

Meeting Agenda
API/PRCI Joint Workshop on Dent Assessment & Engineering Analysis Methods

PRCI Technology Development Center
Houston, TX
August 9, 2018

7:30 – 8:30	Registration/Sign in and Breakfast	
8:30 – 8:45	Introduction and Opening Remarks	Mark Piazza
8:45 – 9:30	Stress Concentration Factor Analysis	Chris Alexander
9:15 – 10:00	Dent Assessment with Considerations of Geohazards & Pipeline Vintage	Yong-Yi Wang
10:00 – 10:15	BREAK	
10:15 – 11:00	PRCI/BMT Dent Fatigue Assessment Method	Aaron Dinovitzer
11:00 – 11:45	Burst and Fatigue Failure of Dent+Gouge	Brian Leis
11:45 – 12:30	LUNCH	
12:30 – 1:15	Strain-based Dent Assessment Approaches	R. Krishnamurthy
1:15 – 1:45	Natural Gas Operators Approach to ECA	Mike Rosenfeld
1:45 – 2:00	BREAK	
2:00 – 2:45	Industry Panel – Approaches to Dent Assessment and Management <i>The panel session will be a facilitated discussion that addresses the practical challenges of managing dents and application of the dent assessment methods presented at the workshop. The panel will include representatives from trade associations, PHMSA, and pipeline operators, including natural gas and hazardous liquids pipeline operators.</i>	CJ Osman Steve Nanney Munendra Tomar Yvan Hubert
2:45 – 3:00	Q&A and Path Forward	Mark Piazza
3:00 – 3:15	Meeting wrap-up and Action Items	Mark Piazza

History of the SCF and Overview of the Dent Validation Collaborative Industry Program (DV-CIP)

**API / PRCI Joint Workshop on Dent
Assessment & Engineering Analysis Methods**

Tuesday, August 7, 2018 | 8:45 to 9:30 AM

PRCI Technology Development Center | Houston, Texas

Prepared by Dr. Chris Alexander, PE
(contributions from Rhett Dotson, ROSEN)

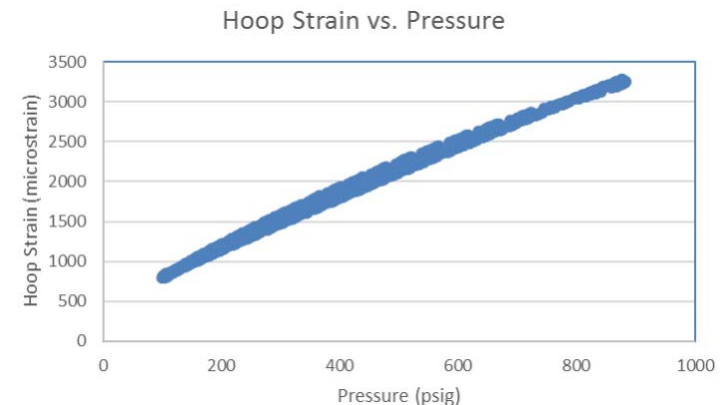
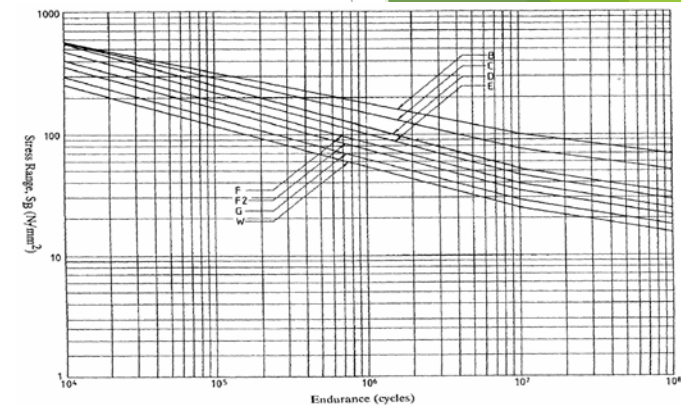
Presentation Overview

- ▶ Brief history on the SCF and its use in evaluating dent severity
- ▶ Use of SCFs in risk ranking 15 dents in an anchor-snagged subsea pipeline
- ▶ The **2015 Dent Validation Collaborative Industry Program** (DV-CIP)
- ▶ Finite Element Dent Assessment Tool (FE-DAT)
- ▶ Elements of the “Ideal” Dent Analysis
- ▶ Thoughts for the future

The SCF

- ▶ The ratio of the peak stress in a body to the calculated nominal stress
- ▶ Widely used and commonly-accepted in a variety of applications
- ▶ When used with S-N curves, SCFs can be used to estimate fatigue life
- ▶ After application of several pressure cycles, stresses in dents behave in a linear manner (elastically)

$$SCF = \frac{\sigma_{peak}}{\sigma_{nom}}$$

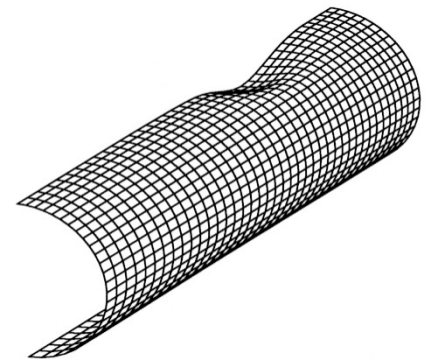


Dents: Past, Present, and Future

- ▶ 1990s – experimental work to estimate fatigue life as a function of dent depth and pipe geometry; early SCF work
- ▶ 1997 – FEA models used to generate “generalized” SCFs (d/D)
- ▶ 1998 – molds used capture dent geometry for FEA
- ▶ 2005 – dent profile based on ILI caliper data
- ▶ 2008 –three-dimensional ILI data used to generate FEA models
- ▶ 2013 – automated FE-DAT dent assessments based on ILI data
- ▶ **The Future: automated dent assessment and response**



Dent in
subsea
pipeline off
the coast of
Hawaii
(circa 1998)



Generalized SCF Tool (1997)

Table 5 Stress Concentration Factors ($\Delta\sigma/\Delta P$) for Unconstrained Dome Dents

Pipe D/t	Residual Dent Depth (percent d/D)									
	1	2	3	4	5	6	7	8	9	10
Low Range Pressure Cycle (0 - 50% MOP)										
34	38.5	42.7	47.1	51.5	56.0	60.7	65.6	70.4	75.4	80.5
68	81.1	103.5	128.9	145.1	164.3	182.5	199.5	215.5	230.4	244.3
High Range Pressure Cycle (50 - 100% MOP)										
34	34.8	38.7	42.5	46.2	49.8	53.2	56.6	59.8	62.9	65.9
68	70.7	87.1	101.4	113.6	123.7	131.7	137.7	141.5	143.3	
Full Range Pressure Cycle (0 - 100% MOP)										
34	32.9	38.0	42.8	47.4	51.7	55.8	59.7	63.4	66.8	70.0
68	71.0	90.8	107.1	119.8	128.9	134.4	136.3			

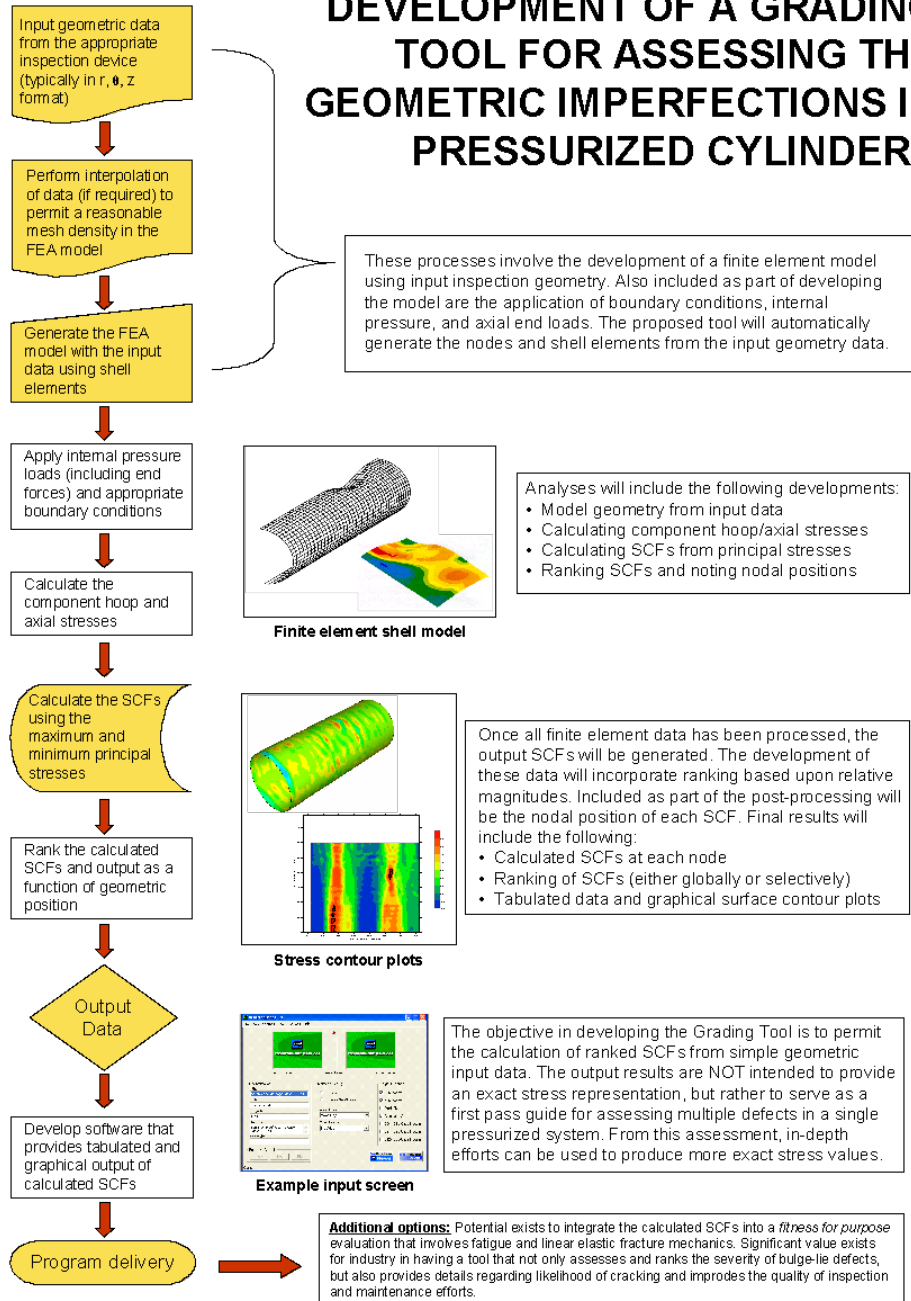
SCF = 4.0

Notes:

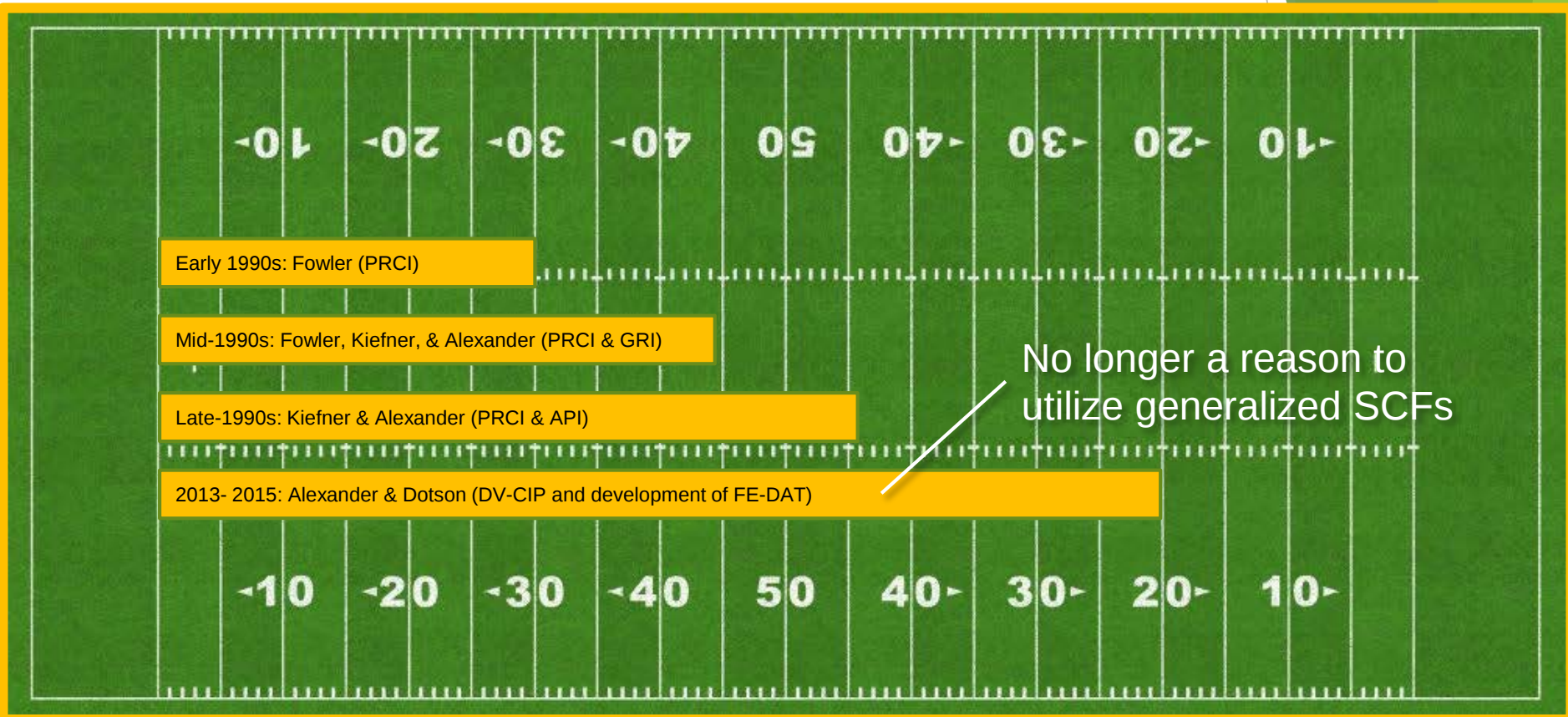
1. Residual dent depths (d/D) based upon maximum analytical dent depths remaining after prescribed pressure range applied to sample for one cycle
2. Pressure ranges based upon percentage of MOP, Maximum Operating Pressure (100% MOP corresponds to 72% SMYS)
3. Tabulated SCF values based upon curve fit of FEA data using a second-order polynomial
4. Number in **bold italics** are extrapolated from the range of minimum and maximum residual FEA dent depths
5. Polynomial curve fitting process produced some invalid values (out of range with other values) and are indicated by cells that have been blacked out (■).

Preliminary efforts that eventually led to the development of an “automated” SCF dent assessment tool (c. 2004)

DEVELOPMENT OF A GRADING TOOL FOR ASSESSING THE GEOMETRIC IMPERFECTIONS IN PRESSURIZED CYLINDERS



History of the SCF



Emergency Response Case Study (2007)

(18-inch diameter pipeline in 2,300 feet seawater)



Paper No. OTC 23454

Application of a Grouted Sleeve to Remediate Damaged Subsea Pipeline

Alessandro Vagata and Bill Bath, Saipem America; Chris Alexander, Stress Engineering; Alexander Aalders, Williams Midstream; Danny Seal, GL Nobel Denton

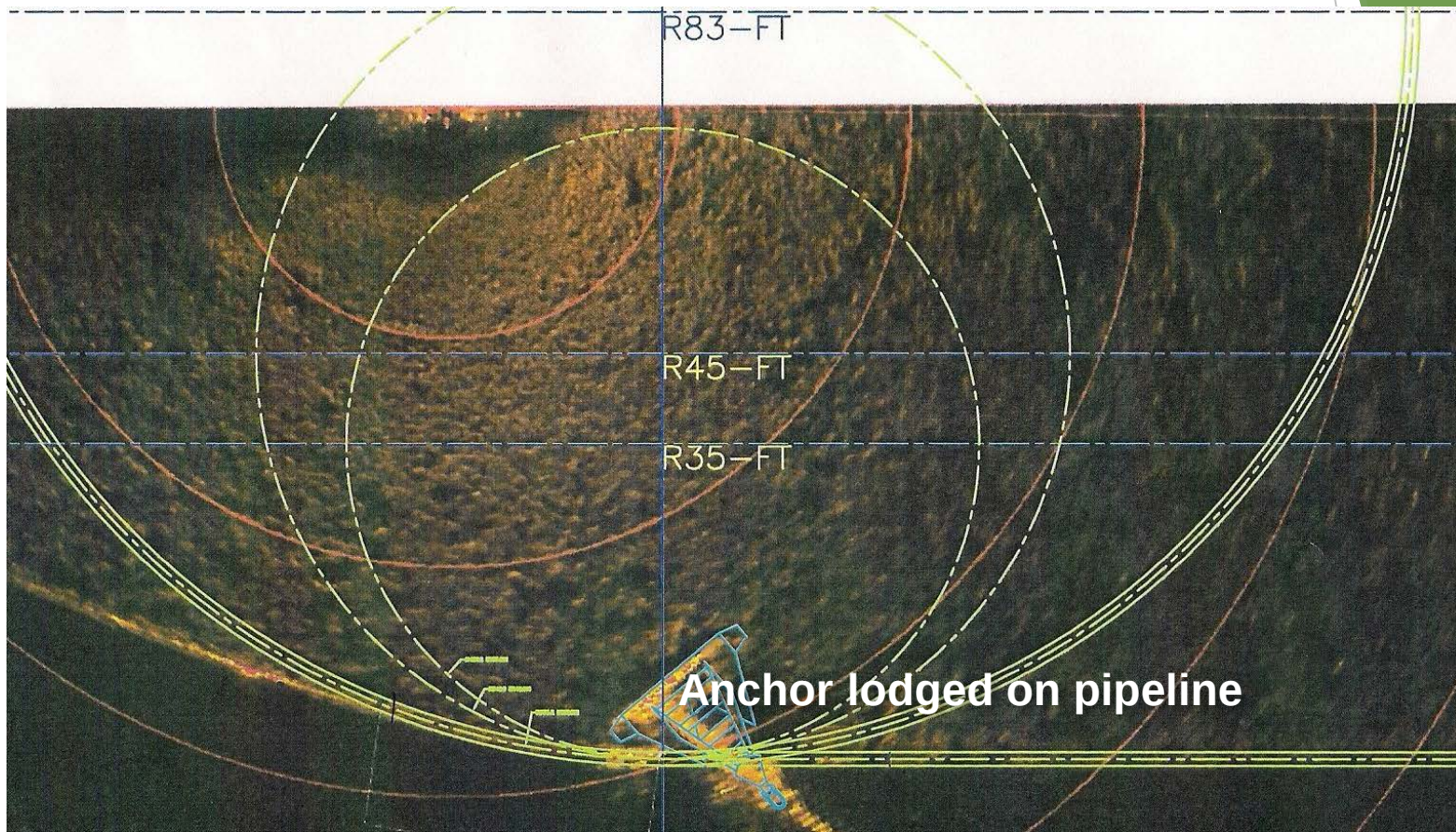
Details on Case Study

- ▶ 18-inch diameter pipeline in 2,300 feet seawater struck by an anchor
- ▶ Pulled laterally 1,200 feet, although no loss of product (natural gas)
- ▶ Inspection efforts included ROV fly-over and in-line inspection (i.e. hi-resolution caliper and MFL)
- ▶ Extensive analysis and testing efforts, including sleeve repair validation
- ▶ Costs associated with damage/repair to deepwater subsea pipelines can be on the order of \$15-25 MM
- ▶ Having an organized response plan in place increases likelihood of recouped costs

Subsea Field Measurements



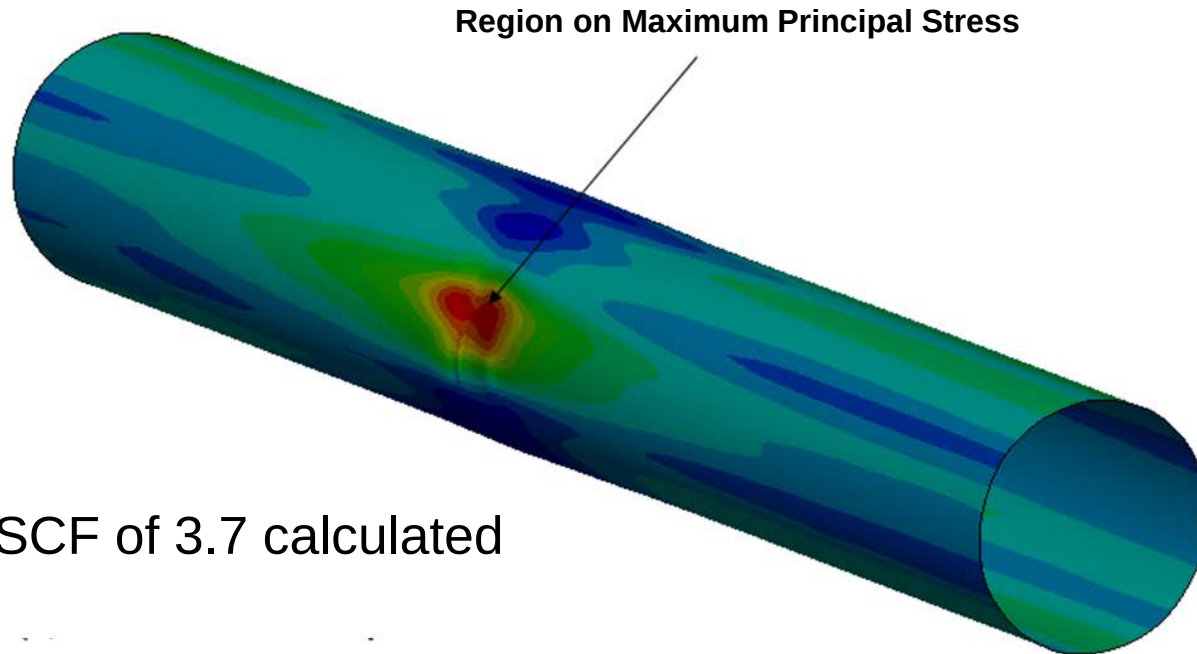
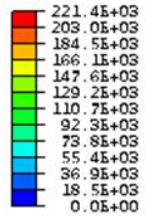
Sonar Image Measurements



Finite Element Model of Dent

Legend Stresses in psi

S. Max. Principal
SP0S. (fraction = 1.0)
(Avg: 75%)



SCF of 3.7 calculated

15 dents were identified in the damaged pipeline,
SCFs used to help prioritize response activities.
Maximum dent depth of 7.4% with 11% metal loss.

Full-scale Dent Installation



Burst Testing



Dent Validation Collaborative Industry Program (DV-CIP)

Final report issued August 2015

ROSEN

empowered by technology

DV-CIP Participants

OPERATORS

DOW
NiSource
Pacific Gas & Electric
Southern Star
Williams Gas Pipeline

REPAIR COMPANIES

Air Logistics, Inc.
Allan Edwards
Armor Plate, Inc.
Fyfe Co.
Neptune Research, Inc.
Pipe Wrap

The logo for ROSEN, featuring the word "ROSEN" in a bold, blue, sans-serif font. The letter "O" is stylized with a red dot in the center.

empowered by technology

Testing conducted at:



What was the DV-CIP?

- ▶ The DV-CIP was a program focused on helping operators achieve greater confidence between **dent performance** and **ILI detection**
- ▶ The benefit for operators is **reduced digs** (only digging when necessary) and **safety in digging** (understanding dent severity)
- ▶ With the addition of composite repair companies' participation in the DV-CIP, operators have another source for **repairing dents** as part of the validation effort
- ▶ Evaluated 47 dents in an 18-month period

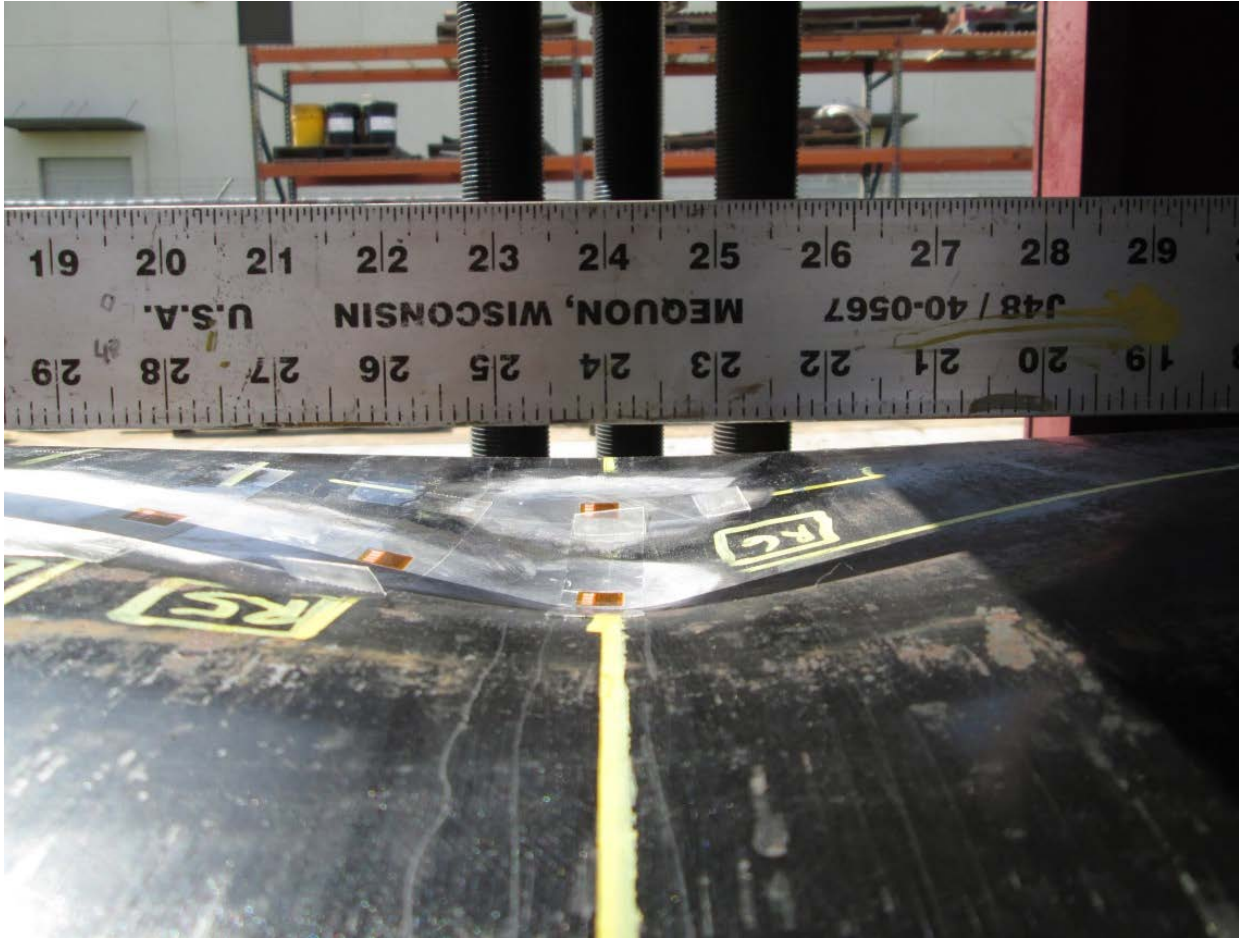
Pre-DV-CIP Study (1/5)

- ▶ Study to evaluate dent assessment methodology using ILI data and finite element models
- ▶ Installed a 15% initial dent in a 24-inch x 0.25-inch pipe (pressure during installation process)
- ▶ Post dent inspection (2 methods)
 - ▶ Optical scanner on outside surface of dented pipe
 - ▶ ROSEN measured dent and provided ILI geometry data
- ▶ Strain gages (SG) used quantify stresses in dent
- ▶ Pressure cycle dent to failure ($\Delta P = 72\% \text{ SMYS}$)
- ▶ Finite element (FEA) model using ILI data
- ▶ Comparison of SG and FEA stresses

Pre-DV-CIP Study (2/5)



Pre-DV-CIP Study (3/5)

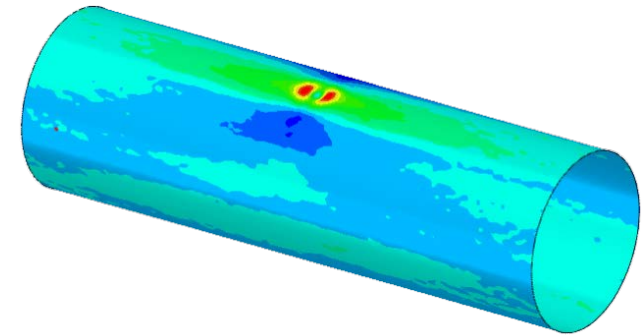
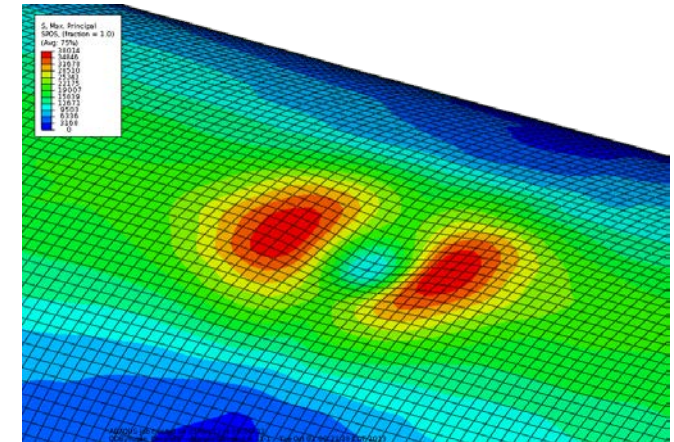


Pre-DV-CIP Study (4/5)



Pre-DV-CIP Study (5/5)

- ▶ Stress concentration factors (SCFs) calculated for dent:
 - ▶ Strain gages: SCF = 3.23
 - ▶ Optical scan: SCF = 3.80
 - ▶ ROSEN ILI: SCF = 3.28
- ▶ ROSEN SCF **within 1.5%** of strain gage SCF
- ▶ Failure at ~ 39,000 cycles with $\Delta P = 72\%$ SMYS



**Finite Element Model Dent
Assessment Tool (FE-DAT)**

DV-CIP “Goal” Insights

- ▶ Comparing stresses calculated using ILI geometry data versus experimental measurements
- ▶ Validated ROSEN’s **Finite Element Dent Assessment Tool** (FE-DAT) – *currently being used*
- ▶ Increasing understanding of interacting threats:
 - ▶ Dents in seam and girth welds
 - ▶ Dents with corrosion
 - ▶ Constrained versus unconstrained dents
- ▶ Other variables for consideration
 - ▶ Composite reinforcement
 - ▶ Effects of filler material on steel sleeve performance

Test Methods and Results

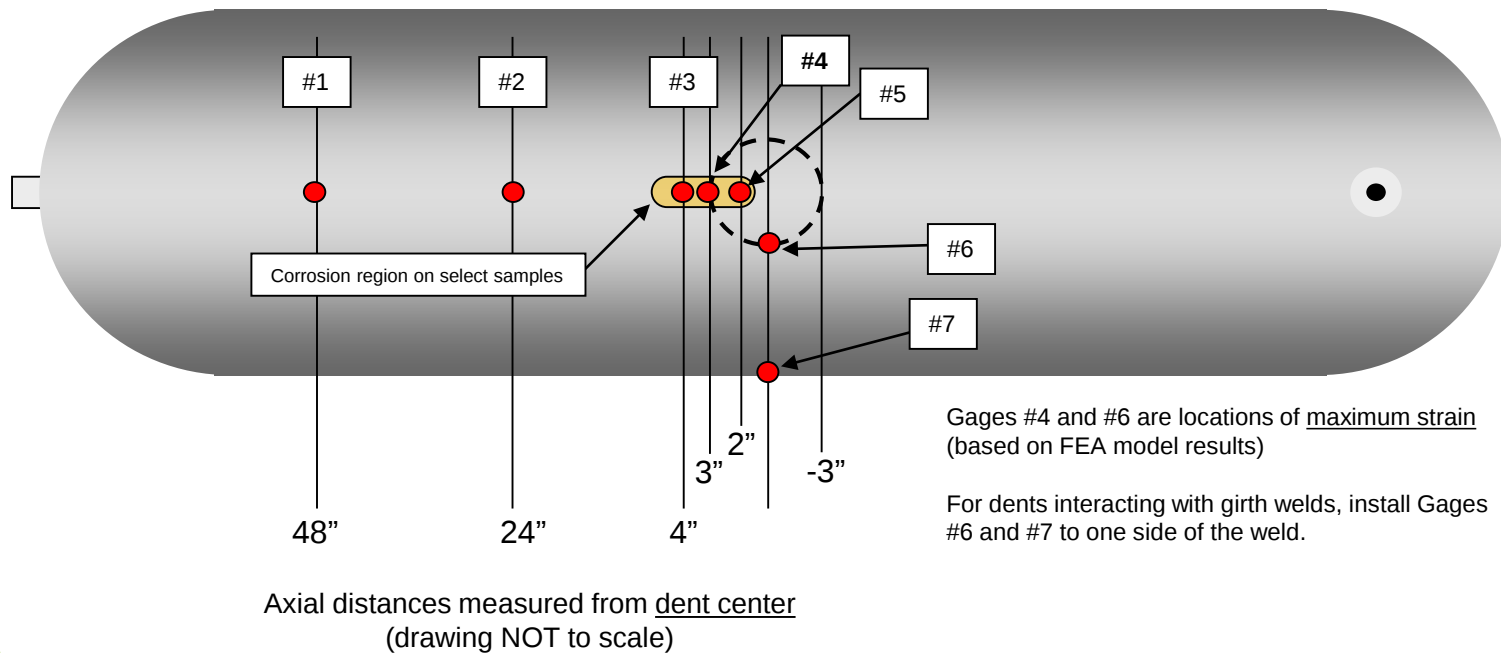
Testing Methods

- ▶ All **repair systems** tested using 24-inch x 0.25-inch, Grade X42 pipe with 15% deep initial plain dent
- ▶ Strain gages installed in dented regions
- ▶ Simulated **corrosion** used on some samples
- ▶ Some dents installed in **seam and girth welds**
- ▶ Cycling typically up to 72% SMYS
- ▶ Operators also tested constrained dents that included some severe indenter geometries

Testing Matrix

Company	Total Number of Dents	Plain Dents (PD)	Dents in Seam Weld (SW)	Dents in Girth Weld (GW)	Dents with Corrosion (DC)	Constrained Dents	Notes
Composite Repair Companies							
Air Logistics	1	1					
Allan Edwards	2	2					Evaluating with and without filler material
Armor Plate	4	1	1	1	1		
Fyfe	3	1	1		1		
NRI	4	4					1 extra PD sample using 12-inch pipe
NRI (Round 2)	6	6					4 dents in 12-inch and 2 in 24-inch pipe
NRI (Round 3)	4	4					4 dents in 12-inch pipe
Pipe Wrap, LLC	2	1			1		
Unrepaired Dent	1	1					
TOTAL	27	21	2	1	3	0	
Pipeline Companies							
Dow Chemical	4	4					8-inch and 16-inch
NiSource Gas Transmission & Storage	4					4	24-inch x 0.288-inch, Grade X65
Pacific Gas and Electric Company	4	4					16-inch x 0.25-inch & 12.75-inch x 0.375-inch
Williams Companies, Inc.	4					4	22-inch and 26-inch
Southern Star	4				3	1	26-inch x 0.375-inch (dents constrained)
TOTAL	20	8	0	0	3	9	
PROGRAM TOTAL	47	29	2	1	6	9	

Test Sample Layout



Selected Test Results

- ▶ Unrepaired dent
- ▶ Repaired dent
 - ▶ E-glass system (with and without corrosion)
 - ▶ Carbon system
 - ▶ Steel sleeve (with and without filler material)
- ▶ Severe constrained dent study

Repaired Dent Test Results

- ▶ Unrepaired dent: 23,512 cycles (baseline data)
- ▶ Repaired results (select systems)
 - ▶ E-glass composite system:
 - ▶ Plain dent: 106,252 cycles (runout)
 - ▶ Dent with 40% corrosion: failure @ 56,726 cycles
 - ▶ Carbon composite plain dent: 102,950 cycles (runout)
 - ▶ Steel sleeve
 - ▶ Plain dent: 101,999 cycles (runout)
 - ▶ Dent with no filler: failure @ 40,877 cycles
 - ▶ All other repairs achieved runout

Summary of SCFs

- ▶ Results based on measured hoop strains
- ▶ Measured SCFs (based on strain gages):
 - ▶ Unrepaired sample, $SCF = 3.72$
 - ▶ Carbon-epoxy repaired sample, $SCF = 1.31$
 - ▶ Carbon-epoxy repaired sample, $SCF = 0.76$
 - ▶ Carbon-epoxy repaired sample, $SCF = 1.22$
 - ▶ E-glass-epoxy repaired sample, $SCF = 1.32$
 - ▶ E-glass-urethane repaired sample, $SCF = 1.3$
 - ▶ Steel sleeve sample with filler, $SCF = 1.25$
 - ▶ Steel sleeve sample with NO filler, $SCF = 4.15$

OPERATOR

Sample Number	Dent Strain ($\mu\epsilon$)	Nominal Strain ($\mu\epsilon$)	SCF	Cycles to Failure	Notes and Comments
A-DC-8-1	3,827	1,162	3.29	11,454	6% deep dent, 30% corrosion (RDD = 6.2%) ⁽¹⁾
A-DC-8-2	3,403	1,162	2.93	49,560	3% deep dent, 30% corrosion (RDD = 2.7%)
A-SW-16-3	4,430	1,372	3.22	6,236	6% deep dent in seam weld (RDD = 3.0%)
A-PD-16-4	5,484	1,399	3.92	5,283	9.5% deep dent using knife indenter (RDD = 3.7%)
B-RD-24-1	1,709	483	3.54	13,393	Axial strains ⁽²⁾ , constrained 6% deep dent
B-UR-24-2	6,522	1,428	4.57	7,861	10% initial deep dent (RDD = 3.3%)
B-PD-24-3	2,352	1,437	1.64	19,713	Partially-constrained initial 6% deep dent
B-AD-24-4	1,659	460	3.61	12,629	Axial strains, 15° angle-constrained 6% deep dent
C-PD-16-1	3,186	1,141	2.79	32,876	4% deep dent (RDD = 1.3%)
C-PD-16-2	6,155	1,148	5.36	9,770	10% deep dent (RDD = 3.5%)
C-PD-12-3	3,397	1,395	2.44	22,935	3% deep dent, 20% corrosion (RDD = 1.4%)
C-PD-12-4	2,541	1,395	1.82	56,552	3% deep dent (RDD = 1.3%)
D-22-IP4-1	1,873	390	4.80	24,858	Axial strains, constrained pyramid ⁽³⁾ indenter, 4% deep
D-22-IS4-2	1,306	429	3.04	15,925	Axial strains, constrained spherical ⁽⁴⁾ indenter, 4% deep
D-26-IS6-3	1,654	422	3.92	10,324	Axial strains, constrained spherical indenter, 6% deep
D-26-IS4-4	1,127	352	3.20	19,643	Axial strains, constrained spherical indenter, 4% deep
E-RD-26-1	1,568	546	2.87	23,114	Axial strains, constrained, 8% deep dent, No corrosion
E-DC-26-2	1,862	495	3.76	17,400	Axial strains, constrained, 8% deep dent, 10% corrosion
E-DC-26-3	2,029	514	3.95	21,683	Axial strains, constrained, 8% deep dent, 15% corrosion
E-DC-26-4	2,486	539	4.61	20,108	Axial strains, constrained, 8% deep dent, 30% corrosion

Notes:

1. RDD corresponds to "Residual Dent Depth"; the dent depth after 10 cycles applied from 0 psi to 72% SMYS. No residual dent depths for constrained dents are provided as no re-rounding occurs with these dents.
2. The SCFs for constrained dents are based on the measured axial strains.

