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FATIGUE ANALYSIS METHODS: THEIR PERFORMANCE EVALUATION FOR A CLASS OF PRESSURE VESSELS WITH WELDED JOINTS

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ABSTRACT

This paper provides a basis for evaluating the performance of a fatigue analysis method for a selected class of welded pressure vessels. After the allowable number of cycles that the method permits for a member of the class is calculated, the question is addressed whether that number of cycles can be regarded as conservative or unconservative. To answer that question, a performance evaluation is proposed that requires a mean life estimate of a representative sample of the selected vessel class from tests, and the predicted mean life and the permissible number of cycles from the method. The performance is based on the ratio of two factors: (1) Achieved Factor – test mean life cycles divided by the permissible number of cycles, and (2) Assigned Factor – predicted mean life cycles divided by the permissible number of cycles. The ratio between the former and the latter defines a Performance Index, which indicates whether, and to what extent, the permissible number of cycles can be regarded conservative or unconservative. For an illustration of the performance evaluation, it is applied to three methods for a class of pressure-cycled carbon steel vessels with welded-on flat plates.

1 INTRODUCTION

Performance evaluation of fatigue analysis methods will be performed for a class of carbon steel pressure vessels that include portions consisting of a cylindrical shell welded to a flat plate. For example, the bottom portion of a vessel in this class could look like that shown in Figure 1. The joint is a full penetration weld on both sides, which is left in as-welded condition. Members of this class can have different dimensions and can be cycled with different internal pressures. The whole class is given the name **Class FB,** which is an acronym for ***"flat-bottom"*** vessels. Class FB is defined for the purposes of this paper and has no connection with other weld class names.

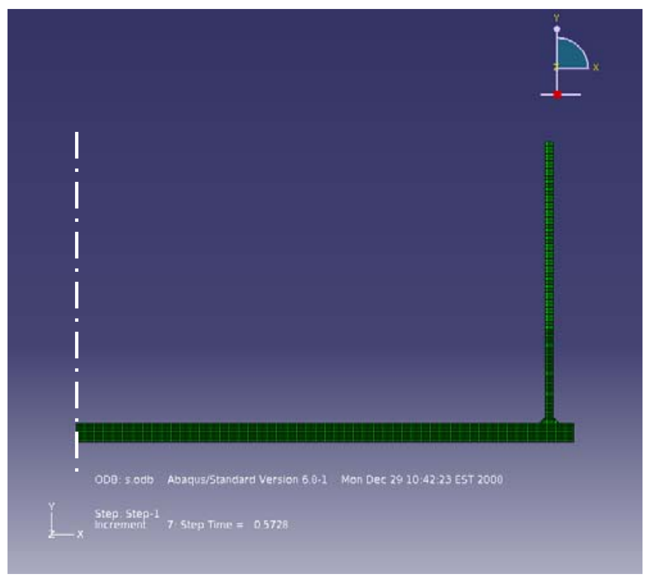


Figure 1: Geometry of vessel under consideration

The question is addressed how to tell whether the number of cycles permitted by a fatigue analysis method for a specified welded vessel from Class FB is conservative or unconservative. The motivation for writing this paper came from the 2005PVP paper by Kalnins, Bergsten, and Rana[1] in which a welded joint was considered between a cylindrical shell and a flat plate, like that shown in Figure 1. When the maximum allowable number of cycles that is permissible for the operation of the vessel cycled at a specified pressure was calculated by three fatigue analysis methods, the numbers of cycles ranged from 4,800 to 75,800.

In the 2005PVP paper[1], no critical evaluation of these cycles was made. No basis could be found for judging which of the methods was giving a "conservative" or "unconservative" result. What is added in the present paper is the idea that such judgment cannot be made by comparing the permissible number of cycles alone and that two more pieces of information are needed.

One is the number of mean life cycles observed in tests, and the other is the number of mean life cycles that is predicted by the method. That idea will be developed in the paper.

It leads to a Performance Index that accompanies the permissible number of cycles given by the method. Index values greater than 1.0 indicate an actual life in excess of the predicted mean life, which is a conservative result. Values less than 1.0 indicate an actual life less than the predicted mean life, which is an unconservative result.

This Index may be of help in identifying specific classes of welded vessels or other components that are not covered adequately by the database that is used by the method.

To illustrate the performance evaluation, it is applied to three methods: the 2004 European Standard EN 13445[2], the Battelle JIP Master Curve method given by Dong and Hong[3], and the method of 2007 Section VIII, Division 2, paragraph 5.5.5, of the ASME B&PV Code[4].

In addition to the main objective of the paper, which is to present the performance evaluation concept, another purpose of the paper is to address the following questions:

1. Are the vessels of Class FB properly placed within the Weld Class FAT 71 of EN 13445[2]?
2. Are the vessels of Class FB adequately represented by the weld classes covered by the Master Curve used in the Battelle JIP method[3]?

