CAAP Annual Report

Date of Report: October 7, 2019

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

A1: First Quarter highlights include a December 12, 2018 Kickoff meeting in Atlanta to discuss contract and technical details with James Kelly (PHMSA), and team members in person or via Skype from Georgia Tech (in person), Colonial Pipeline (last minute cancelation) and Fleet Technologies (Skype).

A2: Second Quarter highlights include acquisition (March 2019) of candidate legacy material, X-52 pipe from Fleet Technologies for nonlinear ultrasound (NLU) measurements.

A3: Third quarter highlights include hosting Derrick Allen, James Kelly, Antoinette Penny and Joshua Arnold (via phone) from PHMSA on April 29 on Georgia Tech campus to discuss project details, student collaborations and laboratory tour. Acquired additional legacy material from Fleet Technologies for nonlinear ultrasound (NLU) measurements in (May 2019): X-60 (US steel), X-45 (National tube), X-52 (Kaiser Steel) and X-70 (Stupp).

A4. Fourth Quarter highlights include poster presentation of results by graduate student Denis Pfeifer at the 46th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE) Conference, July 14-18, 2019, Portland, Oregon. Poster title: "Using Nonlinear Ultrasound to Quantify the Material State of Pipeline Steel Specimens with Mechanical Defects." A copy of this poster is included at the end of this report. This is the most prestigious specialty conference in NDE and it provided the student the opportunity to interact with researchers from around the world, discussing the technical details of his research. It also allowed us to showcase the advances we have made in the first year of this project. Other technical highlights include preliminary development of a theoretical model for the interaction of measured NLU signals and prestrain damage.

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

The primary activities in the first year were on Tasks 1 and 2: Baseline nonlinear ultrasound (NLU) measurements on virgin specimens of three different pipe grades to quantify the effect of material

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

B1: First Quarter highlights, defined and agreed upon a testing plan that includes six Tasks: (1) Baseline nonlinear ultrasound (NLU) measurements on virgin specimens of three different pipe grades to quantify the effect of material variability on the measured NLU parameter, β; (2) NLU measurements on statically loaded (or prestrained) specimens to quantify the effect of material plasticity on the measured NLU parameter, β; (3) NLU measurements on fatigue damaged specimens to track changes in the NLU parameter, β; (4) Determine the influence of corrosion on NLU parameter, β; (5) Development of a predictive model for the measured NLU parameter, β; (6) Model validation for real pipeline specimens.

B2: Second Quarter developed a candidate measurement technique for baseline NLU measurements that is proving to be successful using wedge/transducer generation and an air coupled receiver. Used this setup to obtain cumulative nonlinearity in representative stainless steel (SS) 304 specimens.

B3: Third Quarter measured the NLU parameter, β in the undamaged X-52 legacy material to quantify the inherent state of material nonlinearity in the undamaged material. Manufactured tensile testing specimens with this X-52 material and calculated the actual stress strain curve out to an ultimate strain of approximately 5%.

B4: Fourth Quarter highlights consisted of measurement of the NLU parameter, β in a series of the statically loaded X52 material specimens. Here we used the NLU parameter, β to track the multiple prestained specimens, to demonstrate an increase in β on the order of 50% for strains up to 5%. Started development of a model for interaction of NLU with prestrain to interpret evolution of measured β. These results are shown in section (d) of this report.

(c) Cost share activity

Legacy material provided by Fleet Technologies to the Georgia Tech team, with an approximate value of $2000.

Georgia Tech Personnel partially supported on this project for the first year include: PI Laurence Jacobs, Dr. Jin-Yeon Kim (doctoral level Research Scientist), Mrs. Katie Scott Levy (Doctoral Student), Denis Pfeifer (Masters student), Mr. Eyosias Gideon (Bachelors student), and Mr. Gregor Wettermann (Bachelors 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 (15%);
- masters student (15%);
- bachelors students (10%);
- materials and supplies (10%).

A full accounting will be provided on Federal Financial Report Form (SF425) by 28 October.

