CAAP Annual Report

Date of Report: October 4, 2020

Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Contract Number: 693JK31850006CAAP

Project Title: Predicting Remaining Fatigue Life of a Dent with Corrosion Using Advanced Measurements and Modeling

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Business and Activity Section

(a) Contract Activity

(b) Status Update of Past Annual Activities (Year Two Activities)

The second-year we focused on and completed Task 1, the baseline measurements on virgin specimens from all four different pipe grades received from Fleet Technology (C30532 Grade X60, C30285A Grade X45, C30621 Grade X52, C30221 Grade X70) to quantify the effect of material variability on the measured NLU parameter. We also made significant progress on Task 2, NLU measurements on statically loaded (or pre-strained) specimens to quantify the effect of material plasticity on the measured NLU parameter and Task 5 Development of a predictive model for the measured NLU parameter. Based on the results of Task 1, we modified the experimental plan after consultation and agreement with our Industrial Partners, Colonial Pipeline, and BMT Fleet Technologies. A copy of the revised test plan letter submitted to and approved by Mr. Joshua Around on May 20th is attached at the end of the 7th Quarterly Report.

The revised test plan will be focused on the five groups of experiments and still includes model development and validation.

Group 1: Repeated monotonic loads on 3 or 4 tensile specimens. First, make baseline nonlinear ultrasound (NLU) on each specimen. Apply monotonic strains in steps from minimum to maximum (e.g., 1% -8%), bringing it back to zero and making NLU measurements. Repeat the same procedure on all 3 (or 4) specimens. The objective of these Group 1 experiments is to compare the effect of the different magnitude of strains on one specimen (Baseline specimen is the same). Comparing different specimens allows for the evaluation of the effect of strain cycle on measurements, if any, as well as variability in measurements.

Group 2: Single monotonic loads on 10 tensile specimens. Make baseline measurements, subject each specimen to a single monotonic strain level (0% -8%) only, and then make the NLU measurements.

These results will determine the effect of the magnitude of one monotonic strain level. Comparing these results with Group level 1 specimens (of similar strain magnitude) provides the effect of the strain cycle.
Group 3: Fatigue load Group 2 specimens.
The subject selected specimens in Group 2 to fatigue cycling taking intermittent NLU measurements. Each fatigue test will provide information on the effect of fatigue (accumulated damage on measurements). Comparison of different specimens will provide information on the effect of the extent of pre-strain on measurements. Particularly relevant for dents that see both the monotonic strain as well as fatigue damage.
Group 4: Repeat group 3 specimens with Vintage X-52 pipe material. Now we can examine this typical ferrite pearlite microstructure. 70% of North American pipelines are pre-1970's vintage, and this steel will be more representative of that material.
Group 5: Determine the influence of flat versus round specimen type (if necessary). If Group 1 – Group 4 tests have been carried out on machined flat rectangular specimens, then some of the tests with Grade X-70 (Group 1-3 material) should be repeated with pipe curvature intact to understand the effect/application of the technique on curved surfaces and its effect on the scatter band/repeatability/performance.

B1: First Quarter measured the NLU parameter in two different undamaged legacy materials to continue to quantify the inherent state of material nonlinearity in the undamaged material. In addition, we measured both the classical and nonclassical nonlinearity parameters in a complementary material system, 9Cr-1Mo steel, to quantify better the relationship between microstructure changes during plastic deformation and these measured nonlinear parameters.

B2: Second Quarter token baseline measurements on virgin specimens from all four different pipe grades received from Fleet Technology (C30532 Grade X60, C30285A Grade X45, C30621 Grade X52, C30221 Grade X70) to quantify the effect of material variability on the measured NLU parameter. Published two papers directly resulting from the research in this project:

- Pfeifer, D., Kim, Jin-Yeon, and Jacobs, L.J., "Nonlinear Rayleigh waves to evaluate plasticity damage in X52 pipeline material," *Mechanical Systems and Signal Processing*, Vol. 143 (2020) 106794.
- Fahse, D.N., Levy, K.M.S., Kim, Jin-Yeon, and Jacobs, L.J., "Comparison of changes in nonclassical and classical acoustic nonlinear parameters due to thermal aging of 9Cr-1Mo ferritic martensitic steel," *NDT&E International*, Vol. 110 (2020) 102226.

