Crack Detection, Location, Quantification, and Visualization Using a Distributed Fiber Optic Sensor Based on Optical Frequency Domain Reflectometry

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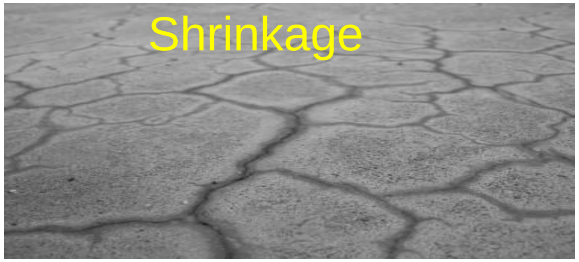
Background problems

- Cracks in metal structures

- Reduce the functionality of the structures
  - Load-carrying capacity, stiffness, and leak-resistance
- Serious consequences and capital loss

Background problems

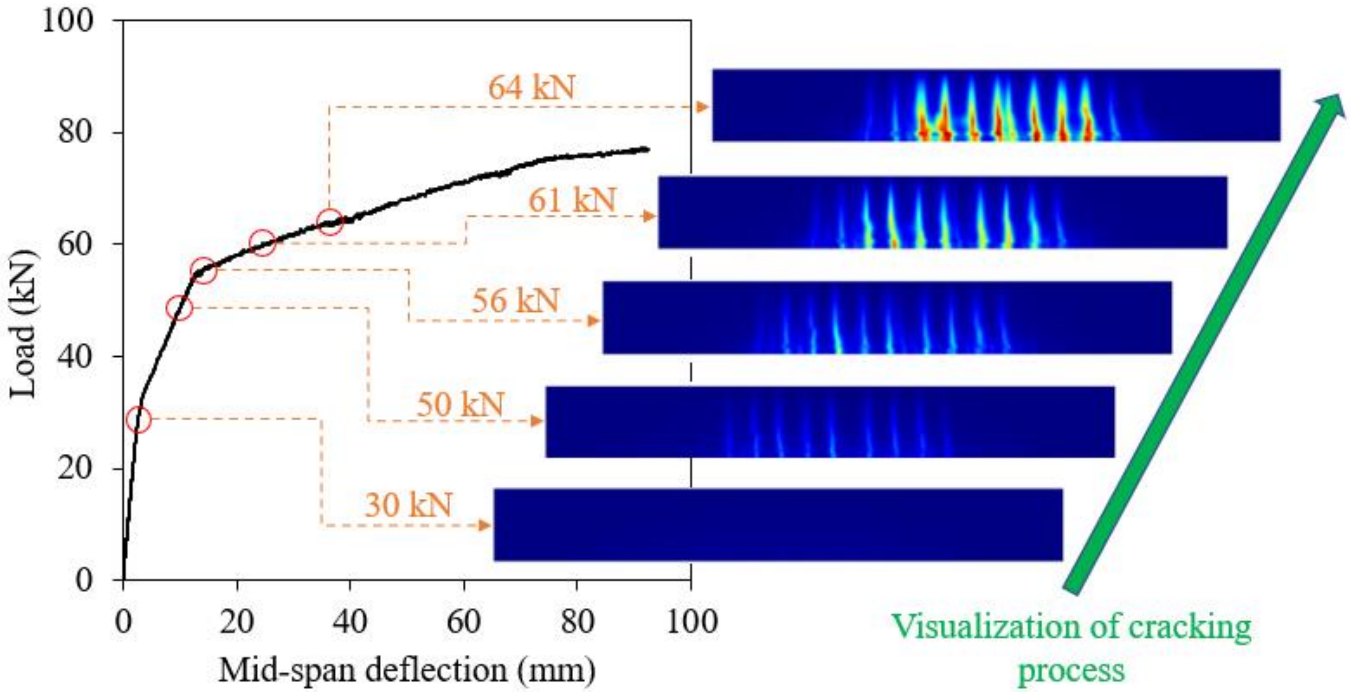
- Cracks in concrete structures



- Reduce load capacity and durability
- Monitoring early cracks
  - ➢ Improve the safety and save the costs

Objectives

- This study aims to develop a method to precisely evaluate crack widths and visualize strains and cracks in structures using distributed fiber optic sensors based on optical frequency domain reflectometry (OFDR).



Contents

References:
[1] Tan, X., & Bao, Y.* (2021). Measuring crack width using a distributed fiber optic sensor based on optical frequency domain reflectometry. *Measurement*, 172, p.108945.
[2] Tan, X., Abu-Obeidah, A., Bao, Y.*, Nassif, H., & Nasreddine, W. (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.
[3] Yan, M., Tan, X., Mahjoubi, S., & Bao, Y.* (2022). Strain transfer effect on measurements with distributed fiber optic sensors. *Automation in Construction*, 139, p.104262.

