REX2024
PRCI Research Exchange

PRCI-REX2024-088: Mechanical Damage Assessment Improvements (MD-5-03, MD-5-04, MD-2-4)

This research was funded in part under the Department of Transportation, Pipeline and Hazardous Materials Safety Administration's Pipeline Safety Research and Development Program. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Pipeline and Hazardous Materials Safety Administration, or the U.S. Government.

Sanjay Tiku
San Diego, California
February 27, 2024

LEADING PIPELINE RESEARCH
Pipeline Research Council International

Introduction

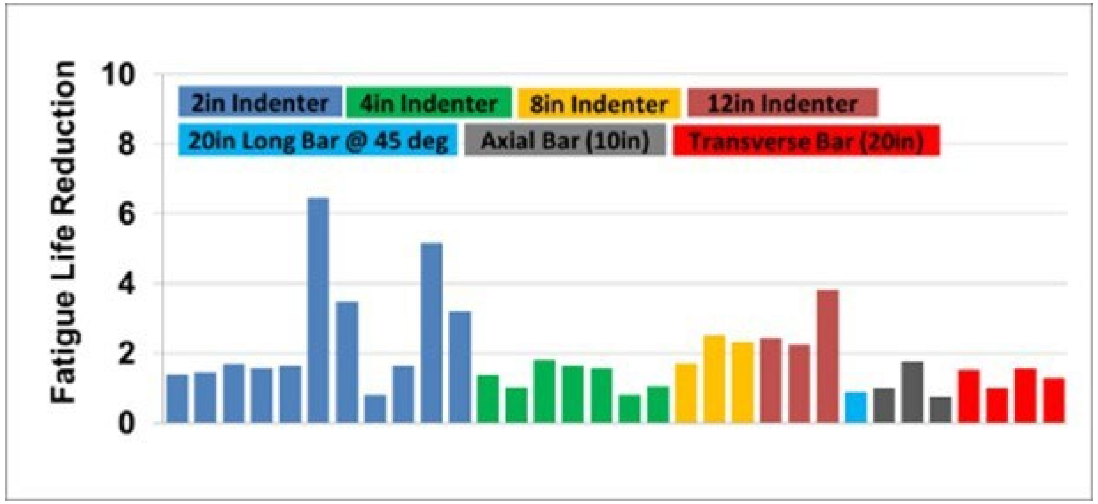
Brief overview of three projects carried out under MD SRP discussed here:

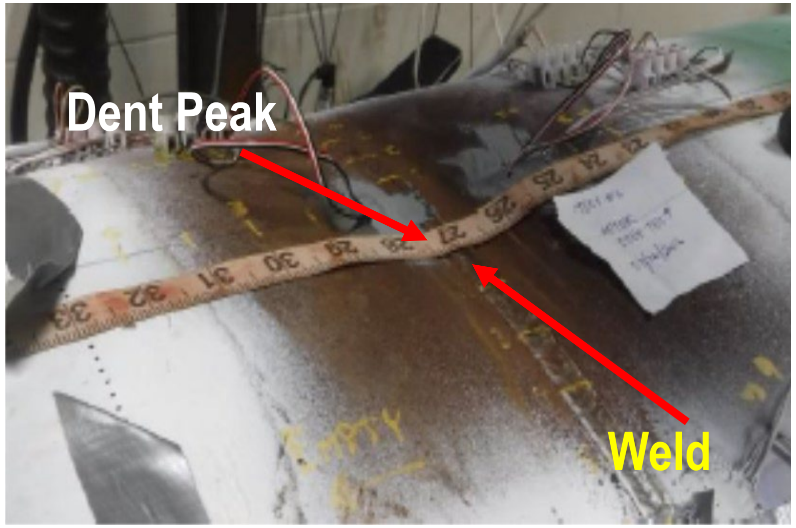
- MD 2-4 Improvement in Dent Assessment and Management Tools
  - Task - Modification of dent weld interaction criteria
- MD 5-04 Screening Tools for Assessing Dents with Metal Loss
  - Determine the effectiveness of the corrosion-gouge discrimination method described in Annex H of API RP 1183, Figure H2
- MD 5-03 Guidance for Performing ECA of Dents- Mega Rule “49 CFR §192.712 (c)”
  - Description of fatigue life estimation approaches incorporated in API RP 1183 and simplification of approaches using SSI (pressure spectrum severity)
  - Development of Level 0.75
  - Dent crack fatigue life estimation for dents with cracks for dents with metal loss scenarios where the metal loss cannot be positively ruled out as a gouge

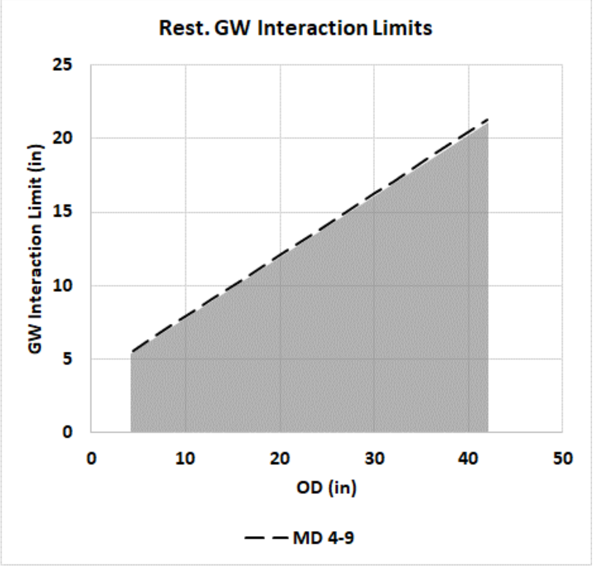
Improvement of Weld Interaction Criteria – MD 2-4

Modification of Dent Weld Interaction Limit

- Fatigue life reduction of 10 was conservatively used based on literature and Full-Scale tests (MD4-2, MD 4-11) where weld was positioned at the critical location (max stress range) within a dent (determined by FE modeling) to get the maximum (conservative) reduction in fatigue life as compared to the similar plain dent
- Maximum fatigue life reduction is due to the co-incidence of weld toe and maximum stress range
- Interaction distance was defined as the distance from dent peak where weld is no longer affecting dent fatigue life and reduction factor of 10 was used for the entire dent weld interaction zone regardless of distance from the dent peak



