Evaluating the Effect of Maximum Stress and Maximum Stress Range on Fatigue Life Assessments of Dents

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Abstract

With PHMSA's issuance of RIN2 of the Final Rule, Engineering Critical Assessments (ECA) have become increasingly important in assessing not only the fatigue life of dents and other integrity threats, but also reinspection intervals. ECA's can be performed for a variety of complex dent features identified from in-line inspection (ILI) or direct examination by following assessment methodologies prescribed in API 1183 along with the fatigue life assessment procedures outlined in API 579.

For those cases requiring a level 3 assessment, finite element analysis (FEA) is often necessary to account for interactions between dents and interacting features (i.e., metal loss, bending strain, seam weld, etc.), which can then be used to determine the fatigue life of the dent. A more accurate fatigue life can be calculated using the FEA results to obtain a stress vs. pressure relationship, which is then paired with the pressure history of the specific line segment being assessed. This stress vs. pressure relationship is extracted from a specific location in the vicinity of the dent from the finite element model, and for the sake of conservatism in the assessment, is either taken from the location of maximum stress or the location of maximum change in stress between pressure cycles. Both stress locations are critical to dent integrity, the former is usually associated with crack generation during the dent formation process, while the latter contributes to the fatigue crack initiation and growth. Depending on the dent conditions (i.e., constrained, unconstrained, dent depth, shape, feature interactions, etc.) these two locations are not always coincident and the resulting fatigue stress range could be significantly different in some scenarios.

For this paper, a collection of 18 dent ECAs are examined to determine under what conditions, such as constraint condition, shape, stress/strain level, etc., the locations of maximum stress and maximum change in stress are not coincident as well as the extent to which these differences impact the overall fatigue life of the dent features.

Introduction

Dent ECAs have become more important and a wider spread methodology in dent evaluation with PHMSA's issuance of RIN2 of the Final Rule[1]. A dent in a pipeline is defined as a local inward depression in the surface caused by an external force that produces plastic deformation in the pipe wall and an overall disturbance in the curvature of the pipeline[2]. The manner in which a dent is created (i.e. construction vs. in-service), and the subsequent restraint conditions (i.e. constrained vs. unconstrained), will have an impact on the potential for crack formation and the dent's response to changes in internal pressure of the pipeline. Circumferential orientation (clock position) is often used to assume the restraint condition of the dent. Dents located on the top side of the pipe segment, above 4 o'clock and 8 o'clock are more likely to be unrestrained, meaning the indenter which contributed to the formation of the dent does not restrict flexing/re-rounding of the dent with changes in internal pressure. While dents located below these clock positions are more likely to be restrained dents where the indenter restricts the flexing and re-rounding of the pipeline in the direct

[1] Pipeline and Hazardous Materials Safety Administration, 49 CFR Part 192 RIN 2, https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-08/Gas-Transmission-2-Final-Rule.pdf, 2022
[2] American Petroleum Institute. Assessment and Management of Pipeline Dents, API Recommended Practice 1183. 2020

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vicinity of the dent. One exception to this is bottom side dents which have been excavated and the rock/constraining object has been removed, at which point the dent will typically behave like an unconstrained dent. These dent-specific parameters, along with the circumferential and axial morphology of the dent are important to consider when performing dent ECAs as they can have a significant outcome on the overall conclusions of the assessment.

For cases requiring a level 3 assessment, FEA is often implemented to account for interactions between multiple dents as well as additional interacting features (i.e. metal loss, bending strain, etc.). When performing detailed finite element (FE) modelling for Dent ECAs, the above-mentioned factors are important to consider to ensure an accurate recreation of the reported dent feature in order to appropriately capture the resulting stresses and strains from not only the dent creation, but also the effects of internal pressure on the re-rounding of the dent. Incorporating these parameters, along with the appropriate pressure loading, FEA can be used to calculate the stresses and strains associated with the subject dent features. The fatigue life of the dent can then be calculated by pairing these stress results from the FEA along with the pressure history of the pipeline segment, which the operator can then use to make crucial integrity management decisions for their pipeline infrastructure.

