The Application of Distributed Optical Sensing for Monitoring Support in Underground Excavations

MASc. thesis submitted to the department of
Geological Sciences and Geological Engineering

Bradley J. Forbes

Queen's University

RMC CMR

Co-supervisors: Dr. Nicholas Vlachopoulos & Dr. Mark S. Diederichs

Presentation Overview

- Introduction:
  - Motivation for research
- Background:
  - Underground support
  - Conventional monitoring
  - Optical strain sensing
- Development of the optical technique
- Verification and demonstration through a laboratory testing scheme
- Major findings and conclusions of research

Motivation for Research

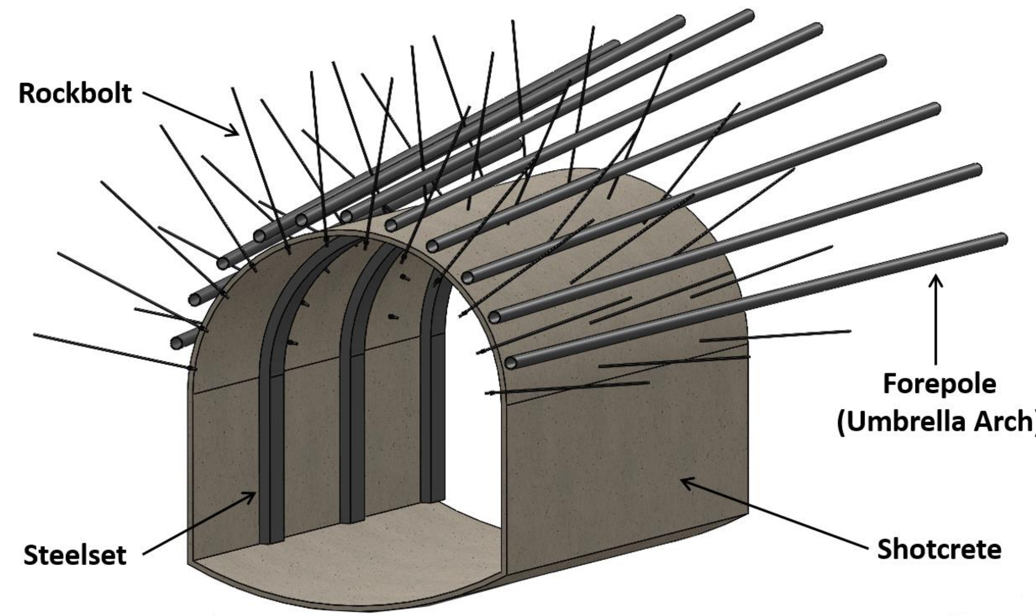
Pasar Rakyat MRT Station, Kuala Lampur, Malaysia

Long-wall mining method, Colorado, U.S.

- Larger and longer tunnelling projects to accommodate resource and public transportation
- Deeper underground mining and nuclear waste repositories

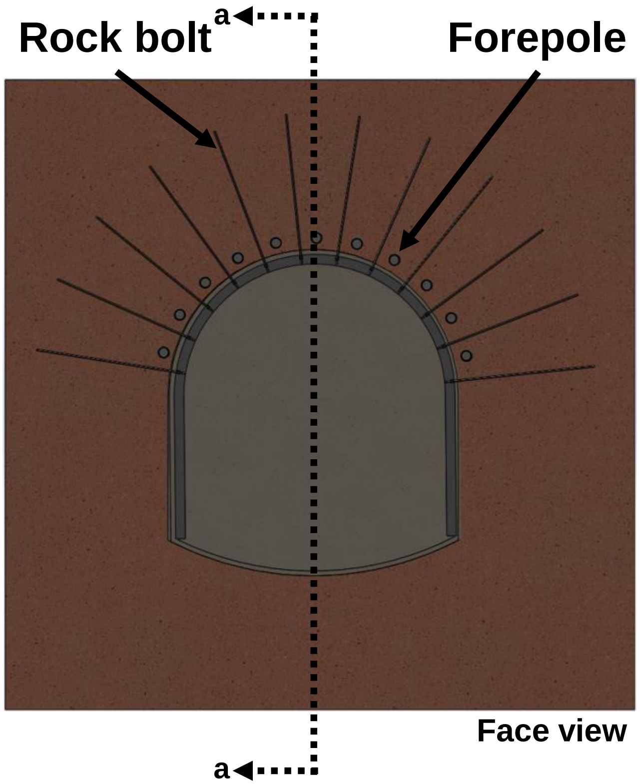
Support in Underground Excavations

- Support systems are often composed of many individual support elements
- Installed in order to maintain excavation stability and maintain project specific guidelines
- This research has focused specifically on:
  - Forepoles
  - Rock bolts