B3: Third Quarter worked with our Industrial Partners, Colonial Pipeline, and BMT Fleet Technologies to develop the modified testing plan, as well as to start development work on a predictive model for the measured NLU parameter when the laboratory was shut down due to COVID-19.

B4: Fourth Quarter concentrated on measuring the NLU parameter, in a series of monotonic strains in steps from minimum to maximum on X-70 material specimens. Here we used the NLU parameter to track the multiple specimens in a series of monotonic strains to demonstrate an increase in strains from 1% to 8%.

(c) Cost share activity

Legacy material provided by Fleet Technologies to the Georgia Tech team, with an approximate value of $6000.

Georgia Tech Personnel partially supported on this project for the first year include: PI Laurence Jacobs, Dr. Jin-Yeon Kim (doctoral level Research Scientist), Mr. Hengyu Yang (Doctoral Student) and Katie

Scott Levy (Doctoral Student).

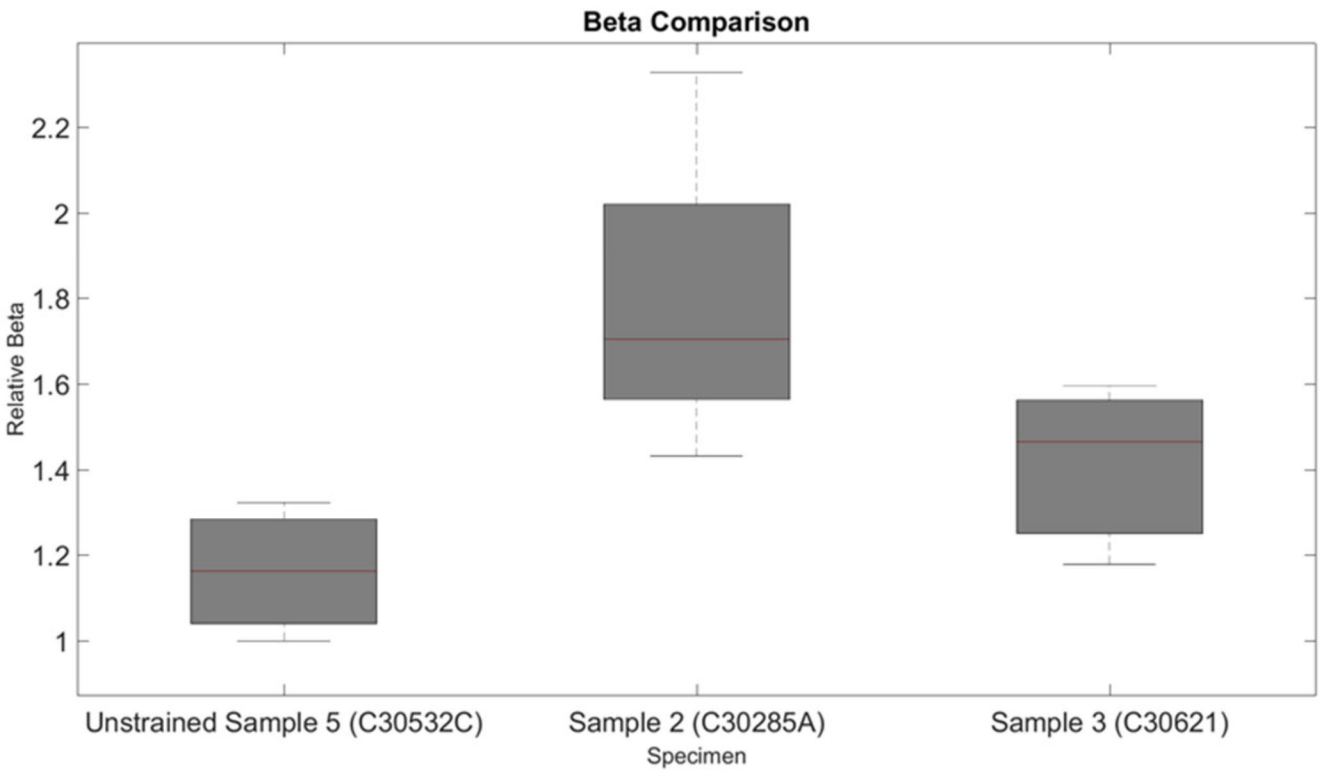
Personnel services support/expenses from Georgia Tech in this first year expended approximately 30% of the total three-year contract amount. This 30% was mainly spent on personnel support and materials and supplies:

- support for the doctoral research scientist (50%);
- doctoral student (40%);
- materials and supplies (10%).

