Modeling Slow Crack Growth under Thermal and Chemical Effects and Accurate NDT of Cracks for Fitness Predictions of Polyethylene Pipes

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Acknowledgment of support: PHMSA and Brown School of Engineering

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Team

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- **Cost Share and Support:** Brown University School of Engineering and Brown Graduate School

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PI Experience

PI energy industry work

ExxonMobil Upstream Research, *Offshore* (Houston, TX)

- *Subsea and Arctic Senior Research Engineer* — *2010*
- *Worldwide Deepwater Drilling Coordinator* — *2011 – 2012*
- *Marine Team Lead* — 2013 – 2014

ExxonMobil Corporate Strategic Research (Clinton, NJ)

- Advanced Research Associate — 2015 – 2016

ExxonMobil Upstream Research, *Offshore* & *Environment* (Spring, TX)

- *Mechanics Team Lead and Fitness for Service Area Lead* — *2017 – 2018*
- *Senior Technical Professional Advisor - Mechanics of Materials* — *2018*

Objectives

Plastic pipes are increasingly used due to their lightweight, low installation costs, ease of maintenance, and corrosion resistance, with ***8.3 billion feet of plastic pipeline*** *(4.4 billion feet Main and 3.9 billion feet service) transporting natural gas and 55 million residential and commercial gas* lines (service). High-density PE (HDPE) is preferred polymer for gas transport lines. **2022 data*

Non-visible flaws can grow over time and can cause catastrophic failure.

Objective 1: Develop a slow crack growth model for HDPE that accounts for the effects of stress loading with the *thermal and chemical effects*.

Objective 2: Develop a method using computational finite element simulations for convolutional neural network (CNN) to accurately predict embedded hidden crack's key characteristics for HDPE. *(The key is to be able to quantify crack using a fast microsecond raw ultrasound wave data that is essential to scan long pipelines)*

Objective 2 helps detect and quantify existing cracks using a proposed new NDE approach, and *Objective 1 is aimed to provide a better assessment of HDPE pipeline integrity by helping predict the remaining life when a crack is detected and sized.*

Research tasks performed

Objective 1 research activities

- Experimental work to study creep, very slow strain rate, and rate-dependent response of HDPE.
- Studied, analyzed and compiled relevant experimental data from published long-term creep tests of HDPE samples under different chemical and thermal exposures.
- Developed a new slow crack growth model incorporating the stress, thermal and chemical effects.
- Calibrated the model parameter using experimental data
- Checked the model’s predictive abilities using independent experimental data.

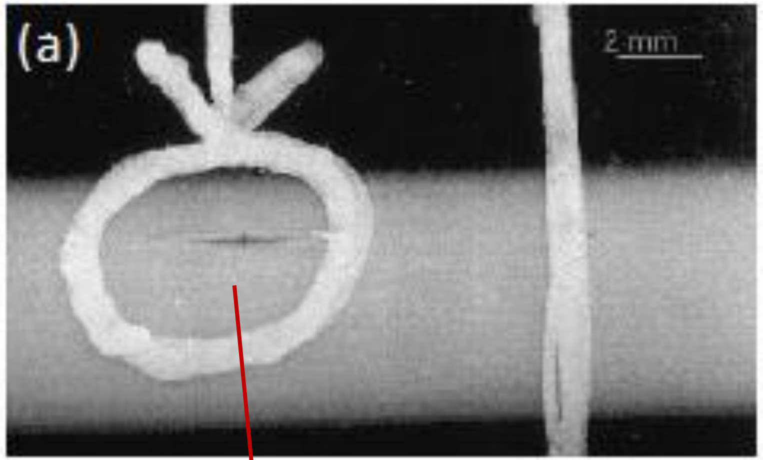
Objective 2 research activities

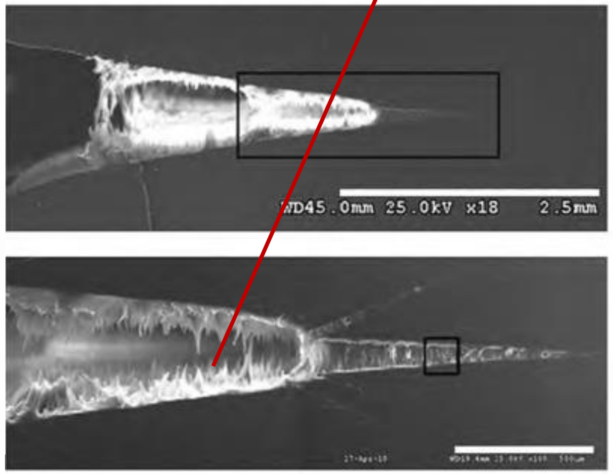
- Developed and proposed an automatic crack characterization ultrasonic non-destructive evaluation (NDE) method using neural network models to eliminate human involvement.
- Develop finite element simulations for ultrasound NDT of HDPE.
- Applied high-fidelity synthetic data from finite element simulations to train a CNN for two critical crack parameters of various lengths and locations for embedded hidden cracks.
- Built an experimental set-up and conducted ultrasound NDT on HDPE specimens to independently validate the performance of FEA-trained CNN in accurately predicting both the location and size of embedded cracks simultaneously in real-life HDPE test specimens.

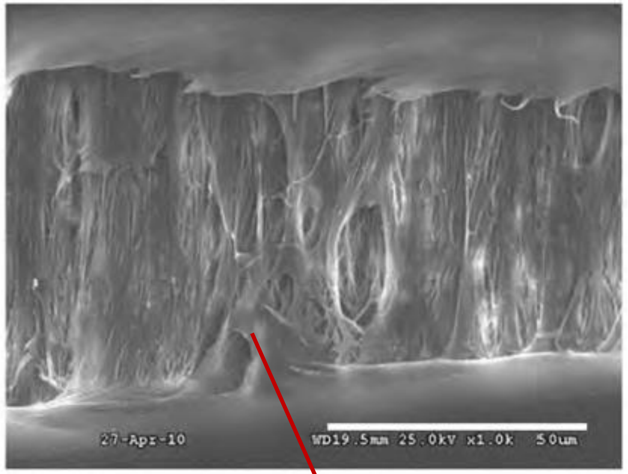
Research Outcomes 1:
A new slow crack growth model for high-density polyethylene under thermal and chemical environment

Failure in polyethylene pipes

Slow crack growth leading to discontinuous bands in HDPE





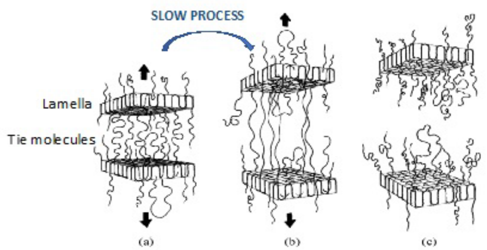


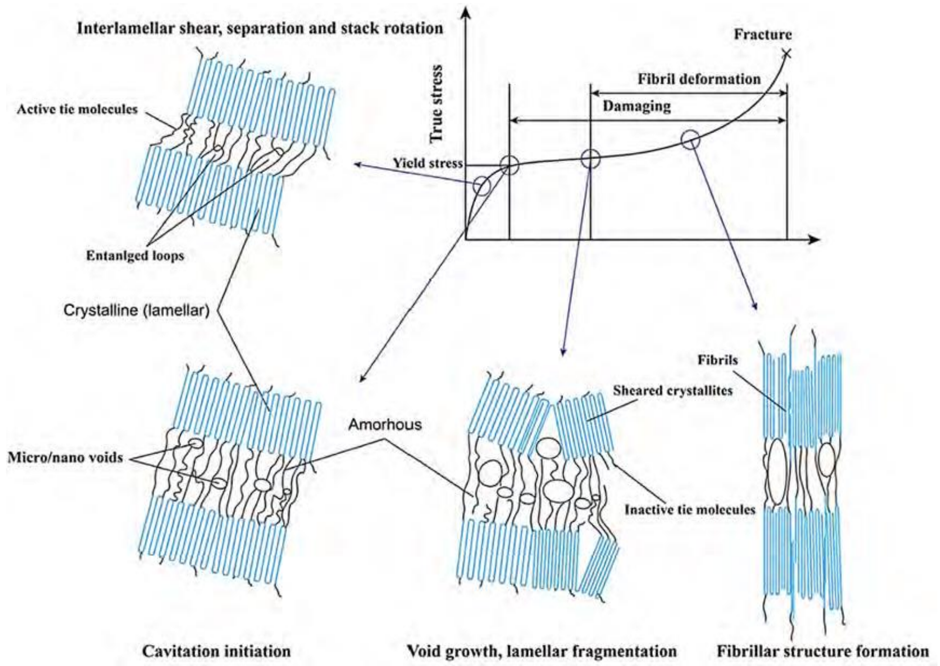
Internal pressure driven brittle type overall macroscopic crack failure

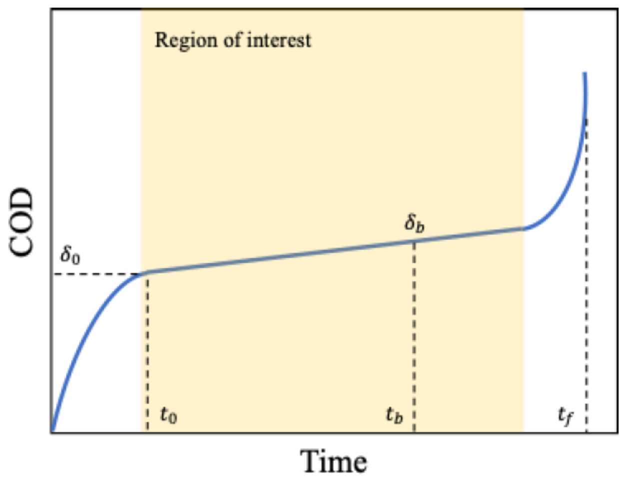
scanning electron microscope (SEM) image of craze microstructure in HDPE

