Achieving Resilient and Smart Concrete Bridges by Mapping Strains and Cracks Using Distributed Fiber Optic Sensors

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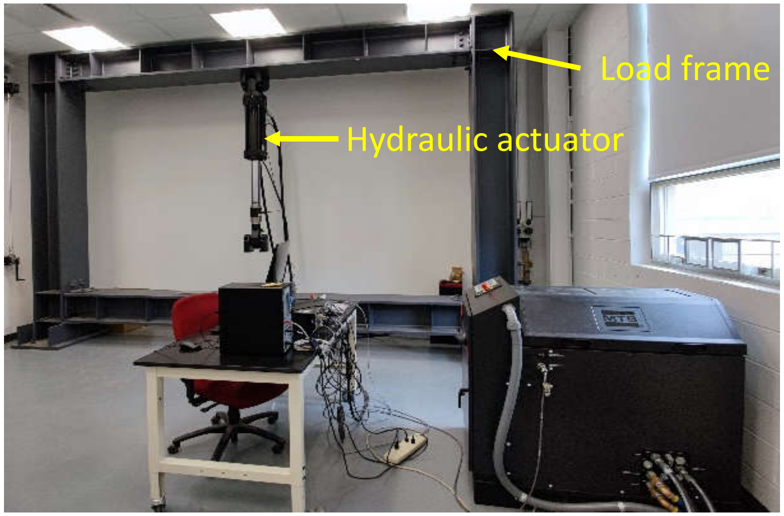
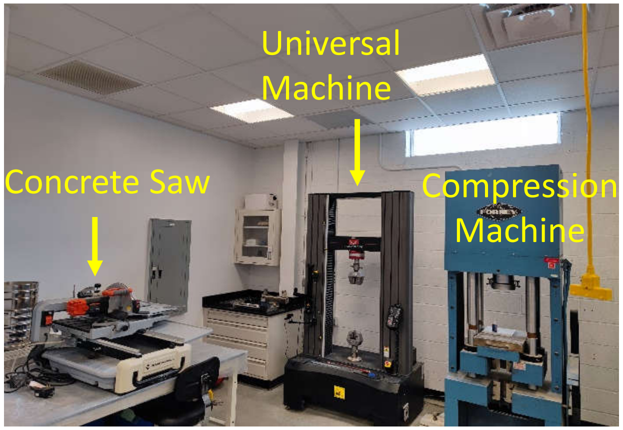
Smart Infrastructure Laboratory

- The newly-upgraded Smart Infrastructure Lab is equipped for large-scale structural testing.
  - ➢ MTS high-capacity hydraulic actuator (static & fatigue tests)
  - ➢ Advanced instruments (optic cameras, fiber optic sensors, etc.)
  - ➢ Robots for bridge condition assessment



Advanced Concrete Technology (ACT) Lab

- The newly-upgraded ACT Lab is well-equipped for large mixing, testing, and multi-scale characterization of concrete.
  - ➢ Six mixers (volumes: 340 L, 19 L, and 5L)
  - ➢ Load frames and environmental chambers (temperature & humidity)
  - ➢ Characterization instruments (isothermal calorimeter, TGA, MIP, etc.)



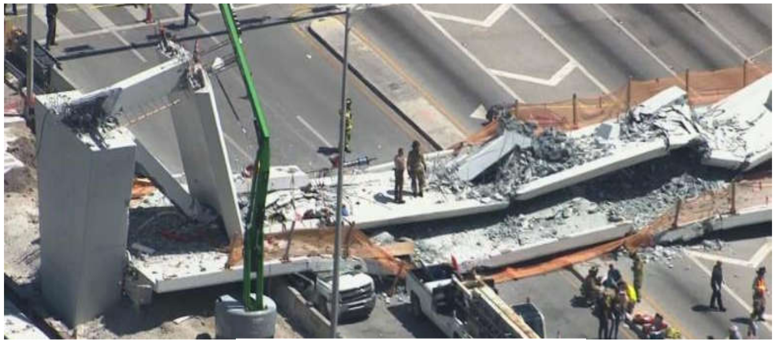
Background problems

- Bridges are subjected to cracks that can compromise the load capacity and durability of bridges.

Shrinkage

Temperature gradient

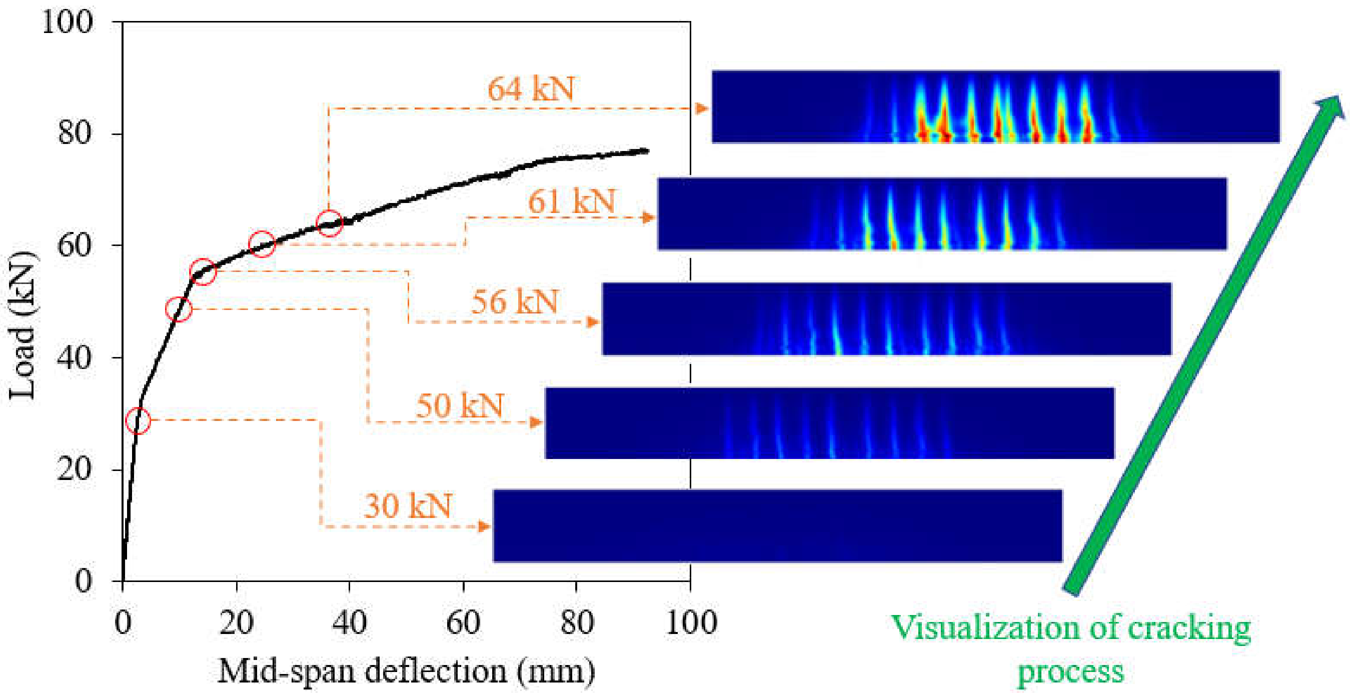
Overloading



Other effects

Objectives

- This study develops a method to measure and visualize strains and cracks in concrete using distributed fiber optic sensors based on optical frequency domain reflectometry (OFDR), aiming to improve resilience of bridges by providing detailed information of the condition and enabling timely repair of the bridges.