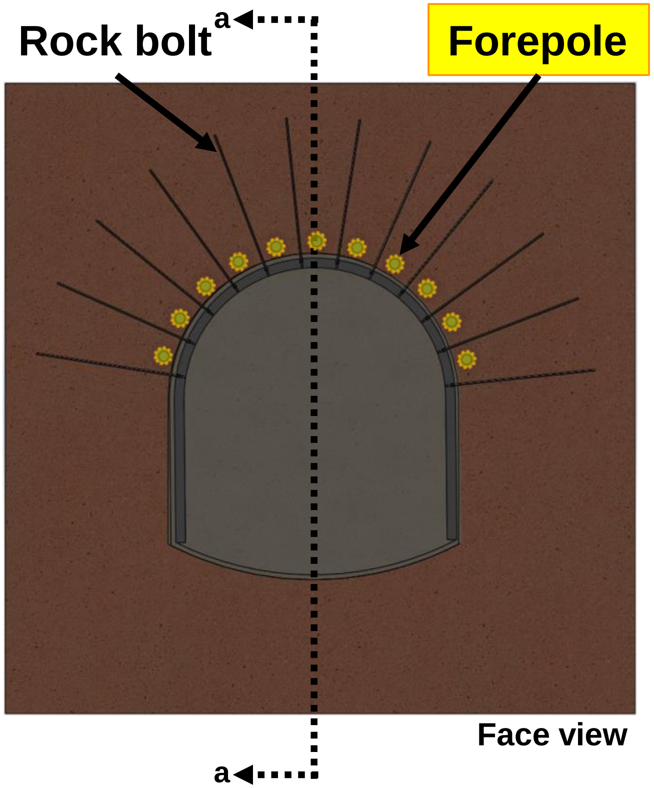


Example support system

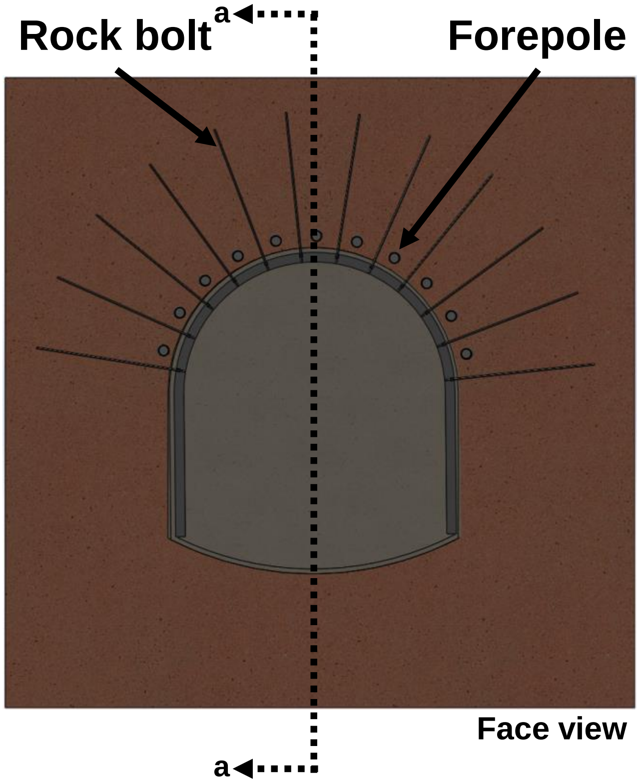
Forepole Support