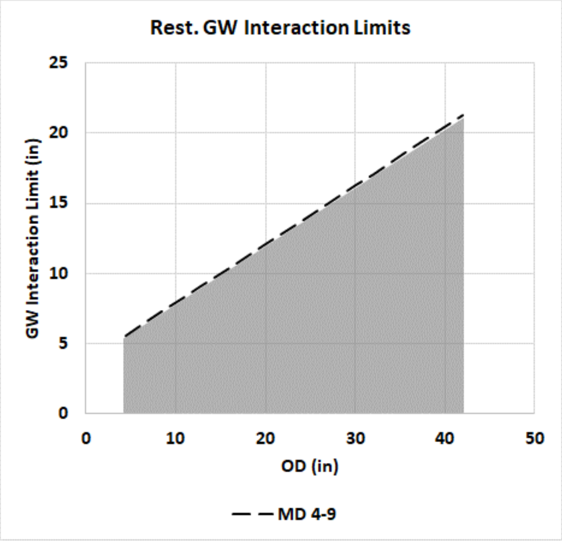


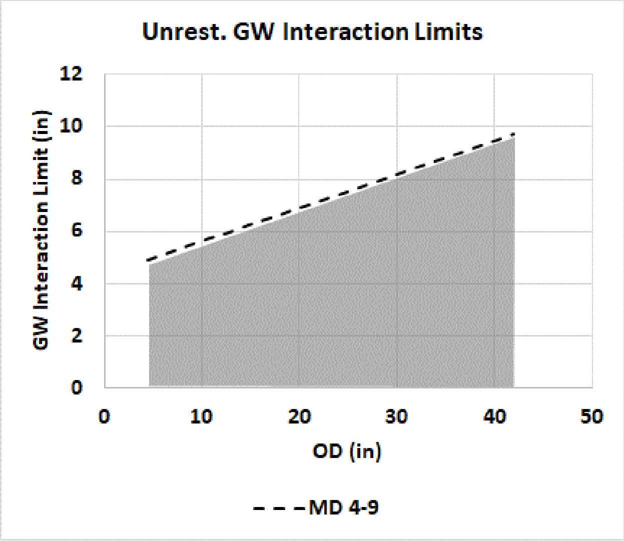


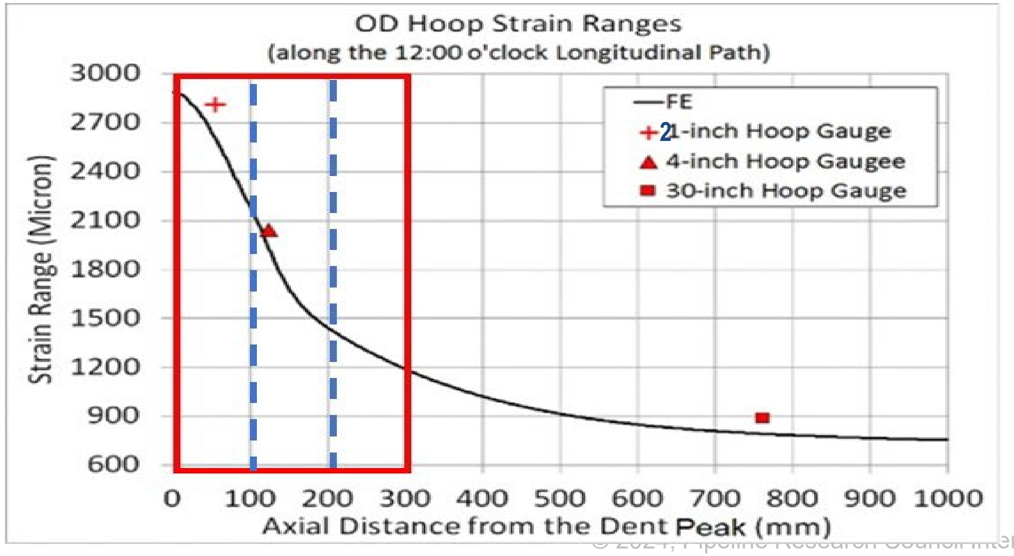
Improvement of Weld Interaction Criteria

Modification of Dent Weld Interaction Limit

- Dents have a high stress range gradient, and the stress range quickly reduces as it moves away from the maximum stress range location
- Higher upper-bound weld interaction limits observed were coming from axially long and flat indenters which resulted in axially long dents.
- An approach was devised where different interaction limits were established based on an axial length parameter (L/OD). $L = US\ L^{AX}_{50\%} + DS\ L^{AX}_{50\%}$. Axially long dents were observed to have longer interaction limits while shorter dents had shorter limits.
- After developing the different interaction limits based on dent length, the weld interaction zone was further divided into sub-zones. As the weld moves away from the dent peak the life reduction factor gets reduced.



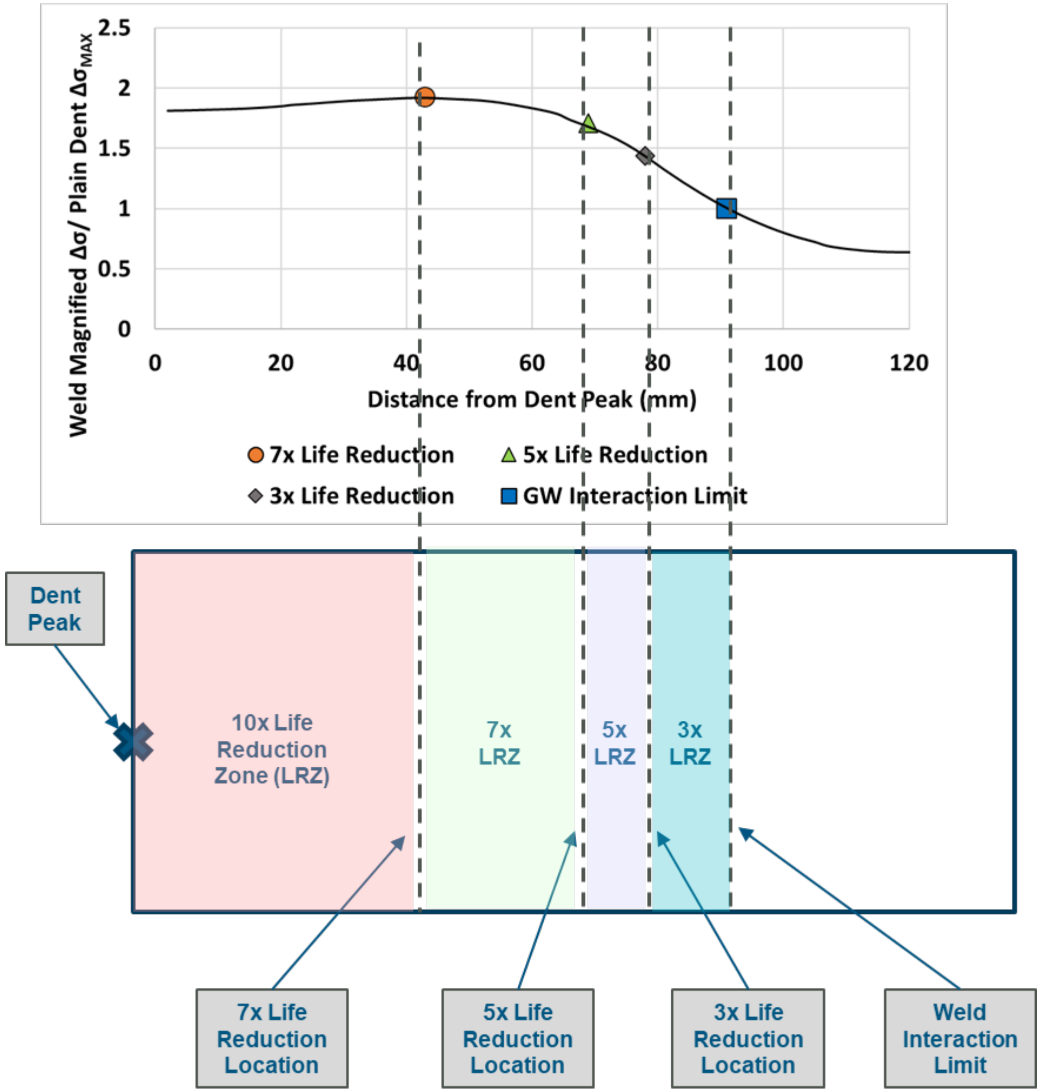




Improvement of Weld Interaction Criteria

Modification of Dent Weld Interaction Limit

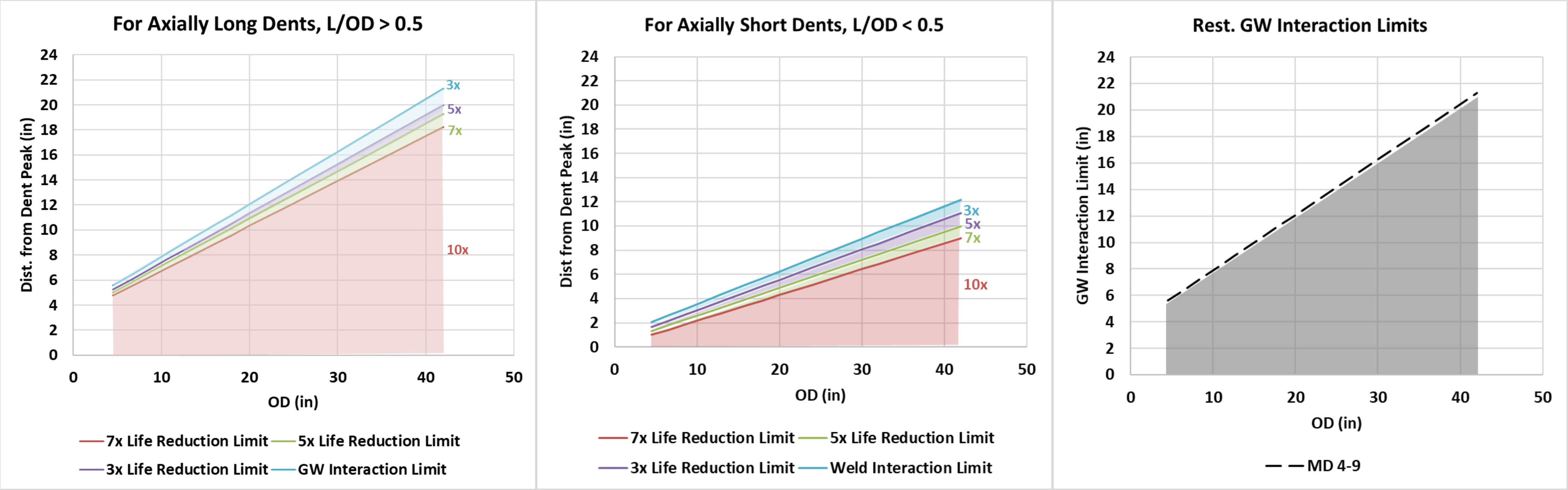
- As welds are placed further away from the plain dent maximum stress range location, the reduction in life induced by interaction decreases. Based on this, different interaction sub-zones were derived with life reduction factor decreasing with distance away from the dent peak
- The sub-zones were extracted from dent FE dent models
- For GW interaction, the upper bounds of the sub-zone limits were extracted for all dents with a particular OD.
- For LSW interaction, global upper bounds were evaluated for all FE dent cases.



