CAAP Quarterly Report

Date of Report: 03/31/2020

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

Contract Number: 693JK31950008CAAP

Project Title: Distributed Fiber Optic Sensor Network for Real-time Monitoring of Pipeline Interactive Anomalies

Prepared by: Dr. Yi Bao and Dr. Ying Huang

Contact Information: Email: yi.bao@stevens.edu, Phone: (201) 216-5223

For quarterly period ending: 03/29/2019

Business and Activity Section

(a) Contract Activity

Discussion about contract modifications or proposed modifications

None.

Discussion about materials purchased

None.

(b) Status Update of Past Quarter Activities

High level summary of the work performed for the reporting period.

In the second quarter, the university research team partially completed Task I and Task IV of the above mentioned project, including experimental testing on the responses of two types of distributed fiber optic sensors subjected to temperature change, strain change, and cracks, in addition to advising two graduate students and two undergraduate students, as well as an outreach event to primary school students in New Jersey on Jan. 29th, 2020 to expand the educational impact of this project.

(c) Cost share activity

None.

(d) Task I: Developing and Characterizing Distributed Fiber Optic Sensors

In Task I, we aim to develop and characterize distributed fiber optic sensors under (i) deformation, (ii) corrosion, and (iii) excavation, as well as (iv) conducting a sensitivity study. In the second quarter, two activities were performed for Task I, including (1) characterization of the responses of distributed fiber optic sensors subjected to temperature change, strain change, and cracks through experimentation; (2) trainings of two graduate students and two undergraduate students for experimental testing of fiber optic sensors, and outreach activities with local primary school students including a campus visit event.

Detailed discussion and descriptions for the following:

1. Background

In the last quarterly report (the first report for October 1, 2019 to December 29, 2019), distributed fiber optic sensors were shown to be promising for measuring multiple types of anomalies and likely advantageous over the other existing methods, with regard to the measurement accuracy, sensitivity, and spatial distribution measurement over a long distance. However, the sensitivity of distributed fiber optic sensors has not been fully investigated through experimentation. Although in the PI's previous research, a distributed fiber optic sensor was experimentally tested over a large temperature range (upper temperature up to 1000 ºC), the distributed fiber optic sensing system (Neubrescope 7020) had limited spatial resolution (down to 2 cm, as specified by the manufacturer – Neubrex, Japan). In this study, the research team tested the temperature responses using a different type of sensing technology and sensing system (Luna ODiSi 6), which has been specified by the manufacturer (Luna) with an improved spatial resolution (down to 0.65 mm).

2. Objectives

In the second quarterly research, there were three main objectives: (1) to characterize and calibrate the distributed fiber optic sensors under temperature changes; (2) to characterize and calibrate the distributed fiber optic sensors under strain changes; and (3) to characterize and calibrate the distributed fiber optic sensors under cracks.

3. Experimental program

3.1. Optical Fibers

Two types of optical fibers have been tested in this quarterly research. The two types of fibers have different packages: one type with the bilayer acrylic coating (outer diameter: 245 µm), and the other type with a tight buffer coating in addition to the bilayer acrylic coating (outer diameter: 900 µm). Each of the optical fiber was connected with a LC/APC connector with PVA coating for mechanical protection. The fiber core is Corning® SMF28e+. The maximum insertion loss is 0.30 dB, and the minimum return loss is 60 dB, satisfying the requirement of making customized distributed fiber optic sensor. The product specifications of LC/APC pigtail are shown in Table 1.

Table 1. Product Specifications of LC/APC pigtail

Connector A	LC	**Connector B**	Unterminated
Fiber mode	9/125 µm	**Fiber count**	Simplex
Fiber grade	G.652.D	**Minimum bend radius**	30 mm
Polish type	APC	**Cable diameter**	0.9 mm
Cable jacket	PVC	**Jacket color**	Yellow
Wavelength	1310 nm/1550 nm	**Durability**	>1000 Times
Insertion loss	≤0.3 dB	**Interchangeability**	≤0.2 dB
Return loss	≥60 dB	**Vibration**	≤0.2 dB
Operating temperature	-40~75°C	**Storage temperature**	-45~85°C

3.2. Equipment

The temperature sensitivity coefficients of the distributed fiber optic sensor were tested using an environmental chamber (model: Associated Environmental Systems) and distributed sensing system (model: LUNA ODiSi 6102). The mechanical testing was conducted using a universal load testing frame (Instron 3382A, load capacity: 100 N). Fig. 1 shows the adopted equipment in the experiment.