H. Hamouda et al, *Polymer* 42 (12), 2001
Almomani et al., *Materials & Design* 227, 2023

Crack-tip opening distance (COD) in slow crack growth

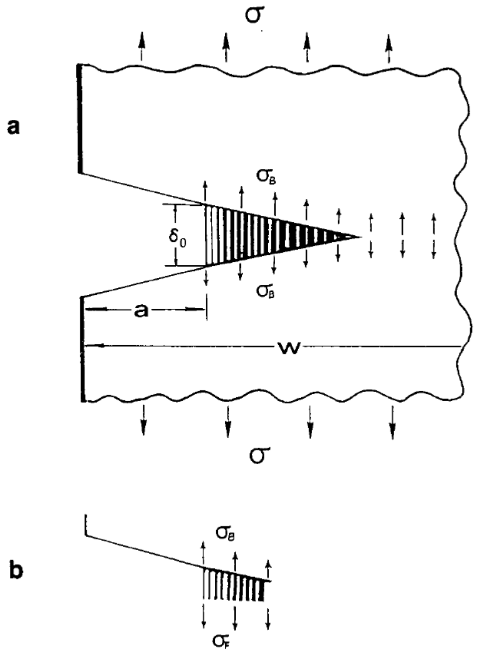






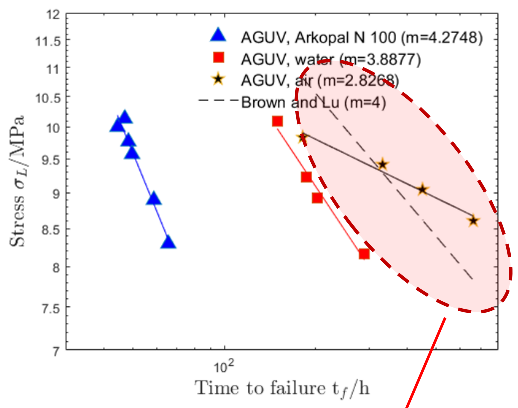
COD versus time for a typical PE material

$$\dot{\delta} = \frac{\delta_b - \delta_0}{t_b - t_0}$$



Brown and Lu, *Polymer* 36, 1995
Almomani et al., *Materials & Design* 227, 2023

Proposed SCG model for chemical environment exposure



Dotted black line prediction from Brown and Lu model. It does not work well for chemical exposure situations and does not have chemical exposure failure prediction ability.

$$\frac{\dot{\delta}}{\delta_0} = \frac{\sigma_F}{\eta}$$

Brown and Lu's assumption for COD

$$\boxed{\frac{\dot{\delta}}{\delta_0} = \frac{\sigma_A}{\eta}\left(\frac{\sigma_F}{\sigma_1}\right)^{m/2-1}}$$

Proposed new model for COD

$$\dot{\delta} = \frac{K^4}{d_0 E \sigma_Y}(1-\nu^2) \quad \text{where} \quad K = Y\sigma\sqrt{\pi a}$$

COD from Dugdale theory for plane strain condition

$$\dot{\delta} = \frac{\sigma_Y Y^4 (1-\nu^2)^2 \sigma^2 a^2}{\eta d_0 E^2 \sigma_C^2}$$

Brown and Lu's SCG model

$$\boxed{\dot{\delta} = \frac{\sigma_1 \sigma_A d_0}{\eta \sigma_Y}\left(Y\sigma\sqrt{\frac{(1-\nu^2)\pi a_0}{E\sigma_1 d_0}}\right)^m}$$

New SCG model

Proposed SCG model for chemical environment exposure

$$\dot{a} = \kappa \frac{\sigma_1 \sigma_2 d_0}{\eta \sigma_Y} \left(Y\sigma \sqrt{\frac{(1-\nu^2)\pi a_0}{E \sigma_1 d_0}} \right)^m \exp\left(-\frac{Q}{RT}\right)$$

where $\sigma_2 = \dfrac{\sigma_A}{2a \tan\left(\theta/2\right)}$

Chemical exposure term

Unit correction factor

Temperature term

$$t_f = \frac{\eta \sigma_Y x}{\sigma_1 \sigma_2 d_0 \kappa} \left(Y\sigma \sqrt{\frac{(1-\nu^2)\pi a}{E \sigma_1 d_0}} \right)^{-n} \exp\left(\frac{Q}{RT}\right)$$

Medium	κ	$x(m)$
water	6	1.1e-11
Arkopal	1	3.2e-11

Time to failure is based on the final failure crack length or CTOD criteria.

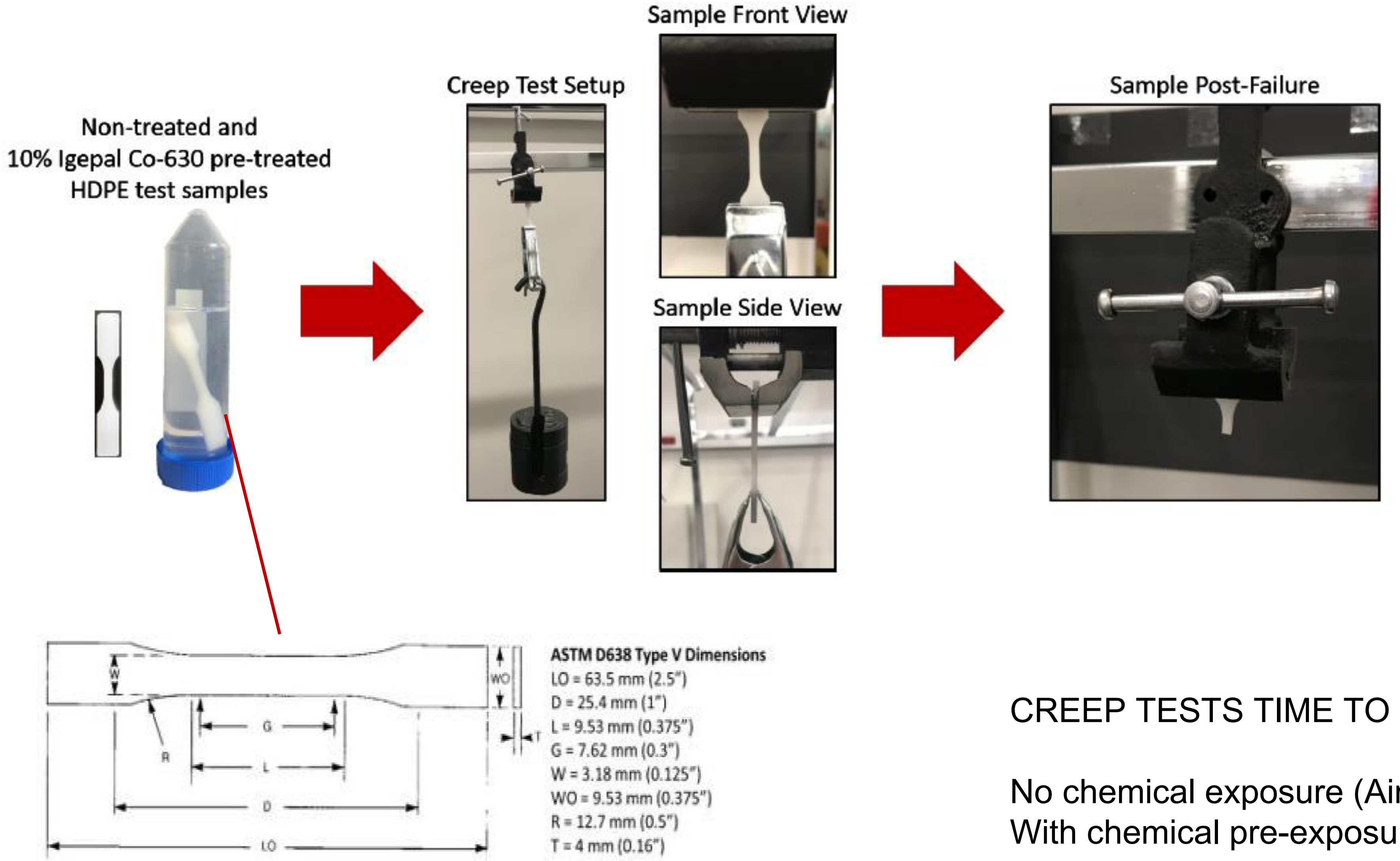
New SCG model

Parameter	Description	Parameter	Description
$\dot{\delta}$	COD rate (m/s)	$\dot{a}$	crack depth growth rate (m/s)
σ_1,σ_2	fitting parameters (Pa)	σ	applied stress (Pa)
E	Young's modulus (Pa)	ν	Poisson's ratio
Y	geometric factor	a_0	initial crack length (m)
η	viscosity (Pa.s)	d_0	primordial thickness (m)
Q	activation energy (J/mol)	R	universal gas constant (J/mol.K)
T	temperature (K)	κ	chemical exposure constant
x	unit correction factor (m)	$m,\ n$	exponents

Parameters in the proposed SCG model

$m = 10,\ n = 5$
$Q_{water} = 100\ kJ/mol, Q_{Arkopal} = 110\ kJ/mol$
$\sigma_1 = 121\ KPa, \sigma_2 = 67\ MPa$
$d_0 = 35\ \mu m, \eta = 1.13e10\ Pa\ s$

SCG experiments



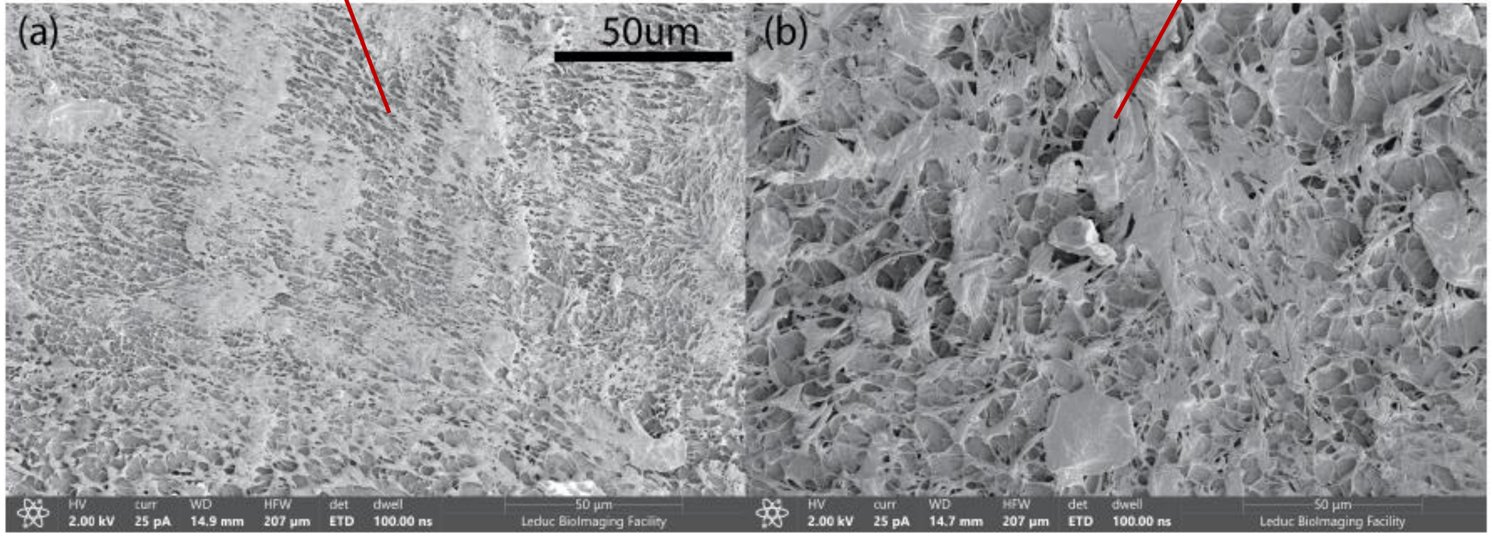
CREEP TESTS TIME TO FAILURE AT 3 MPA:

No chemical exposure (Air) - 160 days
With chemical pre-exposure (Igepal) – 100 days

Scanning electron microscope (SEM) image

Air-exposed

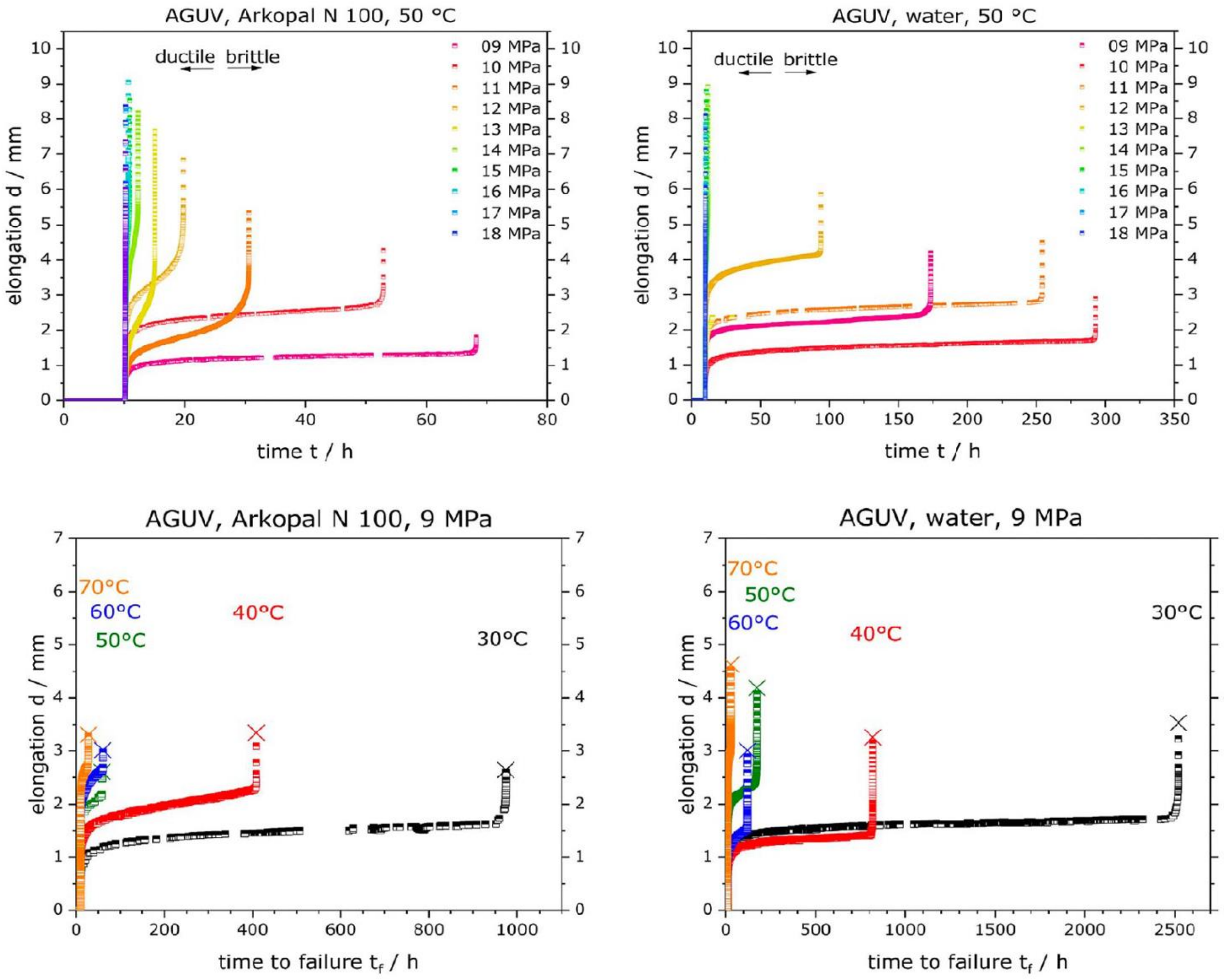
Chemically treated (for 14 days in 10% Igepal solution)



SEM images of creep test HDPE samples captured at 1000X

Creep/Slow crack growth experimental data

Experimental data: Elongation for various temperatures (FNCT – Full Notched Creep Test specimens)



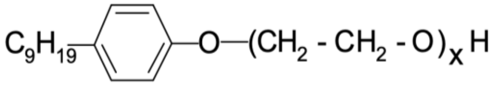
Experimental data from Schilling et al, *Polymer Testing* 64 (2017)

Conversion approximation:

$$a = \frac{l}{\left(\frac{\sigma}{\sigma_{ref}} - 6.2\right)}$$

where σ_{ref} (= 1.25 MPa)

Arkopal structure



Nonylphenolpolyglycolether
(x = number of added-on molecules of ethylene oxide)

Arkopal (also Igepal) (nonylphenolpolyglycolether), is a nnonionic surfactant used as an environment stress cracking ESC agent to accelerate SCG in polyethylene and is the standard for ESC testing under ASTM *D1693 (Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics)*

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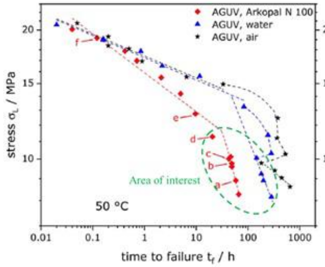
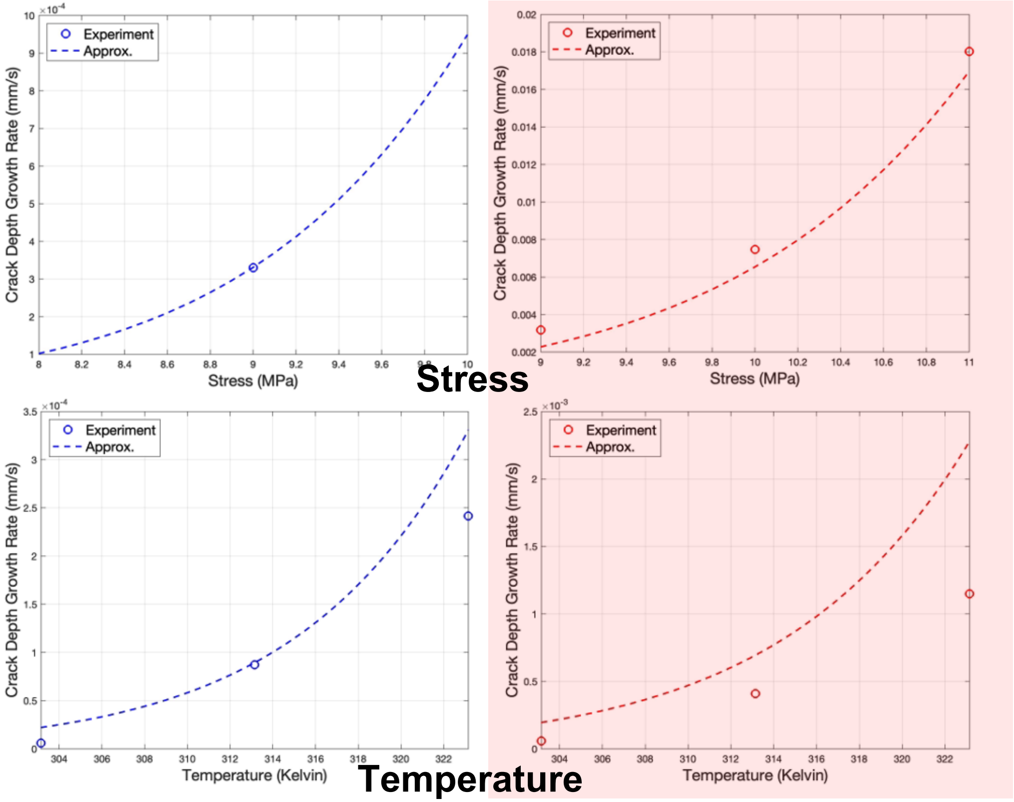
Calibration of new SCG model



