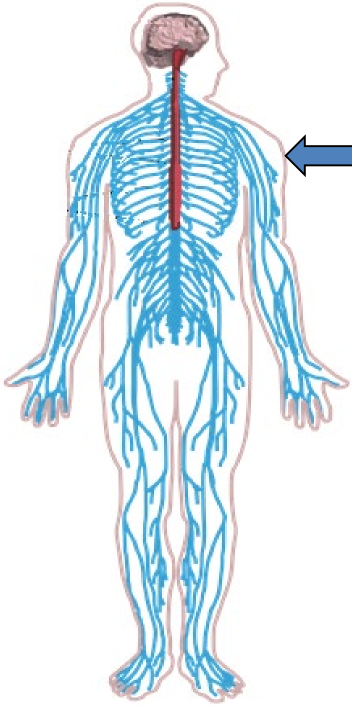
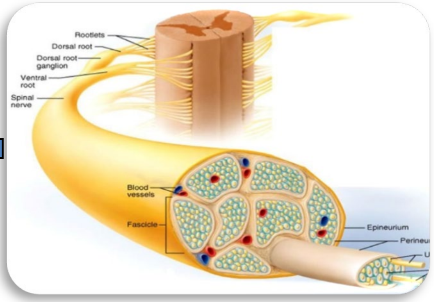
Fiber Optic Sensors for Real-time Monitoring of Civil Infrastructure

Yi Bao, Ph.D.
Assistant Professor in Civil Engineering
Advanced Structure and Process Innovation Research (ASPIRE) Laboratory
Department of Civil, Environmental and Ocean Engineering
Stevens Institute of Technology
Phone: (201) 216-5223
Email: yi.bao@stevens.edu
Webpage: https://web.stevens.edu/facultyprofile/?id=2308

Goal

- My research aims to advance condition monitoring technologies for civil infrastructure through innovations of fiber optic sensors.



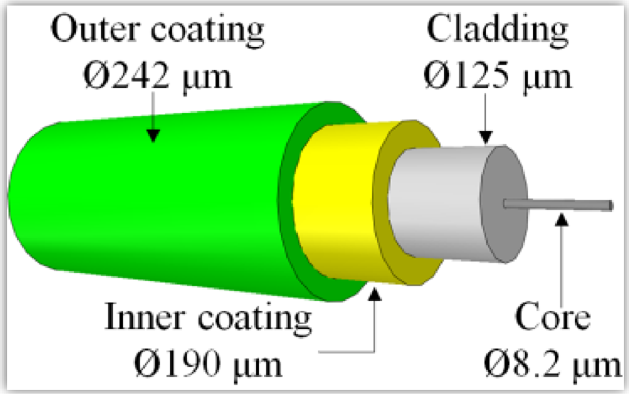


Objectives

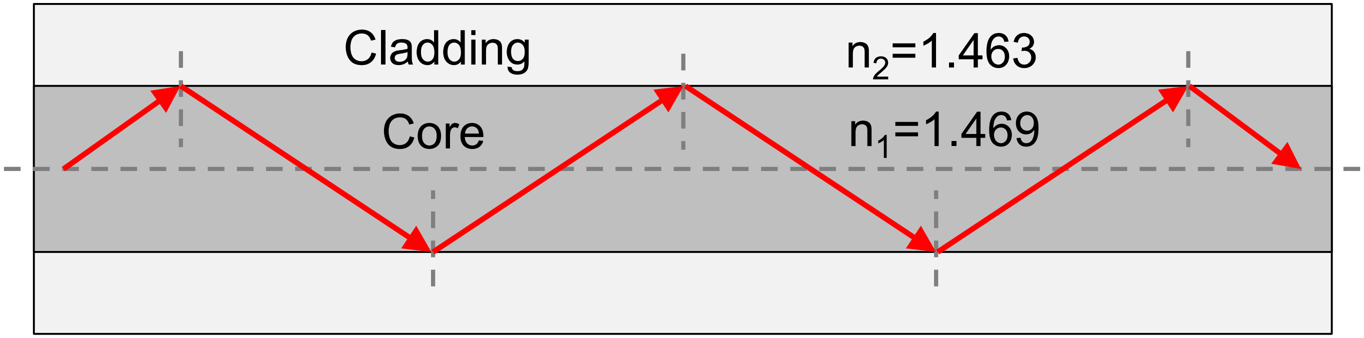
- This research addresses the following challenges:
  - To develop a high-resolution (centimeter order) condition monitoring technique using fiber optic sensors;
  - To detect, locate and quantify shrinkage cracks in concrete;
  - To detect, quantify and predict delamination in layered concrete;
  - To develop novel corrosion sensors for reinforced concrete.