When calculating the fatigue life of dent features from level 3 dent ECAs, typically it is expected that the maximum stress location within the dent, during maximum operating conditions (i.e. MOP/MAOP) will provide a worst-case (i.e. shortest) fatigue life. However, one important consideration when evaluating dent features is not only the maximum stress within the dent, but also the maximum stress range within the dent over the range of pressures for the pipeline segment. It should be noted that the two result cases are not always located at the same location within a given dent. DNV worked with TC Energy in performing 18 level 3 dent ECAs for which these two stress states, along with the aforementioned dent-specific parameters, were evaluated to determine the fatigue life of each dent feature. This study will examine under what conditions, the locations of maximum stress and maximum stress range are/are not coincident as well as the extent to which these different stress results impact the overall fatigue life of the dent features.

Finite Element Analysis Overview

The simulation process used to assess each dent feature was chosen to closely replicate the dent morphology by recreating the dent in a nominal pipe model, using FEA. This was accomplished by using the ILI caliper measurements to create a 3D indenter which retained the dent morphology characteristics. The FE model was then established by first creating a nominal representation of the pipe section within the commercially available FEA software Simulia Abaqus Standard, incorporating the ILI-reported outer diameter (OD) and wall thickness parameters. The overall length of each pipeline segment was extended so as to ensure model boundary conditions were far from the dented region and thus not imparting any artificial influence within the region of influence, which consequentially would affect the stress results in the direct vicinity of the dent.

The indenter surface was then imported into Abaqus and rotated and aligned such that the indenter was located at the 12 o'clock position at the midpoint of the pipe segment. A rigid plate was then incorporated directly below the pipe (6 o'clock position) to support the pipe when the indenter was pressed against the pipe surface during the indentation process. Material test reports (MTR) were unavailable for the subject pipeline segments, thus the Ramburg-Osgood formulation[3] was used along with a Young's modulus of $30x10^6$ psi, a Poisson's ratio of 0.3, the specified minimum yield strength (SMYS), and the specified minimum tensile strength (SMTS) from the ILI report for each dent feature to define the elastic-plastic material properties within Abaqus for each dent model. For dent features interacting with metal loss, the nominal pipe model was comprised of solid brick elements and the metal loss feature was incorporated into the model geometry including the appropriate tool tolerances on reported length, width, and depth dimensions. The metal loss feature was aligned with the dent apex in the model in both the axial and circumferential directions, corresponding to the ILI report. For all remaining dents not reported to be interacting with metal loss, the nominal pipe model was comprised of shell elements for computational efficiency.

All of the dent features were assessed as construction related dents and thus were dented under 0 psig internal pressure and included a hydrotest pressure step after indentation, regardless of restraint conditions. The following analysis steps for recreating the dents within Abaqus were followed for all dent FEA models in this study:

- Indenter displaced into pipe with an internal pressure of 0 psig
    - For unconstrained dent features, the indenter was removed from the pipe for remaining pressure steps
    - For constrained dent features, the indenter was held in contact with the pipe for remaining pressure steps
- Pipe was pressurized to hydrotest pressure. If hydrotest records were unavailable, an assumed hydrotest pressure corresponding to 90% SMYS was applied
- Three step-wise pressure cycles were implemented, varying the internal pressure of the pipe between MOP and 0 psig to equilibrate the residual stresses and plastic strains associated with the dent
- Internal pressure increased to the ILI tool-run pressure for comparison of the model results (dent profile) to the ILI caliper data
    - Iterative step here whereby if the profiles were out of agreement, the indenter depth was adjusted such that the final dent depth was deeper than the ILI caliper measurements, while still remaining within the tool tolerance.
- Final step performed incrementally recording FE model results at fixed pressure intervals while the internal pressure was increased from 0 psig to MOP.

Contact behavior between the indenter and the OD surface of the pipe was simulated with surface-to-surface contact assuming hard contact behavior in the normal direction, with frictionless contact in the tangential directions. Couplings and boundary conditions were imposed on the ends of the nominal pipe sections to allow for natural radial growth and expansion resulting from the applied internal pressure loads without over constraining the model. An assembly of the nominal pipe model, indenter, and rigid base plate is shown below in Figure 1.

[3] American Petroleum Institute. Fitness-For-Service. API 579-1/ASME FFS-1. December, 2021.