Comparison of Results

Comparison of Calculated SCF Values

Dent ID	Test SCF	ILI Data SCF				Laser Scan SCF
		Average	Max	Min	St. Dev	
C-PD-16-1	2.79	2.76	3.21	2.48	0.23	2.76
A-PD-16-4	3.92	3.72	4.23	3.39	0.25	3.49
A-SW-16-3	3.22	3.22	3.46	3.01	0.14	3.33

Predicted Cycles to Failure Based on DOE “C” Mean Fatigue Curve

Dent ID	Actual Cycles to Failure	Predicted Cycles Based on Test SCF	Predicted Cycles Based on ILI Data SCF			Predicted Cycles Base on Laser Scan SCF
			Average SCF	Max SCF	Min SCF	
C-PD-16-1	32,876	13,986	14,526	8,562	21,122	14,526
A-PD-16-4	5,283	2,190	2,631	1,678	3,642	3,289
A-SW-16-3	6,236	4,660	4,660	3,623	5,901	4,143

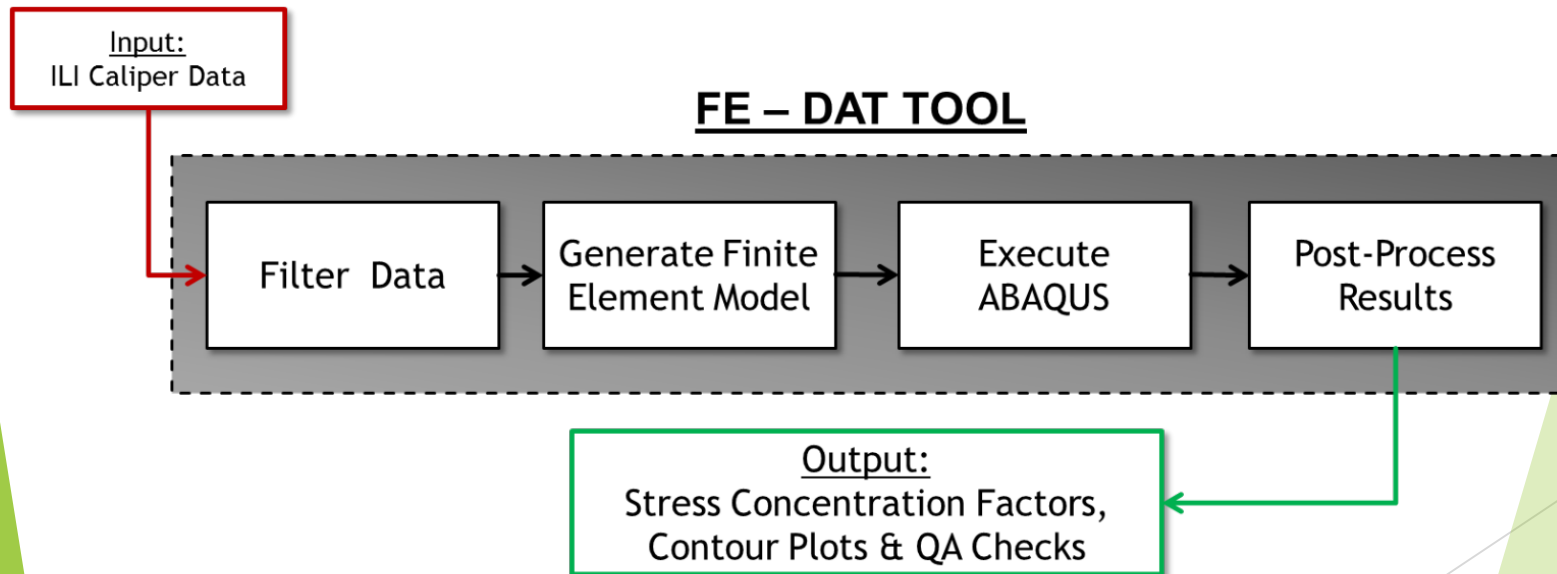
Predicted Cycles to Failure Based on API 579 Multiplied by 20

Dent ID	Actual Cycles to Failure	Predicted Cycles Based on Test SCF	Predicted Cycles Based on ILI Data SCF			Predicted Cycles Base on Laser Scan SCF
			Average SCF	Max SCF	Min SCF	
C-PD-16-1	32,876	12,922	13,298	8,950	17,730	13,298
A-PD-16-4	5,283	3,371	3,832	2,802	4,820	4,485
A-SW-16-3	6,236	5,749	5,749	4,803	6,816	5,284

FE-DAT

(Finite Element Dent Assessment Tool)

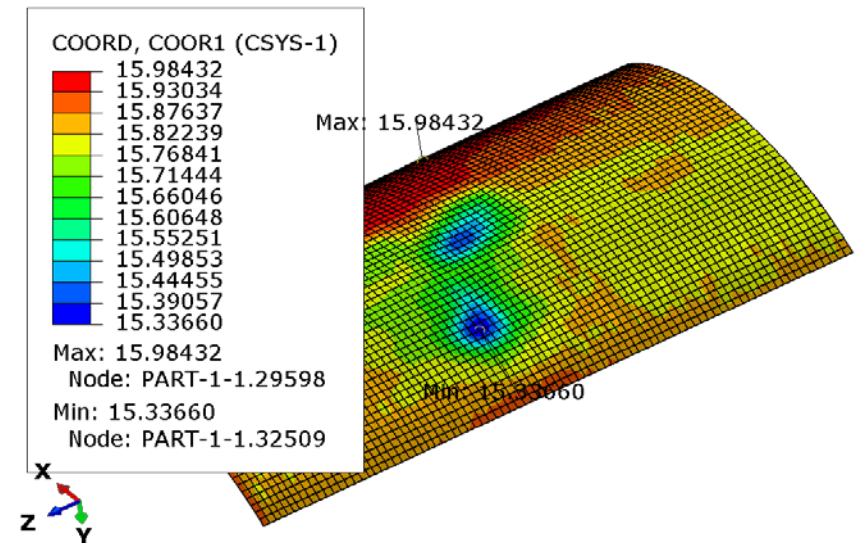
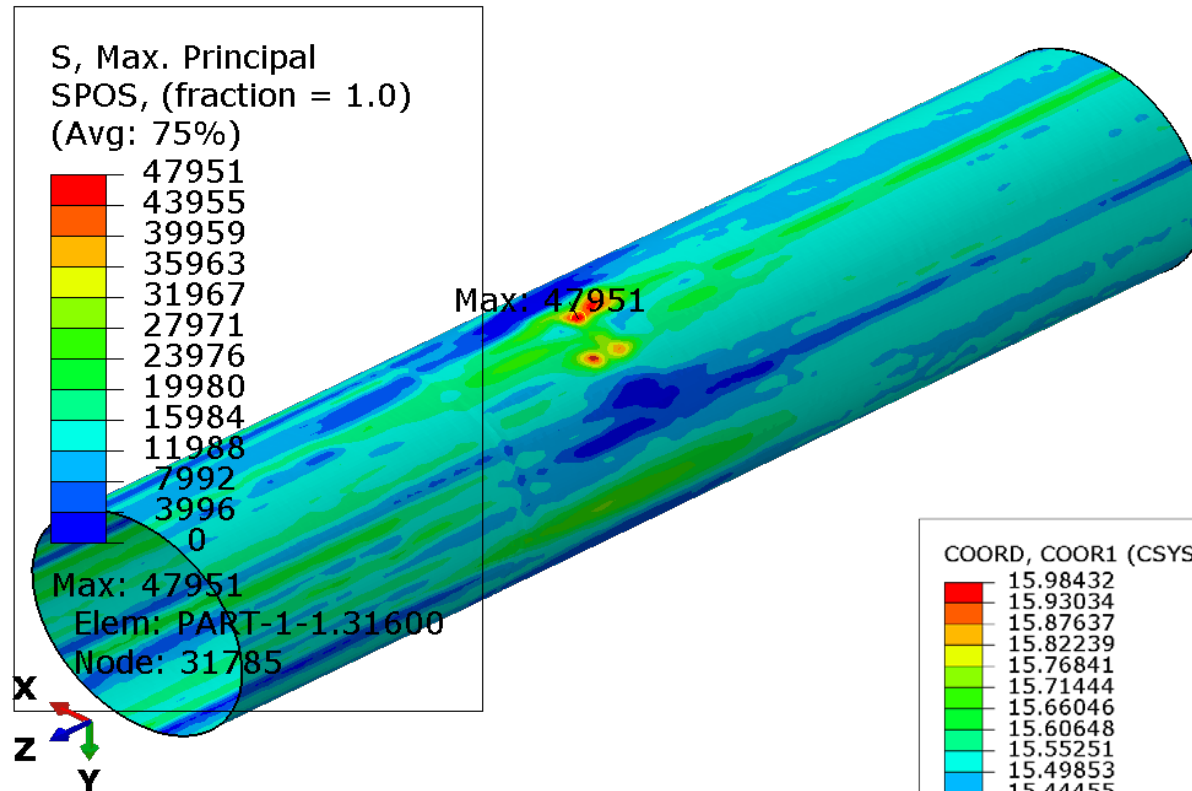
The Finite Element Dent Assessment Tool (FE-DAT) is a process that automates the creation, execution, and processing of finite element models based on ILI caliper data.



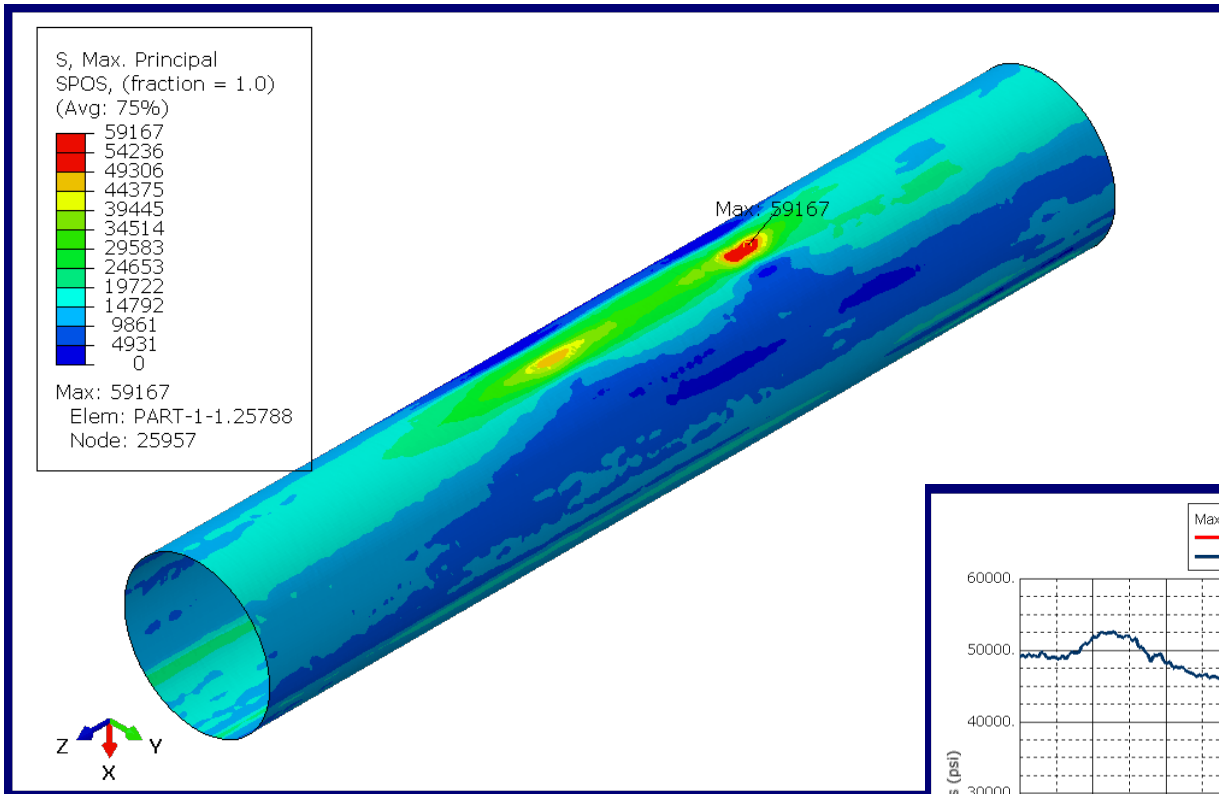
Comments on DV-CIP

- ▶ SCFs are an effective means for comparing relative severity of dents
- ▶ ILI data can be used to calculate SCFs
- ▶ The limitation is not the SCF itself; rather, it's the selection of an appropriate S-N curve
- ▶ Advanced engineering using SCFs and full-scale testing can improve integrity management decisions
- ▶ With the FE-DAT tool, ROSEN has developed a tool that can effectively help operators screen dents

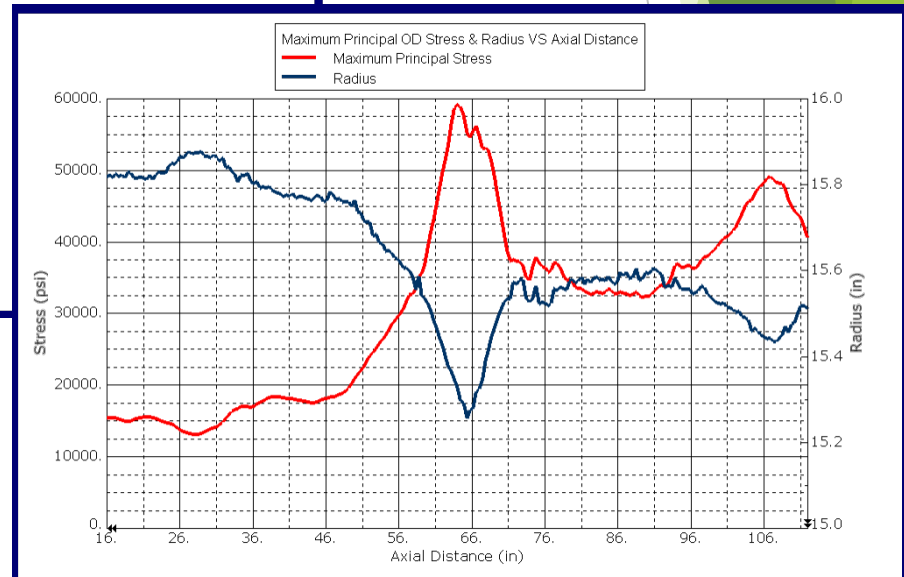
Off-axis Dents



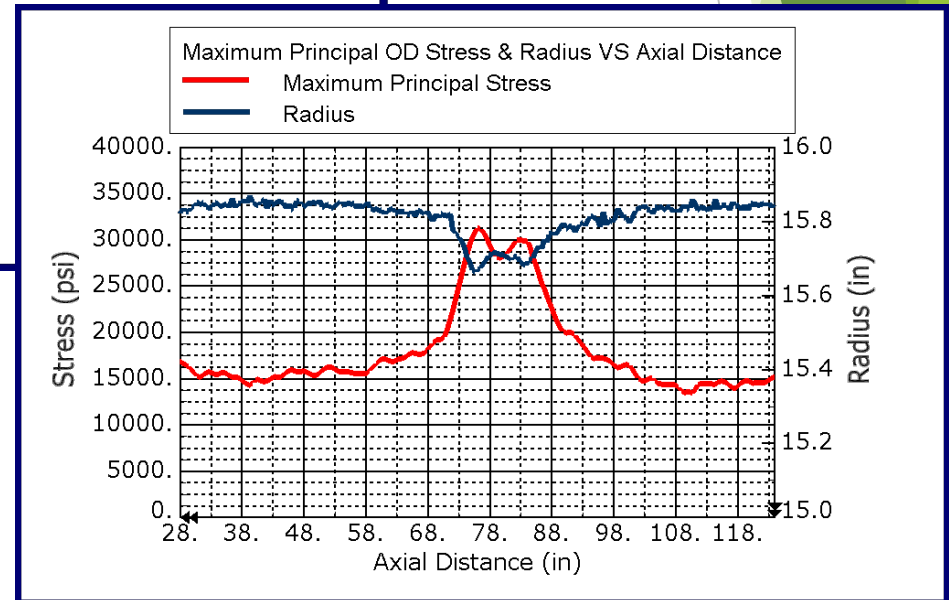
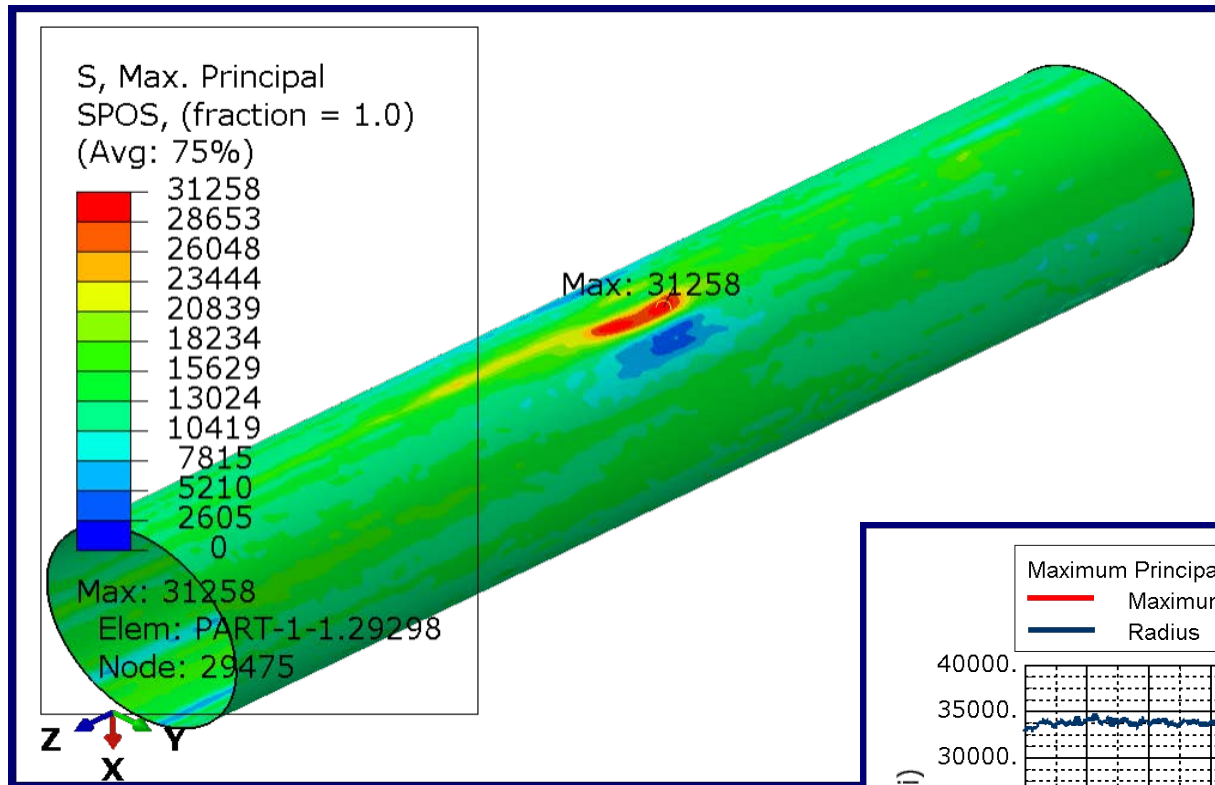
Interacting Dents



Interaction implies the stress field is interacting although the two dents may be separated by a significant distance.



Double Dents



SCF Strengths and Limitations

STRENGTHS

- Integrates ILI geometry data; does not rely on dent depth alone
- Assessment of multiple dents and other geometry features
- A good general risk ranking tool that can be deployed rapidly
- Can be used to estimate remaining life for dents subjected to cyclic service
- Based on fundamental principles understood by most engineers
- Can be expanded to integrate localized corrosion material loss

LIMITATIONS

- Not ideal for high strain / low cycle dents and conditions
- Constrained dents (over-estimation of severity)

The “Ideal” 7-Step Analysis

1. ILI technology provides: dent geometry, residual stress state, and local material properties
2. If applicable, ILI technology provides “global” stresses associated with external loads
3. Pipeline operator has a good handle on past, present, and future pipeline operation, especially with regards to pressure history data
4. Generation of “real time” FEA models using all available information and data
5. Material models that accurately capture behavior of the dent
6. As appropriate and needed, calibrate numerical models using selected full-scale tests
7. Accurate estimate of remaining life using “reasonable” safety factors and actual pressure history data

Thoughts for the Future

- ▶ Continue to work together as an industry (like we're doing today!)
- ▶ Be cognizant of technology advances (as much as possible) and integrate them into future assessment methods
- ▶ Need to better understand failure of shallow dents & high strain / low cycle dent failures experienced by some gas operators
- ▶ Appreciate and integrate role of experimental investigations to validate numerical models
- ▶ Solutions must be practical



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Thank You!

Failure at Plain Dents, Kinked Dents, & Gouged-Dents

API/PRCI Joint Workshop on Dent Assessment & Engineering Analysis Methods

August 9, 2018 / Houston

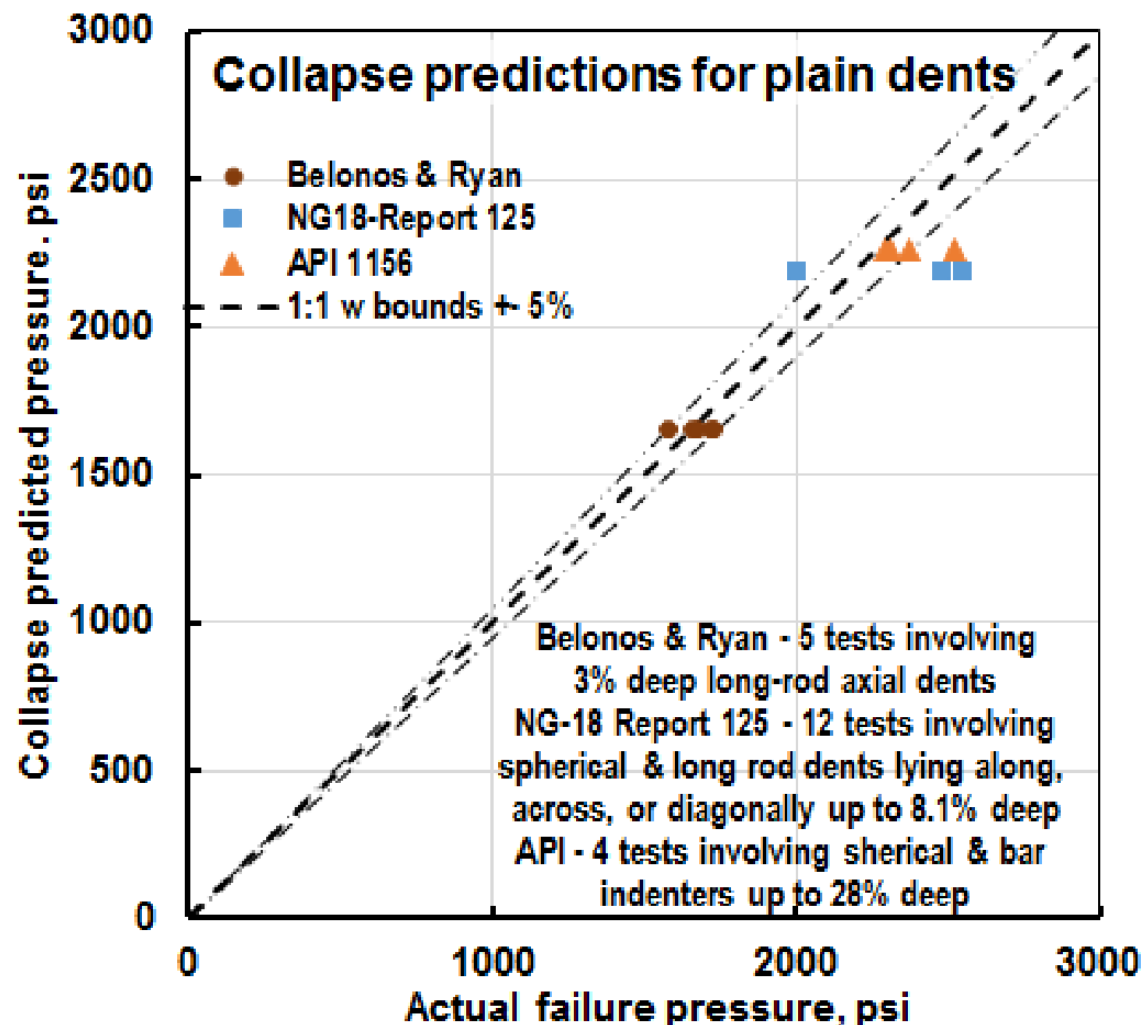
B N Leis
B N Leis, Consultant, Inc.
bleis@columbus.rr.com

Outline

- Plain dents: some questions.....
 - What is it? Do they exist?
 - Could they fail? ... and if you think they can, then by what mechanism(s)?
and with what consequences (LvsR)?
 - Then discuss burst-pressure for these & gouged dents
- Kinked dents and dent-gouge cases: more questions.....
 - What are they? – how do they differ?
 - Do they exist?
 - Could they fail? ... and if you think they can, then by what mechanism(s)?
and with what consequences (L vs R)?
 - Then discuss fatigue predictions for gouged dents
- Summary

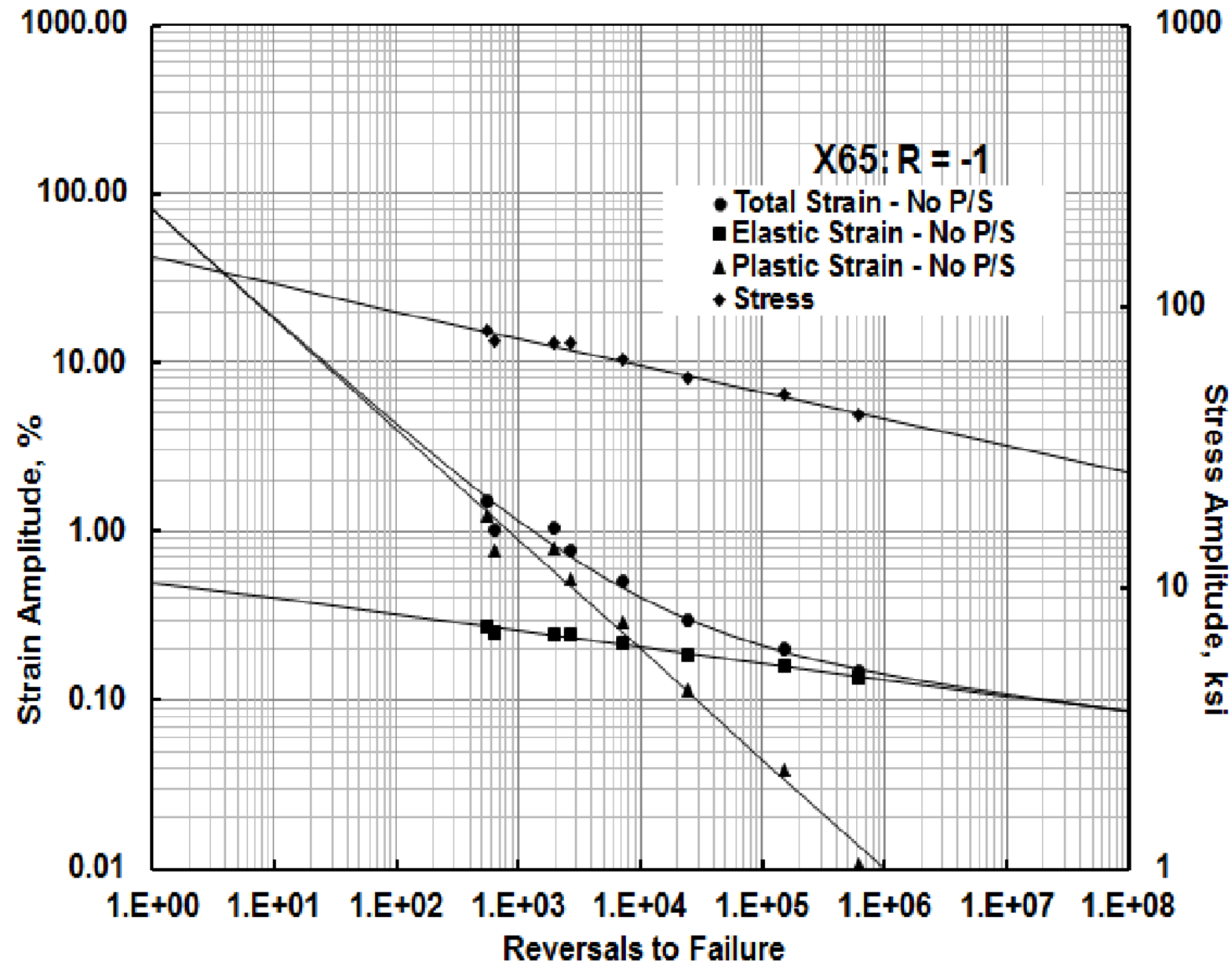
Results for “smooth curvature” features – plain dents

- Burst Tests from late 50s & early 60s
 - they re-rounded & failed at the UTS -- Re-discovered in 1990s



- What about fatigue?
 - Depending on the curvature the life can be infinite
 - But for tight radii of curvature the life can be quite short
- Want to simplify assessment?
 - Set curvature threshold to affect the minimum acceptable life

Dent-Curvature Life Plots



- you could take data such as this – but developed under conditions relevant to pipelines & create pipeline-specific curvature – life plots
- the key is pipe & pipeline relevance testing
- a Reversal = a half-cycle: has relevance in variable-amplitude analysis

Discriminating Features – Some Definitions

- POF (§2.4.2) notes four types of dents ‘complex’ in definitions
 - Kinked
 - Plain
 - Smooth
 - ‘Complex’ added in the definitions
- UKOPA (various) defines three types of dents
 - Dent - depression which produces a gross disturbance in the curvature
 - Kinked - abrupt change in curvature $\leq 5t$
 - Plain or Smooth – smooth change in curvature
- ASME defines dents (B3.4/B31.8) & notes damage/stress raisers
 - Does not discriminate between plain/kinked/smooth nor exclude kinked

Feature Discrimination is Critical

- Depth has little control regarding failure – illustration follows



- Features like these caused a full-bore rupture in heavy-wall pipe



- Need to be able to better discriminate what is on the OD from the ID via ILI

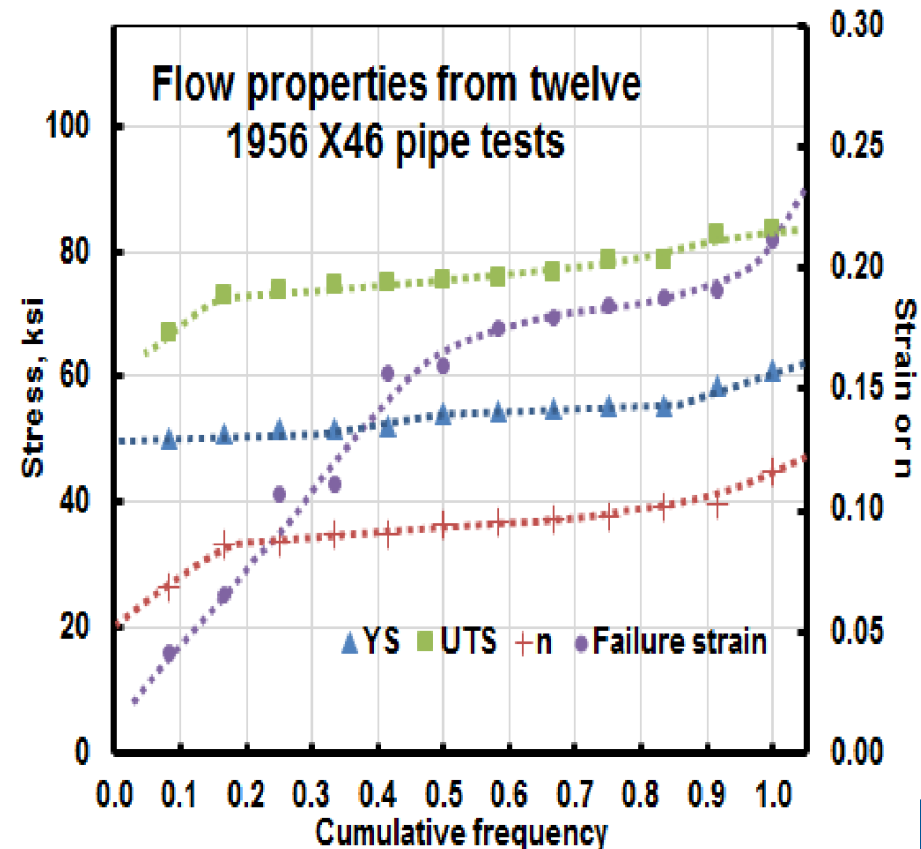
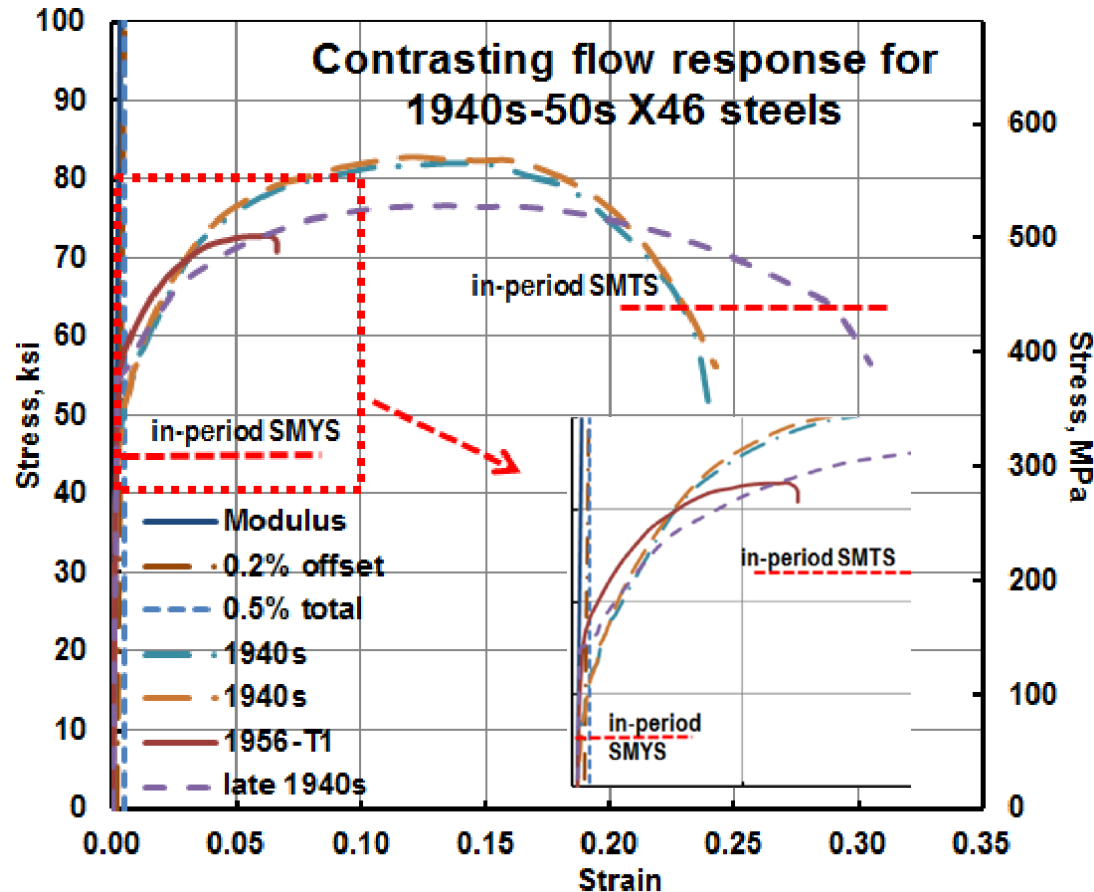
Strain – and other “Acceptance” Metrics

- We can calculate strain from caliper data with sufficient accuracy and resolution -- Petrobas has used very high-quality fast algorithms for strain from caliper tools for almost a decade -- in print now for 7 years
- Can achieve the same outcome for plain dents in terms of ‘shape’ metrics (e.g. BMT)
- The issue is -- what is ‘acceptable’? – whether it is strain, shape,
- Can represent acceptable simply as strain or you could use advanced metrics – like damage (e.g. Blade, but they also advocate strain)
 - but the issue remains:
what is known about the steel in the pipeline & then
what is acceptable for that pipeline or the joint of pipe?

Let’s illustrate

Acceptance Metrics vs the Steel's Resistance

- Steel's 'resistance' to failure determines Acceptance –
- You might have the tensile data to quantify 'damage' for failure analysis – but beyond that it is not 'generic' and it is more uncertain than strain
- What about acceptable strain? generic vs pipeline vs joint of pipe?



Failure Mechanisms & Implications

Collapse

Controlled by strength – failure is ductile

Metrics: UTS, n

Simple Analysis

Upper-bound

Often least consequential

Fracture

Controlled by crack initiation & growth resistance

Can be brittle or ductile – considered ductile here

Metrics: CVN, K_{Ic} , J_{Ic} , dJ/da , constraint

Complex Analysis

Lower-bound

Usually a worst-case

Premature Collapse

Controlled by collapse subject to a strain limit

Metrics: UTS, n , ϵ_L

Still simple

In between bounds

Blind Burst Predictions for Gouged-Dents

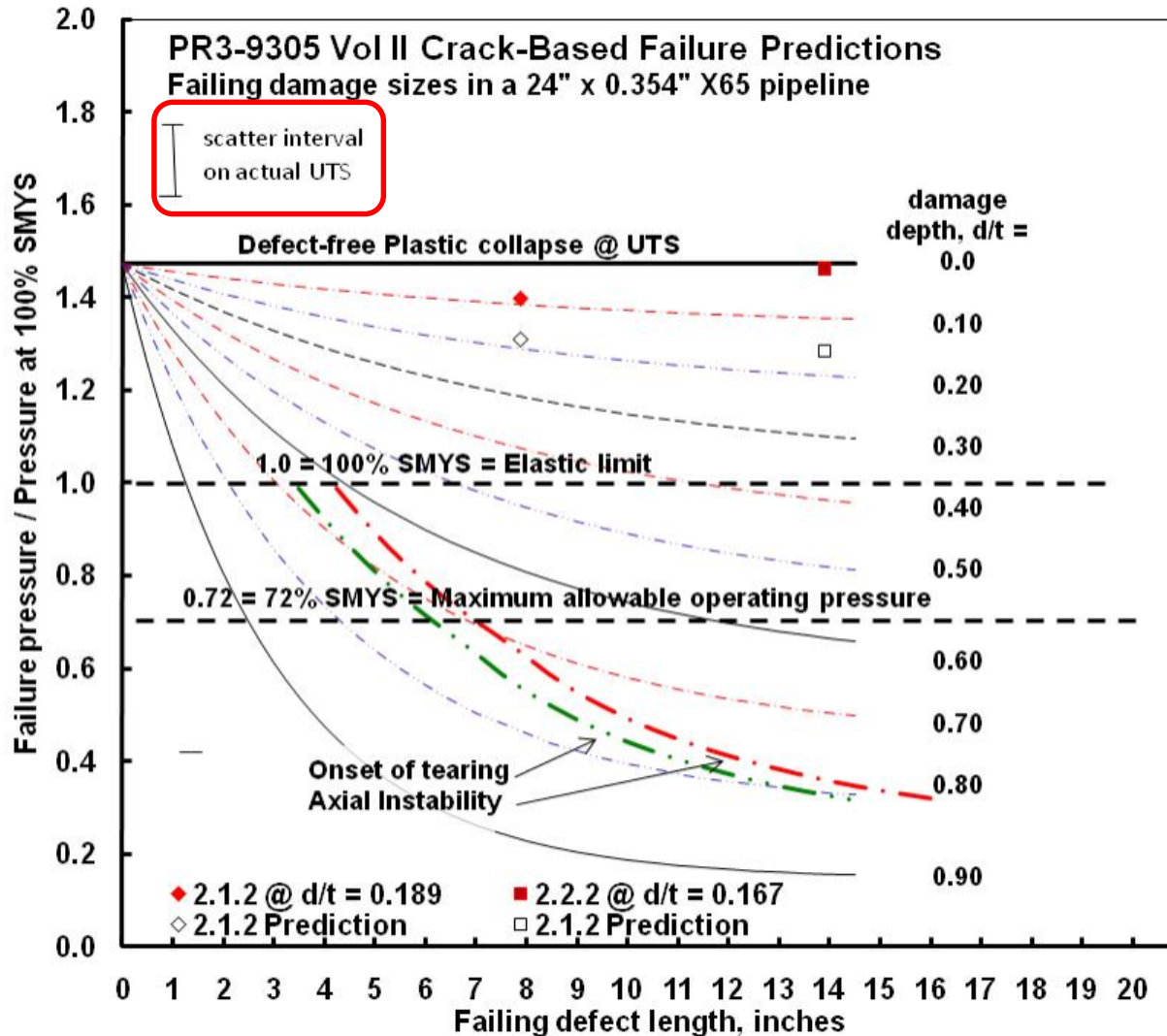
- Such predictions are needed:
 - In screening to judge proximity to failure –
 - preeminent is crew safety in digs – the merit of a dig
 - In FCP analysis to predict critical defect dimensions
- Such predictions differ greatly depending on the failure mechanism (illustrated shortly)
- Let's look first at collapse control – fracture control thereafter

MD-4-4 Burst Pressure Predictions

- **The challenge** – for modern / tough X52 & X70 24" pipe
 - Develop models of burst pressure for gouged dents: 3 examples shown
 - Then predict the fatigue response at these & other gouged dents

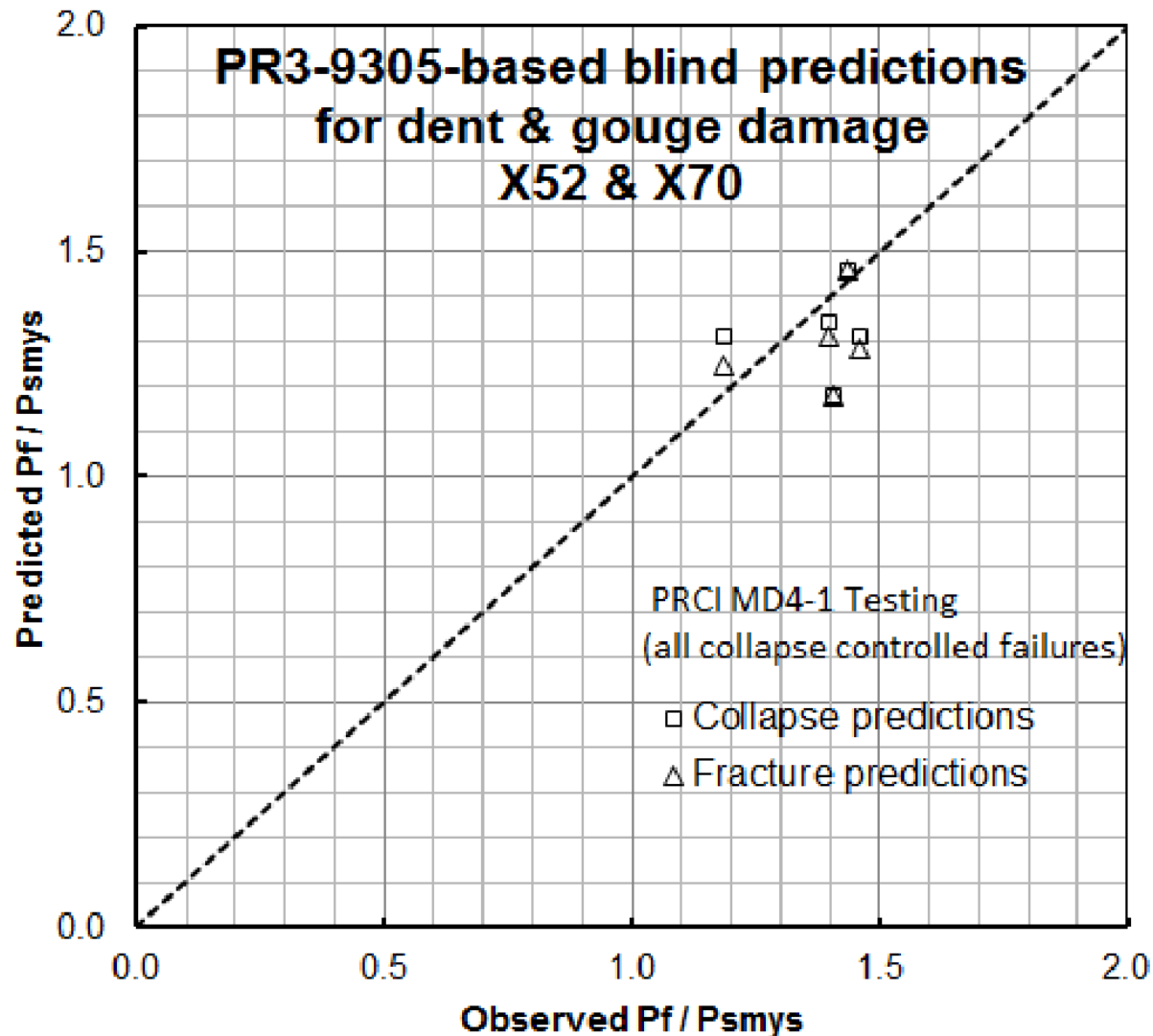


Burst Model: Collapse & Fracture: Some Examples



- Tough steel – enough so to ensure plastic collapse
 - So very high failure pressures
- Associated denting re-rounds so no complexity due to dent
- It is akin to a corrosion problem
- Fracture predictions effectively identical for the same reasons
 - quite simply it is tough enough that the fracture model defaults to collapse
- But what if the toughness was lower?