(a) (b) (c)

Fig. 1. Adopted equipment: (a) environmental chamber, (b) Instron loading test frame, and (c) distributed sensing system.

The environmental chamber uses a heating element that has a temperature ranging from -65°C to +180°C. The accuracy of temperature is ±0.1. The maximum heating and cooling rates are 1℃/s. The load frame uses a load cell with a load capacity of 100 kN capacity. The load measurement accuracy of the load frame is ±0.5% of reading down to 1/500 of load cell capacity option. The data acquisition rate is up to 0.5 kHz. The speed range is 0.005-508 mm/min. Please see the specification details in Fig. 2.

Force Capacity[1]	kN	100
	lbf	22500
Vertical Test Space[3]	mm	1430
	in	56.3
Horizontal Test Space[4]	mm	575
	in	22.6
Testing Speed Range Min-Max (Return)	mm/min	0.005-508 (600)
	in/min	0.0002-20 (24)
Position Control Resolution	nm	60
	µin	2.4

Common Specifications

Force Measurement Accuracy
±0.5% of reading down to 1/200 of load cell capacity. ±1% of reading from 1/200 to 1/500 of the load cell capacity. [1]

Displacement Measurement Accuracy:
±0.02 mm or 0.15% of displacement (whichever is greater)

Strain Measurement Accuracy:
Meets or surpasses the following standards: ASTM E83, ISO 9513, and EN 10002-4.

Testing Speed Accuracy:
(Zero or constant load): ±0.2% of set speed

Fig. 2. Specification details of the load frame.

The distributed sensing system has two activated independent channels, and the maximum sensor length per channel is 10 m in the standard mode, which can be extended to 50 m for up to four channels). The gage pitch can be 0.65 mm, 1.3 mm, or 2.6 mm, which stands for the spacing between two measurement points in the distributed fiber optic sensor. More details of the distributed sensing system are shown in Table 2.

Table 2. Specification details of LUNA ODiSI 6102

Parameter		Specification			Units
Gage Pitch[1]		0.65 mm	1.3 mm	2.6 mm	
Number of channels		1, 2, 4 or 8 channels			
Maximum sensor length per channel	Standard	10			m
	Extended range	50 (available on 4 channels)			m
Gages (measurement locations) per meter		1,538	768	384	gages/m
Maximum gages per sensor	Standard	15,384	7,692	3,846	gages/ch
	Extended range	-	38,461	19,230	gages/ch
Standoff cable length		50 or 100			m
Measurement Rates (Rates are aggregate; divide by number of active channels to determine the per-channel rate)					
Real-time measurement rates (rates with optional rack or tower controller are shown in parenthesis)	2.5 m mode	62.5	125	250	Hz
	5 m mode	20 (40)	40 (80)	80 (160)	Hz
	10 m mode	12.5 (25)	25 (50)	50 (100)	Hz
	20 m mode	6 (12.5)	12.5 (25)	25 (50)	Hz
	50 m mode	-	5 (10)	10 (20)	Hz
HD Strain Measurement					
Strain measurement range		±12,000			με
Resolution		1			με
Instrument accuracy		±1			με
System (instrument and sensor) accuracy[2]		±25	±30	±30	με
System repeatability at zero strain[3]	Standard	< ±20	< ±10	< ±5	με
	Extended range	< ±40	< ±30	< ±20	με
System repeatability across full strain range[4]		±0.55	±0.35	±0.15	%
Dynamic loading rate		1	2.5	5	Hz
HD Temperature Measurement					
Temperature measurement range (standard sensor)		-40 to 200			°C
Resolution		0.1			°C
Repeatability		±0.7	±0.4	±0.2	°C

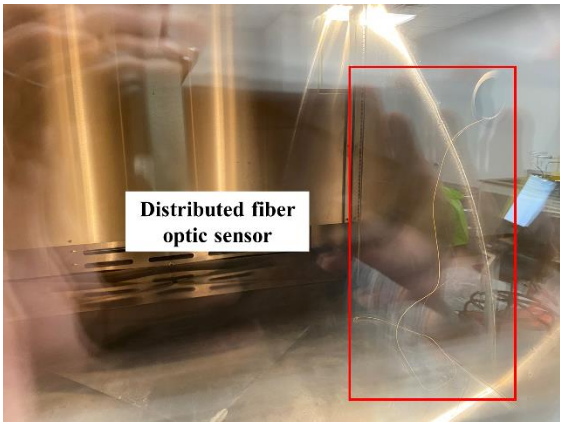
3.3. Experimental characterization under temperature changes

The temperature coefficient of optical fibers was calibrated using a temperature chamber and sensing system. Optical fibers were put in the chamber through a custom porting and connected with the distributed sensing system. The temperature and humidity in the chamber room are simultaneously monitored using embedded highly-accuracy thermocouple and humidity sensors, respectively.

