CAAP Quarterly Report

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Contract Number: 693JK32050001CAAP

Project Title: Modeling Slow Crack Growth Under Thermal and Chemical Effects and Accurate NDT of Cracks for Fitness Predictions of Polyethylene Pipes

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Business and Activity Section

(a) Contract Activity

No modifications were made to the contract.

(b) Status Update of Past Quarter Activities

The project started this past quarter (September 2020 – November 2020). During the first quarter, literature review on existing models for slow crack growth and chemical exposure of high density polyethylene (HDPE) were performed. A research kick-off meeting was conducted using Microsoft Teams with technical representatives and leaders from DOT/PHMSA. We reviewed literature to evaluate HDPE experiments for short time scales as well as for relatively longer time scales to study the slow crack growth (SCG) in HDPE. Preliminary literature review was also conducted to understand modeling and finite element simulations of ultrasonic wave propagation in HDPE and to understand the role of machine learning for non-destructive evaluation of embedded cracks using ultrasound technique. Finite element simulation approach for ultrasonic propagation in a test geometry using HDPE elastic property was laid out using commercial software ABAQUS.

(c) Cost share activity

Partial support for graduate student tuitions and research staff were provided by Brown University School of Engineering as per the cost share agreement.

(d) Tasks: Ultrasonic and Machine Learning Based Crack Measurement Method for HDPE

1. Background and Objectives in the 1st Quarter

1.1 Background

Brown and Lu's proposed a phenomenological model[1] for the SCG rate at room temperature without environmental effects for polyethylene. More recently SCG under chemical exposure[2] was studied using numerical modeling. The chemical exposure numerical model proposed by Ge et al.[2] focuses on experiments and modeling of commercial diesel fuel and hydrocarbon-based surfactant. Typical HDPE usage in pipelines require long term use and integrity[3]. Accelerated testing methods have been used [4][5] where increasing the temperature of the exposure environment reduces the testing period by as much as factor of 5 as shown in Figure 1. Additional papers[6][7] have similar curves from creep tests where there is an initial rapid elongation (short) period followed by a relatively slower elongation rate where the curve is relatively flat until the point of failure.

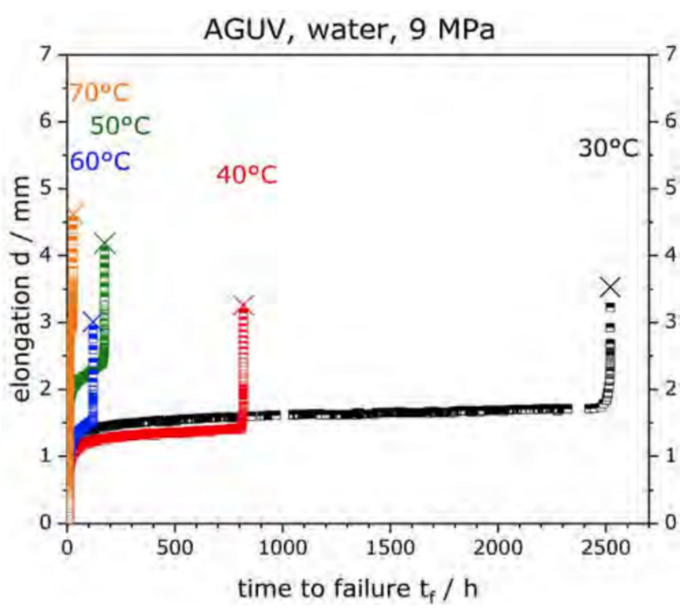

Figure 1. *Example of temperature affecting failure time [4]*

Most experiments utilized either a single edge notch (SEN)[7][8] or a full notch tensile (FN) specimen [9][10][11]. The specimen types in these tests have their unique characteristics and will be further evaluated to see which one of these are ideal for our testing. Single edge notch specimens provide a direct way to observe and measure the crack propagation in real time. Full notch specimens are better for exploring cracks propagation within the material under relatively higher triaxial load conditions (Figure 3). The primary method of measuring the displacements in the test sample is with extensometers[4][12][13][14] [15]. There is little mention of digital or virtual extensometers, which can be cosnidered for our testing. In the literature the creep tests were conducted at stresses around 2 - 12 MPa (resulting in 9e-8 s^{-1} to 7e-5 s^{-1} strain rate). These tests lasted anywhere from 4 hours to over 4 months.

