Multi-modal NDE Assisted Probabilistic Pipeline Performance Evaluation under Interactive Anomalies

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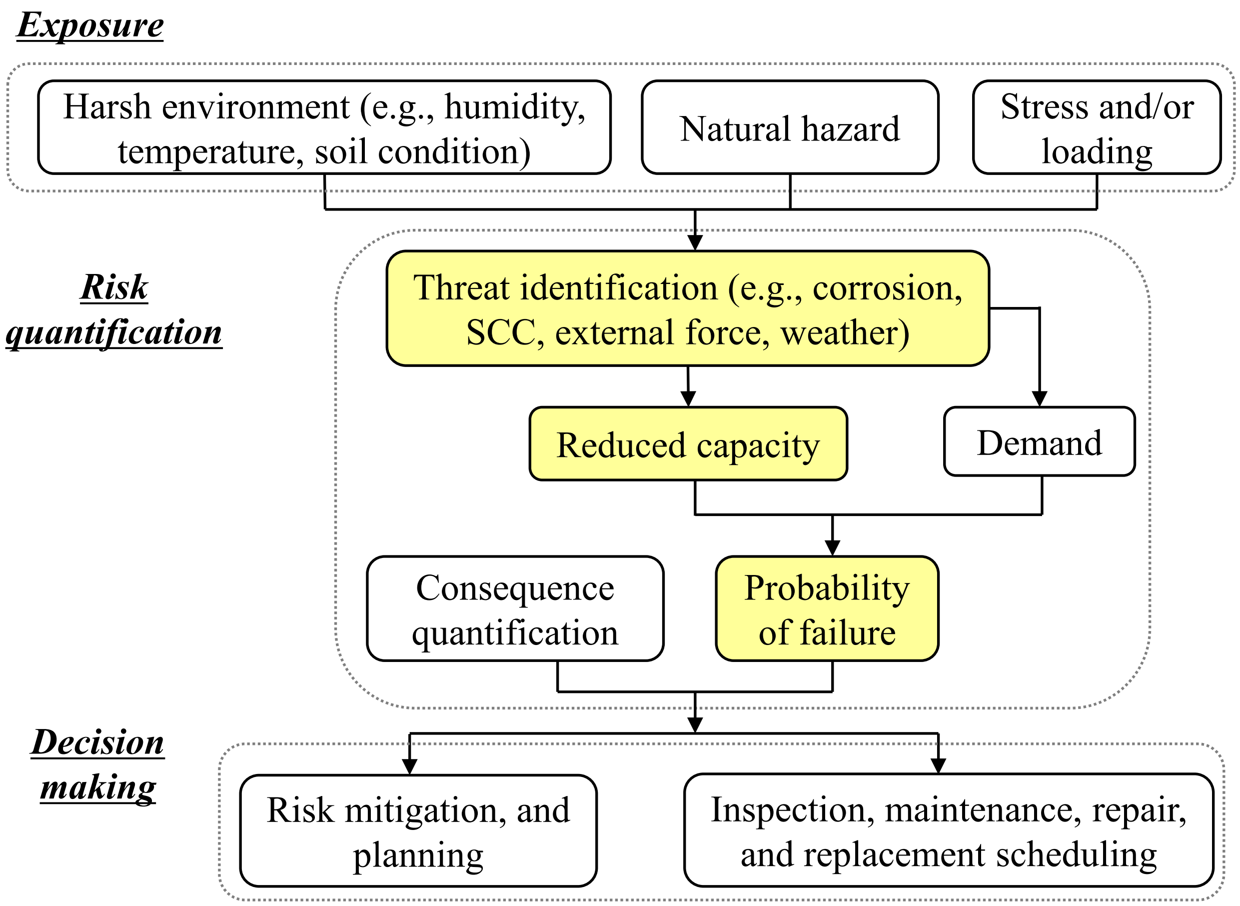
Presentation will start at 12:50pm ET
& be repeated at 1:20pm ET

Background

- Oil and gas pipelines are subjected to various potential threats during their service lives
- Quantitative risk assessment has been often used to evaluate the pipeline integrity considering underlying uncertainties



Goal of the overall project

- Goal: develop probabilistic pipeline performance evaluation framework based on multi-modal NDE under interactive anomalies
- Representative anomalies: isolated & colony defects; corrosion defect & crack-like defect

Task 2 (Michigan State Univ.)