Optical Fiber

- Telecommunication-grade single-mode optical fiber:
  - Core: high-purity fused silica, doped with germanium
  - Cladding: high-purity fused silica, doped with germanium
  - Coatings: mechanical protection

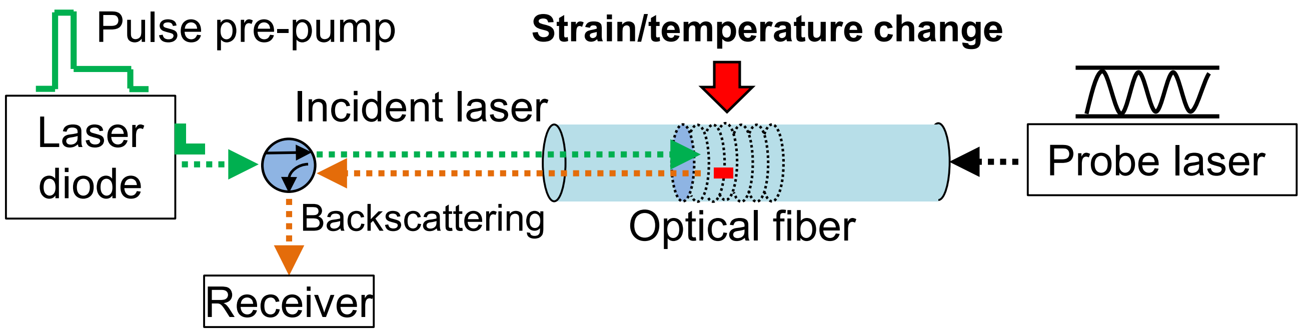


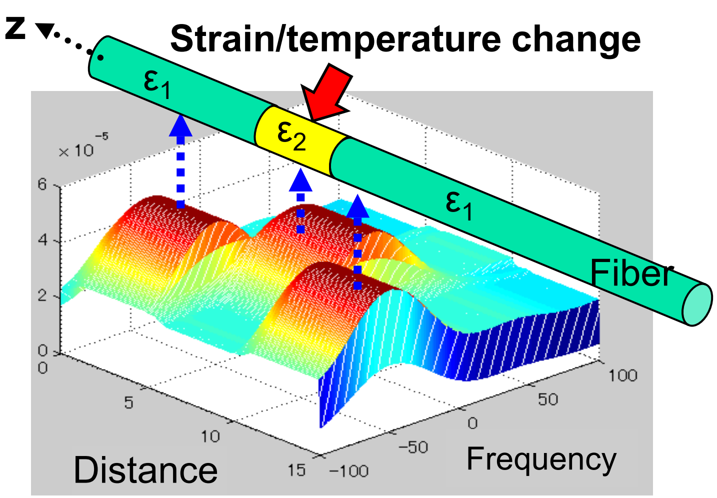
- Light wave is guided through total internal reflection at the core-cladding interface

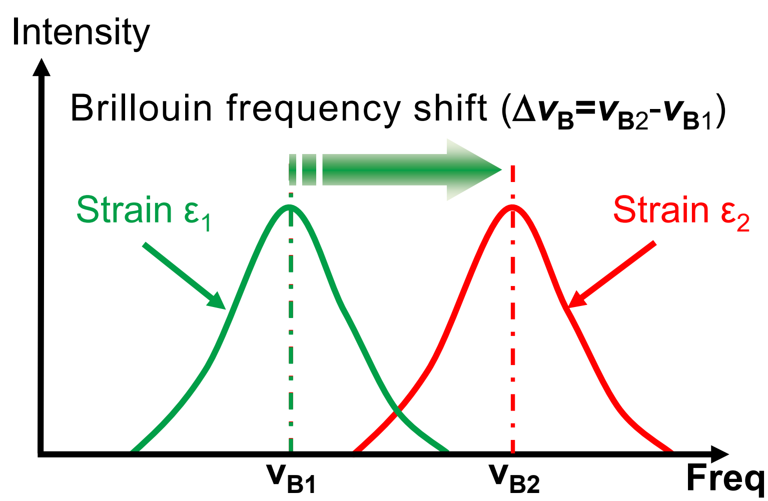


Sensing Technology

- Pulse pre-pump Brillouin Optical Time Domain Analysis (PPP-BOTDA):