Summary of Gouged-Dent Burst Predictions



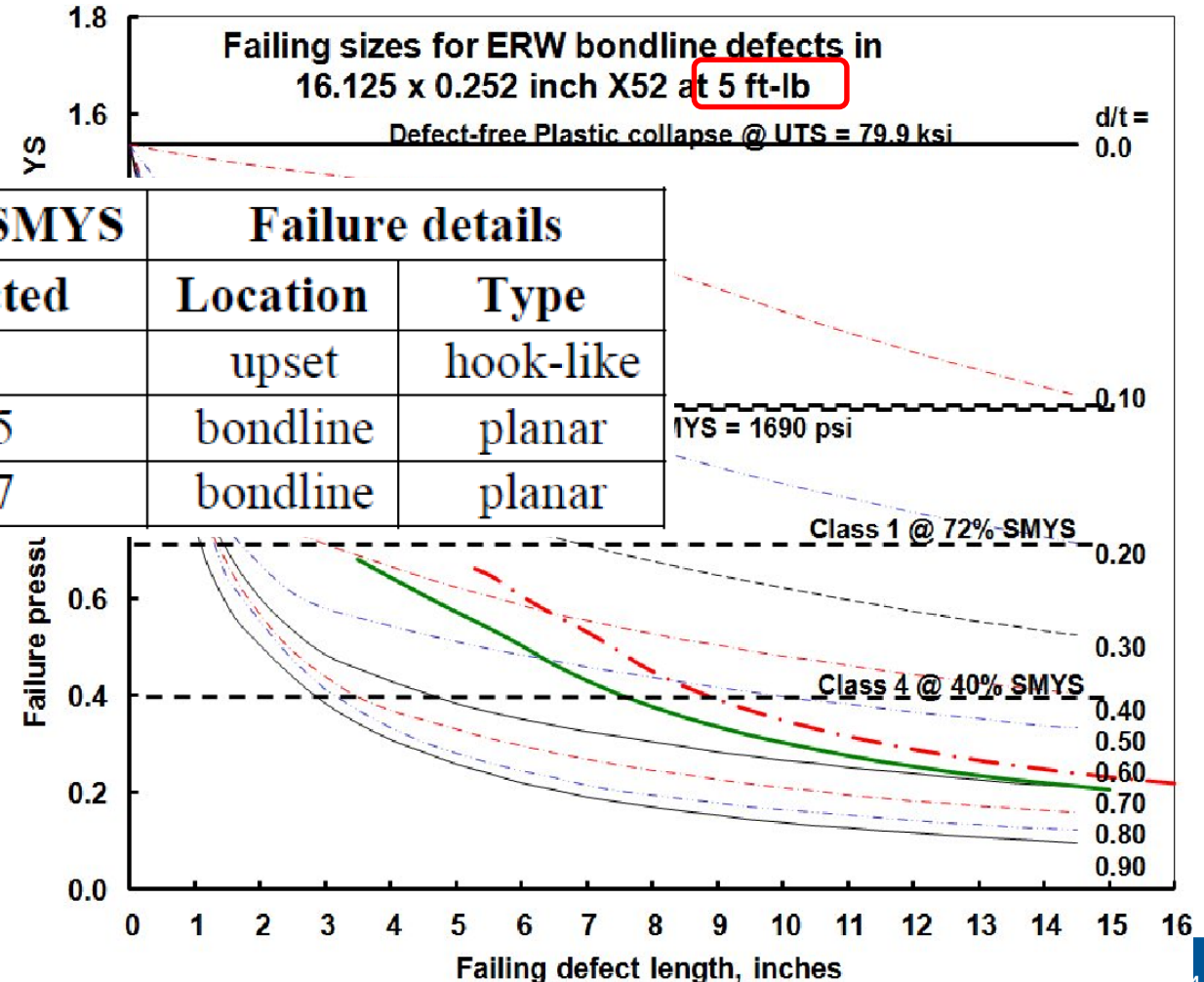
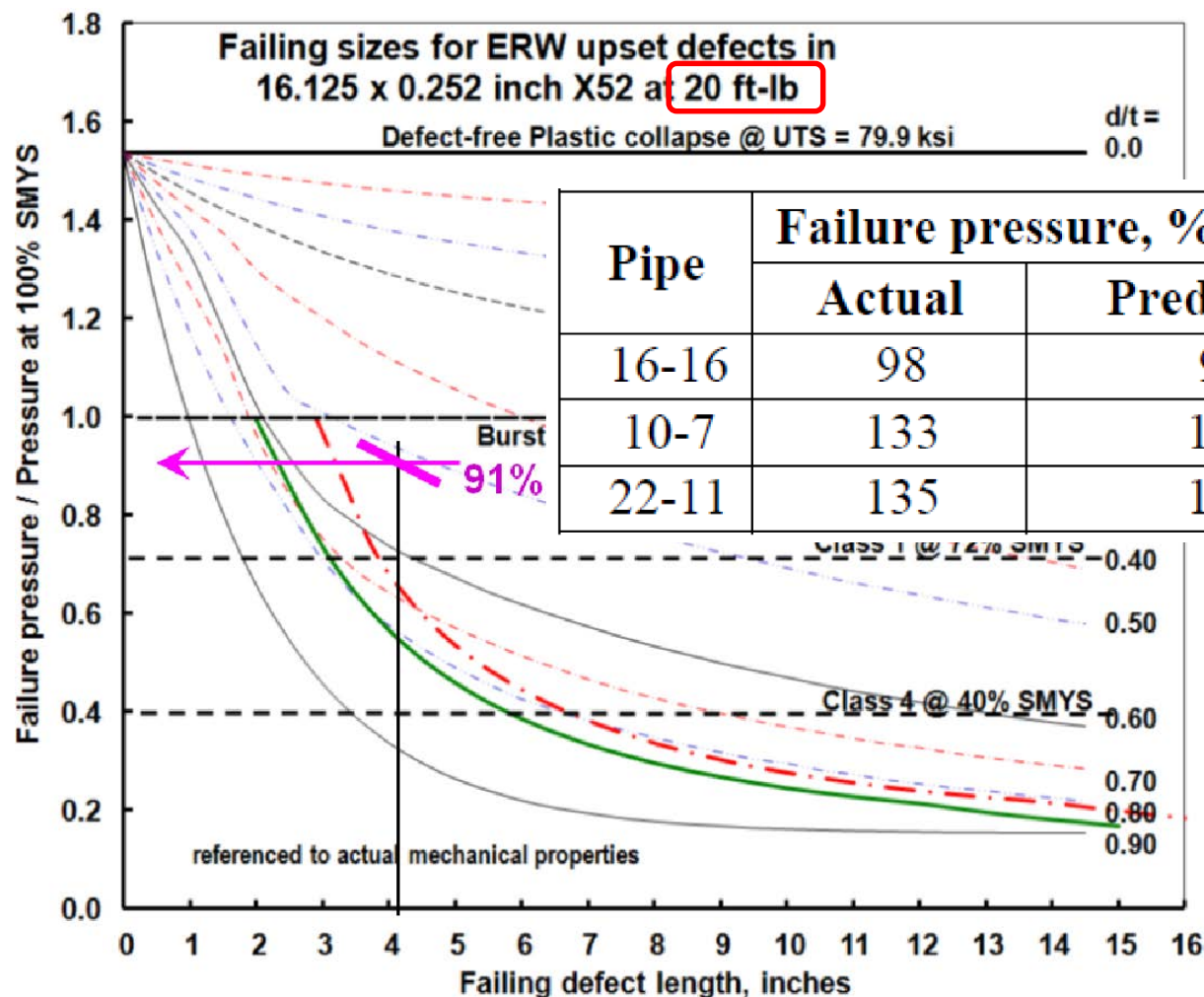
- All are high-pressure failures
- Could you look at this and assert it would fail at 130% SMYS??



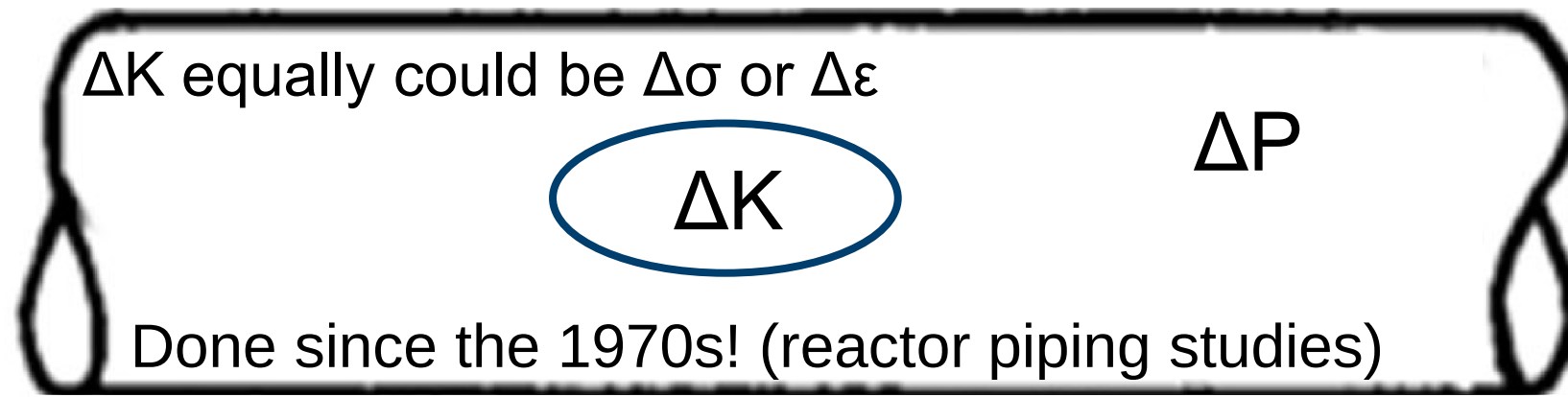
Gouged dents that fail by collapse are not the fear-maker most think they are !!!

What about Fracture Controlled Failure??

- It is all about the toughness! -- example is for LFERW seam cracking
- How different can toughness vs fracture control be? –

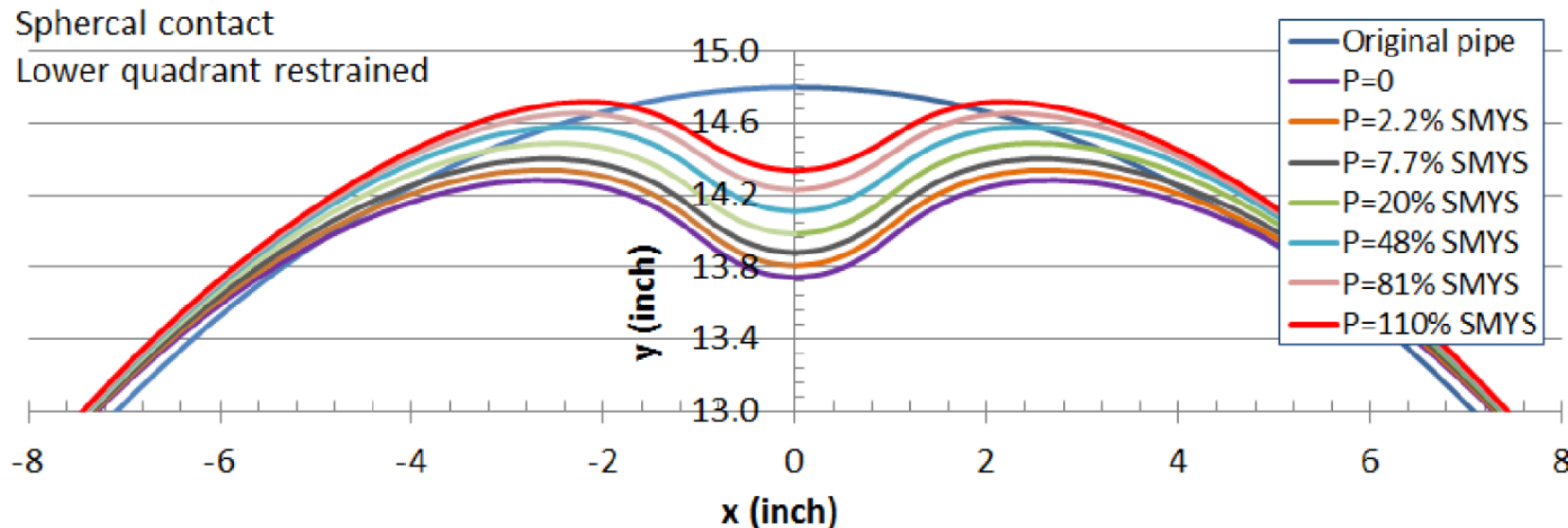


What About Fatigue or FCP at Gouged Dents



$$N = \int_{a_i}^{a_f} f(\Delta K) da$$
$$\Delta K = f(\Delta s, a, \dots)$$
$$da/dN = C_r (\Delta K)^n$$

- Relationship develop between the flexing in the dent & nominal pipe



If $\Delta K / \Delta P$ stays constant (all is linear) then the FCP predictions can be simple!

Feature Response with kinking

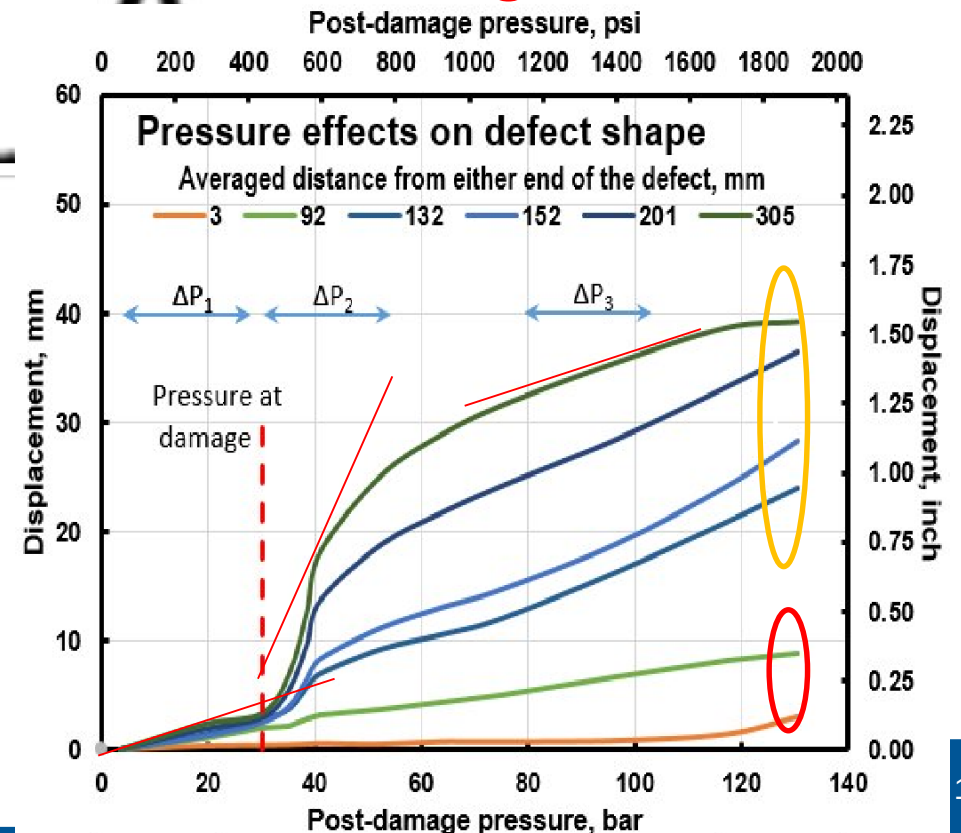
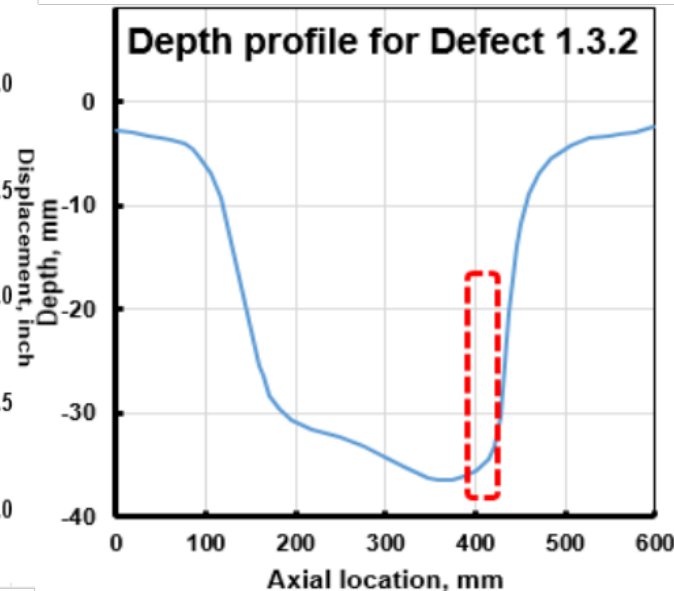
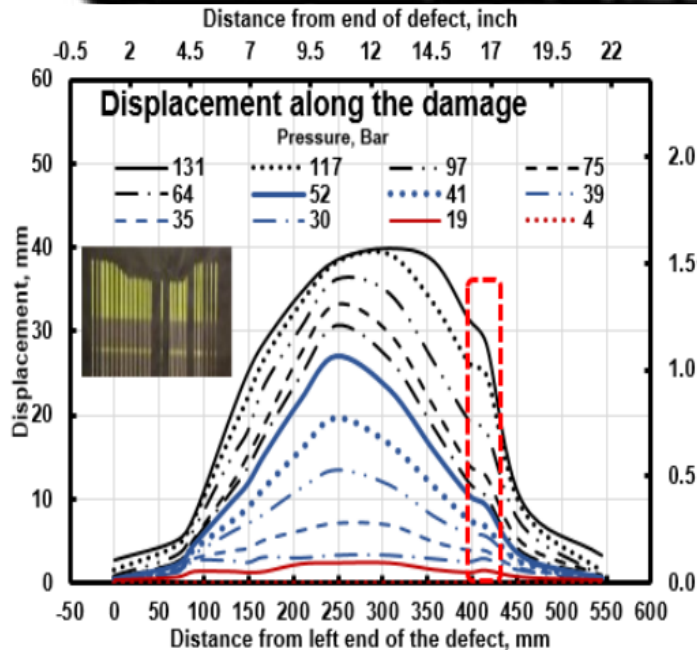
- But ... What happens within the kink's zone of influence?

ΔK equally could be $\Delta\sigma$ or $\Delta\varepsilon$ within the kink

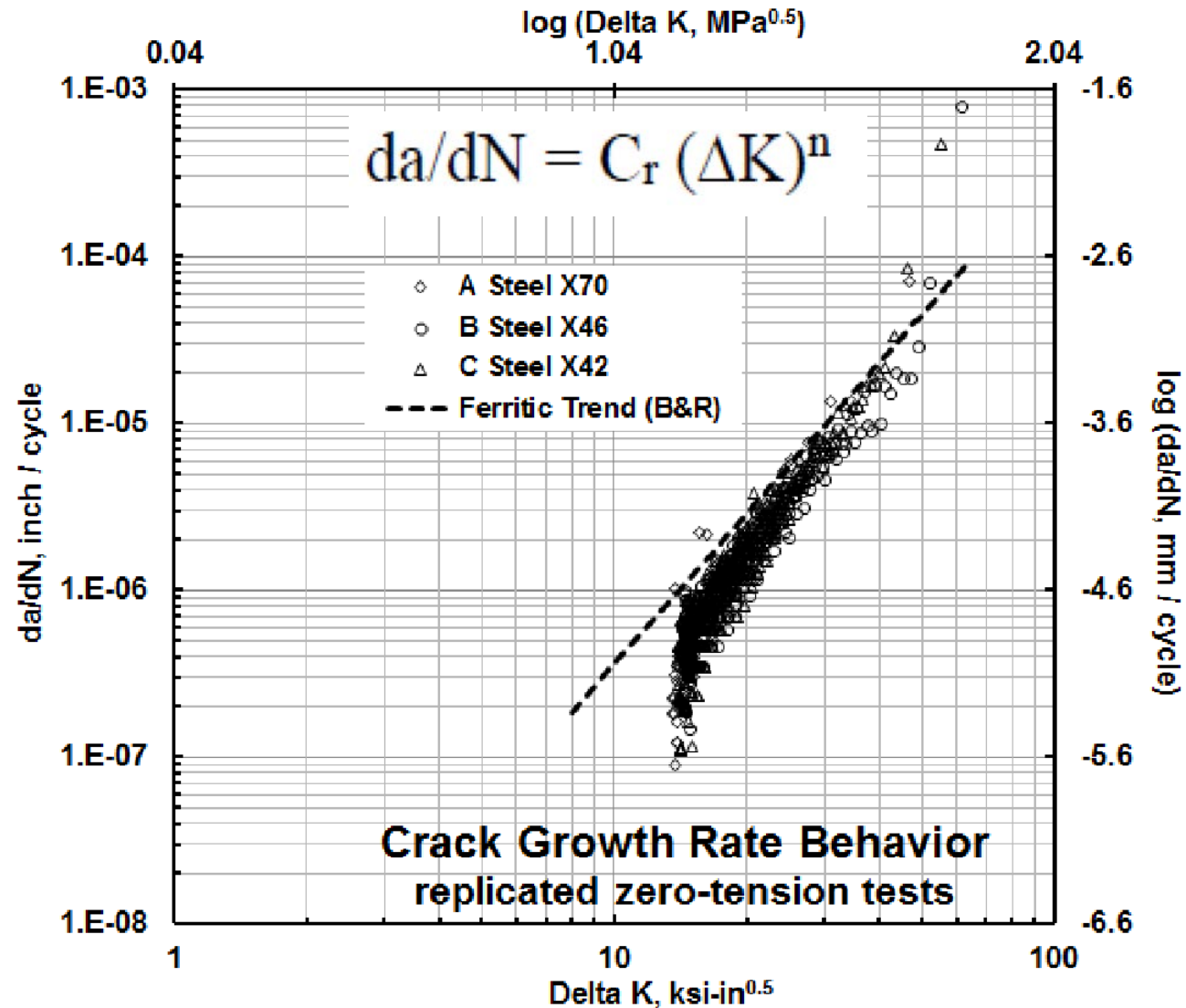
ΔP

ΔK

- Driving Force Implications
It now gets difficult

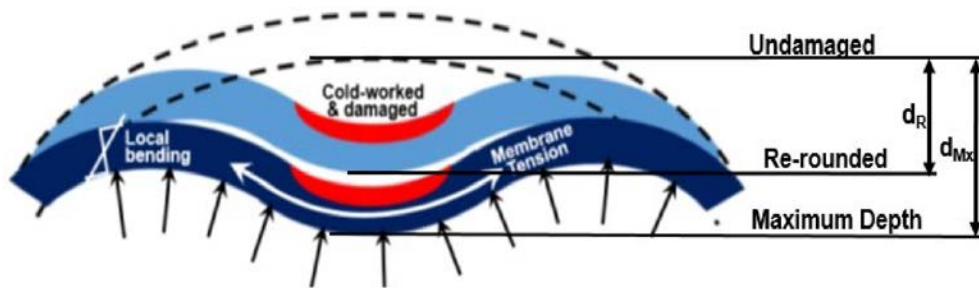


The Upside – the “Resistance” is Simply Characterized



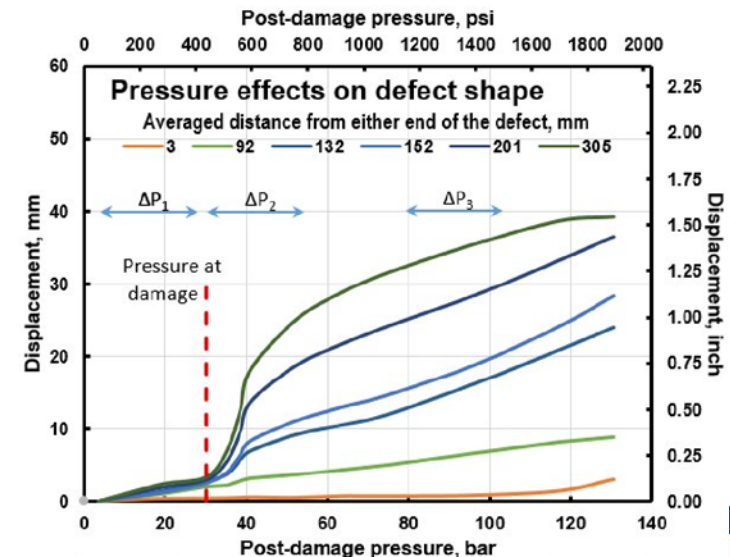
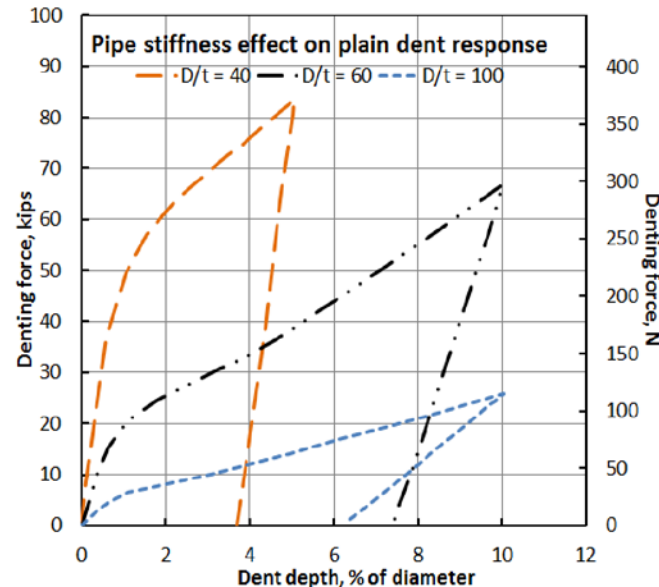
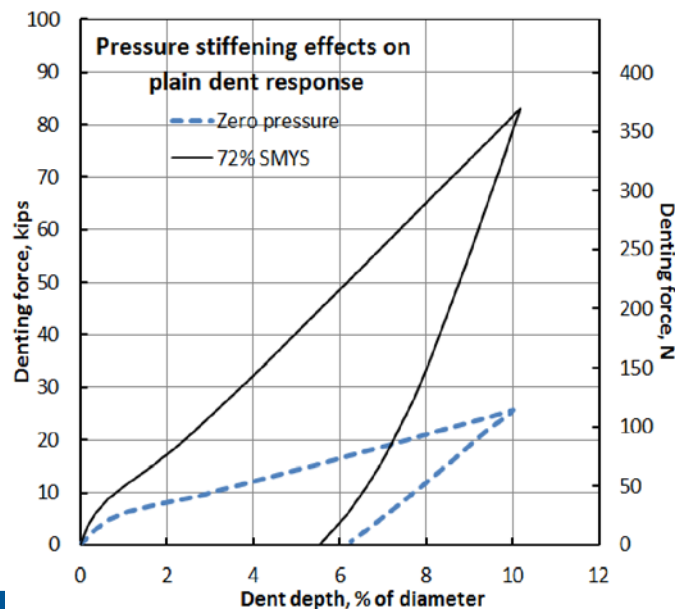
- Limited scatter – few “effects” as process is focused at a crack tip
- The problems don’t derive from issues with resistance as the do for burst predictions
- Rather they develop because the response as ΔK , $\Delta\sigma$, or $\Delta\varepsilon$, within the kink’s effect depend on the pressure when contact occurred (~unknown for field damage).
- Significance of the kinking depends on D/t , P_{mx} , n , & the nature of the cycling
- Some good predictions but also some poor ones

Summary for Plain & Kinked Dents & Gouged Dents



There can be a lot happening local to a dent
 Pipe properties dictate the response
 Kinking poses major complications

- Some aspects are simple & very predictable – toughness is a key
- True plain dents are not a threat to fail in service – likewise for features that are collapse controlled unless very deep and long
- Dent response can depend on pressure at contact and D/t



Summary: the Technology & Validation

- PR-003-9305 Vol I & Vol II & Appendices, w/Battelle, November, 1999
 - Validated via predictions for various field failures
- PR-003-063509, w/Battelle, September 2011
 - Burst validated by blind full-scale tests
 - Fatigue blind-validated for $\Delta K/\Delta P$ = constant cases,
but failed for complex re-rounding cases
due to re-rounding issues
- PR-185-133739-R01 Phase I, w/EWI, December 2015
 - Validated by case-to-case comparison with full-scale tests
 - (Phase II was not funded)

API RP 1183 Dent Assessment Workshop

Houston, TX

August 9, 2018

Start the Day Right!

Safety Share

Facility Safety Basics

Fire and other alerts

Exit locations and Muster points

Other conditions



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Back to School Driver Safety

Be Prepared

Allow extra time

Brake early

Inclement Weather

Be Alert

Smith System Keys – think kids...

...but kids do dumb things (acorns and trees?)

Is there an OQ for driving a bus?

Diligence in neighborhoods - passing bus stops

\$5/day!! (Personal crusade)

API RP1183 – Basis & Drivers

PHMSA Draft Final Rules – natural gas & hazardous liquids

NTSB Recommendation

Recent operator experiences

Consolidating 15 years of R&D on dents in pipelines

15 years of operator experience with IMP

Depth is not the key parameter

Improvements in inspection capabilities

Improvements in **dent assessment**

Work with PHMSA to develop an acceptable Engineering Analysis approach for dent assessment and management

API RP1183 – Current Status

Several meetings of the RP Team

Divide and conquer – Task-level teams

- Dent formation and failure modes

- Definition and characterization

- Screening of dents and operational susceptibility

- Assessment methods/approaches

- Remediation, mitigation, repair

- Field guidance

Routine meetings with RP Team

Goal for draft document by Jan 1 2019

Agenda

7:30 – 8:30	Registration/Sign in and Breakfast	
8:30 – 8:45	Introduction and Opening Remarks	Mark Piazza
8:45 – 9:30	Stress Concentration Factor Analysis	Chris Alexander
9:15 – 10:00	Dent Assessment with Considerations of Geohazards & Pipeline Vintage	Yong-Yi Wang
10:00 – 10:15	BREAK	
10:15 – 11:00	PRCI/BMT Dent Fatigue Assessment Method	Aaron Dinovitzer
11:00 – 11:45	Burst and Fatigue Failure of Dent+Gouge	Brian Leis
11:45 – 12:30	LUNCH	
12:30 – 1:15	Strain-based Dent Assessment Approaches	R. Krishnamurthy
1:15 – 1:45	Natural Gas Operators Approach to ECA	Mike Rosenfeld
1:45 – 2:00	BREAK	
2:00 – 2:45	Industry Panel – Approaches to Dent Assessment and Management <i>The panel session will be a facilitated discussion that addresses the practical challenges of managing dents and application of the dent assessment methods presented at the workshop. The panel will include representatives from trade associations, PHMSA, and pipeline operators, including natural gas and hazardous liquids pipeline operators.</i>	CJ Osman Steve Nanney Munendra Tomar Yvan Hubert
2:45 – 3:00	Q&A and Path Forward	Mark Piazza
3:00 – 3:15	Meeting wrap-up and Action Items	Mark Piazza

Responding to ILI Indicated Dents with Metal Loss: GPAC Meeting Outcome and a Proposed Simplified Process

M.J. Rosenfeld, Kiefner & Associates
PRCI / API Joint Meeting, Houston, Aug. 8 2018



- Record of the meeting publicly available at <https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=132>.
- Repair criteria for all conditions including dents under 192.485(c), 192.711, 192.713, and 192.933 are covered on presentation slides 136-153 (of 199).
- Includes public comments to NPRM and PHMSA's responses.
- GPAC meeting discussion regarding dents is covered on
 - Day 2 transcript pages 294-299 (of 346) and
 - Day 3 pages 21-25, 30-31, 50-59, 122-124 (of 283).
- Final voting summary slides regarding dents, page 20 (of 25).

6. NPRM Proposed Repair Criteria

Existing Anomaly Type HCA Only	Existing Timing HCA Only	NPRM Anomaly Type Applies to both HCA and Non-HCA	NPRM Timing Applies to both HCA and Non-HCA
Predicted Failure Pressure (PFP) $\leq 1.1 \times$ MAOP	Immediate	PFP $\leq 1.1 \times$ Maximum Allowable Operating Pressure (MAOP) (same for HCA, new for non-HCA)	Immediate
Dent w/Metal Loss (ML), cracking, or stress riser	Immediate	Dent w/ML, cracking, or stress riser (same)	Immediate
Any other anomaly requiring immediate action	Immediate	Any other anomaly requiring immediate action (same)	Immediate
(no current requirement)		Metal loss $> 80\%$	Immediate
		Metal loss affecting DC/LF/HF ERW/EFW seam	Immediate
		Significant SCC	Immediate
		Significant SSWC	Immediate



6. NPRM Proposed Repair Criteria

Existing Anomaly Type HCA Only	Existing Timing HCA Only	NPRM Anomaly Type Applies to both HCA and Non-HCA	NPRM Timing Applies to both HCA and Non-HCA
Smooth dent > 6% Top side dent (TSD)	1 year	Smooth dent > 6% (TSD) (same)	1 yr (same for HCA) 2 yr (new for non-HCA)
Dent > 2% at weld	1 year	Dent > 2% at weld (same)	1 yr (same for HCA) 2 yr (new for non-HCA)
(no current requirement)		PFP ≤ 1.25 (Class 1) 1.39 (Class 2) 1.67 (Class 3) 2.00 (Class 4)	1 yr (new for HCA) 2 yr (new for non-HCA)
		General corrosion > 50%	1 yr (new for HCA) 2 yr (new for non-HCA)
		ML > 50% at crossing/circumferential/girth weld	1 yr (new for HCA) 2 yr (new for non-HCA)
		Gouge or groove > 12.5%	1 yr (new for HCA) 2 yr (new for non-HCA)
		Any indication of crack or crack-like defect that is not an immediate condition	1 yr (new for HCA) 2 yr (new for non-HCA)



6. NPRM Proposed Repair Criteria

Existing Anomaly Type HCA Only	Existing Timing HCA Only	NPRM Anomaly Type Applies to both HCA and Non-HCA	NPRM Timing Applies to both HCA and Non-HCA
Bottom Side Dent (BSD) > 6%	Monitored Condition	Same for HCAs; New requirements for non-HCAs	
TSD > 6%; analysis demonstrates critical strain levels not exceeded	Monitored Condition		
Dent > 2% at weld; analysis demonstrates critical strain levels not exceeded.	Monitored Condition	Same for HCAs N/A for non-HCAs	



6. Repair Criteria

192.485(c); 192.711; 192.713; 192.933

Public/Committee Comments on Repair Criteria (3/2/18):

- PHMSA should allow operators to use ECA to evaluate dents.
- **PHMSA**: the original repair criteria for dents were developed in the early 2000s timeframe for both HL and gas integrity management rules.
- Both ILI technology and analytical techniques to assess dents have advanced significantly since that time. PHMSA has gained confidence in applying ECA techniques to analyze dent defects through recent application of dent ECA in special permits.
- Consistent with applying proven analytical techniques to evaluate corrosion metal loss and cracking defects, PHMSA suggests including a dent ECA procedure in the final rule as shown on the next slide.



6. Repair Criteria

192.485(c); 192.711; 192.713; 192.933

Public/Committee Comments on Repair Criteria (3/2/18):

- **PHMSA: Summary of suggested ECA for Denting:**
 - Evaluate potential threats for the pipe segment in the vicinity of the dent including movement, loading, and cathodic protection;
 - Review HR-MFL and HR-Deformation inline inspection data for damage in the dent area and any associated weld region;
 - Perform pipeline curvature-based strain analysis using recent HR-Deformation inspection data;
 - Compare dent profile between the recent and past HR-Deformation inspections to identify significant changes in dent depth and shape;
- (cont.)



6. Repair Criteria

192.485(c); 192.711; 192.713; 192.933

Public/Committee Comments on Repair Criteria (3/2/18):

- **PHMSA:**

Summary of suggested ECA for Denting (cont.):

- Identify and quantify all loads acting on the dent for a basis for ECA;
- Evaluate strain level associated with dent and any welds using Finite Element Analysis (FEA), and calculate the plastic strain limit damage factors to infer the possibility of a crack;
- Estimate the fatigue life of the dent using FEA with the operational pressure data and different fatigue life prediction models, which must have reassessment safety factor of 2.



6. Repair Criteria

192.485(c); 192.711; 192.713; 192.933

Public/Committee Comments on Repair Criteria (3/2/18):

- PHMSA should allow operators to use ECA to evaluate dents.
- **PHMSA**: (cont.)
PHMSA suggests that operators be allowed (but not required) to use ECA analysis for the following dent-related repair criteria:
 - Dent with indication of metal loss, cracking, or stress riser
 - Smooth topside dent > 6% diameter (or 0.50 in. deep for $D < \text{NPS}12$)
 - Dent > 2% diameter (or >0.25 in. deep for $D < \text{NPS}12$) that affects pipe curvature at a girth weld or seam weld
- Dents analyzed by ECA, but shown to not exceed critical strain levels would be included in the repair criteria as Monitored Conditions.



6. Repair Criteria

192.485(c); 192.711; 192.713; 192.933

Public/Committee Comments on Repair Criteria (3/2/18):

- Repair criteria for dents with metal loss should distinguish between topside and bottom-side dents (similar to the repair criteria for smooth dents).
- **PHMSA:**
 - The dent with metal loss criterion was part of the original integrity management (IM) rule (2003).
 - PHMSA recognizes that topside dents represent the need for a more urgent response than bottom-dents. Some existing HCA dent repair criteria already make this distinction.
 - PHMSA suggests applying this concept to dents with metal loss in non-HCA locations (similar to smooth dents). (cont.)



6. Repair Criteria

192.485(c); 192.711; 192.713; 192.933

Public/Committee Comments on Repair Criteria (3/2/18):

- Repair criteria for dents with metal loss should distinguish between topside and bottom-side dents (similar to the repair criteria for smooth dents). (cont.)
- **PHMSA:** (cont.) Also, to reduce unnecessary excavations, PHMSA suggests revising this immediate condition as follows:
 - Allow engineering critical assessment (ECA) to analyze dent anomalies with indications of metal loss, cracking or stress riser, and prioritize repair criteria as follows:
 - Immediate: topside defects that exceed critical strain levels,
 - 2 Year: bottom-side that exceed critical strain levels, and
 - Monitored: defects that do not exceed critical strain levels.



6. Repair Criteria

192.485(c); 192.711; 192.713; 192.933

Public/Committee Comments on Repair Criteria (3/2/18):

- Industry commented that the proposed criterion of a gouge or groove greater than 12.5% of nominal wall thickness is duplicative and addressed by the dent with metal loss and cracking criteria.
- **PHMSA**: acknowledges that the proposed criteria using engineering critical assessment to analyze dents and cracks would adequately address gouges and grooves and suggests deleting this repair criterion on that basis.



- Natural gas pipeline operators noted that large proportions (~80-90%) of “Immediate response” conditions were related to “dents with metal loss” that are not real threats.
- PHMSA noted that the reportable incident data for 2002-2017 showed many more incidents due to cracking in dents in HL pipelines compared with NG pipelines (by approximate factor of 5-7).
- Dents with metal loss on top of pipe will be a higher priority than those on bottom. Interpretation: Position on pipe (top vs bottom) will be a proxy for whether the metal loss is a gouge or corrosion in an absence of definitive indication by ILI.

