Critical Review and Improved Fatigue Life Prediction Models for Unconstrained Single Peak Plain Dents Based on EPRG Approach

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Abstract

In API RP 1183, the EPRG 2000/API579 Level 2 model is adopted as an alternative approach to PRCI shape-parameter method for Level 2 fatigue severity assessment of unconstrained single peak plain dents in pipelines. This model along with its earlier version, EPRG 1995, has been commonly used for dent integrity assessment in North American and worldwide because it is recommended by the highly recognized Pipeline Defect Assessment Manual (PDAM). However, Pipeline industry practice in North America found that the EPRG equations provide conservative, in many cases, very conservative predictions that may have resulted in unnecessary excavations and repairs. Therefore, the objective of this paper is to improve the model accuracy and less conservatism. A critical review of EPRG/PDAM fatigue life prediction models (1995 model and its 2000 update) and other models including PRCI shape-parameter fatigue severity model (Level 2) and FEA/BS7608 fatigue life prediction (Level 3) are performed and presented first, which provides a basis for improvement of EPRG equations from both safety and cost-effective perspectives. The improved and refined model is then developed with PRCI MD 4-2 full-scale fatigue testing data and validated using PRCI MD 4-11, MD 4-14 and MD 4-15 full scale fatigue test results. Finally, a comparison among the refined model, EPRG 2000/API 579 Level 2 model, and API RP 1183 Level 2 and Level 3 models is made, which provides a framework to further carry out the study of dent-interacting with welds, gouge, cracks, and corrosion.

INTRODUCTION

Pipelines can be mechanically damaged by external force from third-party intrusion, contact with rocks in the backfill, or by settlement onto rocks [1-3]. A dent is defined as a local inward depression in the pipe surface caused by an external force that produces pipe wall plastic deformation and a disturbance in the curvature of the pipe from its original shape. Dents can be commonly characterized by the following six types [2, 3]:

1. Plain dent, i.e., dent without geometrically coincident features, e.g., corrosion, gouge, weld.
2. Dent with coincident features, e.g., corrosion, gouge, weld.
3. Single peak dents
4. Multiple peak dents.
5. Constrained (Restrained), and
6. Unconstrained (Unrestrained) dent.

Dents have caused frequent pipeline failures [4-7]. However, failures from plain dents alone are rare [1, 2]. Plain dents do not have direct or immediate consequences. The Department of Transportation (DOT) [7, 8] and the Fuel Manufacturers Association in Brussels Belgium (CONCAWE) [7, 9] reported this type of fatigue failure about 8.3% and 6% of the reported failures, respectively. Because of its importance, extensive efforts have been made worldwide to identify factors associated with time-

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delayed fatigue failure using both experimental and analytical approaches since the late 1950s [9-11]. The capability of a damaged, dented pipeline to withstand pressure cycles has been the object of numerous studies worldwide [12-34], and numerous methods for performing dent fatigue assessments are now available for pipeline operators [3-8, 13-16] to use. For example, EPRG proposed two methods: one published in 1995 [34] and the other one in 2000 [15]. The PDAM called them EPRG 1995 and EPRG 2000, respectively. Moreover, EPRG 2000 has been adopted and incorporated into API 579 [35]. API RP 1183 refers to it as the EPPRG/579 approach and recommends it as an alternative for Level 2 plain dent fatigue life assessment. For clarity and originality, we call it EPRG 2000 instead of the EPRG/API 579 approach in this study throughout the paper.

EPRG 2000, along with its earlier version, EPRG 1995, has been commonly used for plain dent fatigue life assessment in North America and worldwide because it is recommended by the highly recognized PDAM. However, Pipeline industry practice in North America found that the EPRG models provide conservative, in many cases, very conservative predictions that resulted in unnecessary excavations and repairs. Therefore, the objective of this investigation is twofold: (1) Improvement of EPRG model accuracy and level of conservatism from both a safety and cost-effective perspectives, and (2) providing a more realistic equation that pipeline operators can easily use for fatigue life assessment with confidence and less conservatism.

In this paper, a review of the scientific basis for the EPRG 2000 model is performed and presented first, which provides a basis for the improvement. Then, the EPRG 2000 Equation is improved utilizing the most recent PRCI Mechanical Damage (MD) project MD 4-2 full-scale fatigue testing data [36]. Validation of the improved model with PRCI MD 4-11, 4-14, and 4-15 data [37,38,39] is also presented. The improved model is further refined for better comparison with API RP 1183 Level 3 assessment approach and easy to use. A comparison of the accuracy and conservatism between the improved/refined EPRG model and the original EPRG 2000 is made to demonstrate that the improved/refined model is significantly better than the original EPRG 2000 from both a safety and cost-effective perspective. Examples for how to use the simple Microsoft excels to estimated remining fatigue life are presented. Finally, the newly refined EPRG model is compared with API RP 1183 Level 2 and Level 3 models to demonstrate the benefits of the refined model over API RP 1183 Level 2 and 3. This ongoing work provides a methodological framework to further study dent interaction with welds, gauges, cracks, and corrosion.

REVIEW OF THE SCIENTIFIC BASIS OF THE EPRG 2000 MODEL

EPRG 2000 was developed based on a semi-empirical stress-life in the form of Basquin equation, i.e., Equation (1) below:

$$N = C(A)^m \qquad (1)$$

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where A is the independent variable, C and m are the coefficients and index of the Basquin equation, and N is the Cycles to fatigue failure, the dependent variable.

Equation (2) is the EPRG 2000 model for cycles to fatigue failure developed by EPRG in 2000 [15]:

$$N_c = \frac{5622}{SF}\left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)^{5.26} \tag{2}$$

where A = $\frac{\sigma_{UTS}}{2\sigma_A K_d}$ accounts for the effect of material, stress concentration factor and cyclic stress on fatigue life, which is a function of

a. material strength, s_{UTS}, i.e., the higher the σ_{UTS}, the longer the fatigue life would be.

b. stress concentration factor K_d due to the presence of dent depending on pipe geometry, dent geometry and depth, i.e., the higher the Kd is, the lower fatigue life would be.

c. the mean cyclic stress s_{mean} and stress range Ds, i.e., the higher the s_{mean} and Ds, the lower the fatigue life.

d. SF is the safety factor to account for uncertainty of the prediction and class of location.

On the scientific basis of the model, the coefficients C and index of m are adopted the existing experimentally established S-N curve from the German Institute for Standards DIN 2413-1:1993-10 part 1, *that is*, C=5622 and m= 5.26, resulting in extremely conservative results in fatigue life prediction. DIN 2413-1:1993-10 part 1 is a German standard for the design of steel pressure pipes, and is now withdrawn [15, 32]. Equations (3) through (7) below are the detailed formular and definitions of each of the parameters in EPRG model (Equation 2).