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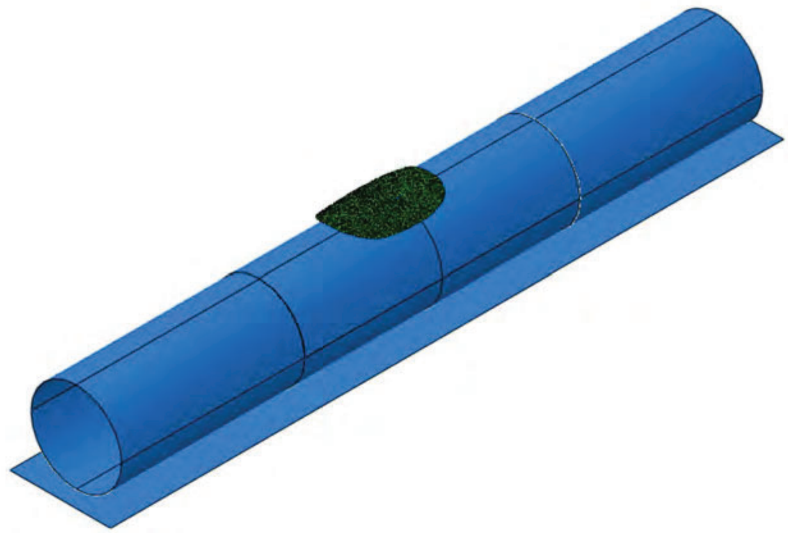

Figure 1. Sample Dent Model Assembly with Nominal Pipe Model, Indenter, and Rigid Plate

FEA-Based Fatigue Life Analysis

Once appropriate agreement was achieved between the modelled dent and the reported dent profiles, both axially and circumferentially, the stresses were extracted from the model at fixed pressure intervals between 0 psig and MOP. The location of the maximum circumferential stress within the dent was extracted as well as the location of maximum circumferential stress range in the event that the two locations were not coincident. The location of maximum circumferential stress range was determined by taking the difference in circumferential stress magnitude at each node in the model at MOP and 0 psig. Compressive stresses were not included in this delta stress calculation to avoid skewing the calculations since the stresses in compression range have negligible contribution to crack propagation of the dent.

Once this stress vs. pressure relationship was developed, the internal pressure range from each cycle identified in the provided pressure history for each dent, using rainflow cycle counting (RCC) performed in accordance with ASTM Standard E1049[4], was converted to a stress range using the relationship developed by the FEA model in order to calculate the fatigue life of each dent feature.

The fatigue life for each dent was calculated using hypothetical pressure histories developed to assess all dents in both aggressive as well as non-aggressive pressure spectra. This sample pressure cycle was scaled based upon diameter, wall thickness, and pipe grade to further ascertain the effects of max stress and max delta stress on the fatigue life of the dent features when faced with vastly different pressure cycles.

[4] ASTM, 2017, "Standard Practices for Cycle Counting in Fatigue Analysis E1049-85 (Reapproved 2017)", ASTM International.

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Discussion

An overview summary of the dents included in this study are shown below in Table 1. In total, 18 dents were included across 8 different gas pipelines, operated by TC Energy. Each of these various parameters will be discussed in further detail in the sections that follow.

Table 1. Overview Summary of Dents Included in Study

Dent ID	D/t	OD (in)	t_{wall} (in)	SMYS (ksi)	Length (in)	Width (in)	Depth (%OD)	Constrained/Unconstrained
1	80.0	20	0.250	35000	5.604	5.261	2.50%	Unconstrained
2	80.0	20	0.250	35000	3.144	3.927	1.98%	Unconstrained
3	80.0	20	0.250	35000	3.432	3.927	1.21%	Unconstrained
4	80.0	20	0.250	35000	4.032	3.480	1.70%	Unconstrained
5	76.7	24	0.313	52000	25.700	10.321	3.19%	Constrained
6	76.7	24	0.313	52000	27.376	9.781	5.15%	Constrained
7	76.7	24	0.313	52000	14.457	9.958	3.15%	Constrained
8	76.7	24	0.313	52000	24.647	10.325	1.98%	Constrained
9	88.6	24	0.271	60000	25.012	10.763	1.99%	Constrained
10	80.0	20	0.250	60000	15.516	9.163	3.06%	Constrained
11	80.0	20	0.250	60000	15.396	6.545	2.97%	Constrained
12	104.0	26	0.250	60000	16.056	13.614	6.43%	Constrained
13	64.0	24	0.375	65000	16.620	9.860	2.61%	Unconstrained
14	76.7	24	0.313	52000	6.142	7.323	1.60%	Constrained
15	76.7	24	0.313	52000	5.433	3.661	2.07%	Constrained
16	25.5	12.75	0.500	52000	7.680	3.756	0.70%	Constrained
17	25.5	12.75	0.500	52000	7.800	4.082	0.78%	Constrained
18	93.5	36	0.385	65000	19.416	13.904	5.09%	Constrained