Improvement of Weld Interaction Criteria

Modification of Dent Weld Interaction Limit – Restrained Dents

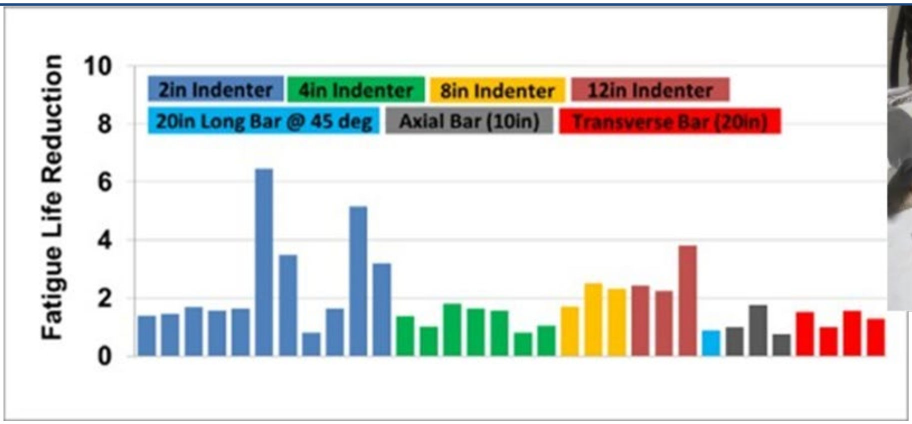
- Axially short and long dents were defined
- Different fatigue life reduction factors of (10, 7, 5 and 3) and associated zones were defined
- There is no change in maximum reduction factor of 10 but is applicable when weld is very close to the dent

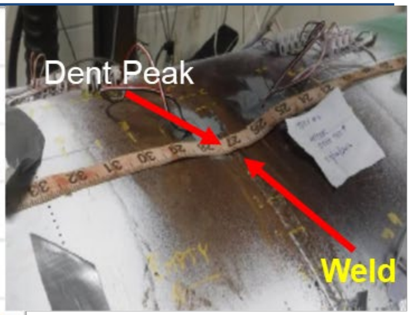


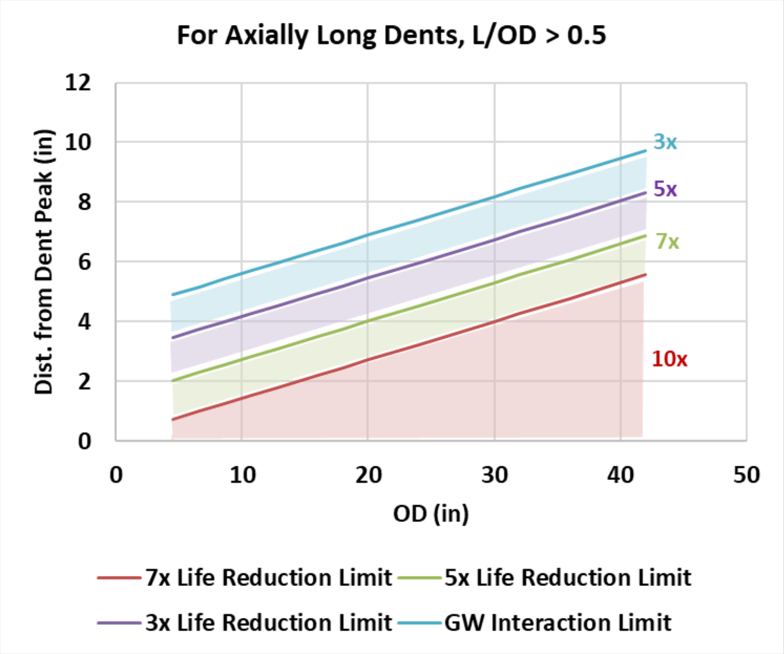
Improvement of Weld Interaction Criteria

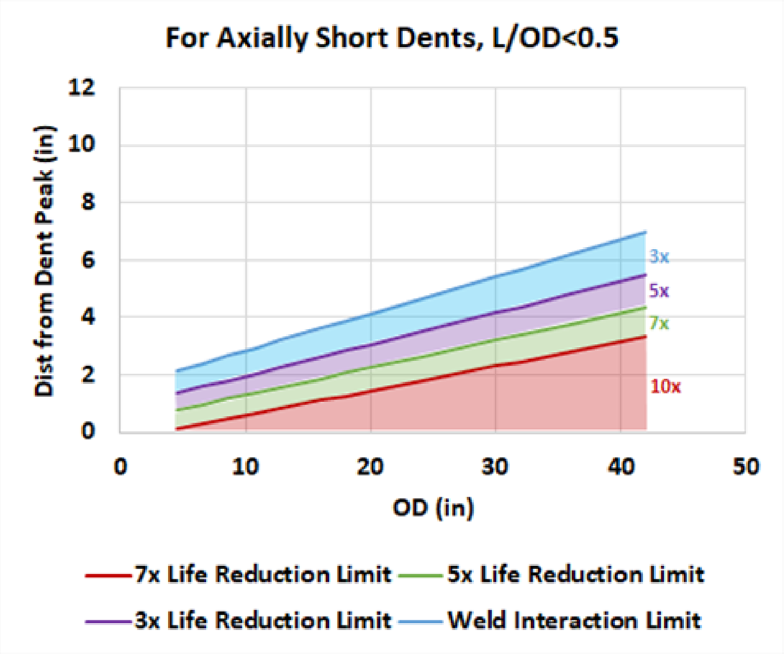
Modification of Dent Weld Interaction Limit – Unrestrained Dents

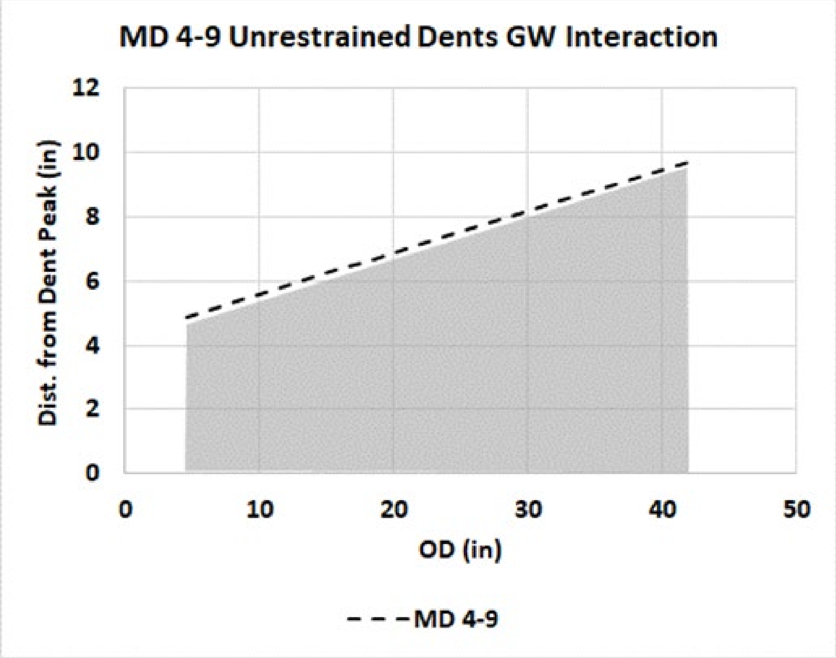
- Axially short and long dents were defined
- Different fatigue life reduction factors of (10, 7, 5 and 3) and associated zones were defined











MD 5-04 Screening Tools for Assessing Dents with Metal Loss

Objective

- Determine the effectiveness of the corrosion-gouge discrimination method described in Annex H of API RP 1183, Figure H2