Based on the failure data that were available to represent Class FB vessels, the results of the performance evaluation indicate that the answer to the first question is yes and to the second no.

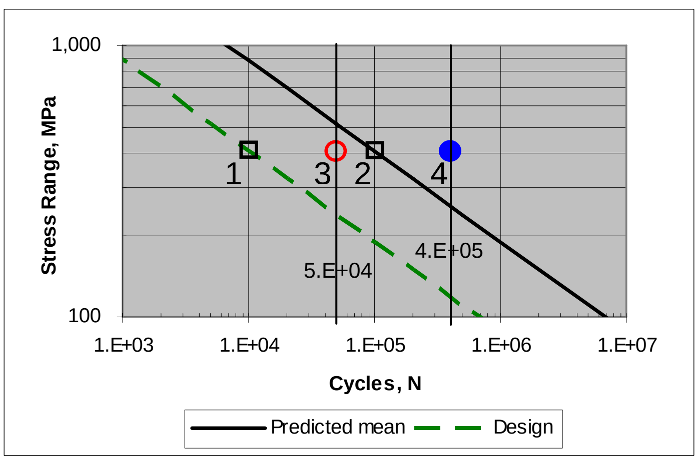


Figure 2: Predicted mean and fatigue design S-N lines of hypothetical method being evaluated

2 PERFORMANCE BASIS

The Assigned and Achieved Factors define a Performance Index, which is the ratio of the Achieved Factor to the Assigned Factor.

2.1 ASSIGNED AND ACHIEVED FACTORS

The basis for the performance evaluation will be explained for a hypothetical method and a hypothetical vessel. The method uses parallel straight lines to define the predicted mean life and the fatigue design S-N line. Such lines for the method are shown in Figure 2.

The two lines of Figure 2 define an Assigned Factor on cycles that is applied to the mean line to get the fatigue design line. This factor is obtained by dividing the number of cycles on the predicted mean line by the corresponding permissible number of cycles at the same stress level. These cycle numbers are identified as Points 2 and 1 and marked by squares in Figure 2. The Assigned Factor is defined by equation (1).

$$AssignedFactor = \frac{N_{Predicted-mean}}{N_{Permissible}} = \frac{N_2}{N_1} = 10 \quad (1)$$

For the performance evaluation, this factor is compared with the corresponding factor that is actually achieved in test. It is defined by equation (2).

$$AchievedFactor = \frac{N_{Test-mean}}{N_{Permissible}} \quad (2)$$

Assume that the test mean life cycles of the vessel have been determined and the cycled stress range that is used by the method calculated. In Figure 2, that stress range is assumed to be 400 MPa.

The performance of the method depends on the location of the test mean cycles with respect to the predicted mean cycles. Two possible locations are shown in Figure 2. One is such that the test mean cycles fall to the right of the predicted mean line, as indicated by Point 4 and marked by a blue, full circle. The other is such that they fall to the left of the predicted mean line, as indicated by Point 3 and marked by a red, empty circle.

For the hypothetical example, the former and latter locations lead to the factors defined by equations (3) and (4).

$$AchievedFactor = \frac{N_4}{N_1} = 40 \quad (3)$$

$$AchievedFactor = \frac{N_3}{N_1} = 5 \quad (4)$$

The factors of equations (1), (3), and (4) lead to the basis of the performance evaluation of the method with respect to the hypothetical vessel, which is considered next.

2.2 PERFORMANCE INDEX

The basis for judging the method for a specific vessel is the Performance Index, which is defined by equation (5).

$$PerformanceIndex = \frac{AchievedFactor}{AssignedFactor} \quad (5)$$

For the hypothetical method and vessel used in Figure 2, the summary of the evaluation is given in Table 1.

Table 1: Performance Index

Circle	Assigned Factor	Achieved Factor	Performance Index
Point 4, full blue	10	40	4.0
Point 3, empty red	10	5	0.5

As seen from Figure 2, the hypothetical method would permit cyclic operation of the vessel for 10,000 cycles at the stress range of 400 MPa. If the test mean life indicated a Performance Index of 4.0 (blue circle), that would be a conservative result. If the Performance Index were 0.5 (red circle), that would be an unconservative result.

Another interpretation of the Performance Index is possible. For those methods that set the fatigue design S-N lines by statistics, the probability of failure for a large number of vessels is part of the method. For example, if it is set at mean minus three times standard deviation and the Index is 1.0, the probability is that three vessels out of 2,000 would fail. If the Index is greater than 1.0, fewer than three will fail, and if it is less than 1.0, more than three will fail.

3 FATIGUE DATA FOR CLASS FB VESSELS

3.1 TEST MEAN LIFE LINES

The fatigue data representing Class FB vessels will be taken from the results of the fatigue test program conducted by the Paulin Research Group (PRG) of Houston, Texas, U.S.A. The results were reported in two ASME-PVP papers by Hinnant [5,6].