When Maximum Circumferential Stress Coincides with the Maximum change in Circumferential Stress within a Dent

Surveying the compendium of the dent ECA results, the dents were sorted by multiple parameters in an attempt to find a discernible trend when the maximum circumferential stress location is or is not coincident with the maximum circumferential stress range location. The dents were sorted by D/t ratio, restraint condition (i.e. constrained/unconstrained), SMYS, reported dent aspect ratio, and dent depth. A summary of the dents where the location of maximum circumferential stress was and was not coincident with the maximum change in circumferential stress as a function of D/t ratio is shown below in Figure 2. The same comparison is shown as a function of restraint condition, SMYS, reported dent aspect ratio, and dent depth in Figure 3 - Figure 6, respectively.

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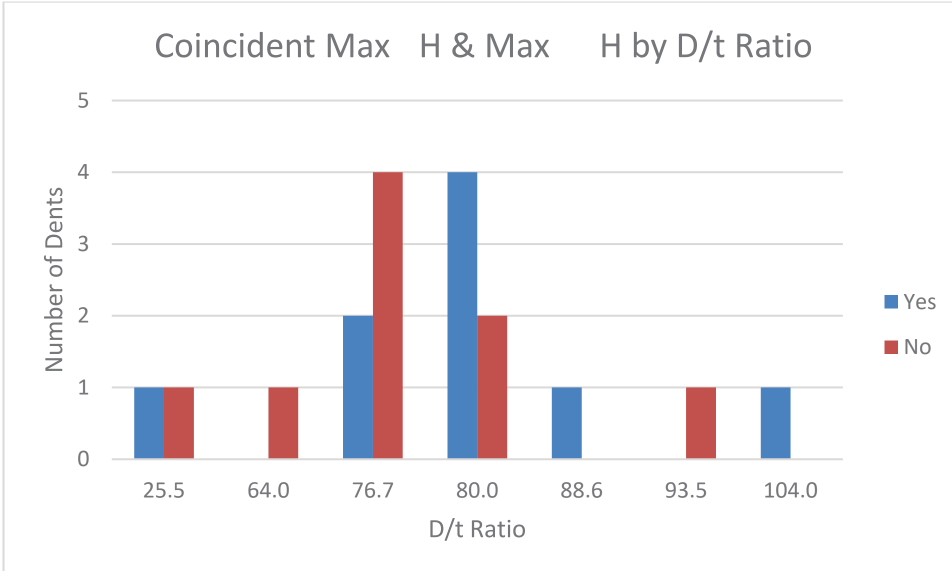

Figure 2. Summary of Coincident Maximum Circumferential Stress and Maximum Change in Circumferential Stress as a function of D/t ratio

Figure 3. Summary of Coincident Maximum Circumferential Stress and Maximum Change in Circumferential Stress as a function of Restraint Condition