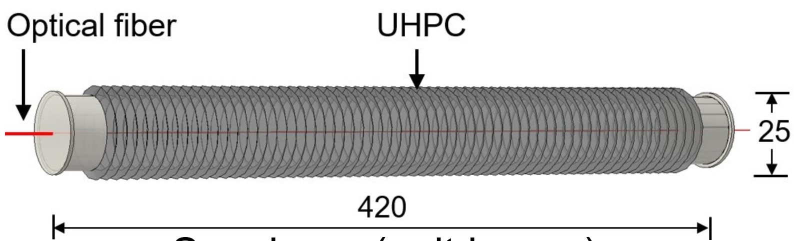




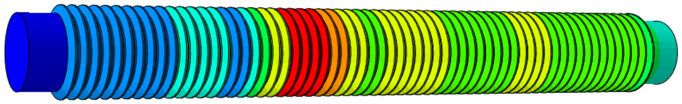
- Brillouin frequency shift: $\Delta v_B = C_\varepsilon \Delta\varepsilon + C_T \Delta T$

Application 1: Measure autogenous shrinkage of ultra-high performance concrete (UHPC)

- Non-uniform shrinkage strain was measured for the 1st time

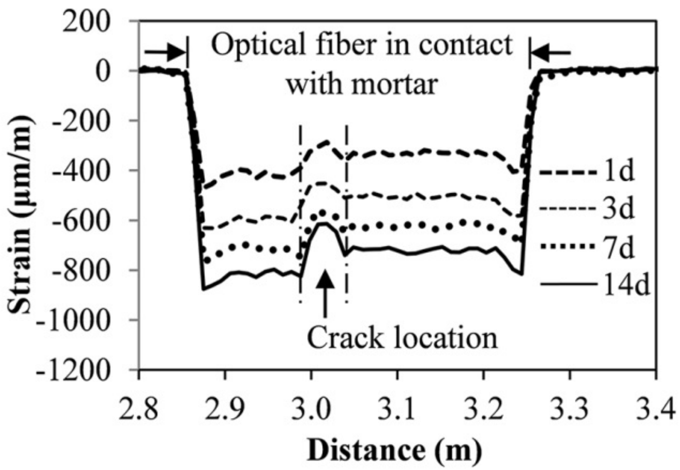


Specimen (unit in mm)



Non-uniform shrinkage strain

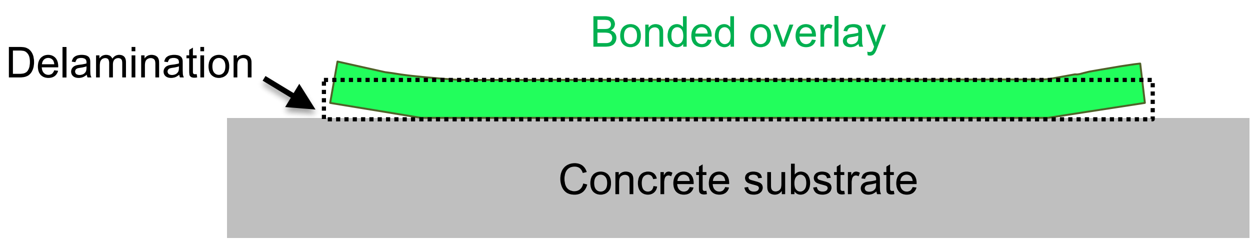
Test set-up for average shrinkage strain

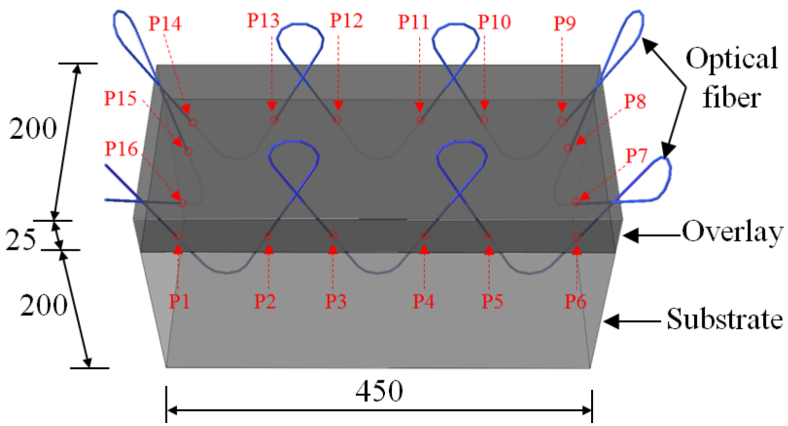


Bao, Y., Meng, W., Chen, Y., Chen, G., Khayat, K.H. (2015). “Measuring mortar shrinkage and cracking by pulse pre-pump Brillouin optical time domain analysis with a single optical fiber.” *Materials Letters,* 145, 344–346.