The tests included the total of eleven unique fatigue specimens of the general type as that shown in Figure 1, but with varied dimensions and pressure. Ten were made of carbon steel and one of stainless steel. One had the weld on one side only. The total of 43 unique failure points was obtained.

Nine of the carbon steel vessels fit the description of Class FB and will be selected for its representation.

Before the data of the 36 fatigue failure points could be subjected to linear regression to establish the test mean line, two things had to be considered. One is that 16 of the failure points came from vessels tested in Houston city tap water and 20 in air. In order to make comparisons with the predicted number of mean life cycles free of adverse environmental effects, the data points tested in water had to be adjusted to bring them up to the corresponding level of life cycles if tested in air. This was achieved by multiplying the water-test cycles by an environmental factor, defined by F_{en}.

Hinnant[6] summarized the adverse environmental effects of Houston water on fatigue failure of the tested vessels and estimated F_{en} values ranging from 1.135 to 1.35, with a note that the higher value may be conservative.

For the performance evaluation of the present paper, the "New Model (2006)", which is given in Table 1 of the PVP2006 paper by Higuchi[7], will be used to calculate the F_{en}. The input that was used in Higuchi's formula is in Table 2.

Table 2: Input for environmental effect

Dissolved Oxygen > 0.5 ppm
Sulfur content in steel= 0.035%
Strain rate/sec = 0.9%
Strain amplitude= 0.225%
Temperature = 25 deg. C

Based on this input, a factor of $F_{en} = 1.16$ was obtained. Its value fits within the range of Hinnant's estimates. It will be used to multiply the number of life cycles of the 16 of the failure points that came from vessels tested in Houston city tap water.

The second thing to consider is that the type of the stress and the slope of the mean line that are used in the linear regression to get the test mean line should match the type of the stress and the slope of the predicted mean life S-N line of the method. For example, after multiplying the water data by 1.16, assuming the structural stress as the stress type, and an S-N slope of 3, the 36 data points and the mean line are shown in Figure 3.

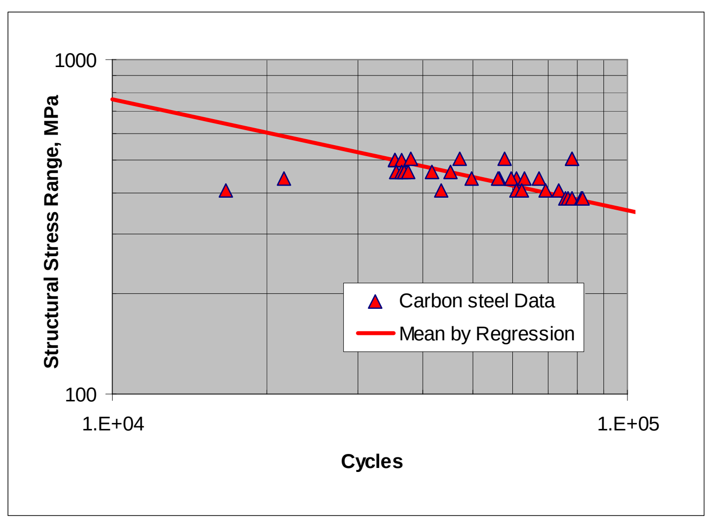


Figure 3: Data and test mean line if plotted at structural stress range

Using linear regression of the 36 failure points at the cycled structural stress gives the test mean line of equation (6), which is drawn in Figure 3. The structural (membrane plus bending) stress range ($\Delta\sigma_s$) is in MPa.

$$N = 16{,}375^3 \times \Delta\sigma_s^{-3} \qquad (6)$$

While the cycles will be the same for all methods, the ordinates of the failure points will be different for methods that use different type of stress to plot the data. This means that the linear regression will have to be repeated for each of the methods that is evaluated and its equation of the test mean line established.

3.2 PERMISSIBLE CYCLES FOR ONE VESSEL FROM CLASS FB

It is also of interest to compare the maximum allowable number of cycles that is permitted by a method for one vessel selected from Class FB. The one selected is referred to as Joint #1 in Hinnant's paper[5]. Its material is SA-516 Grade 70 carbon steel and its dimensions are shown in Figure 4 and Table 3.

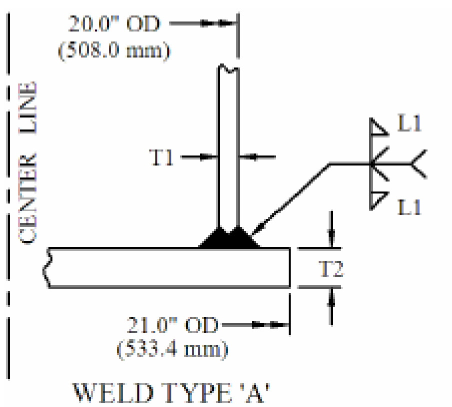


Figure 4: Weld type A joints of PRG test program

Table 3: Weld joint dimensions in mm

Material	Joint	T1	T2	L1
Carbon steel	#1	4.51	9.73	3.18

This vessel was cycled to failure between the pressure of zero and 0.414 MPa (60 psi). The pressure medium was Houston city tap water.