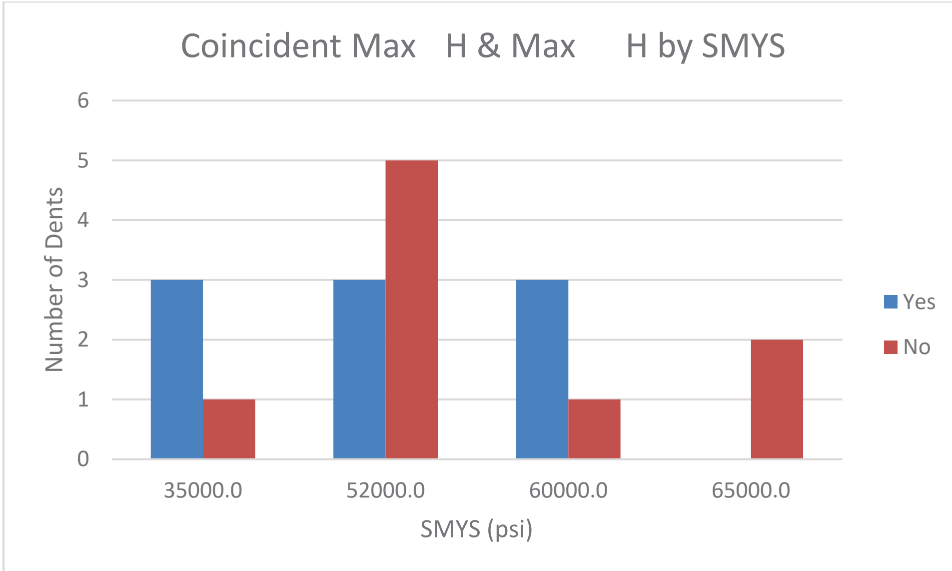

Figure 4. Summary of Coincident Maximum Circumferential Stress and Maximum Change in Circumferential Stress as a function of SMYS

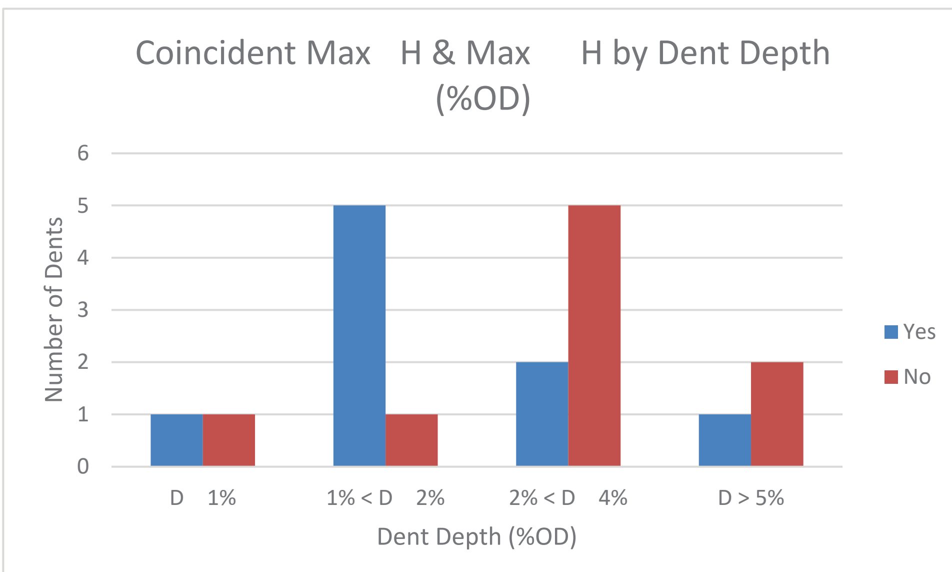

Figure 5. Summary of Coincident Maximum Circumferential Stress and Maximum Change in Circumferential Stress as a function of Dent Depth