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$$\sigma_A = \sigma_a \left[1 - \left(\frac{\sigma_{max} - \sigma_a}{\sigma_{uts}} \right)^2 \right]^{-1} \quad (3)$$

$$\sigma_a = \left(\frac{\sigma_{max} - \sigma_{min}}{2} \right) \quad 4)$$

$$K_d = 1 + C_s \sqrt{\frac{t}{D_o} (H_o)^{1.5}} \quad (5)$$

$$K_g = 1 + 9 \left(\frac{d_g}{t} \right) \quad (6)$$

$$\sigma_{uts} > \frac{\sigma_{max} + \sigma_{min}}{2} \quad (7)$$

σ_{uts} = Ultimate Tensile Strength, MPa
σ_A = Stress amplitude at mean stress correction using Gerber model or equivalent nominal fatigue stress range, MPa
σ_a = Stress amplitude, MPa
σ_{max} = Maximum stress, MPa
σ_{min} = Minimum stress, MPa
K_d = Stress concentration factor due to dent
K_g = Stress enhancement factor for gauge = 1.0 when gauge is not present.
d_g = Maximum depth of the gauge, mm = 0 (assumed).
H_o = Dent depth when not pressurized, mm
C_s = Dent shape factor, 2.0 for smooth dent ($r_d \geq 5t$) and 1.0 for sharp dent ($r_d < 5t$)
t = pipe wall thickness, mm
D_o = pipe outside diameter, mm
r_d = radius at the base of dent, mm

Because of the extreme conservatism of EPRG 2000 in fatigue life predictions based on pipeline operators' experience, an attempt has been made to improve EPRG 2000 with the same A=$\frac{\sigma_{UTS}}{2\sigma_A K_d}$ but better c and m using the PRCI MD 4-2 full-scale testing data and to develop a more realistic estimation of dent fatigue lives, which is presented in the following section.

IMPROVEMENT OF THE EPRG 2000 EQUATION

For the improvement of the EPRG 2000 equation, the following approach is used:

- Based on the understanding of the scientific basis, the EPRG 2000 formula remains unchanged for the refinement:

$$N_c = c\left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)^m \quad (8)$$

- Instead of selecting c and m from any existing dent-free S-N curves, the least squares linear regression in logarithmic scale (the above equation renders itself as a straight line) is used to determine c and m utilizing the PRCI MD 4-2 full-scale fatigue testing data for the imporvement.
- s_{UTS} and s_A are the same as the data points given in the MD 4-2 report [36].
- K_d is a function of OD (the pipe outer diameter), wt (the pipe wall thickness), Ho (the dent depth at zero pressure), and C_s (the dent shape factor):

$$K_d = \text{Stress concentration factor due to dent} = 1 + C_s\sqrt{\frac{H_0^{1.5}t}{D}}$$

C_s = 2 for smooth dents with radius > 5t
C_s = 1 for sharp dents with radius < 5t

Because the PRCI MD 4-2 [36] only reports the outer diameter of the pipe, D, and wall thickness, no H_o and C_s are available, therefore, K_d is back-calculated from DOT #432 Closeout Report [40], the same method as used by Stantec[32].

BACK-CALCULATED K_d

A Microsoft spreadsheet is compiled for back-calculating $K_{d,}$ **Error! Reference source not found.**. In the table, Column 8 is the back-calculated K_d. Column 9, i.e., the last column, is the EPRG 2000 predicted cycles to failure N using the back-calculated K_d in Column 8. Column 7 is the EPRG 2000 predicted cycles to failure N by BMT [40]. The N values in Columns 7 are the same as in Column 9, indicating that the back calculated K_d values are correct. Therefore, these back-calculated K_d values will be used for improving EPRG 2000, which will be presented in the following section.

Table 1: A comparison of the number of cycles to failure predicted by EPRG 2000 using the back-calculated K_d in the last column and predicted by BMT [40] in seventh column, showing they are the same.

1	2	3	4	5	6	7	8	9
Spec.#	Pipe Identification	OD (mm)	WT (mm)	SMYS MPa	SMUTS MPa	EPRG 2000 Predicted Cycles to Failure N by BMT[40]	Back Calculated Kd	Check N with the Back Calculated Parameters
7	A	609.6	7.9	358	455	2206	1.897	2206
8	A	609.6	7.9	358	455	441	2.576	441
9	A	609.6	7.9	358	455	263	2.842	263
10	A	609.6	7.9	358	455	345	2.700	345
11	A	609.6	7.9	358	455	435	2.583	435
12	A	609.6	7.9	358	455	1155	2.145	1155
13	B	609.6	8.9	482	565	212	2.663	212
14	B	609.6	8.9	482	565	322	2.459	322
15	B	609.6	8.9	482	565	179	2.750	179
16	B	609.6	8.9	482	565	176	2.758	176
17	B	609.6	8.9	482	565	641	2.157	641
18	B	609.6	8.9	482	565	690	2.127	690
48	C	457.2	7.9	358	455	432	2.587	432
52	C	457.2	7.9	358	455	278	2.813	278
54	C	457.2	7.9	358	455	4393	1.664	4393
56	C	457.2	7.9	358	455	624	2.412	624
57	C	457.2	7.9	358	455	1167	2.141	1167

THE IMPROVED EPRG EQUATION

In accordance with the approach discussed above, the least squares linear regression method is used for establishing the new S-N correlation to improve the EPRG 2000 equation. **Figure 1** shows the PRCI MD 4-2 testing data and new EPRG S-N equation obtained by the least squares linear regression, *i.e.*, Equation (9), in which c = 51309 and m = 2.918:

$$\mathbf{N = 51309}\left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)^{\mathbf{2.918}} \quad (9)$$

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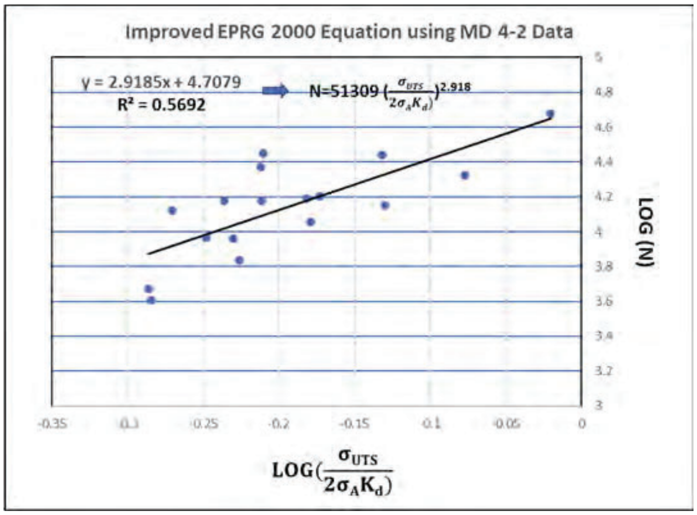