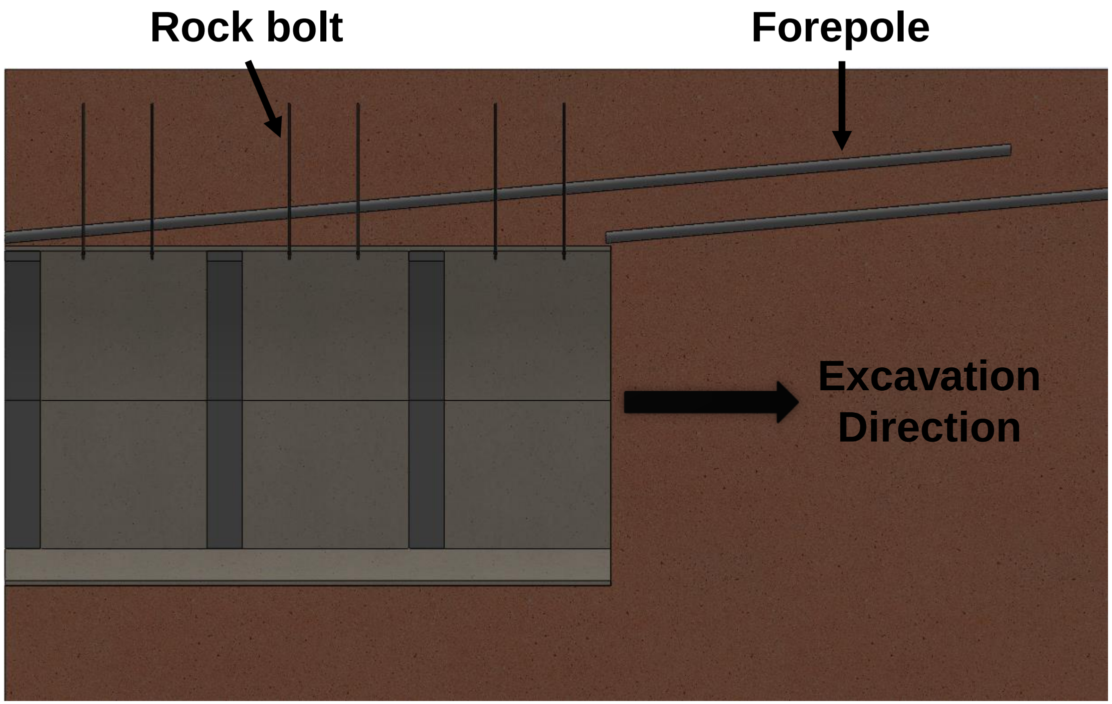


Forepole Support



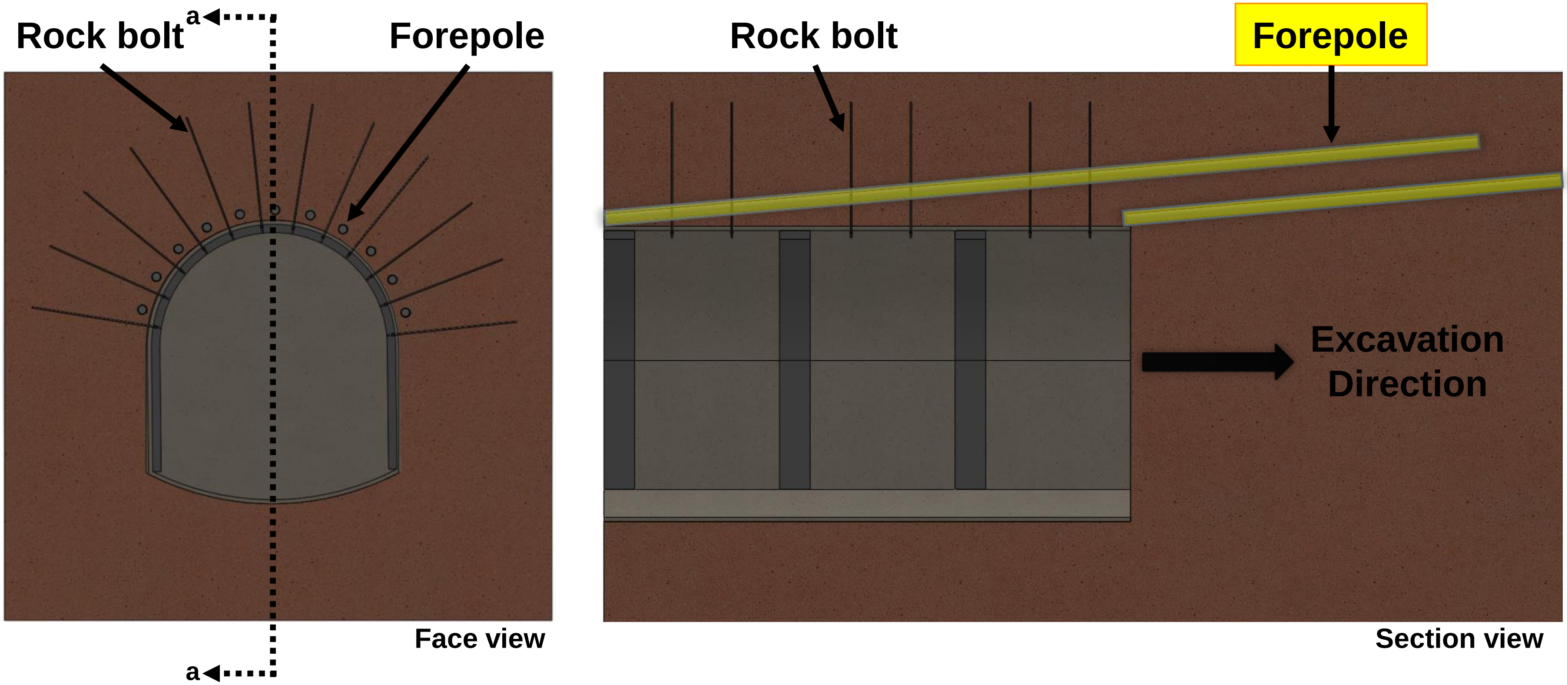
Forepole Support