Crack growth rate

Water

Arkopal



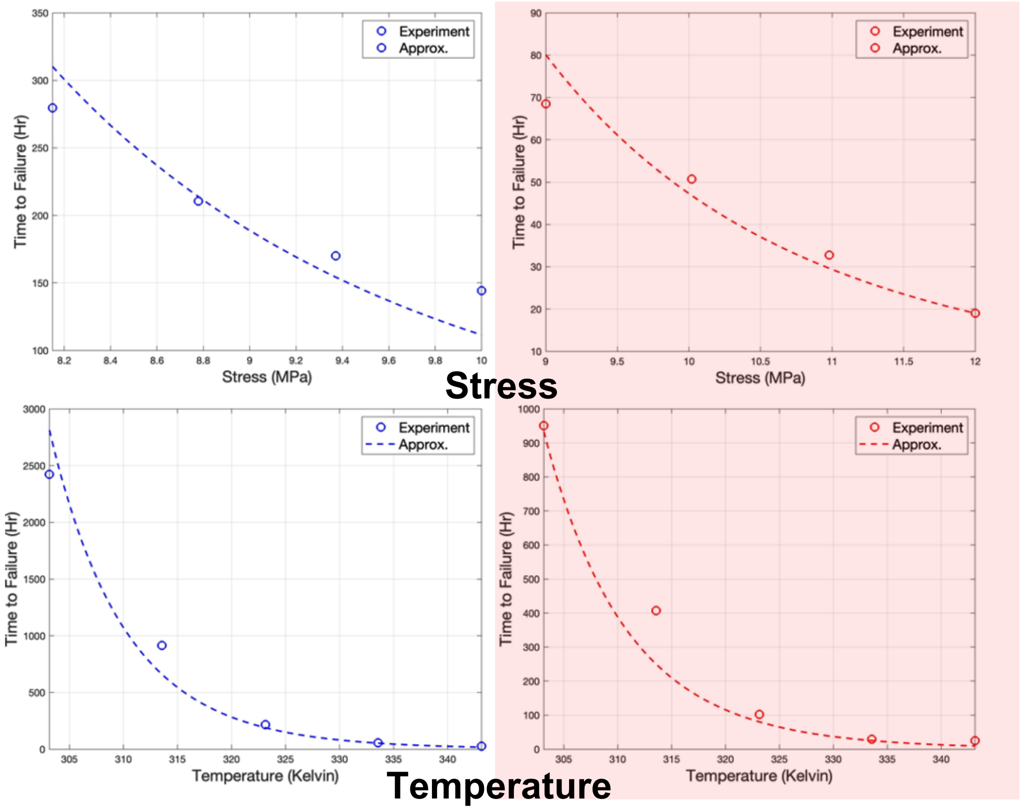
Stress

Temperature

Time to failure

Water

Arkopal



Stress

Temperature

Absolute values are approximations, but the relative values and trends are quite relevant.

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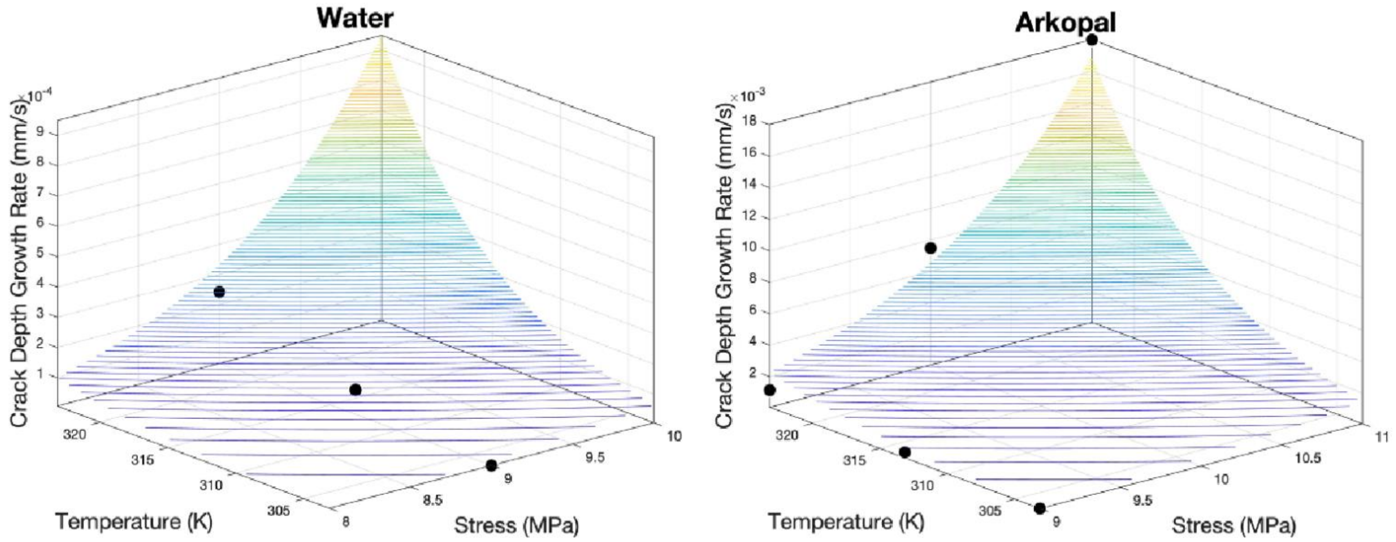
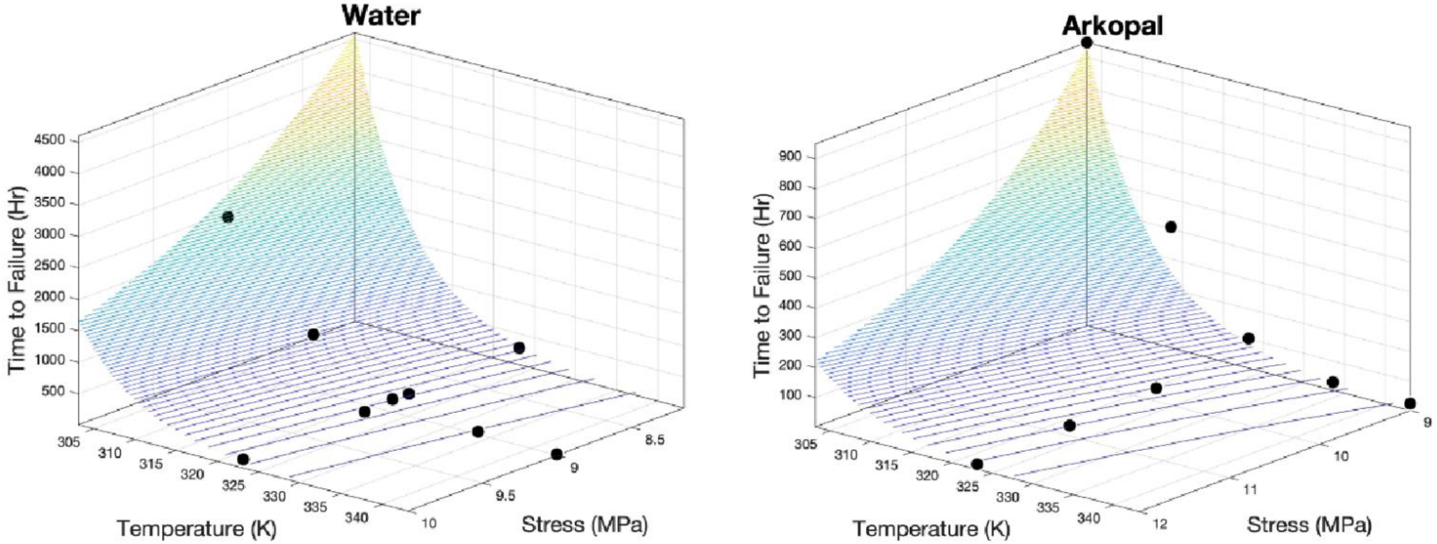
Stress, Temperature and Chemical Environment Dependent SCG Predictions from the new model