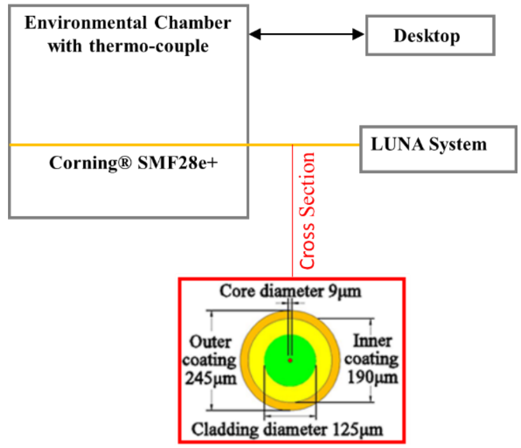
The temperature measured using the thermocouple in the environmental chamber is denoted as T_A. The temperature measured using the distributed temperature sensor is denoted as T_M. The temperature sensitivity coefficient is calibrated by comparing T_A and T_M. More details of the experimental program are shown as follows.

3.3.1. Test set-up and protocol

The test set-up is depicted in Fig. 2. Temperature sensitivity coefficient testing was tested under temperature ramp. With the consideration of the fragility of the plastic coating of fiber, the maximum setting temperature is 160℃. The details of testing set up is shown in Figure 4. We set several temperature stages (-20℃, 0℃, 20℃, 40℃, 60℃, 80℃, 100℃, 120℃, 140℃, and 160℃). The optical fiber was heated to certain stages at 5℃/min loading rate and the temperature was retained for 1 minute.



(a)



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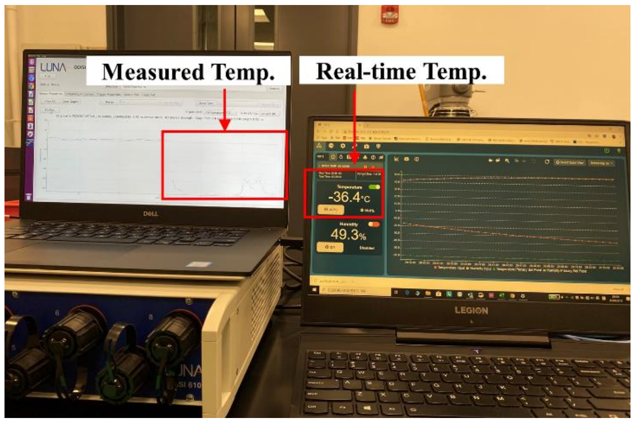
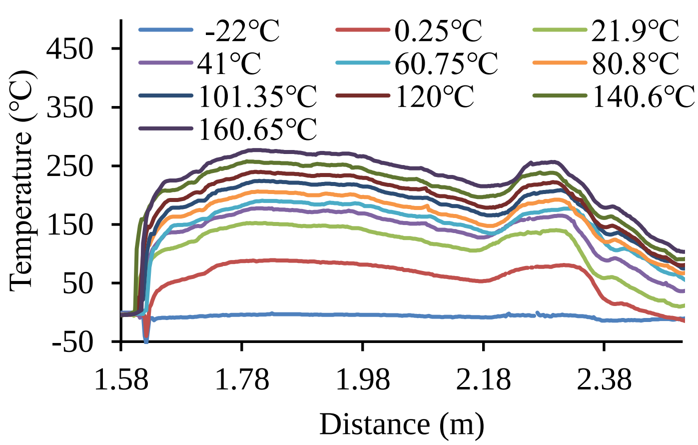


(c)