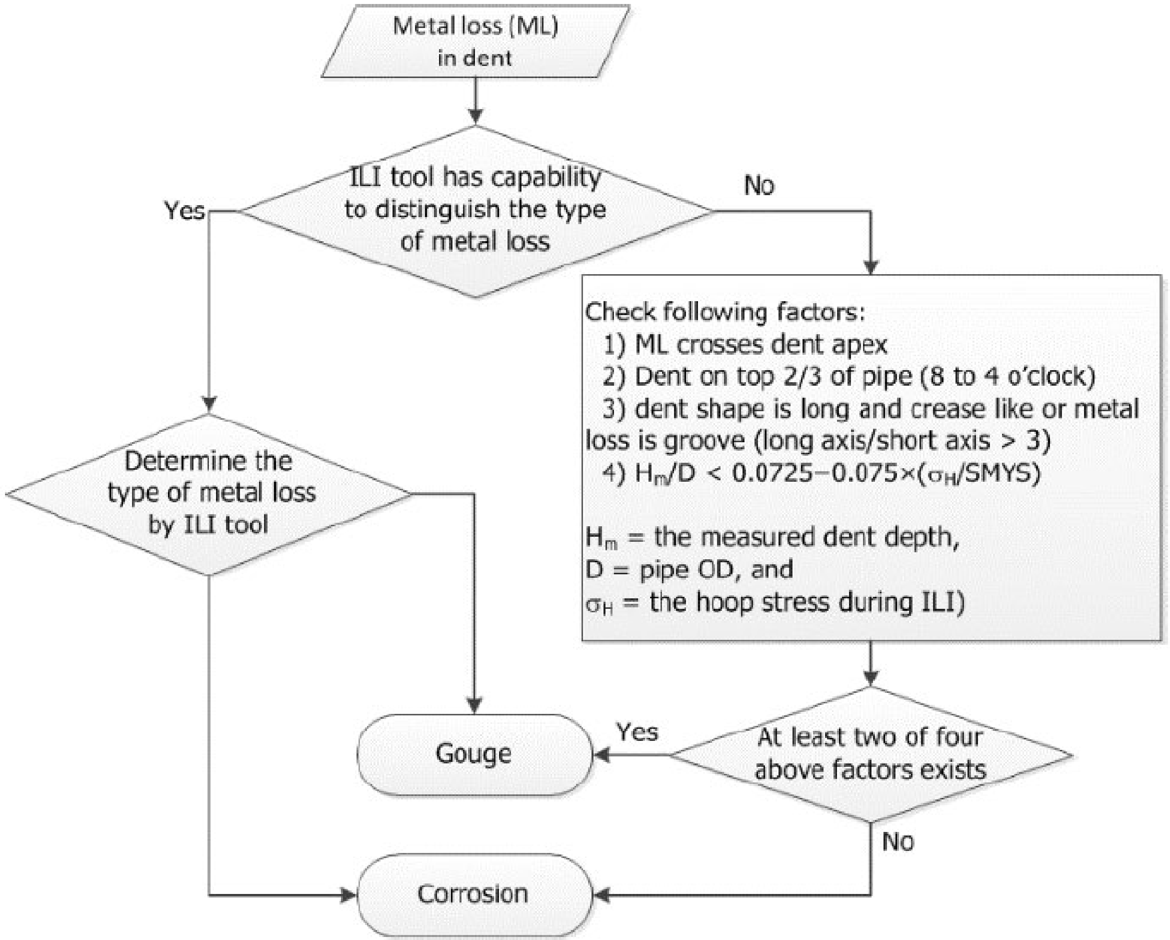
Scope

- Collect ILI data for dents coincident with metal loss features
- Collect corresponding in-ditch data that has categorized metal loss features as corrosion or gouge
- Follow the process as described in Annex H of API RP 1183
- Report the results
- Suggest improvements, if any

MD 5-04 Screening Tools for Assessing Dents with Metal Loss

- **Annex H in API RP 1183 provides a means to screen for gouges in metal loss features coincident with dents**
- **Annex H methodology requires testing 4 queries, with 2 positives indicating a gouge**
  - Q1 – Metal loss (ML) crosses dent peak
  - Q2 – ML on top 2/3 of pipe
  - Q3 – Dent/ML are slender (aspect ratio > 3)
  - Q4 - $\frac{H_m}{D} < 0.0725 - 0.075 * (\sigma_H/\sigma_{smys})$

$$H_m = measured\ dent\ depth,$$
$$D = pipe\ OD,$$
$$\sigma_H = hoop\ stress\ during\ ILI$$



MD 5-04 Screening Tools for Assessing Dents with Metal Loss

Validation of Annex H Screening Method

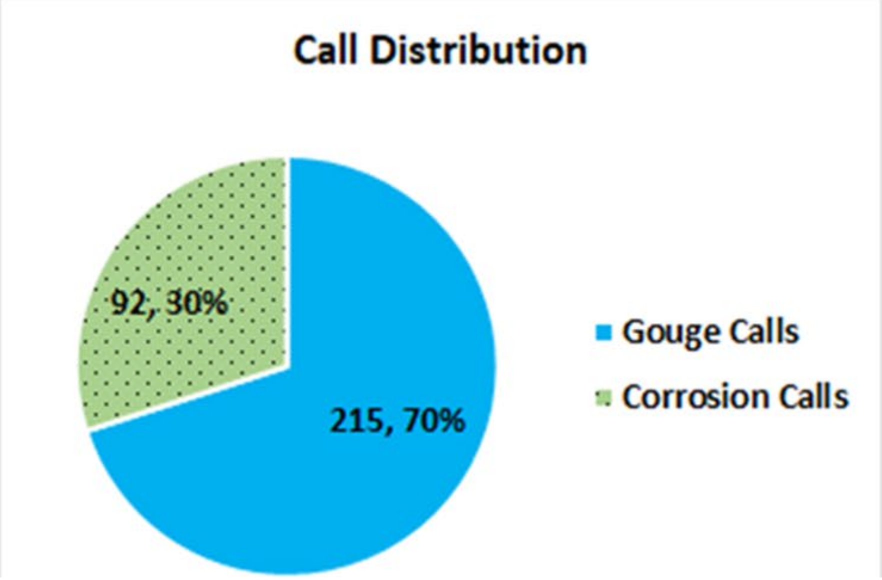
- **307 had corresponding pressure information to apply Annex H screening method**
  - 73 gouges & 234 corrosion features
  - 215 features out of 307 were identified as gouges based on Annex H
  - 63 out of 73 gouges were correctly identified
- **The screening method resulted in 86% of gouges being identified correctly (true positive) and 65% of corrosion features being misclassified as gouges (false positive).**

