CAAP Quarterly Report

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Project Title: Fundamental Understanding of Pipeline Material Degradation under Interactive Threats of Dents and Corrosion

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Business and Activity Section

(a) Generated Commitments – Beyond the sever limitation of COVID-19 pandemic; the research team has strived to continue the project progress. A request of no cost extension will be requested from the CAAP program to carry out all conducted tasks.

(b) Status Update of Past Quarter Activities - The main objective of the proposed work is to enrich the knowledge base for evaluating interactive threats of external mechanical dents and secondary features, through integrated lab-scale experimental and numerical framework to characterize and better predict the remaining safe life and operating pressures, while projecting the needs for mitigation measures.

The proposed experimental-computational framework will address the interacting threats of external mechanical damage, coupled with secondary feature as corrosion or cracking on the integrity management decision. The proposed methodologies utilize: (i) A high throughput lab-scale testing apparatus for simulating the combined threats of external damage induced plastic deformation combined with exposure to corrosion, (ii) A lab-scale experiments to assess the synergistic interaction between different threats and their effects on strength and toughness of corrosion degraded pipeline steel, (iii) Utilization of electrochemical impedance spectroscopy (EIS) as a path way for ILI-implementation to characterize the severity of the corrosion near an external mechanical damage, (iv) A detailed FEM analysis of the different geometric constraints on the variance of local stress and strain state (concentration), and (v) Systematic numerical sensitivity analysis in FEM to quantify metrics for material strength and toughness degradation

with corrosion and under the interacting threats of external mechanical damage, and stochastic interpretation of the variation in reported full scale fatigue testing of dents (PRCI MD 4-2, 4-9).

The main activity during this period focused on tensile-testing for prestrain effect on the corrosion and further calibration of the modeling and simulation framework.

1. Task-2: Conducting laboratory tests to examine the role of residual stresses on electrochemical induced corrosion.
2. Task-4: Developed of the simulation framework within Abaqus finite element simulation package to simulate the combined threat of dents and corrosion on the fatigue life response of pipelines.

(c) Details of the Tasks:

C.1 Task 2- Lab-scale investigation of dent-corrosion interactive threats (Month1-18)

This is an extended task to reveal the role of over-stressing by external mechanical damage (dent or gouge), to lower the threshold stress for crack initiation below the mean operating stress. The main aspect of this work is to (i) study the role of initial corrosion on lowering the residual strength of the pipeline (measured in terms of strength and toughness), and (ii) study the effect of pre-stress on the initiation and progression of the corrosion process (measured in terms of total corrosion charges, and depth and morphology –grooving and subsurface cracks- of the corroded surface).

We have developed a moisturized sample in the last quarter to be used for tensile testing and provide uniform strain within the gage section. The dog-bone sample configuration is optimized by finite element analysis to ensure gradual transition of stress within the gripping shoulder. Tensile testing were conducted on a computer controlled Instron (5960) frame with displacement rate of 33.34μm/s. The test was conducted under strain control utilizing noncontact video extensometer for automated strain recording and control of the strain rate. The utilized micro tensile sample and the loading fixtures are shown in Fig.1.

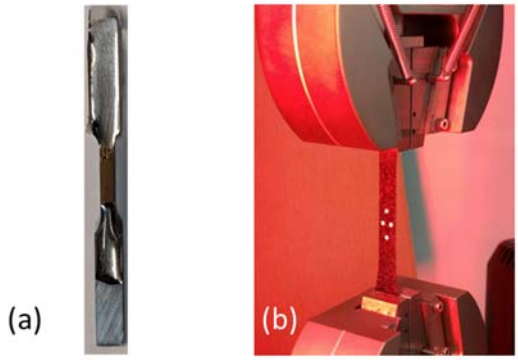

Figure 1: (a) Miniaturized test sample with a well-defined window for corrosion, by epoxy coating. (b) Tensile wasted sample tested with noncontact video extensometer for automated strain recording and control strain rate.

A set of tensile samples of X-70 pipeline steel were tested under displacement control to a predetermined engineering strain of 0.5, 1, 2.5%. The chosen strain range represents atypical residual plastic strain level found within the dent shoulder and apex of a dented pipe. Summary of the recorded stress-strain curves for the examined set of samples are shown in Fig. 1. For the tested set, the stress-strain curves are remarkable repeatable with will identified yield stress of 600MPa and consistent level of post-yield hardening characteristics.