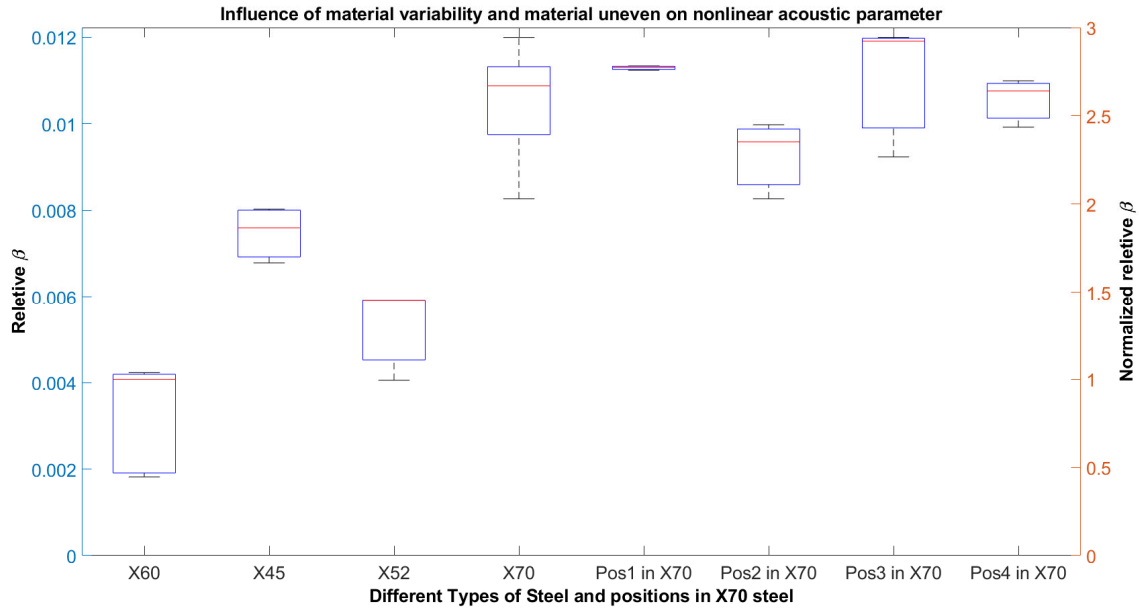
A full accounting will be provided on Federal Financial Report Form (SF425) by end of October.

(d) ***Task 1: Baseline NLU measurements on virgin specimens from three different pipe grades***

D1: Measured the classical NLU parameter, β, in two different undamaged legacy materials provided by Fleet Technology in the fifth quarter. The results show a significant level of variability in the undamaged material, with changes on the order of 20% within individual materials. These results are shown in the Figure below.



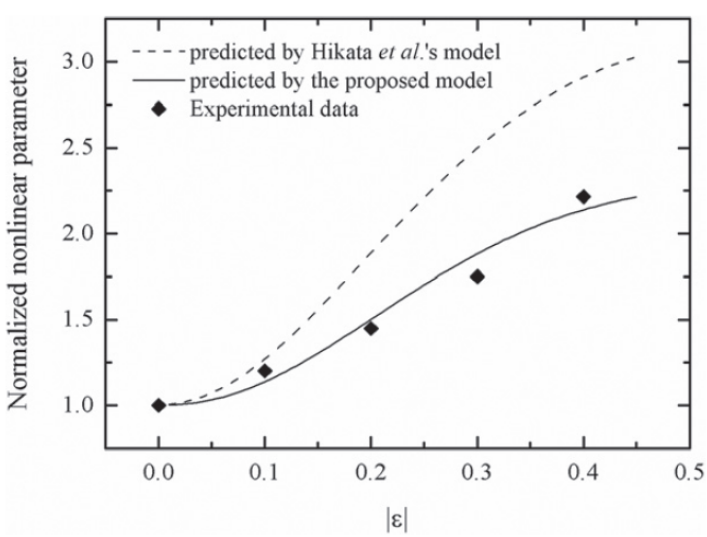
D2: Second Quarter measured the classical NLU parameter β in the X70 steel sample on four different positions to investigate the material inner uneven. The results are shown in the figure below. The results indicate a 20% measurement variation in β at different positions on the same specimen. This variation can not be ignored, and further measurements will be done at the same point in one specimen to minimize unnecessary measurement error. The baseline measurements of all four types of undamaged legacy materials provided by Fleet Technology are shown below. The measurements indicate significant variability in the undamaged material, with changes on the order of 20% within individual materials.



