2006):

- The Neuber-based procedure for estimating pseudo elastic structural stress in low-cycle regime is only needed when performing linear FEA when pseudo elastic load or stress is not known

Item #7

The note in Part 5.5.5 which indicates that Neuber's rule will not affect the high cycle fatigue data where structural stresses are wholly elastic is not true. As currently implemented in Part 5 Rev 22, the Neuber's adjustment can result in errors of up to 10% on stress, or 35% on life when no plasticity exists at all.

See Appendix A for a detailed explanation on the perceived error in the Neuber's rule implementation.

In Part 5, a note to the Neuber's correction procedure indicates that the method should always be used and that high cycle applications for which the stresses are entirely elastic will not be affected (the elastic structural stress will not be modified).

However, this is not true. Using the stated rules, the rules will result in errors up to 10% of the expected elastic stress. If strains are substituted into Eq. 5.52 and stresses are directly solved for, the resulting pseudo elastic stress will be 105% of the expected elastic stress. If stresses are substituted into Eq 5.53 and the plastic strain is solved for, then predicted pseudo elastic stress is 110% of the expected elastic stress. This is error will result in a 35% difference in the calculated fatigue life.

The note given in Part 5 is as follows:

> NOTE: The modification for low-cycle fatigue should always be performed because the exact distinction between high-cycle fatigue and low-cycle fatigue cannot be determined without evaluating the effects of plasticity which is a function of the applied stress range and cyclic stress-strain curve. For high cycle fatigue applications, this procedure will provide correct results, i.e. the elastically calculated structural stress will not be modified.

Item #8

The structural stress method requires the availability of cyclic stress strain curves.

1. Are the cyclic stress-strain curves for aluminum reflective of the welded properties? Some alloyed aluminums will exhibit significant strength reduction in the welded states. One example is 6061 Grade O.
2. How about low temperature cases where material strength may increase with decreased temperature?

Item #9

Although the Master SN method is material independent, the current Div 2 Rewrite implementation will produce fatigue lives up to 200% difference for varied materials.

The fatigue design life can be modified by approximately +/- 200% when comparing the various cyclic stress-strain curve options. However, it has been stated that there is no material dependency and that most all materials described in Annex 3F (excluding aluminum) can be designed to the same fatigue curve. This issue should be resolved.

As an example, consider a design with a structural stress of 76,000. If the material is basic carbon steel, the design life is 3,269 cycles. However, if annealed Type 304 SS is selected, the design life is 1,724 cycles. This represents a difference of nearly 190%.

Appendix A

Case #1 - Substitute strains into Eq 5.53

$$\Delta\sigma_k \cdot \Delta\varepsilon_k = \Delta\sigma_k^e \cdot \Delta\varepsilon_k^e$$

$$\Delta\varepsilon_k = \frac{\Delta\sigma_k}{E_{ya,k}} + 2\left(\frac{\Delta\sigma_k}{2K_{css}}\right)^{\frac{1}{n_{css}}}$$

$$\Delta\varepsilon_k^e = \frac{\left(1-\nu^2\right)}{E_{ya,k}}\Delta\sigma_k^e$$

Platic strain term approaches zero for elastic stresses

Substitute EQ 5.52 and 5.54 into EQ. 5.53

$$\Delta\sigma_k \cdot \left(\frac{\Delta\sigma_k}{E_{ya,k}} + 2\left(\frac{\Delta\sigma_k}{2K_{css}}\right)^{\frac{1}{n_{css}}}\right) = \Delta\sigma_k^e\left(\frac{\left(1-\nu^2\right)}{E_{ya,k}}\Delta\sigma_k^e\right)$$

Rearrange and eliminate modulus on each side

$$\frac{\Delta\sigma_k^2}{E_{ya,k}} = \frac{\left(1-\nu^2\right)}{E_{ya,k}}\Delta\sigma_k^{e\,2}$$

Now, "plastic" stress which lies along the cyclic-stress strain curve is given by:

$$\Delta\sigma_k = \left(\left(1-\nu^2\right)\Delta\sigma_k^{e\,2}\right)^{\frac{1}{2}}$$

Rearranged, the plastic stress is given as:

$$\Delta\sigma_k = \left(1-\nu^2\right)^{\frac{1}{2}}\Delta\sigma_k^e$$

Now, subsititue the plastic stress into EQ 5.54 to calculate the total strain. Again, the plastic term is ignored since it is very small in comparision to the elastic term.