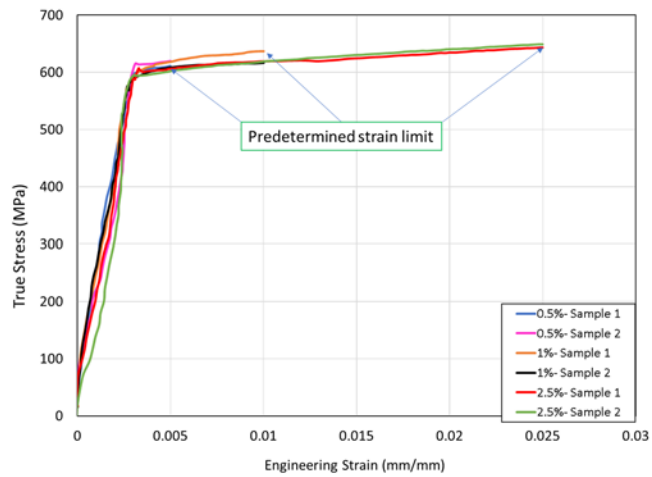

Figure 2: Tensile stress-strain results for predetermined strain levels of 0.5, 1.0 and 2.5%, representing the residual plastic strain level within a shallow dent.

A supporting epoxy holder is developed to support the sample under the electrochemical cell with well the defined area for corrosion. The electrochemical cell exposure window is selected to induce corrosion within the uniform stress region of the sample as shown in Fig. 3. The fixture provided the ability to expose the entire gage length of the sample and thereby provides a large area for exposure to the edge of the samples as well as the ability to test the sample again to failure.

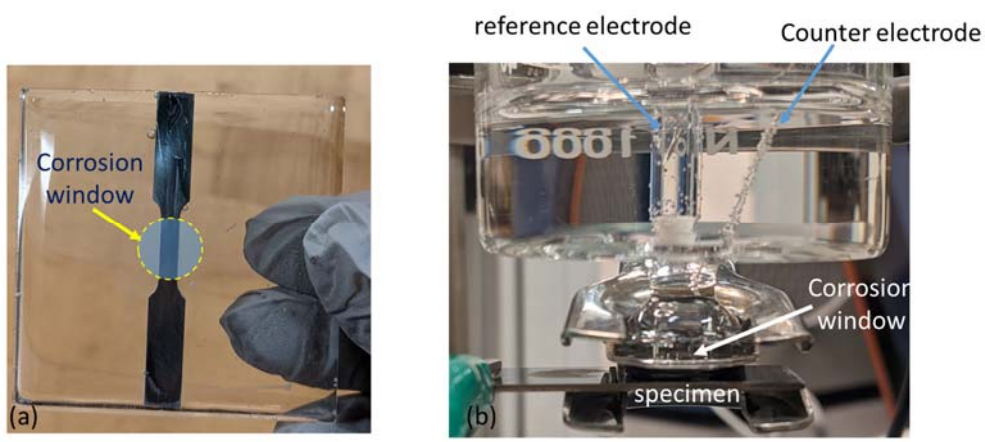

Figure 3: Epoxy fixture to support the tensile sample underneath the electrochemical cell. The marked corrosion window is located within the uniform tensile strain range within the sample. (b) Electrochemical cell with the epoxy holder supporting the sample for the electrochemical experiment.

The combined set of tests of prestrain, then electrochemical exposure will enable the examination of our hypothesis that the increase of dislocation density due to residual plastic strain within the dent area will accelerate the corrosion rate. Moreover, the post exposure test will identify the total strain to failure after exposure and there by setting the ductility limit of the material.

All corrosion experiment were carried out in a high pH electrolyte solution of 1 M NaHCO3 with pH 8.1-8.2 and applied potential in the range of -0.4 to -0.6V relative to vs. Ag/AgCl. First, we performed repeatability study to narrow down the range of susceptibility to stress-corrosion cracking. We have performed current-voltage sweep curve and identified the applied potential in the range of -0.4 to -0.6V relative to vs. Ag/AgCl to be the critical range, as shown in Fig. 4. Second, we performed multiple repeatability test in the range of 25%, 50% and 70% of the peak. This is identified as the distance between the peak and valley within the range of -0.4 to -0.6V, and then identify the percentage shift from the peak. The multiple exposure results are shown in Fig. 5. We have identified that the range of 25-505 of the peak to be the most sensitive domain for SSC and to be used in all our testing.