Figure 1: A plot of PRCI MD-4-2 Full-scale Testing Data and the Improved EPRG equation obtained by Least Squares Linear Regression

To demomstrate the effectiveness of the improved EPRG equation in fatigue life prediciton, error analyses of the predictions by the improved EPRG and the original EPRG 2000 equations are made. The average error between PRCI MD-4-2 testing data and the improved EPRG equation prediction is -6.7%, **Table 2**, less than 1.1 times overestimate the fatigue life. On the other hand, as per the the Pipeline and Hazardous Materials Safety Administration (PHMSA) MEGA rule for pipelines in high consequence areas (HCA), a safety factor of 5 is required. In this case, the SF =5 is quavalent to the confodence level of 97% based on one-tail confidence analysis [41]. The pipeline should be safe and cost-effectively managed. The large standard deviation (Stdev) of the new improved EPRG equation may be attributed to the uncertainty in the back-calculated K_d due to H_o and will be one of the ongoing topics for investigation.

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Table 2: Comparison of the Cycles to Failure Predicted by EPRG 2000 and the Improved EPRG 2000 against the PRCI MD 4-2 Full- Scale Fatigue Test Data

Spec.#	Pipe Identification	N from PRCI MD 4-2 Full Scal Testing	N Predicted by the Original EPRG 2000	Error=(N_{MD4-2} - $N_{EPRG2000}$)/N_{MD4-2}	N Predicted by the Improved EPRG 2000	Error=(N_{MD4-2} - $N_{ImprovedEPRG2000}$)/N_{MD4-2}
7	A	21103	2206	90%	30375	-44%
8	A	28211	441	98%	12435	56%
9	A	6825	263	96%	9335	-37%
10	A	9116	345	96%	10852	-19%
11	A	15063	435	97%	12341	18%
12	A	27575	1155	96%	21214	23%
13	B	13262	212	98%	8283	38%
14	B	15065	322	98%	10444	31%
15	B	4035	179	96%	7541	-87%
16	B	4684	176	96%	7470	-59%
17	B	11415	641	94%	15302	-34%
18	B	15949	690	96%	15940	0%
48	C	23482	432	98%	12294	48%
52	C	9226	278	97%	9627	-4%
54	C	47702	4393	91%	44511	7%
56	C	15473	624	96%	15076	3%
57	C	14091	1167	92%	21336	-51%
			Average Error	95.6%		-6.7%
			Stdev	2.6%		40.7%

In contrast, the average error between the EPRG 2000 prediction and the PRCI MD 4-2 experiment is 95.6%, The average error of 95.6% means that EPRG 2000 is nearly 20 times, i.e., about one order of magnitude under-prediction of the cycles to failure. In addtion, a safety factor of 10 is recommeded by the developer for EPRG 2000 equation, that is, more than two orders of magnitude conservatism which may have resulted in many unnecessary excavations and is unacceptable.

From the above error analyses, the new improved EPRG equation is better than the original ERRG 2000 equation for fatigue life prediction. The improvement is significant.

FURTHER REFINEMENT OF THE IMPROVED EPRG EQUATION

Further refinement of the improved EPRG equation for c and m is made for a better comparison with API RP 1183 Level 3 assessment approach. Two refinements to the improved EPRG Equation are made: (1) rounding up the exponent constant m=2.918 to 3 to be consistent with British Standard (BS) 7608 Class D [42] used by API RP 1183 Level 3, and Paris Law for steels [43] and (2) rounding down the pre-exponent constant c = 51,018 to 50,000 to compensate the round-up of m. The refined new equation (10) of ERPG 2000 is shown as follows:

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$$\mathbf{N = 50000\left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)^{3.0}} \qquad (10)$$

It is noted that the refinement does not alternate the scientific basis of the EPRG approach $A = \left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)$. The further refined equation (10) is slightly more conservative than the improved equation (9). **Figure 2** compares the further refined (Line B) and improved EPRG (Line A) i.e., the cycles to fatigue failure predicted by Equations (10) and (9). From the figure, it is seen that the conservatism depends on the value of $\left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)$. For $LOG\left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)$ =0, there is no difference in the predicted cycles to fatigue failure, and the larger the value of $\left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)$, the bigger the difference will be. The maximum difference in predicted cycles to failure in the figure is (1760-1600)/1760 = 9% on the conservative side, which is small and insignificant.

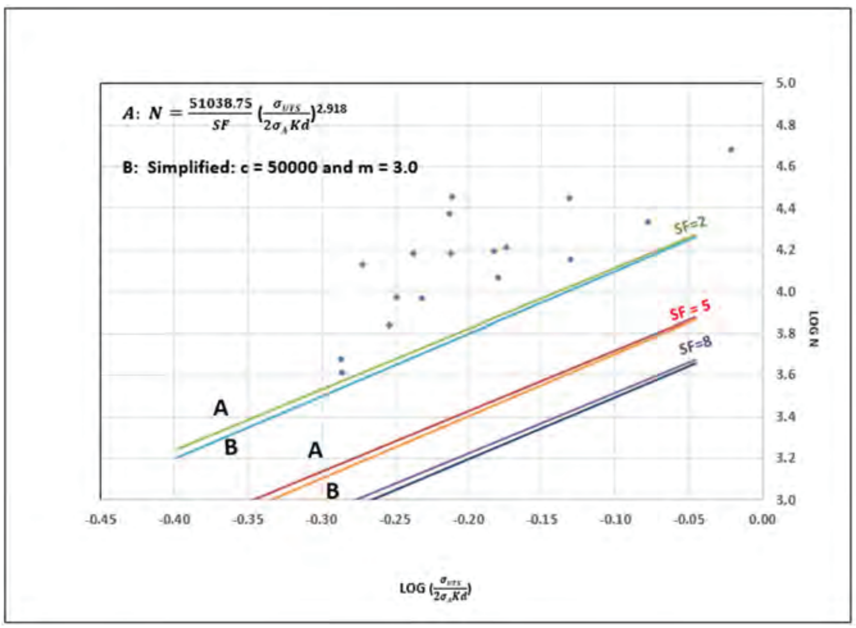

Figure 2: A comparison of the further refined (line B) and original improved (Line A) equations

With the further refined model, prediction error analysis was performed against the PRCI MD 4-2 full-scale test data. **Table 3** shows that the average prediction error and standard deviation of the refined Equation (10) are -1% and 38%, respectively, which is slightly better than the respective predictions (average error: -6.7% and standard deviation 40.7%) of Equation (9). The reason for the refined equation has smaller average error and the standard deviation is unclear, which may indicate that the deterministic value of m=3 is a better exponent associated with a class of material like linepipe steels [41, 43]. Further study for an analytical solution rather than semi-empirically fitting the data may be considered in the future.