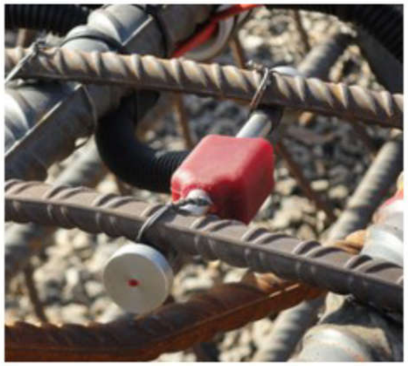
Contents of this presentation

Reference: Tan, et al., 2021. Measurement and visualization of strains and cracks in CFRP post-tensioned fiber reinforced concrete beams using distributed fiber optic sensors. *Automation in Construction*, *124*, p.103604.

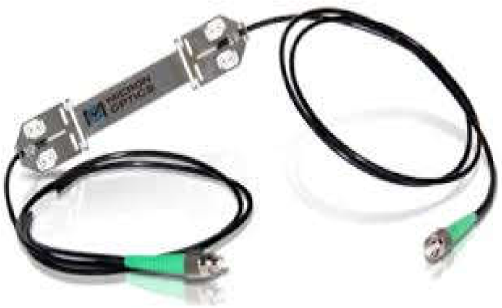
Existing method: type 1

- Point strain sensors
  - Strain gauges, vibrating wire gauges, fiber Bragg grating sensors
  - Difficult to capture cracks (due to short length)
  - Locations of cracks are hard to predict
  - Many sensors must be deployed (unrealistic in many cases)

Strain gauges



Vibrating wire gauges



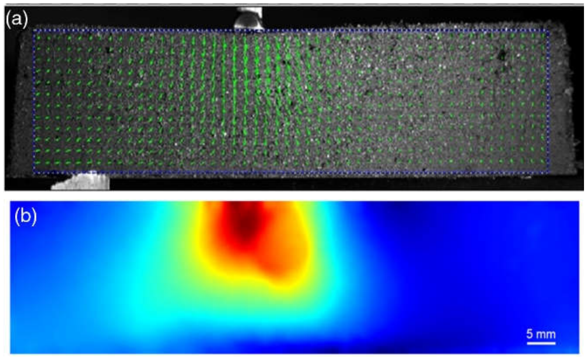
Fiber Bragg grating sensors

Existing method: type 2

- Surface inspection method
  - Photogrammetry, laser-scanning, computer vision
  - Detect and quantify surface cracks
  - Cannot detect hidden (invisible cracks)
  - Accuracy is subjected to many variables

Photogrammetry

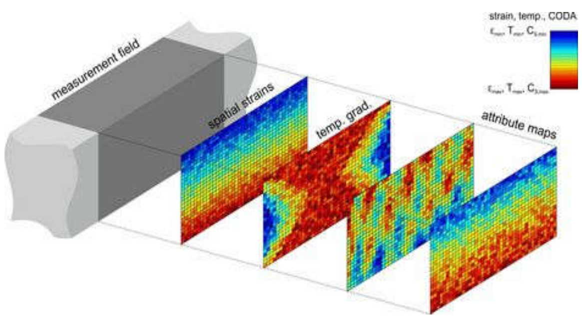
Laser scanning



Digital image correlation

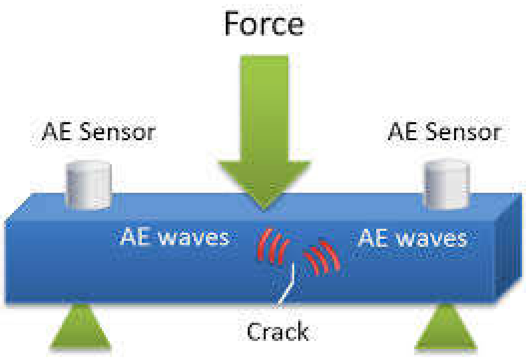
Existing method: type 3

- Non-destructive techniques
  - ➢ Coda wave interferometry, ultrasonic testing, acoustic emission
  - ➢ Based on electromagnetic waves or mechanical waves
  - ➢ Spatial resolutions are limited
  - ➢ Accuracy is subjected to many variables (EMI, humidity, etc.)