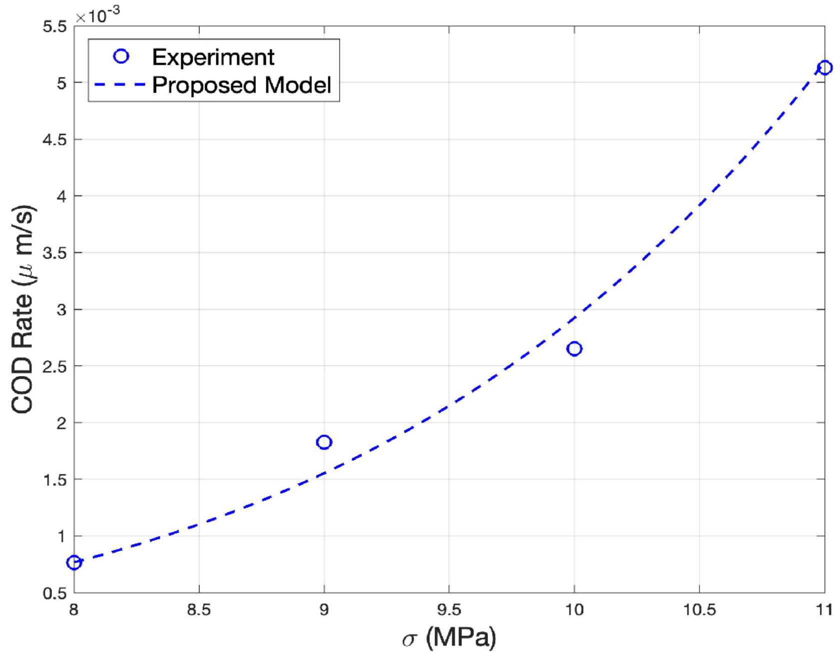


Crack depth growth rate

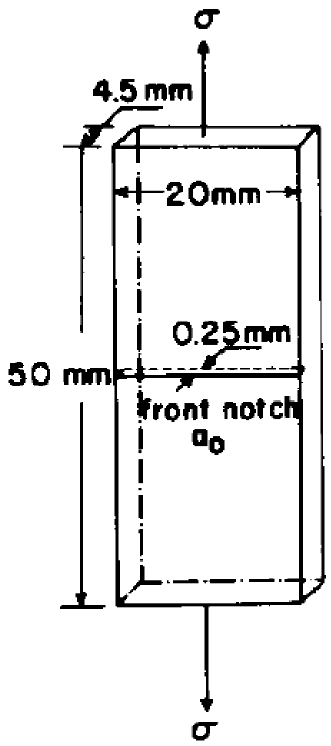


Time to Failure

SCG model prediction for single edge notched specimens



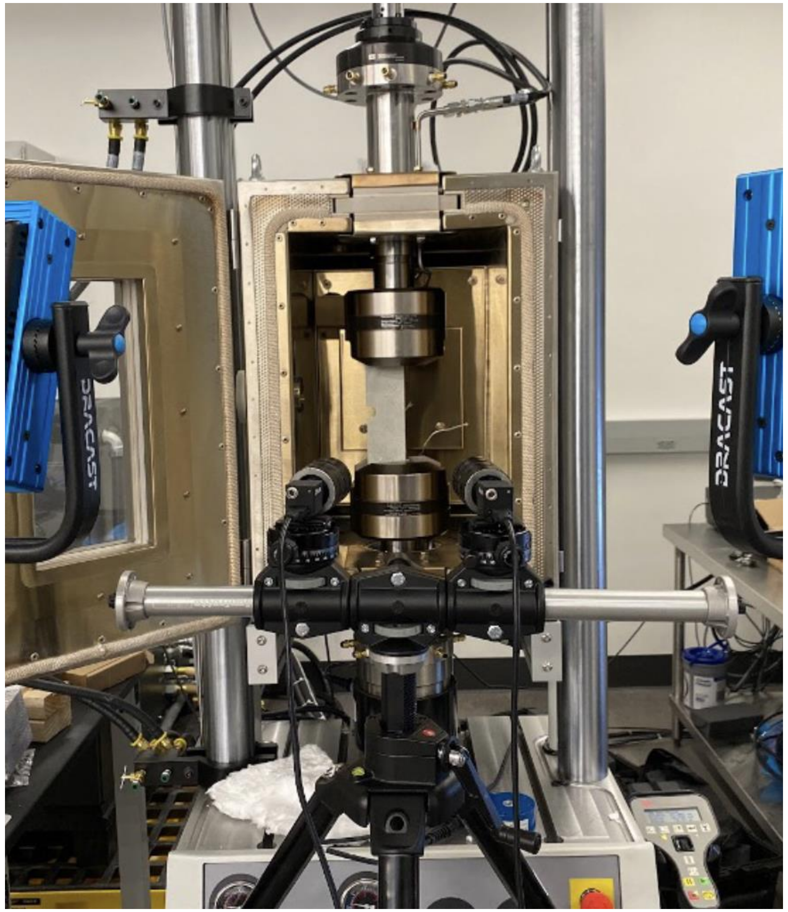
Comparison of COD rate ($\dot{\delta}$) of the single edge notch test (SENT) specimen obtained from new SCG model with experimental data of Brown and Lu. Only basic properties for the experimental material and the geometry parameter (Y) were updated. *This was intended for independent validation of the model.*



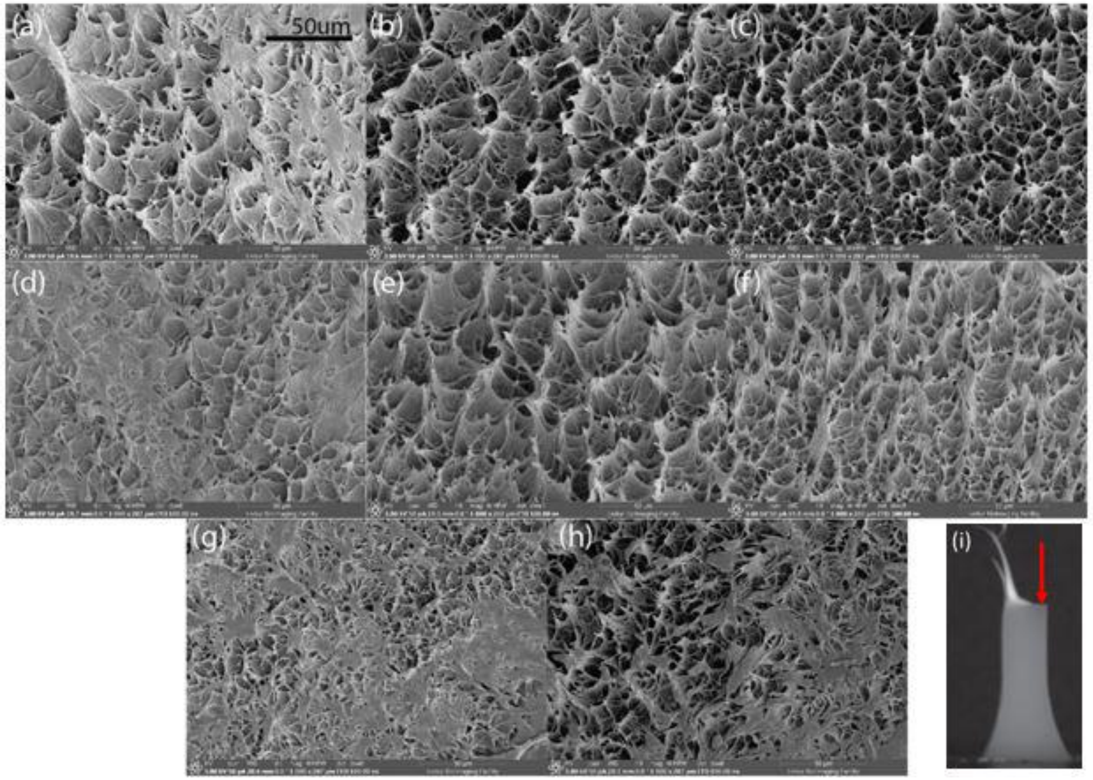
SENT geometry

Brown and Lu, Macromolecular Symposia (1991)

Very slow strain rate and rate dependent response experimental study



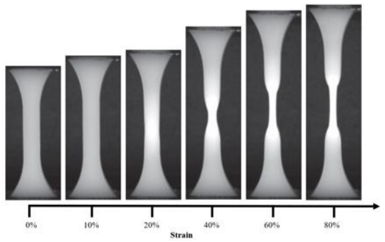
MTS mechanical testing machine
with temperature chamber



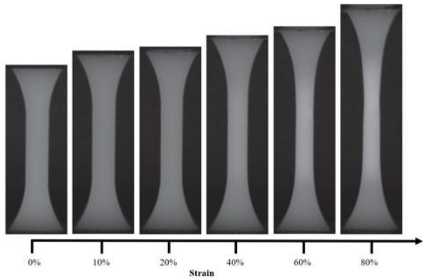
SEM images of the fracture surface near the crack initiation of HDPE samples (0.0003 s−1 strain rate) for different temperatures and exposure environments

(a) Air 22 °C, (b) Air 37 °C, (c) Air 50 °C,
(d) Igepal 22 °C, (e) Igepal 37◦C, (f) Igepal 50 °C,
(g) PBS 22 °C, (h) PBS 37 °C.

Rate and temperature dependent response of HDPE under different exposure



0.3 /s

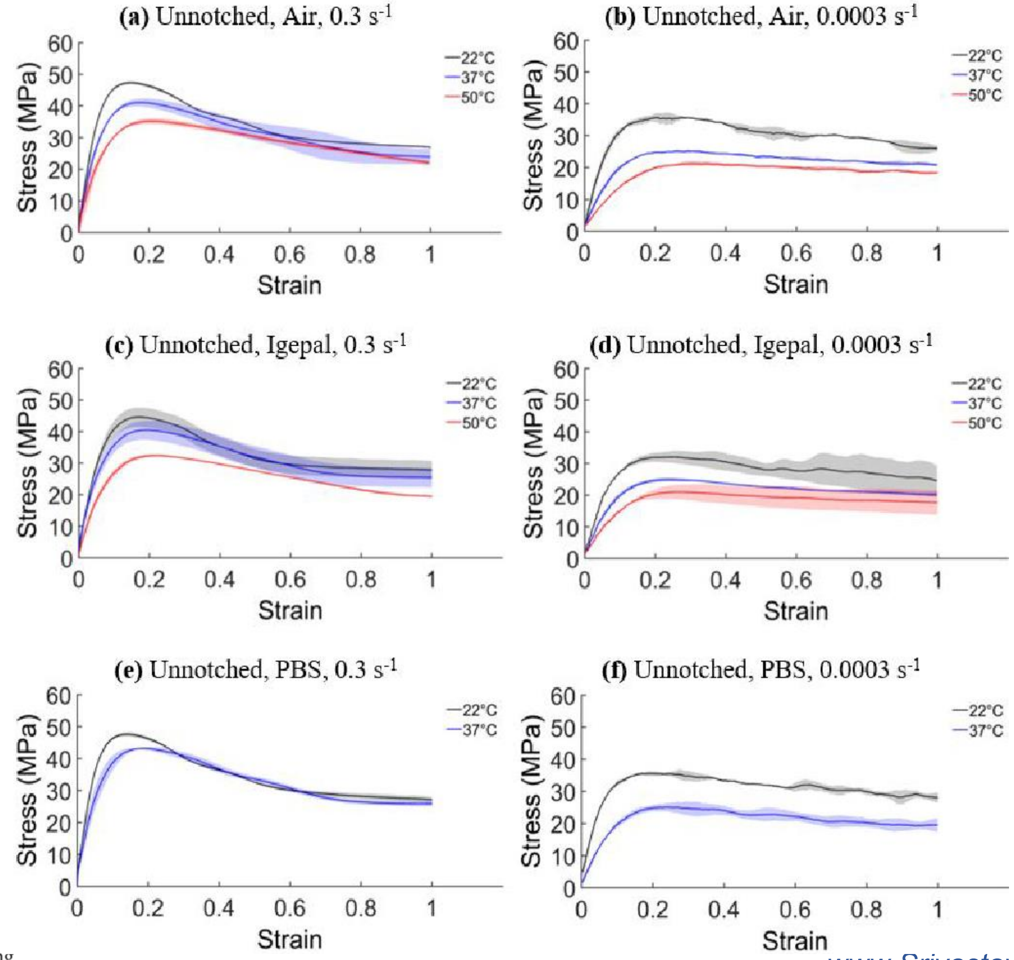


0.0003 /s

Air

Igepal

PBS



Strain Rate =		$0.0003\ s^{-1}$	
Treatment	Temperature (°C)	E (MPa)	σ_{max} (MPa)
Air	22	383	38
Air	37	218	26
Air	50	143	22
Igepal	22	348	33
Igepal	37	233	25
Igepal	50	165	21

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Research Outcomes 2:
Crack Length and Position Measurements using Ultrasound NDT and CNN

Crack length ***a*** is one of the most critical parameter

$$\dot{\delta} \propto a^m \qquad \text{where } m > 0 \qquad \text{(Slow Crack Growth Model)} \qquad (1)$$

$$\sigma_f \propto a^m \qquad \text{where } m = -\frac{1}{2} \qquad \text{(Linear Elastic Fracture Mechanics)} \qquad (2)$$

Nondestructive evaluation (NDE)

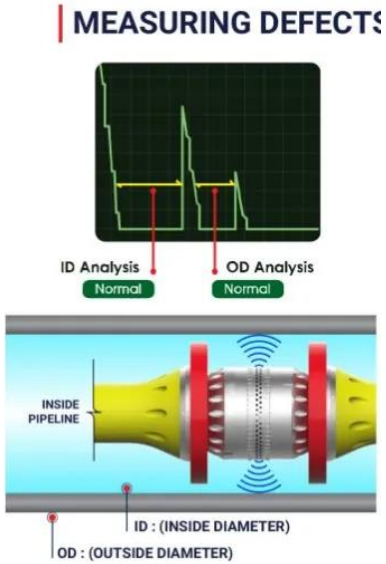
NDE is a non-destructive evaluation inspection technique used to detect and characterize flaws in structures without damaging the material.