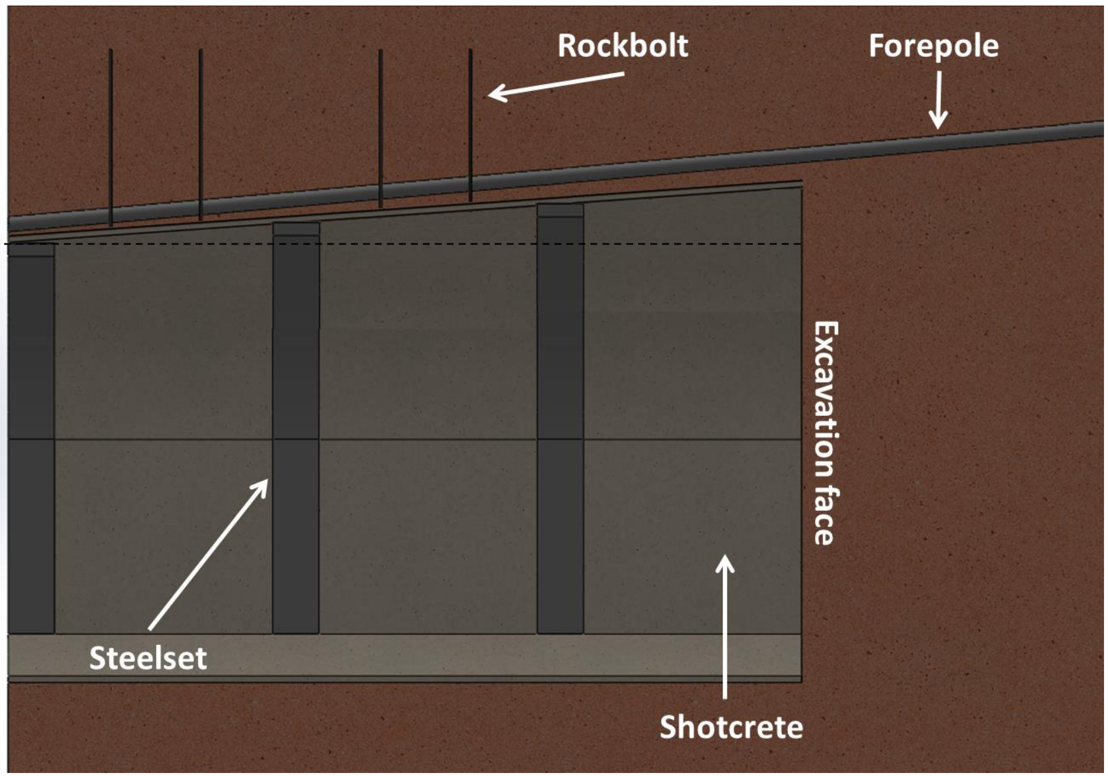
- Support members installed longitudinally ahead of the excavation face