- FEA would be allowed, but its use is not a requirement. Other proven analytical techniques can be invoked.
- Critical material strains should be determined on a case by case basis, using what is known about the pipe materials.
- Note: ASME B31.8-2018 edition will be published with the following revised dent strain of deformation criteria:
 - 40% of average elongation from MTRs
 - 50% of specified min elongation per pipe spec or PO
 - 6% where MTRs are unavailable and pipe spec unknown

Voting Language for Repair Criteria - § § 192.485(c); 192.711; 192.713; 192.933

The proposed rule as published in the Federal Register and the Draft Regulatory Evaluation, with regard to provisions for dent repair criteria, are technically feasible, reasonable, cost-effective, and practicable, if the following changes are made:

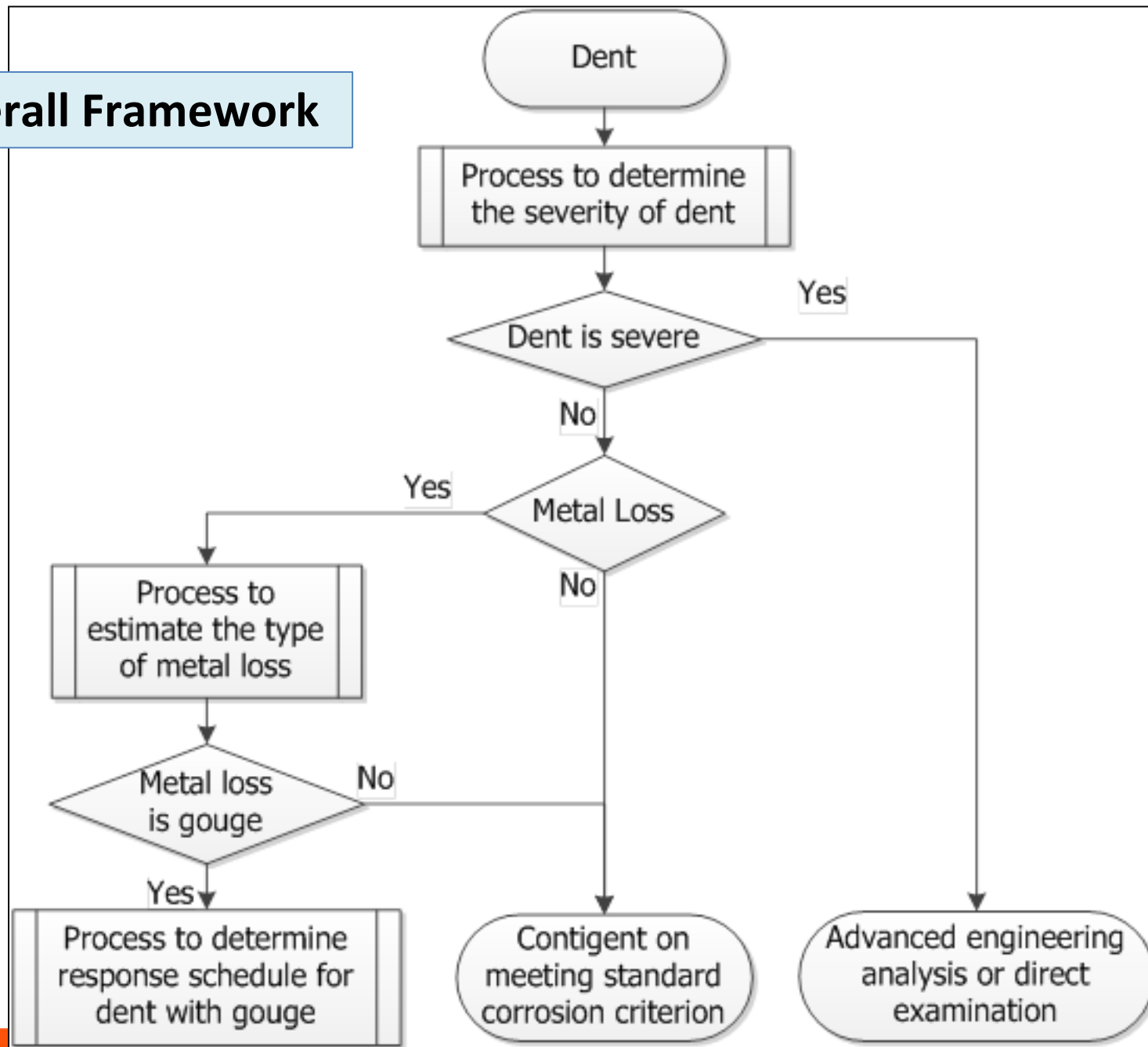
- Allowing (but not require) ECA analysis for the following dent-related repair criteria (HCA and non-HCA):
 - Dent with indication of metal loss, cracking, or stress riser
 - Smooth topside dent > 6% diameter (or 0.50 in. deep for D<NPS12)
 - Dent > 2% diameter (or >0.25 in. deep for D<NPS12) that affects pipe curvature at a girth weld or seam weld
 - Dents analyzed by ECA, but shown to not exceed critical strain levels would be Monitored Conditions; PHMSA will consider language to accommodate alternative ECA methods such as FEA
- Revise the immediate condition for dent anomalies with indications of metal loss, cracking, or stress risers in non-HCAs as follows:
 - Allow an engineering critical assessment (ECA) to analyze dent anomalies with indications of metal loss, cracking or stress risers, and prioritize repair criteria as follows:
 - **Immediate**: topside defects that exceed critical strain levels,
 - **2 Year**: bottom-side that exceed critical strain levels, and
 - **Monitored**: defects that do not exceed critical strain levels.

Approved GPAC
Language 3/28/18

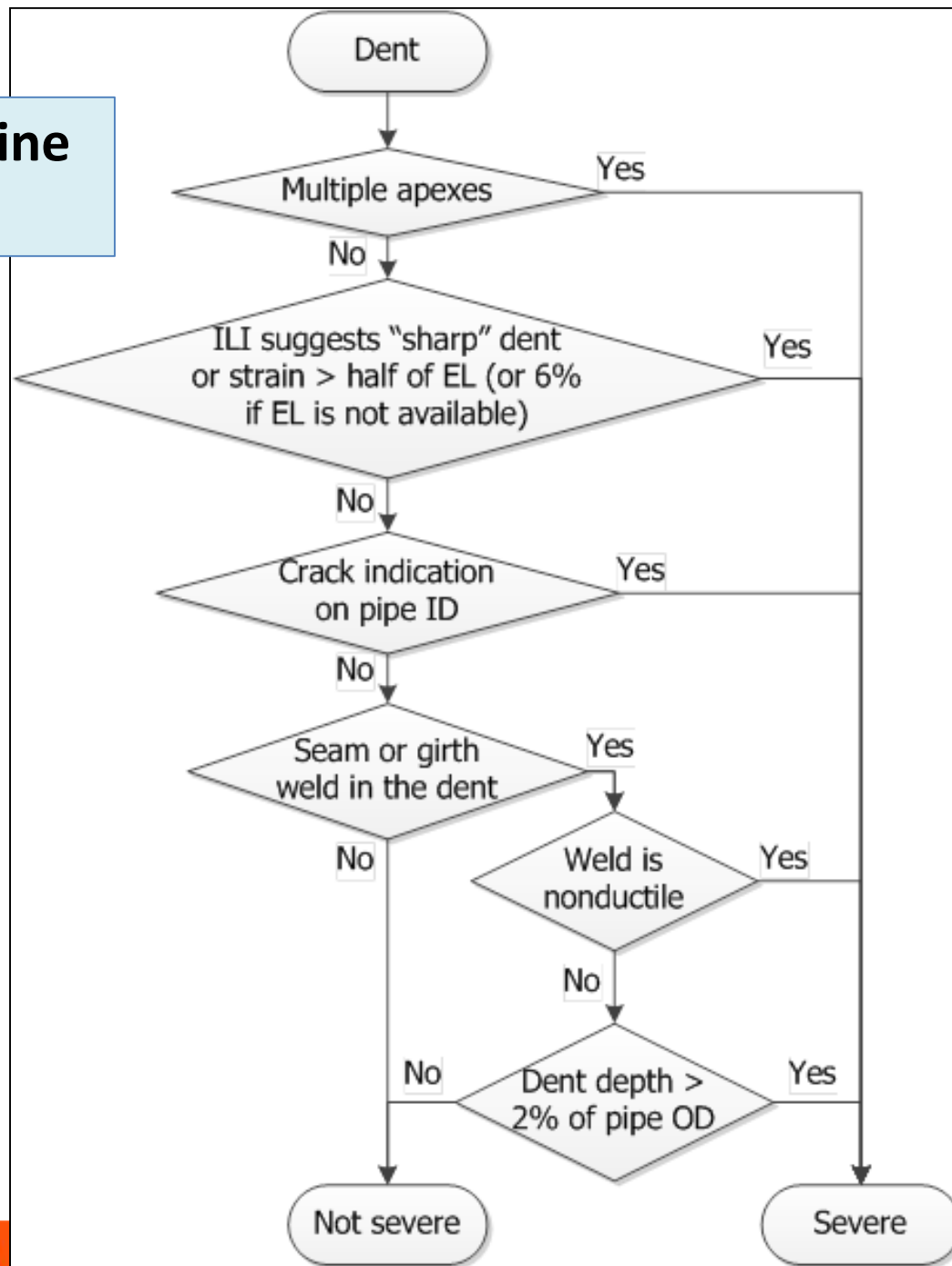


- December 2017, INGAA requested a simple process for addressing dents with metal loss for possible presentation at GPAC and consideration in rulemaking.
- Kiefner prepared the following simplified framework that requires only simple calculations.
- Based on FEA and fracture mechanics from public domain models.
- Could be easily written into a spreadsheet usable by any integrity personnel or technician. Suitable for RP content.
- INGAA did not pursue completion of the work because the PHMSA proposal allowing ECA was considered satisfactory.

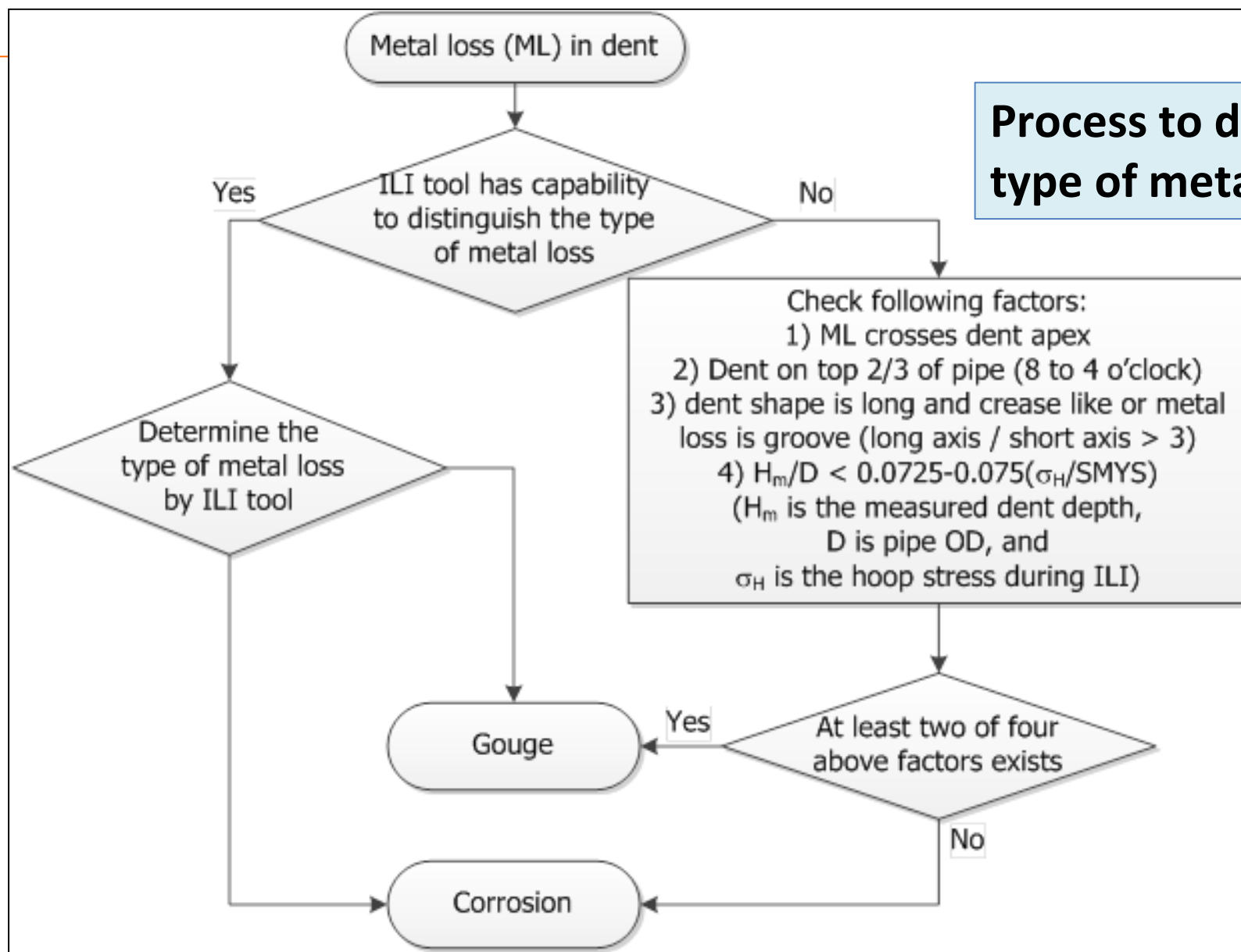
Overall Framework



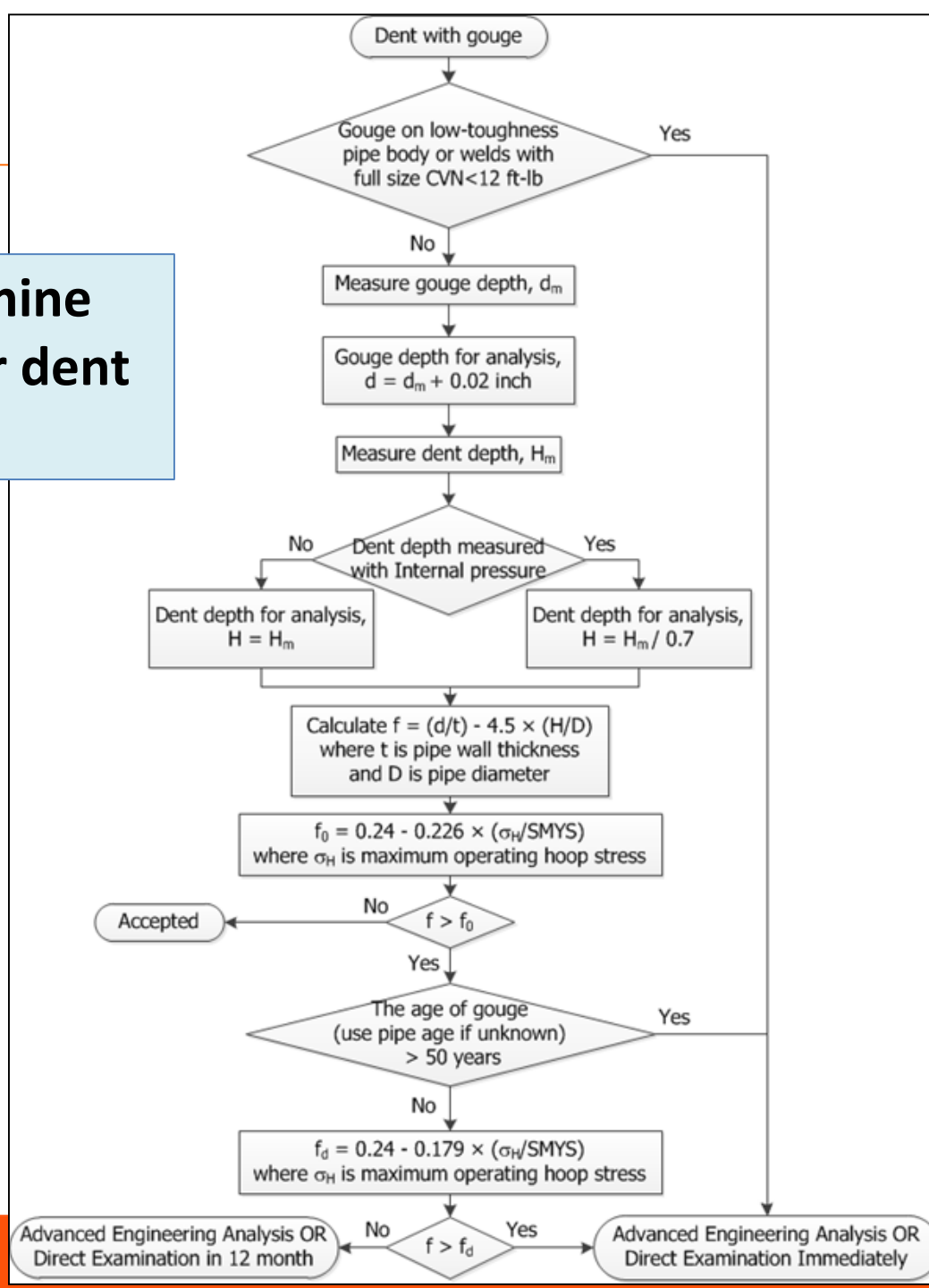
Process to determine dent severity



Process to determine type of metal loss



Process to determine response time for dent with gouge



Questions or comments?

Contact presenter at:

michael.rosenfeld@kiefner.com

Acknowledgements:

C.J. Osman, INGAA

Fan Zhang, Kiefner

Dent Assessment with Considerations of Longitudinal Strain & Pipeline Vintage

Yong-Yi Wang



Center for Reliable Energy Systems

5858 Innovation Dr.

Dublin, OH 43016

614-376-0765

PRCI/API Dent Workshop

08/9/2018

Houston, TX, USA

Overview

- ❑ Field conditions that can introduce longitudinal strain
- ❑ Evolution of pipe manufacturing and its impact on basic pipe properties
- ❑ Impact of dents on critical (buckling) strain
- ❑ Implications of stress-strain response on dent assessment
- ❑ Concluding remarks

Sources of Axial (Longitudinal) Strains

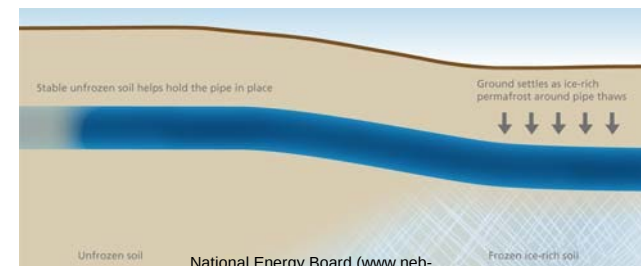
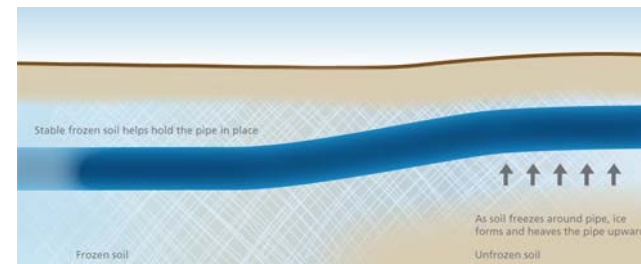
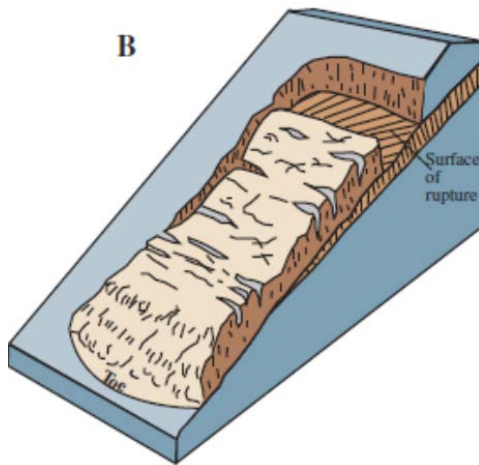
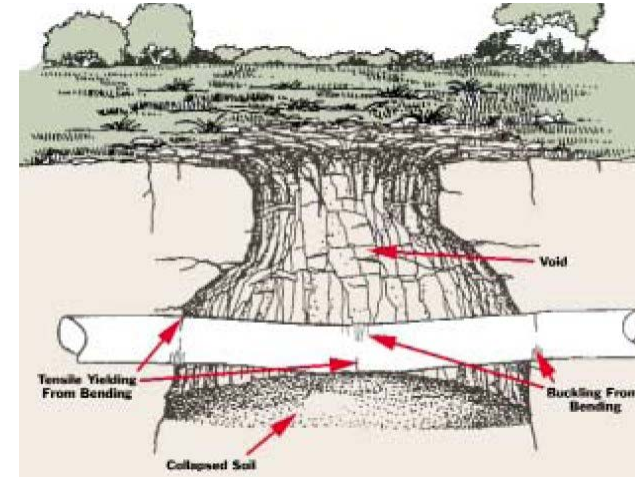
- ❑ Conditions generating axial strains - most onshore pipelines
 - ❖ Differential settlement
 - ▶ Tie-in at crossings
 - ▶ Excavation/dig of pipelines that have been in service for a while
 - ❖ The profiles of trench and pipes don't completely match.
 - ❖ Pipe ends are forced together at tie-in locations.
 - ❖ Temperature change
- ❑ Conditions generating high axial strains - many onshore pipelines
 - ❖ Slow ground movement, e.g., landslide
 - ❖ Washout at water crossings

Pipe moved laterally after excavation. There were axial strains in the pipe.



Ground Movement Events Can Cause High Axial Strains

- ❑ The tolerance of many pipelines to such events is often not known.



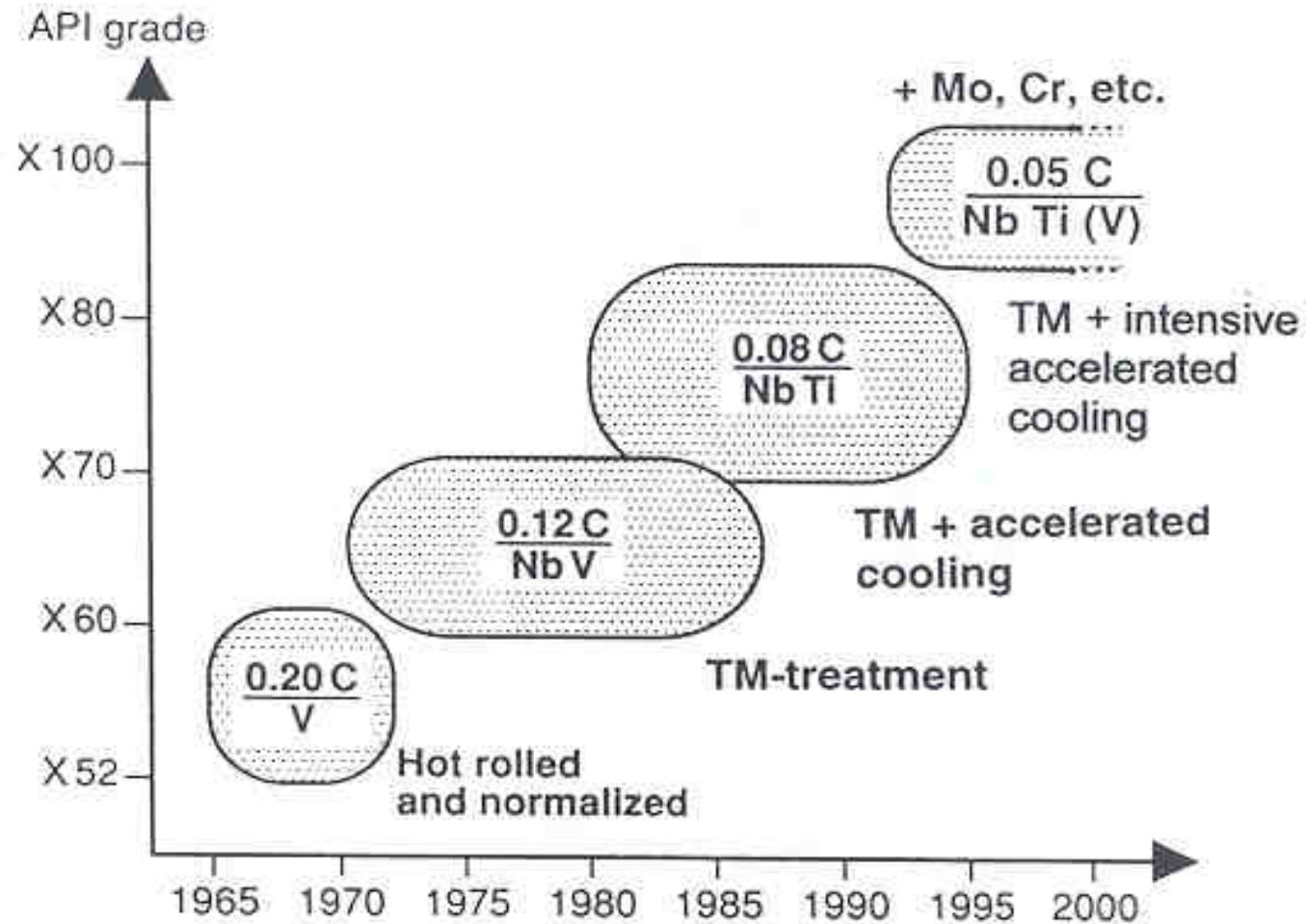
National Energy Board (www.neb-one.gc.ca)



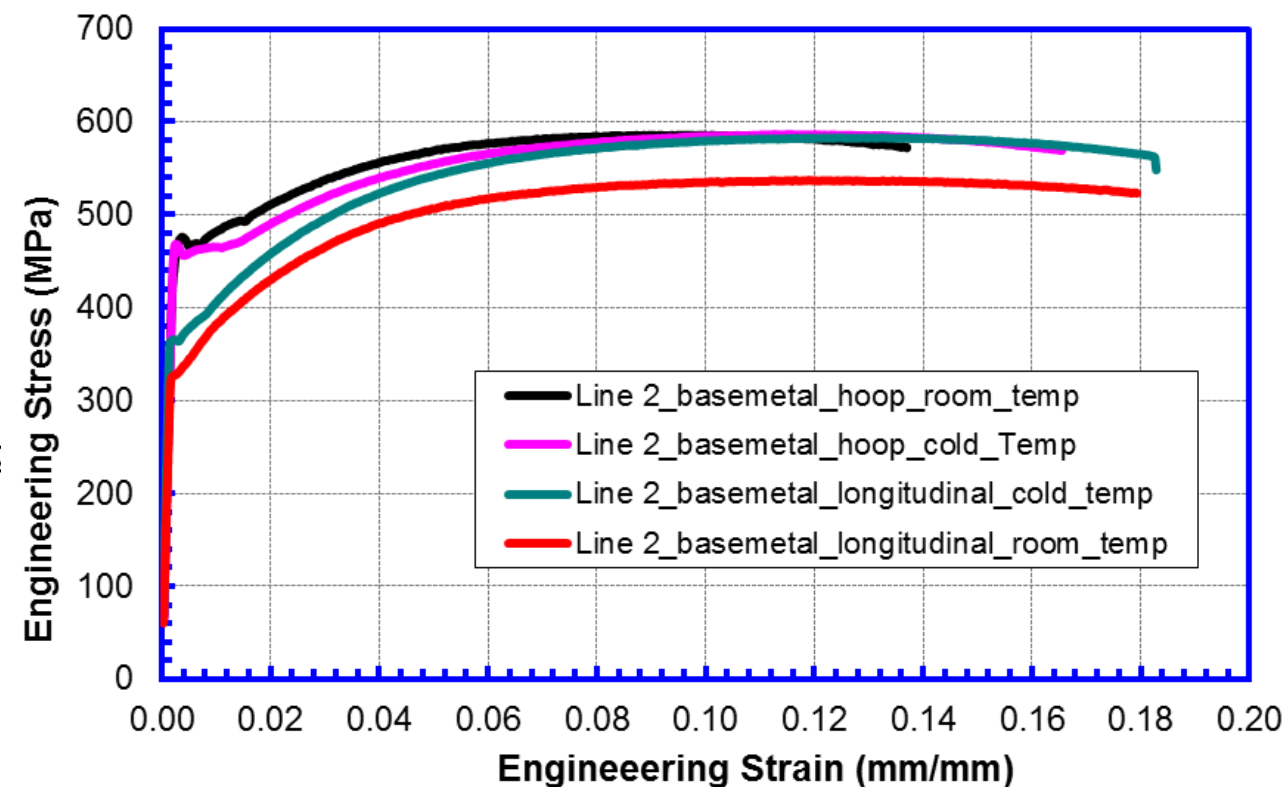
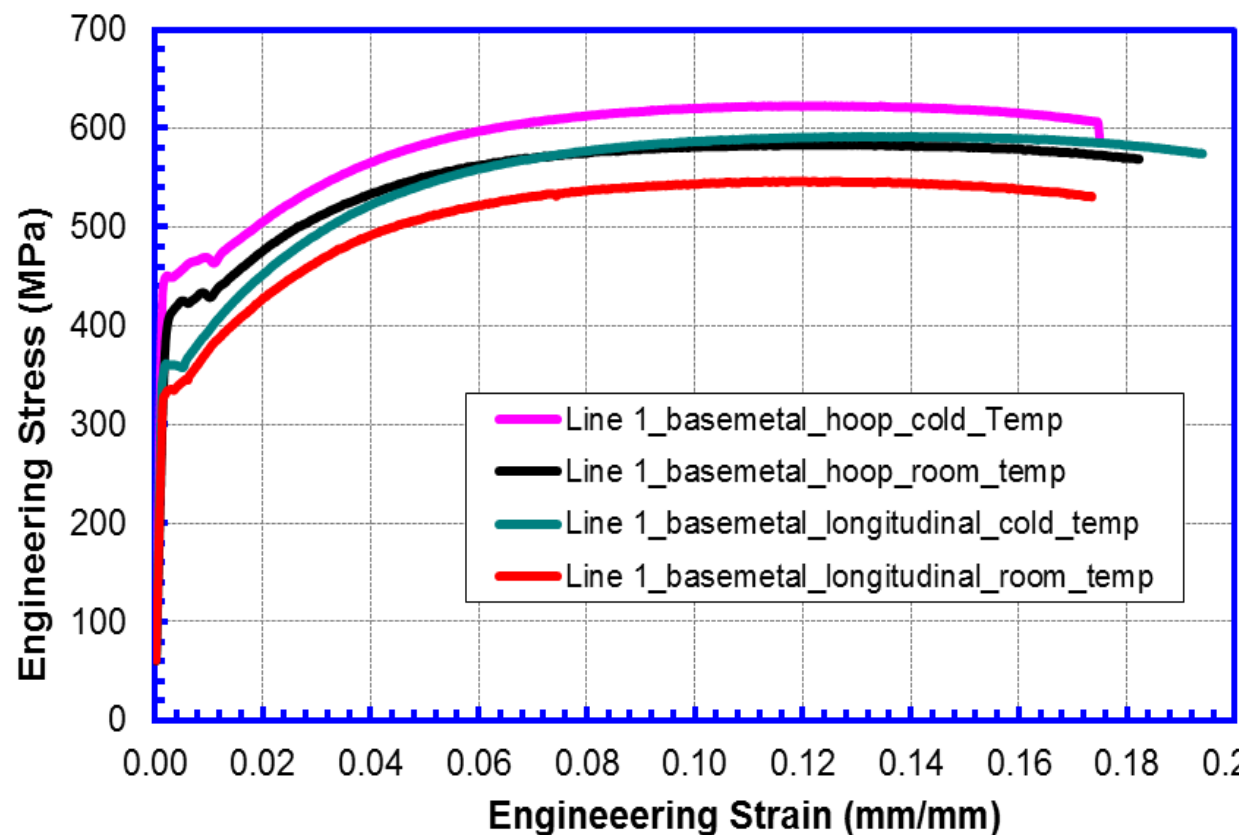
Evidence of Axial (Longitudinal) Strains and Our Practice

- ❑ IMU runs of pipelines in flat Texas farmland indicate:
 - ❖ One high axial strain location in every 1-2 miles of pipeline.
 - ❖ High strain: strains $> 0.2\%$, pipes are in near- or post-yield state from axial strain alone.
- ❑ Our practice
 - ❖ Field practice
 - ▶ Internal pressure, thus hoop stress, is actively managed.
 - ▶ Longitudinal stress/strains in most cases are not actively managed.
 - ❖ Testing and analysis
 - ▶ Hoop stress is generally higher than axial stress.

Evolution of Linepipe Manufacturing

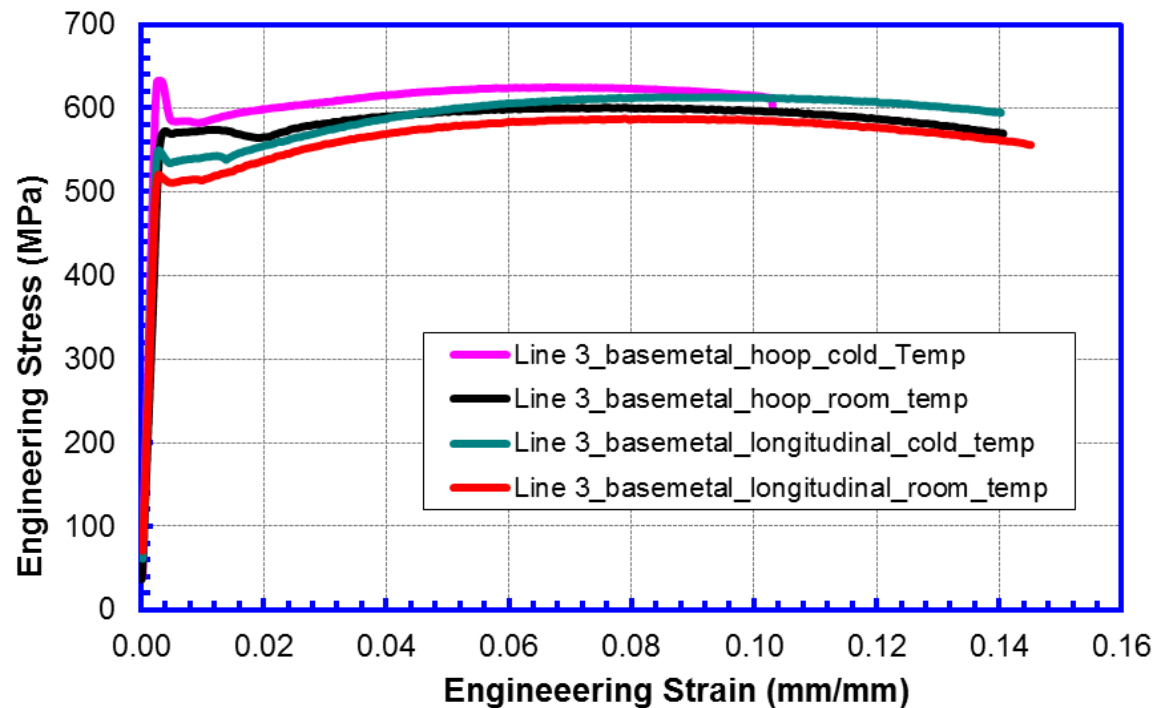


Evolution of Tensile Properties

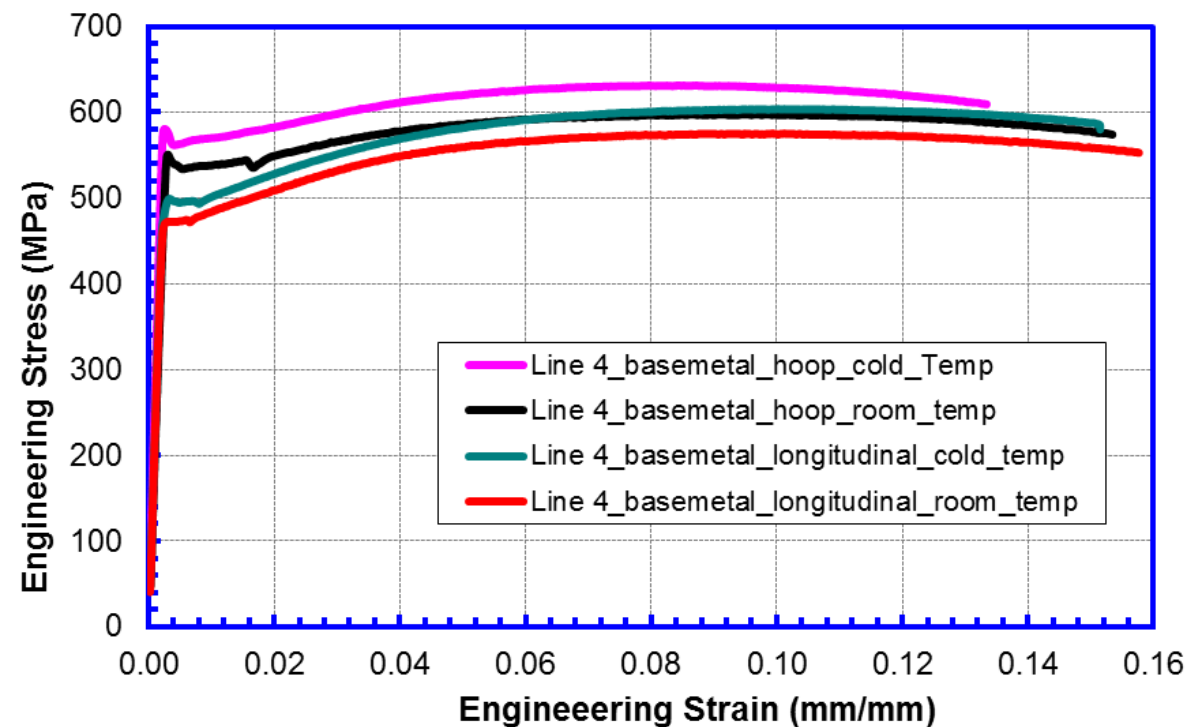


Evolution of Tensile Properties

□ Line 3: late 1960's, X60

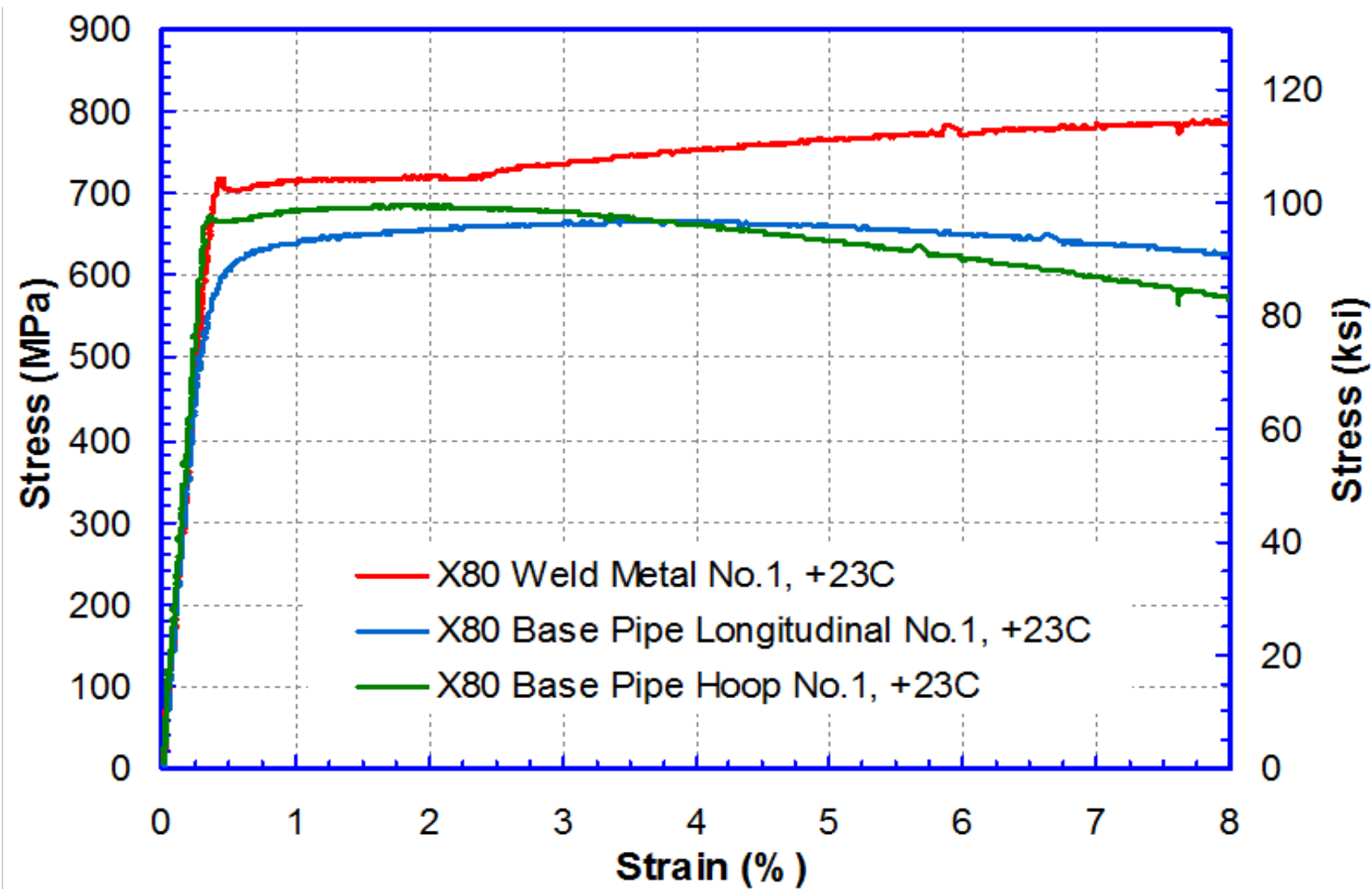


□ Line 4: late 1980's to early 1990, X65



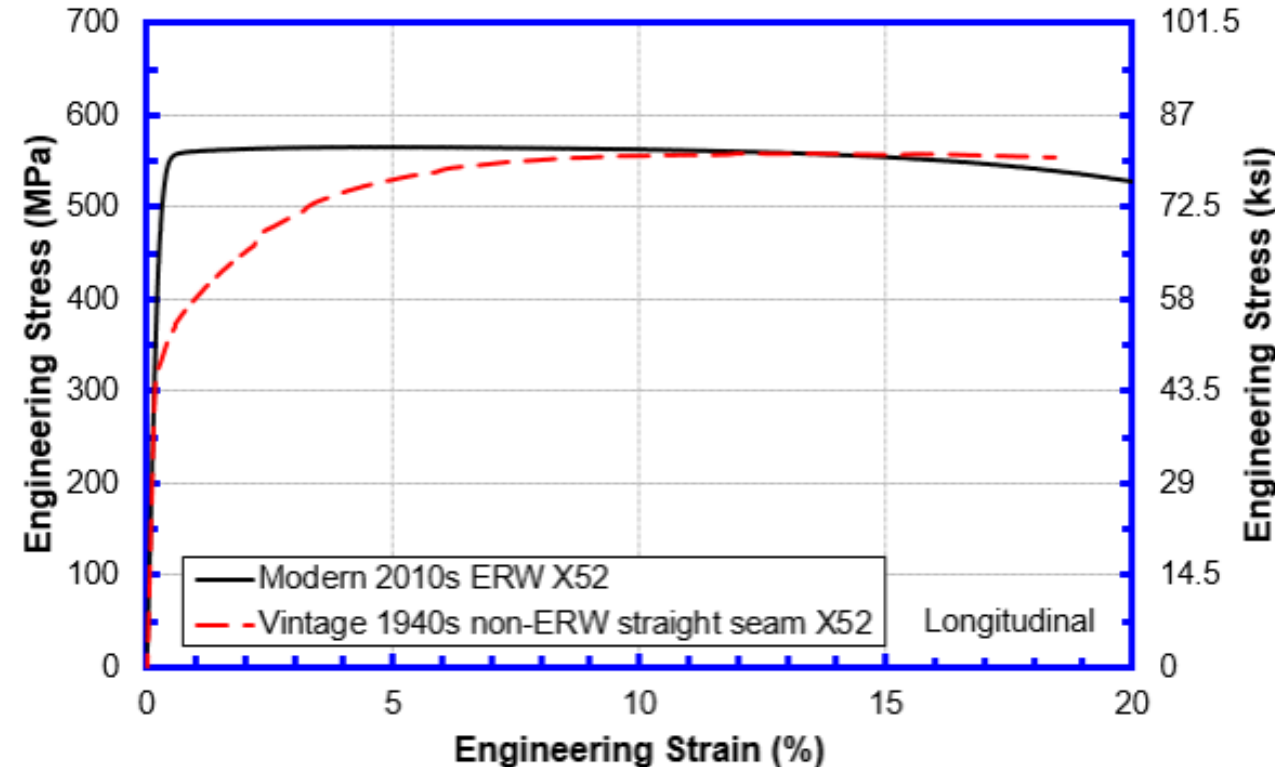
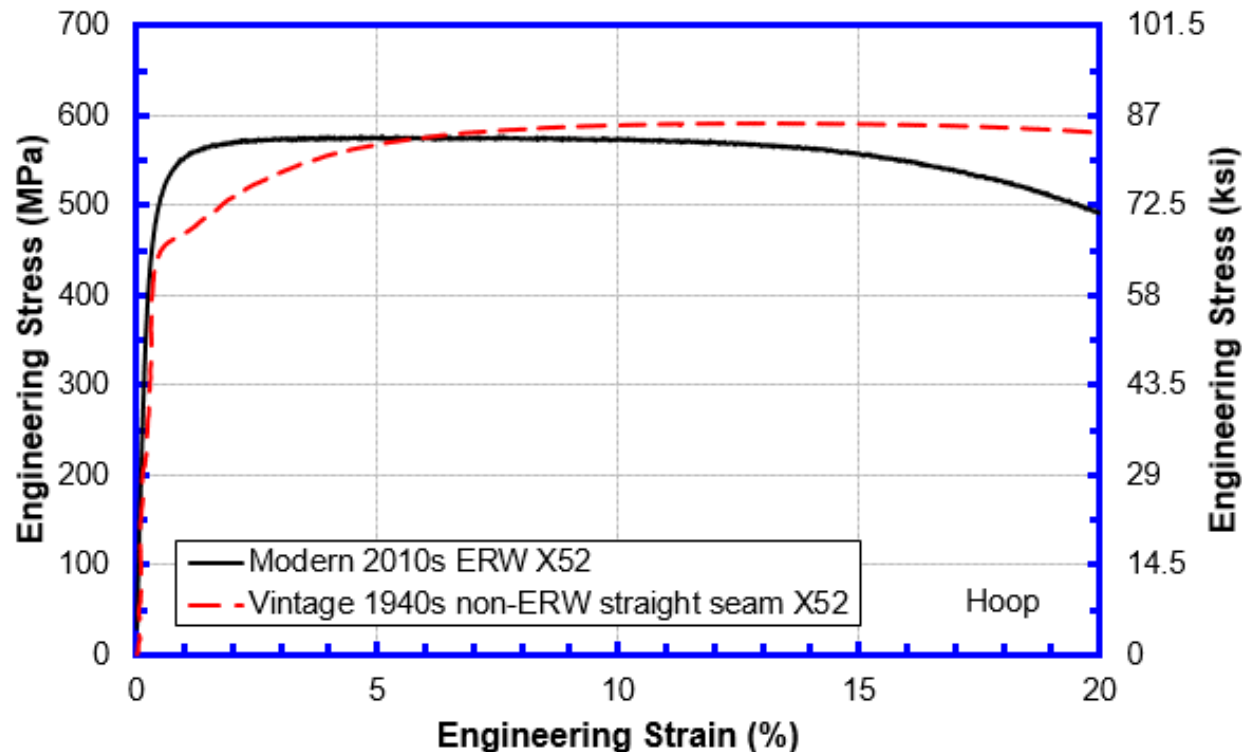
Evolution of Tensile Properties