- **Ultrasonic testing**
- Infrared testing
- Electromagnetic testing
- Magnetic particle testing

Manual ultrasound NDT

Example: ILI detects flaws using smart pipeline integrity gauges (PIGs) with NDT techniques

Ultrasonic smart PIG



Willems et al., *European Conference on Non-destructive Testing*, 2010

https://www.dacon-inspection.com/pipeline-services/intelligent-pigging/ultrasonic-in-line-inspection-ili-pigging/

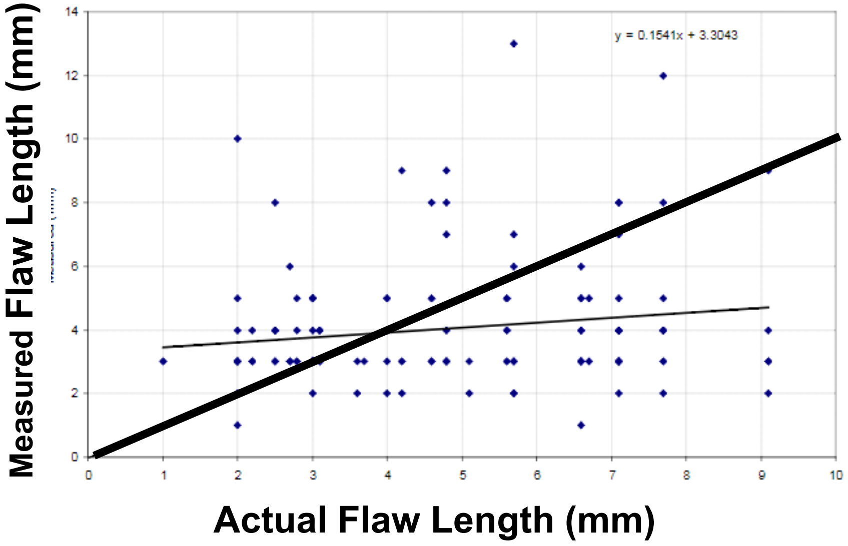
https://www.eddyfi.com/en/product/rscan-manual-ultrasonic-system

Motivation

"Information for the procurement and conduct of NDT," *The British Institute of Non-Destructive Testing*, 2008.

Current HDPE pipe integrity challenges:

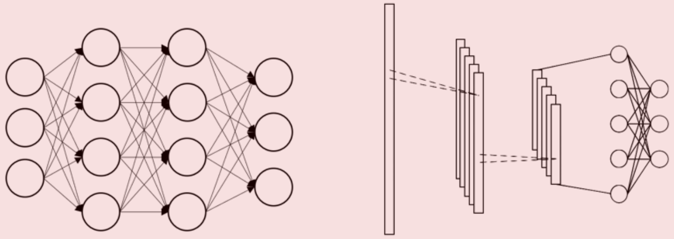
- **Interpretation from human operator**
- <u>Black line:</u> ideal interpretation (metal)
- Blue dots: real experiment data (metal)
- **Lack of fast quantification NDE**



Current limitations:

1. Interpretation uncertainty

Machine learning



ML when trained can be very useful but where is the data?

2. Lack of training data from experiments

Training data fact sheet

- Very scarce for hidden flaw
- Not well-labeled
- Extremely costly from experiments

Quantification of an embedded crack: Our methodology

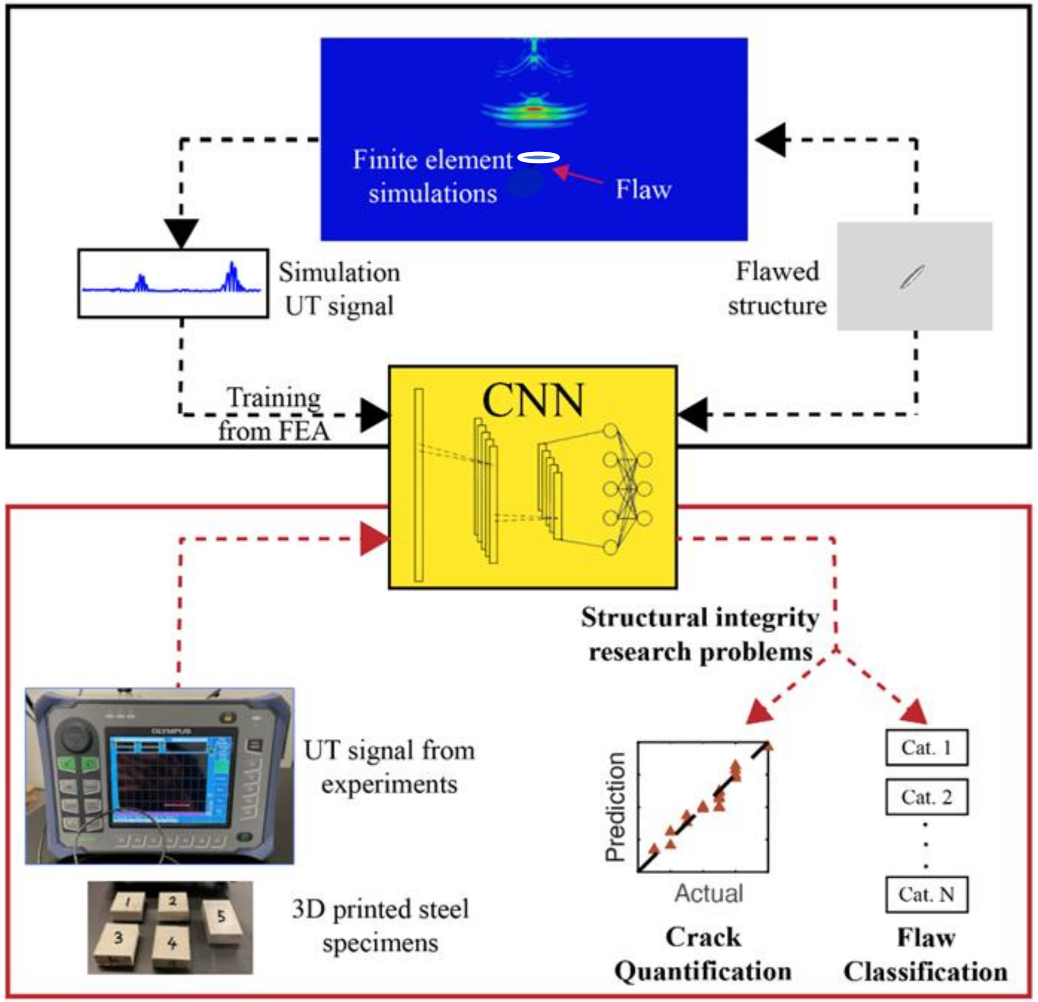
Our Proposed Method:

- **FEA** of ultrasound NDT – A scan (fast scan)
- Simulation-based, **well-labeled** training data
- Microseconds fast obtained unprocessed1D signal-based (Ultrasound A-scan based) **CNN**

  (The proposed method solves the problem of a lack of a non-destructive evaluation methodology that can ***rapidly and accurately*** *predict embedded crack length and position simultaneously in long HDPE pipes.)*

- **Validation with independent real-life lab experiments**

Computation



Experiment

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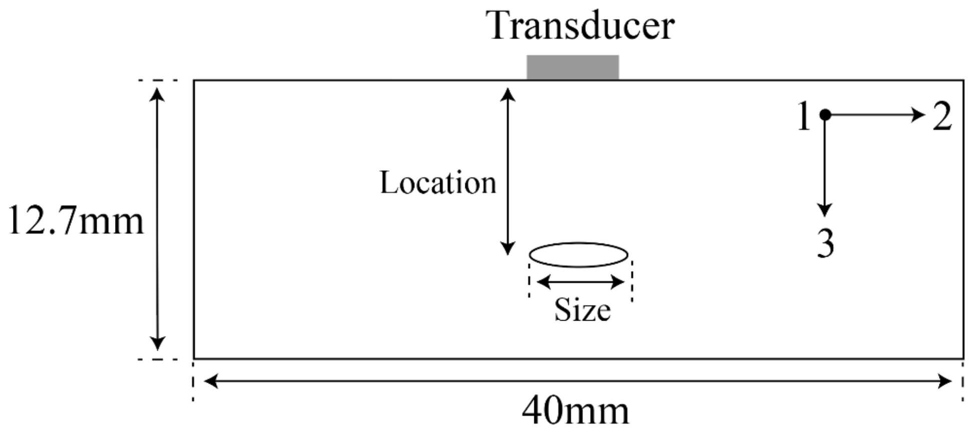
3D numerical simulation representing ultrasound NDT

Abaqus/Explicit

- Dynamic analysis
- Time dependent pressure BC
- Nodal displacement



3D Geometry. Penny-shaped crack.

Crack length/size to its thickness ratio varied from 2 to 12.