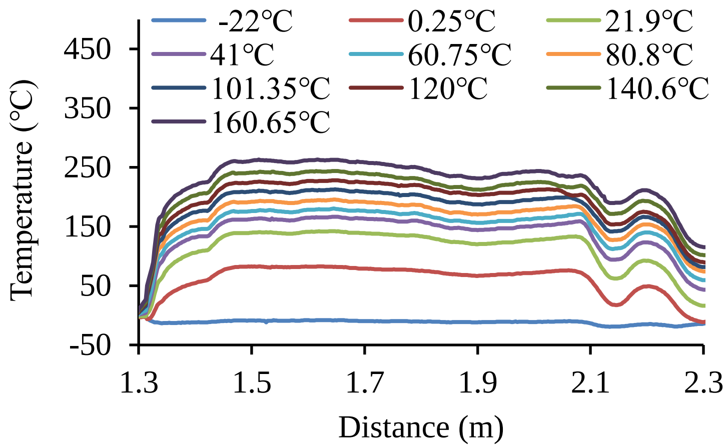
Fig. 3. Experimental test set-up: (a) a photo of the tested distributed fiber optic sensor in the chamber during testing (the distributed sensor in the red box), (b) depiction of the set-up, and (c) simultaneous measurement using the two systems for calibration.

3.3.2. Test results

In total, two pigtails have been tested at elevated temperatures. Results are shown in Fig. 4. The optical fiber behaved almost linearly with the developing of rising temperature. The slope of trend line of real tensile strain and measured tensile strain is 1.29 that can be taken as the temperature sensitivity coefficient of the optical fiber.



(a)



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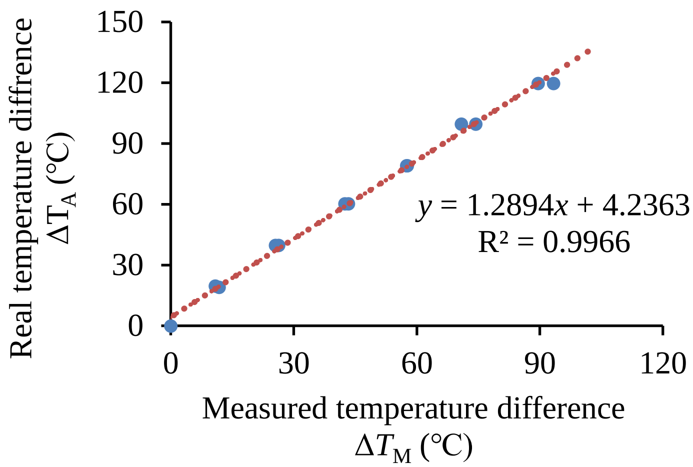


(c)

Fig. 4. Temperature coefficient test results: (1) specimen 1, (b) specimen 2, and (c) calibration curve.

3.4. Experimental characterization under strain changes

The strain coefficient of optical fibers was calibrated using a loading frame (Instron 3382) and distributed sensing system (Luna ODiSi 6). Two types of optical fibers (bare fiber and packaged fiber) were attached on the surface of a steel plate. The real-time deformation and loading force were simultaneously recorded by desktop equipped with Instron loading frame. The real strain (ε_A) was determined by the load frame. Strain (ε_M) in the optical fiber was measured by the distributed sensing system for calibrating the strain sensitivity coefficient.

3.4.1. Experimental test set-up and protocol

Strain sensitivity coefficient of optical fibers was tested under tension load. Considering the fragility of the optical fiber, the optical fiber was attached on steel plates at the two ends of the optical fiber, and the steel plates were gripped by the load frame. The gage length of the optical fiber was 380 mm. The test setup is shown in Fig. 5. The tension test was conducted under displacement control. The loading protocol is shown in Fig. 6. We set several displacement stages (0.4, 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6 mm), which can be transformed into tensile strains (1052, 1579, 2105, 2631, 3158, 3684 and 4210 με), given the gauge length (380 mm). The displacement rate was 0.2 mm/min. At each stage, the strain value was sustained for 10 seconds for operating the measurement.