□ X80 2000's



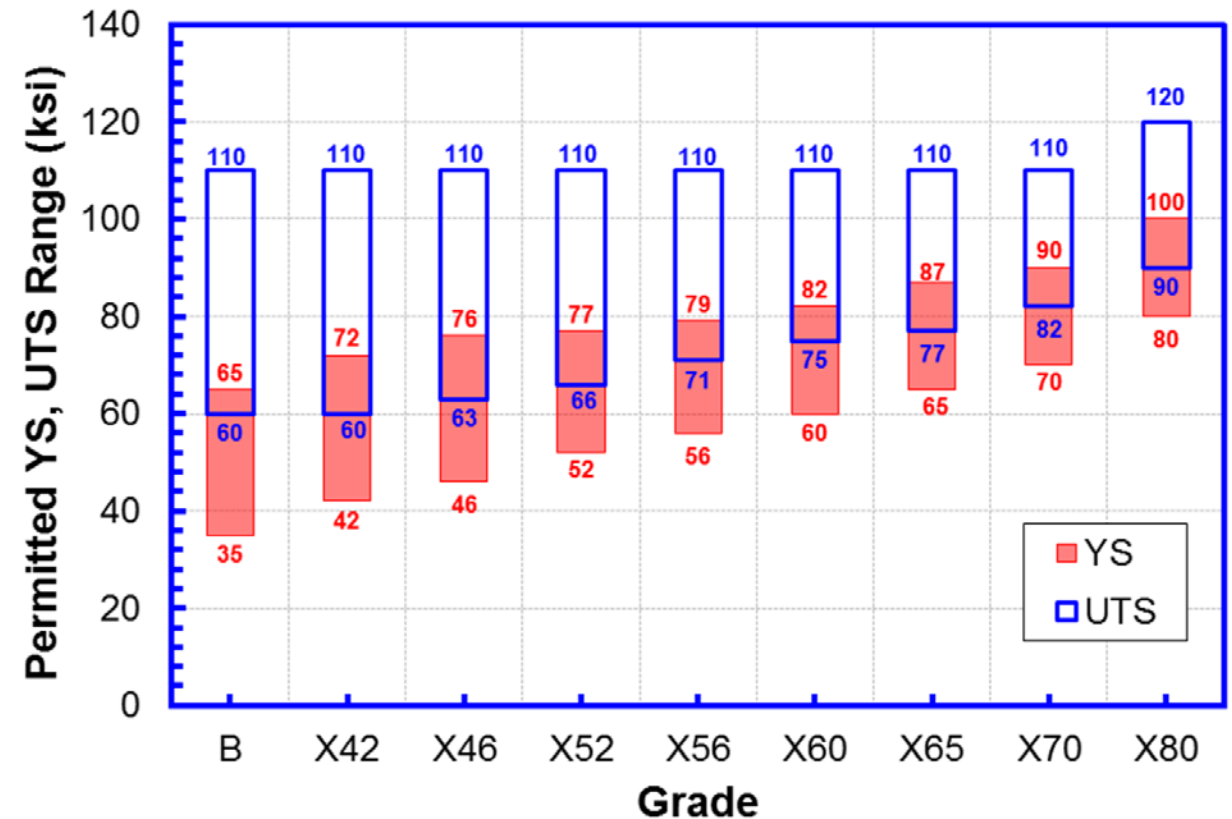
Same Grade of Pipe Can Have Vastly Difference Property

- ❑ Newer pipes:
 - ❖ Microalloyed TMCP steels
 - ❖ Low strain hardening
 - ❖ Long uniform elongation



Range of Pipe Strength

- ❑ Pipe strength can be significantly higher than the specified minimum strength
 - ❖ PSL 2 pipes have upper limit
 - ❖ PSL 1 pipes have no upper limit
 - ❖ Even some vintage X52 pipes can have yield strength > 80 ksi
- ❑ Implications
 - ❖ Strain hardening capacity and uniform elongation (strain at UTS) typically does down with increasing strength
 - ❖ Weld strength can be lower than the strength of pipe. Weld area can become sites of strain concentration.



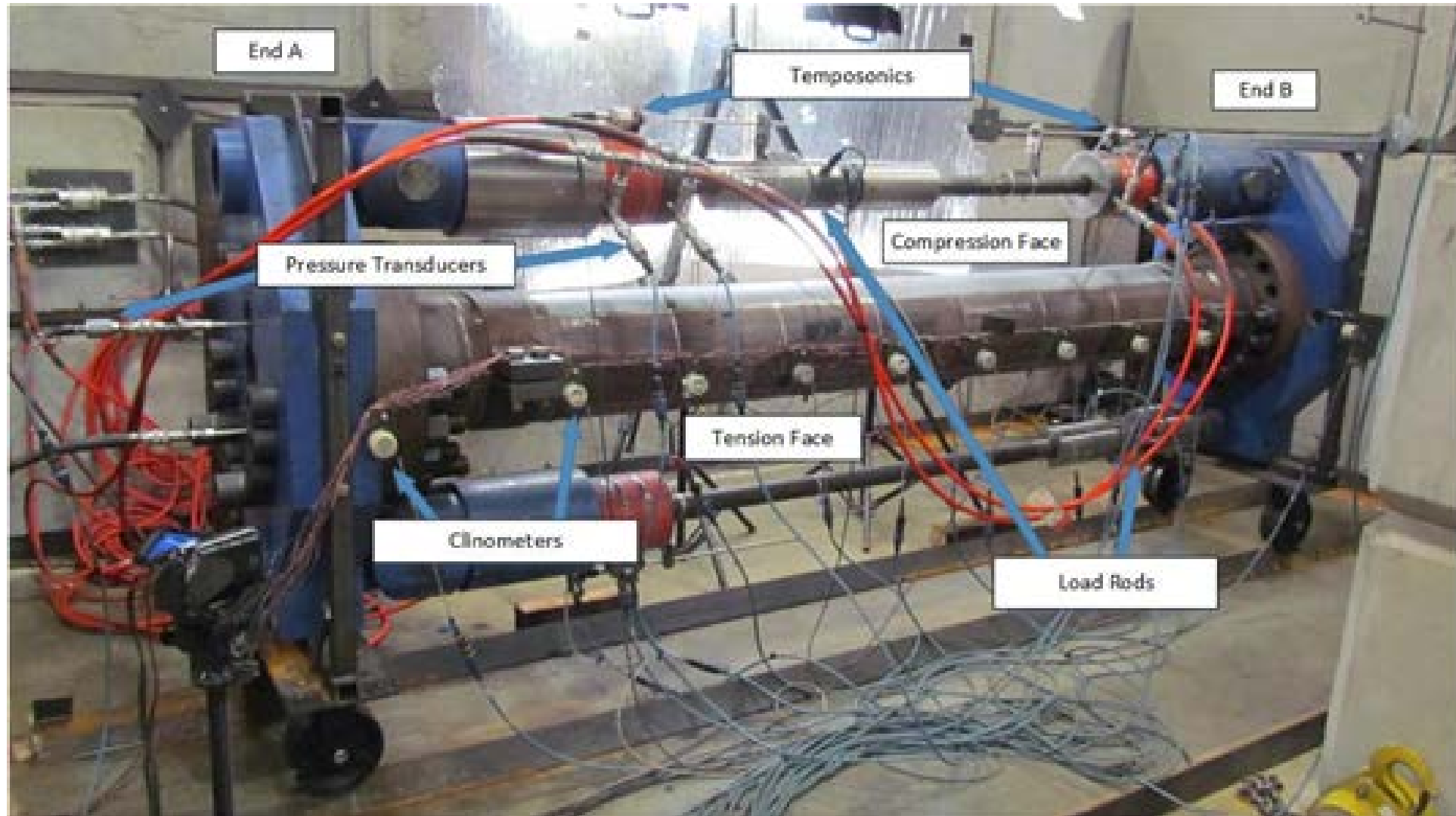
Test of Pipes with Dents – PHMSA Supported Work

- ❑ Dents of different depth were created.

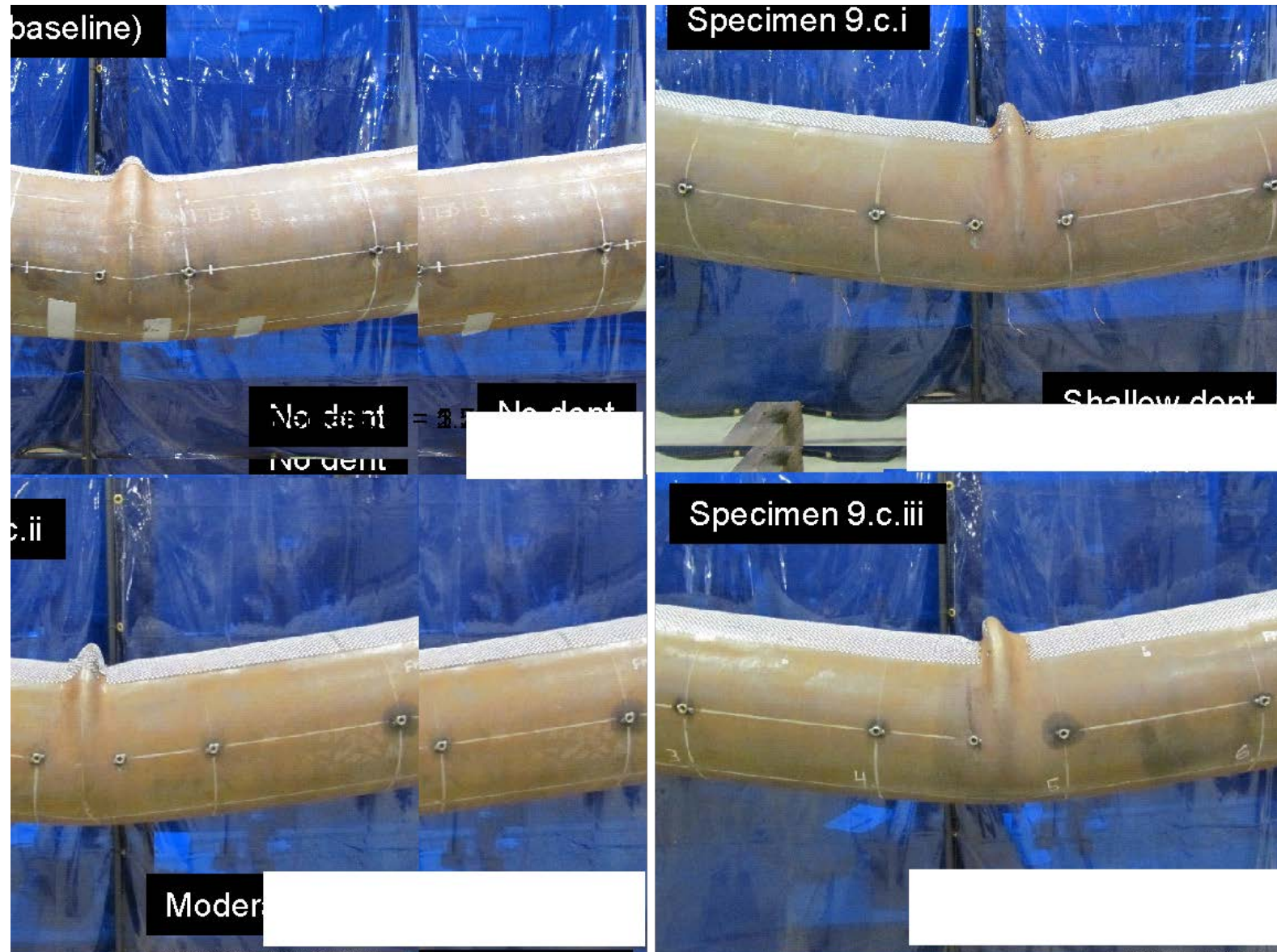


Test of Pipes with Dents – Done at CFER

- ❑ Pipes with dents were loaded in lateral bending.

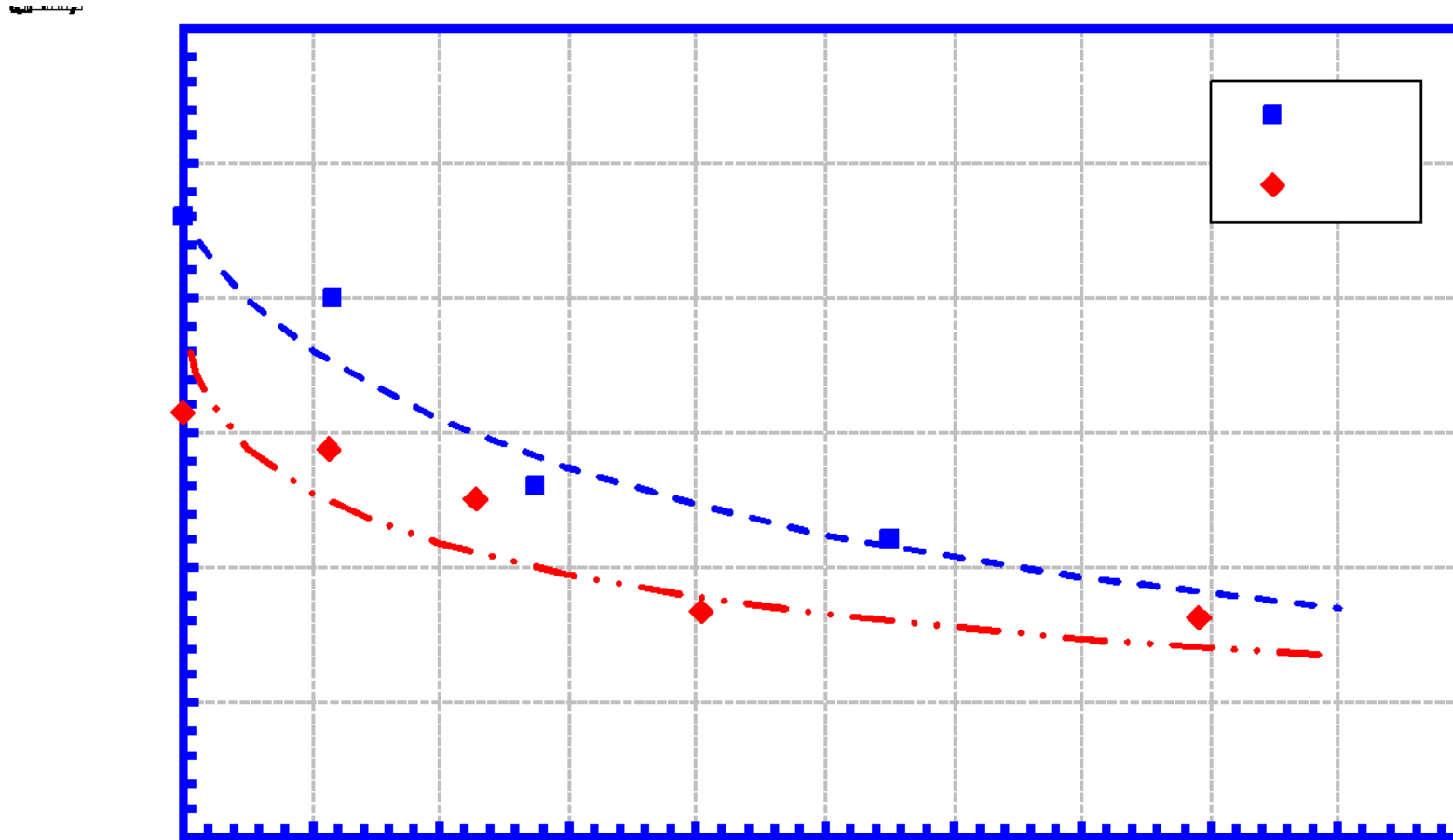


Test of Pipes with Dents – Post-Test Images



Critical Strain as a Function of Dent Depth

- Critical strain: nominal strain over a 2D gauge length at maximum bending moment



Applications and Path Forward

- ❑ Impact of dents on critical (buckling) strain
 - ❖ Stability of a pipeline in a washout conditions
 - ❖ Assessment of spans
- ❑ Biaxial stress vs. ASME design stress criteria

Hoop Stress / SMYS	Additive Longitudinal Stress / SMYS	Sum of Longitudinal Stresses from Sustained and Occasional Loads /SMYS	Longitudinal stress / SMYS from Equivalent Combined Stress Criterion				Final Allowable Longitudinal Stress / SMYS, Excluding Occasional Loads	
			Tensile Longitudinal Stress / SMYS		Compressive Longitudinal Stress / SMYS			
			Shear Stress Criterion	Mises Stress Criterion	Shear Stress Criterion	Mises Stress Criterion	Tensile	Compressive
0.72	0.90	0.90	1.62	1.01	0.18	0.29	0.90	0.29
0.60	0.90	0.90	1.50	1.03	0.30	0.43	0.90	0.43
0.50	0.90	0.90	1.40	1.04	0.40	0.54	0.90	0.54

Applications and Path Forward

- ❑ Impact of tensile properties on dent assessment – work under way
 - ❖ Impact of material properties in dent formation
 - ❖ Dent assessment that accounts for
 - ▶ Changes in strain hardening and uniform strain (reflected by pipe manufacturing, thus, vintage)
 - ▶ Axial (longitudinal) loading

Concluding Remarks

- ❑ Buried pipelines are not elongated pressure vessels.
- ❑ In some instances, stress/strain in axial (longitudinal) direction can be greater than that in hoop direction.
- ❑ Pipes of the same grade can have vastly different stress-strain response.
 - ❖ The difference can impact the strain redistribution during (local) plastic deformation process.
- ❑ The impact of stress-strain response of pipes of different vintage on dent integrity assessment is being investigated.
- ❑ In the application of assessment methods, limits of the methods should be stated and defined.
 - ❖ Grade may not a good reference

Thank You

- ❑ Discussion and comments

Dent Integrity Management

API/PRCI Joint Workshop on
Dent Assessment & Engineering
Analysis Methods
August 9, 2018



Outline

- **PRCI Dent Fatigue Assessment
Background - Motivation**
- **Research**
 - Full Scale Testing
 - Modeling
 - Results
- **Application**

Dent Research Motivation

Understanding of Dent Fatigue Life & Predictive Tools Were Lacking

Needed to consider

- Plain dents
- Dents with interacting features (metal loss and welds)
- Effect of restraint condition

The projects, sponsored by PRCI & US DOT generated full scale cyclic load trial data suitable for the validation of dent fatigue models

- The experimental data collected includes:
 - Detailed dent depth profiles
 - Experimental loading data
 - Pipe wall strain measurements
 - Detailed material property information

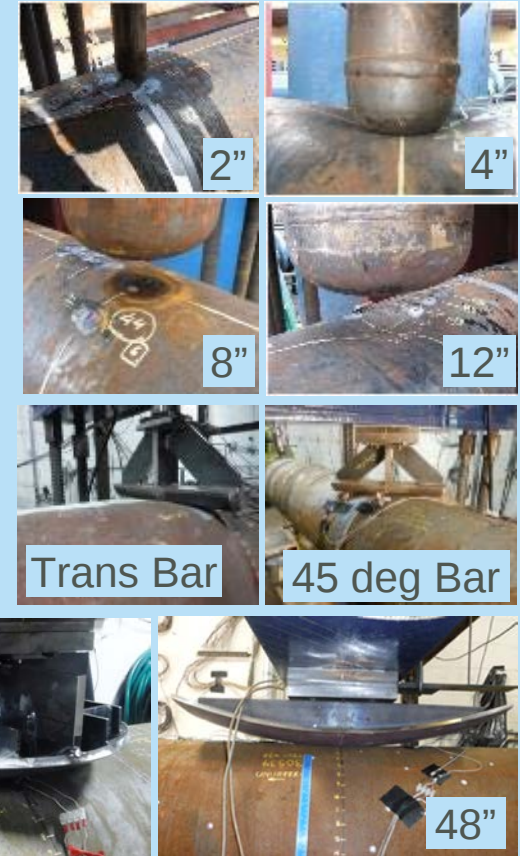
Dent Full Scale Testing

Dent Fatigue Models not Adequate and Needed Data for Validation

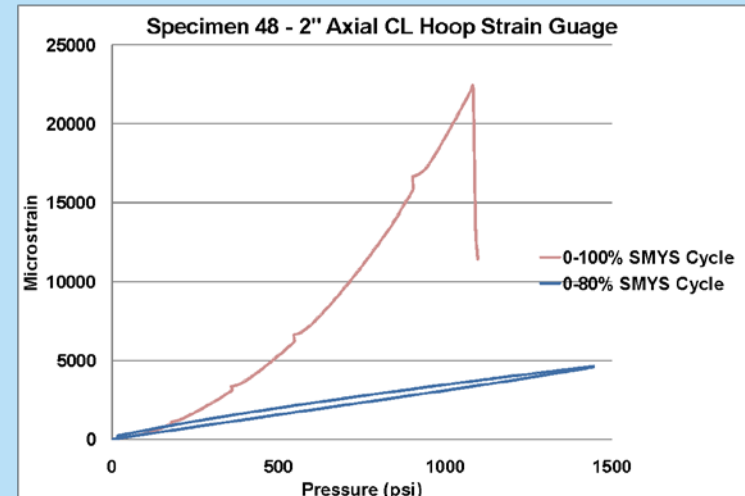
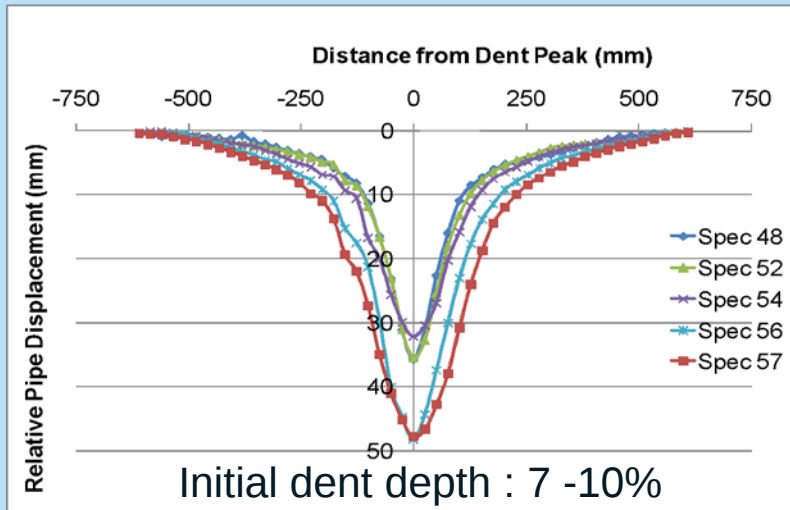
- Complete testing to consider factors of interest
 - Dent shape and restraint condition
 - Pipe geometry, grade, vintage
 - Loading cycle magnitude
 - Interacting features (corrosion, welds)

Collect Data to Describe Dent Response to Cyclic Internal Pressure Loading

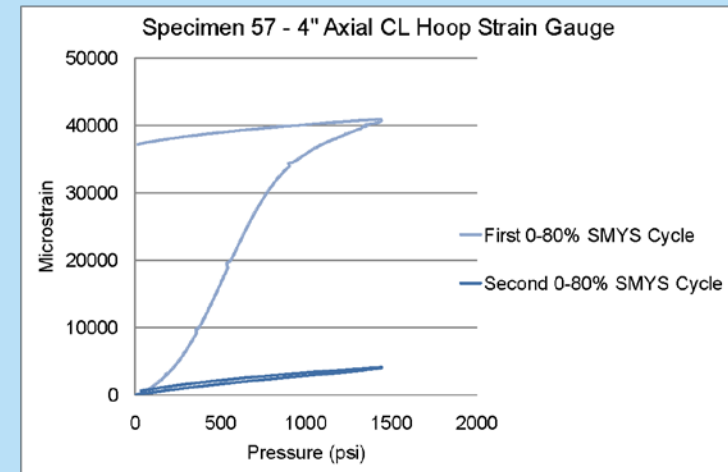
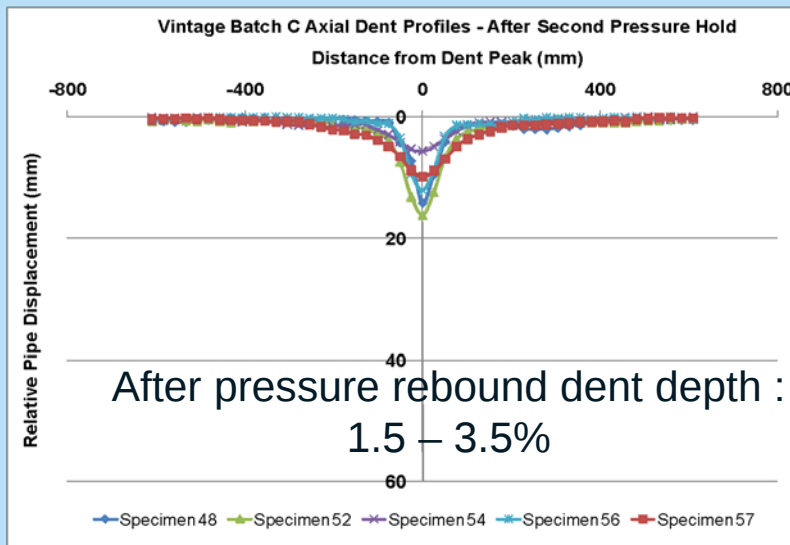
- Pipe characterisation (geometry, material properties, interacting features)
- Indentation (indenter shape, indentation depth / load / strain, rebound)
- Cyclic behaviour (dent displacement, strain)
- Fatigue life and cracking characteristics



Full Scale Test Program: Results



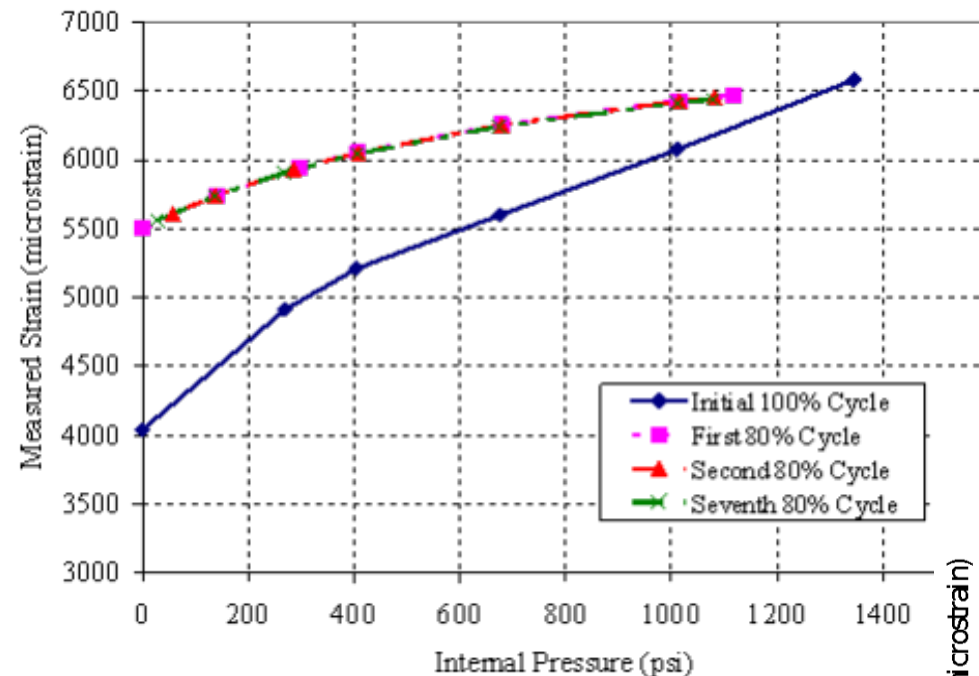
Strain cycle due to dent rebound, first pressure cycle (2-4%)



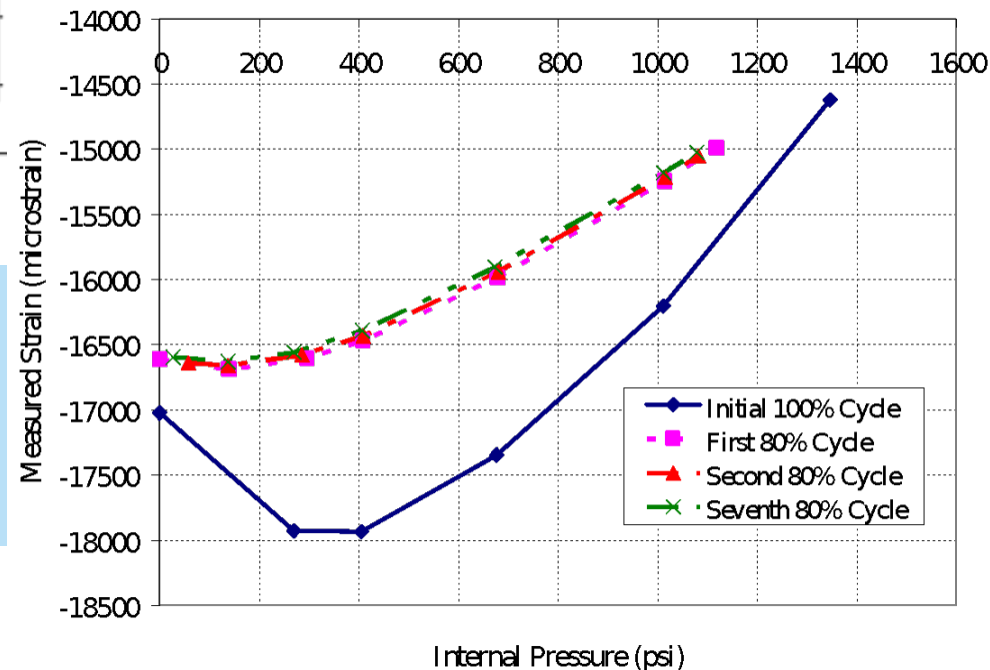
Non-Linear Relation between Pressure and Strain

- Non-Linear Response Between Pressure and Strain

Strains (4" from dent) versus Internal Pressure

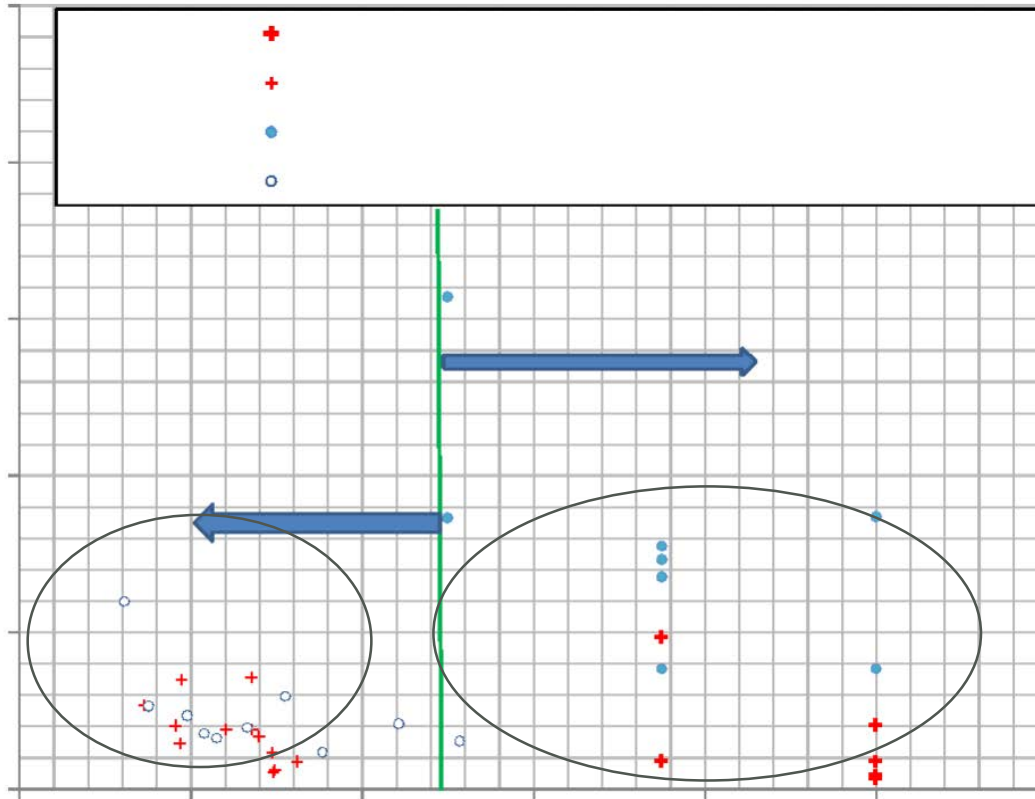


Strains (6" from dent) versus Internal Pressure



Dent Full Scale Testing- Plain Dents

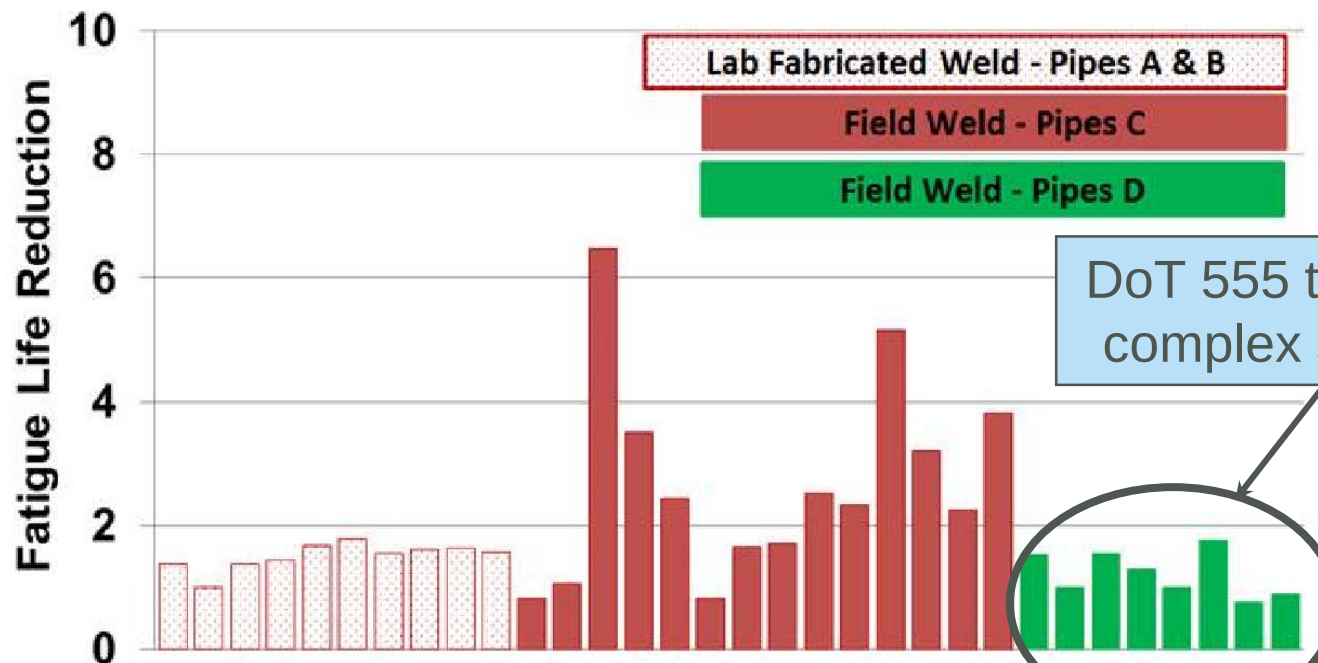
Dent Depths versus Fatigue Life



- Deeper restrained dents > 5% have similar or longer lives than shallow < 2% deep unrestrained dents
- Removing indenter from restrained dents will lead to shallow unrestrained dents and potentially more susceptible to fatigue

Results - Dent Weld Interaction

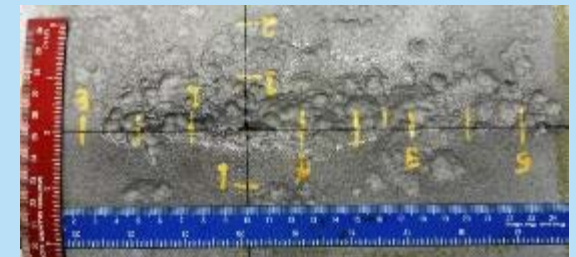
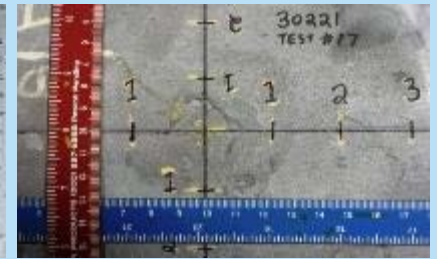
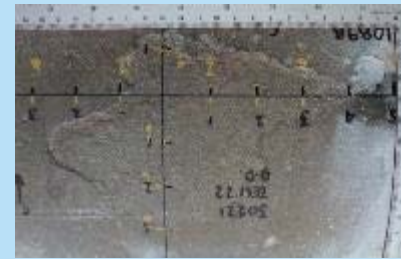
Maximum reduction in life 6.5X observed due to dent weld interaction



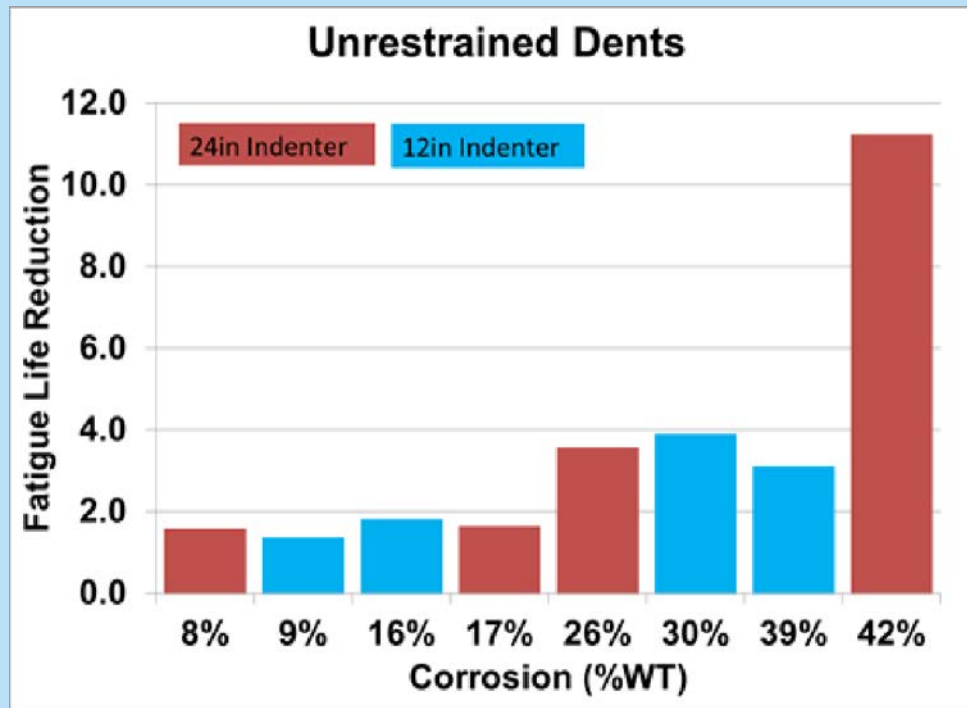
Dent Full Scale Testing

Dent Corrosion Interaction

- Corrosion positioned at critical location within dent for maximum reduction in fatigue life
- 10 to 40% natural corrosion depth considered
- Unrestrained Dents
 - OD surface crack initiation reduced fatigue life (thickness red. & surface finish)
 - Life reduction 2-4X for depth 20% - 35% wall
- Restrained Dents
 - ID surface crack initiation minor reduction in fatigue life (thickness red. only)
 - Life reduction 1.4X for depth 25% – 35% wall