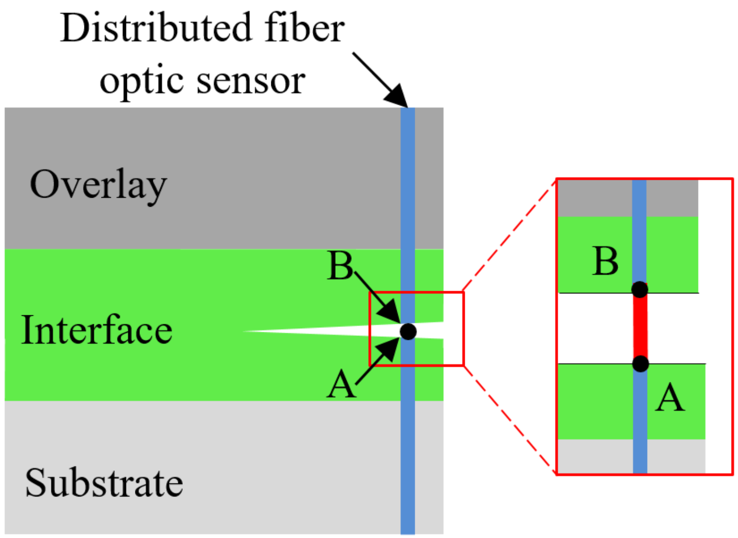
Application 2: Cracks / Debonding in Concrete Pavement Overlays

- Shrinkage of UHPC produces stresses in bonded overlay



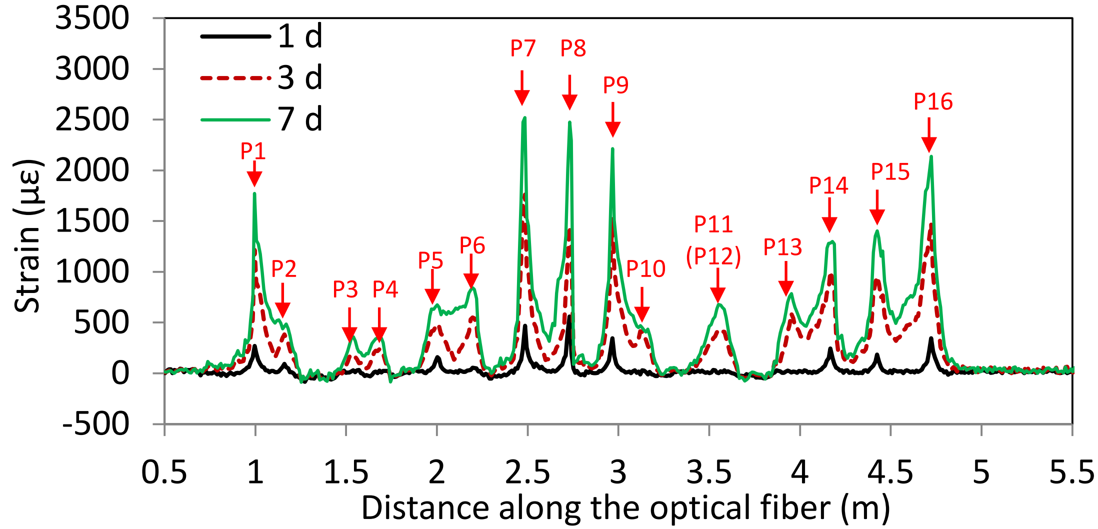


Overlay specimen (unit in mm)



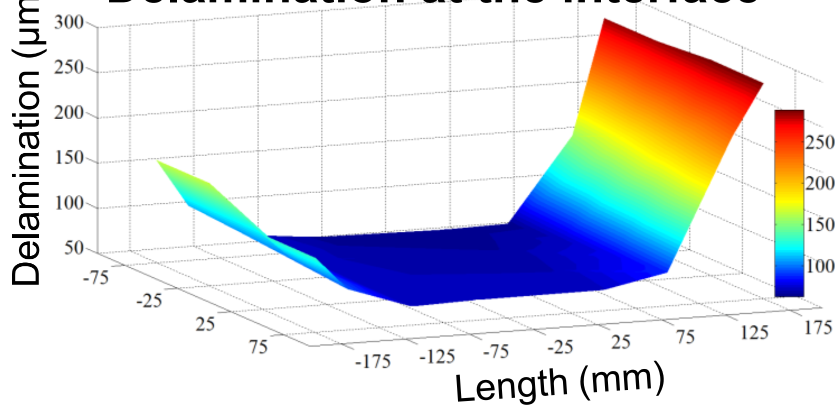
Bao, Y., Valipour, M., Meng, W., Khayat, K.H., Chen, G. (2017). "Distributed fiber optic sensor-enhanced detection and prediction of shrinkage-induced delamination of ultra-high-performance concrete bonded over an existing concrete substrate." *Smart Materials and Structures*, 26(8), 085009.