Coda wave interferometry

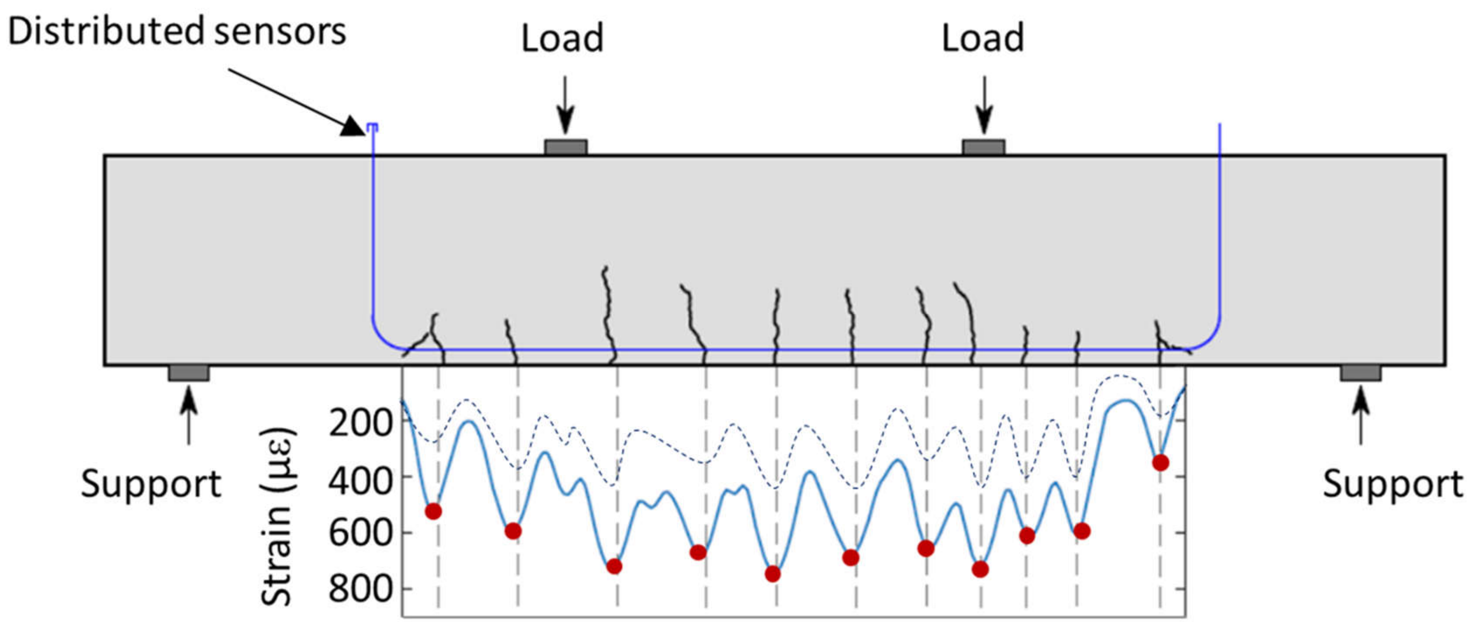

Ultrasonic testing



Acoustic emission

Fiber optic sensors for monitoring cracks

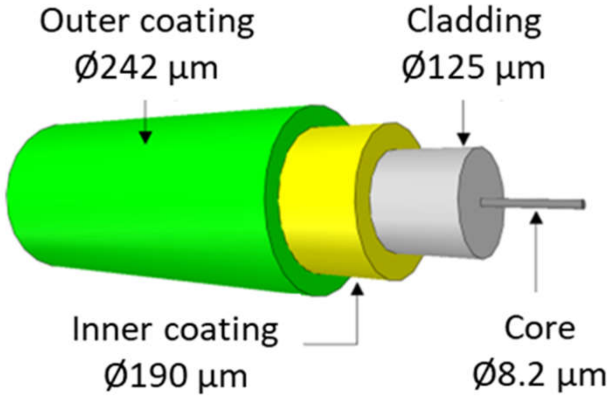
- Capable of detecting and locating cracks
- Widening of cracks is traced by the increase of the peak



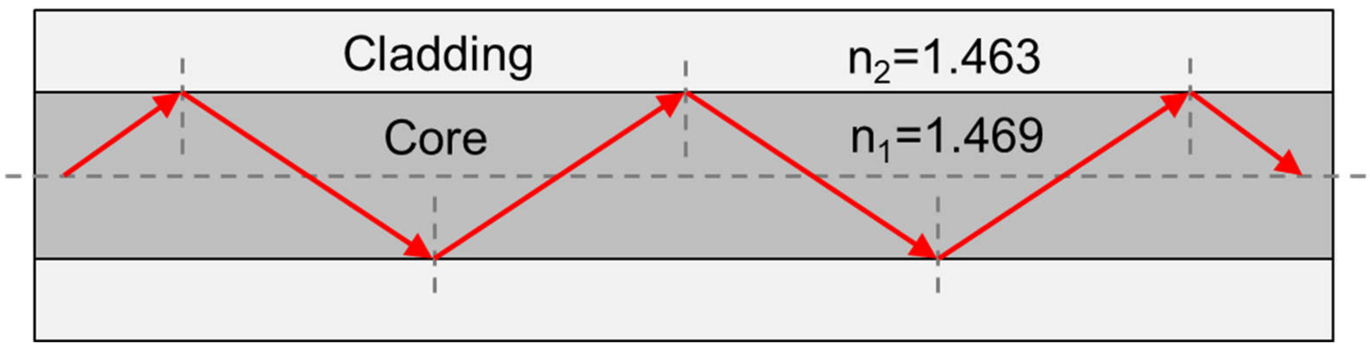
Matching between visual crack formation and fiber optic strain amplitudes

Optical fibers

- Telecommunication-grade single-mode optical fiber:
  - Core: high-purity fused silica, high refractive index
  - Cladding: high-purity fused silica, low refractive index
  - Coatings: mechanical protection



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



Categories of fiber optic sensors

- Categorization based on the sensing principles:

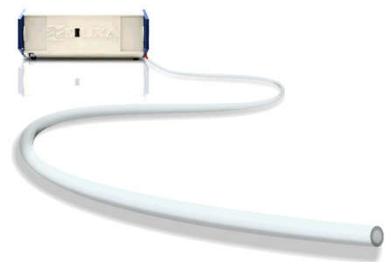
➢ Grating-based sensors (fiber Bragg grating or FBG, long period grating or LPG)

➢ Interferometer sensors (Michelson, Fabry-Perot, Mach-Zehnder)

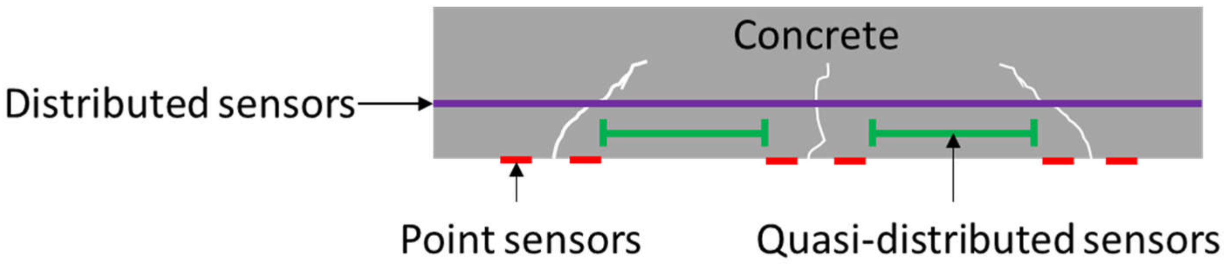
➢ Distributed sensors (Brillouin scattering, Rayleigh scattering, Raman scattering)