Existing method: type 1

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

Strain gauges

Vibrating wire gauges

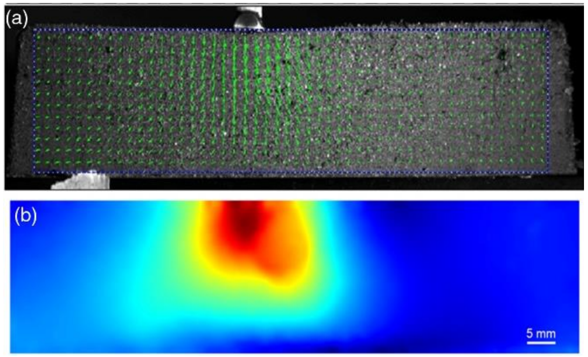
Fiber Bragg grating sensors

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

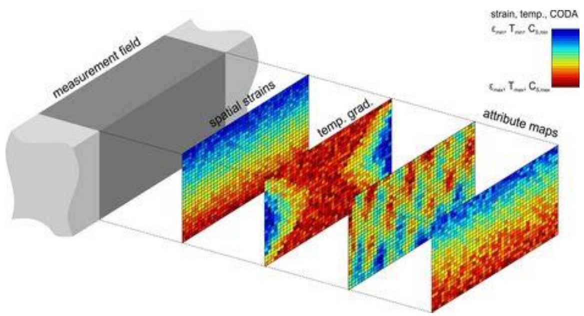
Laser scanning



Digital image correlation

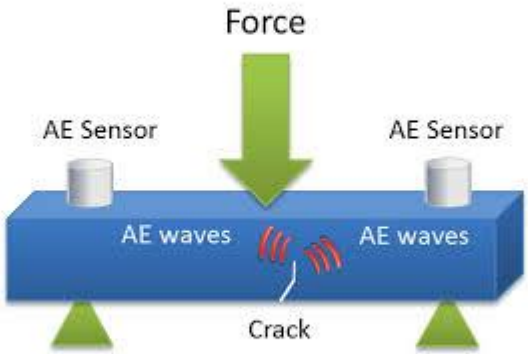
Existing method: type 3

- 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

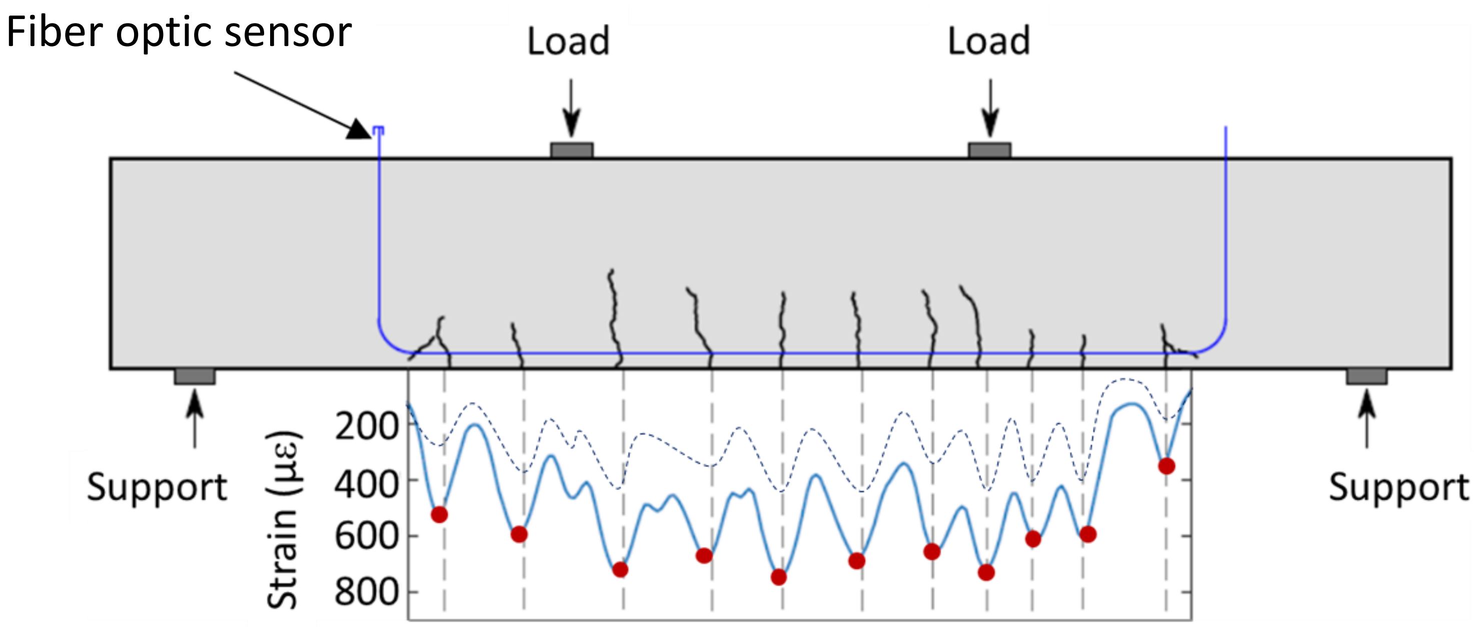
Ultrasonic testing



Acoustic emission

Fiber optic sensors for monitoring cracks

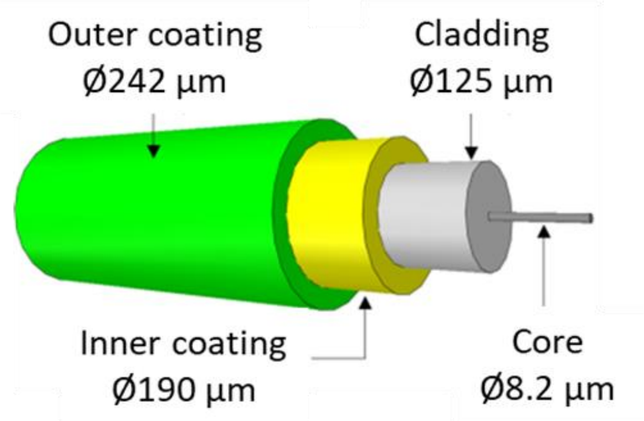
- Capable of detecting and locating cracks
- Widening of cracks is traced by the increase of the peak



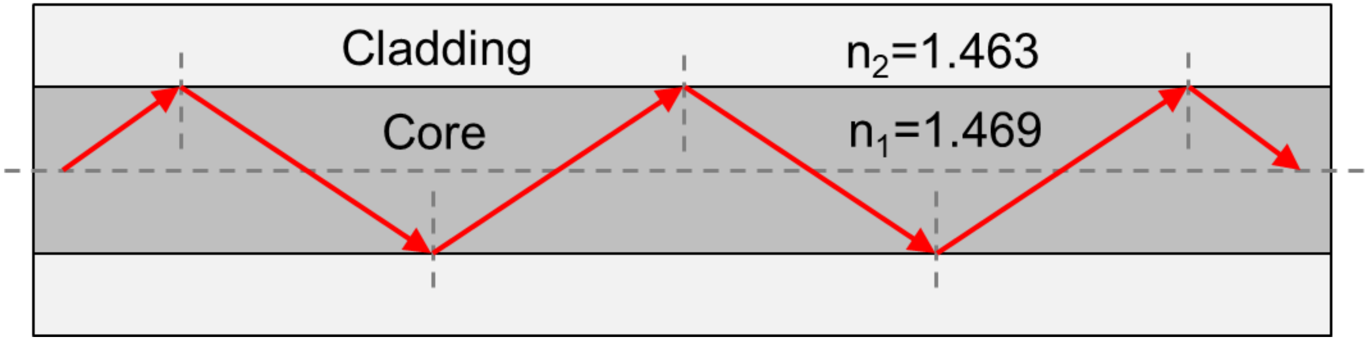
Matching between visual crack formation and fiber optic strain amplitudes

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:

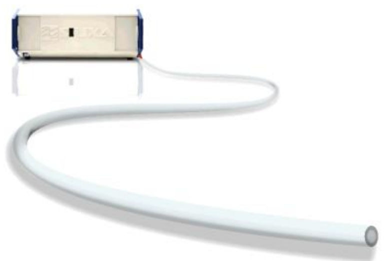
➢ Grating-based sensors (fiber Bragg grating or FBG, long period grating or LPG)

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

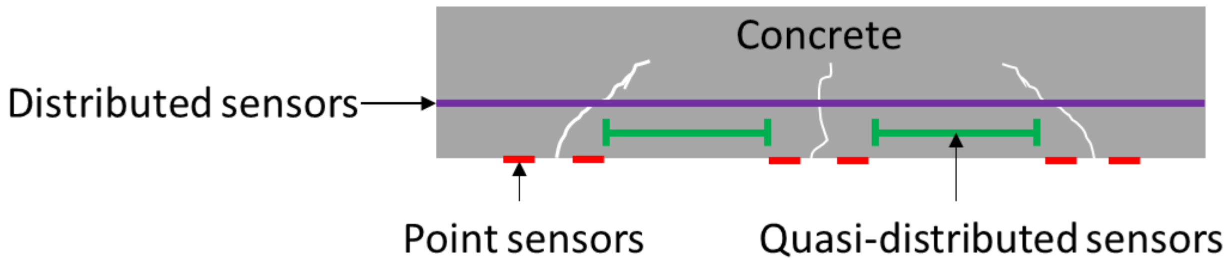
➢ Distributed sensors (Brillouin scattering, Rayleigh scattering, Raman scattering)

Fiber Bragg grating sensor

Michelson sensor

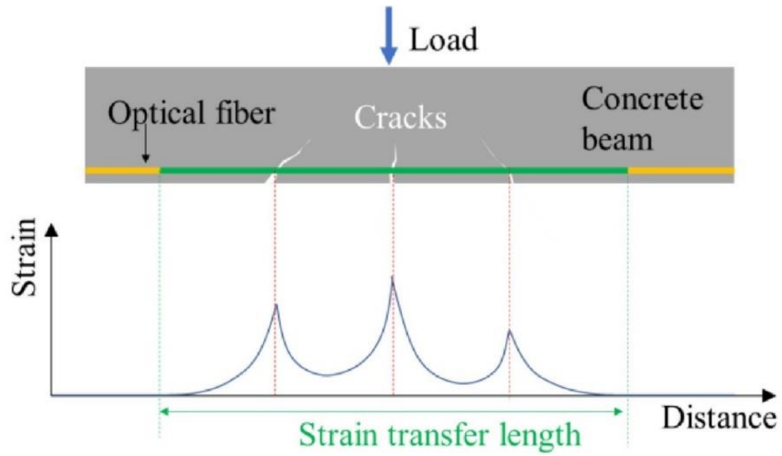


Distributed sensor

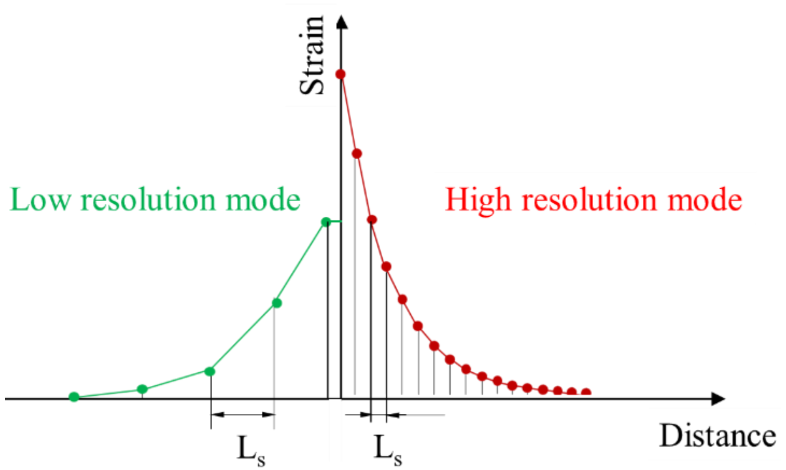


Current challenges

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



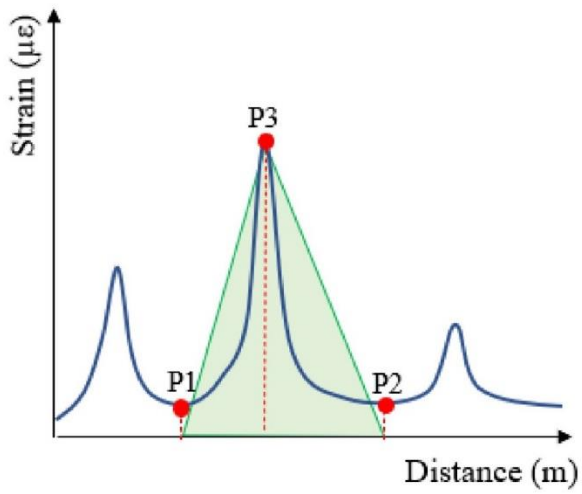
Actual strain distribution



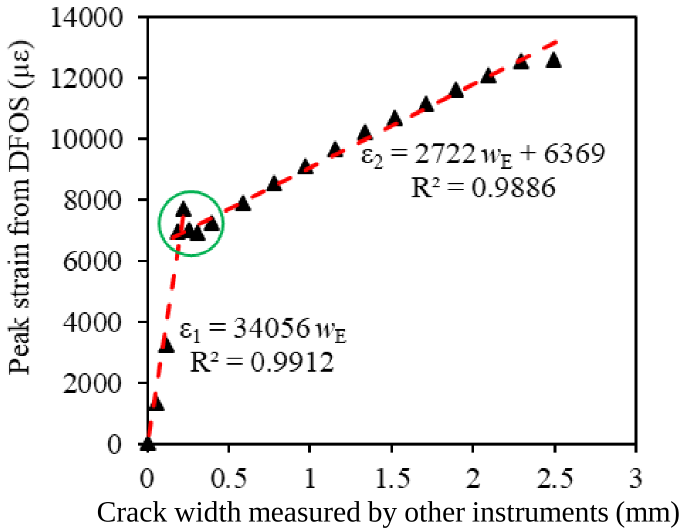
Measured strain distribution

Current challenges

- Accuracy for crack width quantification methods:
  - Method 1: Area of the green triangle
  - Method 2: Empirical relationship between crack width and the peak strain
  - Method 1 & 2 assume that the strain distributions in the vicinity of the cracks are linear