Having decided to use Joint#1 as a sample, a finite element model was built and the Abaqus[8] computer program was used to get the stresses on the crack plane (Figure 5) that are listed in Table 4. The stresses are of the type used by the methods considered for performance evaluation in the following sections. For EN 13445, the maximum principal linearized stress range is used, and, for the methods that use the Master Curve[3], the stress type is a function of the structural stress, which is defined as the membrane plus bending stress of Table 4 on the crack plane shown in Figure 5.

Table 4: Calculated stresses on crack plane, in MPa

Joint	Membrane Stress Range	Bending Stress Range	Principal Linearized Stress Range
#1	11.34	490.00	508

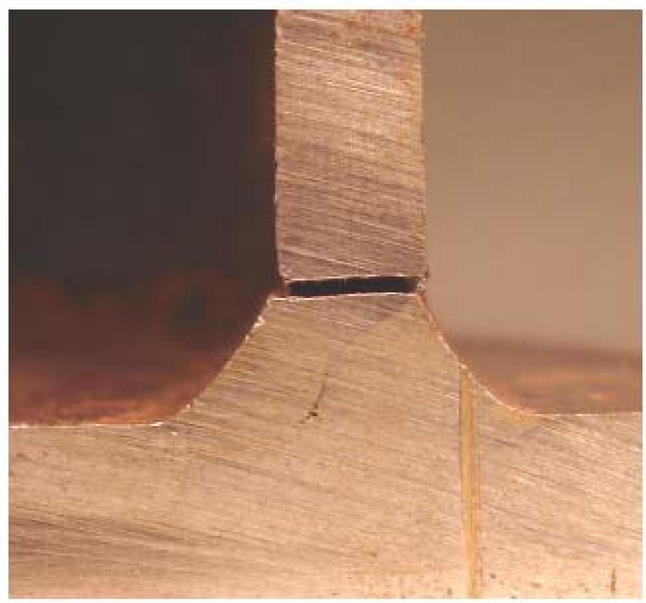


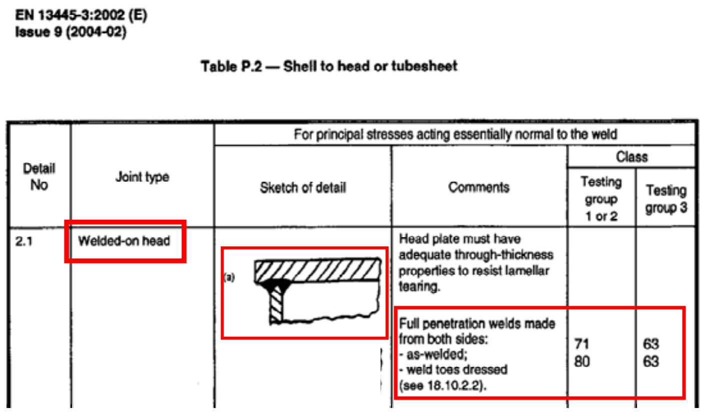
Figure 5: Location of fatigue failure (photo provided by Chris Hinnant)

The performance evaluation will now be applied to three fatigue analysis methods with respect to Class FB Vessels.

4 EUROPEAN STANDARD EN 13345 METHOD

4.1 WELD CLASS FAT 71

For this method, Class FB vessels are placed in EN 13445 Weld Class of 71 (FAT 71) as shown in Figure 6.



EN 13445-3:2002 (E)
Issue 9 (2004-02)

Table P.2 — Shell to head or tubesheet

Detail No	Joint type	For principal stresses acting essentially normal to the weld		Class	
		Sketch of detail	Comments	Testing group 1 or 2	Testing group 3
2.1	Welded-on head	(a)	Head plate must have adequate through-thickness properties to resist lamellar tearing.		
			Full penetration welds made from both sides: - as-welded; - weld toes dressed (see 18.10.2.2).	71 80	63 63

Figure 6: Weld Class FAT 71

Figure 6 is copied from Clause 18 of EN 13445-3:2002, Annex P, Issue 9 (2004-02): *Classification of weld details to be assessed using principal stresses.* Testing groups 1 or 2 are comparable to the NDE applied to the joints of Figure 4.

4.2 PREDICTED MEAN LIFE S-N LINE FOR FAT 71

The predicted mean life S-N line for FAT 71 weld joints is not given in EN 13445-3:2002[2]. Its equation was derived from Figure 7, which was taken from the final report of a TWI project led by S. J. Maddox[9]. The two dashed lines denoted by $Mean \pm 3SD$ in Figure 7 made that possible. The dot-dash predicted mean line was drawn on top of Maddox's figure.

