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Incorporating Strain Hardening and the 3D Shape of Metal Loss into Corrosion Assessment

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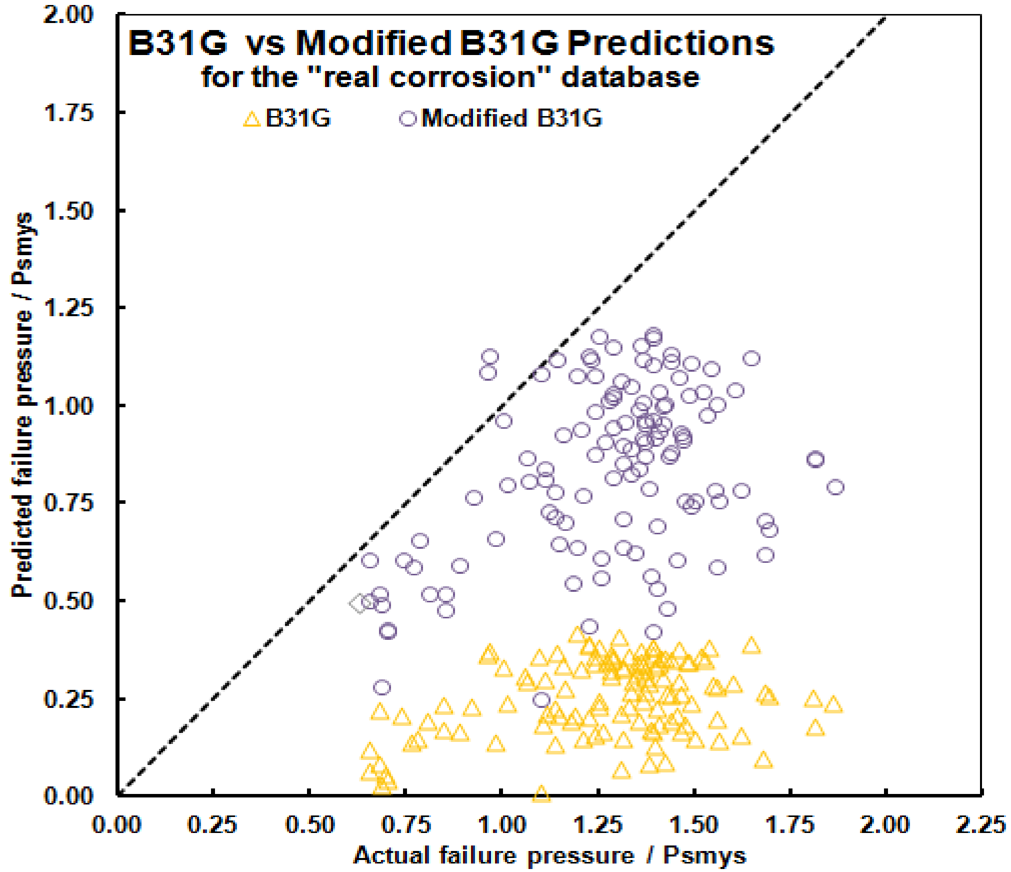
Overview

- Background and incentives
- Existing metal loss assessment models
- Reference stress function
- Burst pressure predictive model of isolated metal loss
- Conclusions and future work

Background and Incentives

- Corrosion anomalies
  - Remain a major threat to the integrity of natural gas and hazards liquid pipelines
- Existing assessment models
  - Use simplified metal loss geometry and shape
  - Do not take account of pipe material strain hardening rates
  - Do not accurately quantify interaction/coalescence
  - Can produce overly conservative burst pressure prediction

Comparison between Predicted and Measured Burst Pressure*



*Leis, B.N., Zhu, X.-K., and McGaughy, T., 2016, Phase I Report of PRCI Project EC-2-7.

