CAAP Quarterly Report
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Project Title: Multi-modal NDE Assisted Probabilistic Pipeline Performance Evaluation under Interactive Anomalies

Prepared by: Kiswendsida Jules Kere, Kuan-Chen Huang, Karthik Gopalakrishnan, Vivek Rathod, Qindan Huang, Qixin Zhou, and Yiming Deng

Contact Information: Qindan Huang, qindan.huang@marquette.edu, 414-288-6670
Yiming Deng, dengyimi@egr.msu.edu, 517-884-0926
Qixin Zhou, qzhou@uakron.edu, 330-972-7159

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Business and Activity Section

(a) Contract Activity

The one-year subcontract to Michigan State University (MSU) is ended as planned. New subcontract to Marquette University is proposed in this quarterly period due to PI Dr. Huang's job transition from The University of Akron (UAkron) to Marquette University; and this subcontract is still in the approval process.

(b) Status Update of Past Quarter Activities

In the past quarter, we continued making progress in Task 1, Task 2, and Task 3. In particular, due to COVID-19 the exposure testing in Task 1 had to be paused in the middle of March, and we resumed the testing in early June. For Task 2, we adopted Floquet-Bloch technique to identify dispersion curves of the pipeline. For Task 3, we collected failure pressure data of a pipeline with colony corrosion defects and evaluated the prediction performance of the existing models for a pipeline with colony corrosion defects.

(c) Cost share activity

N/A in this quarterly period.

(d) Technical approach

The goal of this proposed study is to develop probabilistic pipeline performance evaluation framework based on multi-modal NDE assisted by physical and mechanical modeling under interactive anomalies. This study will utilize the experimental testing and numerical analysis to generate more realistic defect shapes and colony profiles, which will be used for characterization and validation of interactive defects non-destructive evaluation (NDE). Meanwhile, the identified defect profile will be used for the probabilistic defect time-evolution model development, which is crucial for reliability evaluation of pipeline performance under interactive defects. In addition, probabilistic models of failure pressure of a pipeline containing corrosion and cracking-like defects will be developed, achieving predictions that are unbiased with reduced variability and considering defect interaction. Specific technical objectives are proposed as follows:

- Generate realistic corrosion and cracking defect profiles through laboratory testing and electrochemical simulation;
- Establish an expanded NDE framework for interactive anomalies by probabilistic characterization of defect profiles;

- Establish a comprehensive failure pressure database including corrosion and cracking defects, and isolated and colony defects;
- Develop probabilistic time-evolution models for defect profile quantities based on NDE defect characterization;
- Develop probabilistic failure pressure prediction models incorporating defect interaction;
- Investigate the impact of various physical quantities and uncertainty sources on pipeline reliability.

To achieve the proposed research objectives described in Section 2, four tasks are developed.

- Task 1. Realistic defect profiles generation using experiments and COMSOL (Drs. Zhou & Deng)
  - Task 1a. Defect configuration in a corrosive environment
  - Task 1b. Defect configuration with cracks in a corrosive environment
- Task 2. NDE framework development and validation for interactive defect detection and state characterization in both lab and field environments (Dr. Deng)
  - Task 2a. Multi-scale and multi-physics modeling
  - Task 2b. NDE system development
  - Task 2c. Multi-modal data processing for interactive anomalies
- Task 3. Probabilistic capacity model development considering interactive anomalies (Dr. Huang)
  - Task 3a. Establishment of a failure pressure database
  - Task 3b. Probabilistic failure pressure model development
- Task 4. Probabilistic model development of anomaly time-evolution and reliability evaluation (Dr. Huang)

1. Task 1: Realistic defect profiles generation using experiments and COMSOL

1.1 Background and Objective in the 5th Quarter

The objective of Task 1 is to generate realistic corrosion profiles through environmental exposure testing. The defect shapes and colony profiles will be used for NDE and for the probabilistic defect time-evolution model development.

1.2 Research Progress in the 5th Quarter

The exposure testing was continued conducting this quarter at UAkron. The testing metal is ground low-carbon steel with a similar composition as the API series pipeline metals. The sample is flat sheet with the size of 3” × 3” × 3/32”. The samples were in the exposure of 5 wt.% NaCl fog in an environmental chamber following the ASTM B117 salt spray testing protocol. At different time points during the exposure testing, one or several samples were removed from the environmental chamber for infinite microscopy characterization.

As previously, five different locations on the testing metal were chosen for the infinite microscopy scanning, which are center, left top, left bottom, right top, and right bottom of the surface. Two quantities can be obtained from the infinite microscopy scanning: the average depth (d_{avg}) and the maximum depth (d_{max}) of the scanning area. To evaluate the depth of the whole surface area, the sample mean and sample standard deviation of d_{avg} and d_{max} from the five scanning locations were calculated and shown in Figure 1. As expected, in general the means of d_{avg} and d_{max} of one sample increase with time during the 16-week exposure time. The increased of d_{max} demonstrate the generation of the corrosion depth under the corrosive environment.

Some duplicated samples were also exposed in the environmental chamber following the ASTM B117 testing protocol, and investigated by infinite microscopy characterization for the average depth and the maximum depth. Figure 2 shows the sample mean and sample standard deviation of d_{avg} and d_{max} of all the exposed samples during the 16 weeks immersion testing. These data will be further analyzed to determine

the sample variation under the same environmental condition.