Pulse amplitude

$$A = \begin{cases} \cos(2\pi f t)\left[1 - \cos\left(\frac{2\pi f t}{m}\right)\right], & 0 \leq t \leq \frac{m}{f} \\ 0, & \text{otherwise.} \end{cases}$$

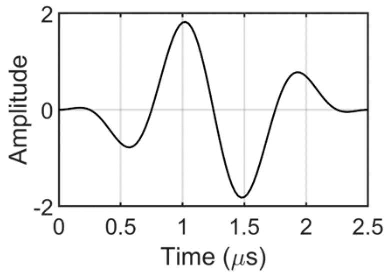
Parameter	Length	Position
Min	1 mm	3 mm
Max	6 mm	11 mm

Averaged 3-direction displacement

$$\text{Signal }(t) = \frac{1}{n}\sum_{i=1}^{n} u_3^i(t)$$

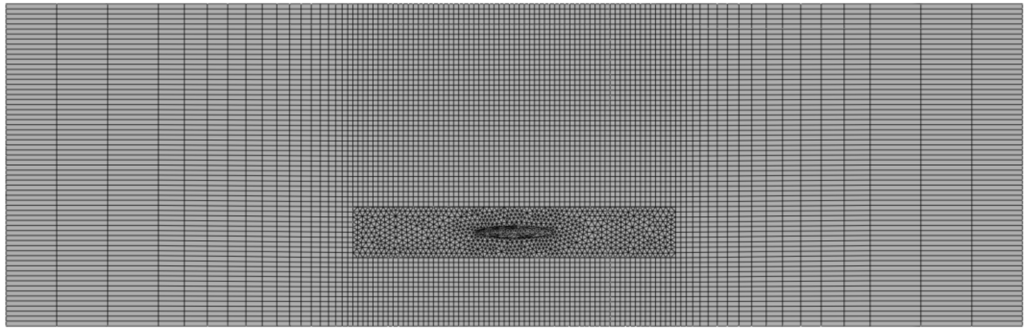
Normalization

$$\text{Signal }(t) = \frac{|\text{ Signal }(t)|}{max(|\text{ Signal }(t)|)}$$



1 MHz Ultrasound

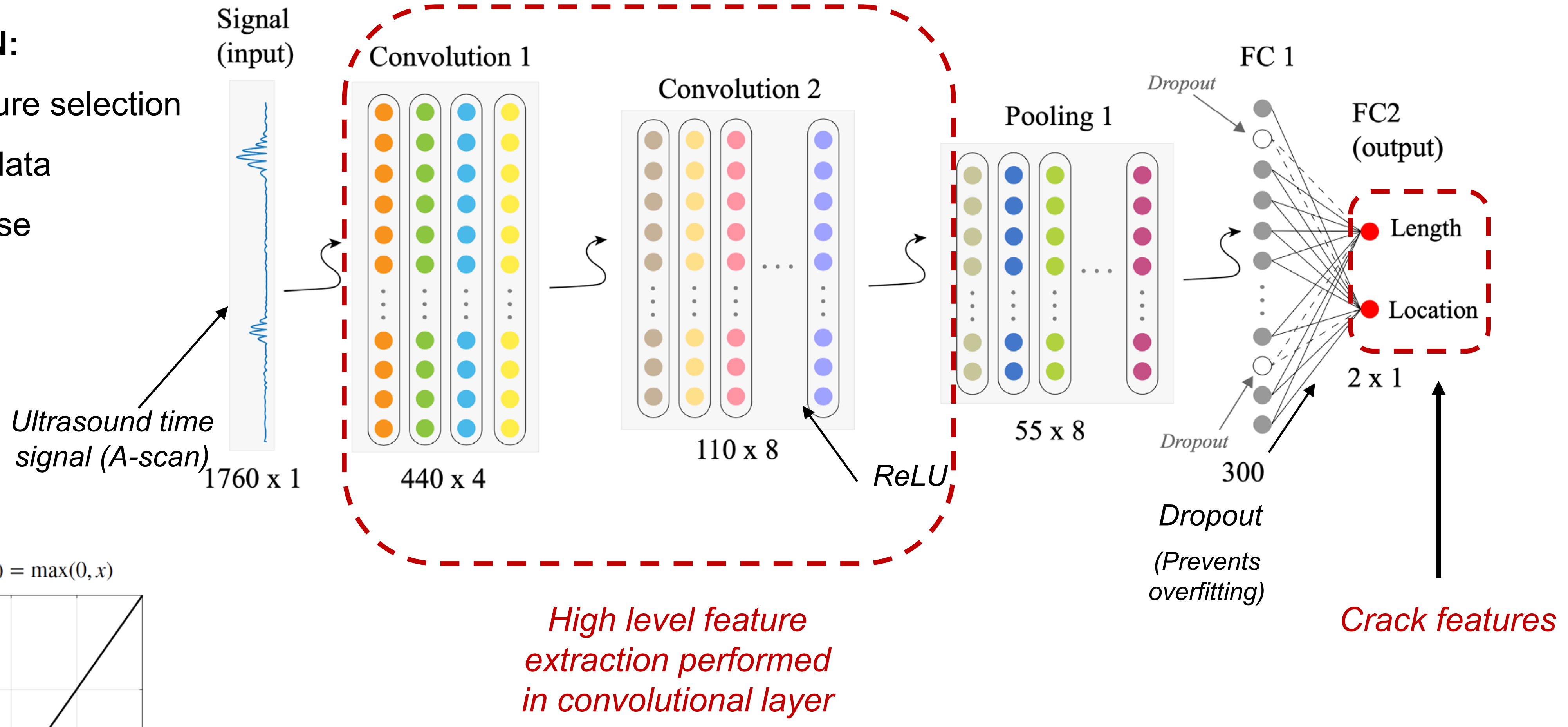
FEA mesh

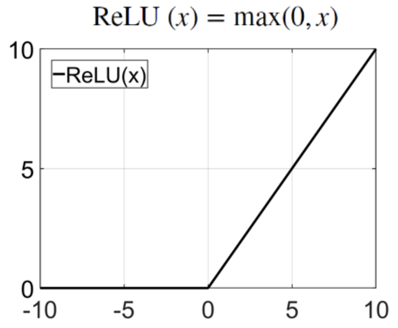


1D Convolutional neural network (CNN)

Signal-based CNN:

- No manual feature selection
- Fewer training data
- Resistant to noise





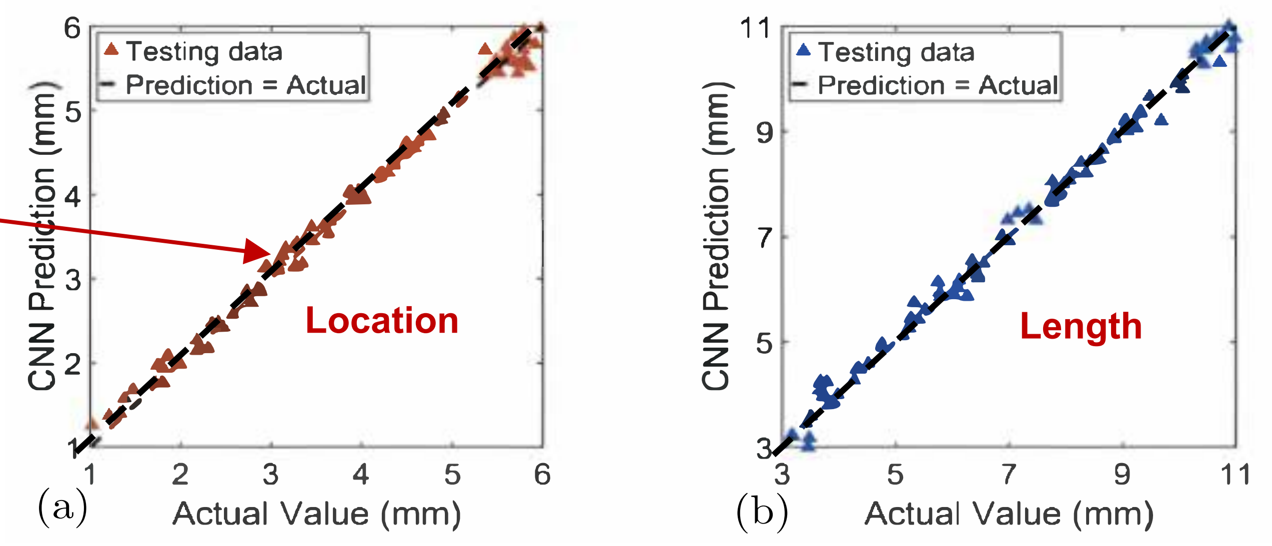
Results: Training and testing of a CNN

CNN was trained for 2000 epochs for a learning rate of 0.0005

1600 training data, 100 testing data

From simulations:

45° line



Embedded crack characterization

Crack feature	Length	Location
Error (MAPE)	**3.2%**	**2.5%**

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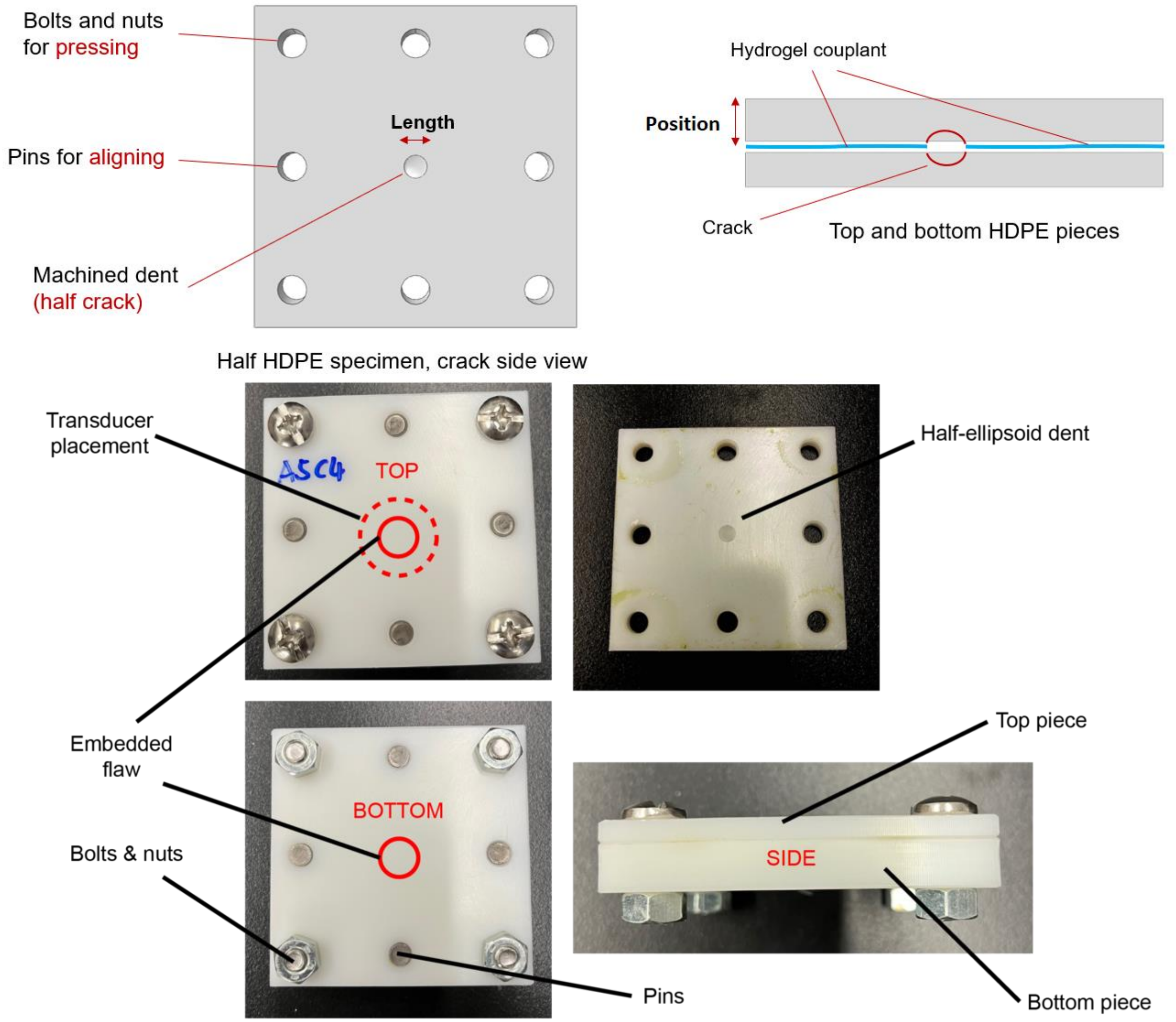
Validation using HDPE samples: sample preparation