Method 1



Method 2

Proposed research

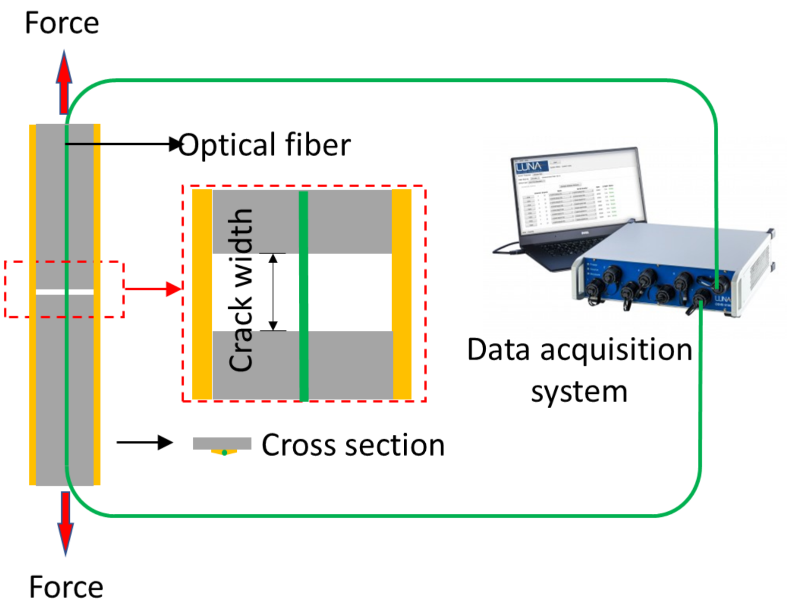
- To develop a crack width quantification method based on OFDR
- To investigate the effects of three key parameters:
  - Coating thickness
  - Spatial resolution
  - Spacing between adjacent cracks
- To monitor multiple cracks using a single distributed sensor
- To visualize cracks in typical structures for autonomous condition assessment

Optical frequency domain reflectometry

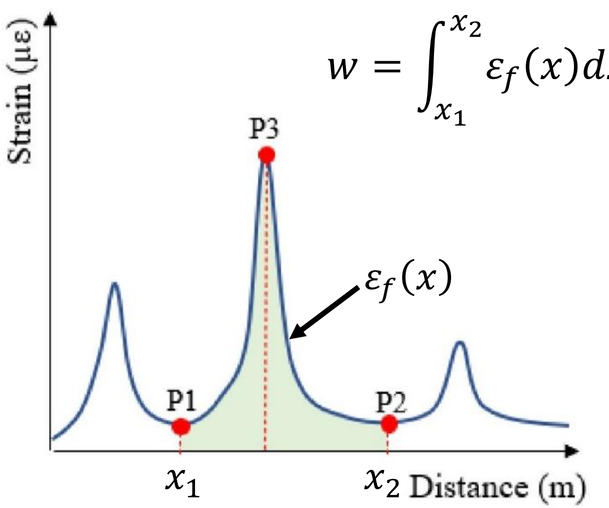
- Immunity to EMI
- High resolution (0.65 mm)
- Large strain range (~16,000 με)
- High sensitivity
- High stability
- Long durability
- Quantify the crack widths

Experimental studies

- Crack width quantification method
  - ➢ Crack widths are calculated by the integration of strains
  - ➢ An extensometer: validate the crack widths



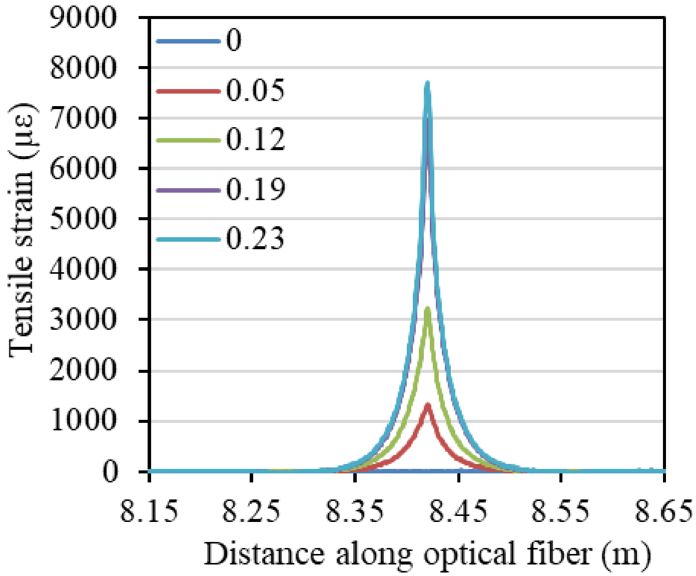
Special cracking specimen



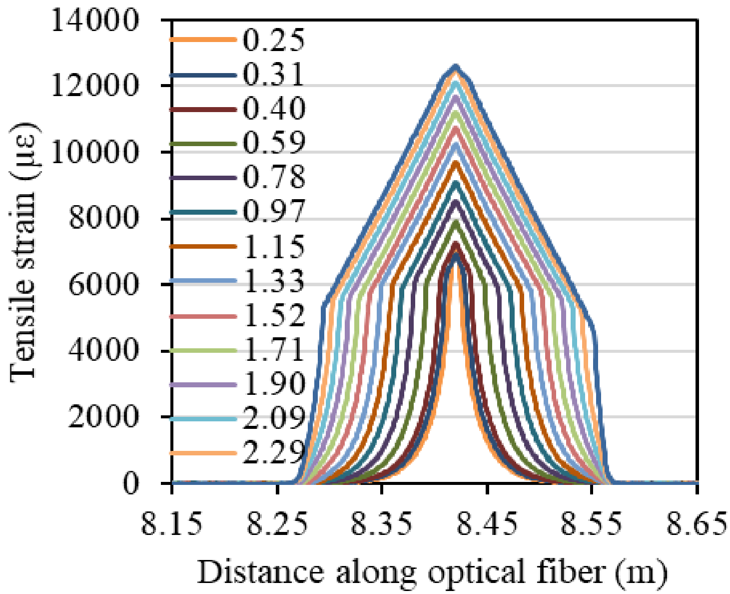
Proposed method

Experimental studies

- Crack width quantification method
  - ➢ Crack initiation: sharp peak
  - ➢ Debonding stage: peak widening with the increase of crack width
  - ➢ Slipping stage: debonding length propagating throughoutly



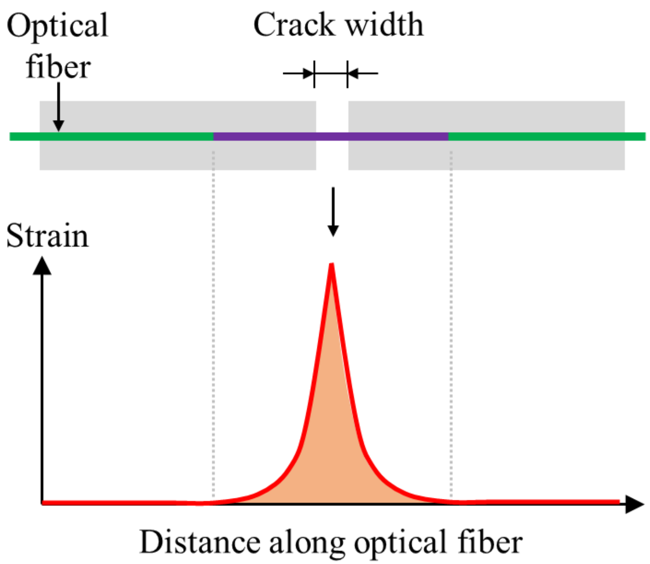
Crack initiation stage



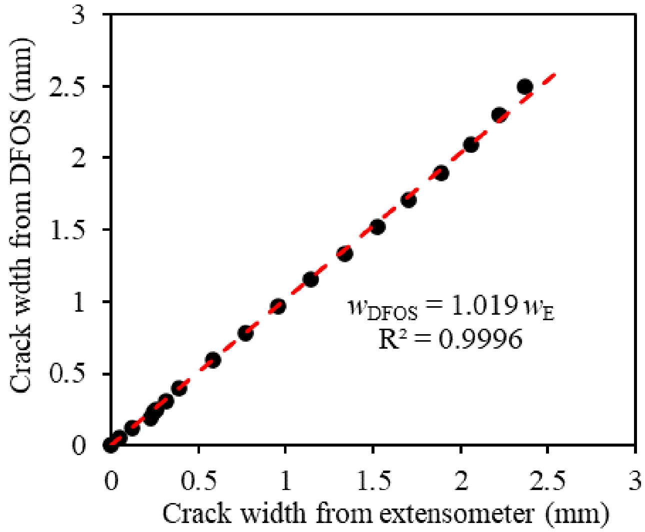
Debonding stage

Experimental studies

- Crack width quantification method
  - ➢ Linear fitting curve
  - ➢ Accuracy of crack width: 7.2 µm