Some testing samples are also exposed to another corrosive environment per ASTM G85 standard for exposure testing. As the 4-week exposure data has not showed the significant increase in depth in this quarter, the G85 exposure testing results will be presented in the next quarter report.

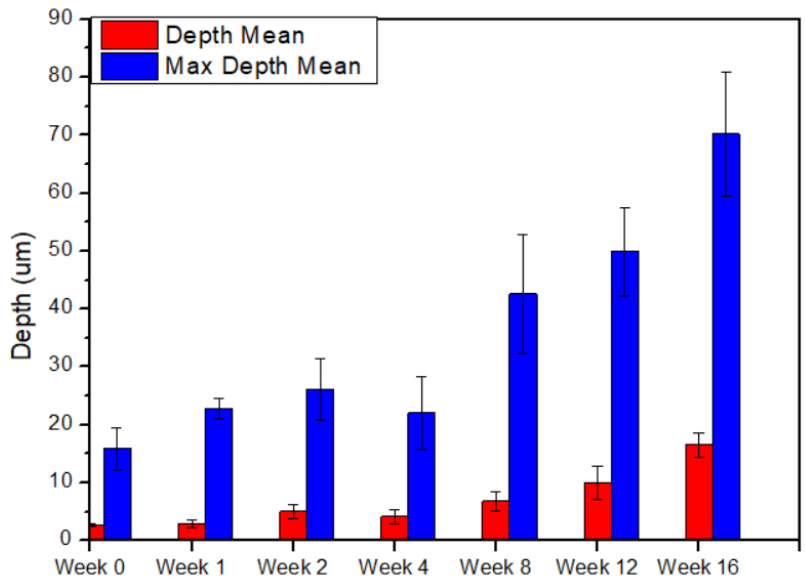


Figure 1. The sample mean and sample standard deviation of the average depth and the maximum depth of the scanning area of one sample during the exposure testing.

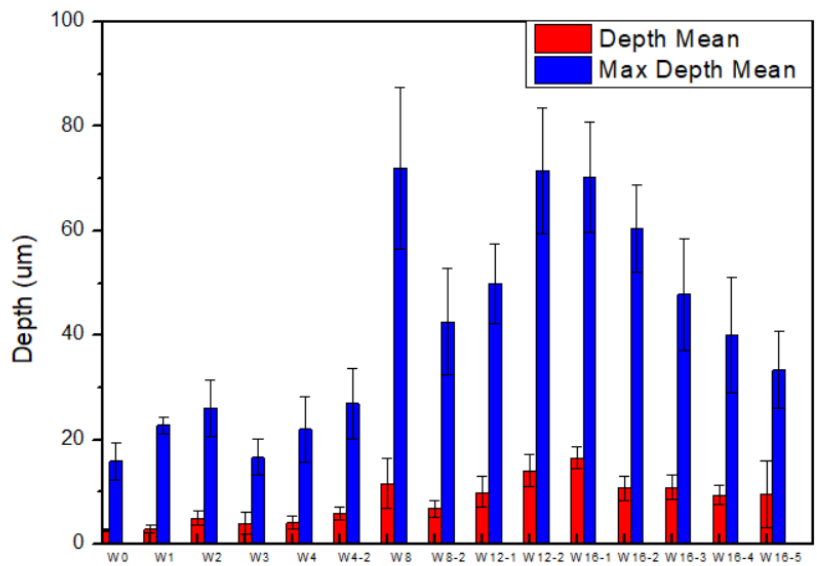


Figure 2. The sample mean and sample standard deviation of the average depth and the maximum depth of the scanning area of all the samples during the exposure testing.

1.3 Future Work (Next Quarter)

The testing samples will keep being exposed to ASTM G85 environment for the next quarter in order to achieve more severe corrosion. One additional set of testing samples will be exposed to ASTM B117 environment. The testing samples after the 16-week B117 exposure testing will be shipped to MSU for the NDE testing.

2. Task 2: NDE framework development and validation for interactive defect detection and state characterization in both lab and field environments

2.1 Background and Objectives in the 5th Quarter

Background

In the earlier report, we adopt Floquet-Bloch (F-B) technique [1] to identify dispersion curves of the pipeline geometry directly. However, the dimension of the pipe used in the simulation was different than the actual dimension of the CAAP samples. Thus, it is necessary to update the simulation with actual dimensions.

Objectives in the 5th Quarter

To objective of Task 2 in this quarter is to update dimensions used in the simulation.

2.2 Research Progress in the 5th Quarter

The outer diameter of the steel pipe is changed from 100mm to 450.7 mm with a wall thickness of 8.1 mm. There are three fundamental modes in the low frequency region (under $f = 50\ KHz$): longitudinal mode 'L0' where the particle movement is primarily in-plane, torsional mode 'T0' (shearing motion), and flexural mode 'F0' where the particle motion is out-of-plane in nature. Figure 3 shows the eigenfrequency analysis results of the pipeline.