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

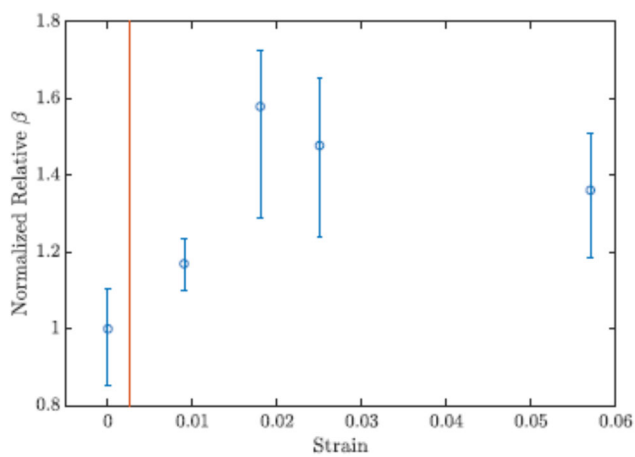
D1: First Quarter worked with Fleet and Colonial on candidate list of legacy materials. Modifying experimental setup for NLU measurements on these specimens.

D2: Second Quarter modified experimental setup for NLU measurements on these specimens. Measurement setup consist of a contact piezoelectric (PZT) transducer plus wedge and a non-contact air coupled ultrasonic receiver. The modifications include proper angle for incident waves for the pipe material, and changes to the scanning system for pipe geometry.

D3: Third Quarter measured the NLU parameter, β in the undamaged X-52 legacy material to quantify the inherent state of material nonlinearity in the undamaged material.

D4: Fourth Quarter refined and improved the NLU measurement procedure on these curved surfaces and thus reduce the measurement error. Compensation for this curvature is critical to the development of a field measurement procedure. Technical issues required a model of the actual acoustic energy wave path in order to track the same component of the waveform. Please note that we only examined a single pipe grade, instead of a total of three, to develop a better understanding of the overall behavior of the measured NLU signals. It is expected that the two different pipe grades will behave in a similar fashion, so it was more important to get an overall understanding of the NLU signals.

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



D3 and D4: Work on this task was accomplished in the Third and Fourth Quarters. Designed and manufactured tensile testing specimens with this X-52 material. Tested multiple specimens to calculate the actual stress strain curve out to an ultimate strain of approximately 5%. Then conducted a series of interrupted tests on multiple tensile specimens, where prestrain is induced in the specimen and then the acoustic nonlinear parameter is measured on these specimens. The figure above shows the measured NLU parameter, β in the five different X-52 specimens. One specimen is unloaded (0 strain) and the error bars of β presented in this figure is a measure of the material variation in the X-52 material. Then four other specimens are loaded to plastic strains between 1% and just over 5% as shown. The measured NLU parameter, β increases by approximately 50%, although the error bars increase. Current work is relating the measured β to changes in dislocations in the X-52 material.

1. Background and Objectives in the First Year

1.1 Background

The goal of this research is 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 what are 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 from a modeling and measurement perspective, by considering this problem from a dislocation/material level. From a measurements 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 the success of this approach 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 variance of existing computational.

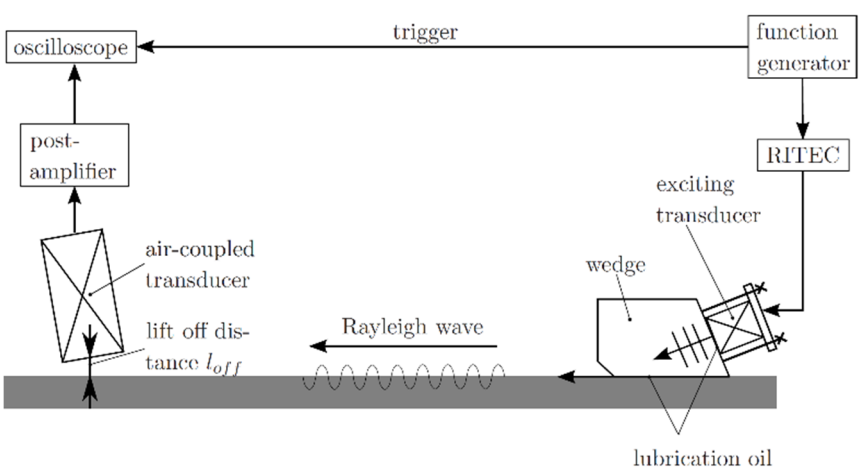
1.2 Objectives in the First Year

The objectives for the first year were to develop and test an experimental procedure that was accurate and effective for these large curved pipe specimens. This procedure was then used to quantify the effect of material variability on the measured nonlinear ultrasound (NLU) parameter, β. The second series of tests produce different levels of statically induced plastic damage on tensile specimens to quantify the effect of plasticity on the measured NLU parameter, β in this material. This prestrain (plastic damage) will also simulate the plasticity caused by dents. We concentrated on a single X-52 legacy pipeline material where we successfully measured the acoustic nonlinearity parameter β in the undamaged material and developed a static loading procedure to prestrain the material.