Probabilistic characterization of defect profiles
- NDE system development
- NDE modeling & validation
- NDE data processing

Task 1 (Univ. of Akron)

Generate realistic corrosion & cracking defect profiles
- Laboratory testing
- Electrochemical simulation

Task 3 (Marquette Univ.)

Probabilistic failure pressure prediction models
- Failure pressure database
- Model development (corrosion, crack-type anomalies, interactive anomalies)

Probabilistic time-evolution models for defect profile quantities

Task 4 (Marquette Univ.)

Reliability analysis
- Impact of various physical quantities and uncertainty sources on reliability

Threat identification → Reduced capacity → Probability of failure

Task 3: Development of probabilistic failure pressure models

Technical gap:

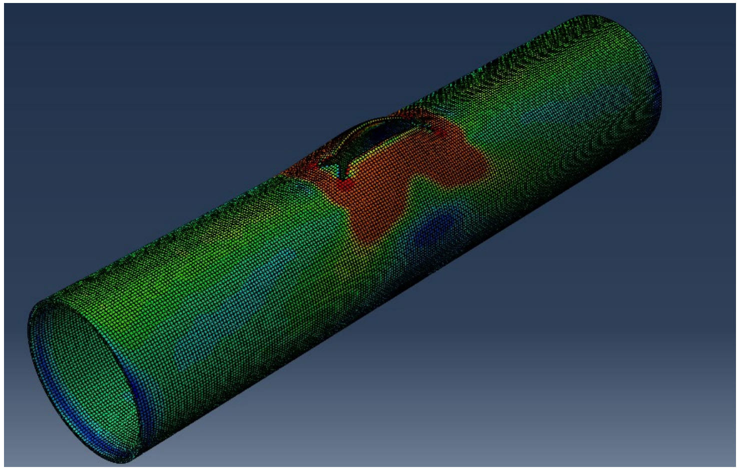
- Many existing models have been developed to predict the failure pressure of a pipeline containing corrosion and crack-like defects, which developed based on factor of safety
- Existing interaction rules have been shown wide variation & are deterministic
- Quantification of all relevant uncertainties

Objective: to develop failure prediction models suitable for risk assessment of pipelines containing the following defects:

- Isolated corrosion defects
- Colony of corrosion defects
- Isolated crack-like defects
- Colony of crack-like defects

Data collection (isolated corrosion defect)

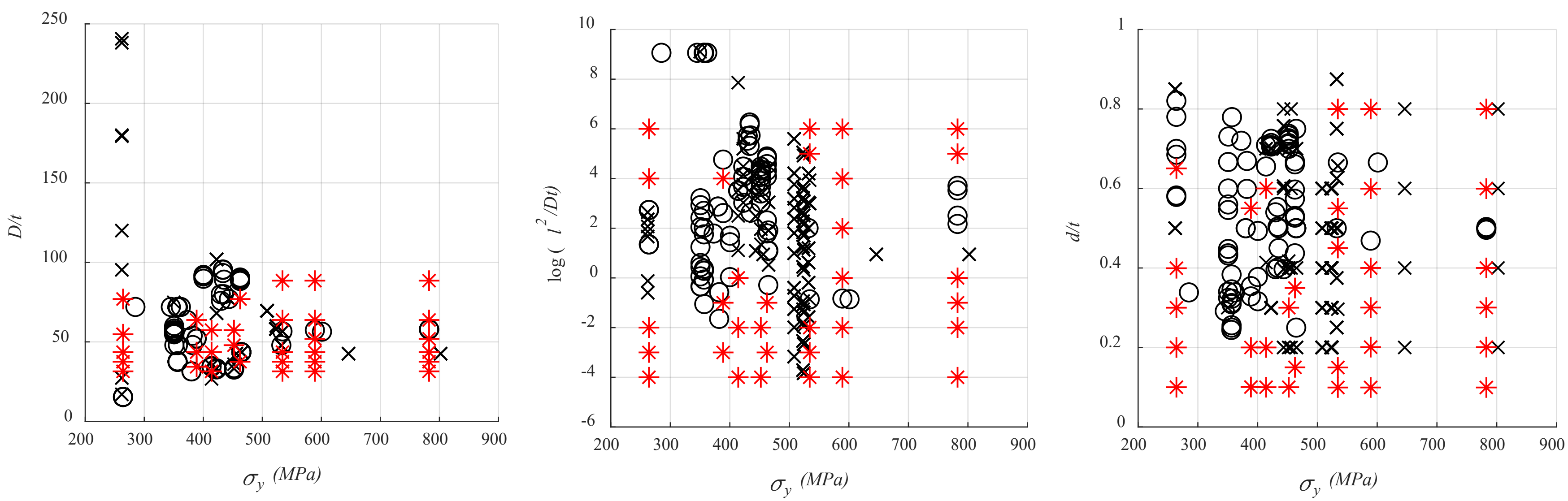
- A total of 401 different burst test results were collected from literature
- Additional data are generated by finite element (FE) analysis