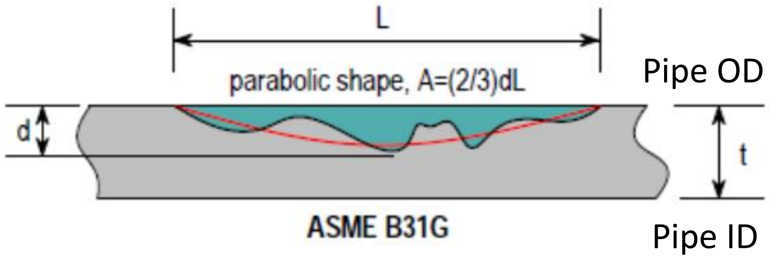
History of Metal Loss Assessment Model Development

The late 1960s	Since 1990s	2018 - present
• ASME B31G • Modified ASME B31G • RSTRENG	• SHELL92 • DNV RP F101 • PCORRC • Others	• R-PCORRC • Psqr • EC-2-10 • Others

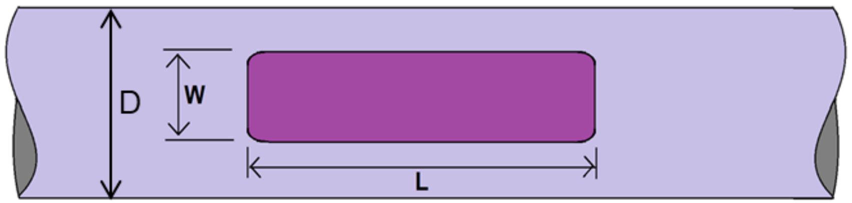
Factors Explicitly Included in Burst Pressure Prediction Models

Metal Loss or Pipe	Contributing Factors	ASME B31G	Modified ASME B31G	DNV RP F101	R-PCORRC	Psqr	EC-2-10
Isolated Metal Loss	Depth and Length	✓	✓	✓	✓	✓	✓
	Width	✘	✘	✘	✘	✘	✓
	Planar Shape	✘	✘	✘	✘	✘	✓
	Longitudinal Profile	✓ Parabolic	✓ Elliptical	✓ Flat-bottomed	✓ Flat-bottomed	✓ Elliptical	✓ Flat-bottomed; also Parabolic; Elliptical
Multiple Interacting Metal Loss	Interaction	✓	✓	✓	✘	✓	✓ in process
	Coalescence	✘	✘	✘	✘	✘	✓ in process
Pipe	Strain Hardening	✘	✘	✘	✓	✘	✓

Longitudinal Profile



Planar Shape



Reference Stress Functions

Parameter Based	Reference Stress Function	Burst Pressure Model	Basis of Function
SMYS	$\sigma_{R,SMYS} = 1.1\ SMYS$	ASME B31G	Empirical fits to test data
	$\sigma_{R,SMYS} = SMYS + 10\ ksi$	Modified ASME B31G	
SMTS	$\sigma_{R,SMTS} = 1.0\ SMTS$	DNV RP F101	Empirical fits to FEA results
	$\sigma_{R,SMTS} = 0.9\ SMTS$	SHELL92	
UTS and Strain Hardening Exponent *n*	$\boldsymbol{\sigma_{R,M} = 2\left(\frac{1}{\sqrt{3}}\right)^{(n+1)} \sigma_{UTS}}$	Ma-2013	von Mises equivalence criterion
	$\boldsymbol{\sigma_{R,T} = 2\left(\frac{1}{2}\right)^{(n+1)} \sigma_{UTS}}$	Abdelghani-2018	Tresca equivalence criterion
	$\boldsymbol{\sigma_{R,ZL} = 2\left(\frac{2+\sqrt{3}}{4\sqrt{3}}\right)^{(n+1)} \sigma_{UTS}}$	R-PCORRC	Average shear-stress criterion or Zhu-Leis criterion
	$\boldsymbol{\sigma_{R,EC-2-6} = (1.0745 - 0.6131n)\sigma_{UTS}}$	EC-2-6	Empirical fits to FEA results
	$\boldsymbol{\sigma_{R,EC-2-10} = \left(\frac{2}{\sqrt{3}}\right)(0.933)^{(n+1)}(1.000 - 0.520n)\sigma_{UTS}}$	EC-2-10	Empirical fits to FEA results