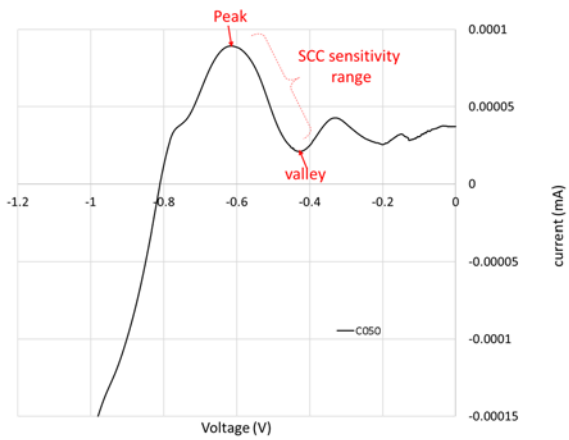

Figure 4: Current-voltage polarization curve to identify the SSC sensitivity range.

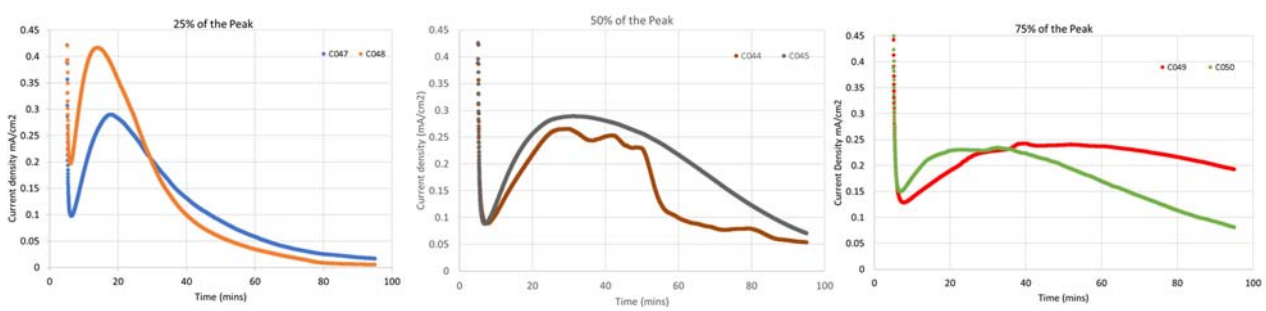

Figure 5: Current-time traces showing the peak current at different applied voltage, as measured by percentage from the peak traces Epoxy fixture to support the tensile sample underneath the electrochemical cell. The marked corrosion window is located within the uniform tensile strain range within the sample. (b) Electrochemical cell with the epoxy holder supporting the sample for the electrochemical experiment.

C.2 Task 4- Experimentally calibrated numerical framework (Month12-36)
In this quarter, we continued the finite element analysis (FEA) to investigate the combined effect of plain dents and corrosion on the fatigue life of pipelines. We continued with the same geometrical model created in the previous quarter to identify the critical residual plastic stain level, corresponding to each indentation depth, and thereby calibrate the required prestrain of our tensile samples. For such calibration, the pipe was indented using a spherical rigid indenter to create a defect (plain dent) on the body of the pipe, as shown in Fig. 6. We have identified correlation between the R/D ratio (indenter radius to pipe diameter ratio), and the d/D ratio, (plain dent diameter to pipe diameter ratio) and the resulting peak plastic strain within the dent base and the dent shoulder.

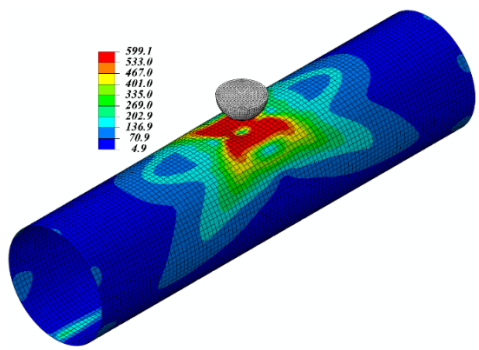

Figure 6: Contours of Von-Mises stress (MPa) for undamaged pipe

(d) Planned Activities for the Next Quarter – As the COVID-19 still hanging over our shoulders. the progress in the next quarter will be tied to the level of access to different laboratory and testing facilities. Though, the focus of the next phase of work will be on conducting additional testing of coupled stress-corrosion cycles to identify the deformation mechanisms responsible for the mechanical degradation of strength and toughness of pipeline steels. In particular we will continue to carry out:

1. Preloading of set of samples to various plastic strains ranging between 0.5 to 5%.
2. Perform electrochemical corrosion experiments on these samples and observe the subtle changes in the current-voltage characteristics as well as the corrosion morphology
3. Perform a tensile stress test to failure to characterize the remaining strength of the samples.
4. Continue the development of the FEA modeling framework.

These measurements would provide some of the material parameters for the numerical framework