Integration method

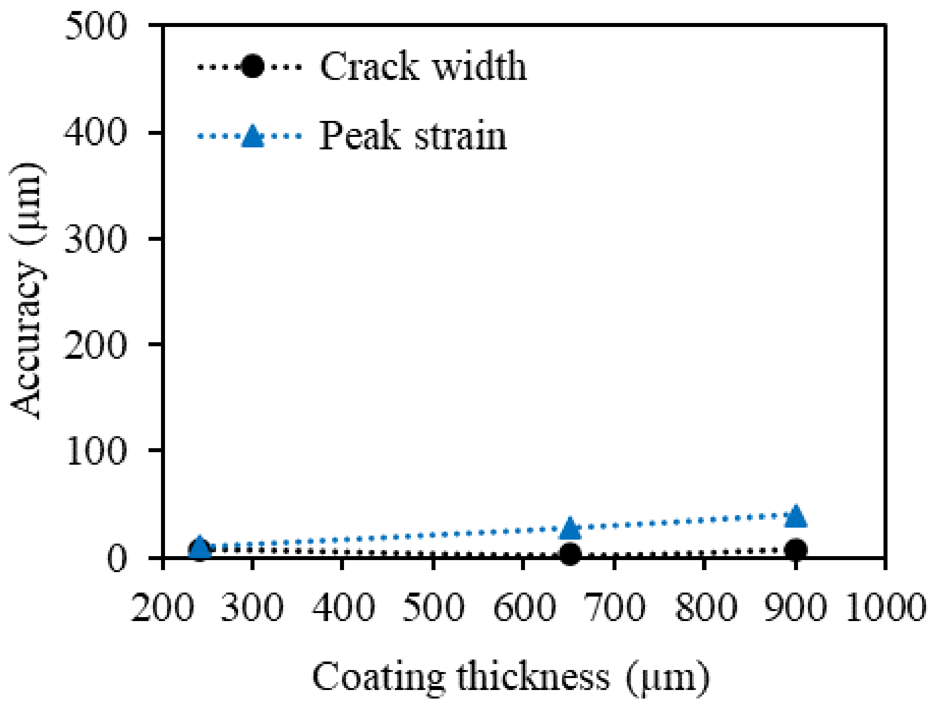


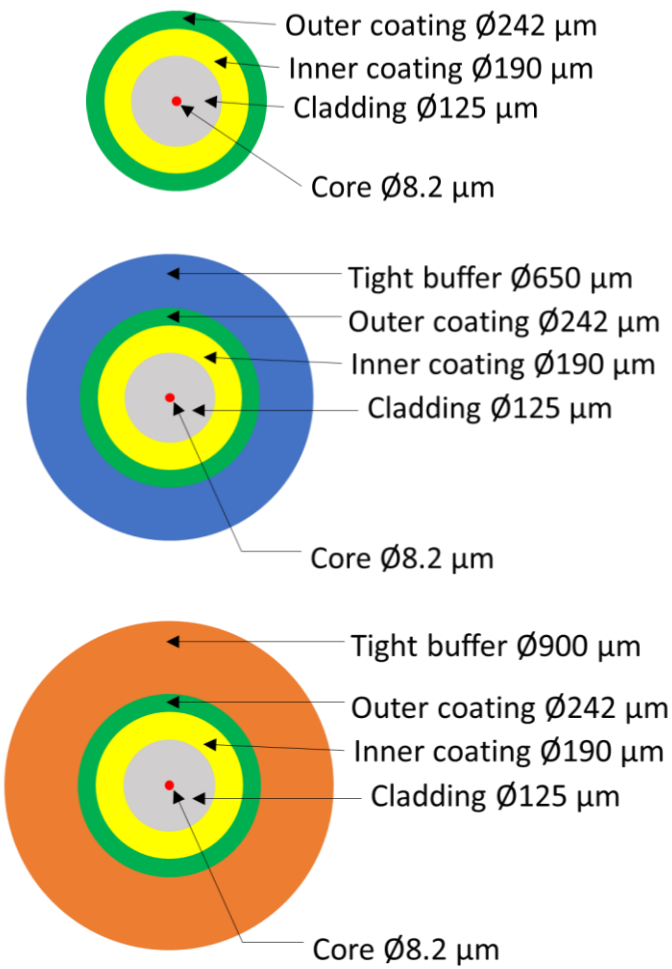
Integration results versus the measured crack widths

Experimental studies

- Effects of coating thickness

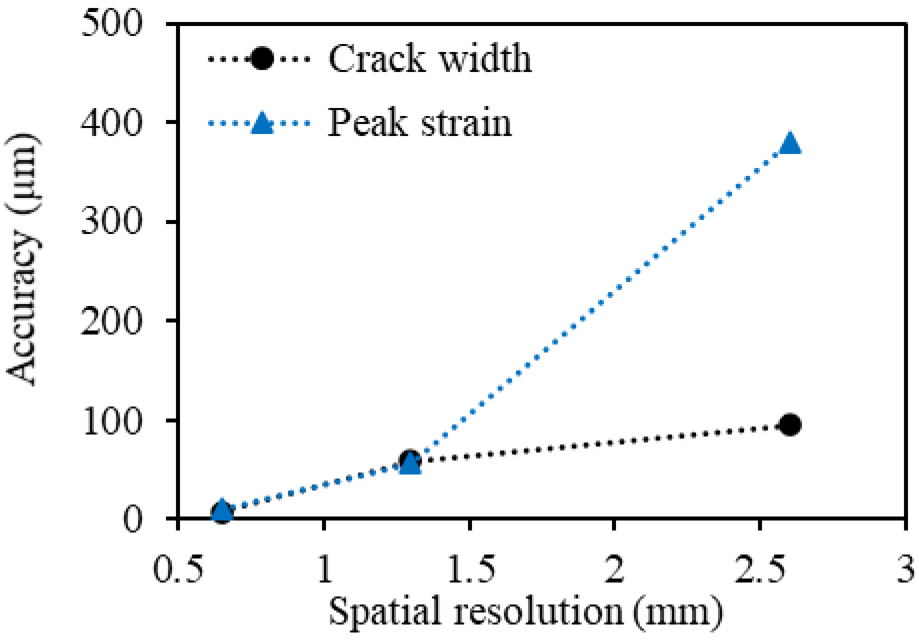
➢ The measurement accuracy of the crack width is insensitive to the thickness of protective coatings





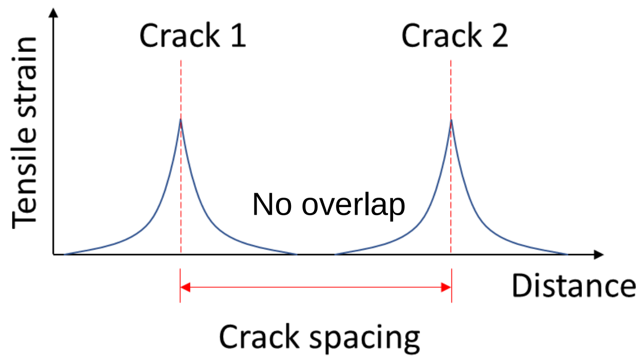
Experimental studies

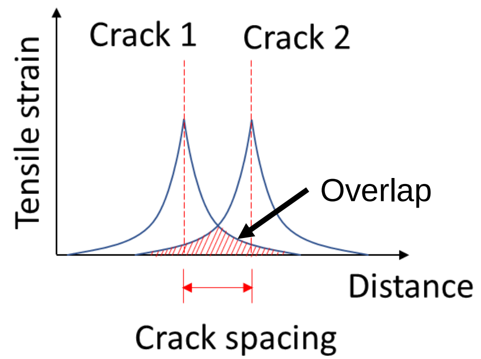
- Effects of spatial resolution
  - Three spatial resolutions (0.65 mm, 1.3 mm, and 2.6 mm)
  - When the spatial resolution is increased from 0.65 mm to 2.6 mm, the accuracy is decreased from 7.2 µm to 72 µm (Proposed method).

