CAAP Quarterly Report

01/08/2024

Project Name: Development of Compatibility Assessment Model for Existing Pipelines for Handling Hydrogen-Containing Natural Gas

Contract Number: 693JK32250004CAAP

Prime University:

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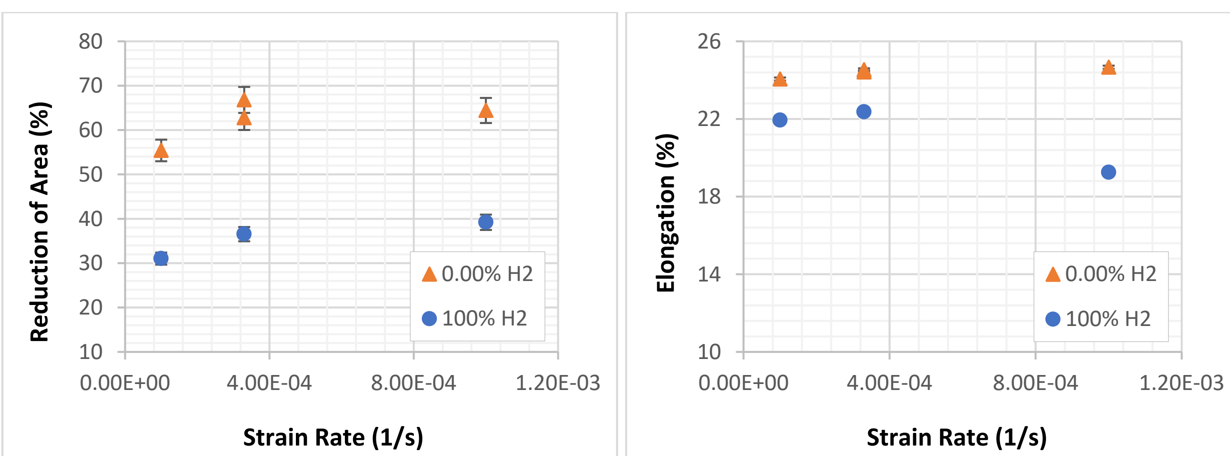
Reporting Period: 09/30/2023 – 12/29/2023

Project Activities for Reporting Period:

Members of the project team continued to maintain the master database to ensure that it contains the most recently measured hydrogen embrittlement data (HE) of carbon steel for pipeline applications (Task 1). As part of the database's ongoing maintenance, periodic data cleaning has been performed to detect and correct inaccuracies and inconsistencies. In addition, the team completed modifying experimental facilities (Task 2.1) and conducted laboratory experiments to determine how HE influences pipeline steel tensile behavior (Task 2.2). We have gathered experimental data sets showing necking behavior of carbon steel including reduction of area and maximum elongation before failure. We have examined the effects of strain rate and gas composition on these tensile characteristics (Fig. 1). Experiments were carried out maintaining negligible amount of oxygen in the system (less than 5 ppm). Final preparations have been made to study the impact of HE on pipeline steel fracture behavior (Task 2.3). We have developed and tested the clip gauges needed for the study. Gauges are made of special strain gauges that are compatible with hydrogen environments and are expected to function without performance loss for an extended period of time.



(a) **(b)**

Fig. 1: Effects of H2 on reduction of area and elongation of pipeline carbon steel X52

Data scarcity is a significant impediment to machine learning-based HE modeling in natural gas pipelines. To solve this problem, we have developed a data integration approach that combines data from one set of mechanical tests with data from other relevant mechanical experiments to predict the impact of HE on metal strength performance. Hence, our team is diligently working to establish data analytics-based (DAB) models for main and intermediate outputs. Models previously developed for forecasting intermediate outputs (Task 3.1) are being used to improve the predictions of a main output models (Task 3.2) that predicts fatigue and fracture characteristics of carbon steels. The main output model for forecasting fatigue characteristics has been completed, and the results are summarized in Appendix A.

During this reporting period, one article was published in the Journal of Engineering Failure Analysis. The paper presents results of data analysis and the development and testing of machine learning algorithms to predict necking behavior of carbon steels in hydrogen environments. The final version of the article is uploaded as a journal publication. Also, the team prepared and presented two posters at the PHMSA's 2023 R&D Forum held at the Westin Crystal City from October 31 to November 1, 2023.

Project Financial Activities Incurred during the Reporting Period:

Table 1 presents expenses during the reporting period in each budget category.

Table 1: Quarterly expense breakdown

Budget Category	DOT-PHMSA	OU Cost Share	Total
Salaries and Wages	$26,480	$0	$26,480
Fringe Benefits	$5,909	$0	$5,909
Equipment	$36,994	$0	$36,994
Travel	$2,118	$0	$2,118
Materials and Supplies	$40,107	$0	$40,107
Tuition	$8,267	$0	$8,267
Indirect Costs	$41,038	$0	$41,038
Total	**$160,914**	**$0**	**$160,914**

Note: Actual expenses may differ slightly from those presented in this table.