- ✓ Abaqus Statics-General procedure is adopted
- ✓ Von Mises criteria is used to determine the failure pressure
- ✓ Corrosion defect is modeled as a rectangular shape
- ✓ Experimental burst test results from the literature are selected for the model validation

Data collection (isolated corrosion defect)

- A total of 32 additional test results were generated using FE analysis
- The new cases are designed to cover the regions where the data collected from literature is scarce



○ Experimental burst tests from literature
× FE burst tests from literature
* New FEM cases

Proposed prediction model formulation

- The proposed models were developed at three levels of pipe ultimate strength
- For each level, the proposed model follows this formulation:

Deterministic prediction from existing prediction model

$$Y = \theta_0 + \sum_{i=1}^{m} \theta_i \hat{y}_i + \sigma\varepsilon$$

Model error

Predicted failure pressure

Existing prediction models

Group	Model
G1: Models based on NG-18	G1-1: ASME B31G Original
	G1-2: Modified B31G
	G1-3: SHELL92
	G1-4: RPA
	G1-5: RSTRENG Effective Area
	G1-6: CSA Z662
	G1-7: DNV RP-F101
	G1-8: Fitnet FFS
	G1-9: Phan et al Modified NG-18
G2: Models based on Buckingham's π theorem	G2-10: Netto et al.
	G2-11: Mustaffa & van Gelder
	G2-12: Netto et al.
	G2-13: Wang & Zarghamee
	G2-14: Phan et al Modified - Netto et al.
G3: PCORRC models	G3-15: PCORRC
	G3-16: Modified PCORRC
G4: RAM PIPE Requal models	G4-17: Original Ram Pipe Requal
	G4-18: Modified Ram Pipe Requal
G5: Models using strain-hardening	G5-19: Zhu & Leis
	G5-20: Zhu - X65
G6: Other approaches	G6-21: Choi et al.
	G6-22: Chen et al.
	G6-23: CUP
	G6-24: Phan et al. - Modified Gajdoš et al.

Model selection

- Comparison of the best models

Level based on σ_u	Level 1		Level 2		Level 3	
	$392 \leq \sigma_u < 600$ MPa		$600 \leq \sigma_u < 700$ MPa		$700 \leq \sigma_u < 891$ MPa	
Model Size	1	2	1	2	1	2
Existing model selected	G6-24	G4-18, G6-24	G1-5	G1-2, G4-18	G1-3	G1-3, G4-18
σ (MPa)	**1.8442**	**1.8018**	**1.2253**	**1.0682**	**1.5616**	**1.3559**

- The model size describes the complexity of the model
- σ describes the accuracy of the model
- The final models are selected based on the balance between the accuracy and the complexity of the models