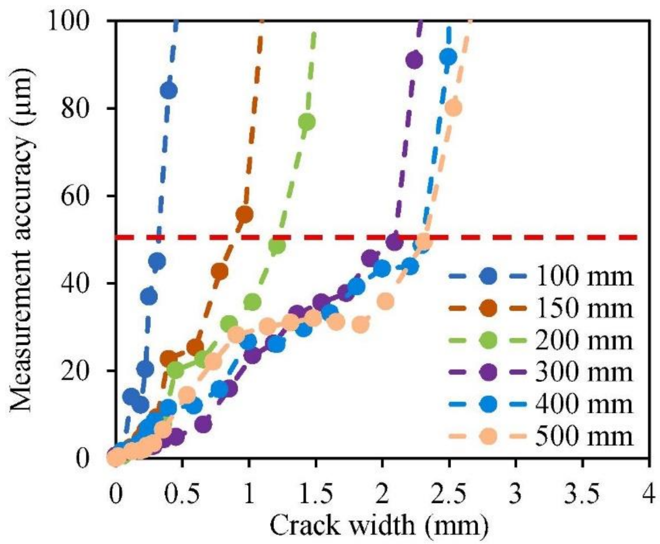


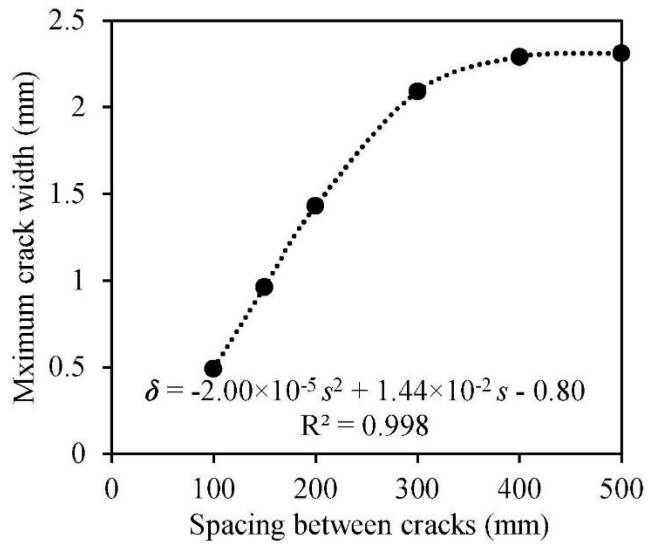
Experimental studies

- Effects of crack spacing



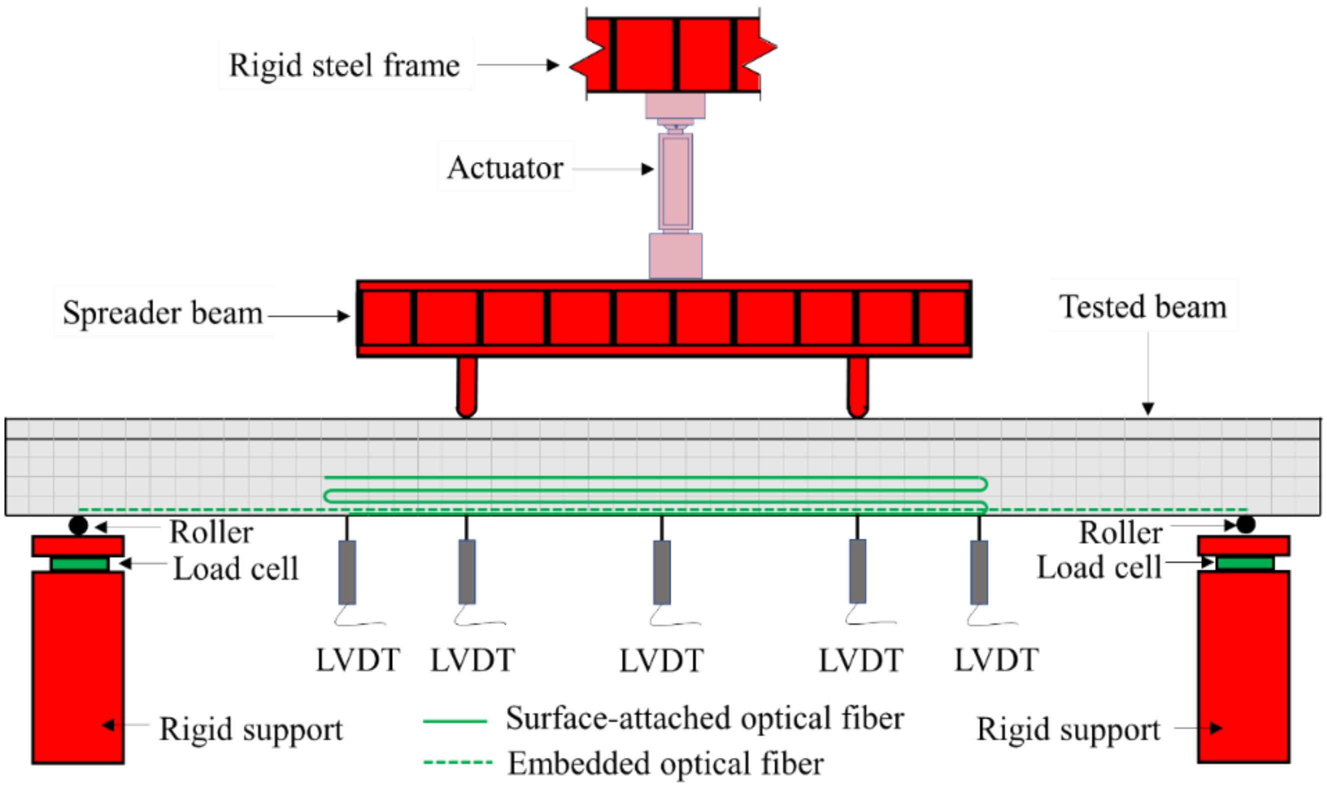






Case study - prestressed concrete beams

- Four-point bending
- Cracks were measured by digital crack scopes and DFOSs.