Table 3: Comparison of the Cycles to Failure Predicted by the modified EPRG Equation against the PRCI MD 4-2 Full- Scale Fatigue Test

N from PRCI MD 4-2 Full Scal Testing	N Predicted by the New EPRG 2000	New Model Prediction Error (N_{MD4-2} - $N_{NEWPRG2000}$)	Error=(N_{MD4-2} - $N_{NEWPRG2000}$)/N_{MD4-2}
21103	29326	-8223	-39%
28211	11708	16503	58%
6825	8719	-1894	-28%
9116	10178	-1062	-12%
15063	11617	3446	23%
27575	20275	7300	26%
13262	7710	5552	42%
15065	9786	5279	35%
4035	7001	-2966	-74%
4684	6934	-2250	-48%
11415	14492	-3077	-27%
15949	15113	836	5%
23482	11571	11911	51%
9226	8999	227	2%
47702	43438	4264	9%
15473	14271	1202	8%
14091	20395	-6304	-45%
		Average Error	-1%
		Stdev	38%

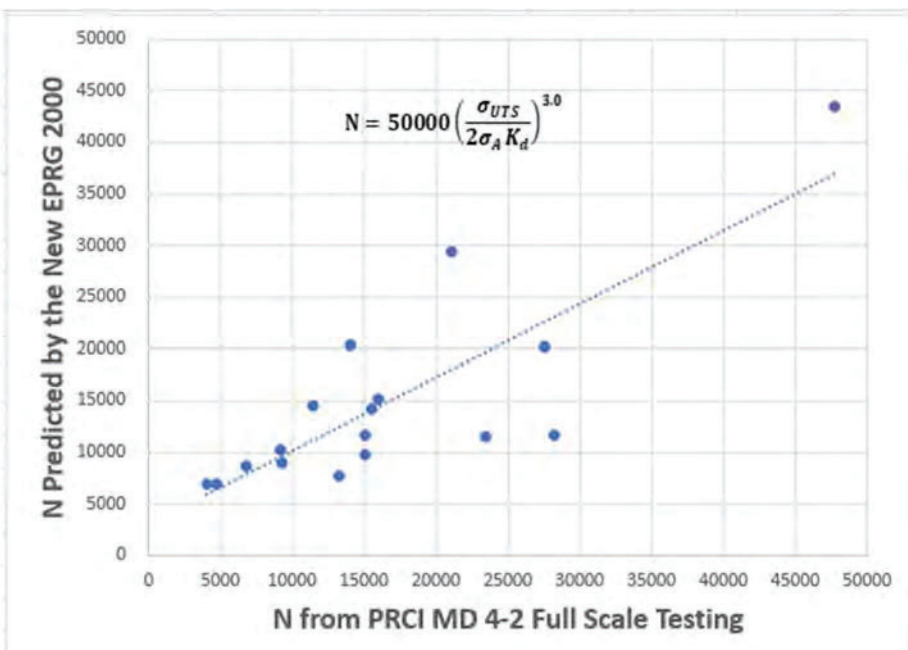

Figure 3: The plot of PRCI MD-4-2 Full-scale Test Data and the Refined EPRG Equation

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VALIDATION OF THE REFINED EPRG EQUATION AGAINST PRCI MD 4-11, 4-14, AND 4-15 DATA

In Section 8.2.5 of API RP 1183 [3], it states that the Level 3 approach is the most general treatment of dent fatigue life assessment. The models should be validated to demonstrate that they agree with full-scale testing data and comply with the Level 3 modeling requirements of API 579 Fitness-For-Service, PART 12 (12.4.4.2) [35]. In the same section, API RP 1183 indicates it is desirable to have simplified approaches that do not require finite element analysis (FEA). Because the refined EPRG equation is considered to be-a simplified Level 3 approach, validation of the refined EPRG 2000 equation with more full-scale testing data is essential.

Figure 4 shows that all the PRCI lab test data from MD 4-2 [36], MD 4-11 [37], MD 4-14 [38], and MD 4-15 [39], are above the SF=2 line except for three out of eleven test data of field dents from MD 4-15 data [39], that are below. However, and more importantly, all the data points (MD 4-2 to MD 4-15) are well above the SF=5 line, indicating that the improved model satisfies the PHMSA MEGA rule [44].

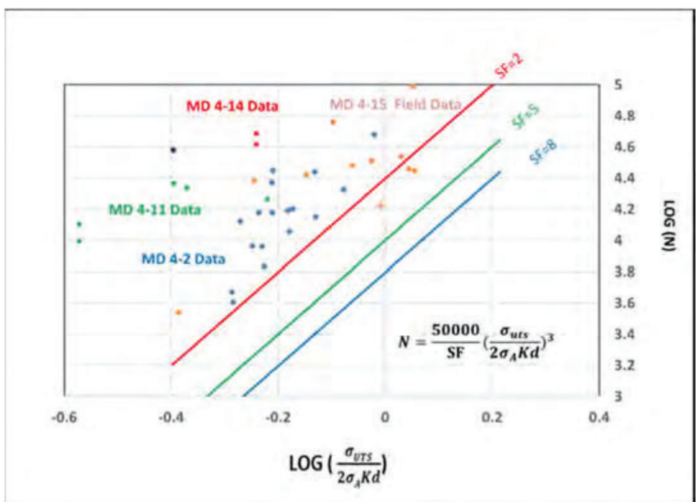

Figure 4: Validation of refined EPRG 2000 Model with PRCI MD 4-2, 4-11, 4-14 and 4-15 Full-Scale Testing Date, Showing All the Data Points Are Above SF = 2 Line Except Three Out of Eleven Test Data of Field Dents

The scatter band for field dent test results is slightly higher than the test results on lab-fabricated dents. The higher scatter band for field dents compared to the lab-fabricated dents is expected [39], considering that the lab-fabricated dents were in controlled conditions. The field dents tested were all removed from former in-service pipelines donated by different pipeline operators and formed under different operating conditions.

EXECUTION OF THE REFINED EPRG 2000 MODEL: EXCEL BASED SOFTWARE

The execution of the refined EPRG 2000 equation can be simply accomplished by using an EXCEL-BASED SOFTWARE for less than one hour for In-line Inspection (ILI) or field excavation data. The software requires seven Inputs: dent depth under Pressure H_p, outer diameter OD and wall thickness wt of the pipe, minimum pipe body ultimate strength s_{UTS}, maximum and minimum cyclic pressures P_{max}, P_{min}, and the dent shape factor Cs. The two outputs for the model predictions of Cycles to failure: one for the modified EPRG 2000 and another for the original EPRG 2000. In addition, the software allows the operator to select the safety factor for each model based on the operator's integrity management plans or PHMSA's rule. **Error! Reference source not found.** shows the screenshots of the software.