Dent Corrosion Interaction – Unrestrained dents



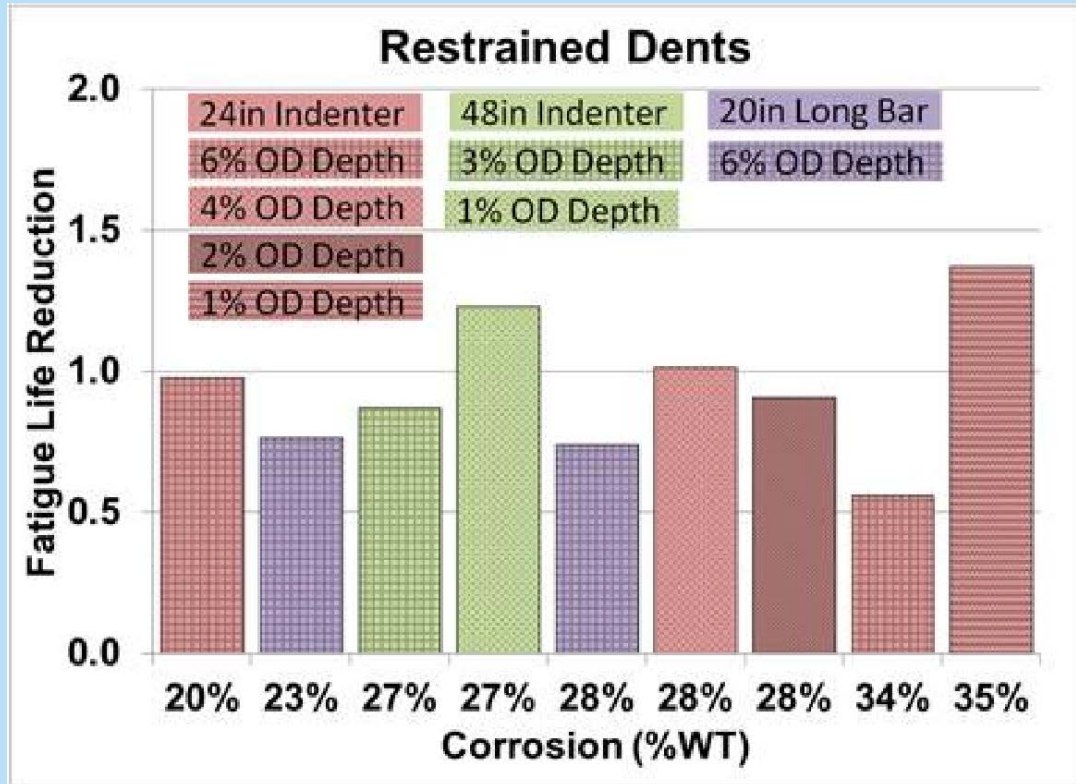
Crack initiation on the OD surface

Fatigue Life gets affected by

- Thickness reduction
- Surface finish

Reduction in life between 2- 4X observed when corrosion depth less than 35%

Dent Corrosion Interaction – Restrained Dents



Crack initiation on the
ID surface

Fatigue Life gets affected by

- Thickness reduction
- No effect of surface finish
due to corrosion on the
OD surface

No Reduction in life between when corrosion depth less than 25%

Maximum reduction in fatigue life of ~1.4X when corrosion depth between 25%-35%

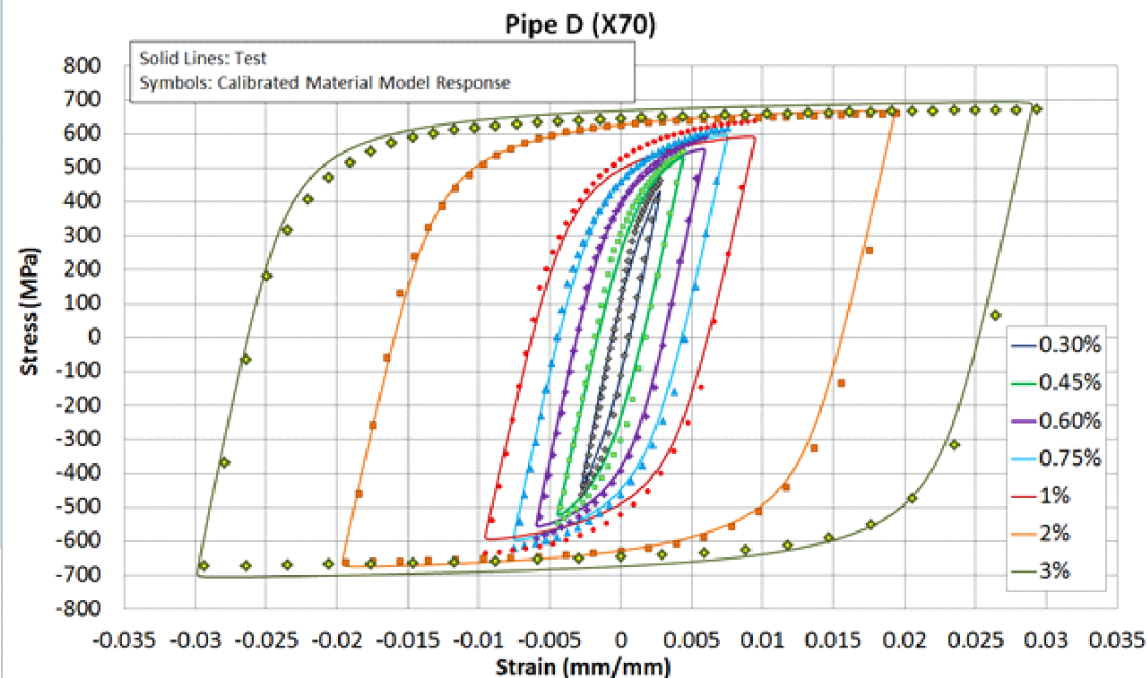
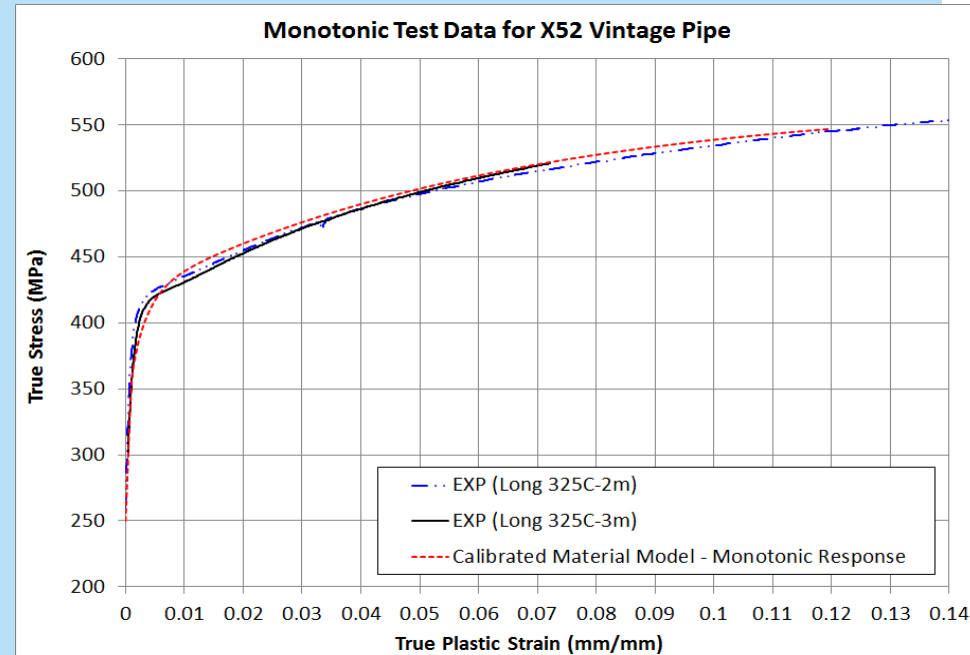
Dent Modeling

BMT developed dent modeling process included

- Nonlinear material
- Indenter contact and removal
- Internal cyclic pressurization

Use Full Scale Test Data to Validate Model

- Demonstrate model agrees with test results



Dent Modeling

API 579-1/ASME FFS-1 2007 Fitness-For-Service

PART 12

ASSESSMENT OF DENTS, GOUGES, AND DENT-GOUGE COMBINATIONS

12.4.4.2 The numerical stress analysis should be performed considering the material as well as geometric non-linearity in order to account for the effect of pressure stiffening on the dent and re-rounding of the shell that occurs under pressure loading.

12.4.4.3 The stress analysis used in the assessment should simulate the deformation process that causes the damage in order to determine the magnitude of permanent plastic strain developed. To simulate the distortion process, an analysis that includes geometric and material nonlinearity as well as the contact interaction between the original undeformed shell structure and the contacting body may be performed. The contacting component may be explicitly modeled as a deformable body or as a simple rigid surface. The analysis should include applicable loadings to develop the final distorted configuration of the shell structure.

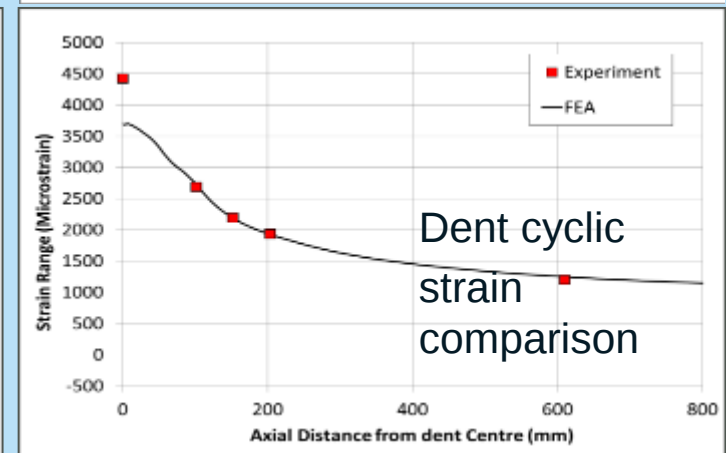
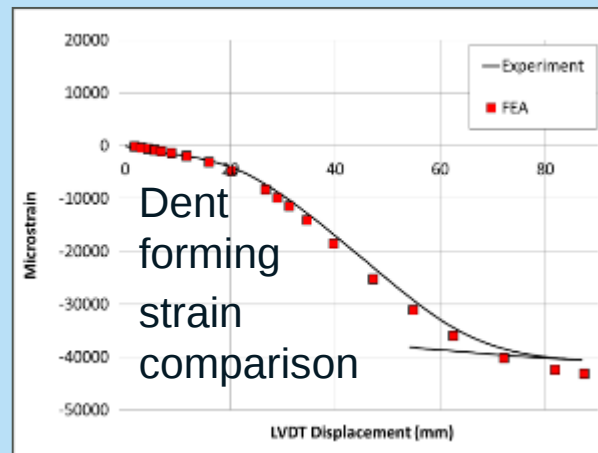
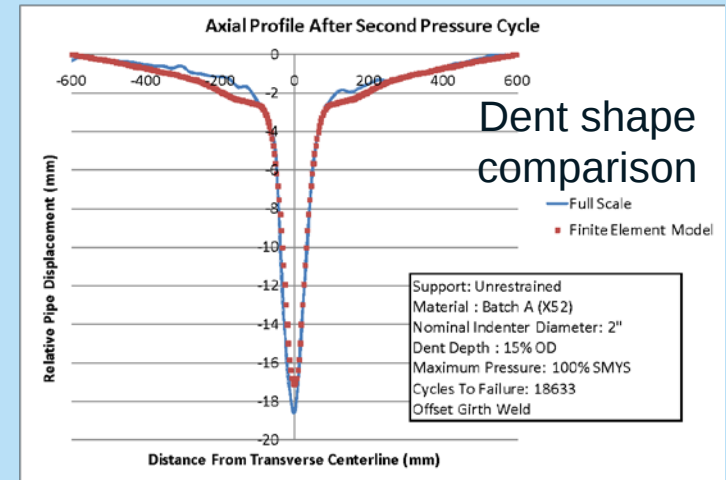
Dent Modeling Validation

BMT developed dent modeling process

- Nonlinear material
- Indenter contact and removal
- Internal cyclic pressurization

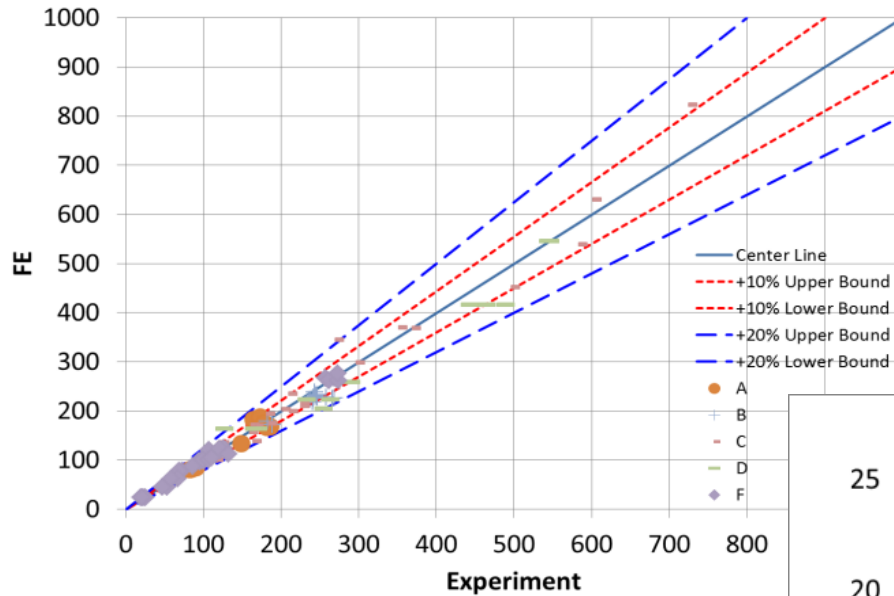
Use Full Scale Test Data to Validate Model

- Demonstrate model agrees with test results



Dent Modeling Validation

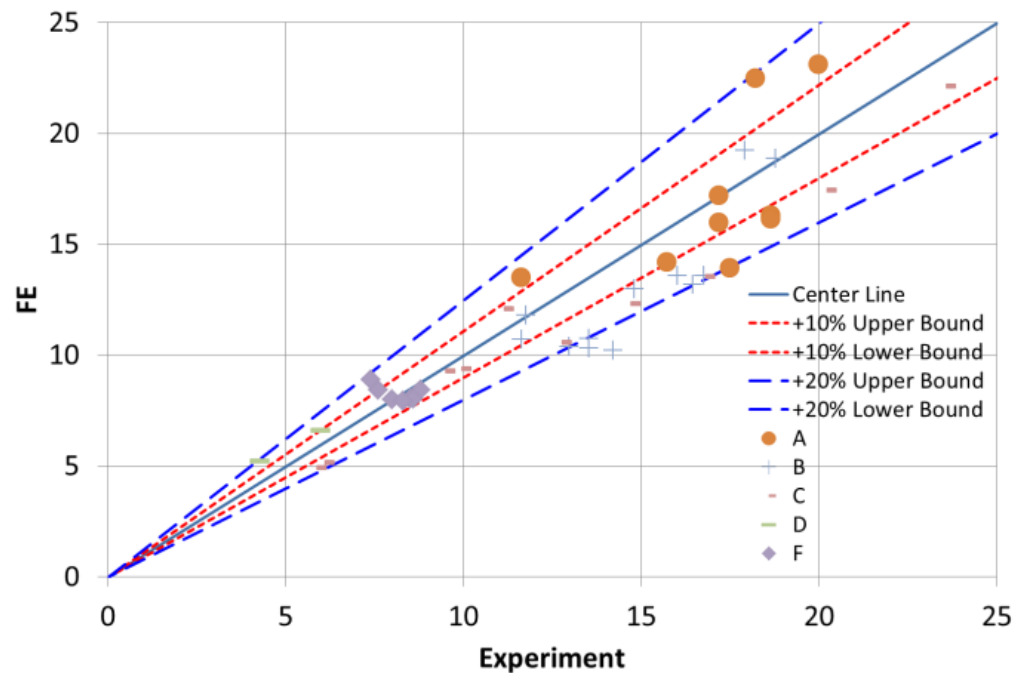
Applied Load (kN)



Dents loads

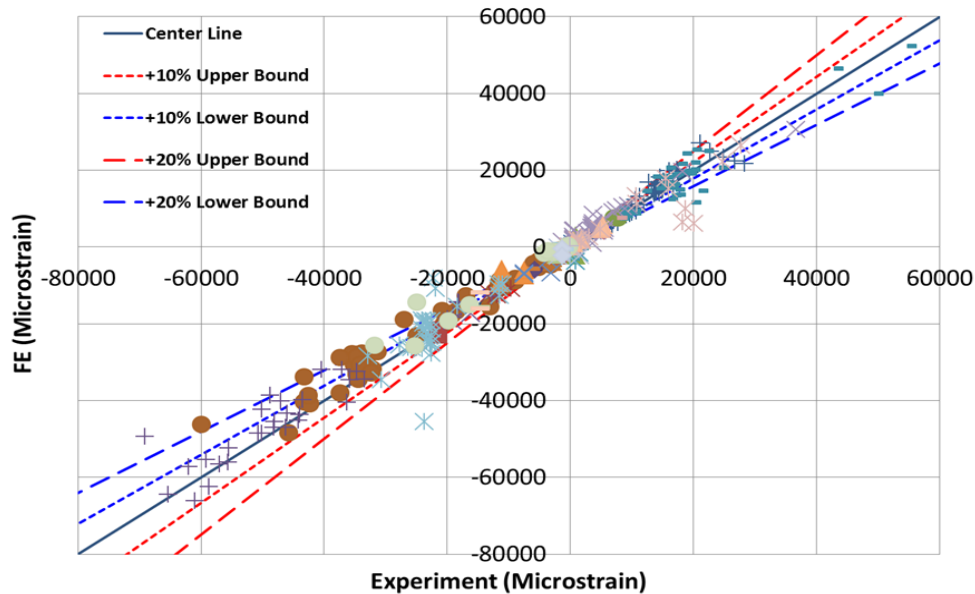
Dent depths

Unrestrained Dents Post Step Residual Depth (mm)



Dent Modeling Validation

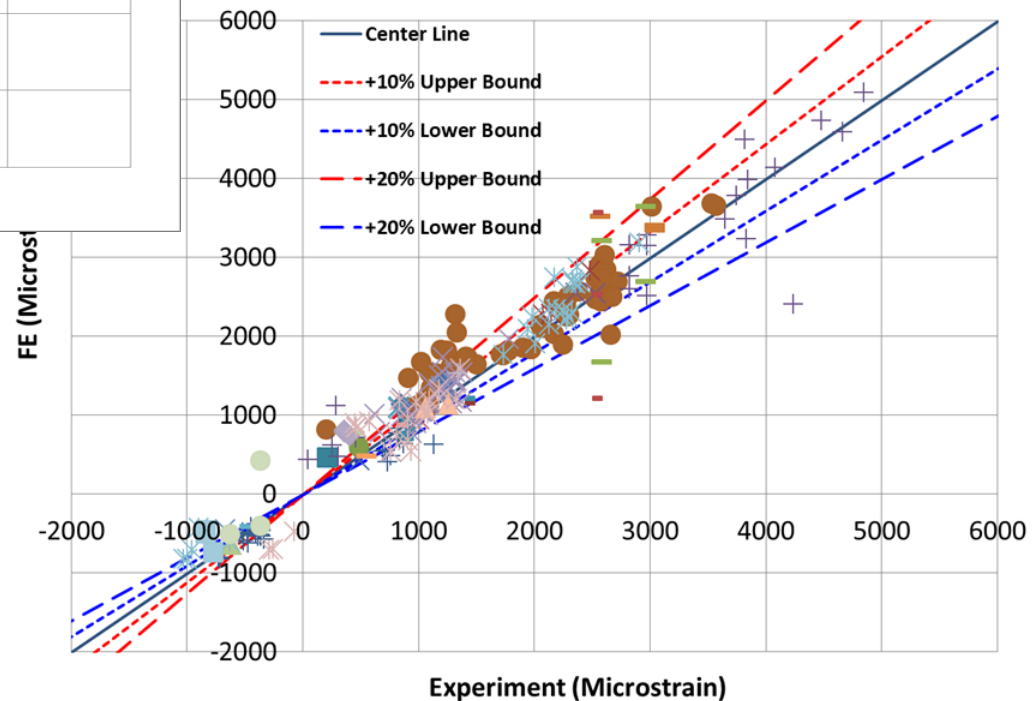
Indentation - Gauges 4 inches to Dent Center



Dent forming strains

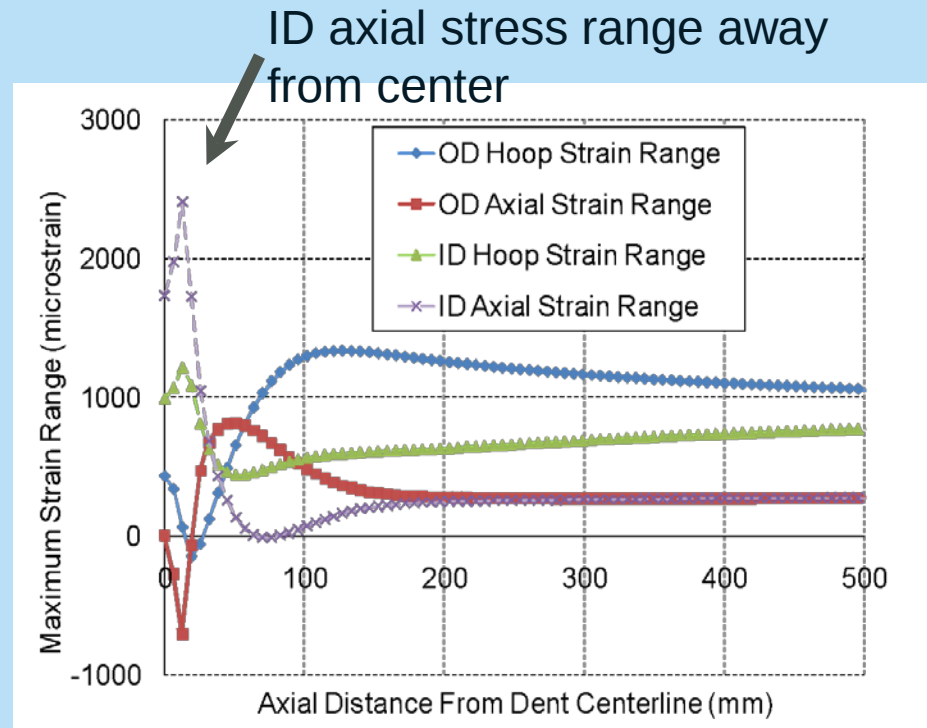
Cyclic strains

Cyclic Range - Gauges 4 inch to Dent Center



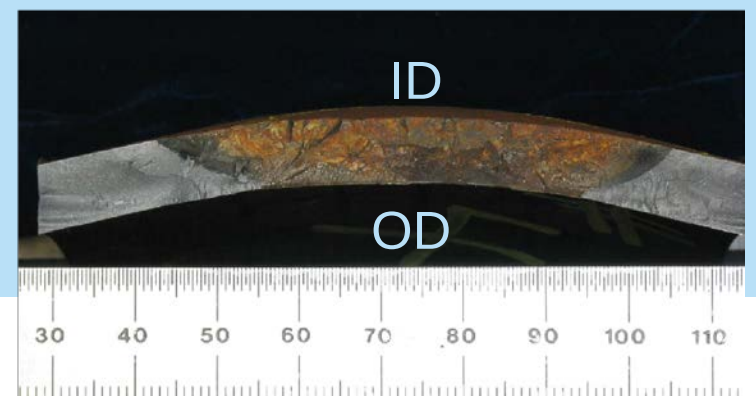
Dent Modeling Validation

Correlating Critical Location (ID/OD) and Critical Stress/Strain (Flaw) Orientation



Crack initiation on the ID surface in the circumferential orientation @ dent shoulder

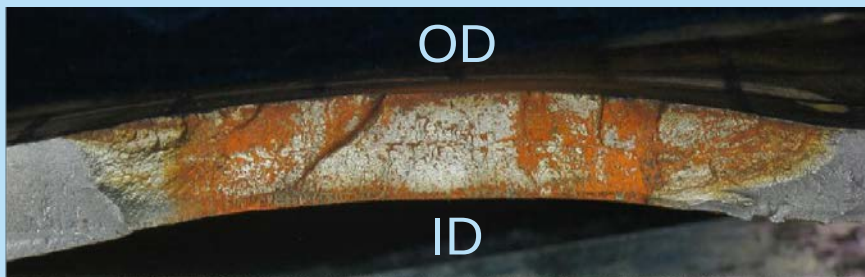
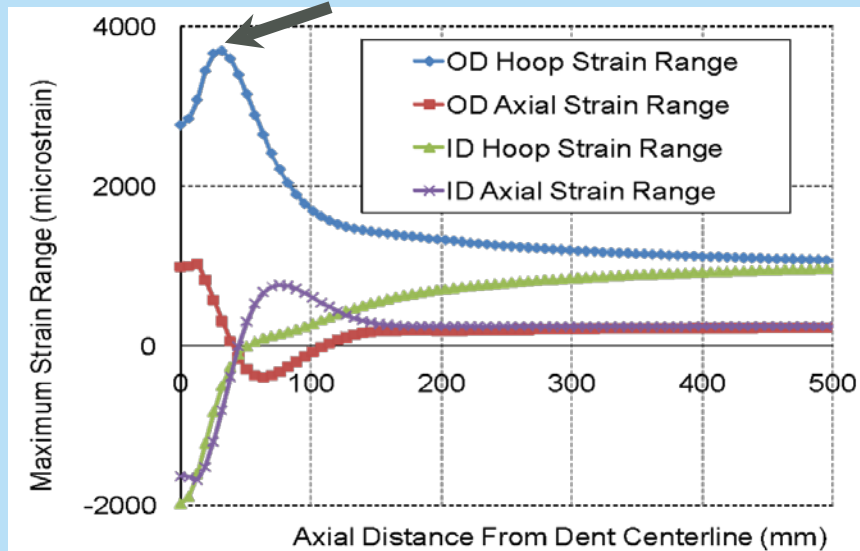
5% Restrained Dent



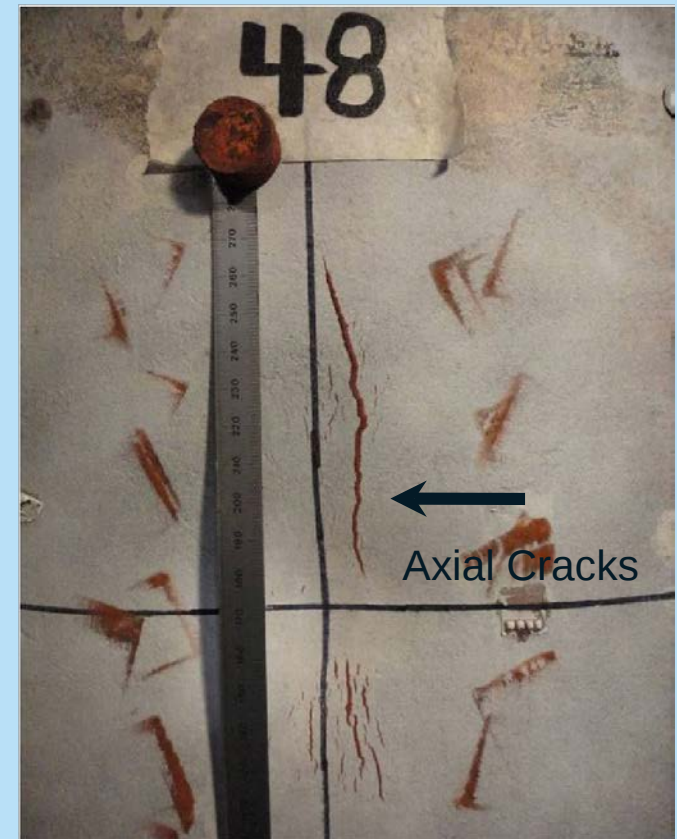
Dent Modeling Validation

Crack Initiation On The OD Surface In The Axial Orientation at Dent Shoulder

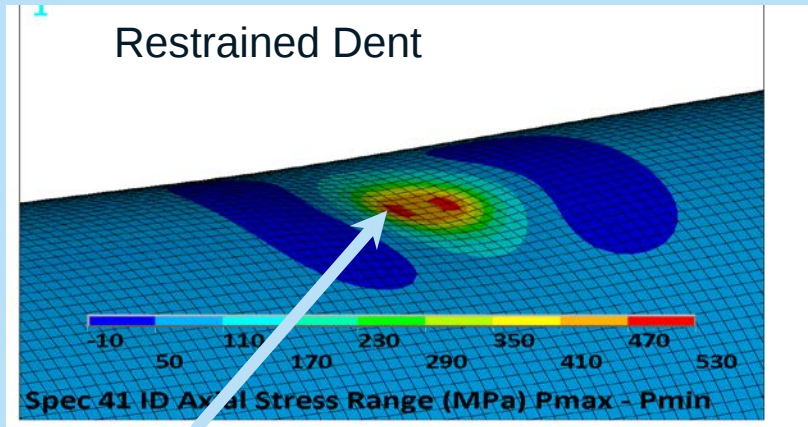
OD hoop stress range away from center



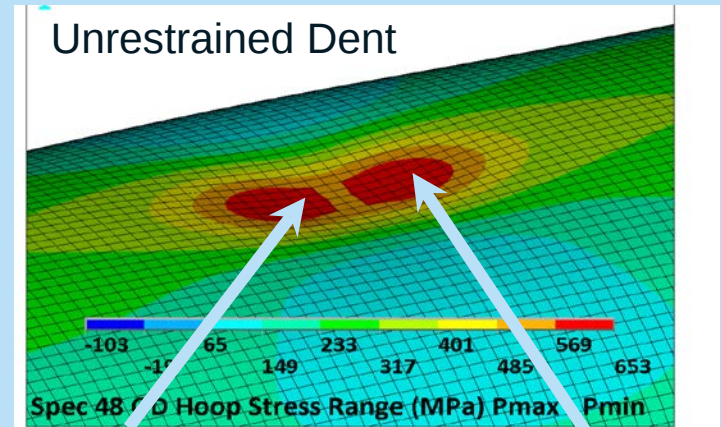
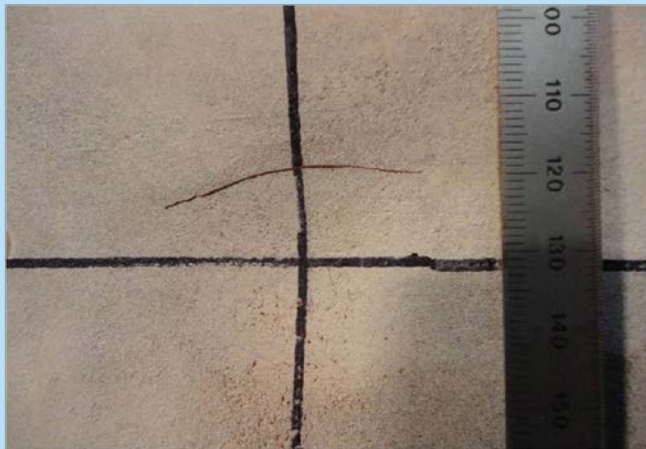
3% Un-restrained



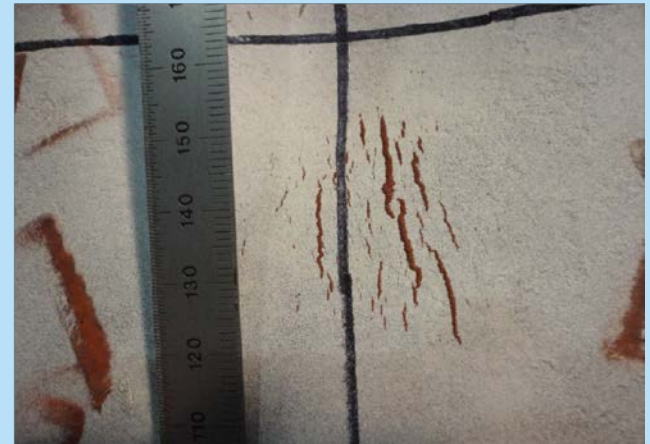
Dent Modeling Validation



High stress range confined to a small area resulting in single dominant crack



High stress range spread over larger area resulting in multiple cracks : Typical LCF cracks



Dent Modeling Matrix for Tool Development

150,000 cases have been evaluated based on pipe d/t, dent shape, pipe grade, pressure range conditions

Pipe OD/Wall Thickness (OD/t)	4.5/0.188, 6.625/0.188, 8.625/0.218, 10.75/0.188, 12.75/0.312, 16/0.218, 18/0.25, 18/0.312, 18/0.33, 20/0.281, 24/0.25, 24/0.33, 30/0.25, 32/0.281, 36/0.281, 42/0.42
Pipe Grade	Grade A, X42, X52, X70
Indenter Shapes	4", 12", 18", 24", 30" & 48" dia elliptical, 4" & 16" diameter spherical, 4" & 8" dia transverse bar, asymmetric complex indenter shapes
Maximum Pressure Pmax (%Psmys)	30% to 100% in increments of 10%
Cyclic pressure ΔP (%Psmys)	Different Pressure Range Combinations between 10% to 80% SMYS
Indentation Pressure (%Psmys)	0% and 30%
Applied Indentation Depth (%OD)	0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 9 & 10 for Restrained Dents 5, 10, and 15 for unrestrained dents

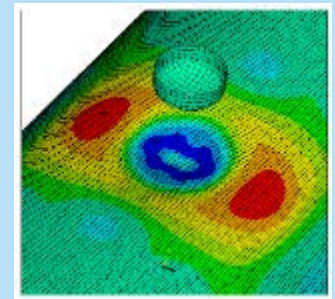
Engineering Tool Development

Developed Assessment Process for Plain Dents

- Level 1: Dent shape severity ranking for plain dents and interacting features
- Level 2: Dent fatigue severity ranking for plain dents and interacting features
- Level 3: Detailed FE modeling and fatigue life assessment

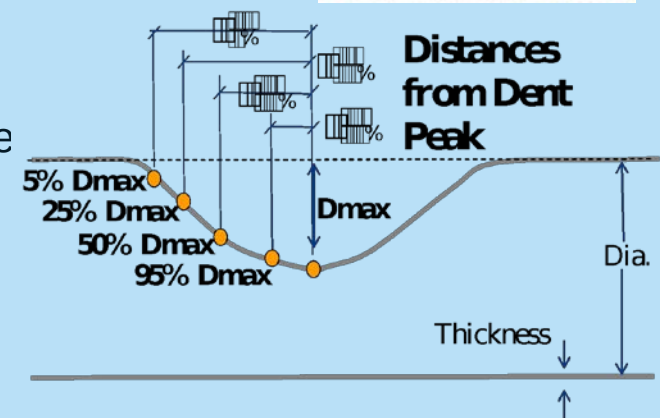
Developed Dent Weld Interaction Criteria

Developed Dent Metal Loss Interaction Criteria



Dent Shape Characterisation

- Dent lengths and areas in axial and circ. orientation use
 - Define restraint condition
 - Define dent shape
 - Estimate fatigue life

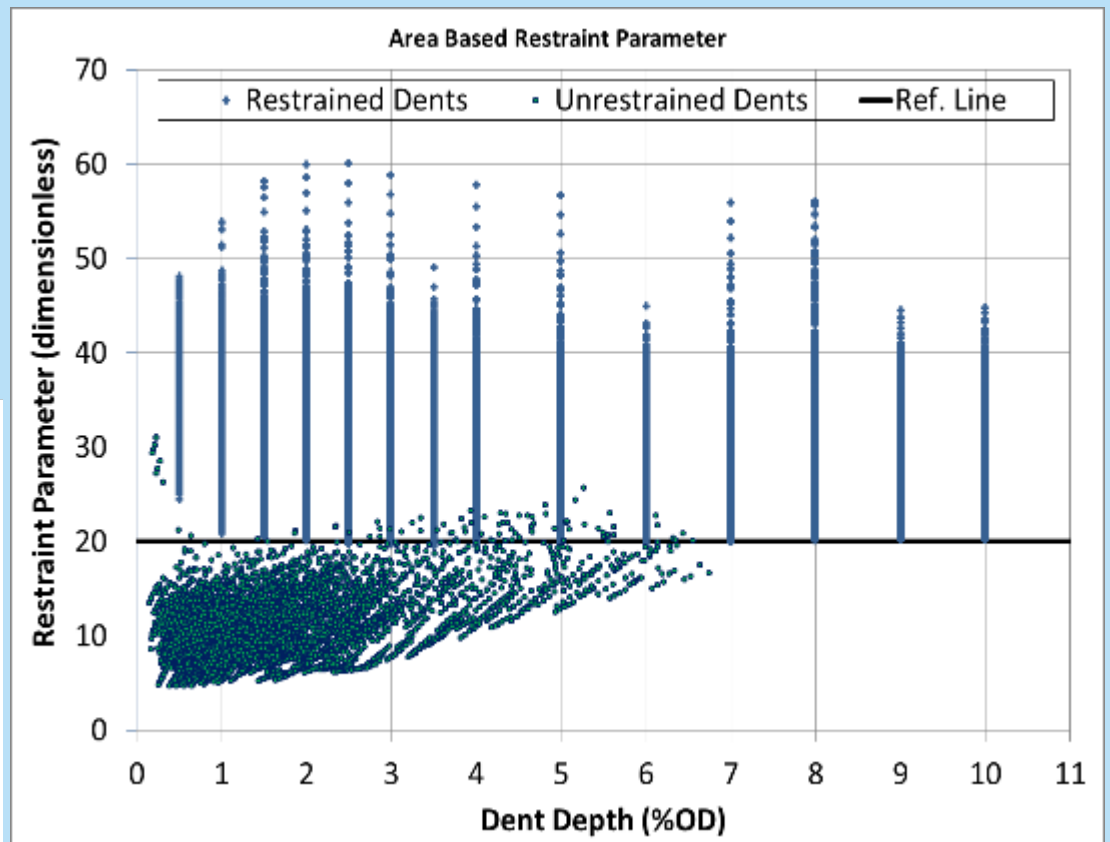
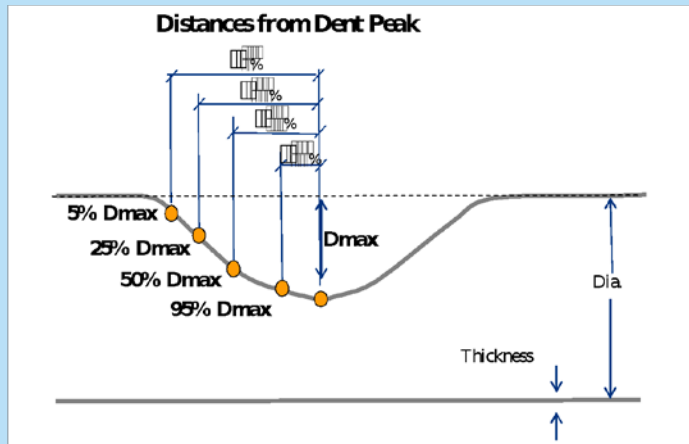


Engineering Tool Development

Restraint Parameter

- Calculated from ILI data
- differentiate between Restrained and Unrestrained dents
 - Wide range of d/t (24 - 128)
 - 4.5"OD - 42" OD
 - Shallow and deep dents

$$RP = \max \left\{ \frac{18 |A_{AX}^{15} - A_{TR}^{15}|^{1/2}}{L_{TR}^{70}}, 8 \left(\frac{L_{AX}^{15}}{L_{AX}^{30}} \right)^{1/4} \left(\frac{L_{AX}^{30} - L_{AX}^{50}}{L_{TR}^{80}} \right)^{1/2} \right\}$$

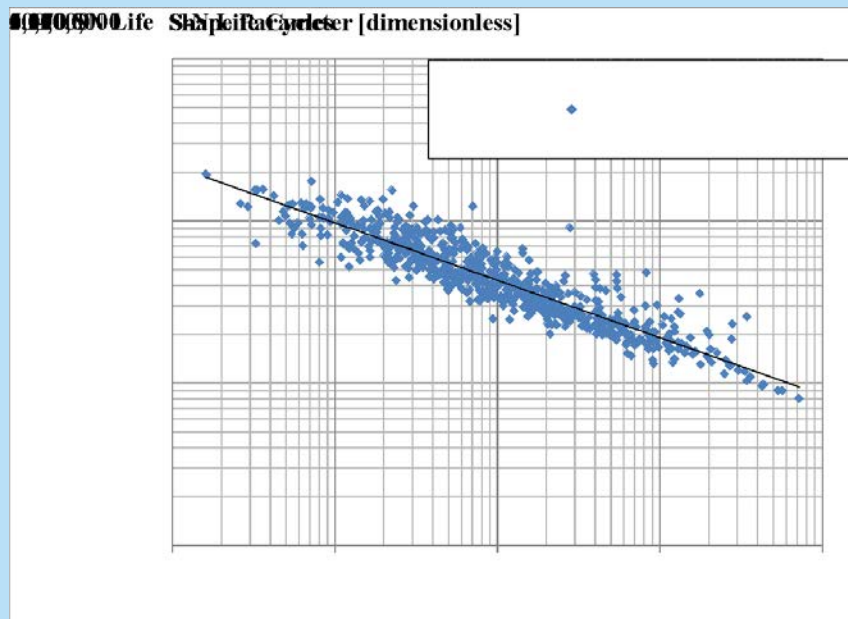


Engineering Tool Development

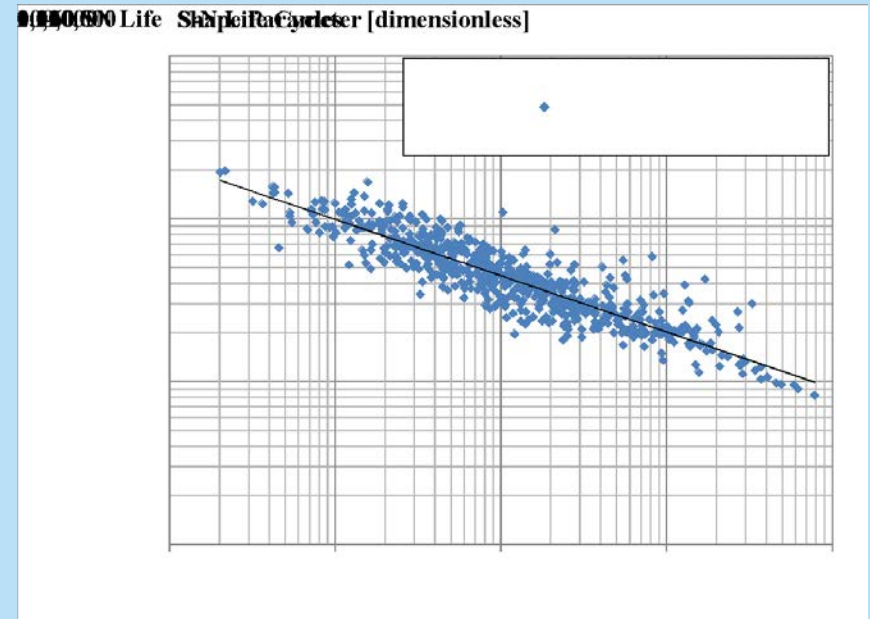
Un-Restrained Dent Correlation

- Ability to predict fatigue life based upon shape parameter
- Similar quality of result for restrained dents