Fiber Bragg grating sensor

Michelson sensor

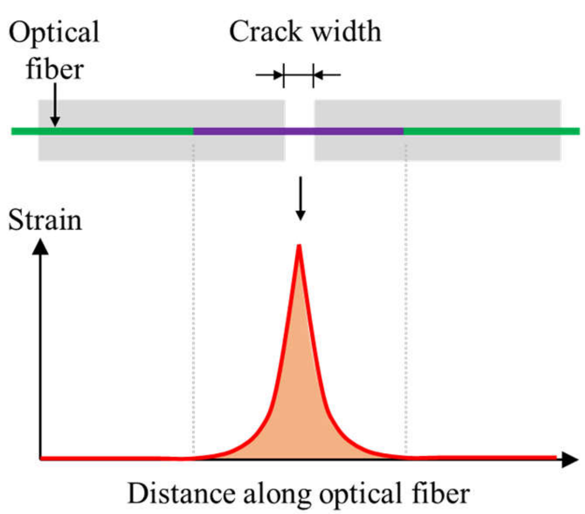


Distributed sensor

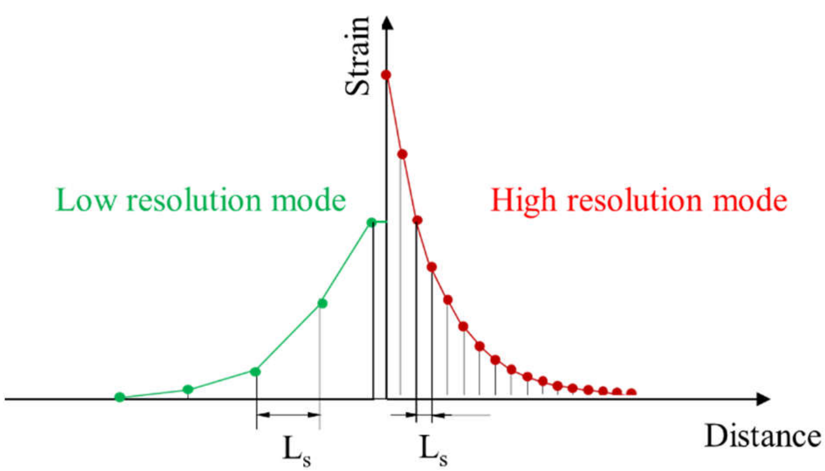


Current challenges

- The accuracy of strain measurement was also compromised by the limited spatial resolution
- Accurate measurements of crack widths requirement higher spatial resolution



Actual strain distribution



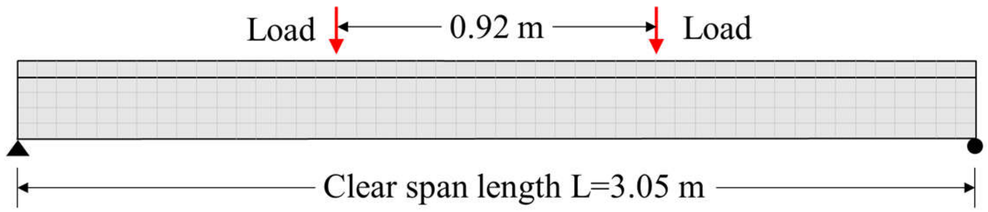
Measured strain distribution

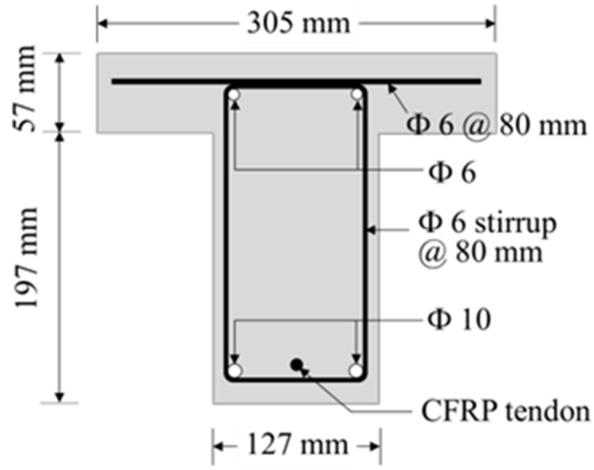
Distributed sensing technology

- Rayleigh optical frequency domain reflectometry (OFDR)
- Immunity to EMI
- High resolution (0.65 mm)
- Large strain range (~16,000 με)
- High sensitivity
- High stability
- Long durability
- Quantify the crack widths

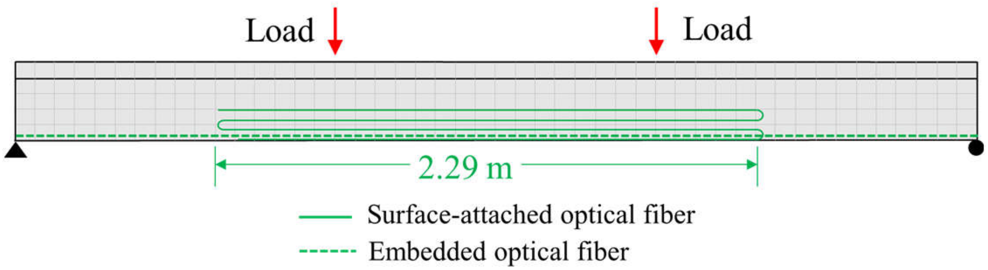
Experimental testing

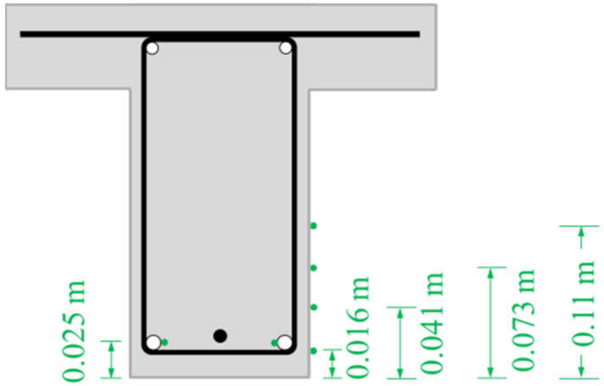
- Beam specimens





- Installation of optical fibers



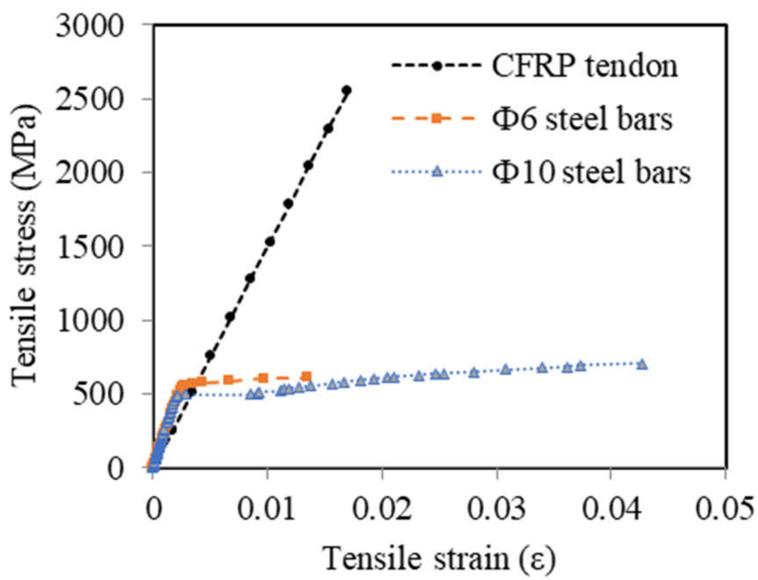


Experimental testing

- Mix proportions of concrete (unit: kg/m^3)