Forepole Support



- Support members installed longitudinally ahead of the excavation face

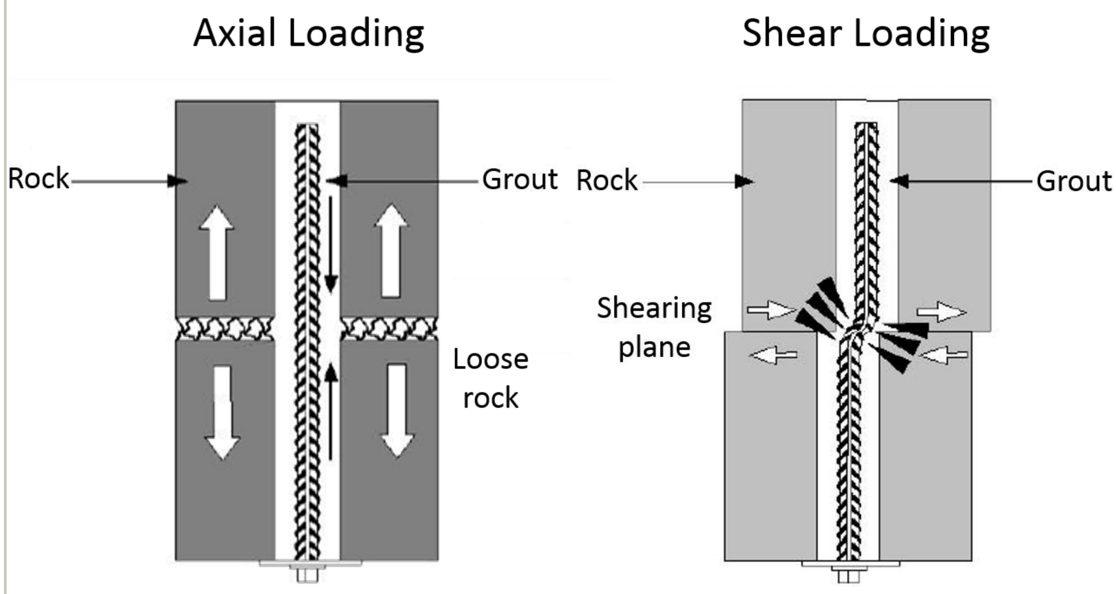
Loading Mechanisms



Forepole Loading

- Continuous multi-span beam under distributed bending
- Load is transferred longitudinally along the support element to the varying foundation arrangement, including:
  - Two steel set (or shotcrete) abutments
  - A steel set and the ground ahead of the excavation face (and shotcrete at the face)
- May provide a component of axial resistance ahead of the excavation face

Loading Mechanisms



Modified after Mark et al. (2002)

Rock Bolt Loading

- Secure gravity, structurally, and stress driven failures surround the excavation
- Primarily considered to undergo axial loading
- Depending on the ground conditions may be loaded in shear