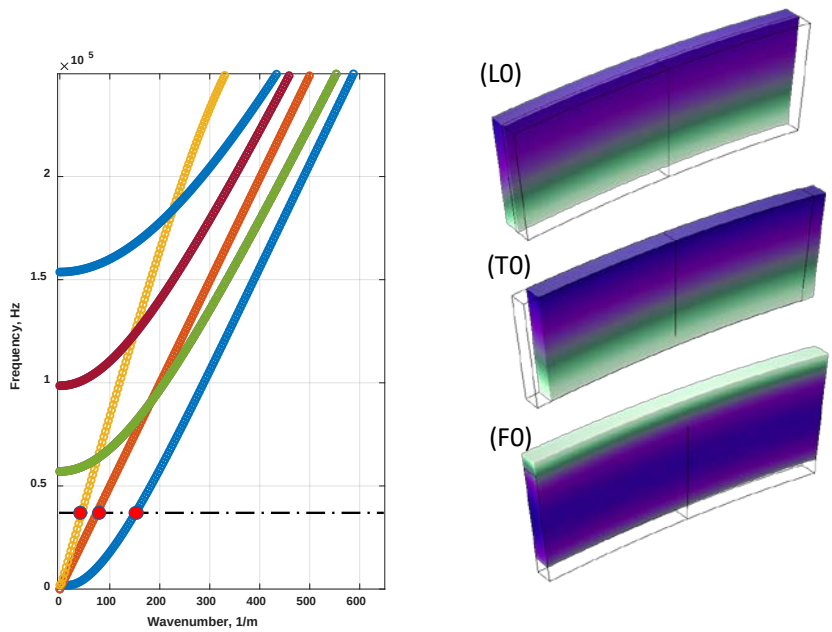


Figure 3. Eigenfrequency analysis of the pipeline: (a) wavenumber versus excitation frequency; (b) mode shapes.

Phase velocity, c_{ph}, and group velocities, c_{gr}, velocities are computed using Eqs. (1) and (2), respectively:

$$c_{ph} = \frac{\omega}{k_x} \tag{1}$$

$$c_{gr} = \frac{{c_{ph}}^2}{c_{ph} - f \cdot a \dfrac{\partial c_{ph}}{\partial (f \cdot a)}} \tag{2}$$

where, $a = \frac{h}{2}$ is the half thickness of the unit cell. The results are demonstrated in Figure 4.

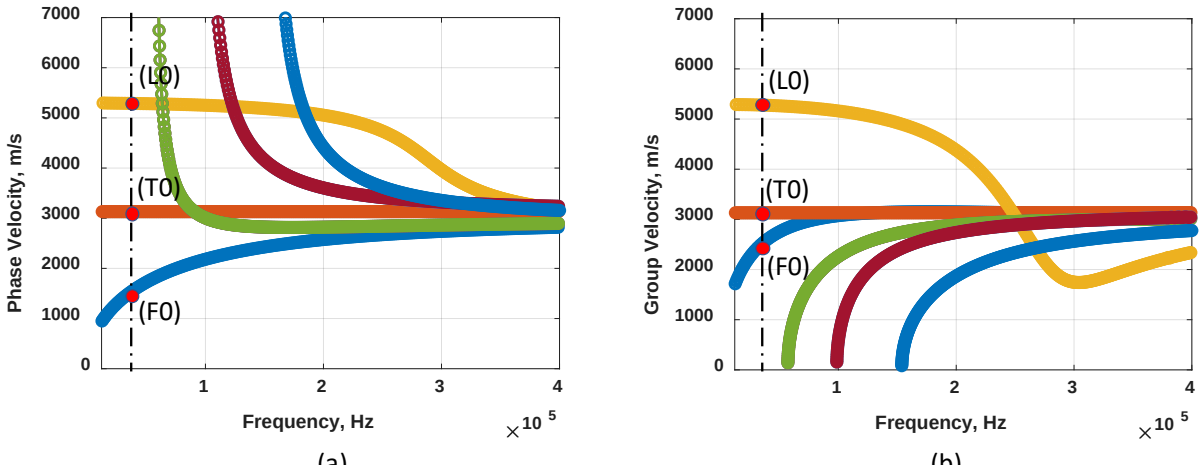


Figure 4. Dispersion curves of a steel pipe: (a) phase velocity; (b) group velocity.

2.3 Conclusions

Based on dispersion analysis of pipe, the fundamental longitudinal mode 'L0' and shear mode 'T0' are optimal for excitation. As shown in Figure 4, both 'L0' and 'T0' modes are largely non-dispersive under 50 kHz, which helps preserve the shape of the excitation signal and simplify the signal processing. In addition, the 'L0' mode is the easiest to identify among the other modes and the reflections in the received signal, as it has the highest group velocity. From the recent dispersion analysis, we now have a better understanding of ultrasound behavior in pipelines.

3. Task 3. Probabilistic capacity model development considering interactive anomalies

3.1 Background and Objectives in the 5th Quarter

Background

The inaccurate prediction of failure pressure capacity is one of the critical issues in risk management of pipeline systems, as it can impede the ability to achieve a target margin of safety. The burst failure mechanisms for corrosion and cracking defects are fundamentally different, and even more complex for interactive anomalies. With corrosion, the burst failure is a ductile failure due to plastic collapse; with cracking defect, the failure includes ductile failure (similar to corrosion) and brittle failure due to fracture. For a colony of closely spaced defects, the residual strength of a pipeline becomes much lower than an isolated defect due to the interaction among the adjacent defects.