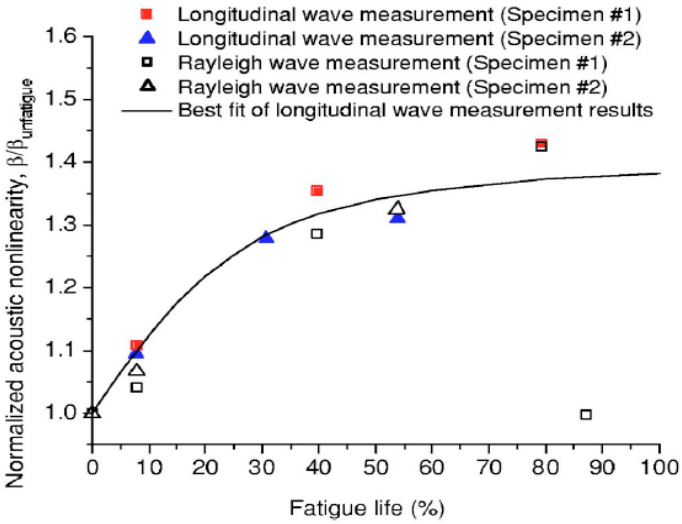
Task 2: NLU measurements on statically loaded (or prestrained) specimens to quantify the effect of material plasticity on the measured NLU parameter, β.

D1: Continued measurements on statically loaded legacy specimens, measuring the classical nonlinearity parameter, β as a function of plastic strain.

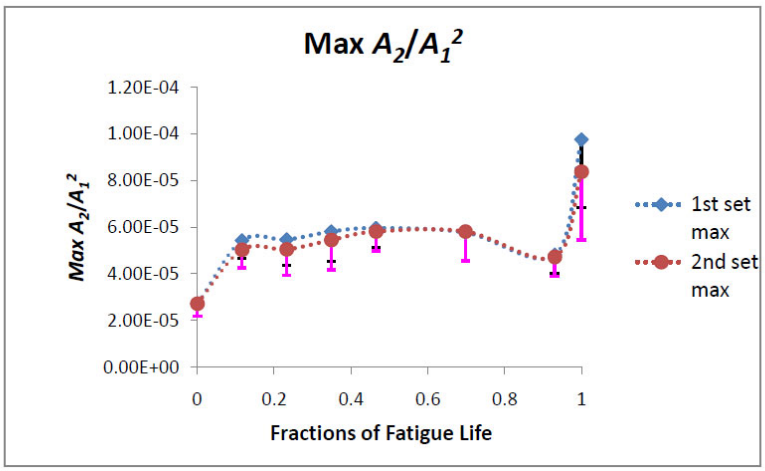
Task 5: Development of a predictive model for the measured NLU parameter, β.



D3: For monotonic load experiments, a predictive model is provided by Jianfeng Zhang et al. 's [1]. This comprehensive model shows the relationship between strain and nonlinear parameters in 304 stainless steel, as shown below. Our proposed Group 1 and 2 experiments described below confirm the correctness of the model in X-70 steel and determine possible material property differences between 304 stainless steel and X-70 steel that could cause the error. The relationship between the absolute value of strain and nonlinear parameter with different models are shown left.