Concrete	Cement	Fly ash	Silica fume	Coarse Aggregate (#57)	Coarse Aggregate (#8)	Fine Aggregate	HRWR	Air entrainer	PP fiber	Steel fiber
Beam-1	308	77	15	900	178	660	0.9	0.25	3	0
Beam-2	308	77	15	900	178	660	0.9	0.25	3	3

- Mechanical properties of steel bars and CFRP tendon



Experimental testing

- Specimen fabrication
  - The beams had coarse aggregates and low flowability
  - The distributed sensors were embedded in concrete
  - The distributed sensors survived through concrete casting

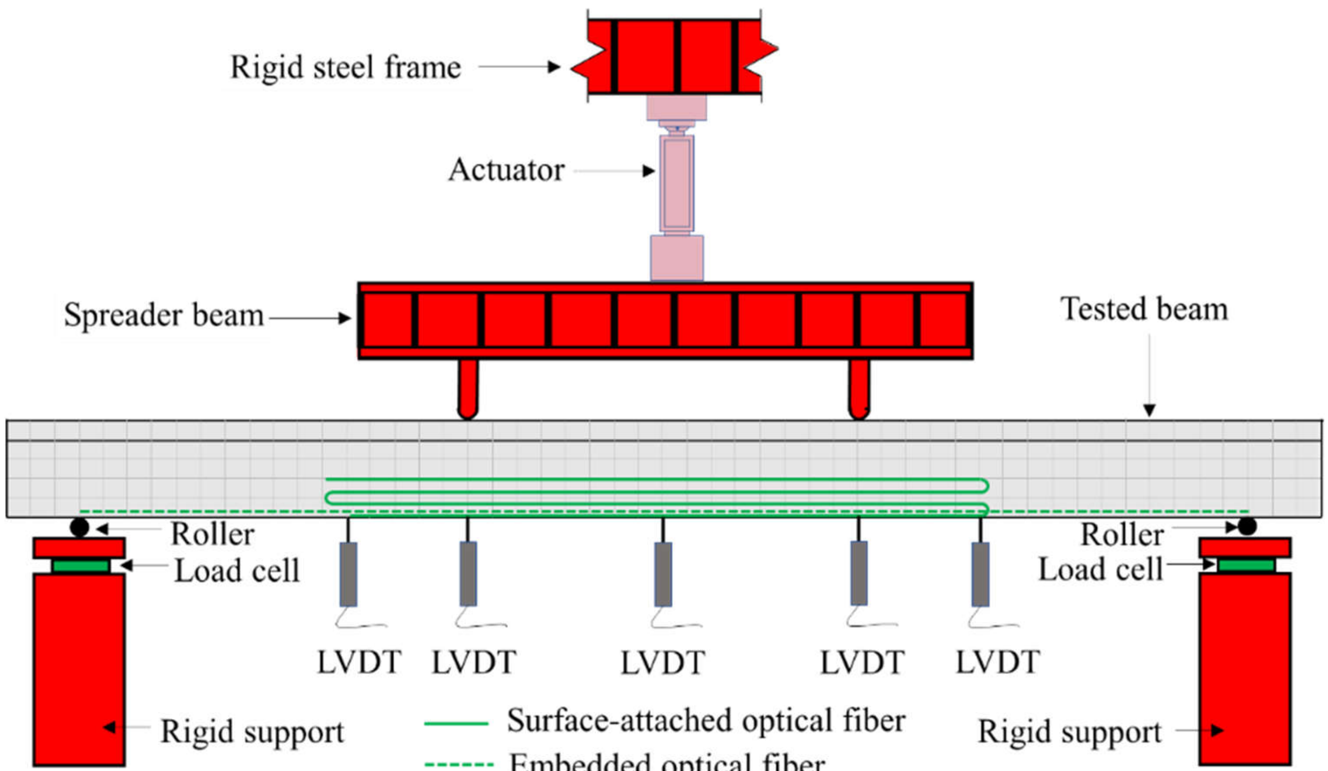
Casting

Vibrating

Finishing

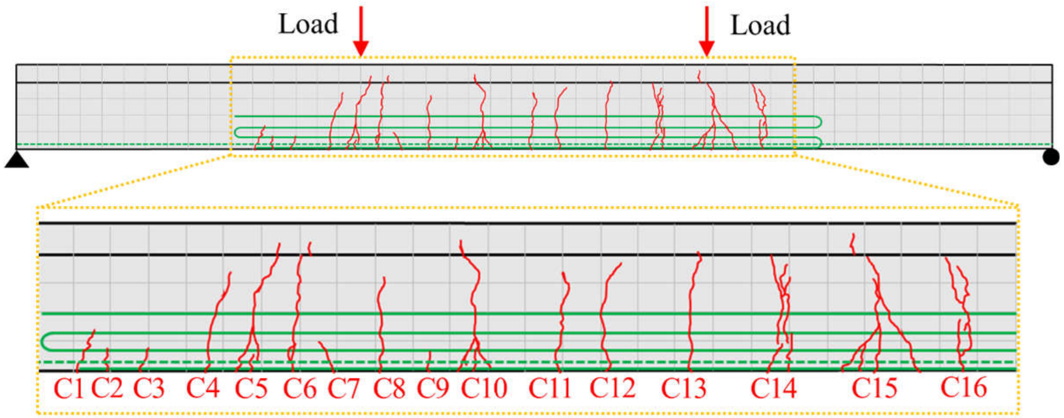
Experimental testing

- Test set-up
  - Four-point bending
  - Deflections were measured by LVDTs



Experimental results

- Visual observation of cracks
  - Multiple densely distributed cracks occurred in crack region
  - Red lines represent major cracks observed by the crackscope
  - 16 cracks are observed