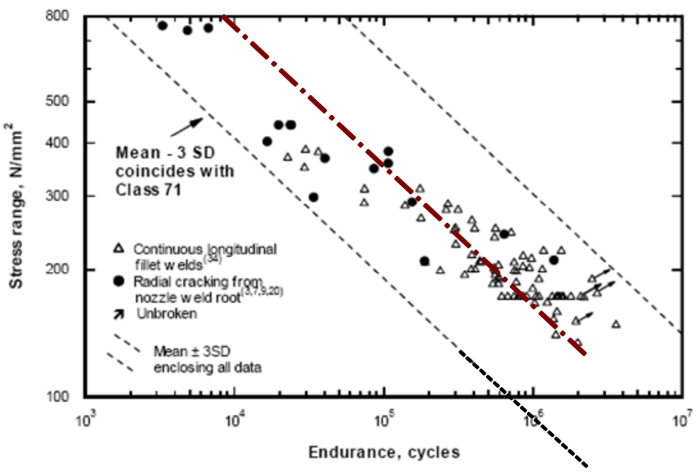


Figure 7: Predicted mean and fatigue design line of class FAT 71

The information that is required from the EN 13445 method includes the fatigue design S-N line for FAT 71. This line is such that it passes through the point defined by the stress range of 71 MPa at two million cycles and has a slope of 3 in the base-10 log space. That line is then given by equation (7), where ΔS denotes the range of the stress type used to plot the data of FAT 71, and the constant is obtained from Table 18-7 of EN 13445 and listed in equation (8).

$$N_{Permissible} = \left(\frac{C_{mean-3SD}}{\Delta S} \right)^3 \qquad (7)$$

$$C_{mean-3SD} = (2 \times 10^6)^{\frac{1}{3}} \times 71 = 8,945.3 MPa \qquad (8)$$

The reason for choosing Figure 7 is that it contains also the dashed line in Figure 7 that is marked "Mean+3SD". Then the predicted mean life S-N line for FAT 71 is obtained as follows. A point was selected on the dashed "Mean-3 SD" line at 10,000 cycles and the corresponding stress was calculated from equation (9), which was derived from equation (7).

$$\Delta S = C_{mean-3SD} \times 10,000^{-\frac{1}{3}} = 415.2 MPa \qquad (9)$$

Then the cycles on the "Mean+3 SD" line were scaled from Figure 7 at the stress of 415.2 MPa to be 400,000. With that information, the standard deviation was calculated from equation (10).

$$SD = \frac{1}{6}[\log(400,000) - \log(10,000)] = 0.267 \qquad (10)$$

Finally, the mean line is defined by equation (11) and the relationship between the mean and the Mean-3SD lines is given by equation (12). Using equations (8) and (10), the constant C_{mean} of the mean line is given by equation (12).

$$N_{Predicted-mean} = \left(\frac{C_{mean}}{\Delta S} \right)^3 \qquad (11)$$

$$\log(N_{Predicted-mean}) - \log(N_{Permissible}) = 3SD$$

$$3[\log(C_{mean}) - \log(C_{mean-3SD})] = 3SD$$

$$C_{mean} = 10^{(C_{mean-3SD} + SD)} = 16,542.7 MPa \qquad (12)$$

Thus, the equation for the predicted mean life for vessels of FAT 71 is given by equation (13), where ΔS is in MPa.

$$N_{Predicted-mean} = \left(\frac{16,542.7}{\Delta S} \right)^3 \qquad (13)$$

This completes the construction of the predicted mean life line of the weld details included in the Weld Class of FAT 71.

4.3 PERFORMANCE EVALUATION

For fatigue assessment of Class FB vessels, the maximum principal linearized stress range ($\Delta S_{max\text{-}PS}$) is a permitted option in Annex P of EN 13445. This option will be used for the performance evaluation.

It is not clear exactly what stress type was used to plot the failure points of the test data accumulated for FAT 71 welds in Figure 7. For Class FB vessels, the bending stress is dominant at the weld toe and there is little difference between the hot-spot, structural, and the $\Delta S_{max\text{-}PS}$ stresses. To make the Annex P option for the test data consistent with the FAT 71 data base, the ΔS that was used in equations (7) to (13) will be assumed to be $\Delta S_{max\text{-}PS}$.

For the performance evaluation, the predicted mean life and fatigue design S-N lines are given by equations (13) and (7), respectively, and are drawn in Figure 8. The test mean life line is obtained by linear regression for a log-log slope of 3 of the 36 failure points of the PRG data base, evaluated at $\Delta S_{max\text{-}PS}$. It is given by equation (14). It could not be plotted on Figure 8 because it would overlay the predicted mean line.

$$N_{Test-mean} = \left(\frac{C_{Test-mean}}{\Delta S_{max\text{-}PS}} \right)^3 \qquad (14)$$

$$C_{Test-mean} = 16,672.8 MPa \qquad (15)$$

The Assigned and Achieved Factors, defined by equations (1) and (2), can also be calculated for any stress range from equations (12). (8), and (15). The results are in Table 5,

Table 5: Evaluation of EN 13445 for Class FB

Assigned Factor	Achieved Factor	Performance Index
6.32	6.47	1.02

The numbers in Table 5 indicate that Class FB vessels are properly placed within the Weld Class FAT 71 of EN 13445. A factor of 6.32 is desired and 6.47 is achieved. The Performance Index of 1.02 is a measure of how well Class FB vessels fit in FAT 71.