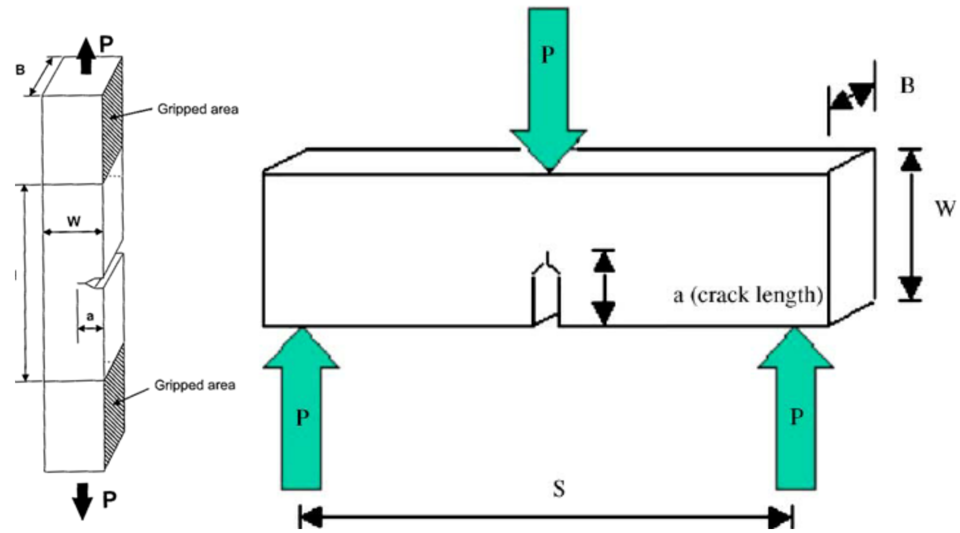

Figure 2: *Examples of a single edge notch tensile (SEN, left) and single edge notch bend (SEB, right) specimens*

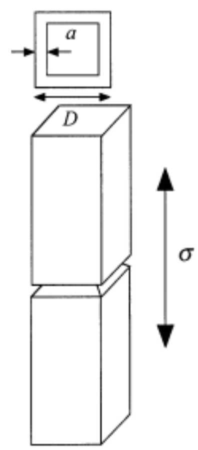

Figure 3: *A Pennsylvania Edge Notch Test (PENT) specimen*

Crack measurement is critical for evaluating the fitness-for-service of HDPE pipelines. An approach for crack detection and characterization of HDPE pipelines is ultrasound nondestructive testing (NDT). To enhance the accuracy of NDT measurements, advanced ultrasonic testing methods have been developed.[16] [17] However, these advanced methods are still limited in their ability to characterize crack size due to significant uncertainties that occur due to reliance on human interpretation.[18][19] Machine learning is effective in eliminating human errors. Current trend in machine learning has proved useful in the application of ultrasonic NDT. Margrave et al.[20] applied various types and configurations of neural networks for flaw type identification in a steel plate. Six types of flaws, crack, porosity, inclusion, slot, side-drilled holes and no flaw were investigated and the performances of different networks were compared in this work. Liu et al.[21] studied direct and indirect ultrasound NDT problems using neural network for crack type and crack size classifications. Cau et al.[22] utilized simulation and artificial neural network (ANN) to classify the position, width and depth of cracks in a pipe. Martin et al.[23] used ANN to classify four types of spot welds including good weld, undersized weld, stick weld and no weld. Sambath et al.[24] and Liu et al.[25] used ANN for the classification of different types of resistance spot welding defects. Yang et al.[16] compared different feature extraction techniques and the performance of the ANN and support vector machine in addition to flaw type classification. Munir et al.[17] applied convolution neural network (CNN) to noisy ultrasonic signals to improve classification performance of different types of welding defects. Wang et al.[18] used CNN to conduct fault detection for data imbalance conditions. Safari et al.[19] used ANN and images of interior defects to determine crack size by image processing for HDPE specifically.