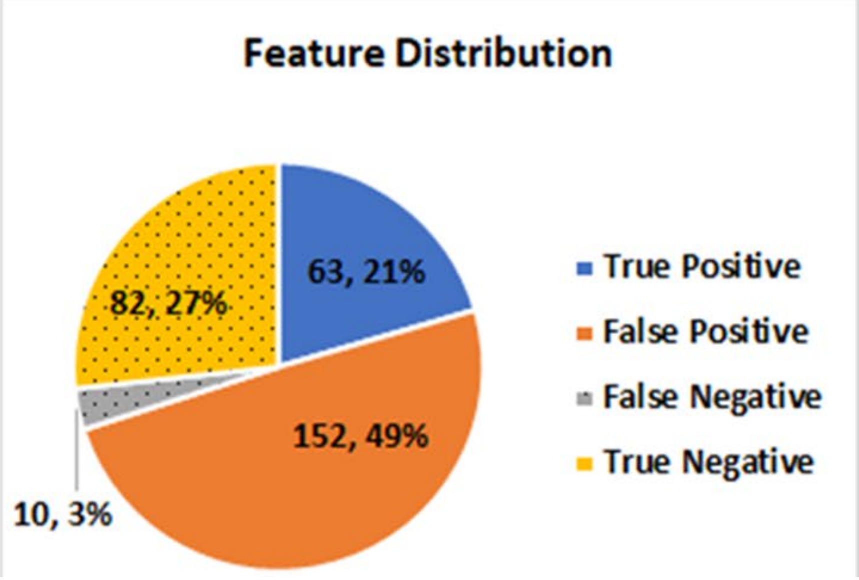
TP: Gouge identified as gouge

FP: Corrosion identified as gouge

FN: Gouge identified as corrosion

TN: Corrosion identified as corrosion

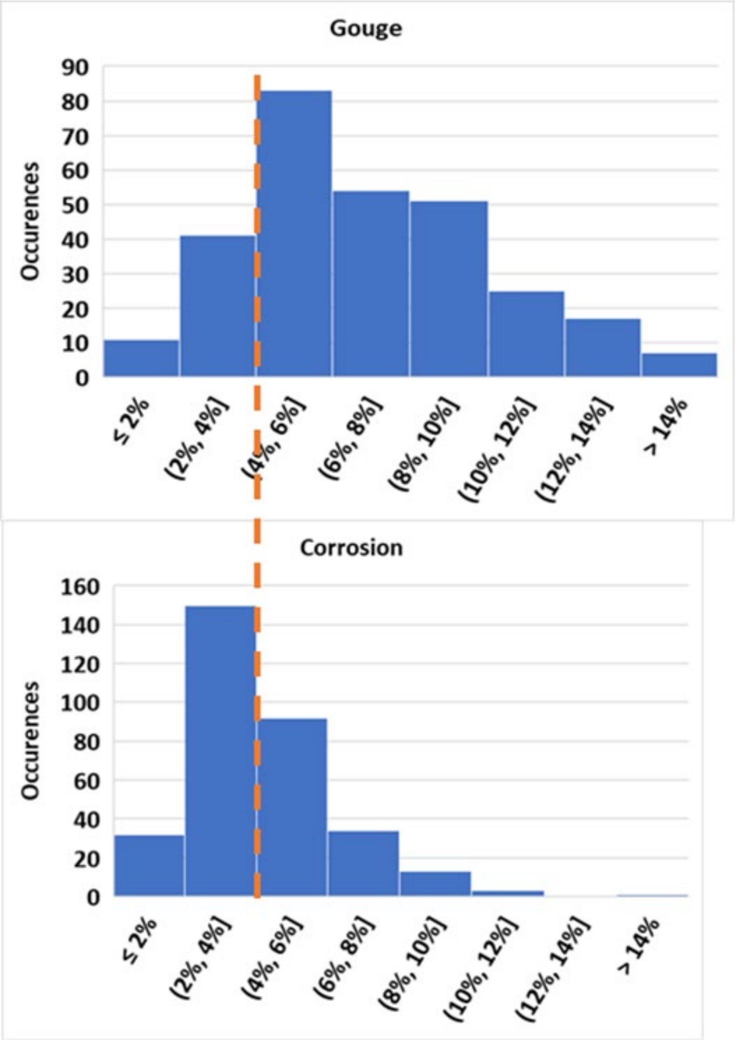




MD 5-04 Screening Tools for Assessing Dents with Metal Loss

Use of Dent Strain for Gouge-Corrosion Screening

- The efficacy of using dent strain as an alternate parameter for screening was also explored.
- 499 data points had dent strain information.
- Dents associated with gouges generally exhibited higher strains, compared to dents associated with corrosion features.
- It can be observed in the figure that majority of the dent-gouge features (~80%) have strain values greater than 4% strain, while ~50% of dent-corrosion features have strains less than 4% and ~80% have strains less than 6%.



MD 5-04 Screening Tools for Assessing Dents with Metal Loss

Machine Learning Algorithm for Screening Gouges

- Logistic regression model was employed. Some of the advantages of the model are:
  - A relatively simple equation can be developed which provides the probability of feature being a gouge/corrosion.
  - The logistic regression model is a probabilistic model, hence, probability of the prediction being a gouge/corrosion is provided.
  - Using various probability thresholds different levels of conservatism can be applied.
  - With a large training set a robust classification model can be developed.
  - The model can be constantly improved with the availability of new training data.

MD 5-04 Screening Tools for Assessing Dents with Metal Loss

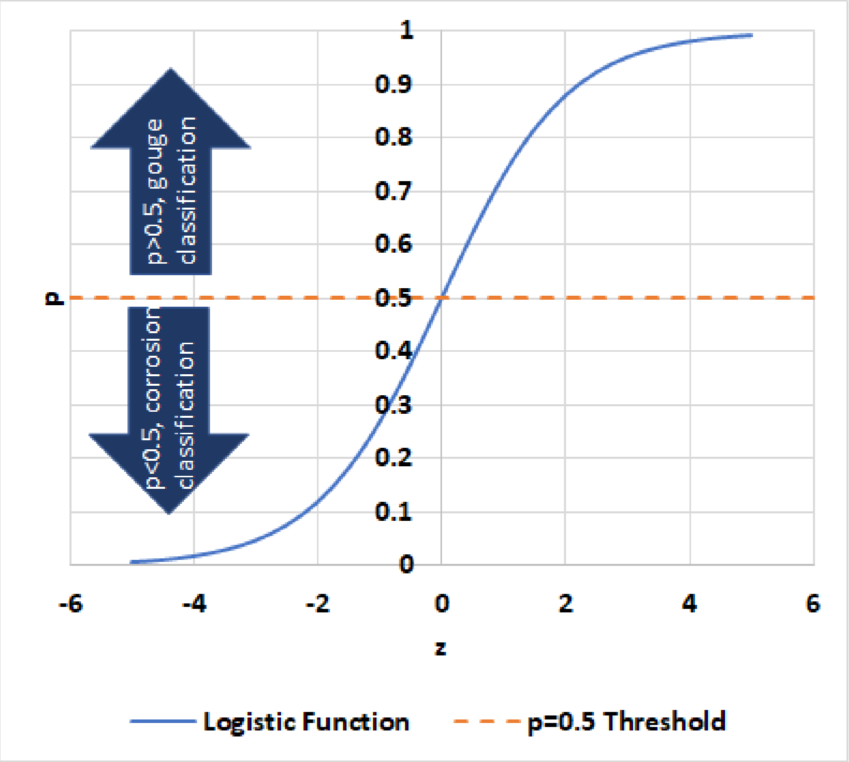
Logistic Regression Model

- Widely used for classification problems. Can use the fitted Logistic function to calculate the probability (p) that a feature is a gouge.
- Logistic function is defined as:

$$p = \frac{1}{1 + e^{-z}}$$

$$z = \theta_0 + \sum_{i=1}^{6} \theta_i X_i$$

- Where, θ_i are the fitted coefficients. X_i are the normalized classification variables. The outputs range from 0 to 1.
- A threshold value of probability (tp) is defined which separates the gouge and corrosion calls. If p > tp then the feature can be considered to be a gouge.



Inputs used – pipe geometry, ML clock location axial and circumferential distance of ML from dent center ML aspect ratio and dent strain

MD 5-04 Screening Tools for Assessing Dents with Metal Loss

- **Training and validation of the Logistic Regression model**
  - ~499 dent-metal loss data points were available for training and testing of the model
  - 80%-20% split was made between training and testing
  - Three sets of randomized training and testing sets were created for cross validation
  - Consistent training accuracy (at tp = 0.5) was observed from the randomized sets indicating the robustness of the fitting and training/testing data size.

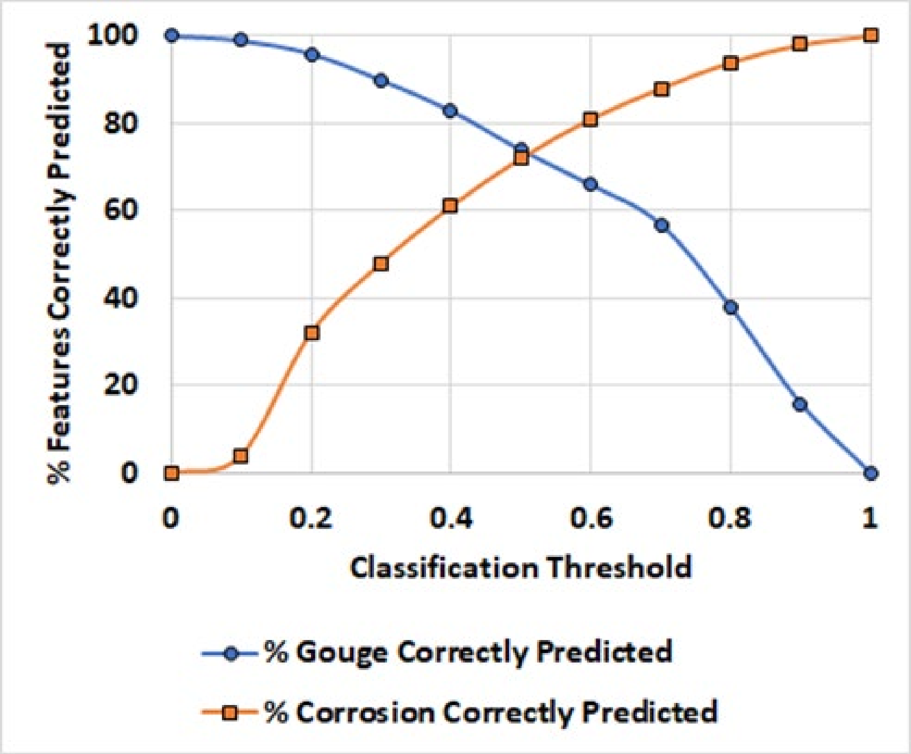
Dataset	Total Gouges	Total Corrosion	True Positive	True Negative	Training/Testing Accuracy
Training 1	151	249	113	179	73
Testing 1	37	62	27	44	72
Training 2	151	249	110	181	73
Testing 2	37	62	29	48	78
Training 3	151	249	112	178	73
Testing 3	37	62	27	46	74

REX2024
PRCI Research Exchange

MD 5-04 Screening Tools for Assessing Dents with Metal Loss

- **Effect of Probability Threshold (tp)**
- Probability thresholds can be altered to achieve different levels of conservatism.
- A standard tp = 0.4, is suggested as it provides good balance between correct gouge and corrosion prediction. A lower threshold like 0.3 can be applied if better gouge screening is required and higher corrosion misclassification is acceptable.