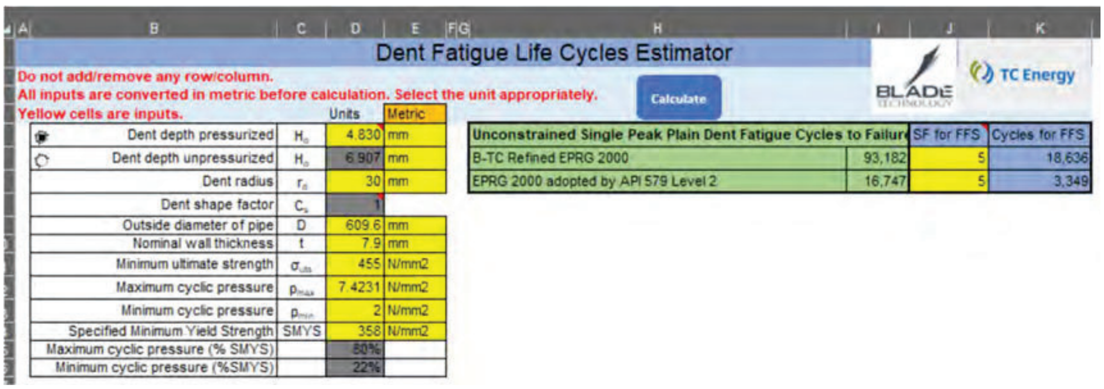

Figure 5: EXCELS Based software showing seven inputs for the calculation and two outputs for Cycles to failure of unconstrained single peak plan dent: one for the refined ERPG 2000 and one for the original EPRG 2000.

COMPARISON OF THE REFINED EPRG 2000 WITH BS 7608 K_R AND FEA-BASED MODEL

As discussed in the previous section, API RP 1183 is desirable to have simplified approaches that do not require Final Element Analysis (FEA) for dent fatigue life assessment. Because the refined EPRG 2000 Equation developed by this study is considered as the simplified Level 3 approach without FEA, a comparison of the refined EPRG 2000 with API RP 1183 Level 3 model (i.e., BS7608 Class D and FEA-based S_r model) is made to demonstrate the fatigue life predictions of the refined EPRG 2000 model is comparable to that of API RP 1183 Level 3 model.

API RP 1183 LEVEL 3 APPROACH – A BRIEF REVIEW

API RP 1183 adopted BS 7608 [42] Class D stress-range Sr-based S-N correlation, Equation (11), for unconstrained single peak plain dent fatigue life prediction:

$$log_{10}(N) = 12.81 - 3log_{10}(S_r) \qquad (11)$$

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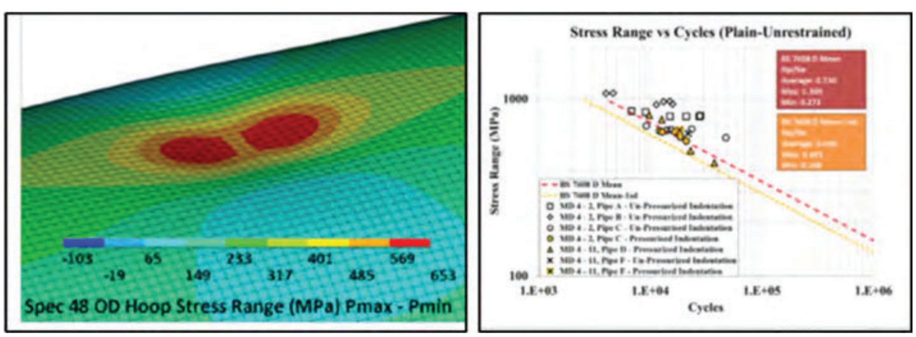
To be easier comparison between BS 7608 [42] Class D stress-range Sr-based S-N correlation and the refined EPRG 2000 Equation (10), the logarithm format of Equation (11) is reformatted to the Basquin equation. This makes BS7608 Class D equation (11) in the Power Law format, Equation (12):

$$\mathrm{N} = 6.46\mathrm{E}12\left(\frac{1}{S_r}\right)^{3.0} \qquad (12)$$

where the pre-exponent constant is C = 6.46E12 and the Power m = 3. Sr is the stress range in any cycle (in N/mm2), which is the only variable in the equation. Even though EPRG has an analytical formula for Sr in 1995 and 2000 [34, 15], which was recommended by PDAM in 2004 [16] and reviewed by Baker [1] for an unconstrained plain dent in 2009, API RP 1183 still recommends using FEA to determine S_r.

Further comparison between Equation (12) with Equation (10), the refined EPRG 2000 equation found no s_{uts} in Equation (12), i.e., no materials' strength property in the equation. This observation has been confirmed in the literature [45], which indicates BS 7608 weld Fatigue lives that "are not dependent on the material because welds are known to contain small cracks from the welding process." This fact is certainly not true for an unconstrained plain dent in base metals. Recalling the previous section, REVIEW OF THE SCIENTIFIC BASIS OF THE EPRG 2000 MODEL, it clearly indicates that the higher the σ_{UTS} is, the longer fatigue life N will be [46,47]. Therefore, this may be one of the fundamental issues associated with the API RP 1183 Level 3 approach.

The stress range S_r distribution for each of the unconstrained plain dents from PRCI MD-4-2 and 4-11 were determined by FEA and is shown in (a) of **Figure 6**. The maximum S_r is extracted for fatigue life predictions using Equation (12), the BS 7608 Class D S-N Design equation [45]. The FEA model predicted fatigue life for unrestrained plain dents prediction is shown in (b) of **Figure** . In the plot, the Y-axis is the Stress Range, S_r, and the X-axis is the cycles to failure.



(a) *(b)*

Figure 6: FEA Stress Range S_r Mapping (a) and the predicted Fatigue life based on Sr, Equations (12) [45]

COMPARISON: REFINED EPRG 2000 V.S. API RP 1183 LEVEL 3 APPROACH

It is noted that in the refined EPRG 2000 equation (10), Y-axis is the dependent variable N, i.e., Cycles to failure while the X-axis is the independent variable, i.e., $A = \left(\frac{\sigma_{UTS}}{2\sigma_A K_d}\right)$, which is the opposite to the X- and Y-axes of API RP 1183 plot. In addition, the API RP 1183 plot only includes two sets of test data, *i.e.*, PRCI MD 4-2 and MD 4-11 data with two straight lines: model prediction and model prediction minus one standard deviation (1 stdev). Therefore, two changes are made to the refined EPRG 2000 plots for comparison: (1) reversed X- and Y-axes and (2) only two sets of data, i.e., PRCI MD 4-2 and MD 4-11 with two straight lines that are the same as used by API RP 1183.