Even with many of the existing works, accurate crack size measurement (quantification) remains challenging, due to the fact that it requires a sufficiently large and diverse database to train a neural network for this cause. Experiment-driven works have their limitations in the sense that it is extremely costly and time-consuming to fabricate enough controlled well labeled samples to create sufficiently large database required for neural network training. We envision that a finite simulation driven approach is suitable for creating a large database without losing real physics of ultrasound wave propagation and reflection. Finite element simulation of ultrasound propagation has been investigated by researchers for metal pipes.[30] In contrast to metallic materials, HDPE is a polymer which has viscoelastic behavior that is time dependent.[31] Moreover, viscoelasticity leads to the attenuation and dispersion of ultrasonic waves.[32][33] The former is caused by the energy dissipation within viscoelastic material and frequency-dependent phase velocity is responsible for the latter. These effects become more dominant as the pipe thickness increases. Our hypothesis is that these effects might be negligible in certain scenarios (e.g. when time scales of attenuation are much larger than the time scales associated with the ultrasound wave return) where the pipe thickness is within tens of millimeters. We will study the effect of viscoelasticity to test this hypothesis.

1.2 Objectives in the 1st Quarter

We aimed to conduct literature review on the SCG of HDPE under different conditions. We aimed to review and develop initial understanding of chemical exposure mechanical test conditions and experimental set-up needs. We also aimed to conduct literature study on finite element simulations of ultrasonic wave propagation in HDPE and machine learning models for crack detection and characterization. We aimed to develop a preliminary finite element simulation methodology for ultrasonic NDT in HDPE material.

2. Experimental Program in the 1st Quarter

2.1 Experimental design

No experiments were performed in the 1st quarter.

2.2 Computational setup

Preliminary computations were started on an existing workstation.

We identified requirements for finite element based numerical simulation of sound waves propagation in HDPE. We chose an ultrasound wave of 1 MHz frequency. We obtained that 10-15 meshes per wavelength provided a numerically stable practical element size. We also considered the Courant-Friedrichs-Lewy (CFL) condition and obtained the maximum allowable time step for our simulations.

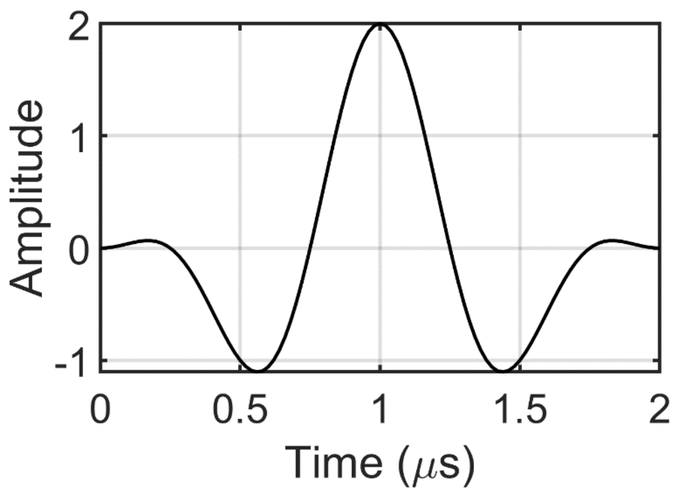

Figure 4. *1MHz, 2 period raised-cosine type pulse signal used in the simulations.*

A plate geometry with width 80 mm and thickness 20 mm is being considered for our simulations where 5 mm linear length at the bottom surface is taken as ultrasound signal exciter. A short 5 mm long ultrasound signal exciter with 1 MHz raised-cosine type waveform as shown in Figure 4 will be applied as boundary condition to the bottom edge of the plate thickness. Anomalies in the form of elliptical crack embedded in the plate will be studied. Our dynamic numerical simulations will be conducted in Abaqus/Explicit and the displacement history profile at the receiver location node in the numerical model will be analyzed. The material properties for the HDPE are summarized in Table 2.

Density (kg/m^3)	**Young's modulus (GPa)**	**Poisson's ratio**
954	1	0.43

Table 2. *Material properties for HDPE*

Overall future goals

We focused on literature review of SCG in PE and HDPE during the first quarter. We examined existing models and experimental methods in investigating PE and HDPE slow crack growth. In the upcoming quarters, we will design experiments to study the slow crack growth and crack propagation in HDPE under different environmental exposure conditions. These experiments will utilize our MTS Bionix material testing machine. Experimental results will be used to conduct mechanistic modeling of slow crack growth. FEA simulations incorporating our new model will be conducted to see how our theoretical model compares with the experiments.

In the first quarter, we conducted literature review on the ultrasound NDT of HDPE pipes and looked into role of machine learning for accurate crack detection in HDPE. In the coming quarters, we will continue to investigate the ultrasound NDT simulations for HDPE. We will also conduct Ultrasound crack detection tests for validation of our finite element simulations and neural network based crack detection method.

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