The limitations of existing work regarding the failure pressure predictions include the following: (1) numerous models are available, but no model is universally accepted; (2) the majority of the models were developed based on the concept of a factor of safety, thus, these models are deterministic and cannot be directly used in reliability analysis; and (3) numerous studies have shown that these models provide over-conservative predictions for both corrosion and cracking-like defects, and the bias needs to be quantified and corrected. This Task 3 is aimed to address the limitations mentioned above, and it includes two subtasks:

- Task 3a. Establishment of a failure pressure database
- Task 3b. Probabilistic failure pressure model development

Objectives in the 5th Quarter

The overall objective for Task 3a is to establish a database for three groups: isolated and colony of corrosion defects, isolated and colony of crack-like defects, and colony of corrosion and crack-like defects. The overall objective for Task 3b is to develop probabilistic failure pressure models for a pipeline with corrosion anomalies, crack-type anomalies, and interactive anomalies with different types.

The objectives for Task 3 in the 5th quarter are (1) to add new numerical cases of pipeline with colony corrosion defects so that a wider range of pipeline properties are covered and (2) to evaluate the prediction performance of the existing models for pipeline with colony corrosion defects considering the newly added cases.

3.2 Research Progress in the 5th Quarter

Additional Numerical Cases

As mentioned in the 1st annual report, a comprehensive failure pressure data was collected from the literature to develop a robust and accurate assessment method for colony corrosion defects. So far, a total of 202 different burst test results were collected, out of which 25 were from laboratory experimental burst tests and 177 were from FEM simulations. However, in the database collected, there was no data for low grade pipeline (e.g., X42, X46, X52, or X55). Therefore, finite element method (FEM) is conducted to generate additional cases that are not covered in the database collected from the literature. Similar to the pipeline with isolate defects, ABAQUS is used for the numerical analysis based on the FEM. Using some results of laboratory experiment tests from the collected database, the validation of the FEM is done by comparing those laboratory test results with the FEM results.

Results and Discussions

FEM validation and new numerical cases

A few laboratory test results from the collected database are selected for the FEM validation. Tables 1 shows the summary of selected test cases and the burst pressure comparison of the test results and the FEM simulation results. Table 2 shows the defects spacing configuration of the selected test cases. In Table 1, all the selected test cases are grade X80. This is because in the database collected so far, the stress-strain curves required to run the FEM analysis are not available for other material grades.

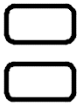
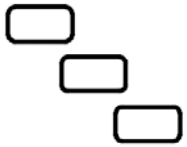
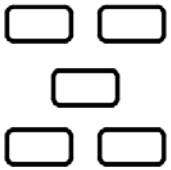
As shown in Table 1, the error percentages between the failure pressures reported in the literature and the failure pressures obtained from the FEMs are all within 10%. Therefore, it is believed the FE models can be used to predict failure pressure for other defect scenarios. In order to cover a wide range of grade in the new numerical cases, the stress-strain curves provided in the collected database with isolated defects are used to generate the FE models with colony defects, since the material stress-strain curves are independent of the defects.

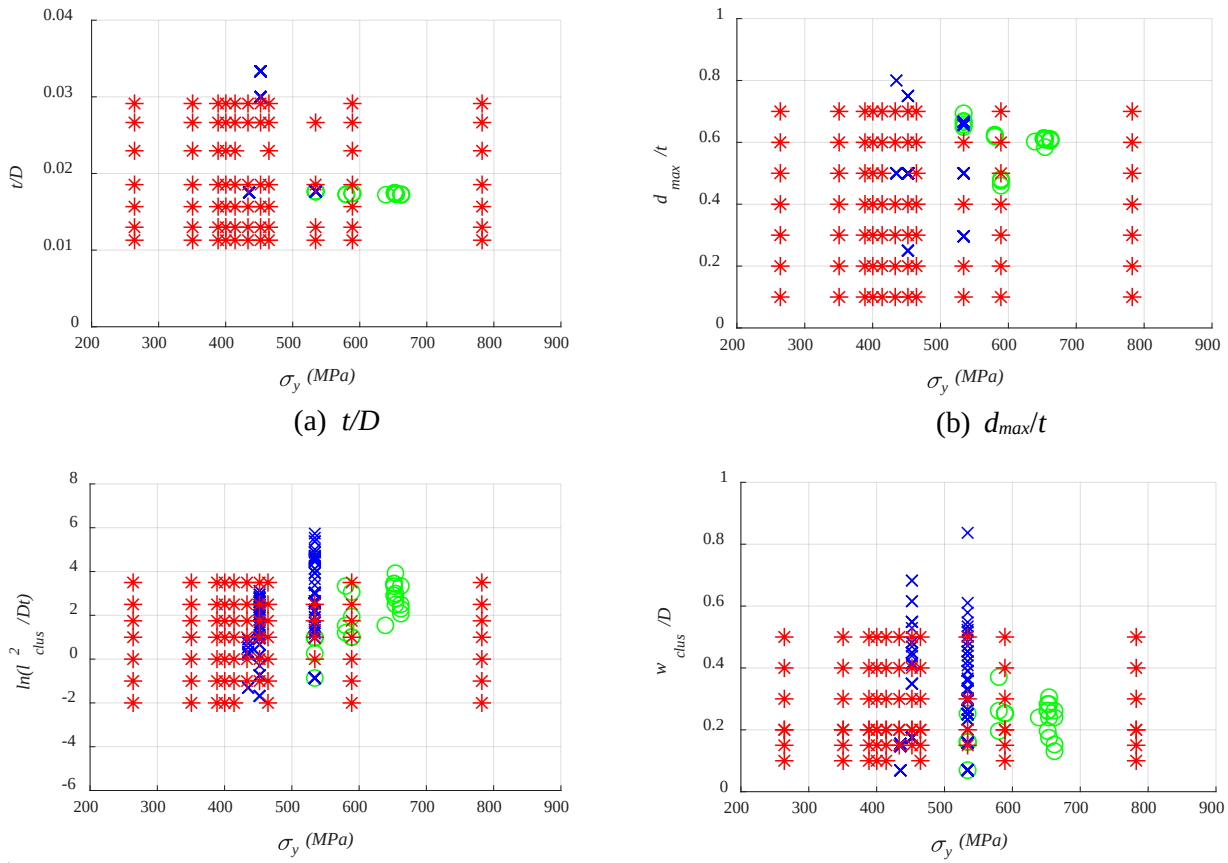
With the validated FE models, a total of 72 new numerical cases are generated and added to the database collected from literature. These new cases are designed to cover a wider range of yield strength (σ_y ranging from 262 MPa to 782 MPa) and four quantities: the ratio of pipe thickness to pipe diameter (t/D), ratio of maximum defect depth within a cluster of defects to pipe thickness (d_{max}/t), ratio of cluster length squared to the multiplication of pipe diameter and thickness (l_{clus}^2/Dt), and ratio of cluster width to pipe diameter (w_{clus}/D). Figure 5 shows the scatter plots of σ_y vs the four quantities for the cases collected from literature and the new FEM cases. As shown in Figure 5, the new cases are designed to cover the regions where the data collected from literature is scarce.