Figure shows the side-by-side comparison of two model plots: (a) the refined EPRG 2000 model and (b) the API RP 1183 Level 3 model. In the figure, the dashed lines are the model predictions, and the solid lines are the model predictions minus one standard deviation. Because the data points above and between the model prediction and minus one standard deviation are nearly the same, it suggests that both models are comparable and equivalent.

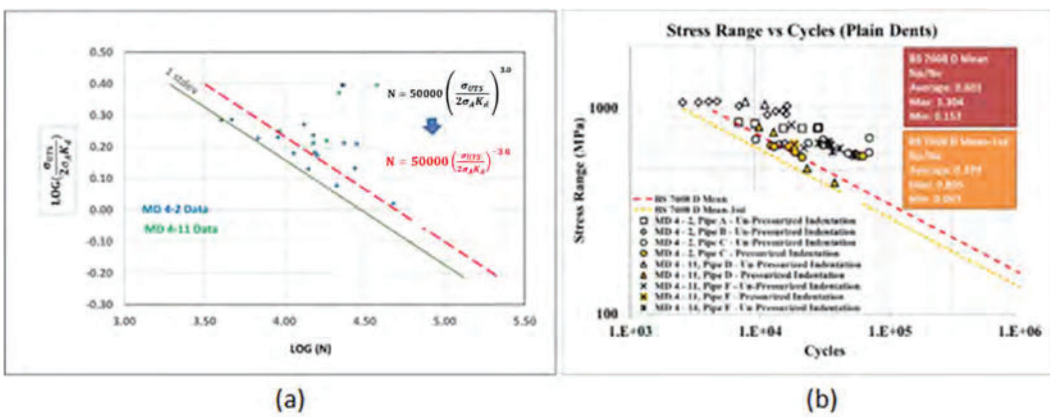


Figure 7: Comparison of (a) the refined EPRG 2000 model prediction and (b) API RP 1183 Level 3 FE Predictions, showing the refined EPRG 2000 model being comparable and equivalent.

Another issue associated with the API RP 1183 approach is its pre-exponent constant, C, being extremely large at 6.46E12, about 1.29E7 times larger than the refined EPRG 2000 equation. This difference could have resulted from having no s_{uts} in Equation (12). This can be shown by equating N, *i.e.*, cycles to failure, the ratio of Sr to $\left(\frac{\sigma UTS}{2\sigma AKd}\right)$ is 505.4 MPa, which is close to the weighted average of σ_{UTS} = 482.1 MPa of X52 (29 specimens), X60 (1 specimen) and X70 (9 specimens), **Error! Reference source not found.**. The difference between these two values is 4.6%, which is small and consistent with *the BS7608 Class D S_r model that does not include materials' property σ_{UTS} [45].*

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Table 4: Weighted Average of s_{uts} for the steel grades used for full-scale testing.

Single Peak Unonstrained Plain Dents							
Steel Grade	MD 4-2	MD4-11	MD 4-15	MD 4-14	Sum	UTS MPa	UTS Multiplied the # of Specmens tested
X70	6	3	0	0	9	565	5085
X52	11	2	12	2	29	455	13195
X60	0	0	1	0	1	520	520
				Sum	39	Sum of UTS	18800
						Weighed Avearage	482.1
						Meaured	505.4
						Difference between WA and Measured	23.3
						Percentage of Error	4.6%

DISCUSSION

Recently, a verification study of fatigue-based methods in API RP 1183 for estimating the fatigue life of pipeline dents was conducted by Zhu [10]. This is the most comprehensive study executed through detailed review and calculations, that identified the self-inconsistencies between API RP 1183 screening and assessment methods. Zhu indicated that for the PRCI Level 2 shape-based assessment, it is a great challenge for users to calculate fatigue life for a plain dent because a set of extremely complicated curve fitting equations need to be used for determining the shape parameter, shape factor, pressure factor, grade scale factor, scaling factor, and others. It is unusual that all curve fitting equations have either an integer or a common fraction as the exponent for an assumed power function. It is nonsensical from the point of view of statistical analysis. This raises a concern about whether the shape-based fitting equations are adequate or correct. Based on review and comments, the present authors fully concur with Zhu's opinion because:

- API RP 1183 and its referred original work do not provide a scientific basis for shape parameters. This makes it difficult for users to check and use the shape-based parameter (SP) assessment given by API RP 1183 or in its referred original report and papers [40].
- In many cases, the SP approach was established on and validated against full-scale trials. Do the words "against full-scale trials" mean against "full-scale FE trials"? If this is the case, the reliability and confidence level validation is questionable because it is "FE validated by FE" [48].
- A total of 65 actual full-scale Tests (57 from MD-4-2 and 8 from other sources outside the PRCI MD project) are used by PRCI [40] to evaluate four existing Dent Fatigue models, namely, API 1156, EPRG/PI 579, Rosenfeld and Fowler model. However, to date, no validation of the SP fatigue model and comparison with other models have been performed since the SP model was established [40, 48].

Because there is a concern about whether the shape-based fitting equations are adequate or correct, and because a set of extremely complicated curve fitting equations need to be used for determining

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the shape parameter, shape factor, pressure factor, grade scale factor, scaling factor, etc., the refined EPRG 2000 model may be considered for use as a Level 2 fatigue life assessment of the unconstrained plain dent for fitness of services when the lower bound material property, upper bound pressure cycling, and upper bound dent geometry from ILI and/or field inspection excavation are used as inputs. This consideration is based on the execution of the refined EPRG 2000 approach being simple and fast (not time-consuming), which is consistent with API 579 failure assessment diagram (FAD) Level 2 for the crack assessment concept.

For critical dent features that require Level 3 assessment, the same refined ERPG model can be used with actual material property, pressure cycling data, and precise sizing data from ILI/NDE as inputs and application of SF =5 for HCA as required by PHMSA MEGA rule, and/or combined with FEA to accurately determine stress concentration factor K_d, (note: it is not the same as stress range S_r in API RP 1183).

Moreover, many papers have been published to demonstrate the implementation of API RP 1183 and the challenges of using API RP 1183 [49-54]. These papers are consistent and support Zhu's comments and concerns. As suggested by PRCI, a peer review of API RP 1183 to address the issues identified by the recently published papers is indeed essential.

It should be noted that further validation of the refined EPRG 2000 model with more lab testing and field failure data is needed and on-going and will be followed with new technical reports and papers for review and updating.