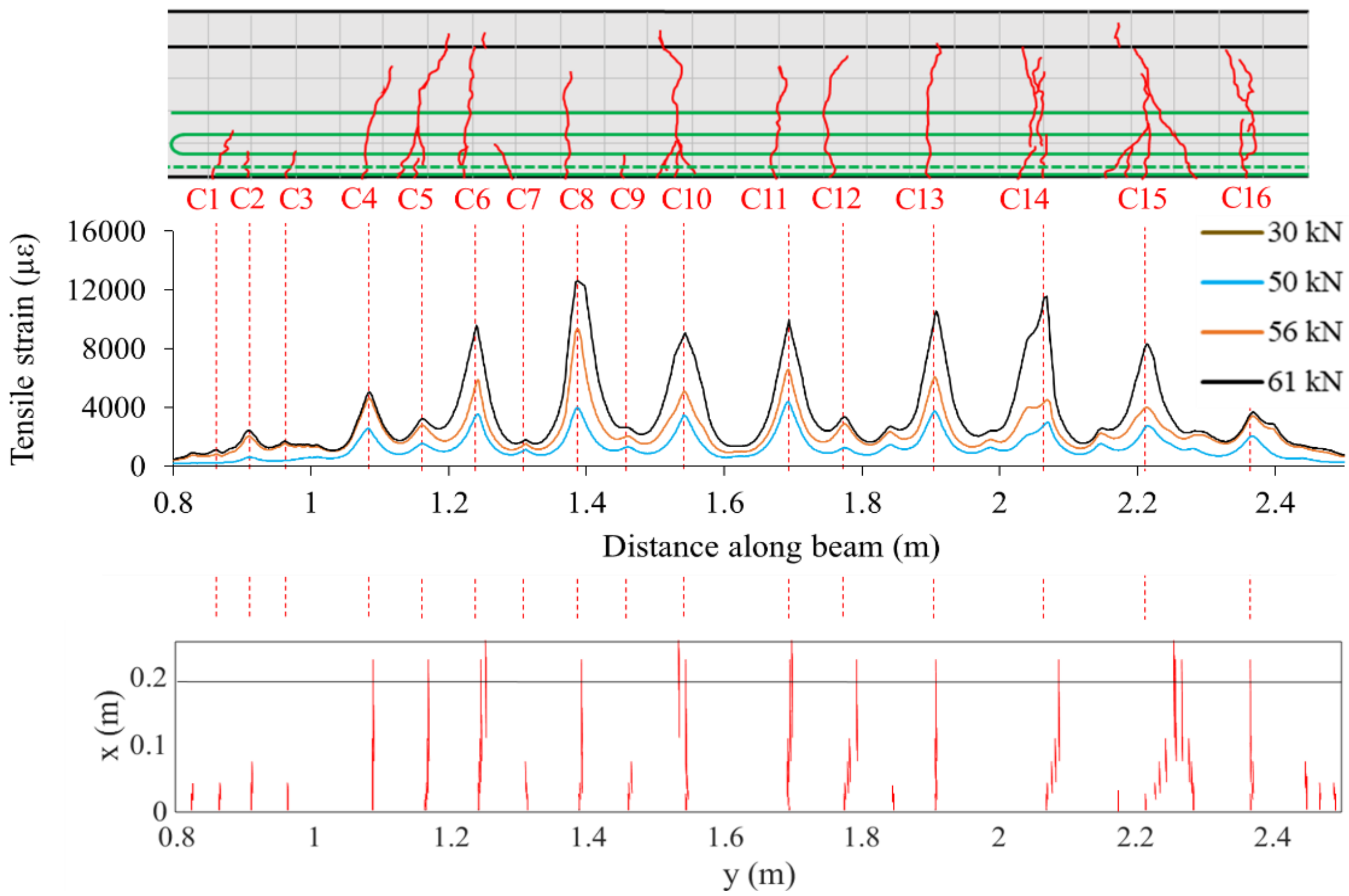
Case study - prestressed concrete beams

- Crack mapping

Visual inspection

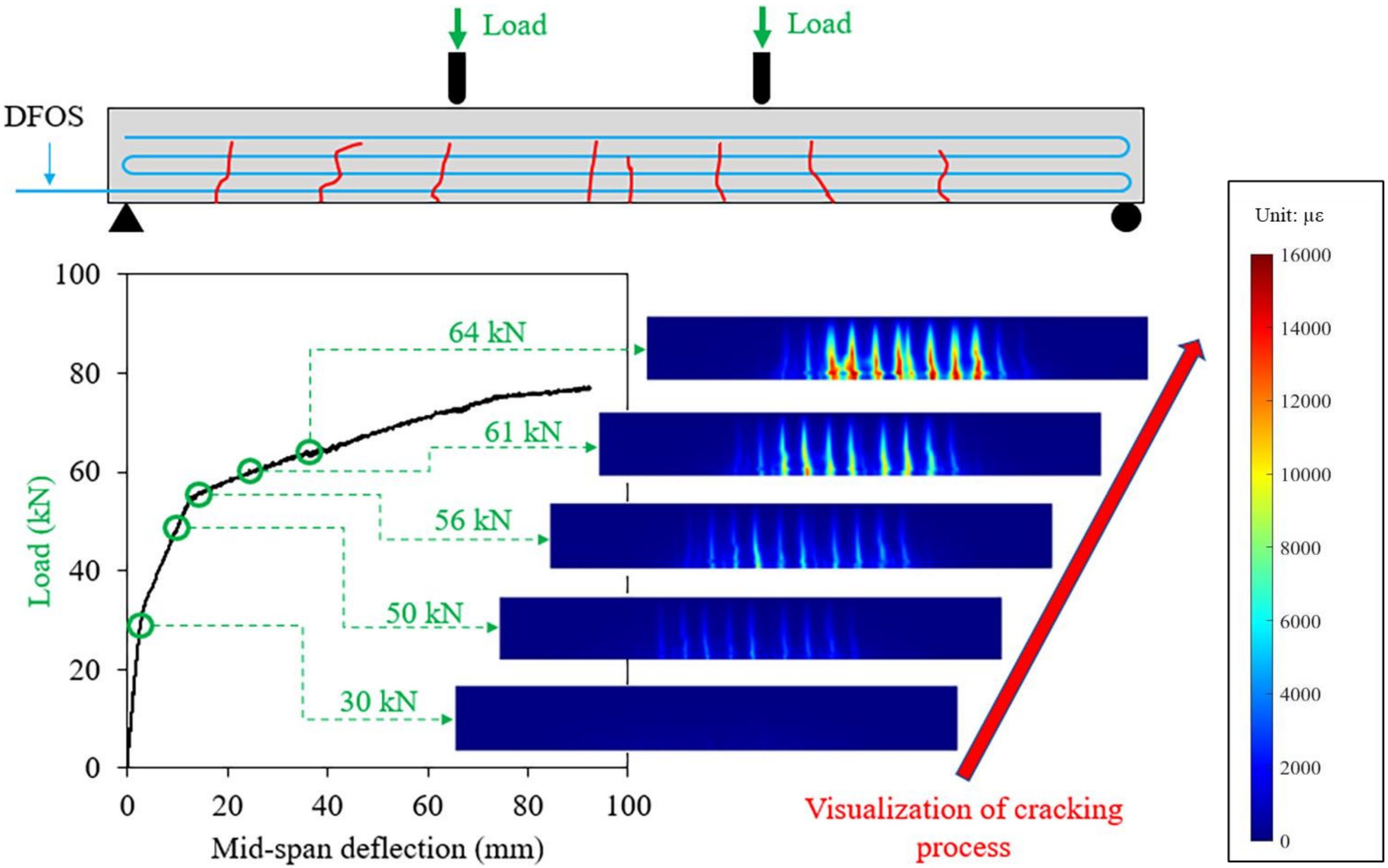
Strain distributions

Crack mapping



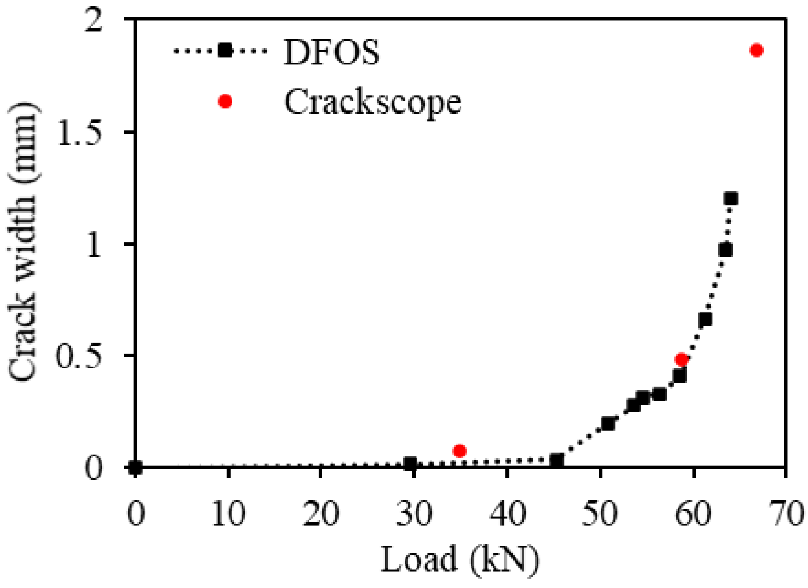
Case study - prestressed concrete beams

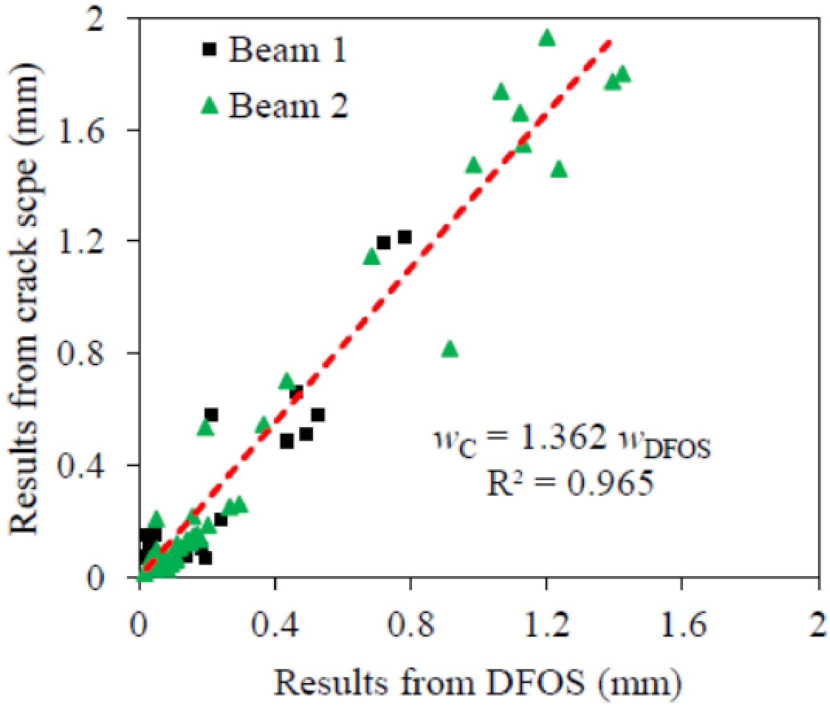
- Crack visualization



Case study - prestressed concrete beams

- Quantification of crack width
  - Crack widths are calculated by the integration of strains
  - The results from the distributed sensor and the crack scope agree well with each other