$$\Delta\varepsilon_k = \frac{\Delta\sigma_k}{E_{ya,k}} + 2\left(\frac{\Delta\sigma_k}{2K_{css}}\right)^{\frac{1}{n_{css}}} = \frac{\left(1-\nu^2\right)^{\frac{1}{2}}\Delta\sigma_k^e}{E_{ya,k}}$$

Next, insert the total strain into EQ 5.55 to calculate the pseudo elastic structural stress.

$$\Delta\sigma_k = \left(\frac{E_{ya,k}}{1-\nu^2}\right)\Delta\varepsilon_k = \left(\frac{E_{ya,k}}{1-\nu^2}\right)\frac{\left(1-\nu^2\right)^{\frac{1}{2}}\Delta\sigma_k^e}{E_{ya,k}}$$

Finally, after some simplification, we arrive at the pseudo elastic structural stress.
Even though the stress is entirely elastic, the pseudo elastic structural stress is not equal to the elastic structural stress which we began with:

$$\Delta\sigma_k = \frac{\left(1-\nu^2\right)^{\frac{1}{2}}\Delta\sigma_k^e}{1-\nu^2} \neq \Delta\sigma_k^e$$

The predicted stress will always be 105% of the expected elastic stress.

$$\frac{\Delta\sigma_k}{\Delta\sigma_k^e} = \frac{\left(1-\nu^2\right)^{\frac{1}{2}}}{1-\nu^2}$$

Case #2 - Substitute Stresses into Eq 5.53

$$\Delta\sigma_k \cdot \Delta\varepsilon_k = \Delta\sigma_k^e \cdot \Delta\varepsilon_k^e$$

Rearranged Equation (5.54)

$$\Delta\varepsilon_k = \frac{\Delta\sigma_k}{E_{ya,k}} + 2\left(\frac{\Delta\sigma_k}{2K_{css}}\right)^{\frac{1}{n_{css}}}$$

$$\Delta\sigma_k = \Delta\varepsilon_k \cdot E_{ya,k}$$

Rearranged Equation (5.52)

$$\Delta\varepsilon_k^e = \frac{\left(1-\nu^2\right)}{E_{ya,k}}\Delta\sigma_k^e$$

$$\Delta\sigma_k^e = \frac{\Delta\varepsilon_k^e\, E_{ya,k}}{\left(1-\nu^2\right)}$$

Substitute 5.52 and 5.54 into Eq. 5.53

$$\Delta\varepsilon_k \cdot E_{ya,k} \cdot \Delta\varepsilon_k = \frac{\Delta\varepsilon_k^e\, E_{ya,k}}{\left(1-\nu^2\right)} \cdot \Delta\varepsilon_k^e$$

Rearrange and eliminate modulus on each side

$$E_{ya,k} \cdot \Delta\varepsilon_k^2 = \frac{\Delta\varepsilon_k^{e^2}\, E_{ya,k}}{\left(1-\nu^2\right)}$$

Rearranged to solve for the plastic strain

$$\Delta\varepsilon_k = \left(\frac{\Delta\varepsilon_k^{e^2}}{\left(1-\nu^2\right)}\right)^{\frac{1}{2}}$$

The pseudo elastic structural stress is solved by inserting the plastic strain into Eq 5.55

$$\Delta\sigma_k = \left(\frac{E_{ya,k}}{1-\nu^2}\right)\Delta\varepsilon_k$$

Substitute plastic strain into Eq 5.55

$$\Delta\sigma_k = \left(\frac{E_{ya,k}}{1-\nu^2}\right)\left(\frac{\Delta\varepsilon_k^{e^2}}{\left(1-\nu^2\right)}\right)^{\frac{1}{2}}$$

$$\Delta\sigma_k = \frac{E_{ya,k}\,\Delta\varepsilon_k^e}{\left(1-\nu^2\right)^2}$$

Pseudo elastic structural stress is not equal to the elastic structrual stress, even though there is no plasticity.

$$\Delta\sigma_k = \frac{E_{ya,k}\,\Delta\varepsilon_k^e}{\left(1-\nu^2\right)^2} \neq \frac{\Delta\varepsilon_k^e\, E_{ya,k}}{\left(1-\nu^2\right)}$$

The predicted stress will always be (1 / 0.91) = 109.8% greater than the elastic stress.