- The increase of the peak's magnitude represents the development of delamination.

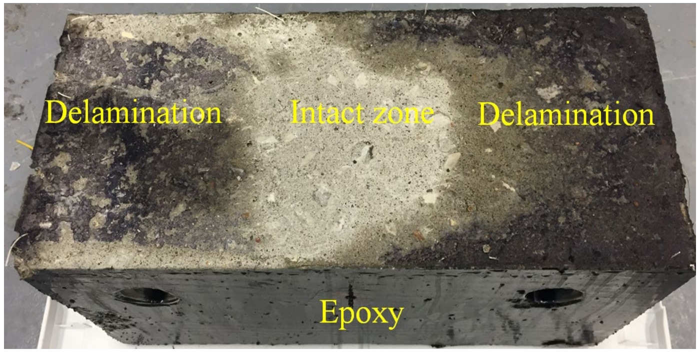


Re-plot

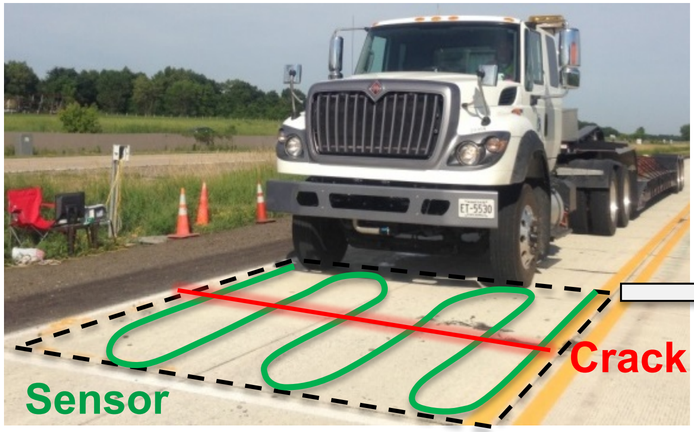
Delamination at the interface



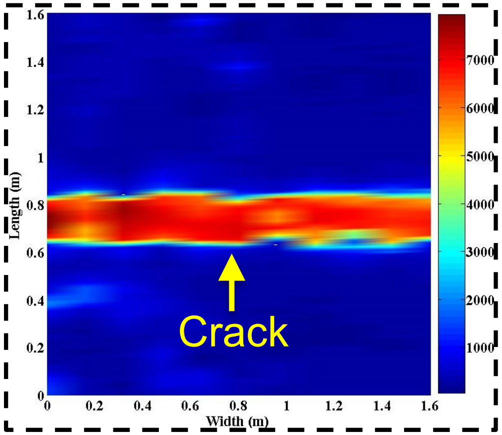
Dye penetrant test



- Distributed sensors are embedded in concrete:
  - Monitor strain, temperature, and cracks
  - Understand degradation mechanisms of concrete pavement overlay in cold weather
  - Improve the design and management of the pavement