Conclusions

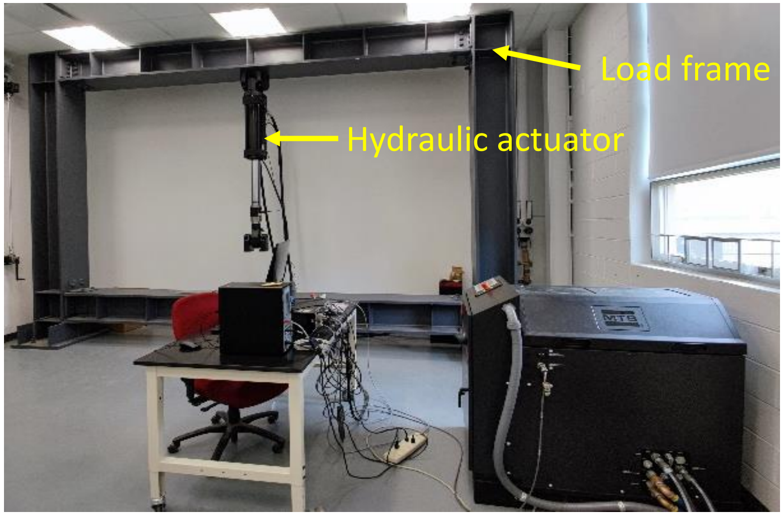
- Crack widths can be real-time measured with proposed method at micro to macro scales throughout the cracking process.
- The measurement accuracy of the crack width is insensitive to different types of protective coatings of optical fibers and dependent on the spatial resolution of strain distribution.
- Multiple cracks can be located and quantified using a single distributed sensor. Increasing the spacing between the cracks tends to improve the measurement accuracy of crack width.
- The distributed sensors are capable of detecting, locating, visualizing, and quantifying cracks, which is promising for timely and effective repair of the structures.

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 University for assistance in casting and loading of the beams.

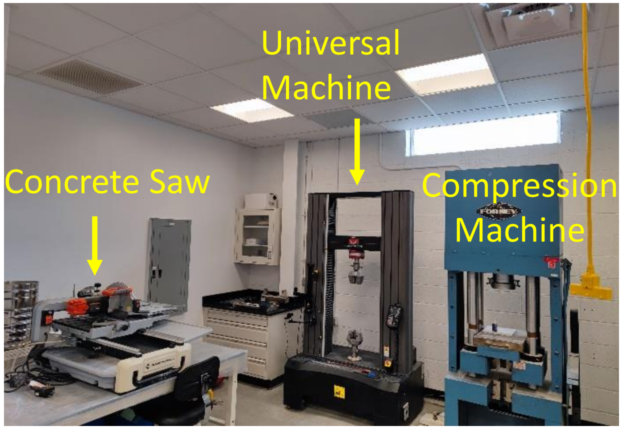
Smart Infrastructure Laboratory

- 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.)



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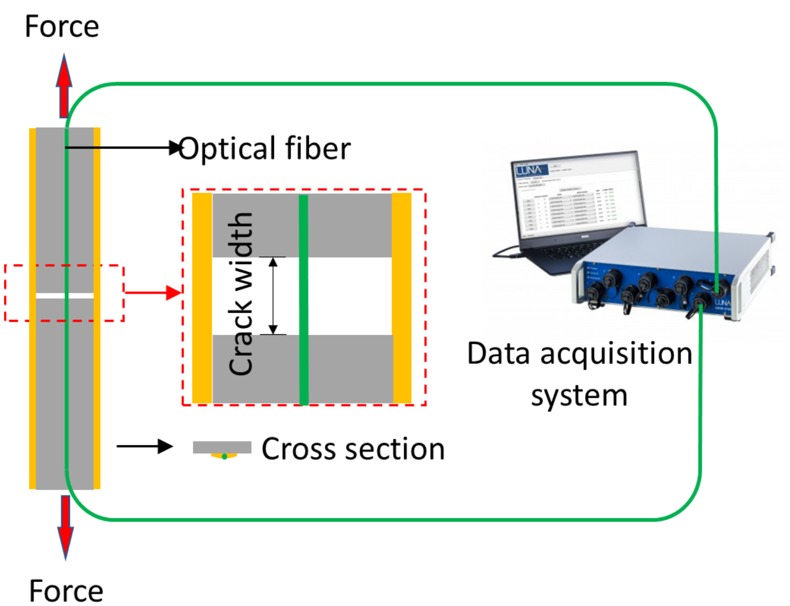
Q & A

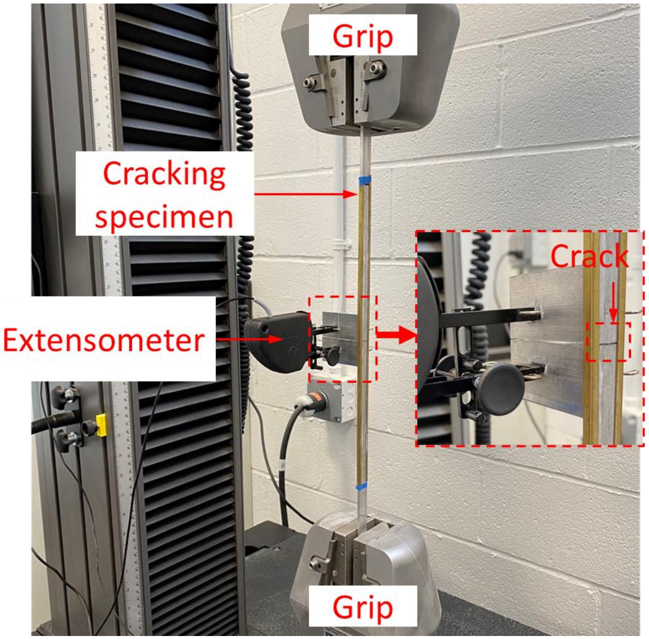
Thank you!

Appendix - experimental studies

- Using Rayleigh optical frequency domain reflectometry (OFDR) techniques with high resolution (0.65 mm)
- Special cracking specimen
- An extensometer: validate the crack widths measured by distributed sensors



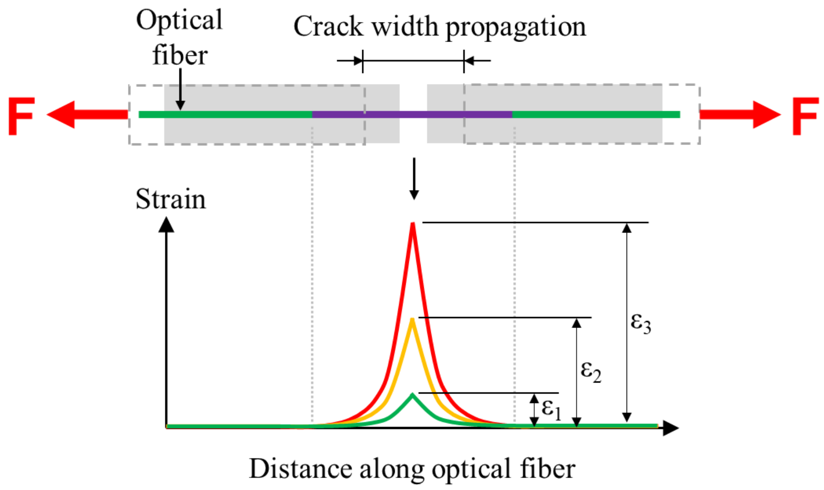
Special cracking specimen



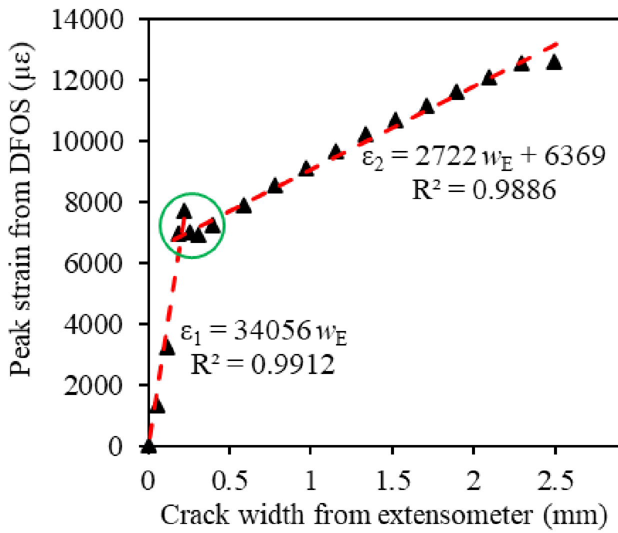
Test set-up

Appendix - method 2 for crack width

- Method based on peak strain
- Bi-linear fitting curve
- Accuracy of crack width: 7.3 µm