Developed models for isolated corrosion defect

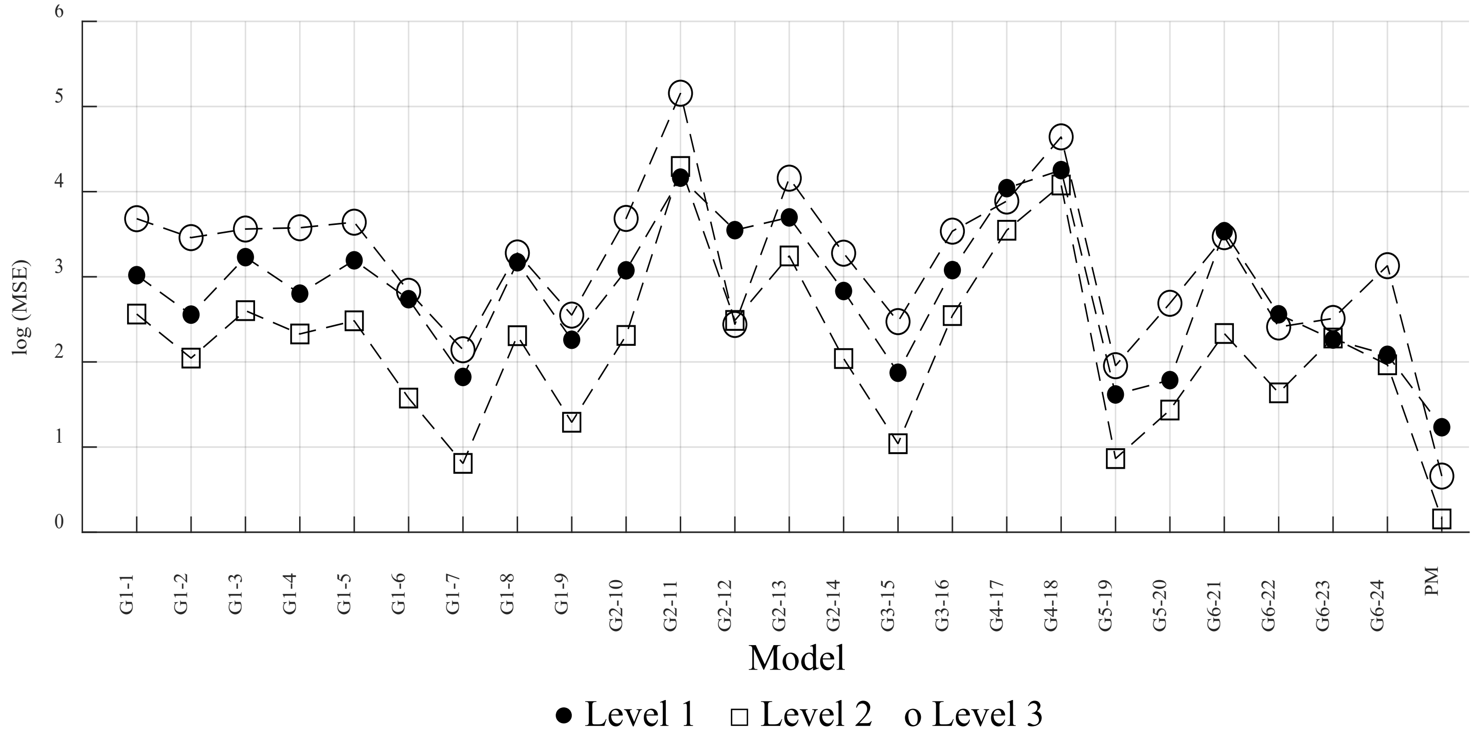
- Final model formula and model parameter statistics