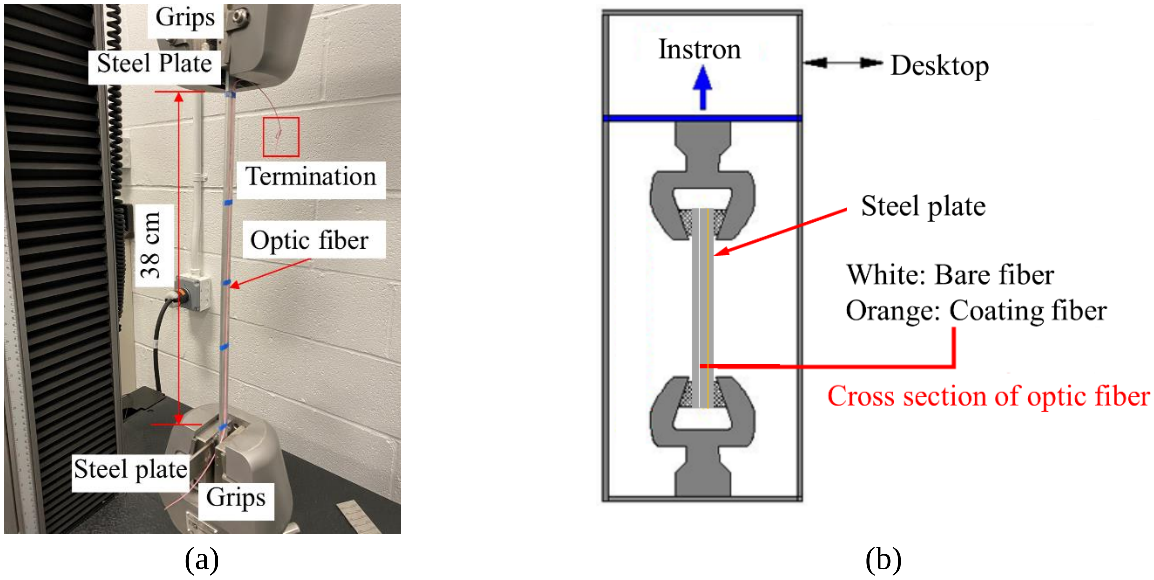


Fig. 5. Experimental test set-up: (a) a photo of the tested distributed fiber optic sensor in the chamber during testing (the distributed sensor in the red box), and (b) depiction of the set-up.

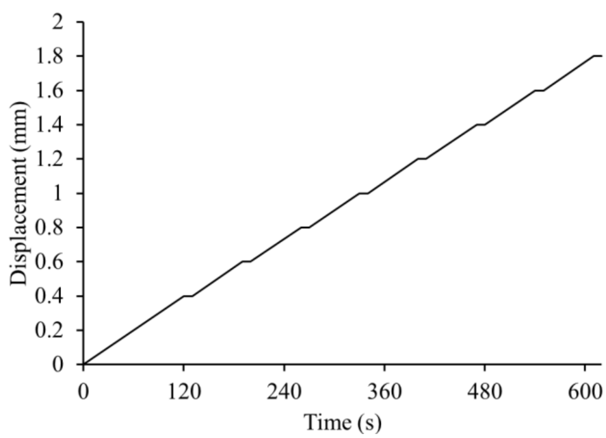
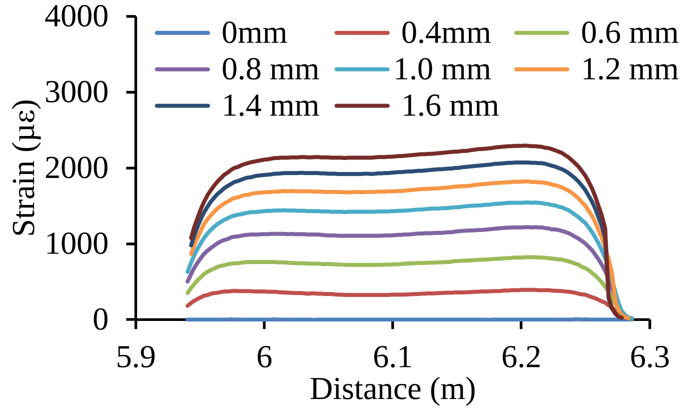


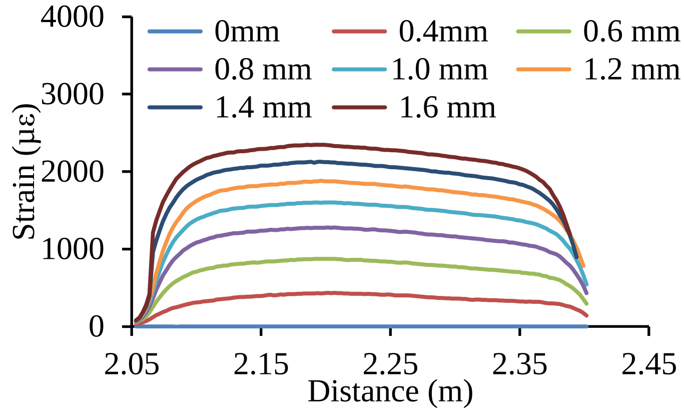
Fig. 6. Loading ramp and hold controlled by Instron loading frame.