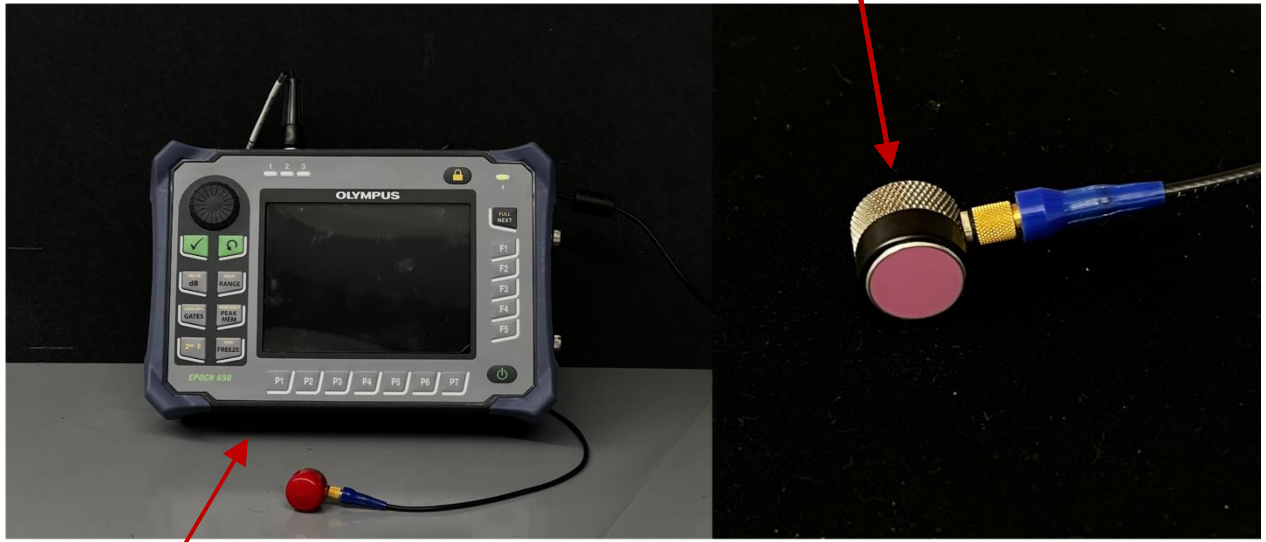


Validation using physical ultrasound NDE experiments

Ultrasound sensor with a hydrogel couplant on a material sample

Ultrasound transducer

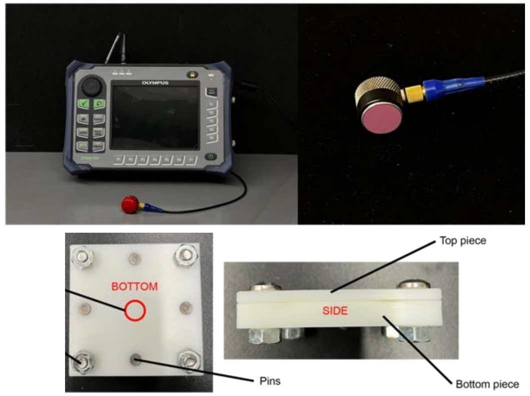
- Single element
- Straight beam
- 1 MHz
- 12.7 mm diameter



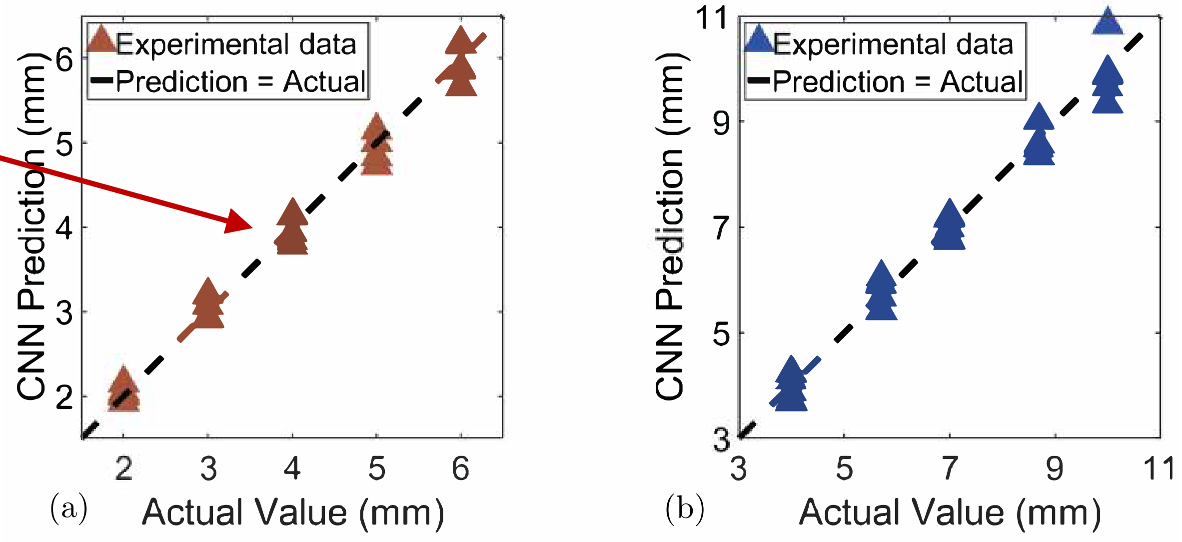
Olympus Epoch 650
Ultrasonic Flaw Detector

Accurate quantification of multiple crack features

- The CNN that was pre-trained only by simulation signals
- Results are shown for crack feature predictions on 25 experimental signals; **these experiments were completely independent**



45° line



Crack feature	Length	Location
Percentage error (MAPE)	**3.2%**	**3.8%**

The methodology can be applied to curved geometries such as pipelines.

Closing remarks

1. **SCG Model**:
   A new model for Slow Crack Growth in HDPE that incorporates thermal and chemical effects has been developed.

2. **Chemical Exposure Effects**:
   Findings show significant differences in failure times between chemically exposed and unexposed HDPE, underscoring the importance of including chemical exposure in the SCG model.

3. **Machine Learning in Non-Destructive Evaluation (NDE)**:
   The study successfully applies machine learning to process fast microsecond acquired unprocessed ultrasound time signals for measuring embedded cracks in HDPE, offering a faster, feasible and more accurate alternative to traditional NDE methods.

Closing remarks (Continued)

4. Industry Implications:

- Future recommendations include further tests and work for SCG model validation, parameter calibrations and model modifications *as needed for specific materials, chemical environments and applications.*
- It is recommended to customize the proposed FEA and CNN-based NDE method for plastic pipeline NDE considering key field variables and flaw types.
- The proposed method should be considered for further development and deployment of advanced NDE units equipped with machine-learning (ML) analysis chips for field use (e.g., an ultrasonic detector with NN in an ILI).
- The proposed method of physically accurate simulations to train ML for NDE can also be applied to other NDE techniques.

Closing remarks (Continued)

5. **Current and Future Critical Research Needs**:

- Need strong support and leadership from federal agencies, industry partners and university researchers to work together to develop robust understanding and 3D models for polymer damage under stress, thermal and chemical exposure.
  - Scientifically and carefully **study** ***microstructural damage mechanisms*** in important polymers and **develop** physics-based continuum scale (practical length scales) 3D damage and failure theoretical frameworks and constitutive models for broader applicability.

- Polymer failure research is critical for onshore (pipelines) and offshore (pipelines, flexibles, risers, etc.) structures where polymers are subjected to long-term exposure degradation and stress.
  - Continued commitment towards (polymer) structural safety from DOT, industry and academia is greatly appreciated.

Closing remarks (Continued)

5. Relevant Publications:

- Sijun Niu, Venkatsai Bellala, Daanish Qureshi, and Vikas Srivastava, A machine learning method to characterize the crack length and position in high-density polyethylene using ultrasound, *arxiv.org*, 2023. https://doi.org/10.48550/arXiv.2304.11497

- Sijun Niu and Vikas Srivastava, Simulation trained CNN for accurate embedded crack length, location, and orientation prediction from ultrasound measurements, *International Journal of Solids and Structures*, 242, 111521, 2022. https://doi.org/10.1016/j.ijsolstr.2022.111521

- Sijun Niu and Vikas Srivastava, Ultrasound classification of interacting flaws using finite element simulations and convolutional neural network, *Engineering with Computers*, 1-10, 2022. https://doi.org/10.1007/s00366-022-01681-y

- Sijun Niu, Enrui Zhang, Yuri Bazilevs, and Vikas Srivastava, Modeling finite-strain plasticity using physics-informed neural network and assessment of the network performance, *Journal of the Mechanics and Physics of Solids*, 172, 105117, 2023. https://doi.org/10.1016/j.jmps.2022.10517

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The project Page with the Final Report and debrief presentation can be found here.

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