Classification Threshold (p)	% Gouge Correctly Predicted	% Corrosion Correctly Predicted
0	100	0
0.1	99	4
0.2	96	32
0.3	90	48
0.4	83	61
0.5	74	72
0.6	66	81
0.7	57	88
0.8	38	94
0.9	16	98
1	0	100



MD 5-04 Screening Tools for Assessing Dents with Metal Loss

Results of Logistic Regression Model and Comparison with other Screening Methods

Data Subset	Total Features	Total Gouges	Total Corrosion	True Positive	False Positive	% of Gouges Identified Correctly	% of Corrosion Identified as Gouge
Q1-Q4 Annex H	307	73	234	63	152	86%	65%
Q1-Q3 + Strain 4%	499	188	311	134	110	71%	35%
Q1-Q3 + Strain 2%	499	188	311	150	183	80%	59%
Q1-Q4 + Strain 4%	181	47	134	43	92	91%	69%
Q1-Q4 + Strain 2%	181	47	134	46	121	98%	90%
Logistic Regression (Test Set) threshold p=0.4	99	37	62	31	25	84%	40%
Logistic Regression (Test Set) threshold p=0.3	99	37	62	33	34	89%	55%

MD 5-04 Screening Tools for Assessing Dents with Metal Loss

Validation of all models using field inspection data as input (more data points were available)

Data Subset	Total Features	Total Gouges	Total Corrosion	True Positive	False Positive	% of Gouges Identified Correctly	% of Corrosion Identified as Gouge
Q1-Q4, Annex H	538	195	343	167	196	86%	57%
Q1-Q3 + Strain 4%	864	399	465	292	175	73%	38%
Q1-Q3 + Strain 2%	864	399	465	319	244	80%	52%
Q1-Q4 + Strain 4%	277	104	173	97	120	93%	69%
Q1-Q4 + Strain 2%	277	104	173	103	154	99%	89%
Logistic Regression threshold p=0.4	825	411	414	342	140	83%	34%
Logistic Regression threshold p=0.3	825	411	414	370	207	90%	50%

MD 5-03 Guidance for Performing ECA of Dents- Mega Rule "49 CFR §192.712 (c)"

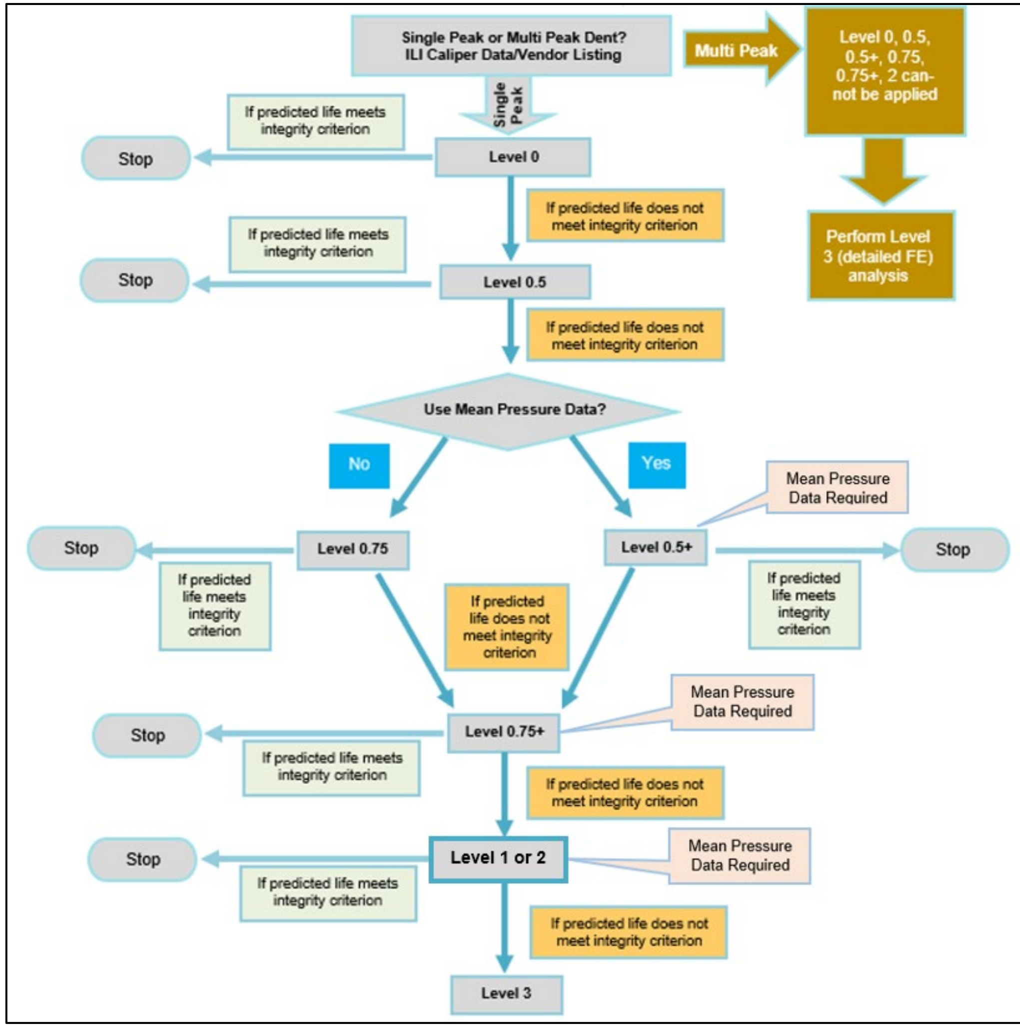
Scope

- **Dent fatigue life estimation techniques**
  - Identification and description of the current dent fatigue life estimation techniques (MD 4-9 & CEPA work) incorporated in API RP1183
  - Describe & define input parameters required for each assessment technique
  - Development of Level 0.75 - Incorporate dent depth (available in ILI listing) to reduce conservatism incorporated in different screening approaches
  - Fatigue life estimation based on SSI only when mean pressure & pressure ranges are not available
- **Dent crack fatigue life estimation**
  - Develop dent fatigue life curves for dents with cracks for dents with metal loss scenarios where the metal loss cannot be positively ruled out as a gouge.
    » *The fatigue curves developed for a range of pipe wall thicknesses, crack lengths, crack depths and dent stress range magnification factors (K_M)*

MD 5-03 Fatigue Life Estimation Approaches

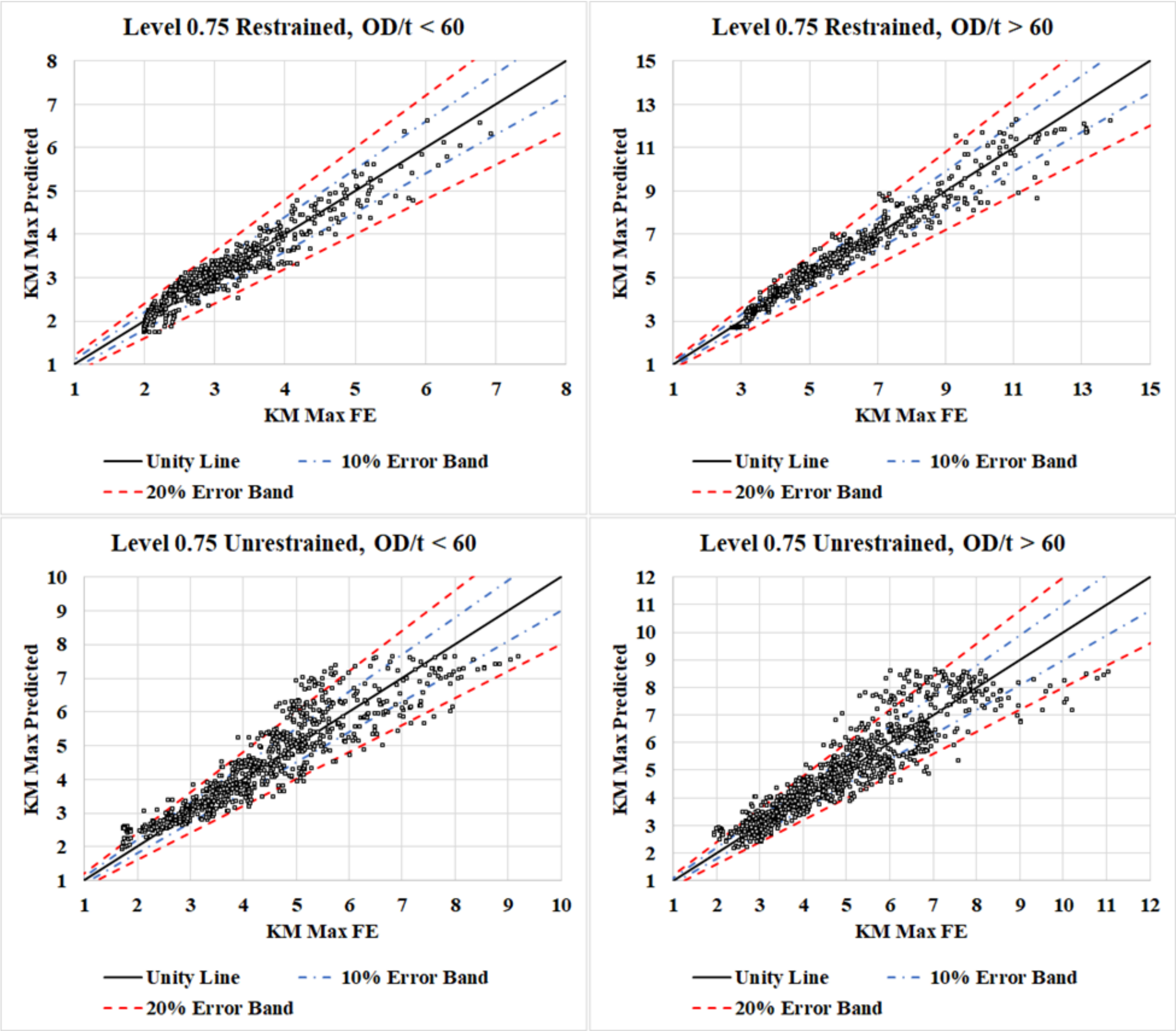
- Defined required inputs for each level of fatigue analysis (screening or assessment)
- Developed flow charts for all levels