3.4.2. Test results

In total, eight tensile stages have been tested, which is shown in Fig. 7. The optical fiber behaved linearly with the developing of tensile displacement. The plateau represents the gauge length of the pigtail fiber. The slope of trend line of real tensile strain and measured tensile strain is 0.5356 and 0.5421 that can be taken as the tensile strain sensitivity coefficient of the optical fiber.



(a)



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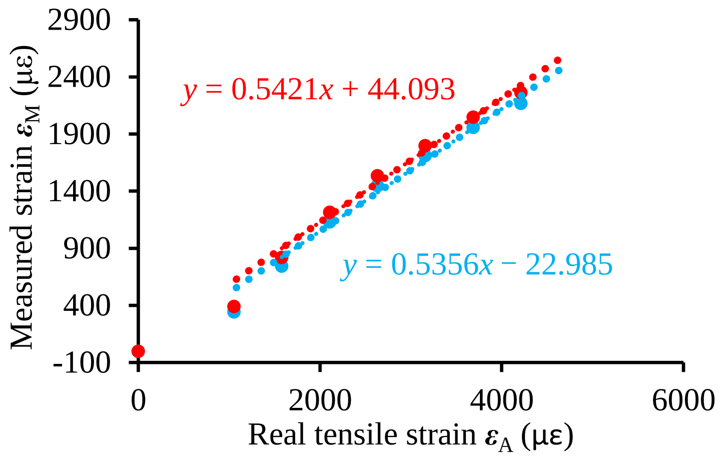

(c)

Fig. 7. Strain coefficient test results: (1) bare fiber, (b) packaged fiber, and (c) calibration curve.

3.5. Experimental characterization under cracks

The crack detection testing was conducted with the load frame and distributed sensing system. Two types of optical fibers were tested. For each type of fiber, the fiber was attached on the surface of two aluminum plates. The relative sliding of the two plates simulated the effect of cracking for the optical fiber. The crack opening width and applied force were simultaneously recorded by desktop equipped with Instron loading frame. The tensile strain in the optical fiber was measured by the distributed sensing system.

3.5.1. Experimental test set-up and protocol

The tension testing was conducted under displacement control at a displacement rate of 0.2 mm/min. Fig. 8 shows the test set-up and the specimen. The specimen was stretched using the load frame. For each specimen, two types of optical fibers were attached on the surface of the aluminum plate continuously using a super glue. After the glue became dry, the tension testing was conducted to mimic the effect of cracking at the contacting interface of the two plates.

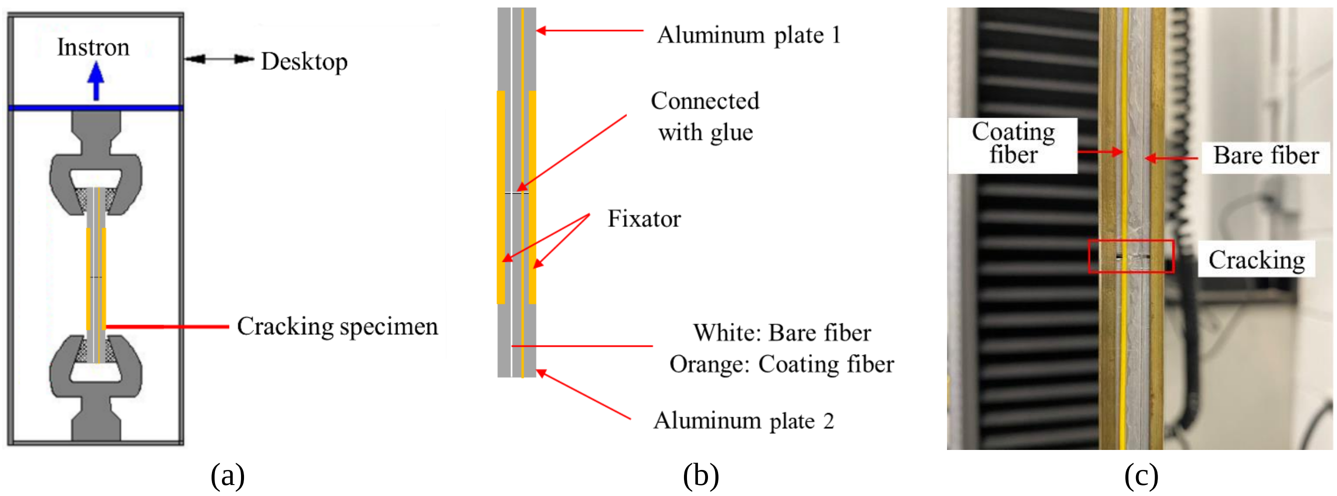

Fig. 8. Experimental test set-up: (a) a photo of the tested distributed fiber optic sensor in the chamber during testing (the distributed sensor in the red box), (b) drawing of cracking specimen and (c) depiction of the set-up.