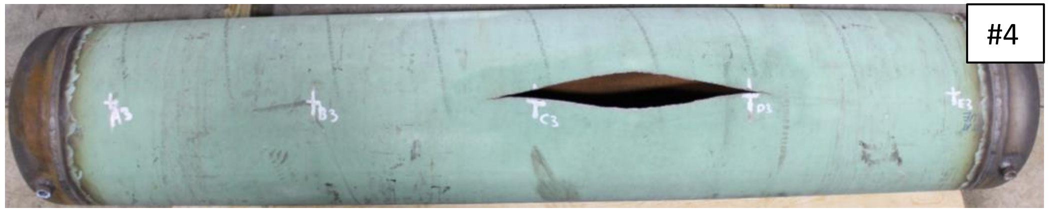
Full-Scale Burst Tests of Defect-Free Pipes

- Successfully conducted 5 full-scale burst tests of purposefully selected pipes with a wide range of strain hardening rates
- Filled the critical gap of rare test data to validate reference stress functions

Burst Test #	Pipe Geometry, Grade, and Seam				Pipe Manufacturing Year	Strain Hardening		P_{exp}
	OD inch	WT inch	Grade	Seam		Level	*n*	psi
1	10.75	0.365	A	Furnace Lap	1929	High	0.200	3561
2							0.205	3252
3	24	0.492	X70	ERW	2017	Low	0.068	3970
4	20	0.375	X52	ERW	2018	Medium	0.100	3146
5							0.100	3122


#1


#2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#5


#3

Comparison of Predicted and Measured Burst Pressure of Defect-Free Pipes

- Good agreement between the predicted and measured burst pressures

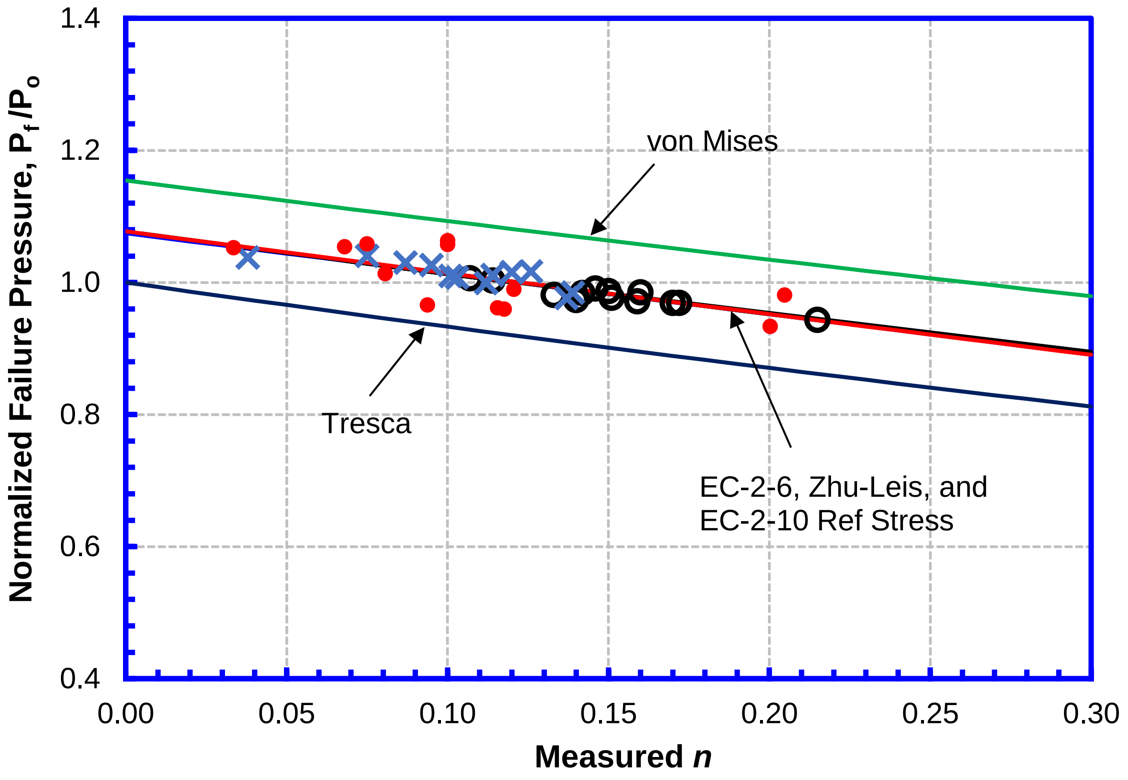
Burst Test #	Measured Pipe Geometry OD	Measured Pipe Geometry WT	YS at 0.5% Total Strain	UTS	Y/T	Measured n	P_{exp}	P_{pre}	P_{pre}/P_{exp}
	in	in	ksi	ksi			psi	psi	
1	10.803	0.376	31.26	52.89	0.59	0.200	3561	3631	1.020
2	10.800	0.325	30.35	53.43	0.57	0.205	3252	3146	0.967
3	24.092	0.497	77.48	89.41	0.87	0.068	3970	3896	0.981
4	20.078	0.382	64.36	76.18	0.84	0.100	3146	3000	0.954
5	20.093	0.382	64.36	76.18	0.84	0.100	3122	2995	0.959
								AVE	0.98
								STD	0.02