The specific cycle numbers for Joint #1 are calculated using the maximum principal linearized stress range of 508 MPa from Table 4. They are listed in Table 6. The test mean cycles for Joint #1 are also indicated in Figure 8.

Table 6: Cycles for Joint #1 by EN 13445

Joint	Predicted mean cycles	Permissible cycles	Test mean cycles
#1	34,524	5,459	35,345

This completes the performance evaluation of the EN 13445 method for Class FB vessels.

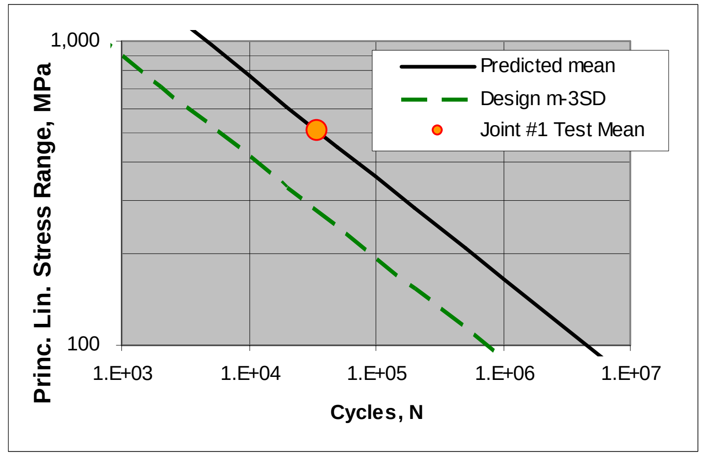


Figure 8: Test mean cycles overlaid on FAT 71 S-N lines

5 BATTELLE JIP MASTER CURVE METHOD

This method is explained in the paper by Dong and Hong[3] and other publications. The predicted mean life line, which is the Master Curve, and the fatigue design line are written in the form of equation (16). The numbers for C and h are in Table 7.

$$N = \left(\frac{C}{\Delta S_{eq}} \right)^{\frac{1}{h}} \qquad (16)$$

Table 7: Constants for predicted mean and design lines

Line	C, MPa	Exponent h
Mean	19,930.2	0.3195
Mean-3SD	11,577.9	0.3195

The equations that are needed for the performance evaluation are listed below. Some of the constants are not the same as those in the 2005 PVP paper by Kalnins *et al*[1] but represent the latest updates that are known to the author.

$$\Delta S_{eq} = \frac{\Delta \sigma_s}{t^{\frac{2-m}{2m}} I(r)^{\frac{1}{m}}} \qquad (17)$$

$m = 3.6$

$\Delta \sigma_s$ = structural stress range

$\Delta \sigma_s = \Delta \sigma_M + \Delta \sigma_B$

$\Delta \sigma_M$ = membrane stress range normal to crack plane

$\Delta \sigma_B$ = bending stress range normal to crack plane

$$t = \frac{thickness}{t_{REF}} \qquad t_{REF} = 1 \cdot mm \qquad (18)$$

$$I(r)^{\frac{1}{m}} = -0.0732 \cdot r^6 + 0.2132 \cdot r^5 - 0.2063 \cdot r^4 \quad (19)$$
$$+0.091 \cdot r^3 + 0.0193 \cdot r^2 - 0.014 \cdot r + 1.1029$$
$$r = \frac{\Delta\sigma_B}{\Delta\sigma_M + \Delta\sigma_B} \quad (20)$$

To be consistent with the Battelle JIP data base, the stress type for the PRG data base of the selected nine vessels and 36 failure points is also ΔS_{eq}. The equation for the test mean line is calculated by linear regression for a log-log slope of 3.130 and is given by equation (21).

$$N_{Test-mean} = \left(\frac{C_{Test-mean}}{\Delta S_{eq}}\right)^{3.130} \quad (21)$$

$$C_{Test-mean} = 16{,}971.1 MPa \quad (22)$$

The predicted mean line (Master Curve), fatigue design line, and test mean line are drawn in Figure 9.

The Assigned and Achieved Factors are calculated from the C constants in Table 7 and equation (22). Together with the Performance Index, they are listed in Table 8.

Table 8: Evaluation of selected weld Class FB

Assigned Factor	Achieved Factor	Performance Index
5.47	3.31	0.60

The numbers in Table 8 indicate that Class FB vessels are not properly placed within the weld classes covered by the Master Curve. A factor of 5.47 is desired and only 3.31 is achieved. The Performance Index of 0.60 is a measure of how far Class FB is from the Master Curve.