Project Activities with Cost Share Partners:

No cost share is reported during this period.

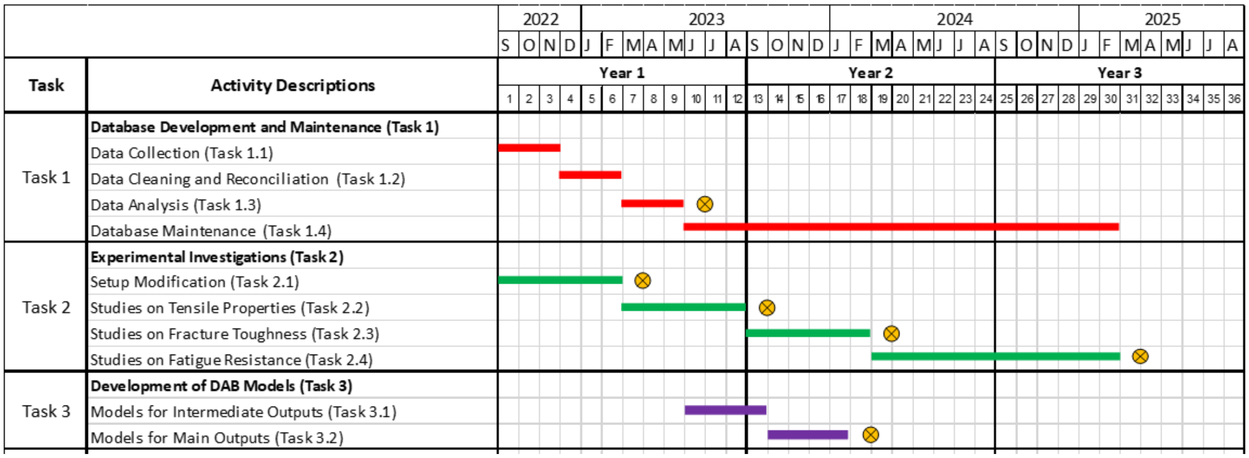
Project Activities with External Partners:

Not applicable.

Potential Project Risks:

We will compensate for the delay caused by autoclave manufacturing by conducting parallel experimental studies (Tasks 2.2 and 2.3). Hence, the delay is not expected to impact the overall project schedule (**Table 2**).

Table 2: Project schedule



Future Project Work:

As part of Task 2.2, our research team will continue to study the tensile behavior of pipeline steel in hydrogen environments. The investigation will vary the type of material (X52, X60, and X70), hydrogen and oxygen concentrations, strain rate, aging time, and system pressure. Furthermore, we will investigate the fracture characteristics of pipeline steels in hydrogen-containing environments. The test variables are material type (X52, X60, and X70), hydrogen and oxygen concentrations, crack-opening displacement rate, exposure time, and system pressure.

Additionally, we have prepared two papers for journal publications to present our findings from our literature survey and modeling of fatigue strength. After thorough editing, the papers will be submitted to appropriate journals. In the coming weeks, we will prepare additional articles based on our experimental results from tensile testing.

Potential Impacts to Pipeline Safety:

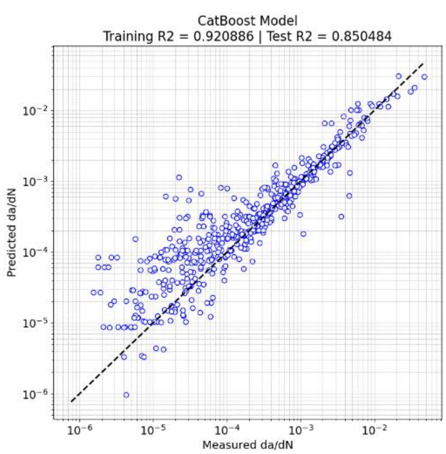
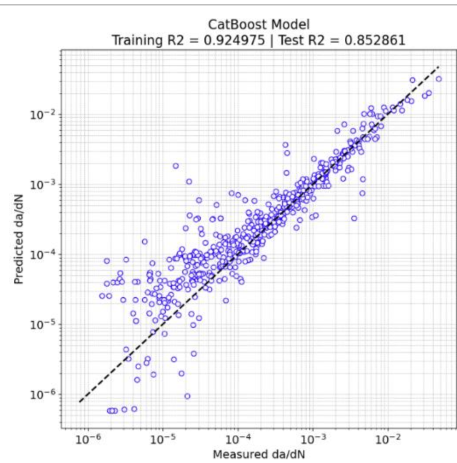
Our machine learning models developed at the current phase of the project can forecast the level of HE that will occur if hydrogen is transported through existing pipelines. Hence, model predictions can be used to establish a safe hydrogen transportation envelope for natural gas pipelines. Newly generated experimental measurements from this study and other relevant research in the HE area will be incorporated into the models to improve their accuracy.