- Burst pressure was predicted via EC-2-10 reference stress function

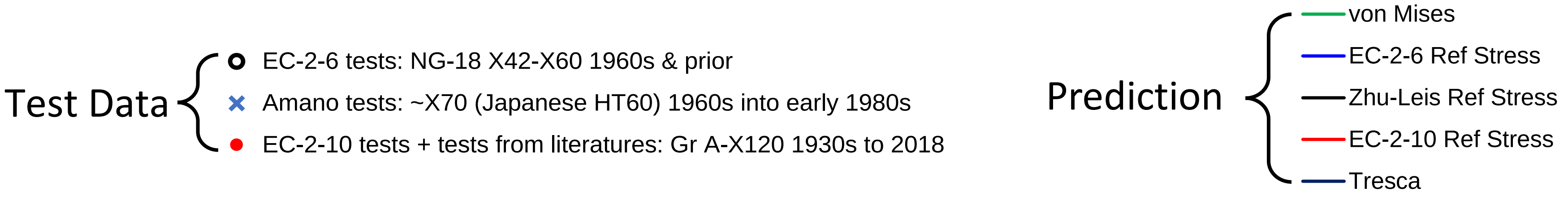
$$P_{pre} = \frac{2}{\sqrt{3}}(0.933)^{(n+1)}(1.000 - 0.520n)\sigma_{UTS}\left(\frac{2t}{D-t}\right)$$

- Strain hardening exponent n from fitting measured stress-strain curves

Validation of Reference Stress Functions

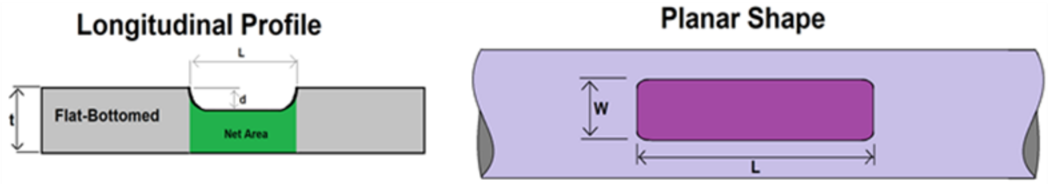


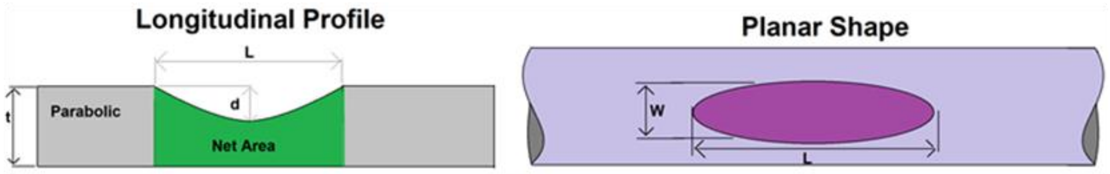
- Burst pressure decreases with the increase of strain hardening exponent *n*
- The von Mise lies above and Tresca falls below the test data
- Zhu-Leis, EC-2-6 and EC-2-10 produce very similar predictions which run through the middle of the test data
- Robust and broad validation of EC-2-6 and Zhu-Leis reference stress
- Zhu-Leis reference stress is recommended.