Crack patterns determined by visual inspection

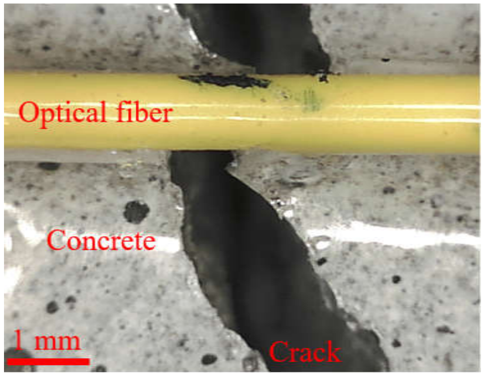
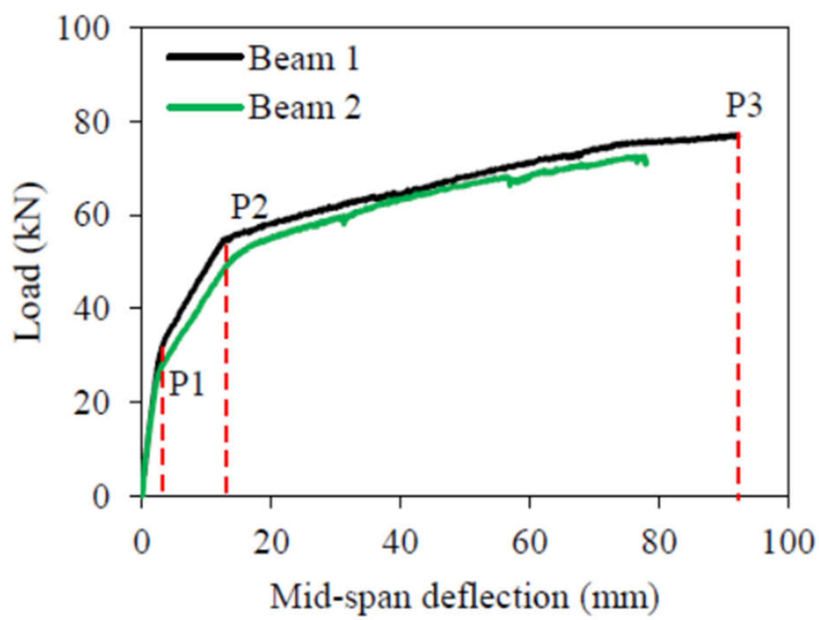


Photo of the crack C10 at the load level of 58.7 kN

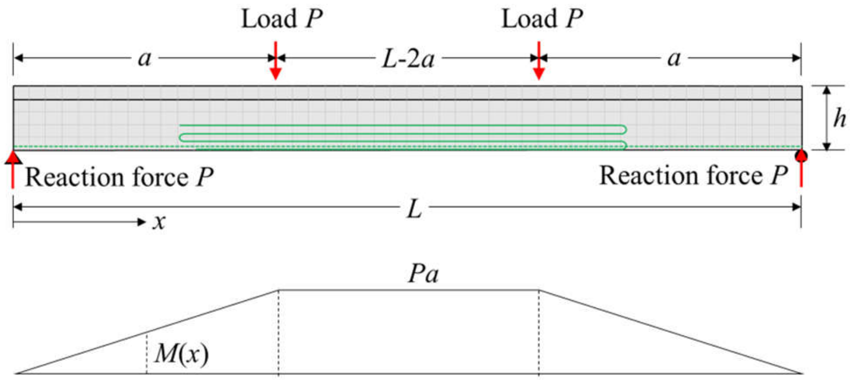
Experimental results

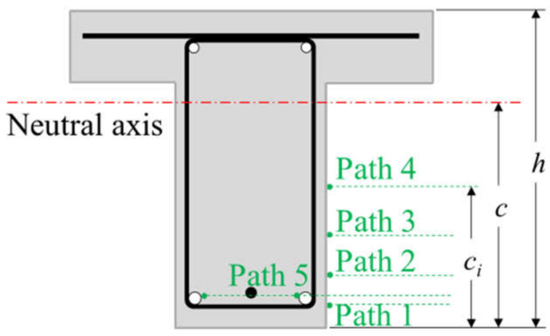
- Load-deflection curves
  - 0 – P1 (34.7 kN): Linear increasing until first crack observed by crack scope
  - P1 – P2: The slope of the load-deflection curve was reduced because more cracks were generated
  - P2 – P3: The slope was gradually reduced to zero

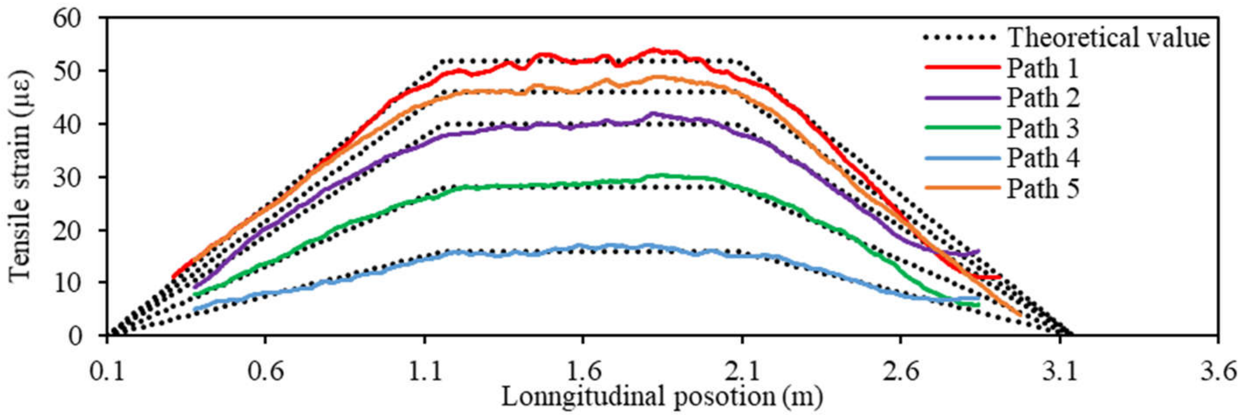


Experimental results

- Strain distributions prior to concrete cracking
  - ➢ The strain distributions measured from the distributed fiber optic sensors are in good agreement with the analytical results