Specific cycle numbers are also calculated for Joint #1 by starting with the structural stress range of 501.34 MPa from Table 4, using the dimensions of Joint #1 listed in Table 3, and then equations (17) to (20). The Equivalent Structural Stress range is 618.69 MPa. The numbers of cycles are in Table 9.

Table 9: Cycles for Joint #1 by Battelle JIP

Joint	Predicted mean cycles	Permissible cycles	Test mean cycles
#1	52,479	9,587	31,733

This completes the performance evaluation of the Battelle JIP method for Class FB vessels.

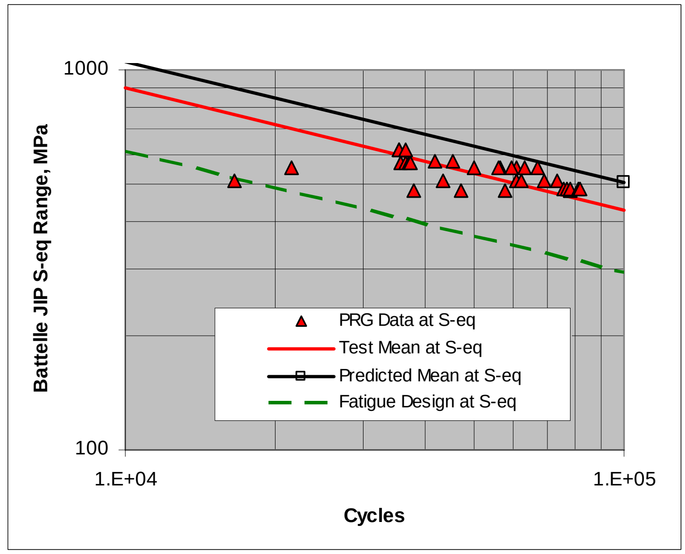


Figure 9: PRG test data and mean line, predicted mean, and design lines, all at ΔS_{eq}, as per Battelle JIP method

6 2007 ASME SECTION VIII-DIVISION 2 METHOD

The method in 2007 Section VIII-Div. 2[4] differs from that of the Battelle JIP method in a significant way. The Equivalent Structural Stress range ΔS_{eq}, which is used in the Battelle JIP method and defined by equation (17), has been replaced by the Equivalent Structural Stress Range Parameter that is denoted by ΔS_{ess} and defined by equation (23).

According to 2007 Div. 2, paragraph 5.5.5, ΔS_{ess} is used for fatigue assessment of welded vessels and components.

$$\Delta S_{ess} = \frac{\Delta\sigma}{t_{ess}^{\left(\frac{2-m_{ss}}{2m_{ss}}\right)} I^{\frac{1}{m_{ss}}} f_M} \quad (23)$$

where

$$m_{ss} = 3.6$$
$$\Delta\sigma = K_{Nonlinear} \Delta\sigma_s$$
$\Delta\sigma_s$ = structural stress range in MPa
$K_{Nonlinear}$ = nonlinearity factor (details in Div 2[4])
$t_{ess} = 16mm$ for vessels of PRG data base (24)
$f_M = 1$ because $R = \frac{\sigma_{min}}{\sigma_{max}} = 0$ for the PRG vessels
$\sigma_{min}, \sigma_{max}$ = min. and max. stresses during cycle
$$R_b = \frac{\Delta\sigma_B}{\Delta\sigma_M + \Delta\sigma_B}$$

$$I^{\frac{1}{m_{ss}}} = \frac{1.23 - 0.364R_b - 0.17R_b^2}{1.007 - 0.306R_b - 0.178R_b^2} \quad (25)$$

What is needed for performance evaluation are the equations for test mean, predicted mean, and fatigue design lines. The test mean line is obtained by linear regression for a log-log slope of 3.130 of the 36 failure points of the PRG data base, evaluated, as required by the 2007Div. 2[4] rules, at ΔS_{ess}. It is given by equation (26).

According to 2007Div. 2[4], paragraph 5.5.5.2.f), the predicted mean and permissible cycles are read from the fatigue curves provided in Annex 3F, Table 3.F.11M, which are given by equations (27) and (28), respectively.

$$N_{Test-mean} = (22,941.9)^{3.130} \times \Delta S_{ess}^{-3.130} \quad (26)$$

$$N_{Predicted-mean} = (19,930.2)^{3.130} \times \Delta S_{eq}^{-3.130} \quad (27)$$

$$N_{Permissible} = (11,577.9)^{3.130} \times \Delta S_{eq}^{-3.130} \quad (28)$$

A rigorous performance evaluation of the Div. 2 method cannot be performed by using these three equations, because the test data and its mean line are derived from the PRG data base evaluated at ΔS_{ess}, while the fatigue curves provided in Annex 3F, Table 3.F.11M, are derived from the Battelle data base evaluated at ΔS_{eq}, which is defined by equation (17).