Table 1. Selected cases for FEM simulation and their results

Reference	Grade	Specimen	Pipe diameter D (mm)	Pipe thickness t (mm)	S_y (MPa)	S_u (MPa)	d_{base} (mm)	l_{base} (mm)	w_{base} (mm)	$(S_L)_{main}$ (mm)	$(S_c)_{main}$ (mm)	P_b (MPa)	FEM (MPa)	Error (%)
[2]	X80	IDTS 3	458.8	8.10	534.1	661.4	5.32	39.60	31.90	20.5	-31.9	20.31	20.48	-0.8223
[2]	X80	IDTS 4	458.8	8.10	534.1	661.4	5.62	39.60	32.00	-39.6	9.9	21.14	22.61	-6.9328
[3]	X80	IDTS 9	459.4	8.00	589.0	731.0	3.85	40.05	32.15	-9.88	9.88	23.06	22.97	0.4076
[3]	X80	IDTS 10	459.4	8.00	589.0	731.0	3.81	40.00	32.08	19.98	10.01	23.23	22.97	1.1365

Table 2. Defects spacing configuration

Specimen	Defects Configuration
IDTS 3	
IDTS 4	
IDTS 9	
IDTS 10	



(a) t/D (b) d_{max}/t

(c) $ln(l_{clus}^2/Dt)$ (d) w_{clus}/D

○ Experimental burst tests × Finite element burst tests *New FEM cases

Figure 5. Scatter plots of selected quantities vs. yield stress (σ_y)

Performance comparison of exiting burst pressure prediction models

The 1st annual report provides a review of two levels of existing assessment methods for burst pressure prediction pipelines with a colony of corrosion defects. The prediction performances of these methods were compared based on the collected database from literature in the previous report. With the newly added numerical cases, the prediction performance are compared here again. It is appropriate to compare the existing models at different levels of yield strength since some of the existing models were developed for a certain level of yield strength. The three levels of yield strength used in the 3rd Quarterly Report is used here to compare the performance of the existing prediction models: Level 1 – low strength (σ_y = [262 433] MPa), Level 2 – moderate strength (σ_y = (433 508] MPa), and Level 3 – high strength (σ_y = (508 802] MPa). Note that in the 1st annual report, the comparison is only done for Levels 2 and 3, because of a lack of data for Level 1 in the collected database from literature. In this present report, the comparison is done for all the three levels since the newly added numerical data cover all three levels.