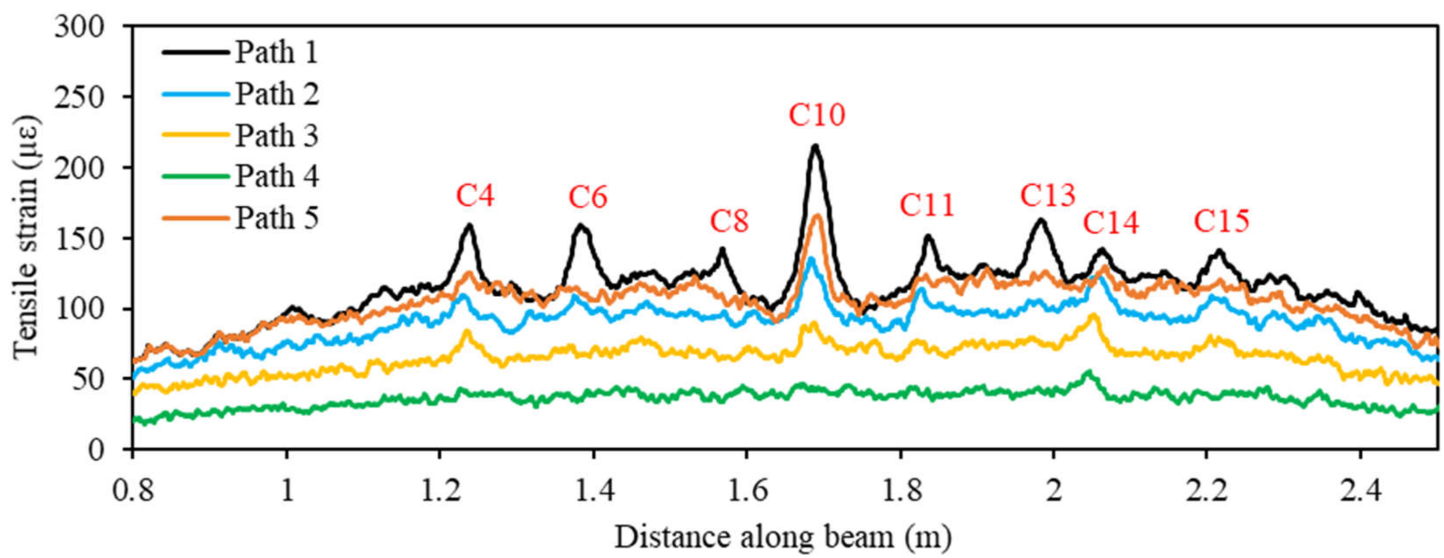






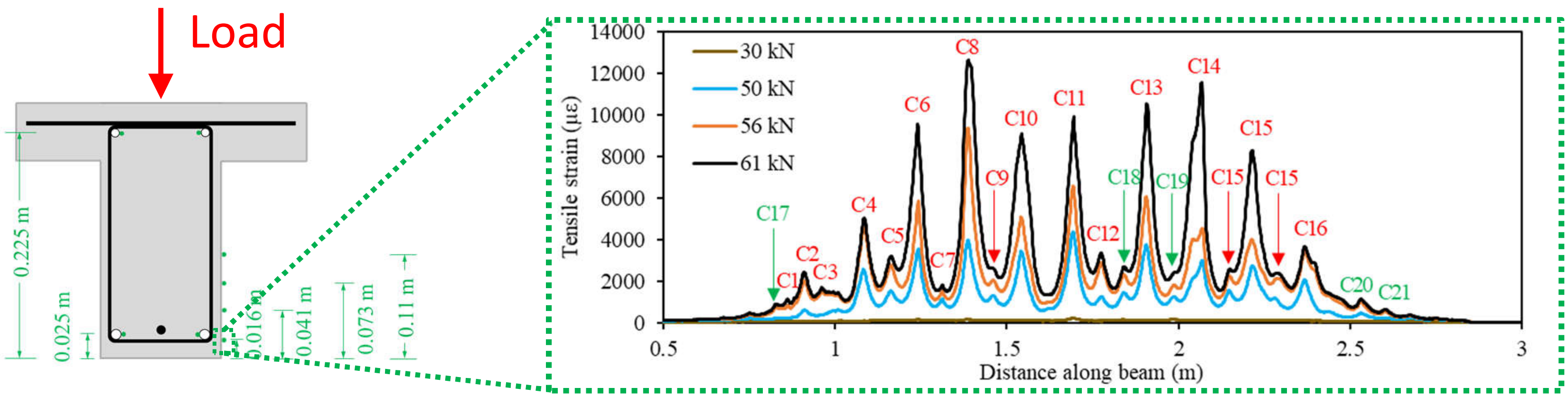
Experimental results

- Crack initiation
  - Strain distributions measured from the five different paths of the distributed sensor in Beam 1 when the applied load was P = 19.6 kN
  - The cracks detected by the distributed sensor were too narrow to be visually observed using a crack scope until the load was increased to P = 34.7 kN



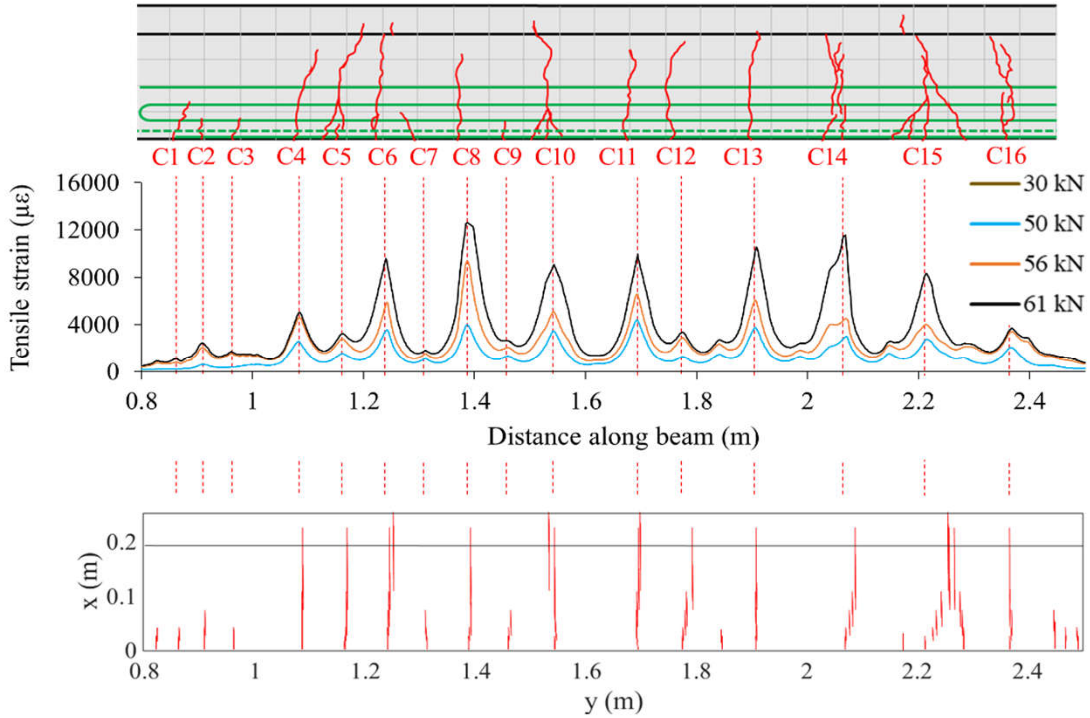
Experimental results

- Strain distribution after cracking
  - With the increase of the load, new peaks appear in the strain distributions, meaning that new cracks are generated in the concrete.
  - The magnitudes of the peaks are increased, meaning that the widths of the cracks are increased.
  - The distributed sensors not only detect the cracks (C1 to C16) that were found through visual inspection, but also detect microcracks (C17 to C21) that were not found using the crack scope.