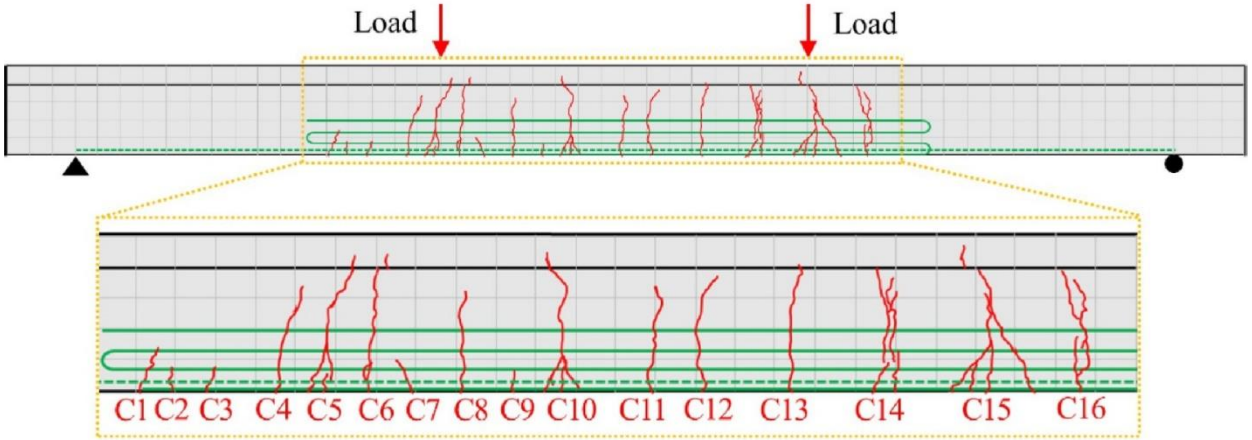
Peak strain method



Peak strains versus the measured crack widths

Appendix - prestressed concrete beams

- Visual observation of cracks
  - ➢ Multiple densely distributed cracks occurred in crack region
  - ➢ Red lines represent crack patterns observed by the crack scope
  - ➢ 16 cracks are observed (C1 to C16)



Crack patterns determined by visual inspection

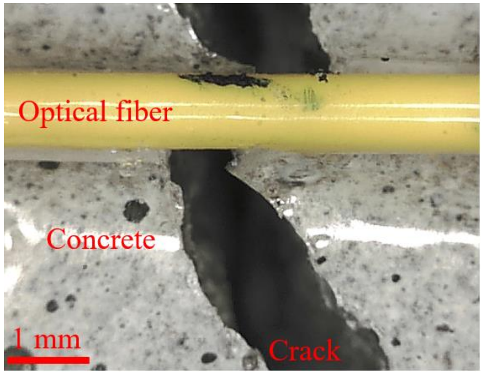
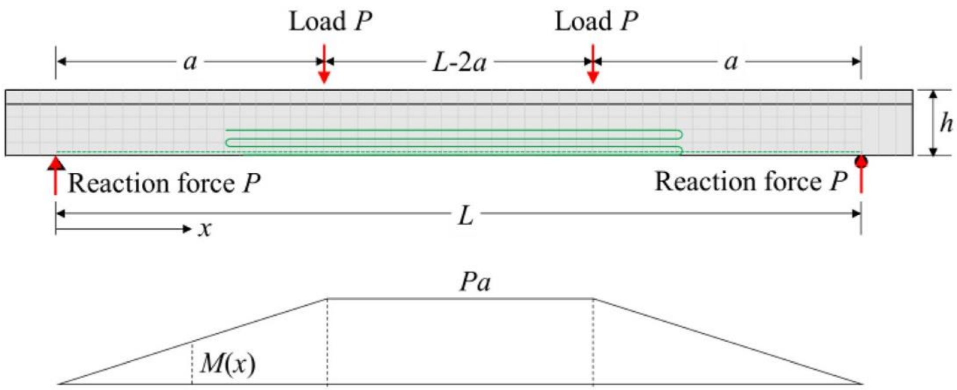
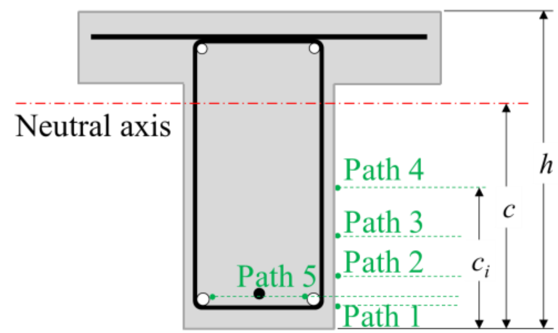


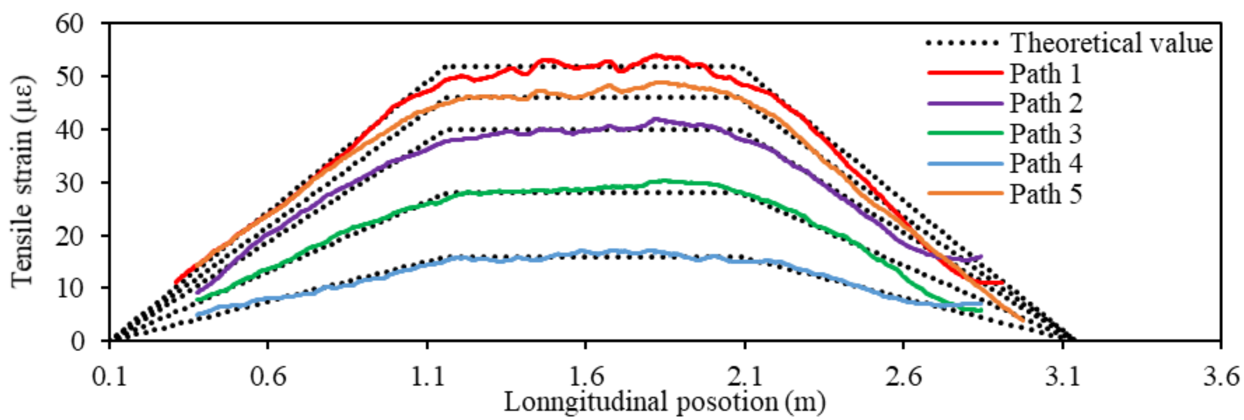
Photo of the crack C10 at the load level of 58.7 kN

Appendix - prestressed concrete beams

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

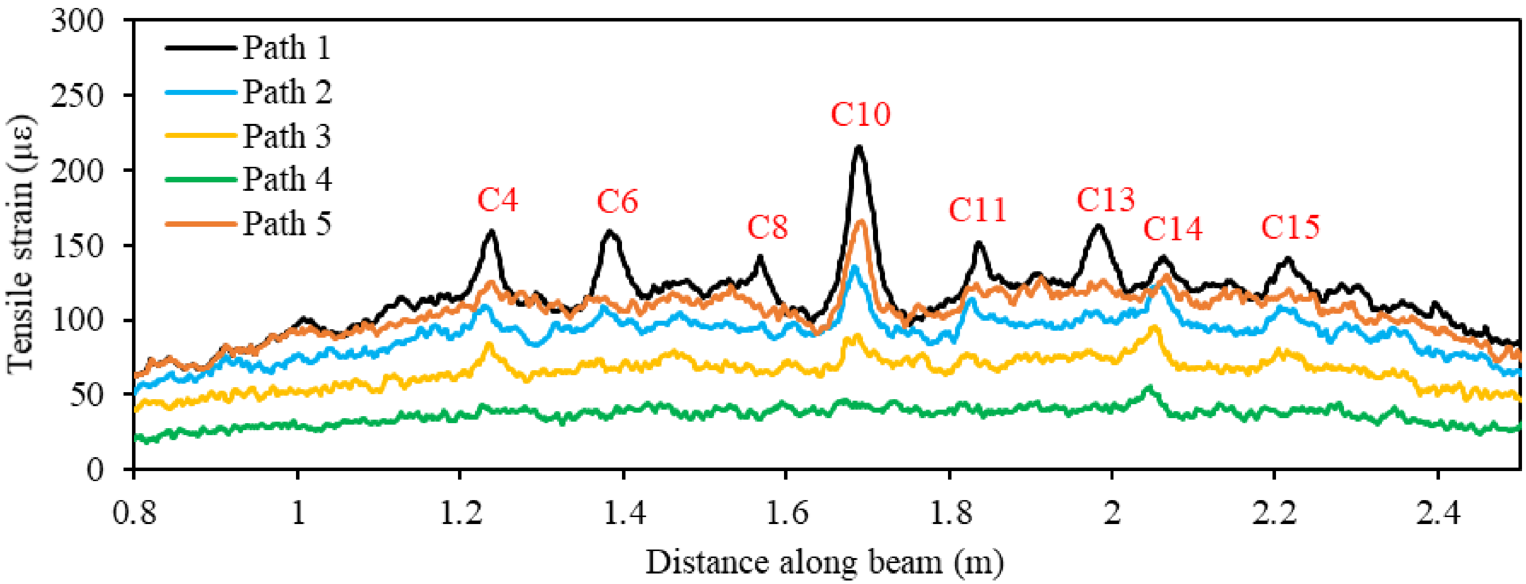






Appendix - prestressed concrete beams

- Crack initiation
  - The cracks detected by distributed sensor when P = 19.6 kN
  - The cracks detected by crack scope until P = 34.7 kN



Appendix - prestressed concrete beams

- Cracking propagation
  - With the increase of the load, new peaks appear in the strain distributions
  - C17 to C21: found only through DFOS
  - The magnitudes of the peaks are increased with the propagation of the crack widths