	Required Inputs	
Screening/Assessment Level	**Using Pressure-Time History Data**	**Using SSI**
Level 0		OD, t, SSI, Restraint condition (shallow/deep classification for restrained dents)
Level 0.5	OD, t, SMYS, Operating cyclic pressure ranges and their counts, Restraint condition (shallow/deep classification for restrained dents)	OD, t, SMYS, SSI, Restraint condition (shallow/deep classification for restrained dents)
Level 0.5+	OD, t, SMYS, Operating cyclic pressure ranges and mean pressures, and their respective counts, Restraint condition (shallow/deep classification for restrained dents)	OD, t, SMYS, SSI, Operational Mean Pressure or Approximate Low, Med or High Mean Pressure*, Restraint condition (shallow/deep classification for restrained dents)
Level 0.75	OD, t, SMYS, Operating cyclic pressure ranges and their counts, dent depth (%OD), Restraint condition	OD, t, SMYS, SSI, dent depth (%OD), Restraint condition
Level 0.75+	OD, t, SMYS, Operating cyclic pressure ranges and mean pressures, and their respective counts, dent depth (%OD), Restraint condition	OD, t, SMYS, SSI, Operational Mean Pressure or Approximate Low, Med or High Mean Pressure*, dent depth (%OD), Restraint condition
Level 1 and Level 2	Level 2 OD, t, SMYS, Operating cyclic pressure ranges and mean pressures, and their respective counts, Dent geometry parameters, Restraint condition (shallow/deep classification for restrained dents)	Level 1 OD, t, SMYS, SSI, Approx. SSI cycles (10-40,30-60 or 50-80) best matching Operational Mean Pressure, Dent geometry parameters, Restraint condition (shallow/deep classification for restrained dents)



MD 5-03 Level 0.75 Fatigue Life Screening

- **Level 0.75 screening approach incorporates dent depth, pressure loading**
- **Regression equations were developed for Level 0.75 and Level 0.75+**
- **K_M (stress range magnification factor) predicted using the developed equations were compared with FEA results**
  - 75% of the data within 10% scatter band and 95% of the data within 20% scatter band



MD 5-03 Guidance for Performing ECA of Dents- Mega Rule "49 CFR §192.712 (c)"

K_M (Stress range magnification factor) Background

- K_M (stress range magnification factor) is ratio of maximum stress range in a dent to the nominal stress range (hoop stress range)

$$K_M = \Delta S_{max} / \Delta S_{nom}$$

- Multiplying nominal hoop stress range (using pressure range) by K_M results in dent stress range
- Conservative as K_M is used as hoop stress range (membrane) multiplier
  - » *Resulting stress range for a dent provides an option to use user selected SN curve or*
  - » *Carry out fatigue crack growth analysis using fracture mechanics formulation*
    - » *Especially useful for dents coincident with metal loss where metal loss cannot be ruled out as a gouge and allows conservative treatment to be considered as a crack, or*
    - » *For dent-crack scenarios where crack sizing is available and can provide remaining fatigue crack growth life*

MD 5-03 Dent Crack Fatigue Life Assessment

Dent Crack Fatigue Life

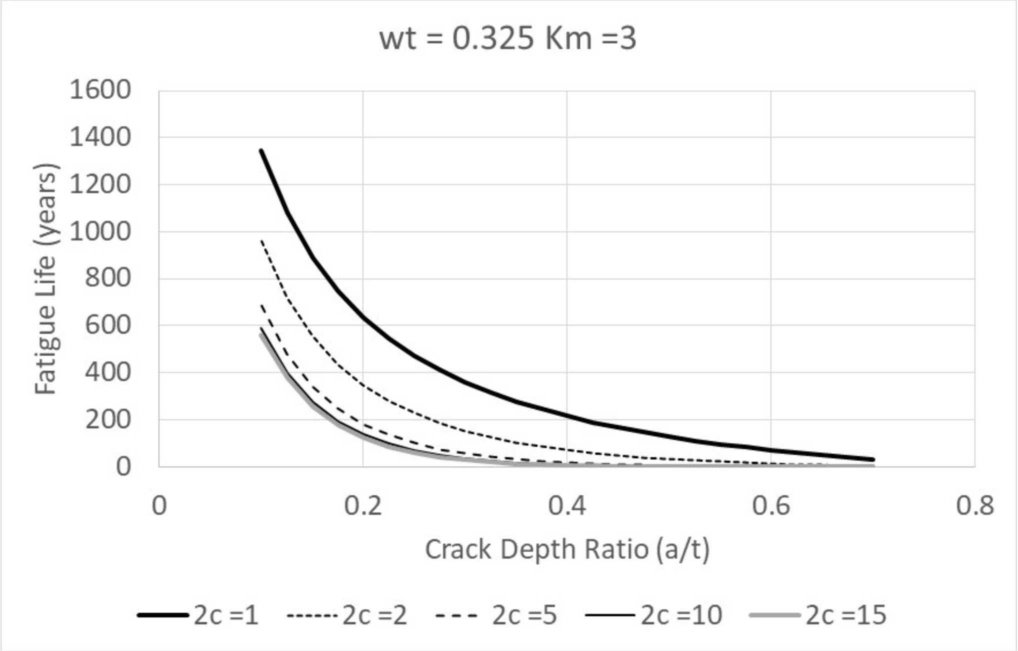
- For dents with metal loss scenarios where the metal loss cannot be positively ruled out as a gouge. Gouge could be conservatively treated as a crack and remaining fatigue life can be estimated.
- Using K_M, dent stress range can be estimated, and fracture mechanics approach used to estimate remaining fatigue life
- The approach is conservative
  - K_M is used as membrane stress range multiplier
  - Gouge is treated as a crack
- Dent crack fatigue curves were developed for a range of pipe wall thicknesses, crack lengths, crack depths and dent stress range magnification factors (K_M)
- Fatigue life curves were developed for
  - Fixed SSI of 10
  - Crack depth range – 0.1- 0.7 WT
  - Crack length range – 1”-15”
  - Wall thickness range – 0.2” – 0.645”
  - K_M range – 1-14 (K_M values derived from different screening/assessment level)

MD 5-03 Dent Crack Fatigue Life Assessment

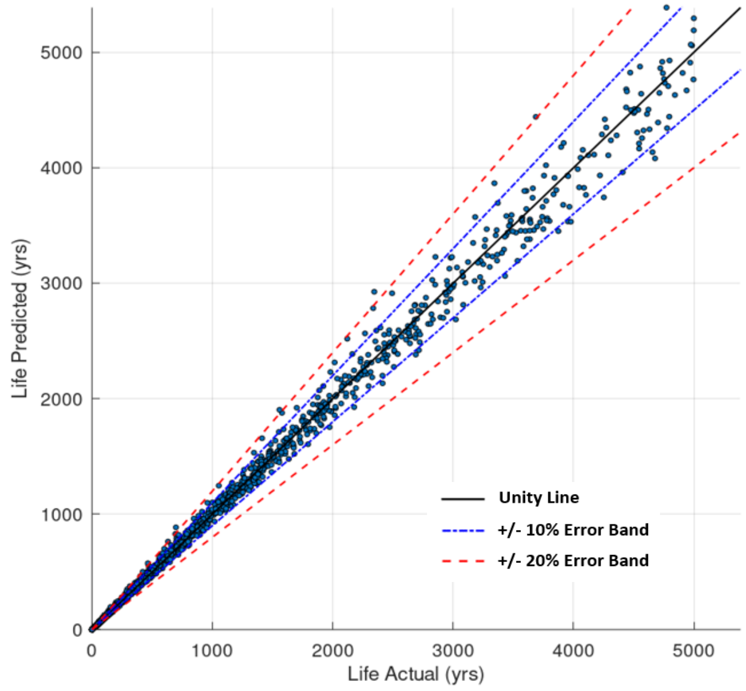
Dent Fatigue Life Curve

- A regression equation was developed
- Fatigue life predicted using the equation was compared against fracture mechanics calculations
- ~92% of the data (6700 data points) within 10% error band