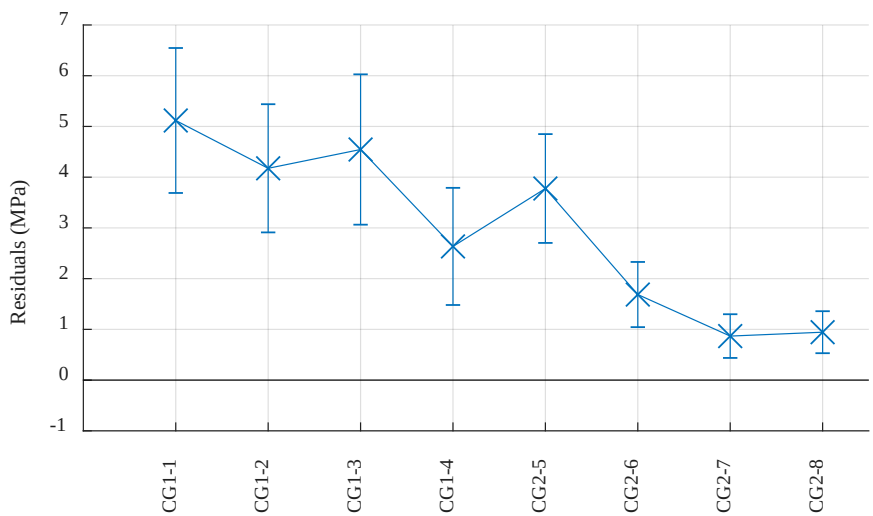
Using the prediction residuals between the actual pressure and prediction (i.e., $P_{act} - P_{pred}$), the performance of a prediction model can be quantified using mean (μ_{res}) and standard deviation (σ_{res}) of the residuals and mean squared error (MSE). All the existing models except the DNV RP-F101 method for interacting defects (referring as *CG2-P6*) for interacting defects are applicable to all the available data, a total of 274 sets of data consists of 72 newly added numerical cases and 202 cases collected from literature.

The DNV RP-F101 method for interacting defects (*CG2-P6*) is only applicable to 149 data in which the

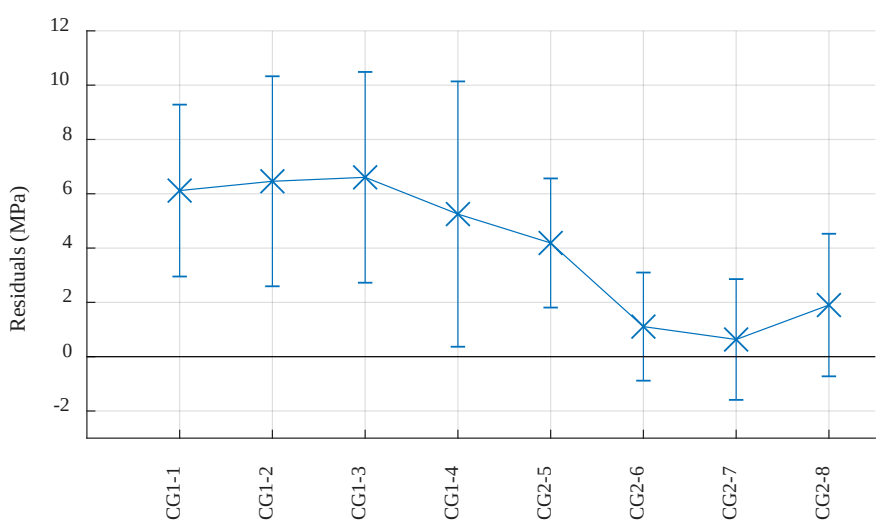
individual defect profiles do not overlap projecting onto the longitudinal plane. Therefore, the model performance comparison is done using two separate data sets: 1st data set refers to the 149 data sets and 2nd data set refers to all the data (i.e., 274 data sets). The results based on these two datasets are shown in Figures 6 and 7, respectively. Thus, in Figure 3, *CG2-P6* model is not included. In both figures the crosses refer to μ_{res}, the horizontal lines refer to $\mu_{\text{res}} \pm \sigma_{res}$, and solid dots are the MSE values.

As shown in Figure 6, all the 8 models (except *CG2-7* for σ_y Level 3) underestimate the failure pressure, resulting in positive μ_{res}. Also, overall the same model performs similarly for all three levels of yielding strength. Figure 6 clearly indicates that the Group 2 methods perform better than the Group 1 methods as the Group 2 methods result in lower values of μ_{res}, σ_{res} and MSE. This shows that assessment methods that use defect depth profile and consider all combinations of adjacent defects give better failure prediction than using interaction rules. In addition, the MTI method (*CG2-P7*) has the lest bias and performs the best for the 1st data set.

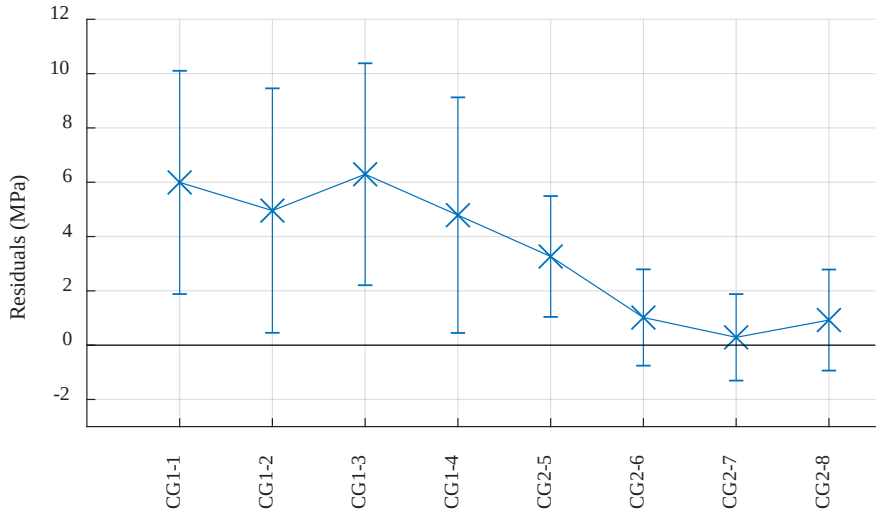
When using the 2nd dataset, Figure 7 compares 7 models' performance and the DNV RP-F101 method (*CG2-P6*) is not included in the comparison. All the models except *CG2-P7* for Level 3 underestimate the failure pressure. Similar to the results in Figure 6 the Group 2 methods have better performance, and the MTI method (C*G2-P7*) have the lest bias and performs the best for the 2nd data set.