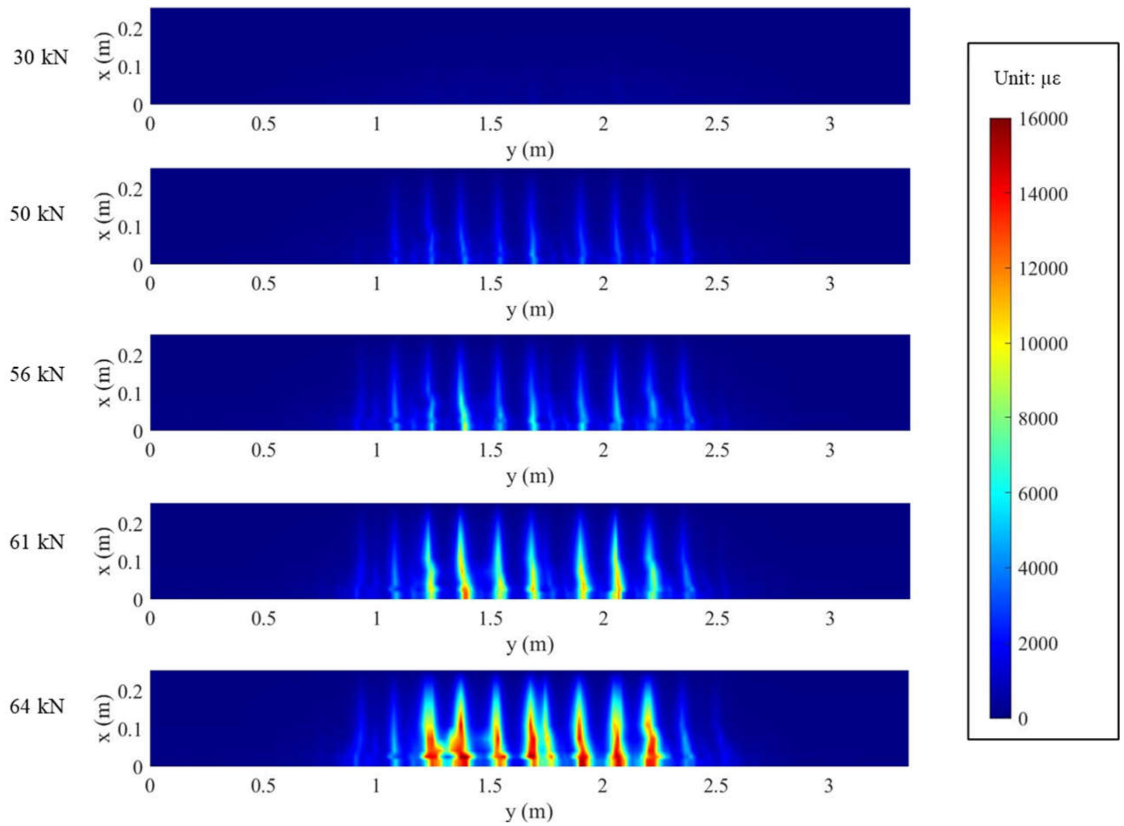
Experimental results

- Crack mapping
  - With the locations of distributed sensors in the concrete beams, the distance along the distributed sensor is correlated with the position in the beam
  - The cracks located by the strain distributions measured from the distributed sensors agreed with the visually observed cracks



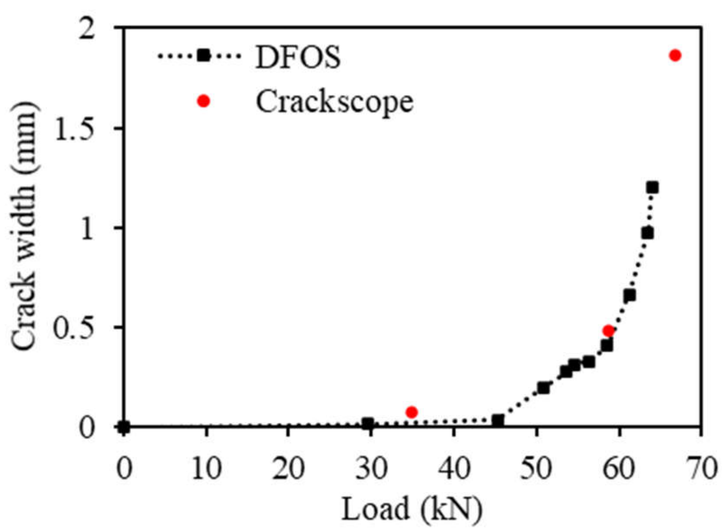
Experimental results

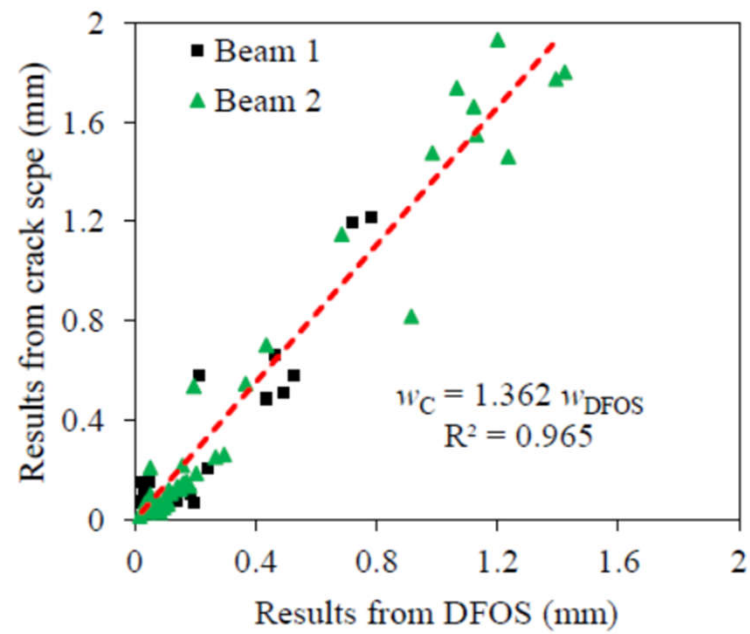
- Crack visualization
  - ➢ The mapping results of the strain distributions can be replotted in the form of contours to visualize the strains and cracks



Experimental results

- Quantification of crack width
  - Crack widths calculated by the integration of strains and compares the results against the crack widths measured from the crack scope
  - The results from the distributed sensor and the crack scope agree well with each other, indicating that the crack width can be measured by the distributed fiber optic sensors





Conclusions

- Strain and crack distributions were measured from distributed fiber optic sensors. The initiation and development of cracks were monitored in real time.
- The distributed sensors are capable of detecting, locating, and quantifying cracks earlier than visual observation of cracks.
- The developed method for installation of distributed sensors enabled the sensors to survive throughout concrete casting and beam testing.
- It is promising to improve resilience of concrete bridges by providing detailed and precise information of the health condition for timely and effective repair of the bridges.

Acknowledgement

- This research was funded by U.S. Department of Transportation [project number: 693JK31950008CAAP], NJ Department of Transportation, and Stevens Institute of Technology.
- We would like to acknowledge Rutgers for assistance in casting and loading of the beams.

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Q & A

Thank you!