Development of Burst Pressure Predictive Model for Isolated Metal Loss

- Analysis approach
  - Numerically simulate burst pressure for a variety of metal-loss geometries
  - Organize and trend the data to develop a predictive model
- Analysis steps
  - Step 1: Perform 2-D and 3-D FEA on rectangular flat-bottomed metal loss
  - Step 2: Develop a model for rectangular flat-bottomed metal loss
  - Step 3: Evaluate the model against existing test data
  - Step 4: Conduct 3-D FEA on other metal loss shapes
  - Step 5: Extend the model to include different shapes





Burst Pressure Predictive Model

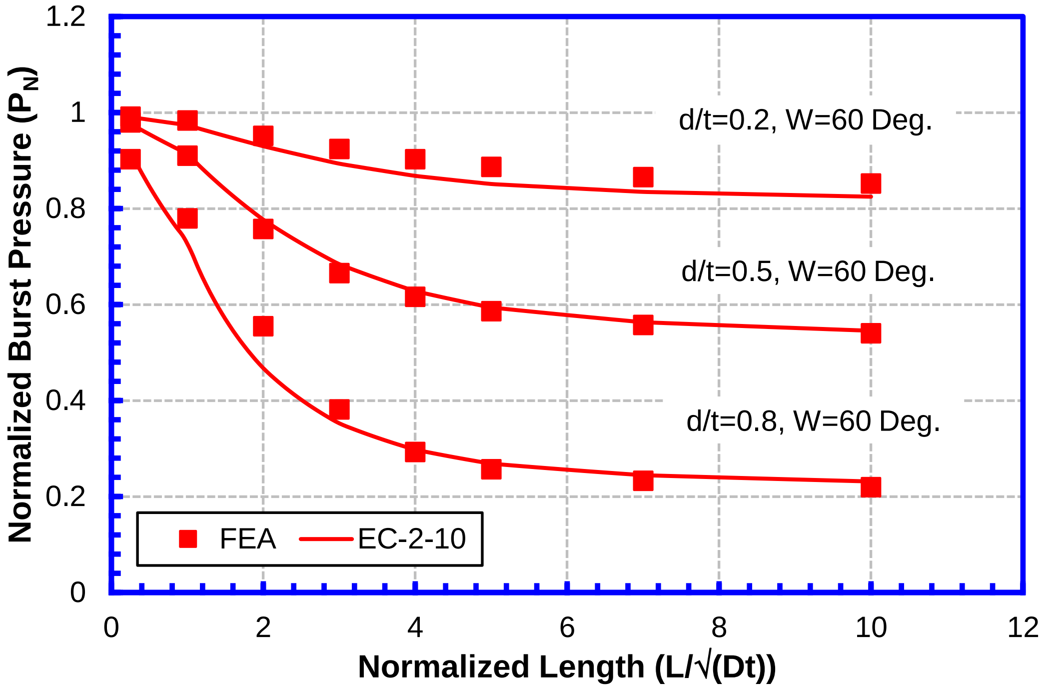
- A model for isolated rectangular flat-bottomed metal loss:
  - $P_N = \frac{(1-d/t)}{1-(d/t)\times F(L/\sqrt{Dt},W)}$
  - $P_b = P_N \times \sigma_{R,ZL} \times (2t/D)$
- Applicable range
  - Normalized depth: $0.1 \leq d/t \leq 0.9$
  - Normalized length: $0.25 \leq L/\sqrt{Dt} \leq 10$
  - Width angle: $2.5 \leq W \leq 180.0$ degrees