Example Remaining Fatigue Life – Dent with Crack

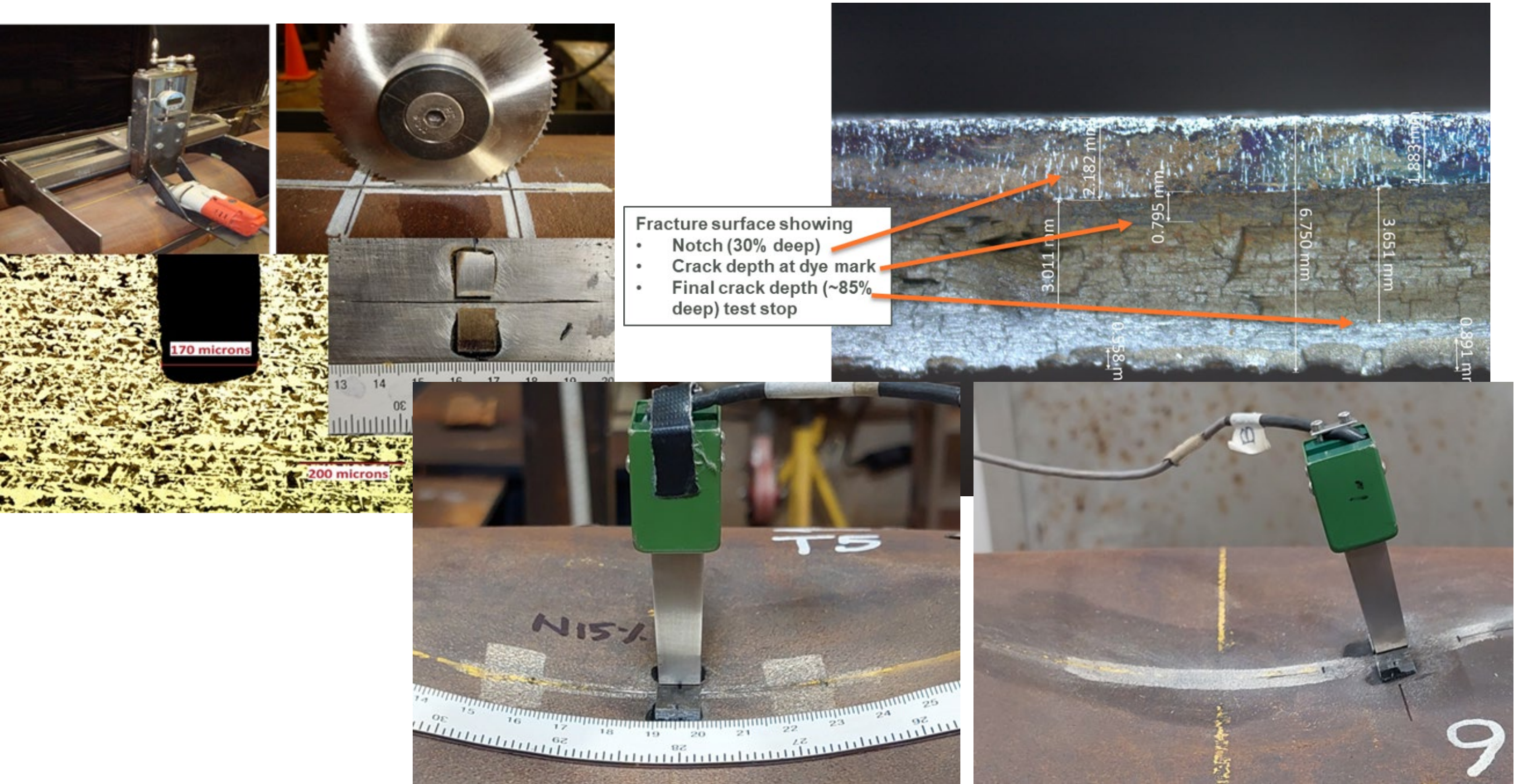


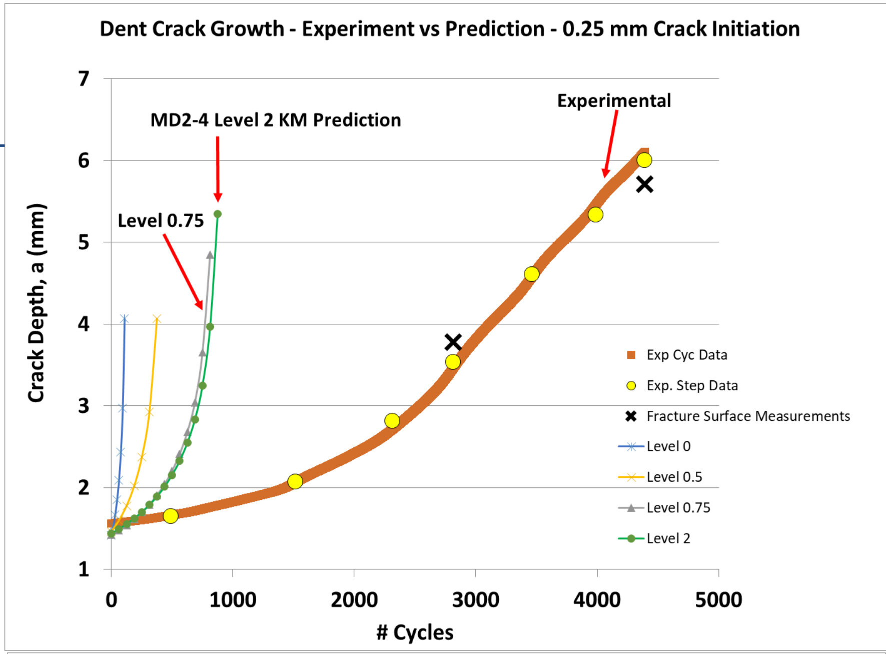
Remaining Dent Crack Fatigue Life Unity Plot

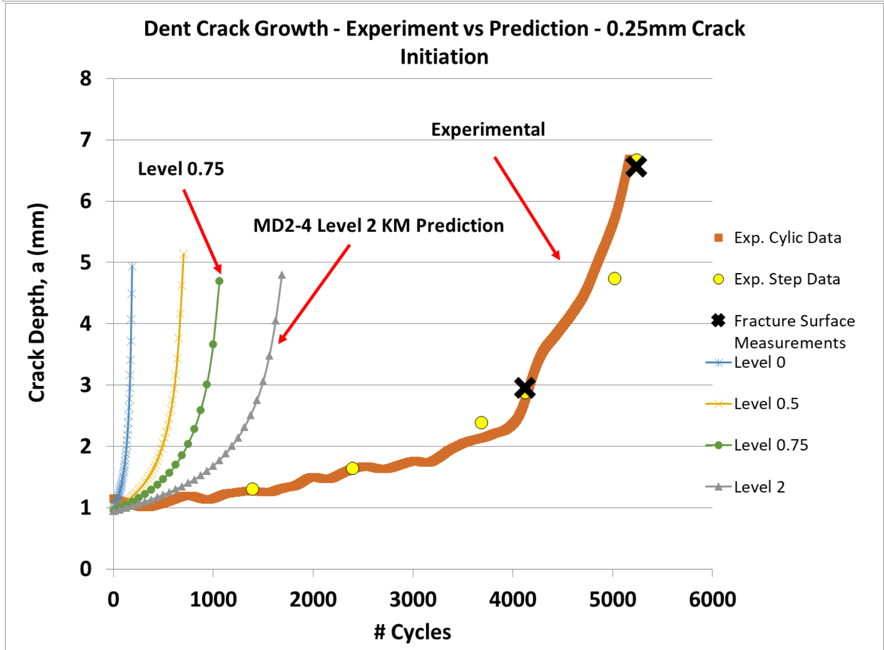


MD 5-03 Full-Scale Test - Dent with Crack

- Full-scale fatigue tests were carried out on dents with cracks to validate the applicability of the K_M approach for dent fatigue crack growth assessment.
- The approach provides conservative crack growth predictions.







Summary

- Modified dent weld interaction approach was developed. This allows the use of lower fatigue reduction factors based on the location of the weld from the dent peak. This will result in reducing conservatism currently inherent in dent weld interaction approach.
- The API RP 1183 Annex H method as well as the Logistic regression method developed as part of this project, can be reliably used by pipeline operators for the classification of ILI reported dents with metal loss. Annex H results in higher percentage of corrosion features being identified as gouges compared to the logistic regression method developed as part of this project.
- Level 0.75 and Level 0.75+ dent fatigue life screening approach have been developed. The screening approach incorporates dent depth that is available from the ILI listing and no detailed dent ILI three-dimensional profile is required.
- The methodology to assess dents with cracks, gouges and metal loss that cannot be ruled out as gouge has been developed.

thank you

REX2024
PRCI Research Exchange

Sanjay Tiku
BMT Canada Ltd

613 219 8183

stiku@ca.bmt.org