20%-60% SMYS



50%-70% SMYS

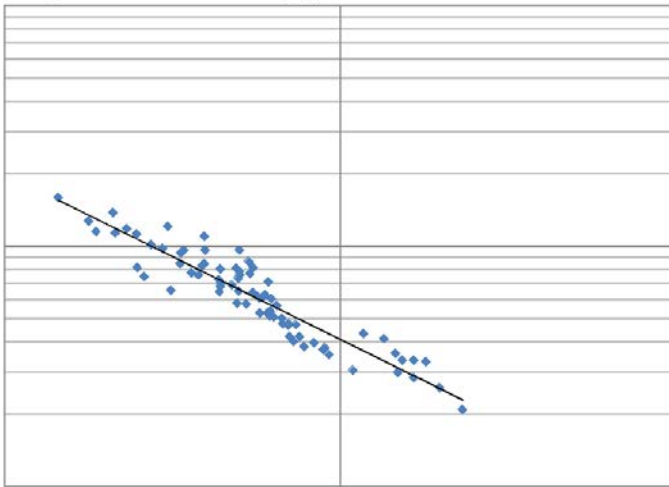


Engineering Tool Development

Shape of Dent Better Predictor than Dent Depth

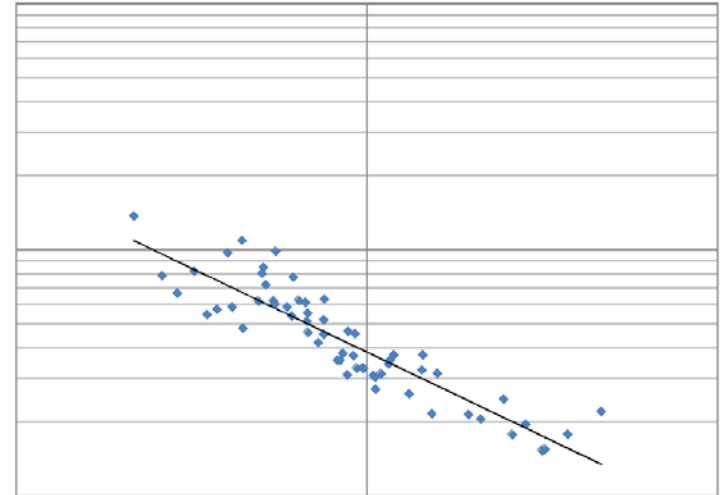
Dent Depth: 2%-3%

FSHgn (38%SD Depthless)
2% and 3% SD Depth



Dent Depth: 6%

FSHgn (38%SD Depthless)
3% and 6% SD Depth



Similar dent depth result in different fatigue lives

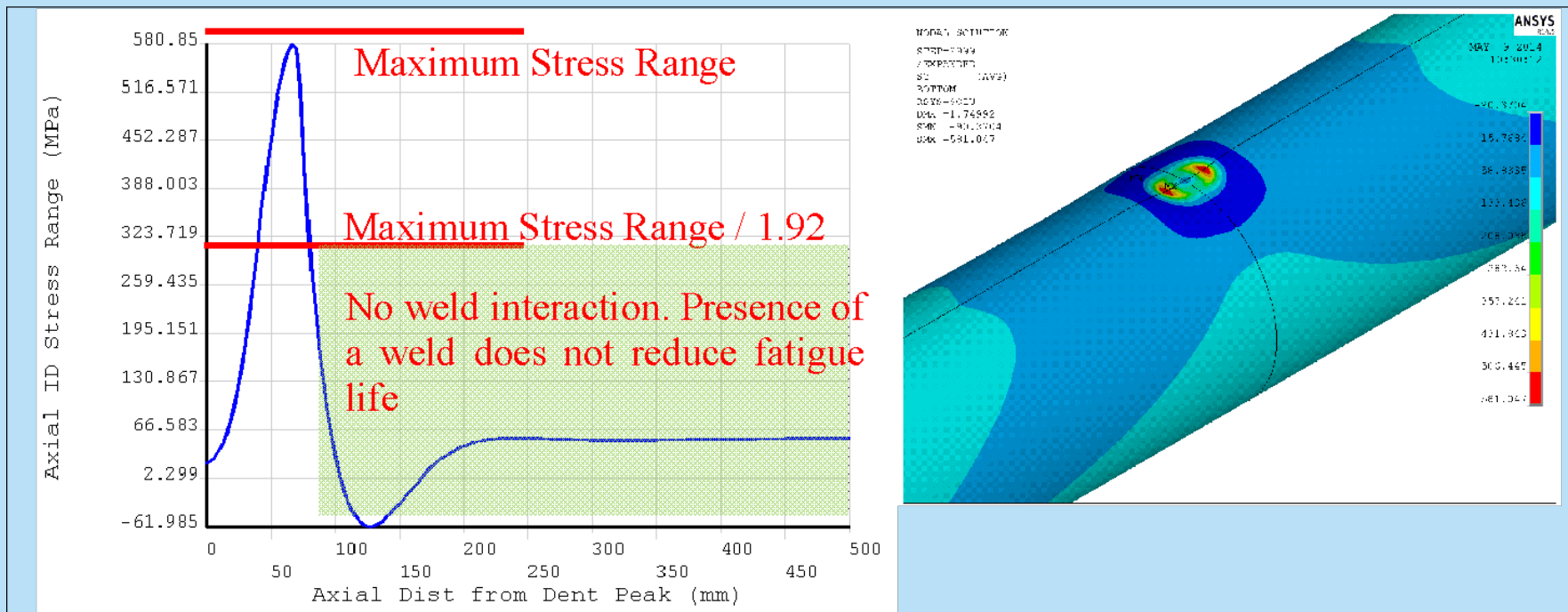
Different dent depths (2%-6%) result in similar fatigue lives,

Correlation between dent shape parameter and dent fatigue life

Dent Weld Interaction

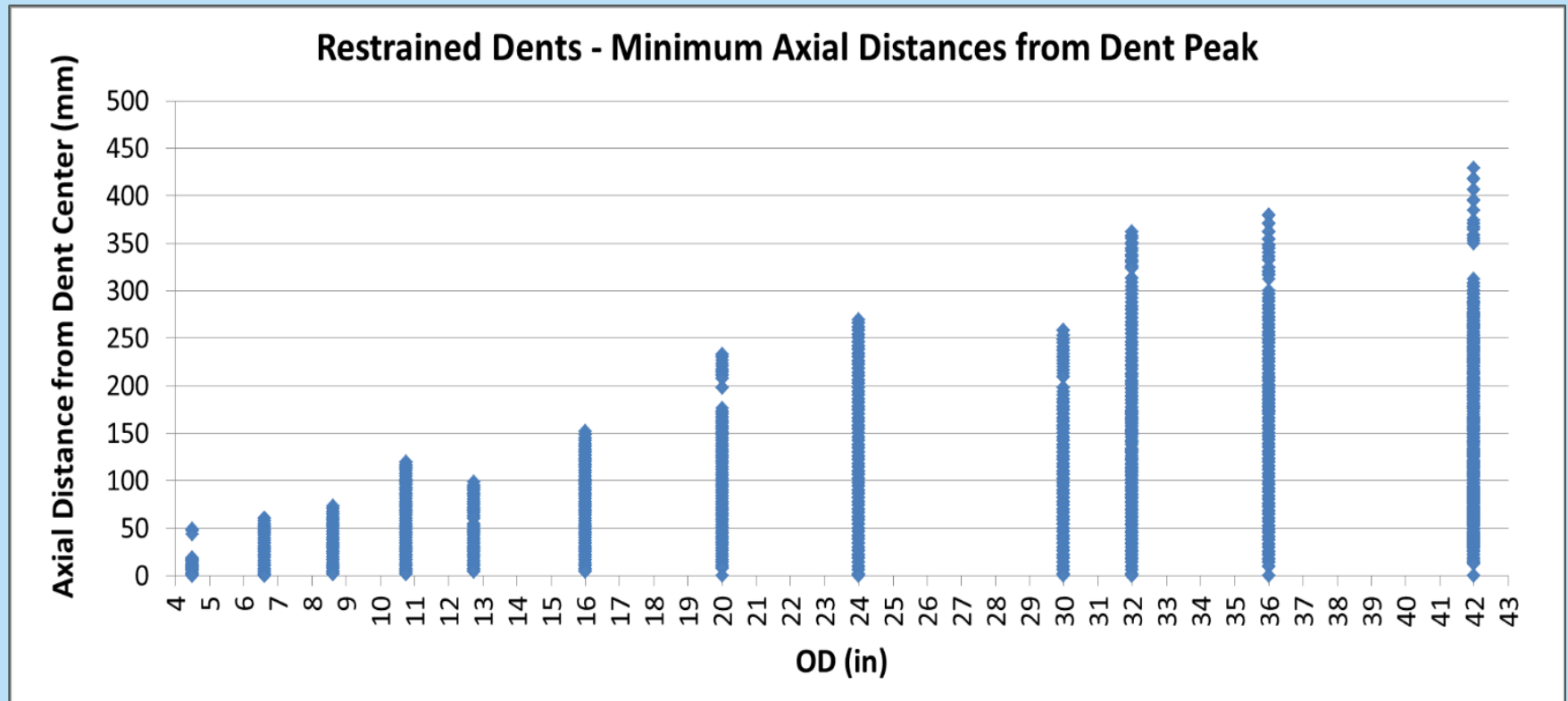
Maximum Reduction in Fatigue Life: ~ 7X from testing

- Stress range would be 1.92X higher based on SN slope of 3
- Identify distance from dent peak where stress range drops to 1.92X the maximum stress range



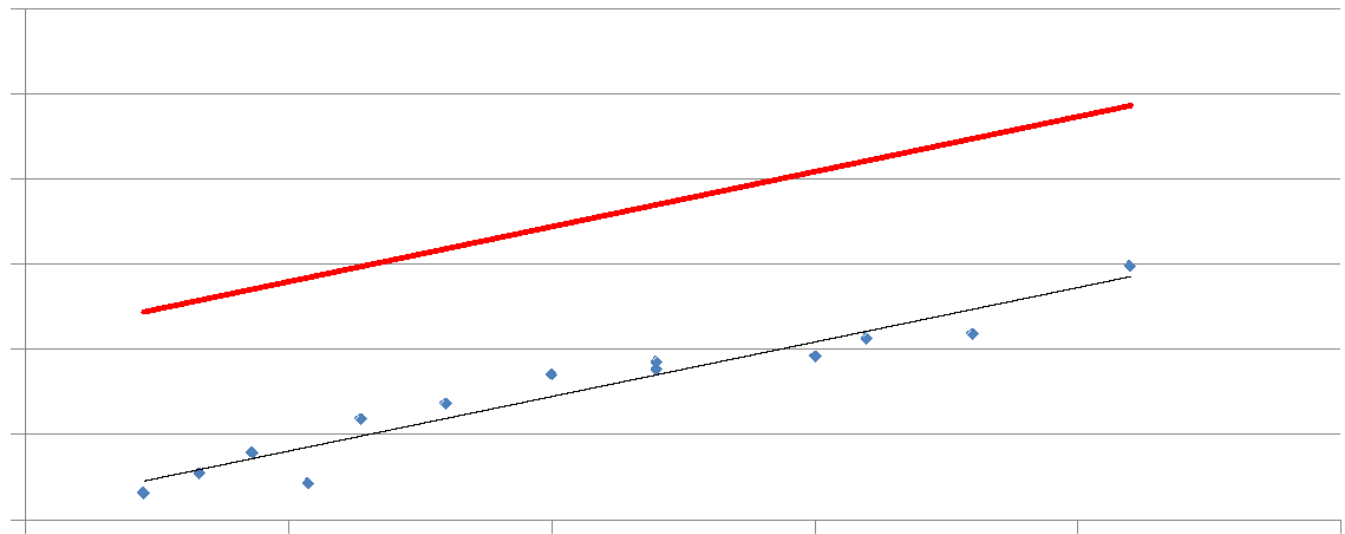
Dent Weld Interaction - Restrained Dents

Based on all the dent models and pressure range conditions identified distance for each OD for dent weld interaction



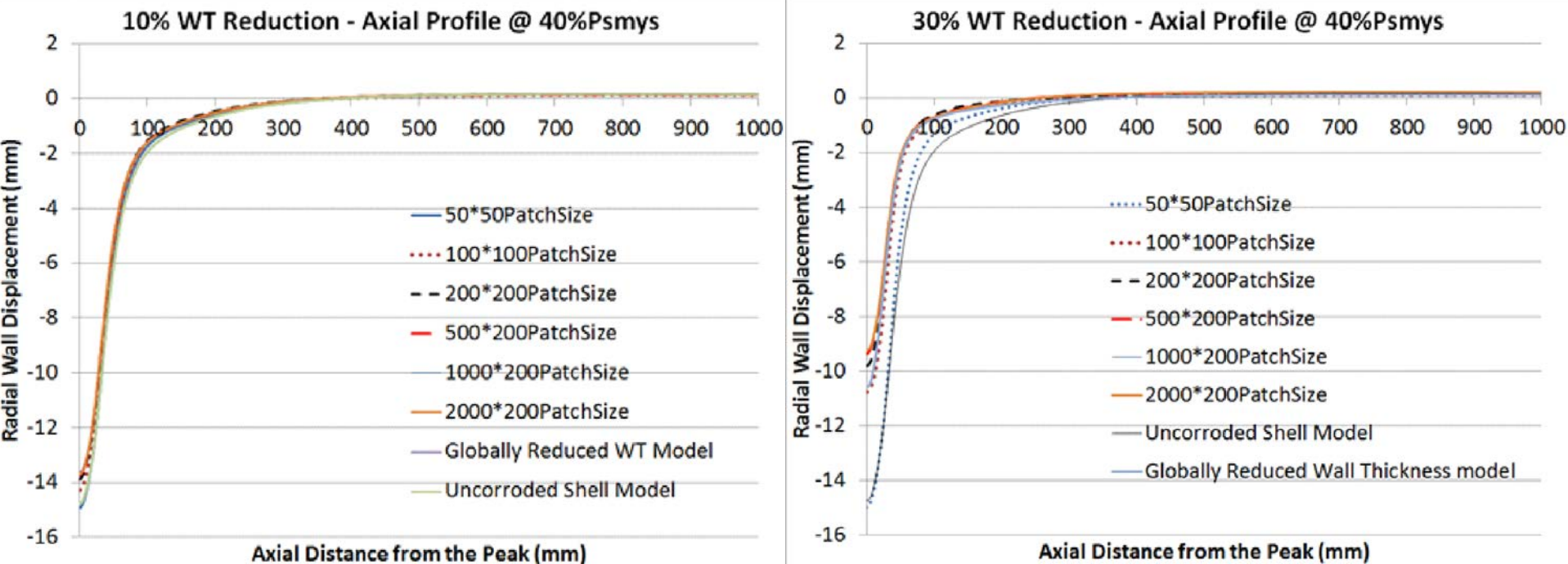
Dent Weld Interaction - Unrestrained Dents

Based on Pipe OD and dent restraint parameter identified distance from dent peak after which there presence of weld will not affect dent fatigue life – Added 4" offset Similar result for restrained dents

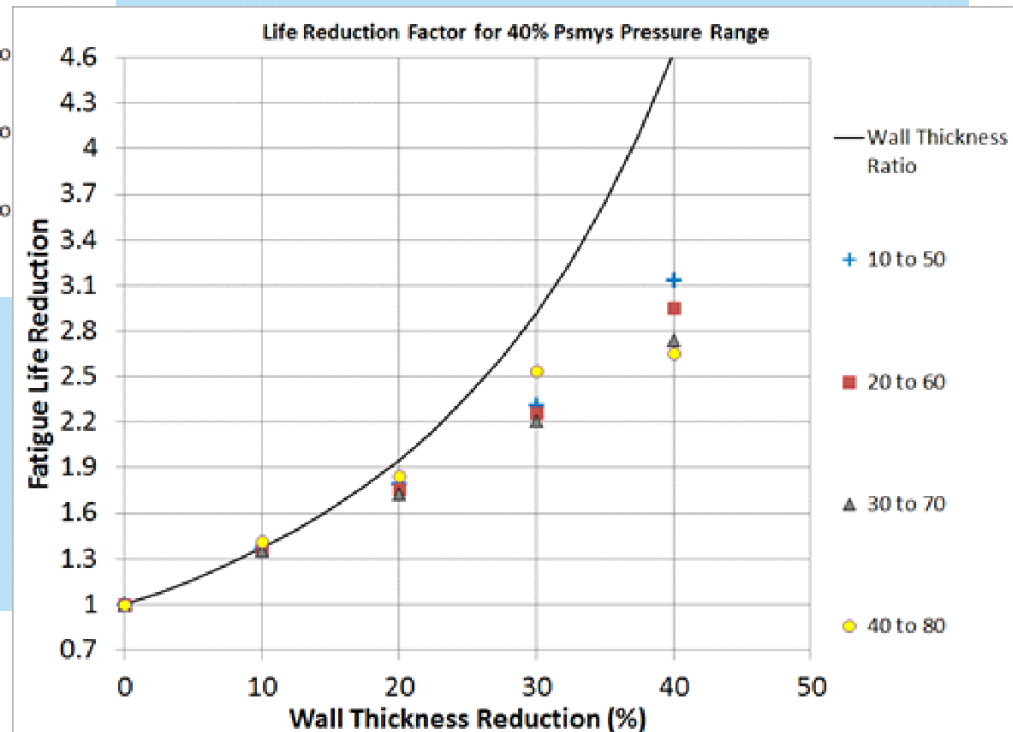
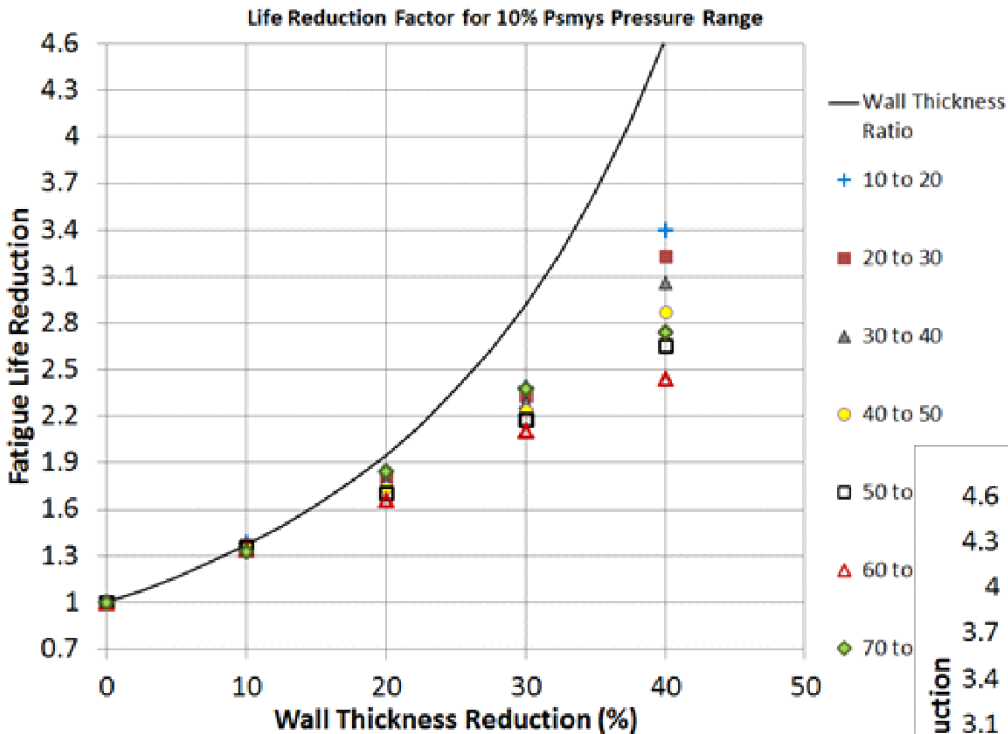


Dent Metal Loss Interaction

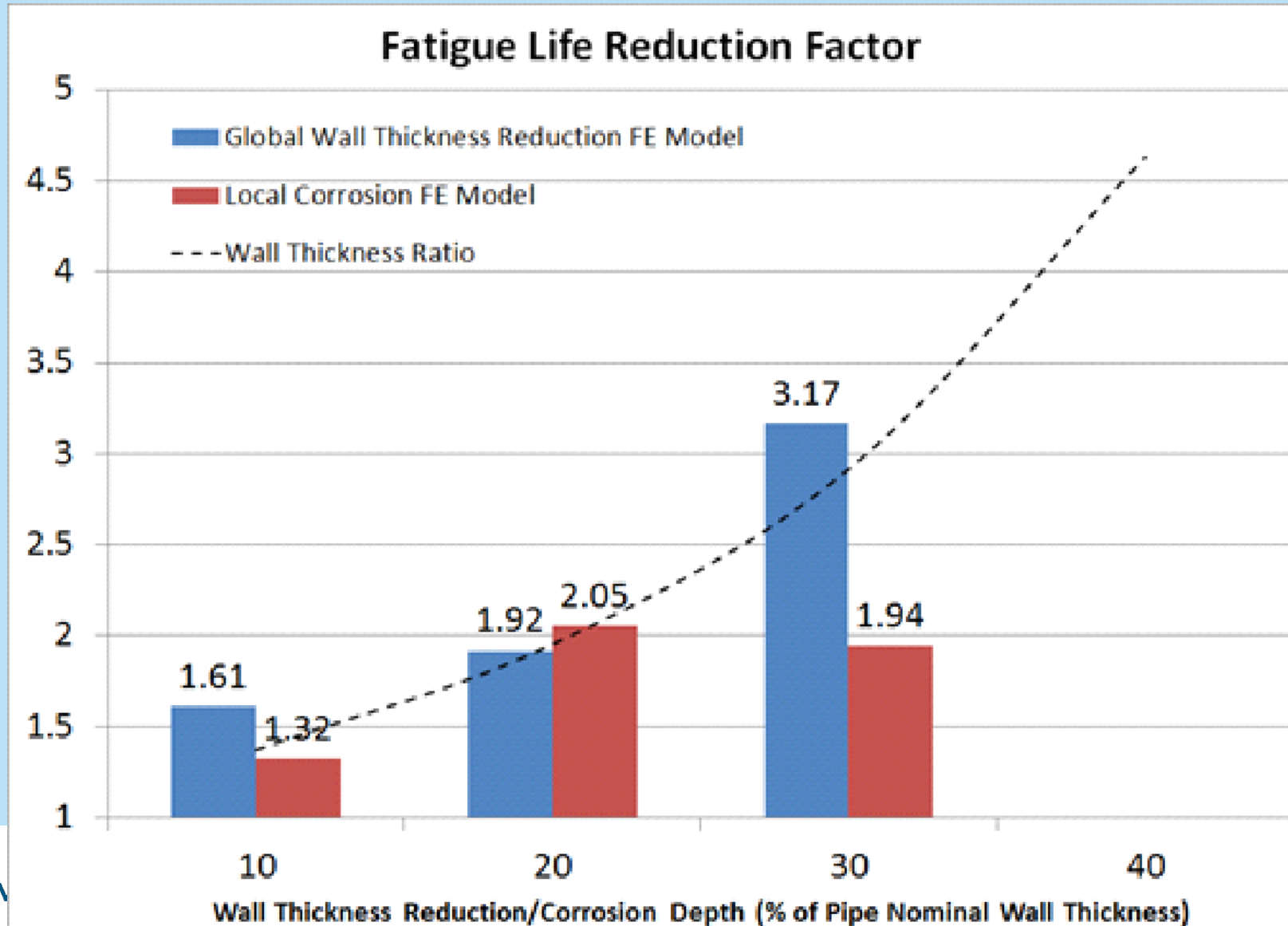
Models developed with different metal loss depth, length and width



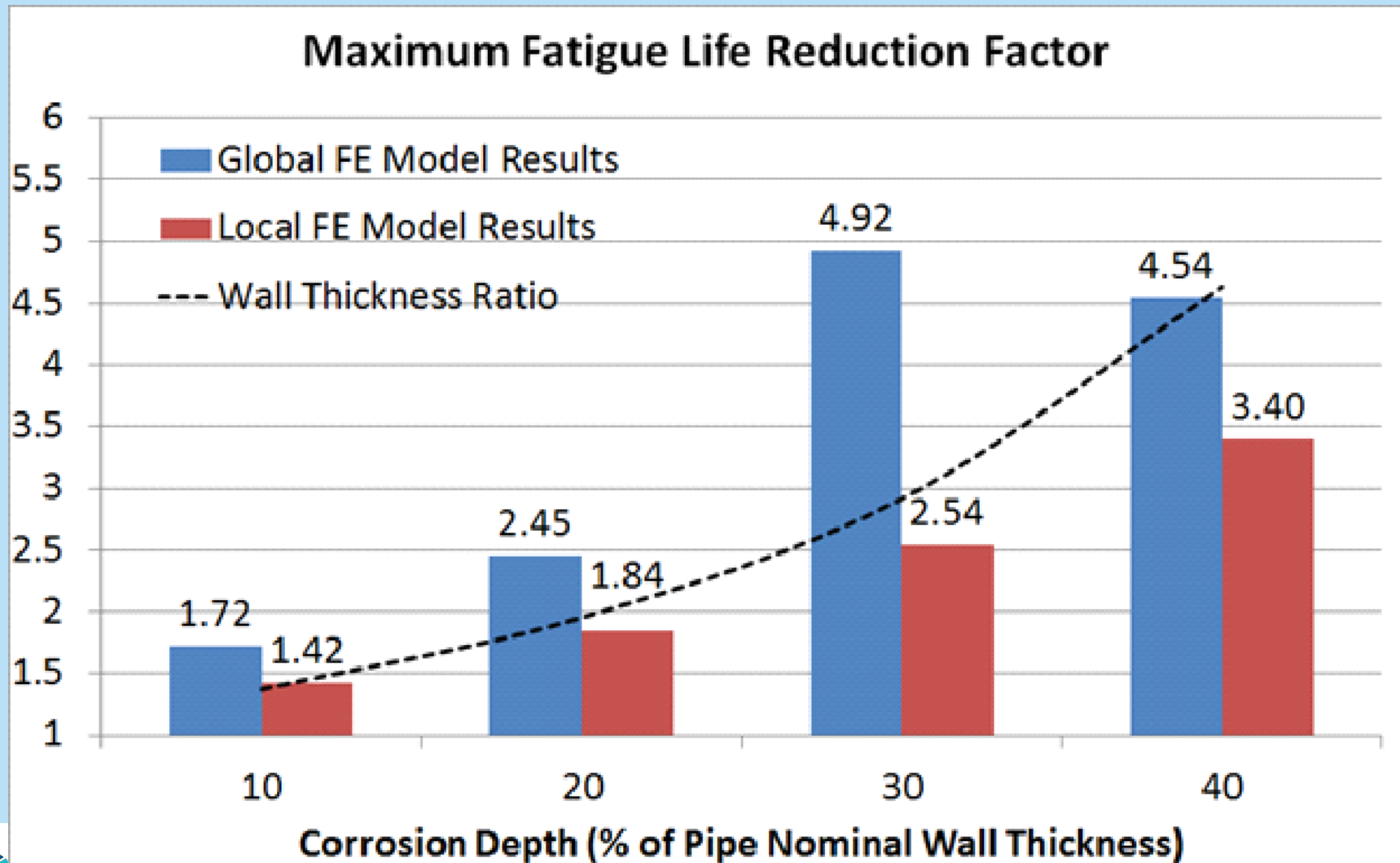
Dent Metal Loss Interaction



Dent Metal Loss Interaction- Restrained Dents

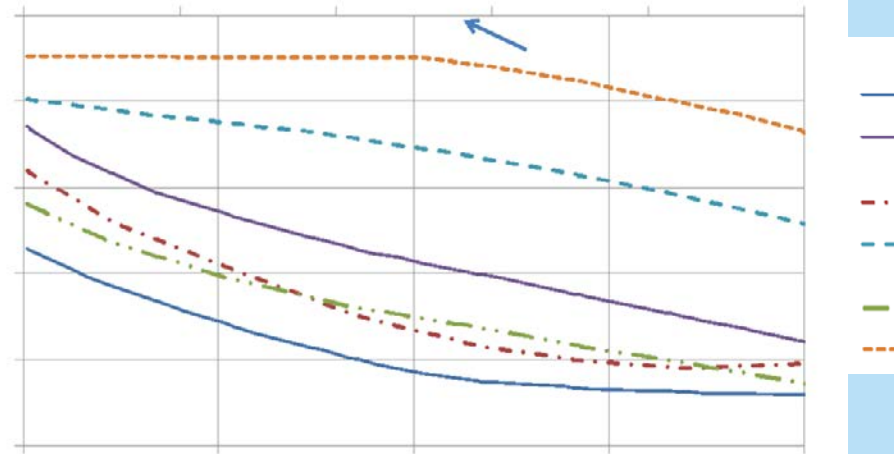


Dent Metal Loss Interaction – Unrestrained Dents



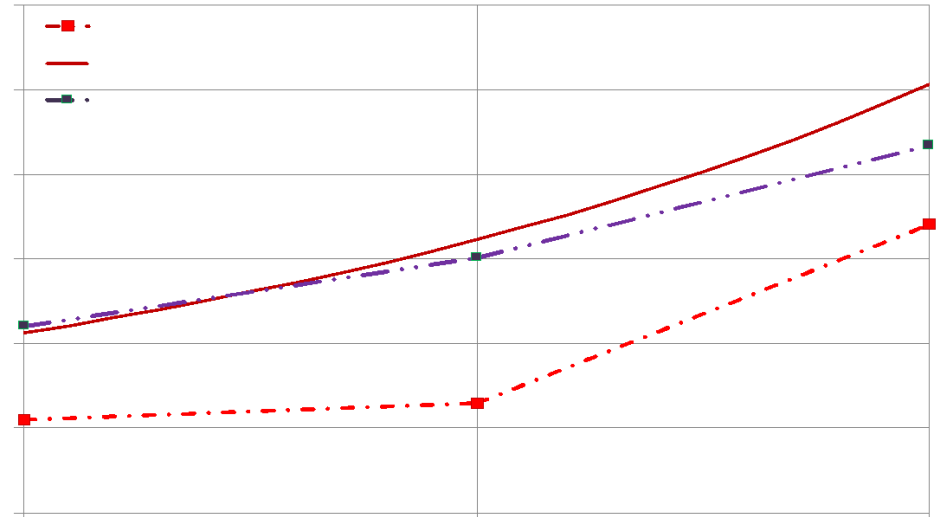
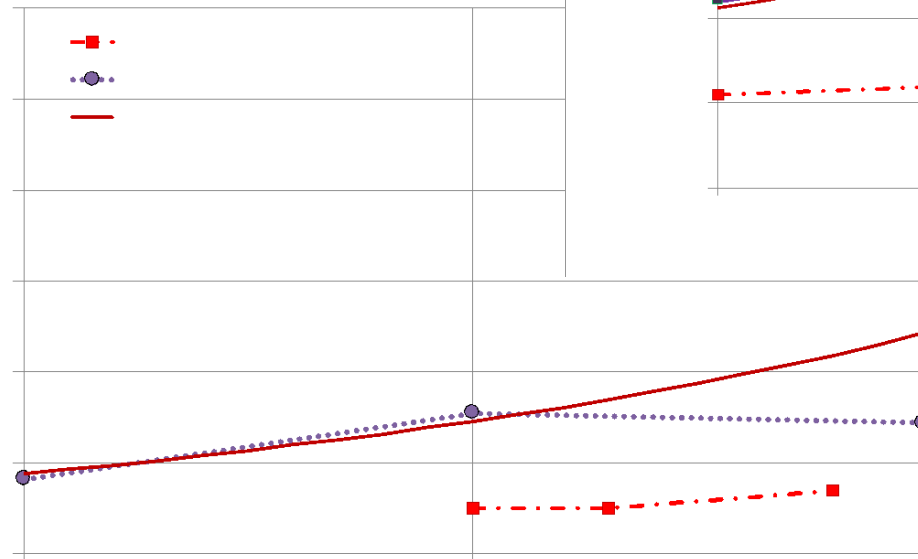
Dent Metal Loss Interaction

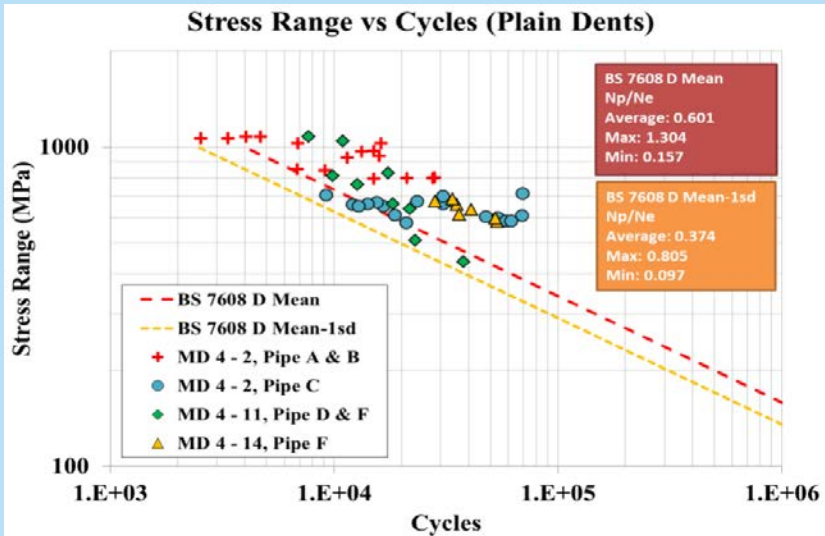
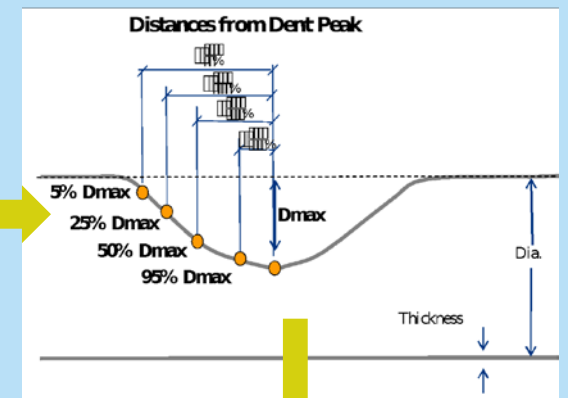
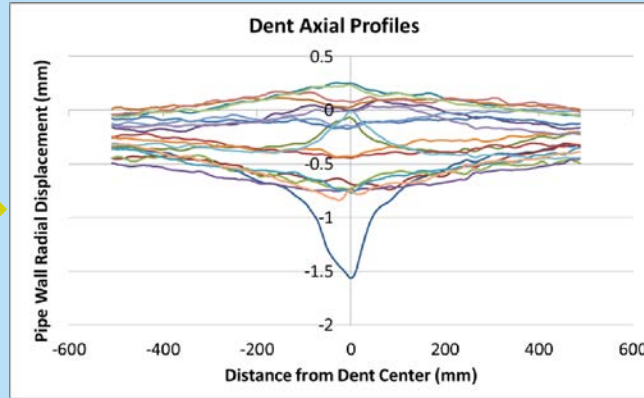
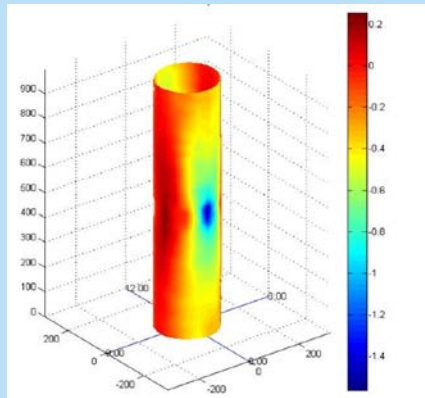
Fatigue life reduction
dependent upon
Surface finish and
metal loss depth



Tensile Strength	With Mirror Finish Surface as Baseline		With Hot Rolled Surface Finish as Baseline		
	Surface Factor		Surface Factor		Fatigue Strength Reduction Factor to Surface Factor
UTS (ksi)	Hot Rolled	Tap Water	Hot Rolled	Tap Water	Tap Water
60	0.75	0.64	1.00	0.85	1.18
70	0.70	0.58	1.00	0.83	1.20
80	0.66	0.53	1.00	0.81	1.24
90	0.62	0.49	1.00	0.78	1.28
100	0.59	0.45	1.00	0.75	1.33
110	0.57	0.41	1.00	0.72	1.39
120	0.55	0.37	1.00	0.68	1.47

Dent Metal Loss Interaction – Validation





Restraint Parameter

Restrained

Unrestrained

Pipe Details

SCADA

Shape Parameters

Impact of Interacting Features

Dent Fatigue Life

PRCI MD 4-9 Modelling Tools

Models consider dent fatigue life

Level 1 – Screens Dent Fatigue
Suceptibility

Level 2 – Calculates Fatigue Life

- No FEA modelling
- All single peak dents
- Restrained and unrestrained conditions
- Interaction with corrosion and welds
- All applied loading conditions

Level 3 – Calculates Fatigue Life

- Detailed FEA modelling
- All dents geometries
- Restrained and unrestrained conditions
- Interaction with corrosion and welds
- All applied loading conditions

Strain Based Dent Assessment

PRCI Seminar

August 2018

- ILI identifies a dent.
 - How do I interpret that it is innocuous or it poses an immediate risk (such as a crack)?
 - Does this dent pose a risk in the future, as a crack?
 - Fatigue/Corrosion fatigue/SCC

Dent

- Characterized by plastic strain damage (dent shape and dimensions related)
- Convert dent shape and dimensions into parameters that we can relate to crack.
 - STRAIN ESTIMATION
 - Geometric
 - Finite element analyses incorporating material properties
 - STRAIN CRITERIA FOR A CRACK
 - DFDI

GEOMETRIC STRAIN

Modified Equation estimate Geometric Strain

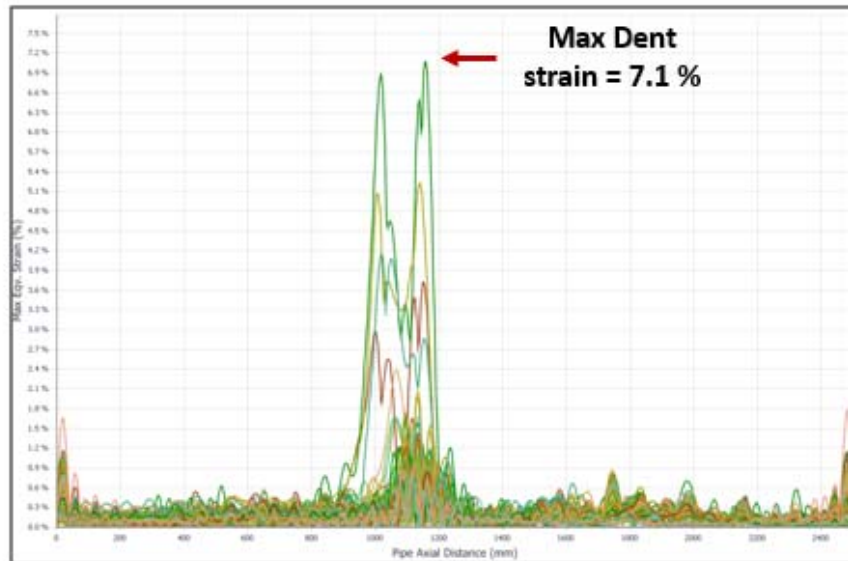
	ASME B31.8	Modified Equation
Circumferential Bending Strain, ε_1	$\varepsilon_1 = \frac{t}{2} \left(\frac{1}{R_o} - \frac{1}{R_i} \right)$	$\varepsilon_1 = \frac{t}{2} \left(\frac{1}{R_o} - \frac{1}{R_i} \right)$
Circumferential Membrane Strain, ε_4	Assumed to be zero	Assumed to be zero for moderate dents, or modeled with changing the length in circumferential direction, or use FEA
Longitudinal Bending Strain, ε_2	$\varepsilon_2 = \frac{-t}{2R_2}$	$\varepsilon_2 = \frac{-t}{2R_2}$
Longitudinal Membrane Strain, ε_3	$\varepsilon_3 = \frac{1}{2} \left(\frac{d}{L} \right)^2$	$\varepsilon_3 = 2 \left(\frac{d}{L} \right)^2$
Shear Strain, γ_{xy}	Assumed to be zero	Assumed to be zero or FEA
Effective strain ε_{eff}	$\varepsilon_{eff} = \sqrt{\varepsilon_x^2 - \varepsilon_x \varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{max} = \text{Max}[\varepsilon_i, \varepsilon_o]$	$\varepsilon_{eq} = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_x^2 + \varepsilon_x \varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{eq} = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_x^2 + \varepsilon_x \varepsilon_y + \varepsilon_y^2 + \gamma_{xy}^2 / 2}$ $\varepsilon_{max} = \text{Max}[\varepsilon_i, \varepsilon_o]$



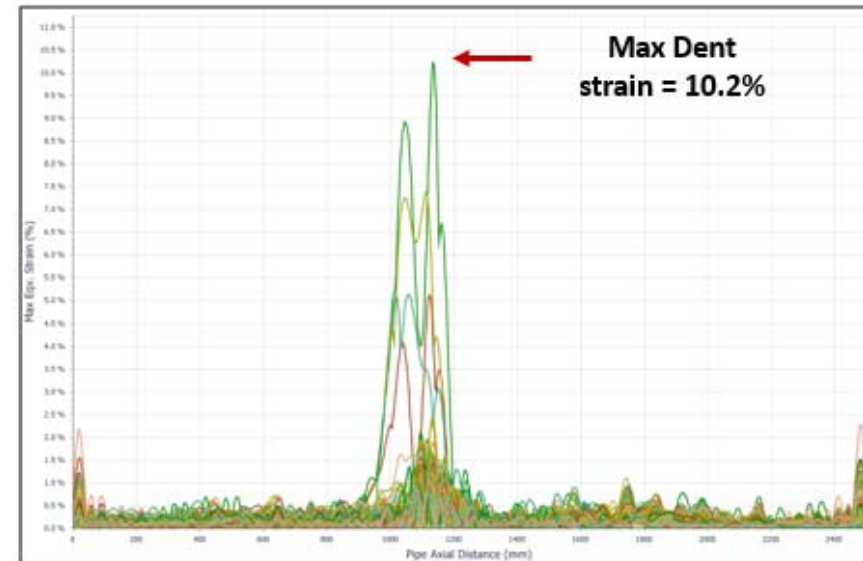
ASME B31.8 generally underestimates the effective (total) strain.
Publications that demonstrate this early 2000's.