Level based on σ_u	Formula	Model Parameters						
		θ_0		θ_1		θ_2		σ
		Mean	Std	Mean	Std	Mean	Std	
Level 1 $392 \leq \sigma_u < 600$ MPa	$\theta_0 + \theta_1 \hat{y}_{24}$	1.8469	0.3180	1.0281	0.0209	-	-	1.8442
Level 2 $600 \leq \sigma_u < 700$ MPa	$\theta_0 + \theta_1 \hat{y}_2 + \theta_2 \hat{y}_{18}$	-2.3322	0.3774	1.0751	0.0271	0.2978	0.0273	1.0682
Level 3 $700 \leq \sigma_u < 891$ MPa	$\theta_0 + \theta_1 \hat{y}_3 + \theta_2 \hat{y}_{18}$	3.4948	0.6490	0.9381	0.0501	0.2420	0.0518	1.3559

- For level 1:

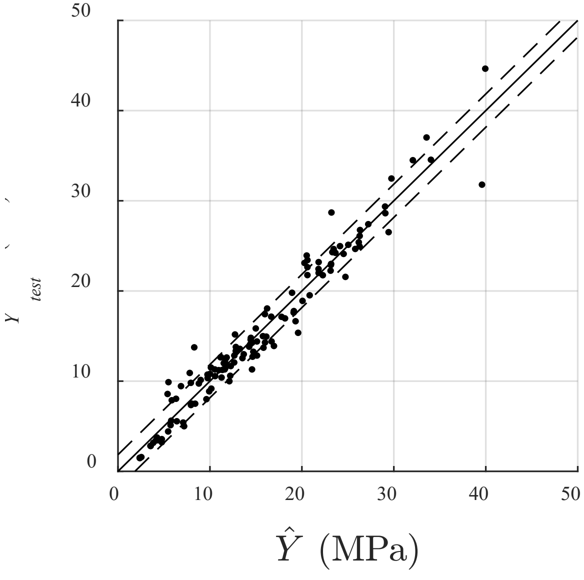
$$P_b = \underbrace{1.8469}_{\theta_0} + \underbrace{1.0281}_{\theta_1} \cdot \underbrace{\frac{2t\sigma_u}{D}\left[1 - \frac{1.24678\left(\frac{d}{t}\right)}{1 + 12.6739\left(\frac{t}{l}\right)}\right]}_{\hat{y}_{24}}$$

Comparison of performance of the proposed models with the existing models for three levels of σ_u

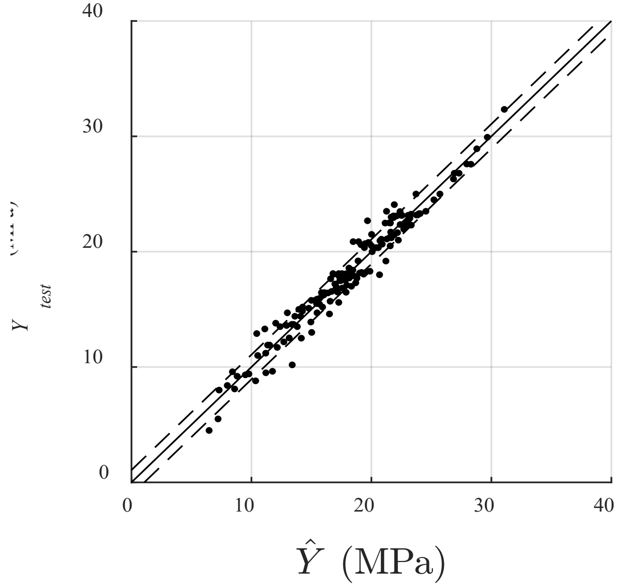


- The mean square error (MSE) measures the combination of the prediction bias and variance
- The proposed models (PM) have the lowest MSE for all the levels of σ_u
- Existing model G5-19 developed by Zhu and Leis has shown to be the best model among the existing models considered for all the levels of σ_u