Field test in Minnesota

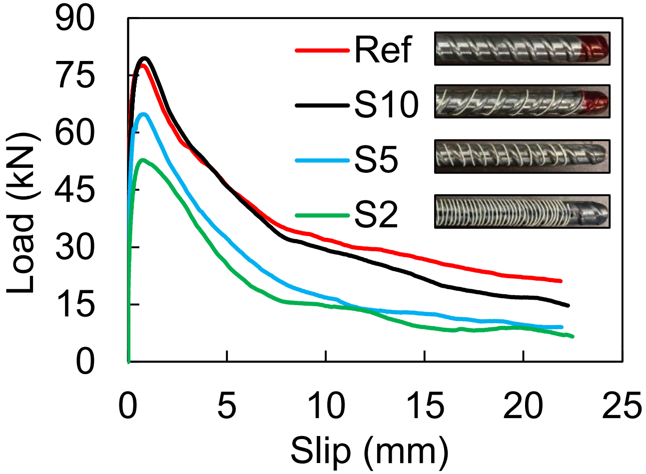


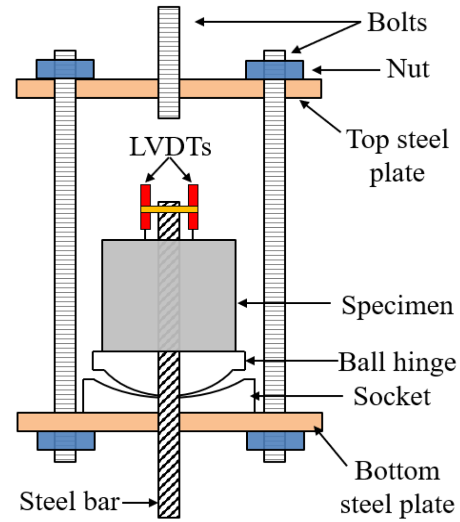
Strain distribution

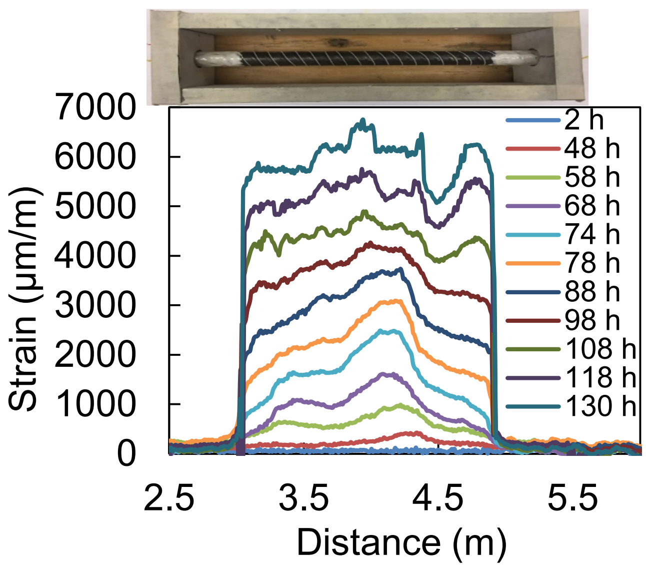
<u>Bao, Y.</u>, Tang, F., Chen, Y., Meng, W., Huang, Y, Chen, G. (2016). "Concrete pavement monitoring with PPP-BOTDA distributed strain and crack sensors." *Smart Structures and Systems*, 18(3), 19p.

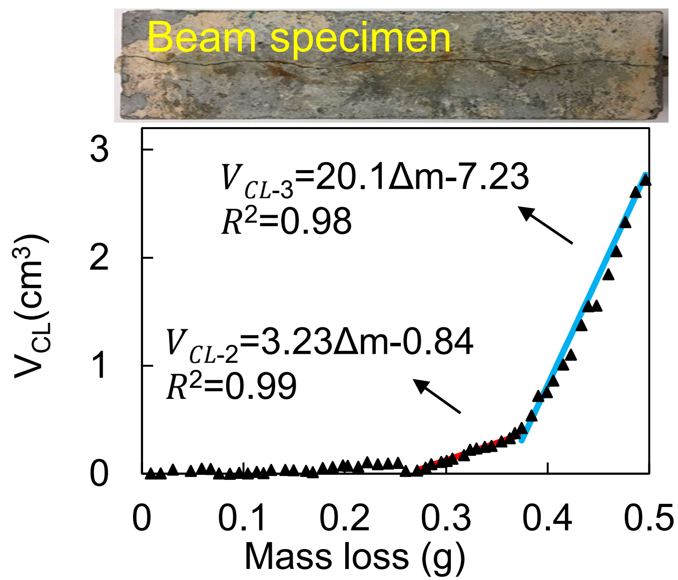
Application 3: Monitoring Corrosion in RC