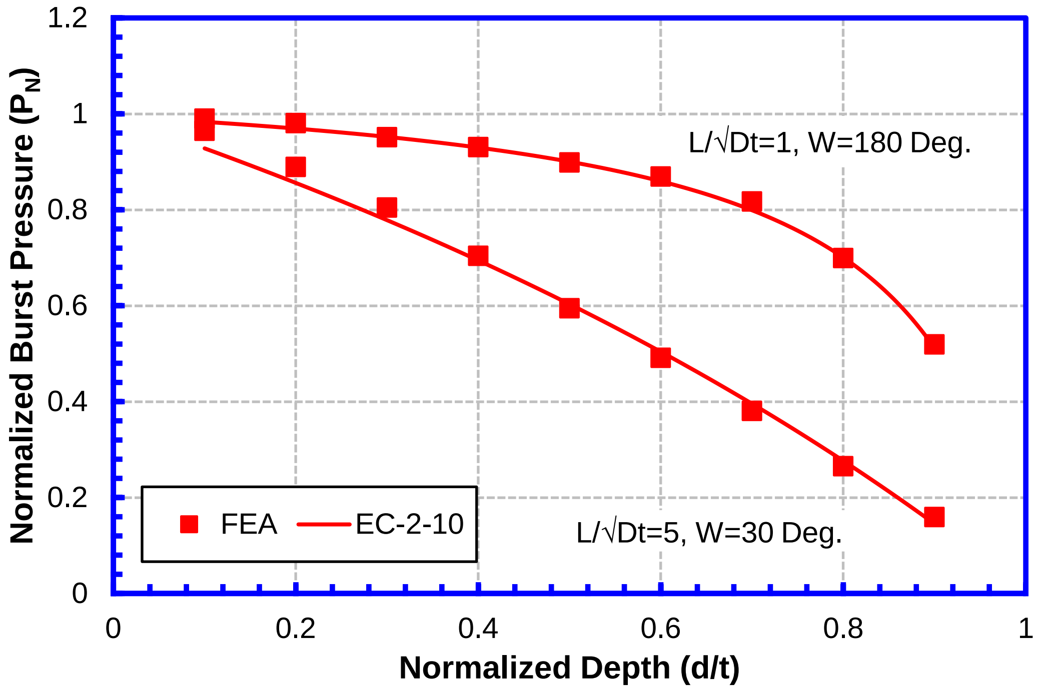
Parameters: Category	Parameters: Symbol	Description of Parameters
Burst Pressure	P_N	Normalized burst pressure of the corroded pipe
	P_b	Burst pressure of the corroded pipe
Reference Stress	$\sigma_{R,ZL}$	Zhu-Leis reference stress
Pipe Geometry	D	Pipe outer diameter
	t	Pipe wall thickness
Metal Loss Geometry	L	Metal loss longitudinal length
	d	Metal loss max depth
	W	Metal loss circumferential width

Function F

F	W (Deg.)							
$L/\sqrt{Dt}$	**2.5**	**10.0**	**30.0**	**40.0**	**60.0**	**90.0**	**135.0**	**180.0**
0.25	0.996	0.995	0.989	0.986	0.978	0.966	0.950	0.930
0.50	0.971	0.970	0.965	0.963	0.957	0.948	0.937	0.924
0.75	0.945	0.945	0.942	0.939	0.937	0.931	0.924	0.920
1.00	0.916	0.915	0.912	0.910	0.908	0.904	0.899	0.895
1.25	0.879	0.876	0.872	0.868	0.866	0.861	0.854	0.845
1.50	0.837	0.831	0.825	0.820	0.816	0.808	0.799	0.786
1.75	0.793	0.784	0.776	0.774	0.764	0.752	0.740	0.725
2.00	0.750	0.740	0.730	0.725	0.715	0.700	0.685	0.670