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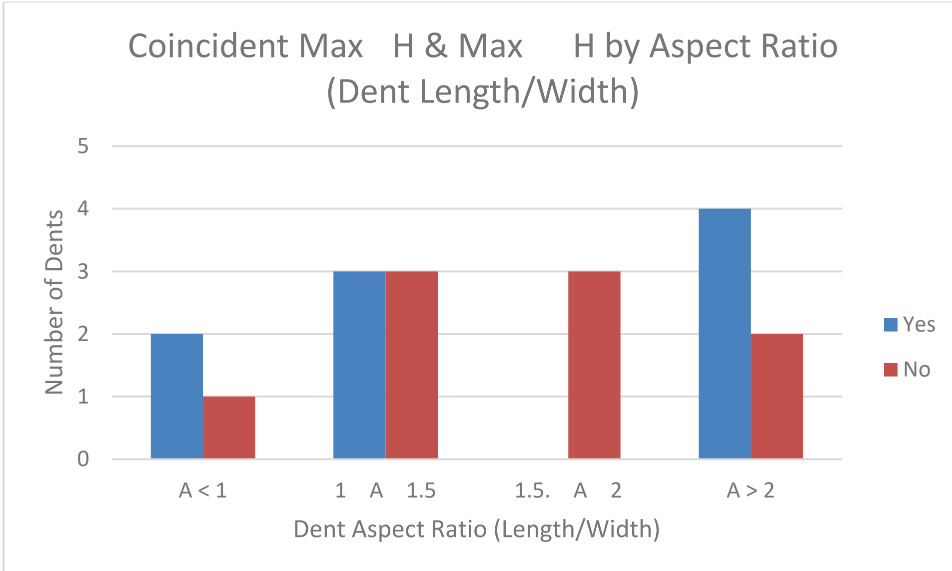

Figure 6. Summary of Coincident Maximum Circumferential Stress and Maximum Change in Circumferential Stress as a function of Dent Aspect Ratio (Reported Length/Width)

Reviewing the summary of the results in the above figures, there were 9 total dents of the 18 evaluated, whereby the maximum circumferential stress and the maximum change in circumferential stress locations were not coincident in the FE model results. For these 9 dents, eight were evaluated as constrained dents based upon the reported o'clock position of the dent apex from the ILI data and subsequently verified from the FEA profile fitting. The remaining dent was a dent interacting with metal loss (ML), whereby the maximum stress location was within the ML region at the dent apex and the maximum stress range location was located at the shoulder. This ML region adds the complexity of a stress riser, therefore skewing the results of the study. This would lead the authors to believe that restraint condition plays a role in whether or not the locations of maximum circumferential stress and maximum change in circumferential stress are coincident. However, considering the sample size of 18 dents, and considering the remaining dents were split 6/3 between constrained and unconstrained cases where these locations were coincident, further evaluation and a larger sample size is needed to justify this conclusion.

Evaluating the remaining parameters, it is unclear if any single one of these parameters (D/t, SMYS, Dent Depth, and Dent Aspect Ratio) has a discernible influence on whether or not the locations of maximum circumferential stress and maximum change in circumferential stress are coincident. It is possible that perhaps a combination of these parameters could be evaluated to find when these locations coincide, however with the limited sample size of <20 dents, there is not enough to draw a conclusion at this time other than it is truly dependent on each individual dent. Thus, when performing a Level 3 dent ECA, consideration should be given not only to the maximum stress location, but also the location of maximum change in stress when evaluating the fatigue life of the dent.

Assessing the Impact on Dent Fatigue Life

As discussed previously, at both locations of interest (maximum stress and maximum stress range), circumferential stresses were extracted at various internal pressures, developing a relationship

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between the stress profile and internal pressure, as presented in **Error! Reference source not found.**. The established relationship between the stress profile and internal pressure was then used to estimate the fatigue lives for each of the dents.

In **Error! Reference source not found.**, the circumferential stress for a plain, undented pipe is also provided as a comparison. Changes in internal pressure (the horizontal-axis) can be related to changes in circumferential stress (the vertical-axis). The relative aggressiveness of the stress range as it relates to changes in internal pressure is evident in the slopes of the curves. In the example in **Error! Reference source not found.**, a pressure cycle between 400 to 600 psig results in a larger circumferential stress range at the maximum stress range location (double-red line) than in either the plain pipe (dashed grey line) or the maximum stress location (solid blue line). Further, the maximum stress location exhibits a smaller circumferential stress range than plain pipe between 400 and 600 psig; however, this is not always the case indicating that the ranges of cycles in the pressure history will have a strong impact on fatigue life.