- Distributed fiber optic corrosion sensor





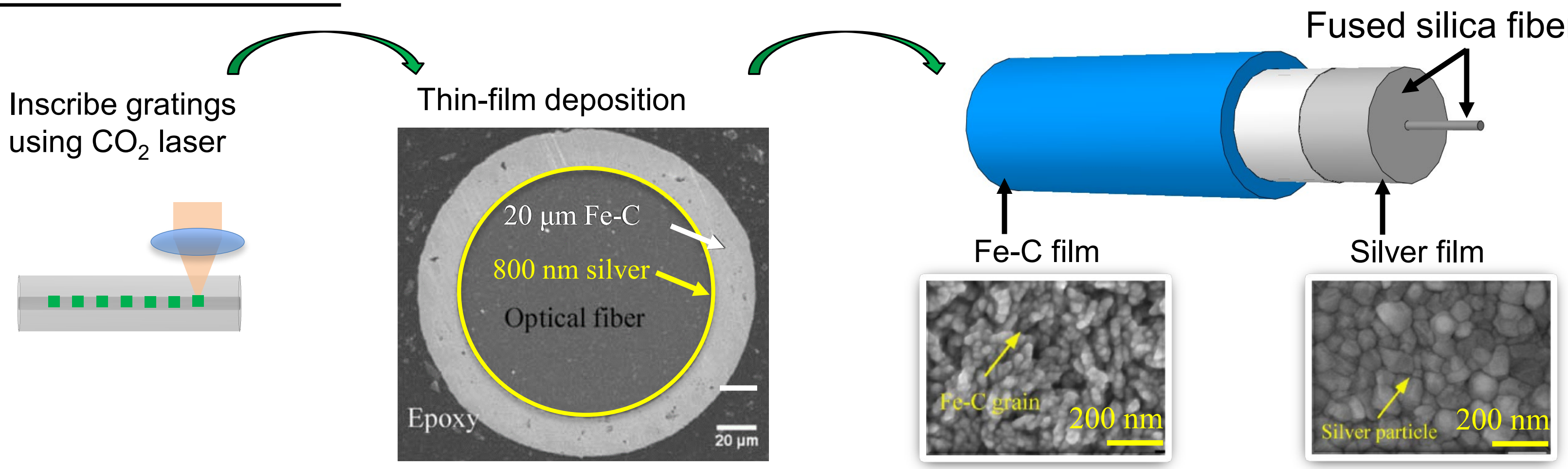




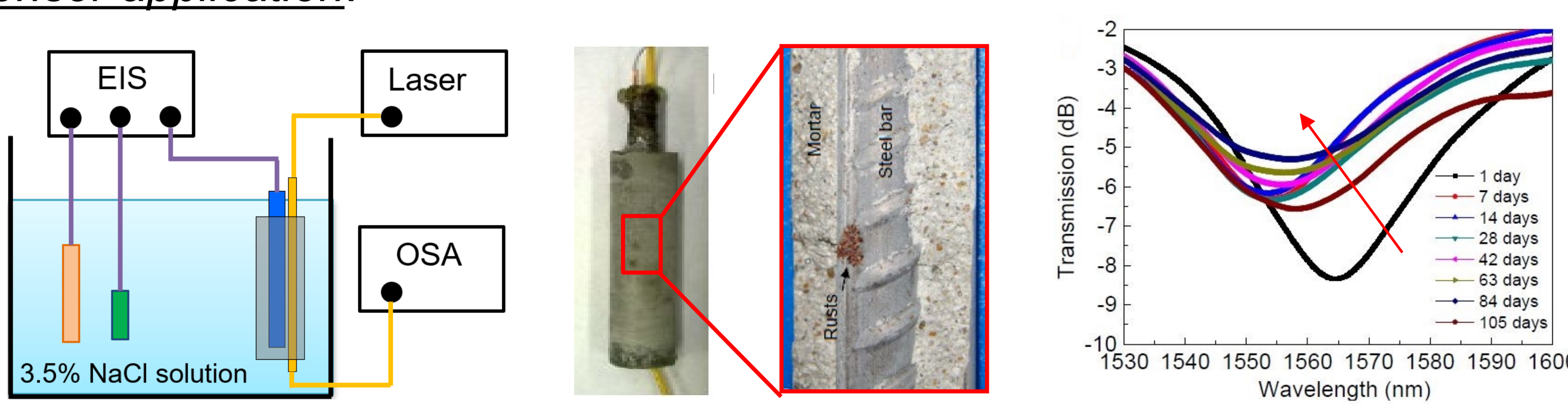
Fan, L., **Bao, Y.***, Chen, G. "Feasibility of distributed fiber optic sensor for corrosion monitoring of steel bars embedded in concrete", *Sensors*.

- Discrete fiber optic corrosion sensor

Sensor fabrication:



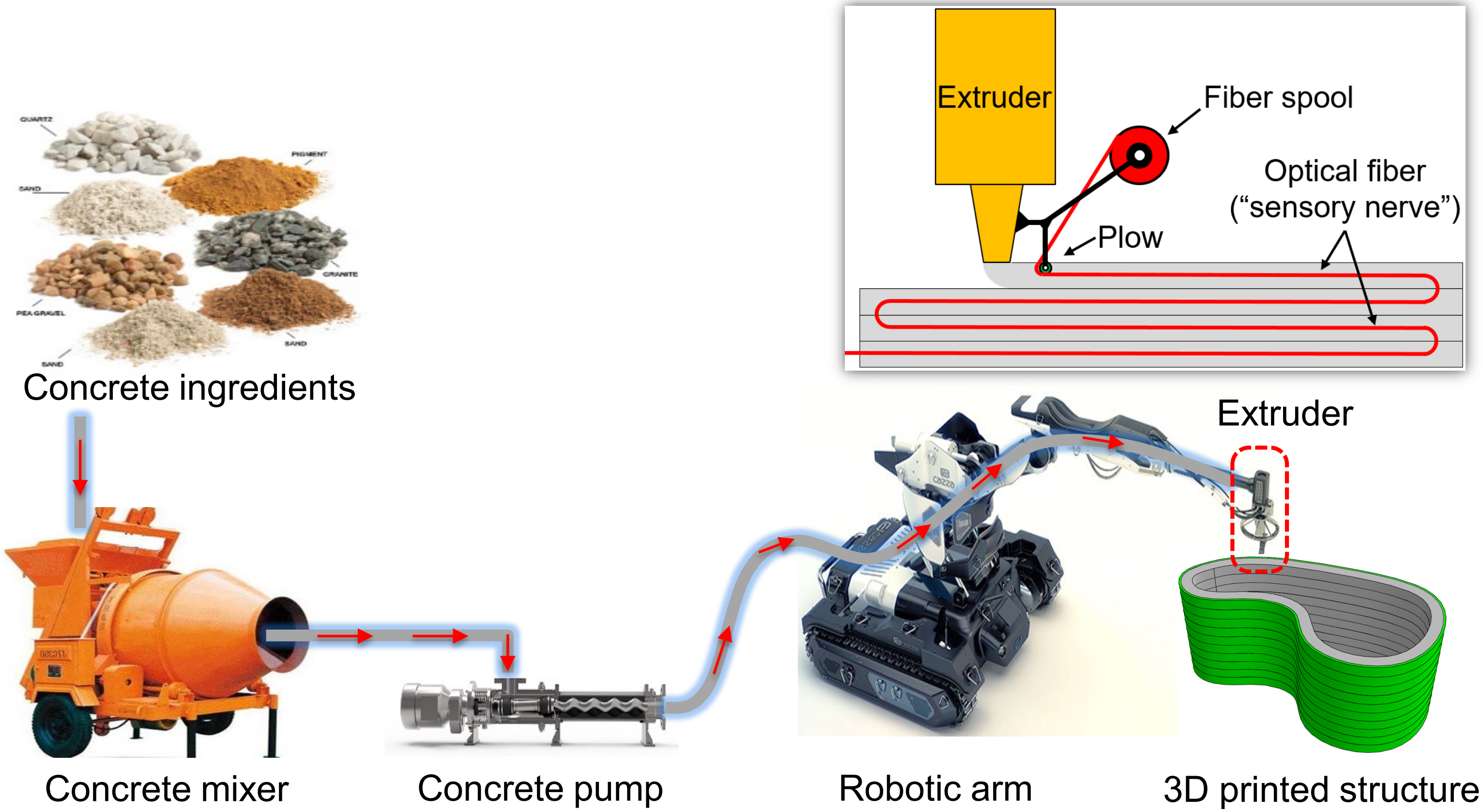
Sensor application:



Chen, Y., Tang, F., **Bao, Y.**, Chen, G., Tang, Y. (2016) "Fe-C coated long period fiber grating sensors for steel corrosion monitoring." *Optics Letters,* 41(13), 344–346.

Application 4: Digital Construction

- Install fiber optic sensors via construction robotic system
  - ➢ monitor and control the concrete 3D printing process
  - ➢ monitor structural health condition for long-term durability



Conclusions

- Distributed fiber optic sensors based on PPP-BOTDA can be used to measure detailed strain distributions with adequate accuracy and long measurement distance (20-50 miles).
- Non-uniform autogenous shrinkage of UHPC and cracks were monitored using the distributed sensor.
- Delamination occurred at the substrate/overlay interface due to early age shrinkage of UHPC, and was detected, located and quantified using the distributed fiber optic sensor.
- The presented fiber optic sensors can be used to detect, locate and quantify corrosion in reinforced concrete.
- Fiber optic sensors become more promising and practical in digital construction.

Acknowledgement

- The research was funded by:
  - US Department of Transportation through the University Transportation Centers (UTC) Program and PHMSA Program
  - Minnesota Department of Transportation
  - National Institute of Standards and Technology (NIST)
  - National Science Foundation (NSF)
  - University of Michigan – Ann Arbor