Example – caliper data with strain estimation

Using ASME B31.8 Total Strain Equation



Improved Total Strain Equation

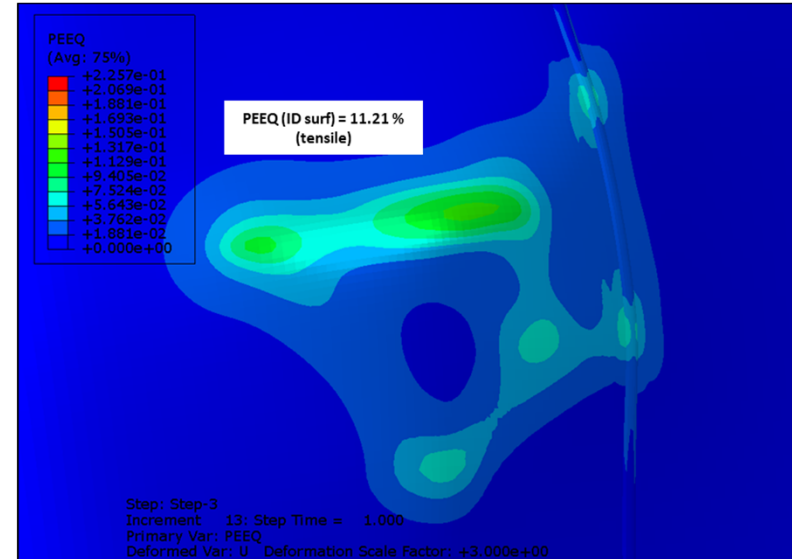
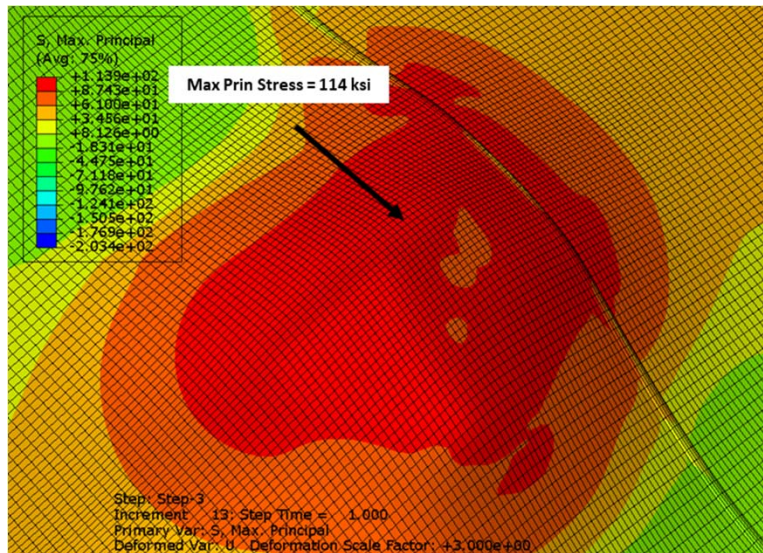


- Dent Depth about 5% of OD

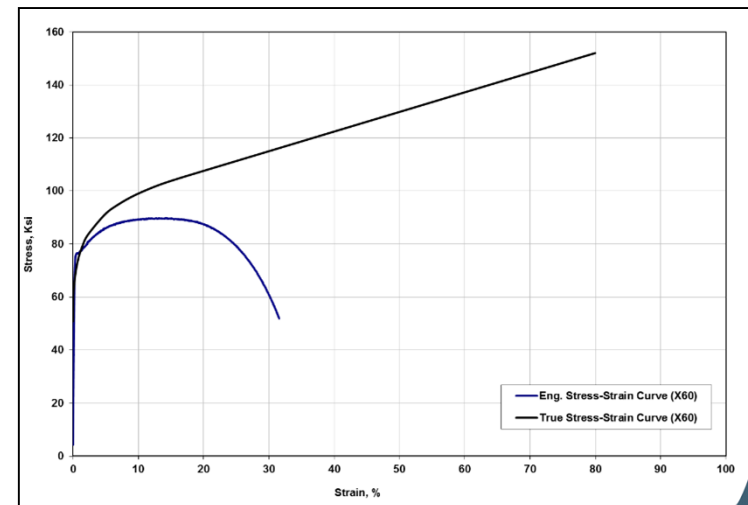
FEA Strain with Material Properties

Example

8



- Dent depth 5%
- FEA strain around 11.2%



Strain Criteria

What is a good Strain Limit Criterion (2007)

10

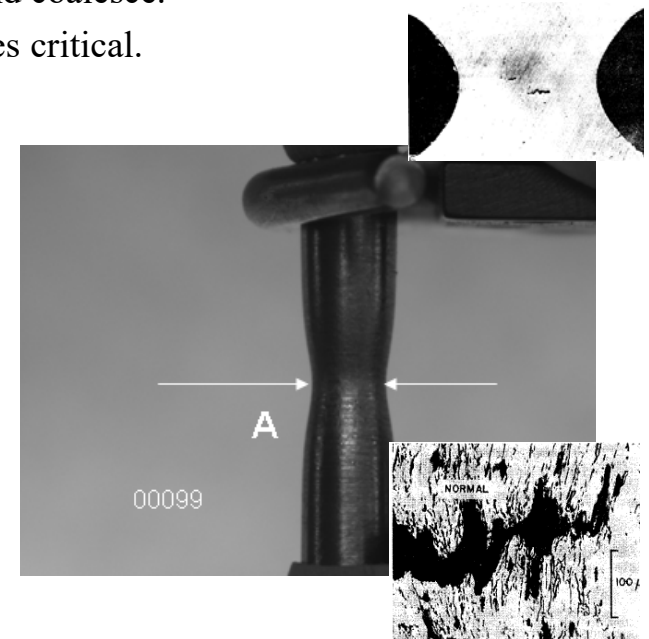
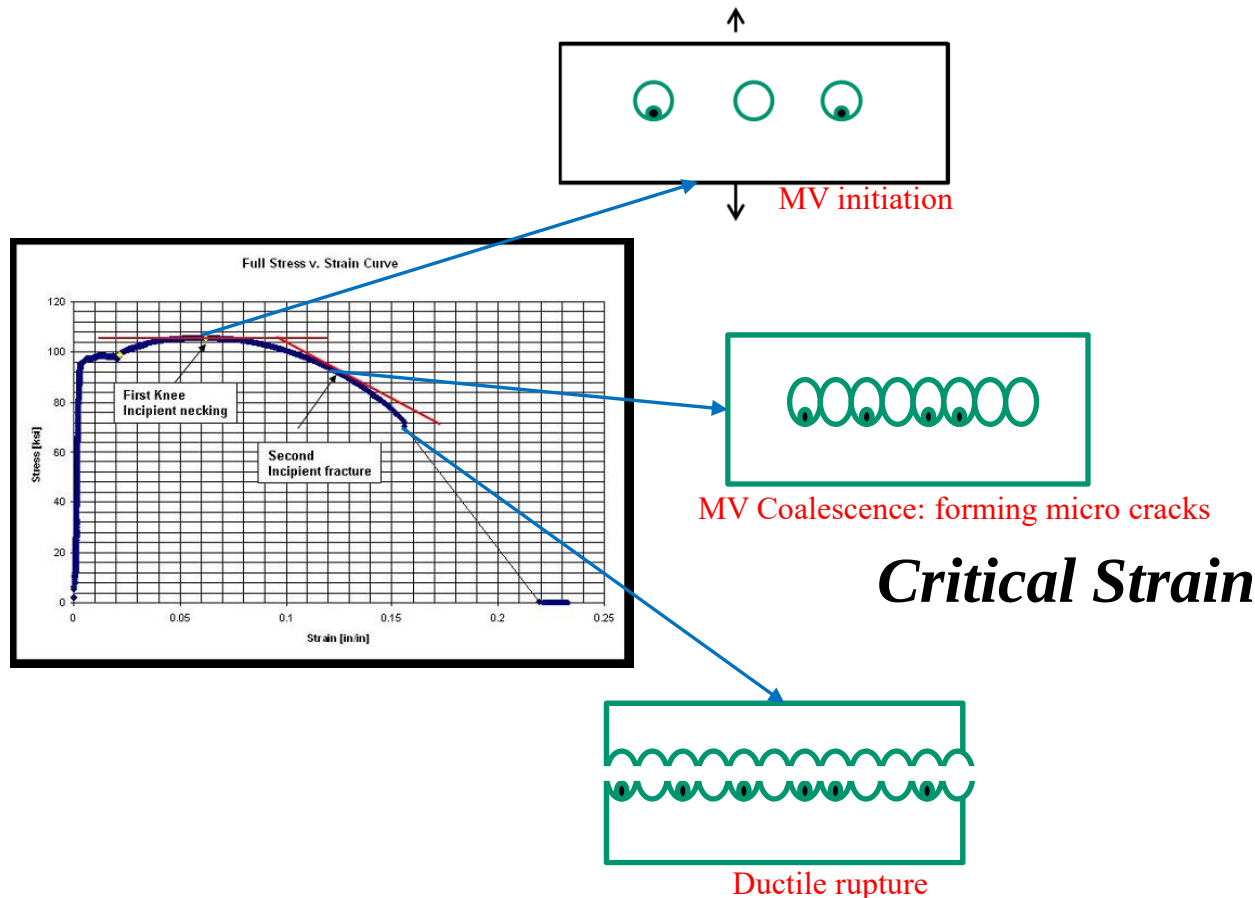
- 6% strain limit for plain dents
 - Introduced into ASME B31.8 in the 2003 Edition
 - Based on an empirical judgment (*)
 - Cracking of the material was sometimes observed in severe buckles where the plastic strain level was 12% or more.
 - Half that value was chosen as a limit.
- Issues of ASME B31.8 criterion
 - Plastic strain level of 12% for cracking is far below the actual.
 - measured strain limit for cracking for most of line pipe steels.
 - One strain limit for all steel grades is not appropriate.

Three alternative strain criteria were proposed based on:

- Critical-strain-based Ductile Failure Damage criterion
 - Quantify progressive damage limit for avoiding onset of failure in ductile materials.
 - Ductile Fracture Damage Index (DFDI) Criteria
- Strain Limit Damage (SLD) Criteria – ASME Boiler & Pressure Vessel (B&PV) Code Section 8, Division 3
- Minimum Specified Elongation Criterion (Francini and Yoosef-Ghods, PRCI Report, 2008)

Plastic Strain Damage Mechanism

- Plastic strain damage for ductile material by micro void (MV) initiation and coalescence mechanism. Typical example is the uni-axial tensile test of ductile metals:
 - Three stage failure: elastic uniform displacement, yield, necking, and rupture
 - Micro voids initiate starting from necking and continue to form and coalesce.
 - Formation cracks and final unstable rupture when the crack reaches critical.



$$\varepsilon_f = 1.65\varepsilon_c \exp\left(-\frac{3}{2} \frac{\sigma_m}{\sigma_{eq}}\right)$$

Critical Strain-Based Criterion: DFDI

13

- Fisher et. al, based on Hancock & Mackenzie's reference strain, proposed a plastic damage failure indicator to quantify the degree of plastic damage.

- Fisher et. al first defined the increment of damage indicator:

$$dD_i = \frac{d\varepsilon_{eq}}{\varepsilon_f} \quad D_i = D_i(\sigma_m / \sigma_{eq}, \varepsilon_{eq}, \dot{\varepsilon}_{eq}).$$

where dD_i is the increment of plastic damage produced by each increment of the equivalent strain, ε_{eq} , ε_f is the failure strain, and D_i is the damage indicator having a general form of

- Fisher et. al then proposed a **Ductile Failure Damage Indicator** (DFDI) to quantify the degree of damage due to plastic deformation. (ratio of strain in dent to critical strain)

$$DFDI = \int \frac{d\varepsilon_{eq}}{\varepsilon_f} = \frac{1}{1.65\varepsilon_c} \int_0^{\varepsilon_{eq}} \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) d\varepsilon_{eq}$$

Critical strain (ε_c , True Strain) is a material's property and defined as failure (onset of crack) strain measured from a uniaxial test

Concepts (Cont'd)

- Ductile Failure Damage Indicator (DFDI)
 - Degree of ductile damage with respect to failure:

$$DFDI = \frac{1}{1.65\varepsilon_c} \int_0^{\varepsilon_{eq}} \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) d\varepsilon_{eq} \text{ or}$$

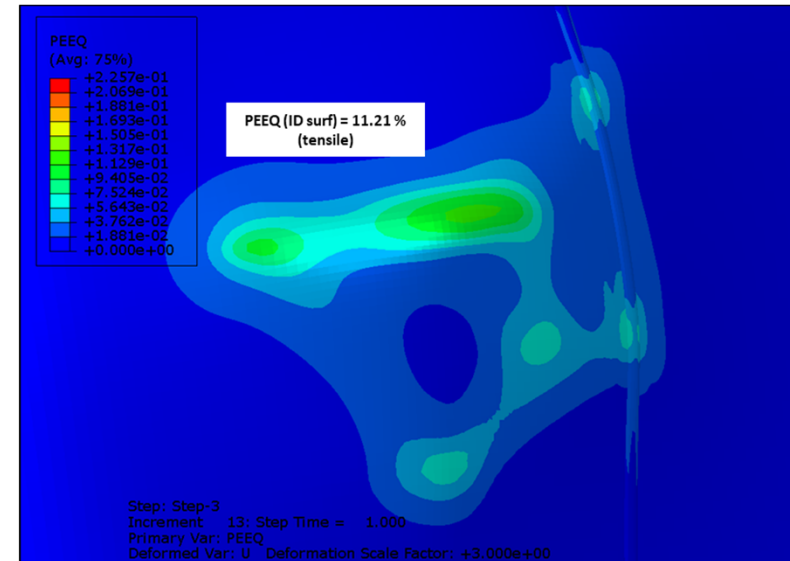
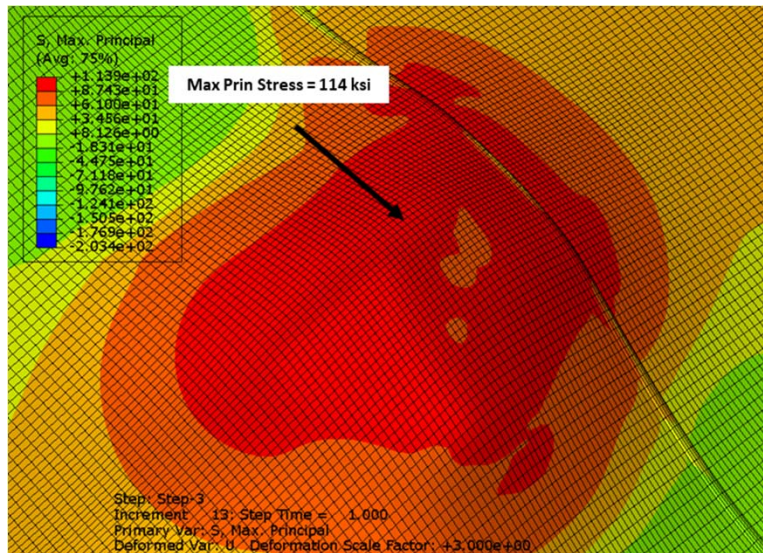
- Failure condition is defined as:

$$DFDI \geq 1$$

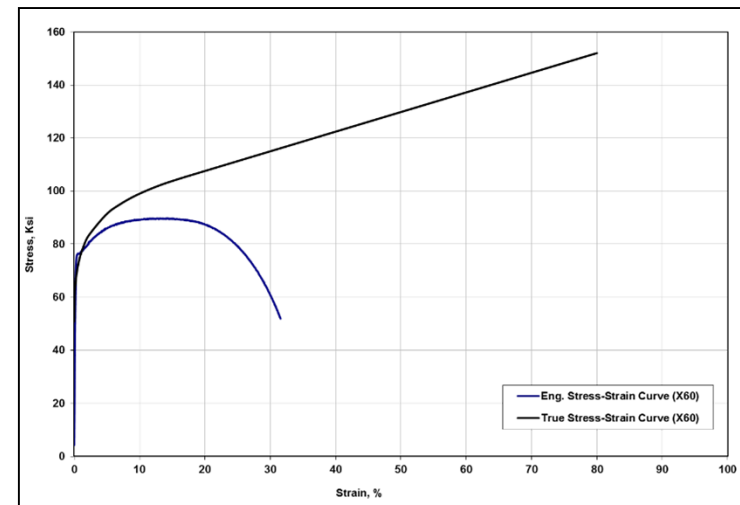
- Calculation of DFDI requires a functional relation between σ_m , σ_{eq} , and ε_{eq} , or numerical solution may be used to determine σ_m , σ_{eq} for each $d\varepsilon_{eq}$.

Uniaxial test gives a material property (ε_c)
DFDI normalizes it to a dent and provides a failure criteria

Example- FEA strain



- Dent depth 5%
- FEA strain around 11.2%
- DFDI 0.342 to 0.45

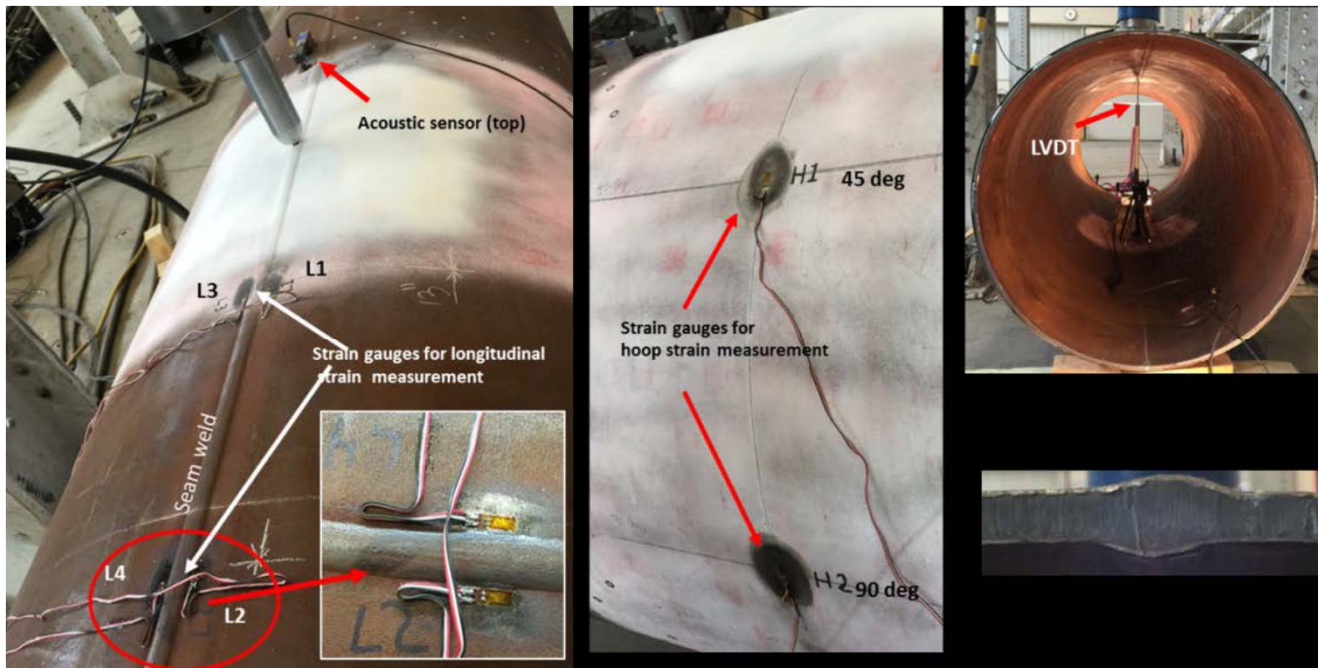


Laboratory Validation

IPC 2016-64548

Experimental

- Denting (NPS 34, X52, Indenter = 1.5" Dia) – Pipe body and weld (seam/girth)
- Test Setup
 - MTS Hydraulic Actuator with Indenter (1.5" hemi-spherical indenter (4032 Al-alloy))
 - LVDT for displacement measurement (OD%)
 - Strain gages for strain measurement
 - Video camera for real time monitoring and recording
 - In-situ Laserscan for real time strain measurement
 - acoustic sensor was mounted close to the dent deformation area to monitor the cracking sound if any during the test



Plastic Strain Damage vs Dent Cracking



Deformation 6%OD: crack
Initiated:



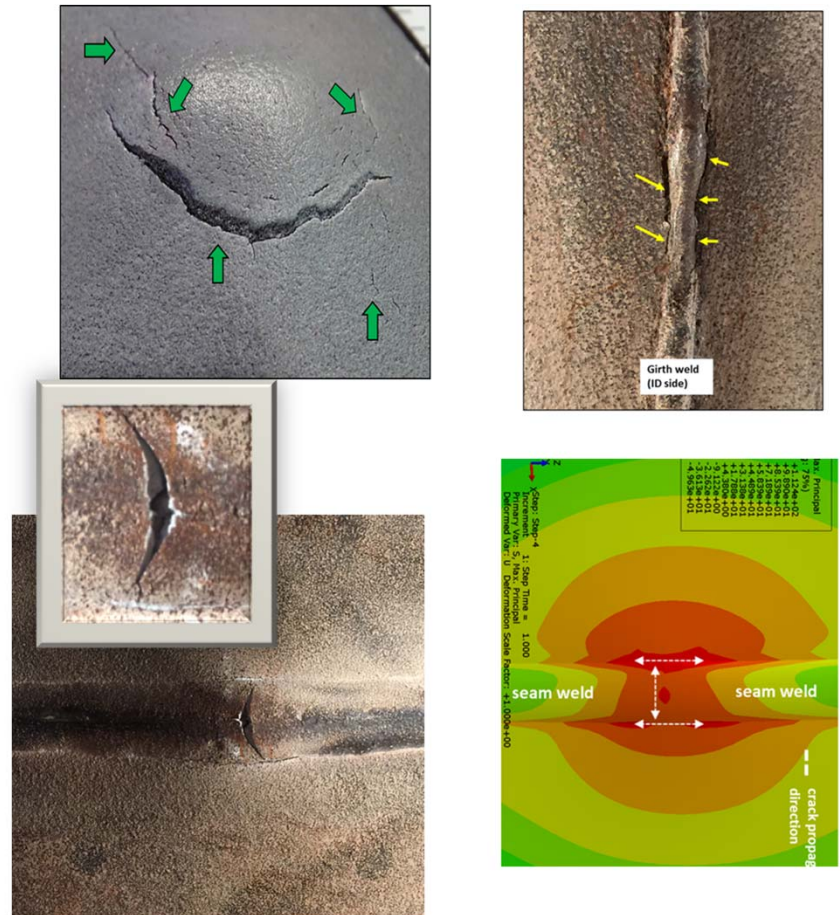
Deformation
12%OD
Deep
circumferential
Crack



13%OD: Weld toe
Crack through-wall

Validation of DFDI

Test #	Pipe Specimen	Dent Location	Max. Eqv. Strain	Upper bound DFDI	DFDI ≥ 1 Criterion	Comments
1	NPS 34; X52 grade; 2.5"/1.5" indenter	Pipebody	30.1%	0.98	Yes. Validated	Several small cracks were found between 12% to 15% OD depth
2			37.5%	1.22	Yes. Validated	Wide-open transverse crack formed at 17.5%OD with several small cracks
3			34.9%	1.136	Yes. Validated	Several micro cracks were found
4	NPS 36; X65 grade; 1.5" indenter	Seam weld	31.2%	0.88	Not validated	Pipe was severely ovalized. Test abandoned & no crack found
5	NPS 34; X52 grade; 1.5" indenter		31.8%	1.05	Yes. Validated	Cracks formed in seam weld/HAZ region at 6%OD
6	NPS 36; X65 grade; 1.5" indenter	Girth weld	31.5%	0.96	Yes. Validated	Cracks formed in girth weld toe region at 6%OD



Out of 6 tests, 5 demonstrated that cracks initiated at the dent ID surface when $DFDI \geq 1.0$, confirming the material critical strain based DFDI is a valid criterion to quantify dent severity, and used to identify leaking dents

Pipeline/Field Validation

Validation

Case-1: Dent Associated With Branched Crack

Summary

ILI Dent Depth = 2.7%OD (<6% OD depth limit)

Associated anomaly = 76% Ext. Metal Loss

Location = Bottom of the pipe / Rock dent

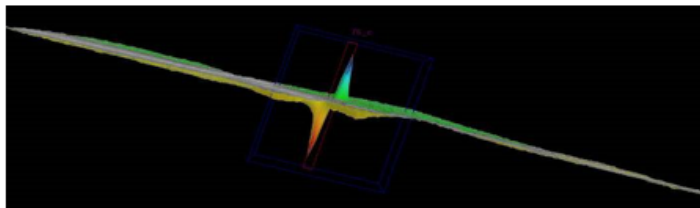
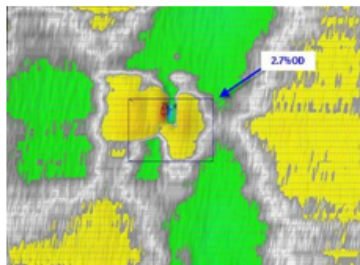
ILI strain = 17.6%

DFDI = 0.97, suggesting possible crack initiation and review of MFL signal characteristics

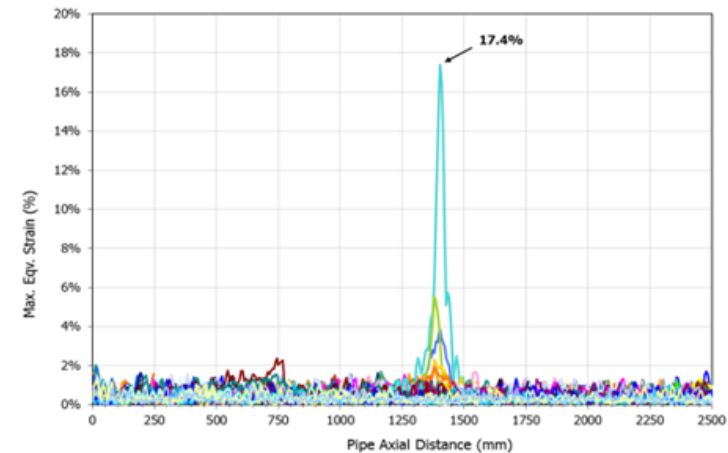
MFL signal review: Single sharp signal at dent apex location (high strain location).

In-ditch finding: Dent with branched cracks at both ID and OD surfaces but no leak detected

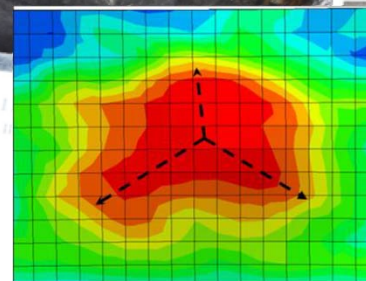
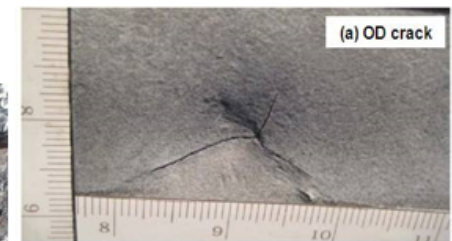
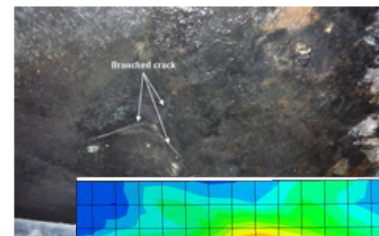
MFL signal



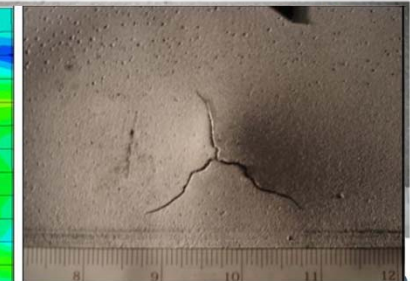
ILI Dent Strain



In-ditch / Lab finding



(a) Max principal stress plot with predicted crack path



(b) Actual crack path

Validation

Case-2: Dent Associated With Gouge

Summary

ILI Dent Depth = 2.7%OD (<6% OD depth limit)

Associated anomaly = None (reported as Plain dent)

Location = Top of the pipe

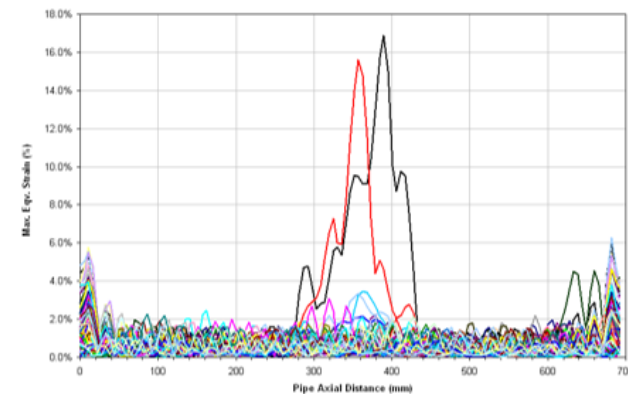
ILI strain = 16.9%

DFDI = 0.93 , suggests to review MFL signal

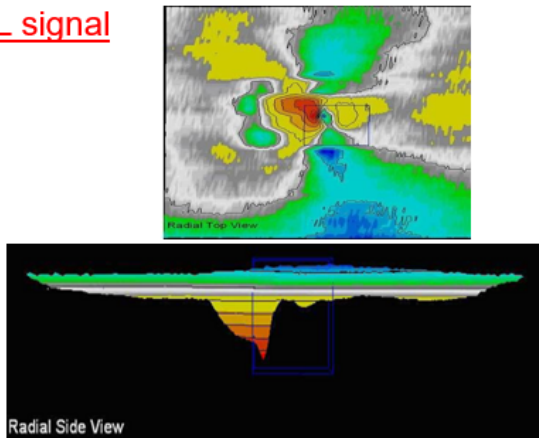
MFL signal review: Observed metal loss signal in dent area. Signal appears to be deep but oriented in circumferential direction. Possible gouge.

In-ditch finding: Dent with gouge/few axial cracks

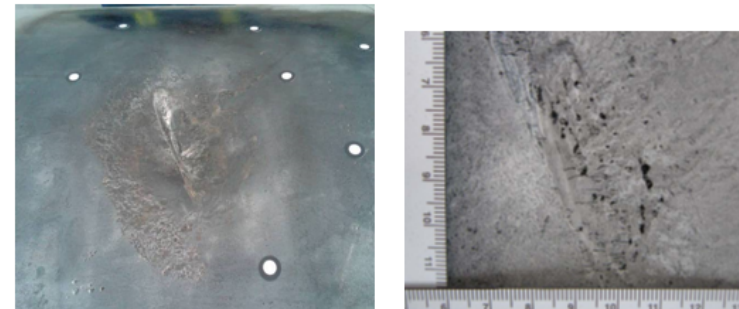
ILI Dent Strain



MFL signal



In-ditch finding



4.5%OD rock dent

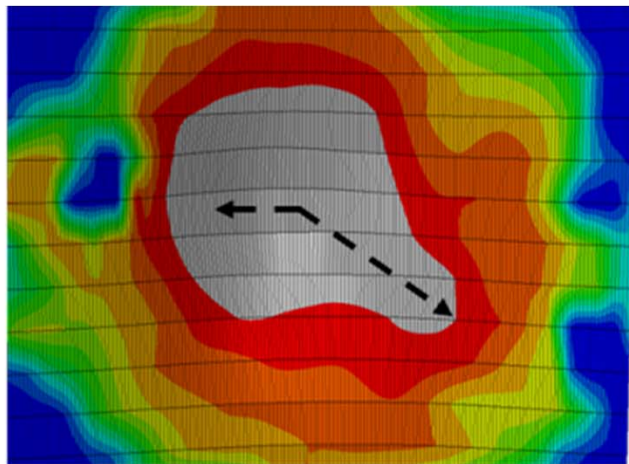
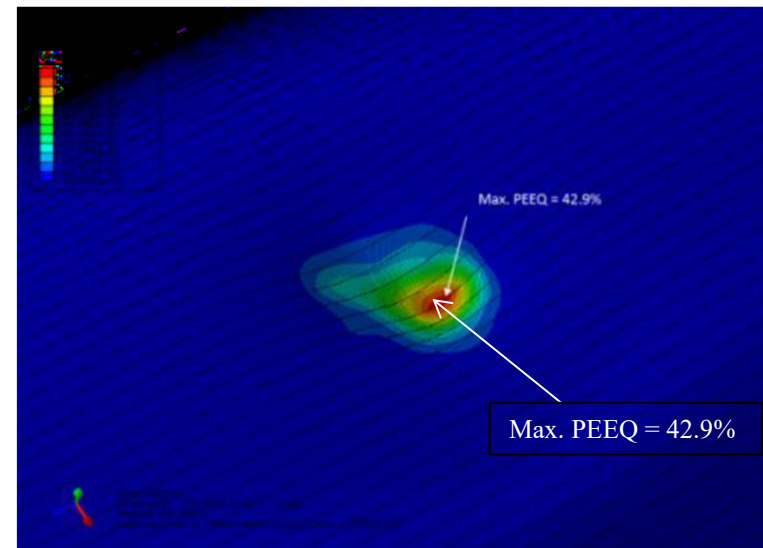
Plastic Damage Models

FEA Max Plastic Eqv Strain = 42.9%

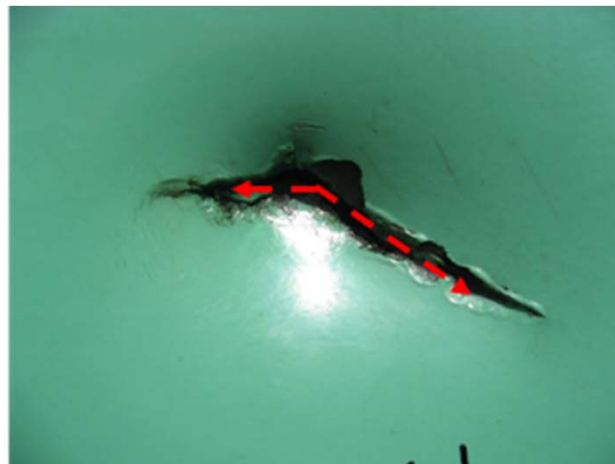
1. DFDI = 1.4 (Susceptible to cracking)
2. SLD = 1.9 (Susceptible to failure)

Both DFDI and SLD models predicted that this dent is susceptible to cracking or failure but SLD model is more conservative than DFDI due to use of minimum specified properties

FEA Result – PEEQ plot



(a) Maximum principal stress plot – indicating probable crack path



(b) Actual crack path

Color-coded contour plot of maximum principal stress plot (indicated probable crack path) vs. actual crack path

For details, refer to IPC2012-90504

Field Validation

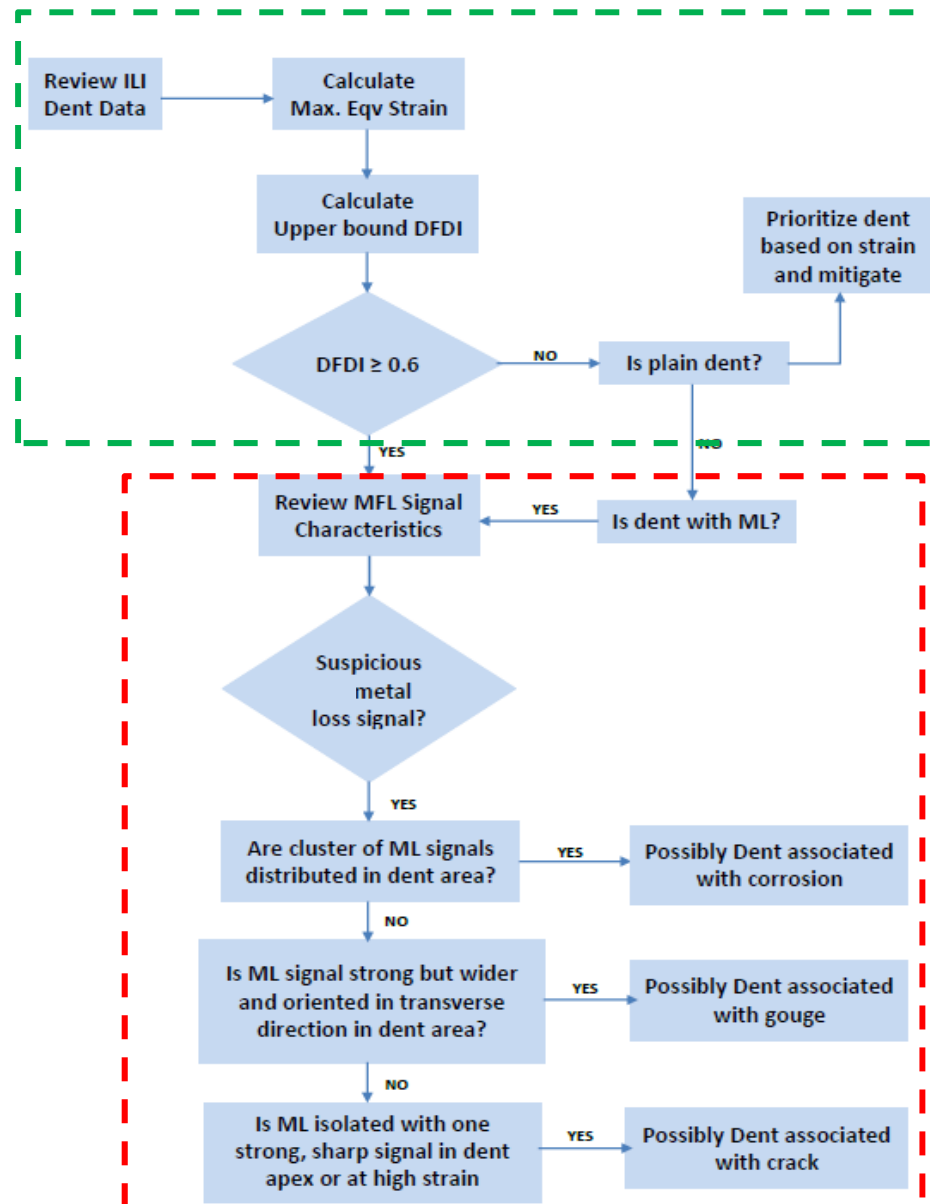
❖ Inspection of three pipeline sections

- Combo ILI reported 6361 dents, 150 dents were selected using screen method (IPC2012-90499;NACE 2858) for study.

❖ Results

- Predicted 7 dents that could be associated with crack or gouges, however 15 excavations were conducted to verify this approach.

Assessment Approach & Flow chart



Initial Condition of the Dent

- Estimation of total equivalent strain either through geometry data or FEA
- Assess critical for the material or make reasonable default assumption
- Calculate DFDI (equations simplified for screening purposes)
- Screen dents based on DFDI plus MFL interpretation
- This does not address whether the dent developed a crack due to fatigue or corrosion fatigue or SCC.

Fatigue Analyses of Dents

Analyses Options

- EPRG method
 - Empirical data and conservative and combined with DFDI is a good screening method.
 - Used without FEA
- Finite Element Analyses
 - Obtain strain range ($\Delta\varepsilon$) that is applied in the dent region

- Markle's Equation

$$N = \left[\frac{0.01655}{(\Delta\varepsilon/2)} \right]^5 \quad N = \left[\frac{0.011031}{(\Delta\varepsilon/2)} \right]^5$$

- Smith Watson Topper Model

$$\sigma_{\max} \varepsilon_a E = (\sigma'_f)^2 (2N_f)^{2b} + \sigma'_f \varepsilon'_f E (2N_f)^{b+c}$$

Maximum stress observed per cycle

Total Strain amplitude

Fatigue Parameters Used in SWT Method

Fatigue parameters: Parameters are obtained by fitting of the true stress/strain data using the Ramberg-Osgood relationship as

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{K'} \right)^{1/n'}$$

K' = Cyclic strength coeff.

n' = Cyclic strain hardening exponent

Step 1: Fatigue strength, σ'_f , and fatigue ductility coefficient, ε'_f , are critical stress and critical strain values respectively.

Step 2: Fatigue strength exponent, b , and fatigue ductility exponent, c , are obtained from the cyclic strain hardening exponent, n'

$$\sigma_{\max} \varepsilon_a E = (\sigma'_f)^2 (2N_f)^{2b} + \sigma'_f \varepsilon'_f E (2N_f)^{b+c}$$

Fatigue Analyses -example

- API 1156 – 111,816 cycles
- MarkI – 19,921 to 2621 cycles
- SWT – 66,740

Small scale initiation testing supports SWT

Summary thoughts

- DFDI validation and refinement of safety factors needs to continue.
- Fatigue modeling should include strain range to have a basic foundation and differentiate between initiation and growth.
 - Initiation (SWT type modeling) defines presence of a crack
 - Understanding of growth critical to time available for repair/rehabilitation when cracks are identified.