1. Experimental Program in the First Year

2.1 Experimental design

Demonstrate the ability to make NLU measurements of β in the unloaded legacy X-52 material.



Modified experimental setup for NLU measurements on these specimens. A schematic of this experimental setup, shown in the figure to the left consists of a contact piezoelectric (PZT) transducer plus wedge and a non-contact air-coupled ultrasonic receiver. The modifications include proper angle for incident waves for the pipe material, and changes to the scanning system for pipe geometry.

2. Results and Discussions

During the first year, it was first demonstrated on the undamaged material showed that it is possible to obtain cumulative increase in second harmonic on actual X-52 legacy material. These results obtained in the Third Quarter indicated that the inherent material variations in this legacy material will not dominate any potential increases in the acoustic nonlinearity parameter due to prestrain.

The Fourth Quarter results showed that the microstructure defect of a plain dent can be simulated as the plastic deformation due to prestain load. We considered a single legacy material, X52 after 40 plus years of service life.

These Fourth Quarter results are presented in the Figure in Task 2 and show that the acoustic nonlinearity increases by 55% for 1.8% strain. The error bars are relatively large and current research is working to decrease them. These error bars are a combination of material variability in this 50 year old legacy material, variability in the evolution of the microstructural damage due to the prestrain, and measurement error. The measurement error is mainly due to the round geometry of the pipeline specimens, which causes issues with tracking the propagation path. Even though this X-52 pipeline material shows a significant material variability that makes the exact classification of damage in the prestrain specimens challenging, a clear trend of increasing measured acoustic nonlinearity with increasing material damage is evident in these results.

The main issues from Year One were both technical and administrative:

From a technical perspective, the round geometry caused issues in the wave propagation, which mainly influenced the results in Task 2. The plan to overcome this issue is to determine if grinding these specimens flat will increase the accuracy of the measurements. Additional solutions include an improved wedge design to increase the transfer of acoustic energy into the pipe. It is important to note that this issue is manly a laboratory one since in the field the waves will propagate circumferentially, as opposed to axially, thus removing the influence of the curvature on the measurement technique. The impact of this issue is mainly in loss of time needed to address the issue and it is not expected to impact the overall deliverable schedule.