SUMMARY

This on-going study aims to improve the EPRG 2000 methodology for fatigue life assessment of unconstrained single peak plain dents in pipelines under cyclic internal pressure. EPRG 2000 was adopted by API 579 and more recently adopted by API RP 1183 as an alternative approach recommended for Level 2 plain dent fatigue life assessment. However, pipeline industry practice in North America has experienced that the EPRG 2000 equations provide conservative, in many cases, very conservative predictions that resulted in unnecessary excavations and repairs. Therefore, improving the model accuracy and level of conservatism is essential from both safety and cost-effective perspectives.

A comprehensive and critical review of EPRG 2000 fatigue life prediction models is performed, which provides a scientific basis for improvement. PRCI MD 4-2 full-scale fatigue test data is used for improving the EPRG model, and PRCI MD 4-11, 14, and 15 data are used for validation. Comparison of the refined EPRG 2000 model with the original EPRG 2000 model shows a great improvement from the average error = 95.6% down to 1%. Further comparison of the refined EPRG 2000 model with API RP 1183 Level 3 BS7608 Class D and FE-method shows that they are comparable and equivalent. The benefits of the refined EPRG 2000 model over API RP 1183 Level 3 FEA approach are simple and can be executed with simple Excel software by pipeline operators'

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integrity engineers without using time-consuming FEA that requires specific numerical techniques. The refined EPRG 2000 approach is the one desired by API RP 1183. This on-going work provides a methodological framework to further carry out the Level 2 FFS assessment for dent-interacting with welds, gauges, cracks, and corrosion.

REFERENCES

[1] Baker, M.," Mechanical Damage in Pipelines", PHMSA for Integrity Management Program under Delivery Order DTRS56-02-D-70036, 2009. mechanicaldamagefinalreport.pdf

[2] Gao, M., Krishnamurthy, R., "Mechanical damage in pipelines: a review of the methods and improvements in characterization, evaluation, and mitigation". Chapter 22, Oil Gas Pipelines – Integrity and Safety Handbook, Ed.by Revie, W., pp.289-326 2015. https://doi.org/10.1002/9781119019213.ch22.

[3] API RECOMMENDED PRACTICE 1183: Assessment and Management of Pipeline Dents, First Edition, 2020, pp. 13-14.

[4] Kiefner, J., and Kolovich, C., "Mechanical Damage Technical Workshop", Feb 28, 2006, Houston TX, USA

[5] Rosenfeld, M.J. "Proposed new guidelines for ASME B31.8 on assessment of dents and mechanical damage", GRI, May 2001

[6] Zhao, J., Lv, Y., Cheng, F., "Standards and methods for dent assessment and failure prediction of pipelines: A critical review", petroleum Science V. 19, pp. 3029-3045, 2022,

[7] Cunha, S., Pasqualino, I., Pinheiro, B.: "Pipeline Plain Dent Fatigue – A Comparison of Assessment Methodologies", IPC 2014, Paper No: 33034, Calgary, Canada

[8] Kiefner, J., Kiefner, B., Vieth, P., "Analysis of DOT reportable incidents for hazardous liquid Pipelines, 1986 through 1996". American Petroleum Institute Publication 1158, 1999

[9] Davis, P., Dubois, J., Gambardella, F., Sanchez-Garcia, E., Uhlig F., (2011). "Performance of European cross-country oil pipelines - Statistical summary of reported Spillages in 2010 and since 1971". Report no. 8/11, CONCAWE, http://www.concawe.com

[10] Zhu, X., "A Verification Study of Fatigue-Based Methods in API RP 1183 for Estimating Fatigue Life of Pipeline Dents", International Journal of Pressure Vessels and Piping, Vol. 205. October 2023., https://doi.org/10.1016/j.ijpvp.2023.104969

[11] Belonos, S., Ryan, R., "Dent in Pipe", Oil Gas J., Vol 56, pp, 155-161, 1958.

[12] Mayfield, M., Wilkowski, G., Eiber, J., "Influence of Toughness on Resistance to Mechanical Damage and Ability of Line Pipe to Withstand Damages, AGA-EPRG Line Pipe Research Seminar III, Houton, TX 1978

[13] Fowler, J., Alexander, C., Kovach, P., et al. "Cyclic Pressure Fatigue Life of Pipelines with Plain Dents, Dents with Gouges, and Dents with Welds", Reports No. PR-201-927 and PR-201-9324, Pipeline Research Committee, American Gas Association, Houston, 1994

[14] Alexander, C. R., and Kiefner, J. F., , "Effect of Smooth and Rock Dents on Liquid Petroleum Pipelines (Phase II)", API Publication 1156-Addendum, American Petroleum Institute, Washington, 1999.

https://doi.org/10.52202/072781-0053

[15] Roovers, P., Galli, M., Bood, R., Mareswski, U., Steiner, M., Zarea, M., “EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damages”, Pipeline Technology, Volume II, Proceedings of the Third International Pipeline Technology Conference, Brugge, Belgium, Ed., Denys, R., Elsevier Science, 2000, pp. 405-425.

[16] Cosham, A., HopkinS, P., “The Effect of Dents in Pipelines – Guidance in the Pipeline Defect Assessment Manual”, Proceedings ICPVT-10 July 7-10, 2003, Vienna, Austria.

[17] Liu, J.H., Francis, A., Theoretical analysis of local indentation on pressured pipes. International Journal of Pressure Vessels and Piping, Vol. 81, pp. 931-939, 2004. https://doi.org/10.1016/j.ijpvp.2004.05.007

[18] Knoop, F., Mannucci, G., Marewski. U., Owen, R., Steiner, M., Wolvert, G., Zarea, Z., “Effect of mean stress on the fatigue behavior of gas transmission pipes”, report on behalf of the EPRG Technical Committee – Design, 3R International, 2006

[19] Cunha, S., Pinheiro, B., Pasqualino, I., “High Cycle Fatigue of Pipelines with Plain Dents – Simulations, Experiments and Assessment”, OMAE 2007-29130

[20] Hyde, T.H., Luo, R., Becker, A., Force-deflection analysis of offset indentations on pressurized pipes. International Journal of pressure Vessels and Piping, Vol. 84, pp.368-377, 2007.

[21] Pinheiro, B., Pasqualino, I., “Fatigue analysis of damaged steel pipelines under cyclic internal pressure”, International Journal of Fatigue 31 (2009) 962–973

[22] Tian, X., Zhang, H., “Failure criterion of buried pipelines with dent and scratch defects”. Engineering. Failure Analysis, Vol.80, pp. 278-289, 2017. https://doi.org/10.1016/j.engfailanal.2017.06.049.