The loading method is shown in Fig. 9. The loading force and the extension were simultaneously recorded by the load transducer and the extensometer. The tensile force showed a sudden drop at the time instant of 115 s, when was taken as a critical moment to characterize the response of the distributed fiber optic sensor for crack detection.

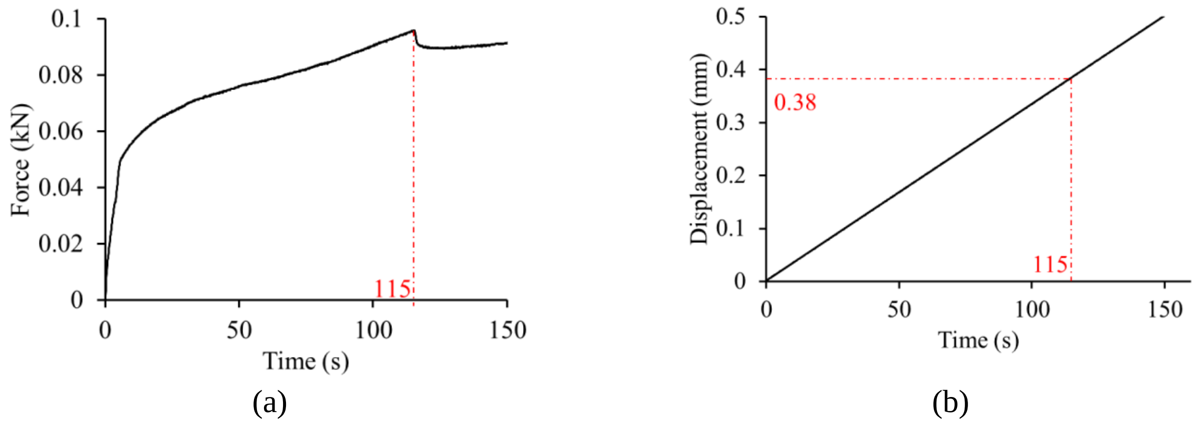

Fig. 9. Loading method controlled by Instron loading frame.

3.5.2. Test results

In total, two types of fibers (fiber with coating and bare fiber) have been tested, and results of time series curves are shown in Fig. 10. We select several time points (0 s, 20 s, 40 s, 60 s, 80 s, 100 s, and 115 s) from the beginning of test to the cracking time, and the peak of curve in each time point represents the cracking propagation process.

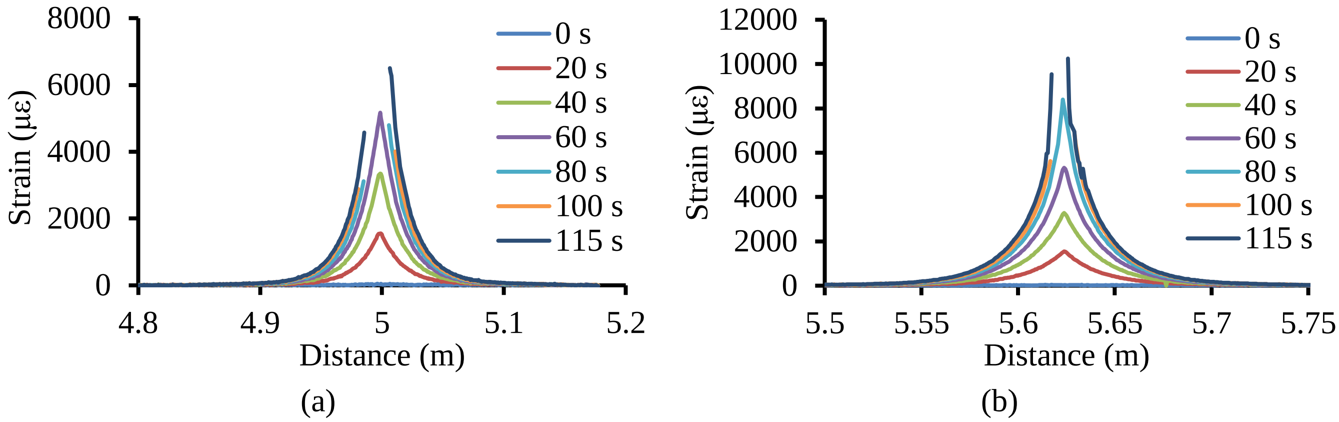

Fig. 10. Strain coefficient test results: (1) fiber type 1, and (b) fiber type 2.