Evaluation of the Model – Compared to FEA and other Model Predictions

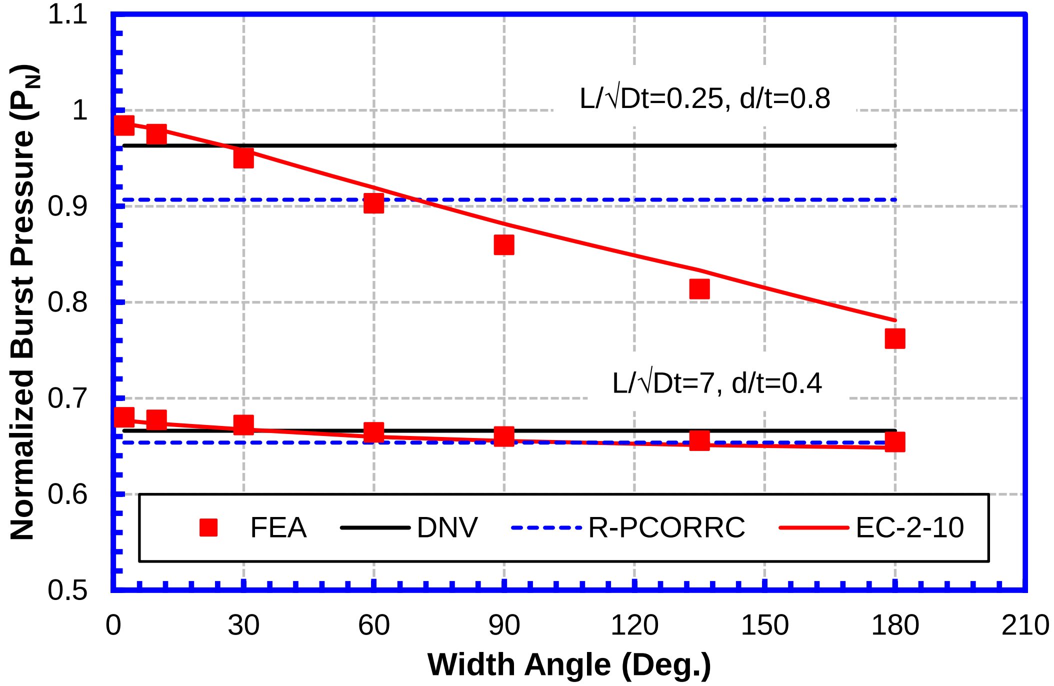




- A good agreement obtained between EC-2-10 model prediction and FEA
- EC-2-10 model captures the trend of burst pressure vs. metal loss length and depth

Evaluation of the Model – Compared to FEA and other Model Predictions – Cont.

Normalized burst pressure vs. width angle of rectangular flat-bottomed metal loss



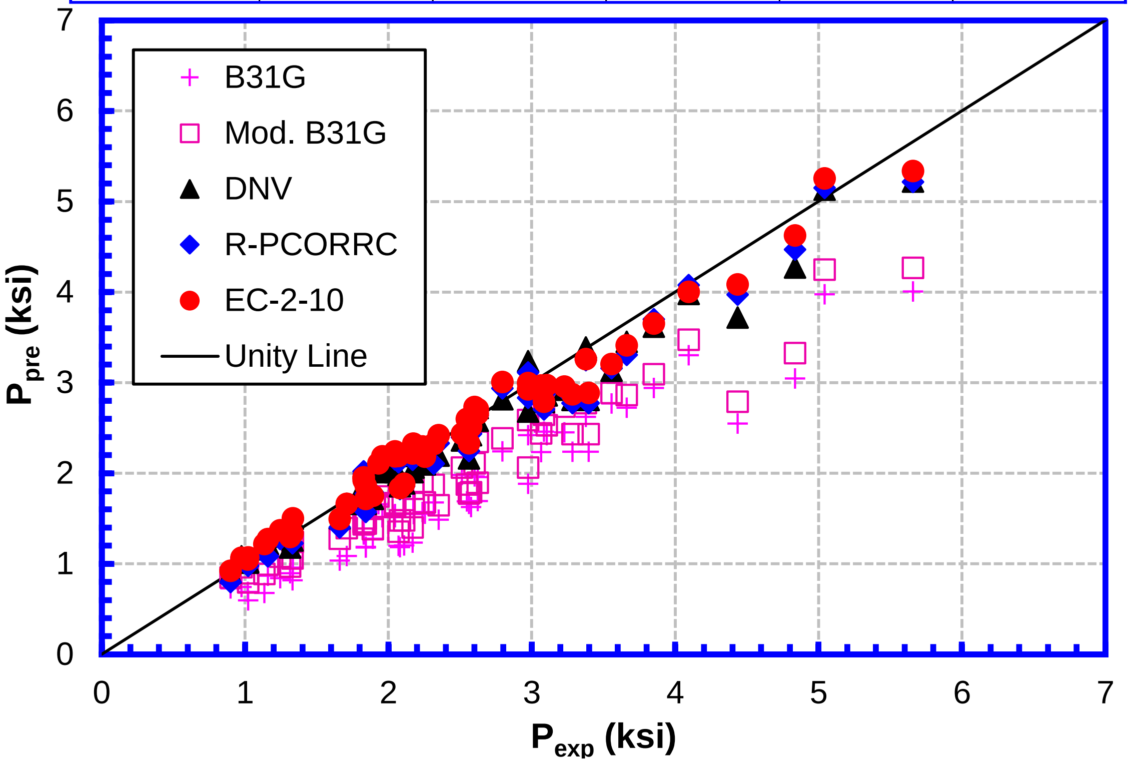
- For short and deep metal loss:
  - EC-2-10 model captures width effects
  - DNV and R-PCORRC don't capture width effects
  - When width angle > ~70°, EC-2-10 model predicts lower burst pressure than DNV and R-PCORRC
- For long and shallow metal loss:
  - Width effects are marginal
  - The predicted burst pressures from these three models and FEA are similar