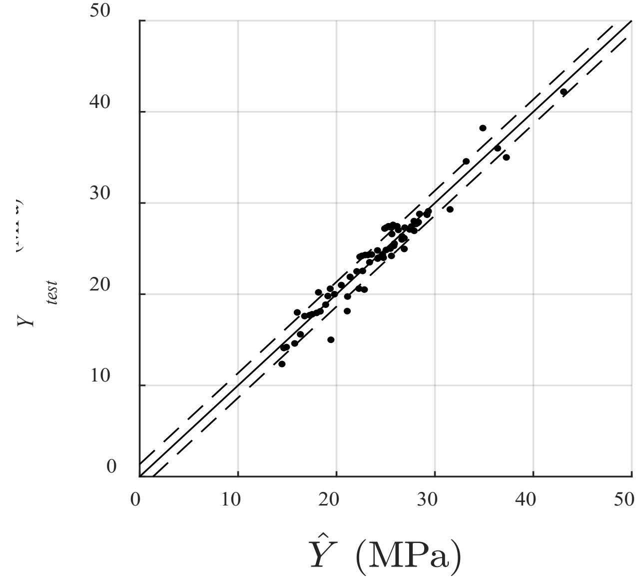
Pressure predicted by the proposed models vs. the observed pressure (80%)



Level 1



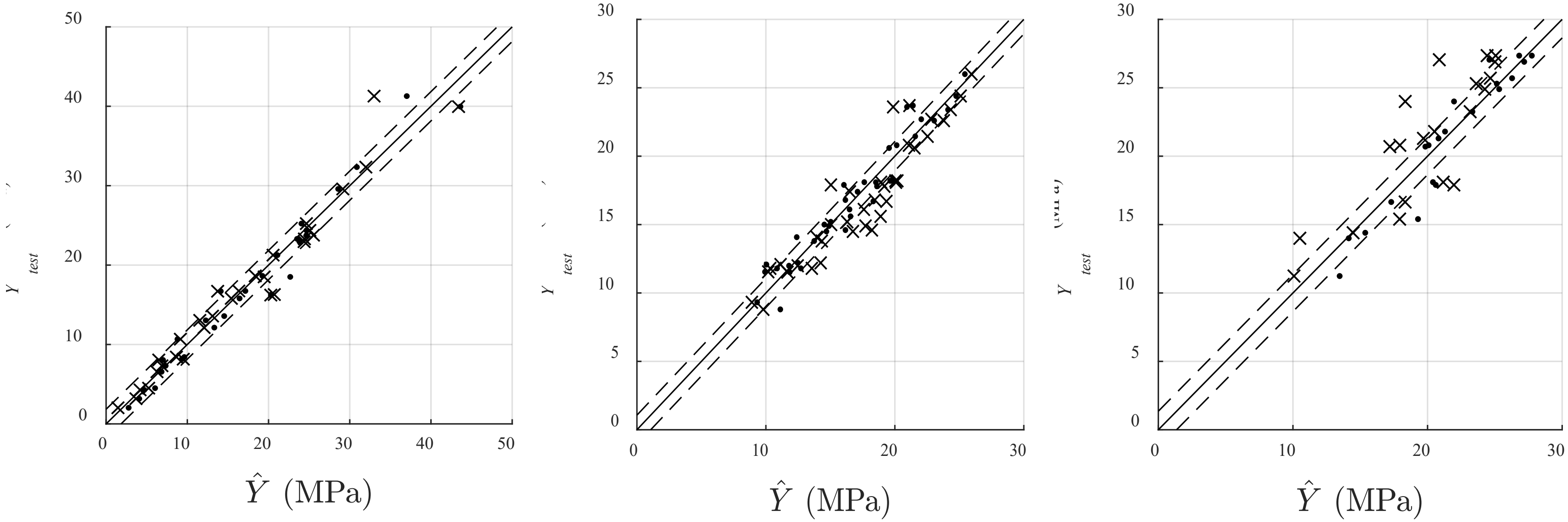
Level 2



Level 3

- If the prediction is perfect, the dots should line up on the 1:1 line
- The smaller the scatter of the dots is, the more accurate the model is
- The proposed models show to be unbiased and accurate, since scatter is small and evenly distributed around 1:1 line

Pressure predicted by the proposed models and best existing model vs. the validation data (20% of data)



Level 1 | Level 2 | Level 3

• Proposed model
x Best existing model

- For each level, most of the proposed model predictions are within the mean ± 1 standard deviation of the model error

- The scatter of the predictions from the best existing model shows only unbiased for Level 1, slightly overestimation for Level 2, and underestimation for Level 3

- The prediction from the best existing model is very similar to the proposed model for Level 1, but the proposed model shows better accuracy for Level 2 and particularly Level 3.