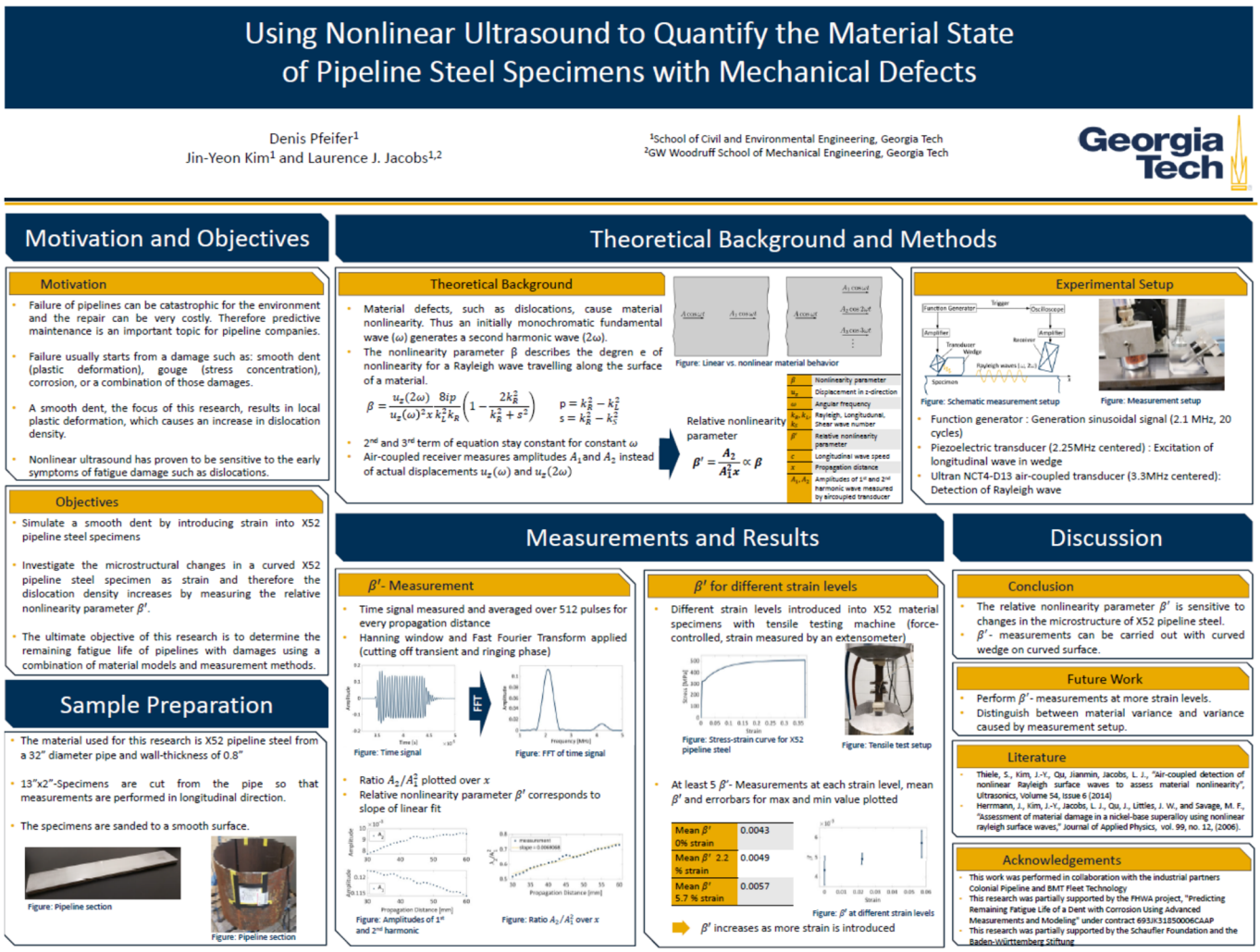
A second technical issue is the age and variability of this legacy pipe material. When compared to modern pipe materials, which have not experienced any routine service loading, the level of variability and the associated measurement error is relatively large. Measurements in similar, undamaged current materials are much more robust and produce lower error bars. The plan to overcome this issue is to constantly improve the measurement setup and procedure, which should lead to significant improvements of the signal to noise (SNR) over time. This issue is inherent to NLU measurements in legacy material and will slow down the project by a month or two at a maximum.

The critical administrative issue in the first year was mainly the delay in obtaining legacy material from Fleet, but this has been remedied and we now have plenty of material. This was mainly an issue for partner Fleet as they needed to identify and procure relevant materials. The other issue has been in obtaining a good graduate student for the measurements. Denis Pfeifer made outstanding measurements, but he has graduated with his MS and has returned to Germany. We are currently looking for a similar MS student, noting that as a doctoral student, Katie Scott Levy is focusing on the critical modelling component. A new MS student will be in place by Spring semester at the latest, and in the meantime undergraduate students will perform a bulk of the work to keep on the measurement schedule.

3. **Future work for Year 2**

Year Two work will look at other undamaged legacy materials provided by Fleet to confirm

similar trends in material variability as observed in this X-52 material. Candidate materials include the lower yield stress, X-45 material, where it is anticipated there will be an increase in material variability, and the higher yield stress X-60 or X-70, where it is expected to have less material variability.

Work will begin on Task 3, NLU measurements on fatigue damaged specimens to track changes in the NLU parameter, β and Task 4 Determine the influence of corrosion on NLU parameter, β.

Poster from QNDE Meeting:
The objective of the research reported in in this poster is to investigate the microstructural changes in a curved X52 pipeline steel specimen as strain and therefore the dislocation density increases by measuring the nonlinearity parameter β. The results of this poster show that the nonlinearity parameter β is sensitive to changes in the microstructure of X52 pipeline steel, and that these β measurements can be carried out with curved wedge on a curved surface.