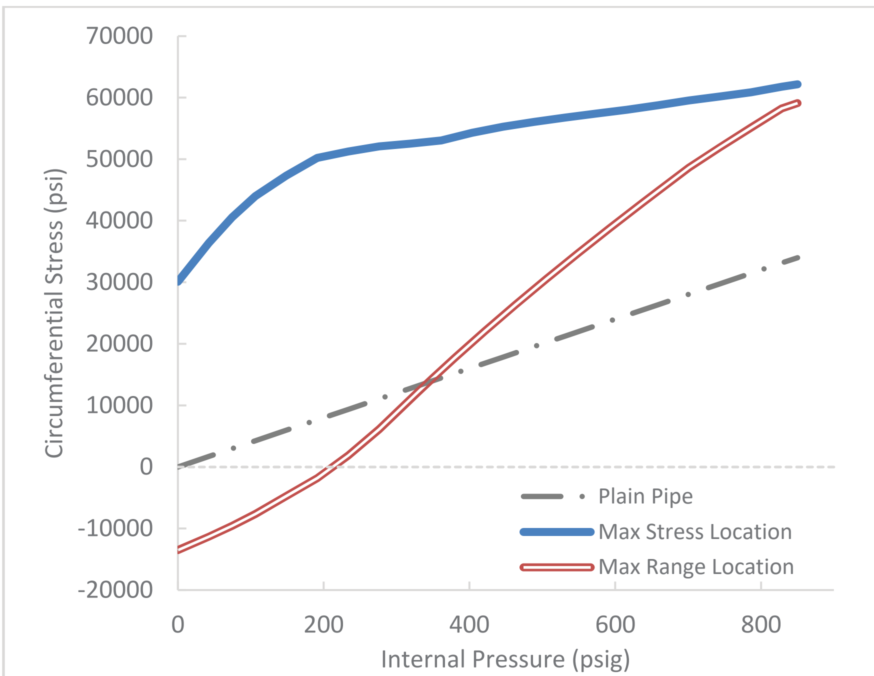

Figure 7. Example Stress Profile and Internal Pressure Relationship

By combining the internal pressure to pipe stress relationship with the operational pressure history, a fatigue life can be estimated. The internal pressure range from each identified cycle (changes along the horizontal-axis of **Error! Reference source not found.**) are converted to an equivalent stress range using the relationship developed via the FEA model (changes along the vertical-axis of **Error! Reference source not found.**).

In order to estimate the fatigue life, the Palmgren-Miner linear damage rule (also called "Miner's Rule") is applied using the pressure spectra. The linear damage rule defines damage as the fraction of life used up by a cycle. When the sum of these fractions reaches 1.0, failure is predicted. The damage caused by each cycle, D_{σ}, defined as:

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$$D_\sigma = \frac{1}{N_{f,\sigma}}$$

where $N_{f,\sigma}$ is cycles to failure at a stress amplitude σ.

The total damage, D, is therefore:

$$D = \sum \frac{n_\sigma}{N_{f,\sigma}}$$

The total fatigue damage of the pressure history is calculated using the relationship between σ and $N_{f,\sigma}$ using BS 7608[5] Class D mean S-N curve constants (shown in the following equation) when σ is in ksi:

$$\log N_{f,\sigma} = 10.0851 - 3 \log \sigma$$

The BS 7608 Class D mean S-N curve was chosen for comparison purposes only. An appropriate S-N should be evaluated based on the pipe material and interaction with a weld. The remaining fraction of fatigue damage, $1/(SF - D)$, where SF is the safety factor (e.g., 10). The fractional fatigue damage per year is then converted to fatigue life.

Error! Reference source not found. contains a summary of the differences in estimated fatigue lives when using hypothetical aggressive and non-aggressive pressure spectra. Aggressiveness was defined using the spectrum severity indicator (SSI), which calculates the number of cycles of a given pressure range required to grow a crack the same amount as the actual pressure time history over one year[6]. The hypothetical spectra were developed such that the SSI of the non-aggressive and aggressive spectra, assuming a pressure range equivalent to 13 ksi, were 500 and 5400, respectively. As shown in **Error! Reference source not found.**, when the maximum stress and stress range locations are different, there is a significant reduction in fatigue life except for two cases:

- Dent ID 14 – The majority of the hypothetical pressure cycles were in a region where the stress-to-pressure relationship had a higher slope (i.e., a larger circumferential stress range) at the location with the maximum stress compared to the maximum stress range location.
- Dent ID 18 – The majority of the hypothetical pressure cycles were in a region where the stress-to-pressure relationship was compressive at the location with the maximum stress range compared to the maximum stress location.