A case study

$$P_f = \int_{g(\boldsymbol{X})\leq 0} f(\mathbf{X})\,d\mathbf{X}$$

P_f: Probability of failure

$f(\mathbf{X})$: Joint probability density function of a vector of random variables, **X**

$$g(\mathbf{X}) = P_b - P_p$$

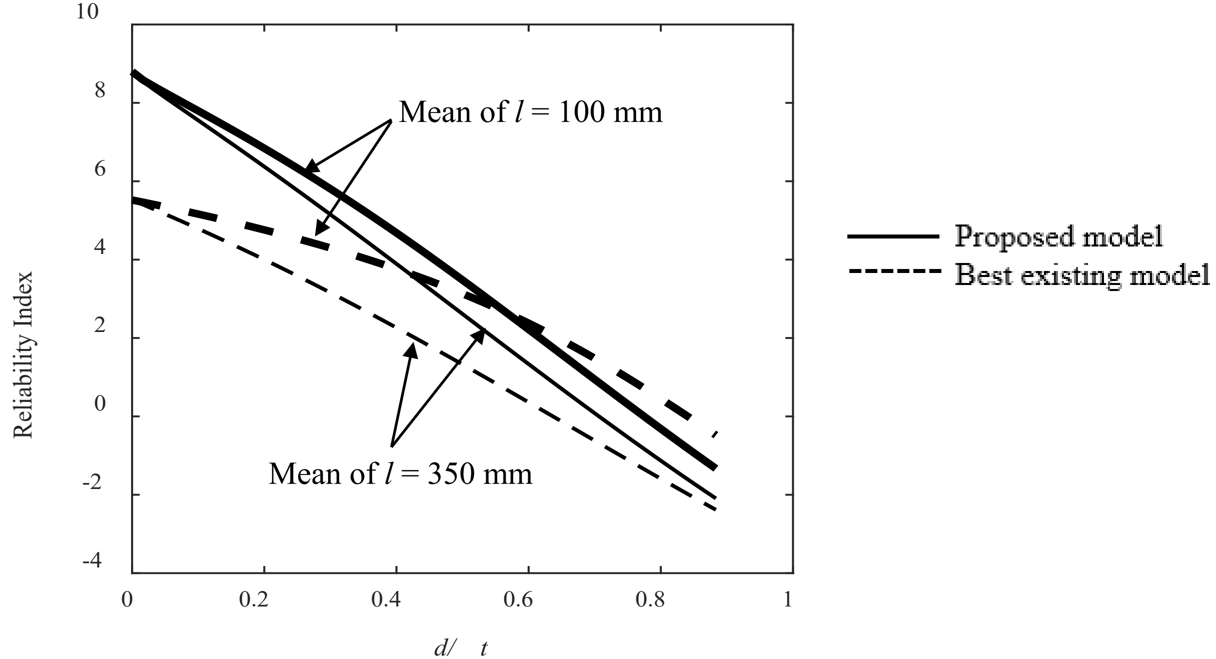
$g(\mathbf{X})$: Limit state function

P_p: Operating pressure of the pipe

P_b: Pressure capacity of the corroded pipe

Distribution parameters of random variables used in the reliability analysis								
Random variable	Distribution	COV (%)	Mean			Standard deviation		
			Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Outside diameter of pipe, *D* (mm)	Normal	5	324			16.2		
Nominal wall thickness, *t* (mm)	Normal	5	6			0.3		
Defect depth, *d* (mm)	Normal	5	-			-		
Defect length, *l* (mm)	Normal	5	100 or 350			5 or 17.5		
Yield strength, σ_y (MPa)	Normal	3	357	534	589	10.71	16.02	17.67
Ultimate strength, σ_u (MPa)	Normal	3	458	661	731	13.74	19.83	21.93
Operating Pressure, P_p (MPa)	Normal	5	7.61	11.39	12.57	0.38	0.57	0.63
Model error in the proposed model (MPa)	Normal	-	0	0	0	1.84	1.07	1.36
Model error in the best existing model (MPa)	Normal	-	0.39	-0.53	0.90	2.23	1.39	2.45