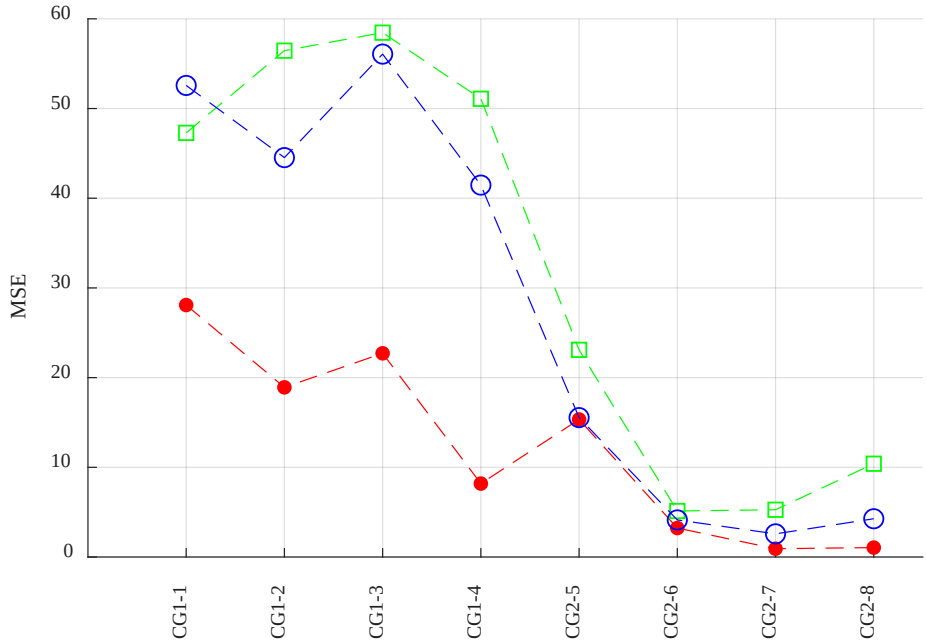
(a) σ_y – Level 1



(b) σ_y – Level 2



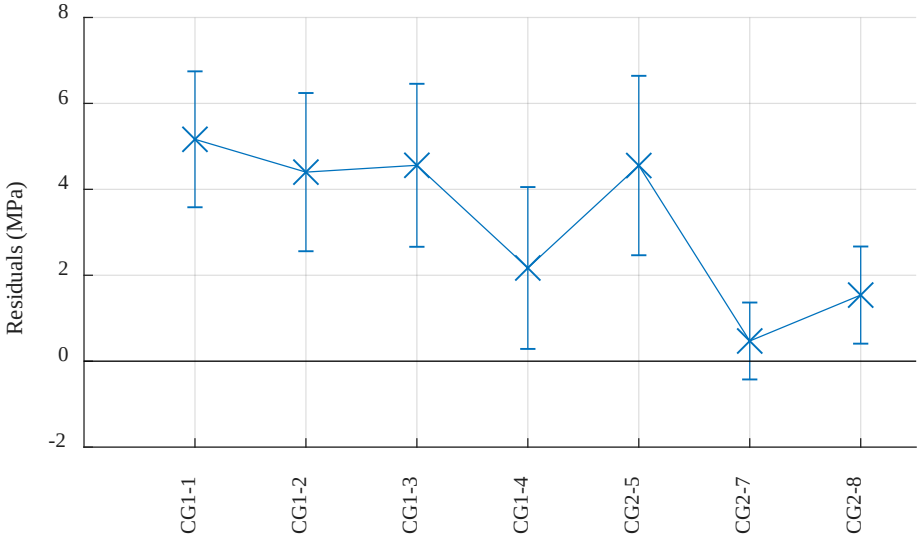
(c) σ_y – Level 3



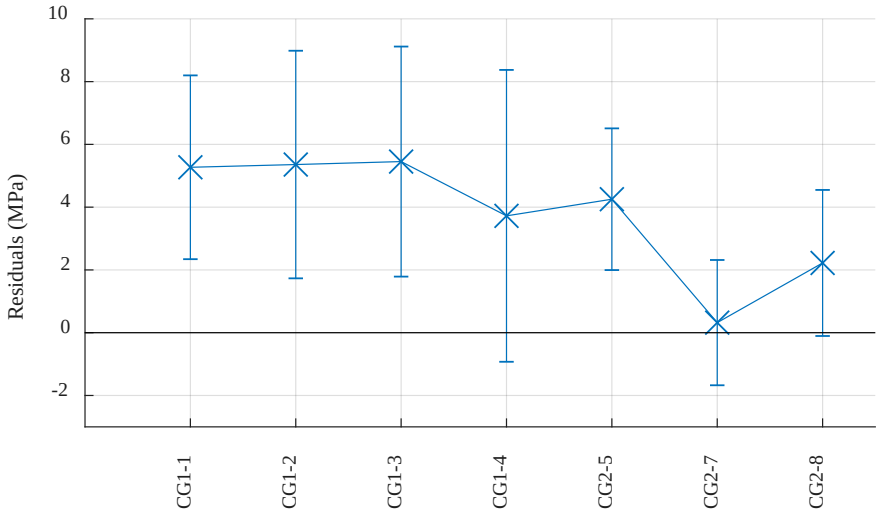
(d) σ_y – All Levels

● Level 1 □ Level 2 ○ Level 3

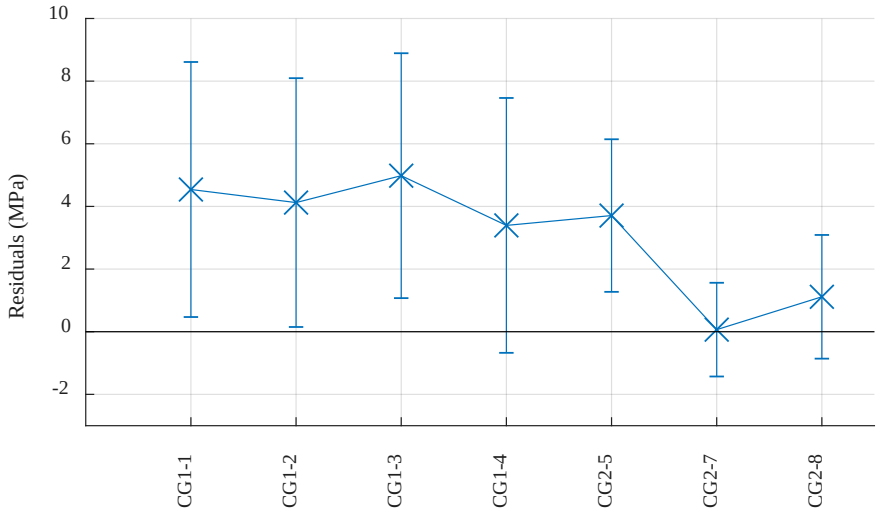
Figure 6. Comparison of model prediction performance for two levels of σ_y based on the 1st data set



(a) σ_y – Level 1



(b) σ_y – Level 2



(c) σ_y – Level 3

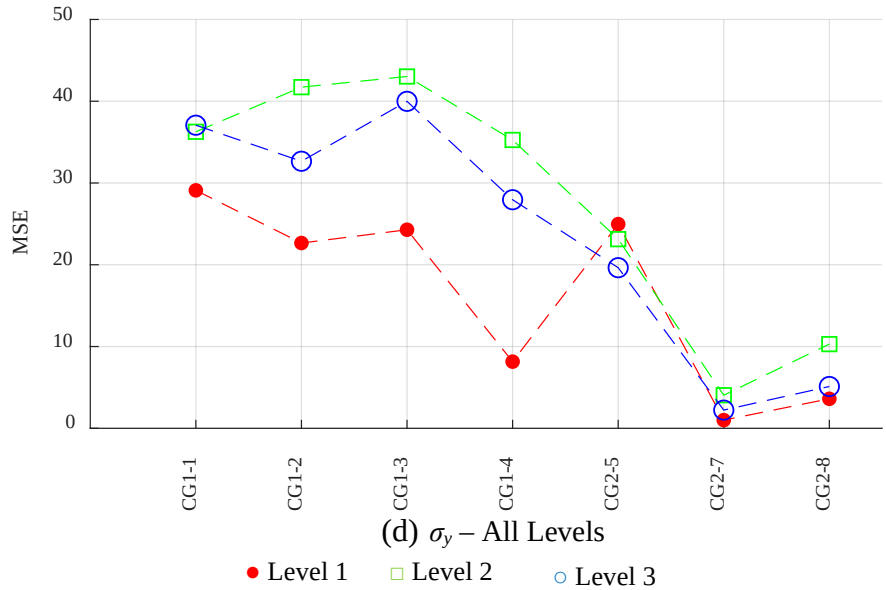


Figure 7. Comparison of model prediction performance for two levels of σ_y based on the 2nd data set

3.3 Future Work (Next Quarter)

In the next Quarter, the research team will continue working on Task 3. In Task 3a, so far we have colony defect database from literature review and also newly added numerical cases and CG2-7 is found to be a good existing model. More numerical cases may be generated while we work on Task 3b. In Task 3b, we will explore the possibility to improve the existing model prediction and add the model error to the improved model.

References

[1] P. Gómez García and J.-P. Fernández-Álvarez, “Floquet-Bloch theory and its application to the dispersion curves of nonperiodic layered systems,” *Mathematical Problems in Engineering*, vol. 2015, 2015

[2] E. Q. De Andrade, A. C. Benjamin, R. D. Vieira, P. R. S. Machado Jr., L. C. Pereira, B. P. Jacob, E. G. C., Joao N. C. Guerreiro, R. C. C. Silva, and D. B. Noronha Jr. “Finite element modeling of the failure behavior of pipelines containing interacting corrosion defects,” in *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, 2006, doi: 10.1115/OMAE2006-92600

[3] A. C. Benjamin, J. L. F. Freire, R. D. Vieira, and E. Q. De Andrade, “Burst Tests on Pipeline Containing Closely Spaced Corrosion Defects,” in *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, 2006, doi: 10.1115/OMAE2006-92131