The problem is that predicted mean and permissible cycles can be read only from an S-N line by entering a stress that is of the same type as that used to derive the S-N lines. These cycles, which are needed for performance evaluation, cannot be read by entering an ΔS_{ess} on S-N lines derived using ΔS_{eq}. The stresses must be of the same type. In order to perform a rigorous performance evaluation of the Div. 2 method, the whole Battelle data base would have to be re-evaluated at ΔS_{ess} and new mean and design lines established.

However, a less than rigorous performance evaluation can be performed by ignoring the stress mismatch and assuming the predicted mean and design lines of equations (27) and (28) to be *ad hoc* lines that are to be used as a Section VIII-Division 2 code requirement.

Under this caveat, the S-N lines needed for performance evaluation are derived from equations (26)-(28), in which the ΔS_{eq} is replaced by ΔS_{ess}, which makes it possible to draw them all on one Figure 10. The ordinate is marked "Div. 2 S-ess Stress Range", meaning ΔS_{ess}.

The Assigned and Achieved Factors are then calculated from the constants in equations (26)-(28). Together with the Performance Index, they are listed in Table 10.

Table 10: Evaluation of Div. 2 for weld Class FB

Assigned Factor	Achieved Factor	Performance Index
5.47	8.50	1.55

The cycle numbers are calculated for Joint #1 by starting with the structural stress range of 501.34 MPa from Table 4, using the dimensions of Joint #1 listed in Table 3, and then using equations (23) to (25). The resulting ΔS_{ess} stress range is 812 MPa. The cycles are listed in Table 11.

Table 11: Cycles for Joint #1 by Div. 2 method

Joint	Predicted mean cycles	Permissible cycles	Test mean cycles
#1	22,373	4,087	34,755

As seen from Figure 10, the test mean line is shifted up in stress from the location shown in Figure 9 for the Battelle JIP method. By Div. 2 rule, the predicted mean line (Master Curve) is kept fixed at the same location as in the Battelle JIP method.

For these reasons, it is expected that the Div. 2 method would be more conservative than the Battelle JIP method. With the Performance Index rising to from 0.60 to 1.55, the numbers in Table 10 and Table 11 confirm that expectation for Class FB vessels.

This completes the performance evaluation of the Section VIII-Div. 2 method for Class FB vessels.

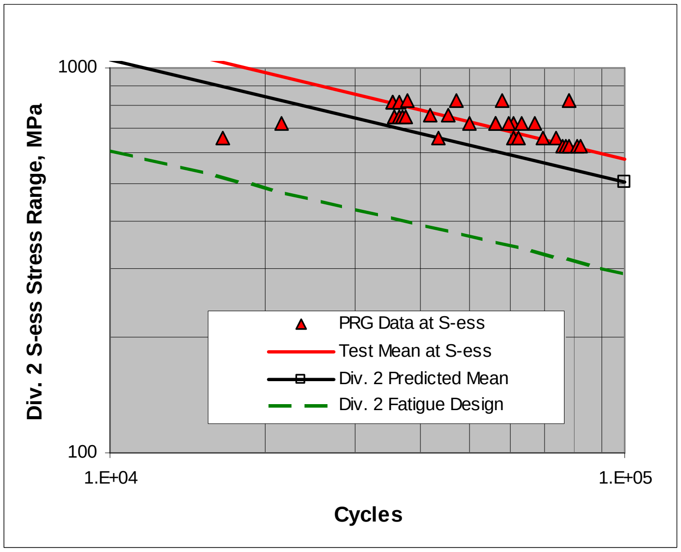


Figure 10: PRG test data and mean line at ΔS_{ess} and 2007 Div. 2 predicted mean and design S-N lines

7 CONCLUSIONS

1. The Performance Index provides a threshold between conservative and unconservative permissible cycles for a given fatigue analysis method. An Index greater than 1.0 means conservative and less than 1.0 unconservative.

2. The permissible number of cycles for Joint #1 and the Performance Index for three methods with respect to Class FB vessels is given in Table 12. According to the concept of performance evaluation of the present paper, the 5,459 cycles permitted by EN 13445 is the best answer of the three methods.

Table 12: Summary

Method	Permissible cycles for Joint #1	Performance Index for method
EN 13445	5,459	1.02
Battelle JIP	9,587	0.60
2007 Div. 2	4,087	1.55

3. The Index of 1.02 for the EN 13445 method supports the placement of Class FB vessels in EN 13445 Weld Class of 71. The permissible numbers of cycles for Class FB are very close to being neither conservative nor unconservative.

4. The Index of 0.60 for the Battelle JIP method indicates that Class FB vessels are not adequately represented by the weld classes that are covered by the Master Curve.

5. The much higher Index of 1.55 for the Div. 2 method arises from requiring the use a stress type for the PRG data base that is different from that which is used for the Master Curve. For wall thicknesses of less than 16 mm (0.606 in.), such conservative results are expected, more so for much smaller thicknesses.

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