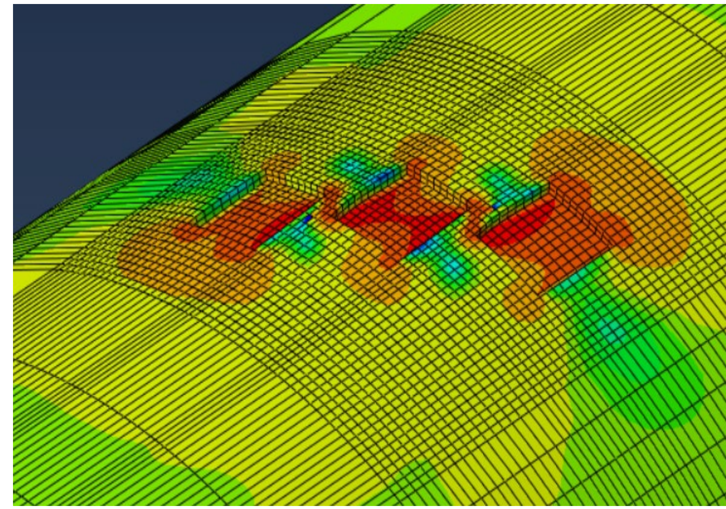
Defect depth-dependent reliability index based on the proposed model and best existing model for level 3

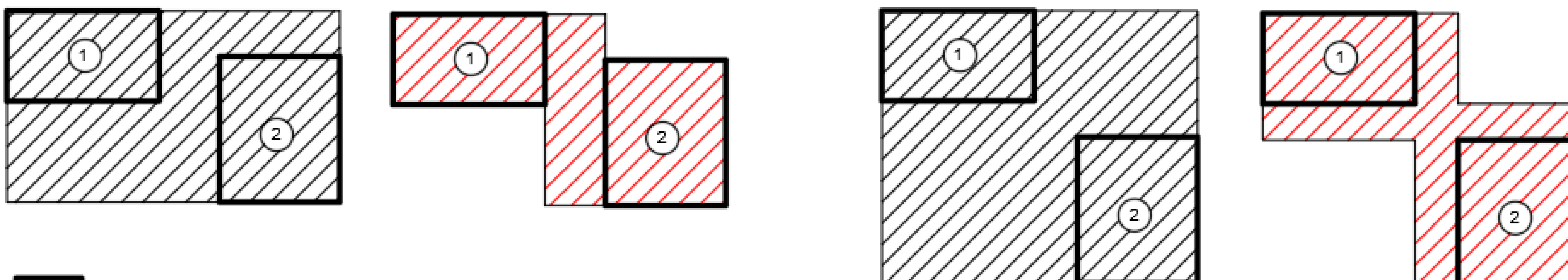


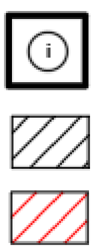
- The reliability index decreases with the increase of the defect depth for a given defect length
- The reliability index is smaller for longer defect length
- The reliability based on the proposed model is higher than the one based on the best existing model, especially for smaller *d*/*t*.

In-Progress: models for colony corrosion defect

- Data collection from literature
- Additional data using FEM with various spacing
- Comparison of existing models (e.g., RSTRENG effective area, DNV RP-F101 for interacting defects, and MTI method)
- A new approach is proposed by modifying the effective area of colony of defects of the best existing model (MTI method)







Defect i, i=1,2

MTI effective area

New approach effective area

In-Progress: models for isolated crack-like defect

- Literature review
- Data collection from literature
- Comparison of existing models (e.g., Ln-Sec equation, API RP 579, BS 7910, and Corlas)

Thank you!

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