Table 2. Fatigue Life Comparison for Max Stress and Max Stress Range Locations

[5] British Standards Institution, Guide to fatigue design and assessment of steel products, BS 7608:2014+A1:2015, dated 31 March 2014

[6] BMT Fleet, "Fatigue Considerations for Natural Gas Transmission Pipelines", 30348.FR (Rev. 02), 30 June 2016, INGAA

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	Non-Aggressive, 500 SSI			Aggressive, 5400 SSI		
Dent ID	Max. Location (years)	Max. Range Location (years)	% Reduction	Max. Location (years)	Max. Range Location (years)	% Reduction
1	21,349	538	97.5%	1,985	50	97.5%
2	1,560	1,560	†	146	146	†
3	680	680	†	63	63	†
4	1,839	1,839	†	172	172	†
5	12,876	2,718	78.9%	1,279	255	80.1%
6	10,549	2,949	72.0%	994	278	72.0%
7	71,582	1,436	98.0%	6,521	132	98.0%
8	5,296	5,296	†	522	522	†
9	2,622	2,622	†	253	253	†
10	42,950	785	98.2%	4,434	72	98.4%
11	2,954	2,954	†	300	300	†
12	239	239	†	21	21	†
13	89,812	1,453	98.4%	8,357	134	98.4%
14	3,584	4,238	-18.2%	340	404	-18.9%
15	11,323	11,323	†	1,057	1,057	†
16	36,203	36,203	†	3,387	3,387	†
17	68,363	26,209	61.7%	6,269	2,453	60.9%
18	29,437	142,857	-385.3%	2,821	12,763	-352.4%

† Maximum stress location and maximum stress range were coincident

Conclusions

In reviewing this collection of 18 dent ECA's, the maximum stress range location resulted in a lower predicted fatigue life than the maximum stress location in all but two unique cases (Dents 14 and 18). For the non-aggressive 500 SSI pressure cycle case, the fatigue lives for all dent features were still quite large (>100 years), however the results for the maximum stress range location were often more than 60% lower than the fatigue lives for the maximum stress location. Similar results were shown considering the aggressive pressure cycling, albeit with much shorter fatigue lives, but in several cases the reduction in calculated fatigue life for the maximum stress range location was multiple orders of magnitude lower than those obtained with the maximum stress location. This further illustrates the conclusion that it is important to consider the maximum stress results as well as the maximum stress range results when calculating the fatigue life, as the two are not always coincident.

It should be noted that all of the result locations (i.e. maximum stress and maximum stress range) in this study were determined comparing stresses at MOP and 0 psig when deciding where to extract results from within the FE model. If the primary operating pressures for a particular line segment are concentrated within a particular pressure spectrum well below MOP, it would be prudent to compare the stress results from the FE model at these lower pressures to ensure the most conservative case is being evaluated for the fatigue life calculation.

Surveying the assortment of dent ECA's in this study, it is difficult to determine conclusively when the location of maximum stress range does and does not coincide with the location of maximum stress. The location of maximum stress range was different than the maximum stress location in nine

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of the 18 cases evaluated in this study. Of those nine cases, eight were constrained dents, with the lone exception being a dent interacting with metal loss, which adds the complexity of a stress concentration and therefore skews the results. This would lead the authors to believe that restraint condition plays a role in whether or not the locations of maximum circumferential stress and maximum stress range are coincident. However, considering the sample size of 18 dents, and considering the remaining dents were split 6/3 between constrained and unconstrained dents where these locations were coincident, further evaluation and a larger sample size is needed to justify this conclusion.

The remaining parameters (D/t, SMYS, Dent Depth, and Dent Aspect Ratio) showed no discernible influence on whether or not the locations of maximum circumferential stress and maximum change in circumferential stress are coincident. While it is possible that perhaps a combination of these parameters could be evaluated to find when these locations coincide, the limited sample size of 18 dents is not enough to draw a conclusion at this time other than it is truly dependent on each individual dent. Thus, when performing a Level 3 dent ECA, consideration should be given not only to the maximum stress location, but also the location of maximum change in stress when evaluating the fatigue life of the dent.

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