For the fatigue experiments, there are two different predictions about the change of β with different material fatigue life. First is provided by Jin-Yeon Kim *et al.*'s [2], second is provided by Balasubramaniam Krishnan [3]. In Balasubramaniam Krishnan's prediction, the Max A_2/A_1^2 represent a through-transmission testing result. This test keeps the distance between transmitter and receiver constant, thus A_2/A_1^2 is proportional to nonlinear parameter β as $\beta \propto A_2/(xA_1^2)$ and x remains unchanged. The major differences happen in the last 10% of fatigue life. We can focus on this area when applying fatigue tests. two predictions about nonlinear parameter change comparison with fatigue life. Two predictions about nonlinear parameter change comparison with fatigue life are shown left



1. Background and Objectives in The Second Year

1.1 Background

This research aims to understand the evolution of material level damage in a dent (or mechanical damage), with and without corrosion. Remaining fatigue life prediction will be possible if we can measure and predict material level damage accumulation under a combination of realistic conditions. The key research question is to determine the fundamental differences, at a material level, that affect the change/reduction in remaining fatigue life for mechanical damage, including a dent and/or gouge, combined with corrosion. This research will address this and understand the root causes of a modeling and measurement perspective by considering this problem from a dislocation/material level. From a measurement perspective, we propose using nonlinear ultrasound (NLU) as a material sensor to quantify the material state of a dent with or without corrosion. NLU has shown to be sensitive to the precursors of fatigue damage, such as dislocations, before the formation of microcracks. The key to this approach's success is understanding or filtering out the background effects of different steel fabrication processes/vintages and different levels of pre-strain to characterize the level of fatigue damage accumulation. Successful completion of this research will provide a better starting point for existing fatigue life prediction models, thus reducing existing computational variance.

1.2 Objectives in the Second Year

The second year's objectives were to test all five different materials supported by Fleet Technology with the experimental procedure that was developed in the first year. The previous experimental results have shown that variations due to these legacy materials in these large

curved pipe specimens is complicating the results. We decided to grind one surface to flat for the rest experiments and make a comparison between flat and round specimen type when other measurements are finished. We concentrated on a single X-70 pipeline material where we successfully measured the acoustic nonlinearity parameter β in the undamaged material and developed a series of test to produce more fundamental results, giving a more general understanding of the efficacy of our proposed nonlinear ultrasonic measurements to predict remaining fatigue life in pipeline materials.

Results and Discussions

During the second year, the First Quarter results show the potential effectiveness of using nonlinear parameters to monitor changes in the microstructure of pipeline material due to the plastic damage of a dent. It was demonstrated that there is a significant difference in the nonlinear ultrasound parameter. Working with our Industrial Partners, Colonial Pipeline, and BMT Fleet Technologies, we have tailored our experimental testing plan to obtain critical improvements to predict remaining pipeline fatigue life better. This in situ NDE technique will provide data that improves the accuracy of remaining life models.

The main issues for Year two was the impact of COVID-19 which stopped all laboratory work on March 19, 2020, and was gradually recovered until July 2020, which delayed the fatigue test and consequent measurement process. But from another aspect, this free time allows us to reconsider and discuss our experimental plan with our partners and to develop a first pass at the predictive model.

1. **Future work for Year 3**

   Year Three work will mainly on the Group 3, 4 and 5 in the revised testing plan, the research objective is unchanged, we will use the result from testing plan and the predictive model for the measured NLU parameter to determine what are the fundamental differences, at a material level, that affect the change/reduction in remaining fatigue life for mechanical damage from a dent (or mechanical damage), combined with a gouge or corrosion.

REFERENCES

[1] Zhang, Jianfeng, Fu-zhen Xuan, and Yanxun Xiang. "Dislocation Characterization in Cold Rolled Stainless Steel Using Nonlinear Ultrasonic Techniques: A Comprehensive Model." EPL (Europhysics Letters) 103.6 (2013): 5. Web.
[2] Jin-Yeon Kim, Herrmann, Jan, Jacobs, Laurence J., Jianmin Qu, Littles, Jerrol W., and Savage, Michael F. "Assessment of Material Damage in a Nickel-base Superalloy Using Nonlinear Rayleigh Surface Waves." Journal of Applied Physics 99.12 (2006): 124913-1-124913-8. Web.
[3] Balasubramaniam Krishnan "Understanding of Materials State and its Degradation using Non-Linear Ultrasound (NLU) Approaches - Phase 3" https://apps.dtic.mil/docs/citations/ADA592196