(c) Task IV: Student Training and Reporting

In Task IV, we recruited and have been training two graduate students (one from Stevens and one from NDSU) and two undergraduate students. Through the research, the students will be trained to become future experts in the related fields. In the second quarter, two activities were performed for Task IV, including (1) training two graduate students and two undergraduate researchers to conduct laboratory testing of the distributed fiber optic sensors; and (2) an outreach event named “Smart Infrastructure” to primary school students as a part of the Sustainable Challenge Program in Jersey City.

2.4 Student Mentoring

During the second quarter, two graduate students (Xiao Tan, Ph.D. student from Stevens, and Luyang, Ph.D. student from NDSU) and two undergraduate research assistants (Gina Blazanin and Hashem Sonbol) were trained to work on this project. The two graduate students were trained to conduct laboratory testing for the distributed fiber optic sensors. Two undergraduate research assistants were hired in January 2020, and they assisted the graduate students to carry out the laboratory testing.

2.5 Outreach Activities

On Jan. 29th, 2020 (1:30 pm to 3:30 pm), an outreach event named “Smart Infrastructure” workshop was conducted based on this project. The workshop is a part of the Sustainable Challenge Program in New Jersey. The PI (Dr. Yi Bao) serves on the panel of the Program. This workshop intended to let the primary school students have basic knowledge to plan and build smart pipelines. It is expected to encourage and generate interests for young kids to pursue pipeline engineering for future college education or careers. Table 3 is the schedule of the event.

Table 3. Outreach Workshop Schedule

1:30	-	1:45	Presenter Arrival
1:45	-	2:00	Student Arrival
2:00	-	2:15	Introduction of the smart infrastructure workshop and sustainable challenge program
2:15	-	3:00	Lecture
3:00	-	3:30	Questions & Answers

Approximately 60 primary school students attended this workshop. One graduate student volunteered in this outreach event to guide the primary school students. Fig. 11 shows the photos taken from this event.

Fig. 11. Visiting primary school students in Jersey City for introducing intelligent pipeline technologies.

3. Future work

In the third quarter, there will be three objectives:

1) Focus on the remaining activities planned in Task I: Developing and Characterizing Distributed Fiber Optic Sensors. Based on the laboratory testing of the distributed fiber optic sensors, we will conduct further experiments on using the optical fiber as distributed sensors to test the sensor responses under multiple individual types of defects and the combined defect conditions.
2) Conduct the research activities planned in Task II: Distinguishing Interactive Anomalies Using Point Fiber Optic Sensors. More specifically, fiber Bragg grating sensors will be tested to evaluate the performance of point sensors under multiple individual types of defects and the combined defect conditions.
3) Supervise the two graduate students in performing research Tasks I and II. The two graduate students will conduct the experiments and analyze the data under the supervision of Dr. Yi Bao and Dr. Ying Huang.
4) Conduct an "Intelligent Pipeline" workshop outreach event in the Sustainable Challenge Program to K-12 students in Jersey City. Dr. Yi Bao and a graduate student will visit a local primary school, presenting the research and discussing with the students.

References

[1] TEMPERATURE / HUMIDITY TEST CHAMBERS. https://www.associatedenvironmentalsystems.com/chambers/temperature-humidity.

[2] Luna ODiSI 6100 Multichannel Optical Distributed Sensor Interrogator. https://lunainc.com/wp-content/uploads/2017/11/LUNA-ODiSI-6000-Data-Sheet.pdf.

[3] Simplex LC/APC 9/125 Single Mode Fiber Optic Pigtail, 0.9 mm PVC Outer Jacket. https://www.fs.com/products/42477.html.

[4] 3382A Series Dual Column Floor Model - Instron. https://www.instron.us/-/media/literature-library/products/2013/07/3300-series-floor-models.pdf?la=en-US.

[5] NEUBRESCOPE NBX-7020 (Specs) - Neubrex Co., Ltd. https://www.neubrex.com/htm/products/pro-nbx7020.htm.