[22] Abdelmoety, A.K., Kainat, M., Yoosef-Ghodsi, N., Li, Y., Adeeb, S., “Strain-based reliability analysis of dented pipelines using a response surface method”. Journal of Pipeline Sci. Eng. V2, 29-38. 2022. https://doi.org/10.1016/j.jpse.2021.11.002[

[23] Tiku, S., Semiga V., Dinovitzer, A., Vignal, G., “Full Scale Cyclic Fatigue Testing of Dented Pipelines and Development of a Validated Dented Pipe Finite Element Model”,012, Paper No: 90427, Calgary, Canada.

[24] Fontanabona, J., Van, K., Gaffard, V., Moumni, Z., Wiet, P.,: “Prevention of Pipeline Dent Failure Under Fatigue Loading Conditions”, IPC 2014 Paper No: 33199, Calgary, Canada

[25] Fredj, A., Dinovitzer, A., Tiku, A., Vigna, G., “Pipeline Mechanical Damage Excavation Process Review and Recommendations”, IPC2014, Paper No: 33618, Calgary, Canada

[26] Tiku, S., Eshraghi, A., Semiga, V., Torres, L., Piazza, M., “Improved Pipeline Dent Integrity Management” IPC 2016, Paper No. 64530, Calgary, Canada.

[27] Tiku, S., Semiga, V., Dinovitzer, A., Piazza, M., Jones, T., “Improvement of Pipeline Fatigue Life Estimation”, IPC2016, Paper No: 64479, Calgary, Canada

[28] Semiga V., Tiku, S., Dinovitzer, A., Wagster, W,. “Evaluation of Fatigue in Gas Pipelines”, IPC2016, Paper No: 64486, Calgary, Canada

[29] Semiga V., Dinovitzer, A., Tiku, S., Vignal, G., “Liquid Pipeline Location Specific Cyclic Pressure Determination”, IPC2018, Paper No: 78717, Calgary, Canada, 2018

[30] Tiku, S., Rana, A. John, A., Dinovitzer, A., “Dent Screening Criteria Based on Dent Restraint, Pipe Geometry and Operating Pressure”, IPC2020, Paper No: 9703, Calgary, Canada, 2020.

 https://doi.org/10.52202/072781-0053

[31] Garbatov, Y., , Soares, G.: "Fatigue reliability of dented pipeline based on limited experimental data" Volume 155, (2017), pp. 15-26. 2017

[32] Shirband, Z., Gosselin, A., Guest, S., Falcon, L., "Pipeline Plain Dent Fatigue Assessment: Shedding Light on The API 579 Level 2 Fatigue Assessment Methodology", IPC 2020, Paper No. 9655, Calgary, Canada.

[33] He, Z., Zhou, W.: "Fatigue reliability analysis of dented pipelines", Journal of Pipeline Science and Engineering, Volume 1, Issue 3, 2021, pp. 290-297

[34] Corder, I., Chatain, P., "EPRG Recommendations for the Assessment of the Resistance of Pipelines to External Damage", 10th biennial Joint Technical Meeting on Line Pipe Research, Cambridge, UK, April 1995.

[35] ANNEX 12A: "API 579-1/ASME FFS-1 2021 Fitness-For-Service"

[36] PRCI Report: Full Scale Fatigue Testing of Dents (Plain Dents and Dents Interacting with Welds and Metal Loss) MD-4-2 Contract PR-214-07351, 2018.

[37] PRCI MD 4-11 Fatigue Life Assessment of Dents with and without Interacting Features, PHMSA DTPH56-14-H-00002, Final Report 2017.

[38] PRCI MD 4-14, Contract PR-214-163714: Full Scale Testing of Shallow Dents with and without Interacting Features", 2019

[39] PRCI MD 4-15, Contract PR-214-183816, "Full-Scale Fatigue Testing of Field Dents", 2021

[40] Dent Fatigue Life Assessment, DOT #432 Closeout Report. January 10,2012

[41] National Institute of Standards and Technologies (NIST): Engineering Statistics Handbook, "Comparison of LS Line and True Line", https://www.itl.nist.gov/div898/handbook/pmd/section4/pmd431.htm

[42] BSI Standards Publication BS 7608:2014+A 1 :2015 "Guide to fatigue design and assessment of steel products", 2015

[43] Anderson, W.E. Discussion: "A Critical Analysis of Crack Propagation Laws" (Paris, P., and Erdogan, F., 1963, ASME J. Basic Eng., 85, pp. 528–533), https://asmedigitalcollection.asme.org/fluidsengineering/article/85/4/534/395739/Closure-to-Discussions-of-A-Critical-Analysis-of

[44] PHMSA MEGA Rule, 49 CFR Part 192, issued on August 4, 2022, p. 214

[45] Altair: BS7608 Welds Technical Background: Class D BS 7608 Welds Technical Background – eFatigue https://www.efatigue.com

[46] Svensson, T., Mare', J.., Wadman, B., «Determination of the Fatigue Limit, Materials and Problems" IM report, Swedish Institute of Applied Mathematics (2000).

[47] Milelle, P., "Fatigue and Corrosion in Metals", Springer Italy, 2003.

[48] PRCI MD 4-9. PR-214-114500-R01 Fatigue Life Assessment of Dents with and without Interacting Features, 2018

[49] Polasik, S., Wu, S, Bratton, J. Dotson, R., Sager, R., "The state of dent screening and shape-based assessments: discrepancies to consider. Proceedings of the 2022 14th International Pipeline Conference, IPC2022-87301, September 26-30, 2022, Calgary, Alberta, Canada.

https://doi.org/10.52202/072781-0053

[50] Kainat, M., Virk, A., Yooset-Ghodsi, N. Bott. S., “Implementation of API 1183 Recommended Practice for Reliability-Based Assessment of Dents in Liquid Pipelines, Proceedings of the 2022 14th International Pipeline Conference, Calgary, Alberta, Canada.

[51] Hardy, J., Newton, C., “Determining Dents-Determining Restraint for dents measured by ILI case study. PPIM 2023 paper No. 18. (2023)

[52] Wang, R., Zhang, K., “Gaps in the Current Strain-based Dent Assessment”, IPC2022-87165

[53] Zhang, S., Zhang, B., Wang, R., “A Transparent ASME B31.8-based Strain Assessment Method Using 3D Measurement of Dent Morphology,” IPC2022-87168

[54] Leis, B., Eshraghi, A, Dew, B., Cheng, F. “Dent Strain and Stress Analyses and Implications Concerning API RP 1183 Part I: Background for Dent Geometry and Strain Analyses During Contact and Re-Rounding” Journal of pipeline science and engineering, Volxx Noxx, 2023

 https://doi.org/10.52202/072781-0053

https://doi.org/10.52202/072781-0053