Evaluation of the Model – Comparison to Existing Full-Scale Test Data

- More accurate and precise burst pressure prediction than ASME B31G and Modified ASME B31G

- Similar burst pressure prediction compared to DNV and R-PCORRC
  - The metal loss size and shape of the tested pipes were limited and not able to quantify width effects.

Predictive Model	P_{pre}/P_{exp}				
	ASME B31G	Mod. B31G	DNV	R-PCORRC	EC-2-10
Mean	0.69	0.78	0.97	0.97	0.99
Std	0.09	0.09	0.07	0.08	0.07
CoV	0.12	0.11	0.07	0.08	0.08



Extension of the Model to other Shapes

- A shape effect factor λ is introduced, such that

$$P_b^{EP} = \lambda\left(d/t\,, L/\sqrt{Dt}\,, W\right) \times P_b^{Rec}$$

P_b^{EP} : predicted burst pressure of metal loss with elliptical planar shape and parabolic longitudinal profile

P_b^{Rec}: predicted burst pressure of rectangular flat-bottomed metal loss

- Given metal loss d/t, $L/\sqrt{Dt}$, and W, λ can be obtained from a look-up table directly or by interpolation.

d/t	$L/\sqrt{Dt}$	W (Deg.)				
		2.5	10.0	30.0	60.0	90.0
0.4	0.25	1.000	1.000	1.000	1.000	1.000
	1.00	1.001	1.014	1.041	1.057	1.062
	2.00	1.017	1.037	1.082	1.139	1.166
	3.00	1.035	1.055	1.108	1.172	1.224
	4.00	1.033	1.052	1.107	1.170	1.223
	5.00	1.038	1.056	1.096	1.150	1.188
	7.00	1.047	1.057	1.083	1.119	1.150
	10.00	1.052	1.055	1.066	1.084	1.112

Conclusions and Future Work

- Conclusions
  - A new burst pressure predictive model, EC-2-10 model, was developed.
  - EC-2-10 model can capture coupled effects of metal loss width along with its planar shape, longitudinal profile, length, and depth.
  - The effects of width on burst pressure depend on the metal loss depth, length, planar shape, and longitudinal profile.
  - Improved burst pressure prediction vs. ASME B31G and Modified ASME B31G. And similar burst pressure prediction vs. DNV and R-PCORRC.
- Future work
  - More full-scale tests are planned to demonstrate width effects.
  - EC-2-10 model will be extended to assess complex real corrosion by quantifying interaction and coalescence.

Thank you for your attention.