Appendix A: Summary of Main Output Model for Fatigue Prediction (Task 3.2)

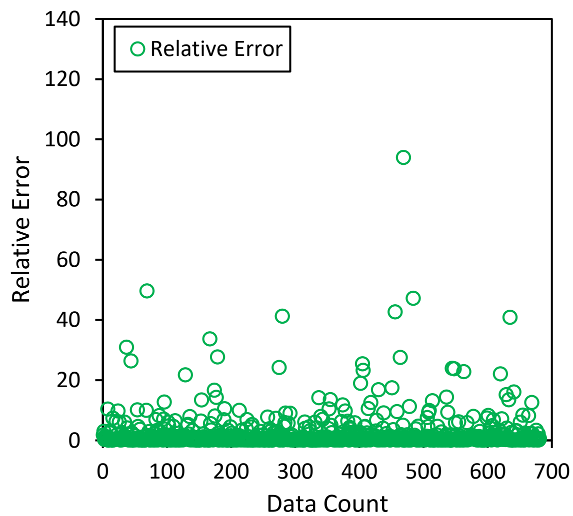
The challenge of data scarcity represents a significant impediment in machine learning applications, particularly in specialized domains such as research on hydrogen embrittlement. Addressing this issue, we have developed a novel approach that leverages data from one set of mechanical tests to predict other relevant mechanical parameters. Specifically, we have employed data meticulously extracted from primary literature sources to predict the fatigue crack growth rate. This data is then utilized within a CatBoost regression model, trained for the purpose of predicting the reduction of area in materials subject to hydrogen embrittlement. It is important to note that the CatBoost model in this study was not trained using fatigue test data; thus, the fatigue data used for predictions was not previously encountered by the model, highlighting the model's robustness and applicability in scenarios characterized by limited data availability.

Building upon the aforementioned approach, we further integrated the predicted reduction of area as a novel input parameter to train a subsequent model aimed at predicting the fatigue crack growth rate. In parallel, we developed a comparative model that excludes this newly derived reduction of area parameter, focusing solely on the prediction of fatigue in pipeline steel materials. This comparative analysis was undertaken to evaluate the efficacy of incorporating the predicted reduction of area parameter into the model. Both models were rigorously assessed using various performance metrics, including the coefficient of determination for both training and testing datasets (R^2), Mean Square Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE). The comparative results of these two models are succinctly summarized in Table **A-1**.

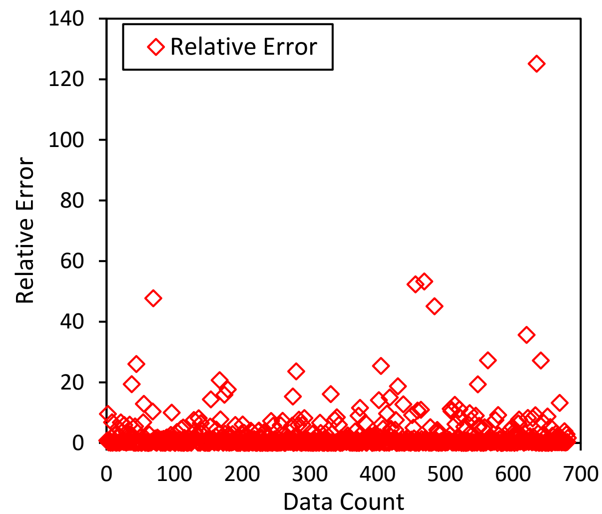
Table A-1: Comparison between model performance with and without predicted reduction of area

Performance Metrics	With Predicted RA Data	Without Predicted RA Data
R^2		
MSE	1.57e-06	1.55e-06
RMSE	0.001253	0.0012431
MAE	0.000309	0.000308
Maximum Error:	93.9	125.1

A notable distinction emerged when examining the scatter in the measured versus predicted fatigue crack growth rate (da/dN) plots. The model excluding the predicted reduction of area (RA) parameter exhibited greater scatter compared to its counterpart that included this parameter. This difference in scatter is quantitatively supported by the maximum relative errors observed in both models: 125.134 for the model without the predicted RA and 93.908 for the model with it. A detailed comparison of the relative error for each predicted fatigue value, both with and without the predicted RA, is illustrated in **Fig. A-1**.



(a)



(b)

Fig. A-1 Relative error of each predicted fatigue data: (a) with RA, and (b) without RA as input parameter

Despite the similarity in conventional performance metrics for both models, the analysis of maximum error and the scatter in the measured versus predicted fatigue crack growth rate plots clearly indicates that the model incorporating the predicted reduction of area demonstrates closer alignment with actual values. This outcome not only underscores the merit of this innovative approach but also contributes significantly to mitigating data scarcity challenges in the evolving field of hydrogen energy. It further elucidates the material applicability in hydrogen transportation, thereby facilitating a deeper understanding of material behavior under hydrogen embrittlement conditions.