Conventional Monitoring

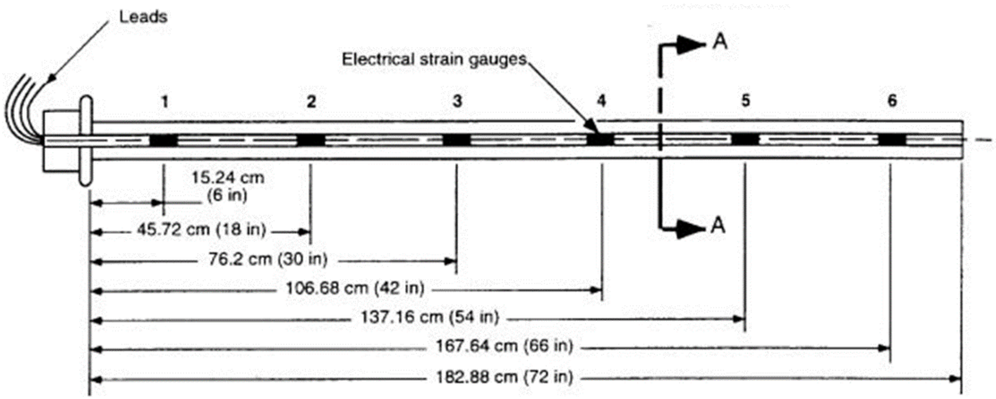
Rock Bolt Monitoring

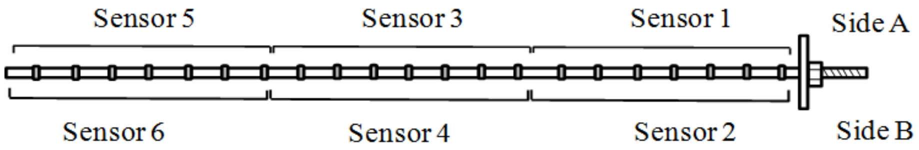
- Electrical resistive strain gauges:
  - discrete measurement points
  - a majority of the bolt length is left unmonitored
- Long base-length inductive strain gauges
  - captures load across entire length
  - separates the bolt into discrete zones

Forepole Monitoring

- Chain inclinometer (2 meter lengths)
  - strain derived from deflection

Modified after Serbousek & Signer (1987)

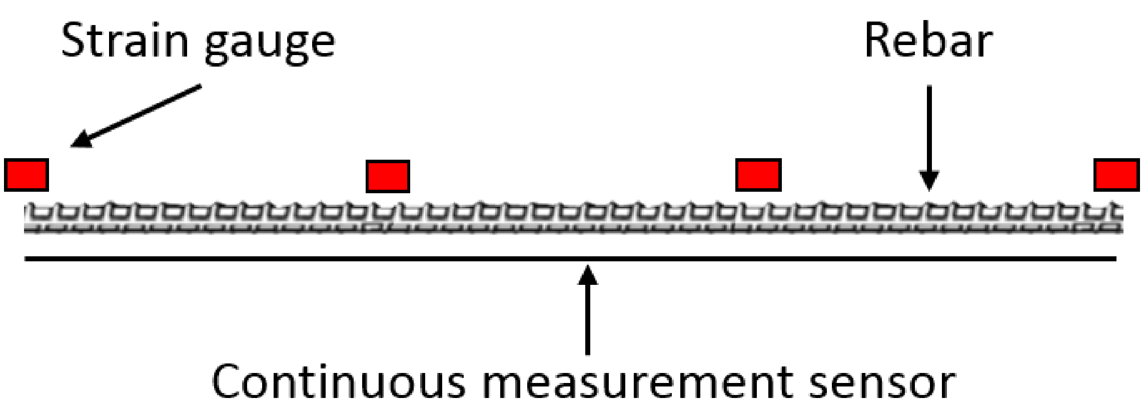




Modified after Spearing et al. (2013)

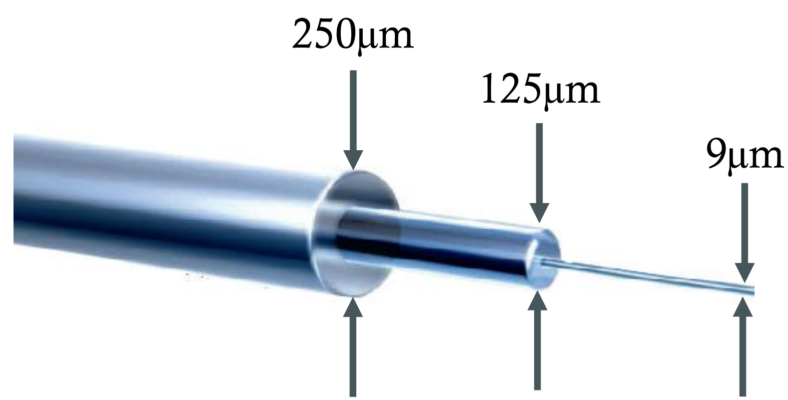
A Continuous Solution?

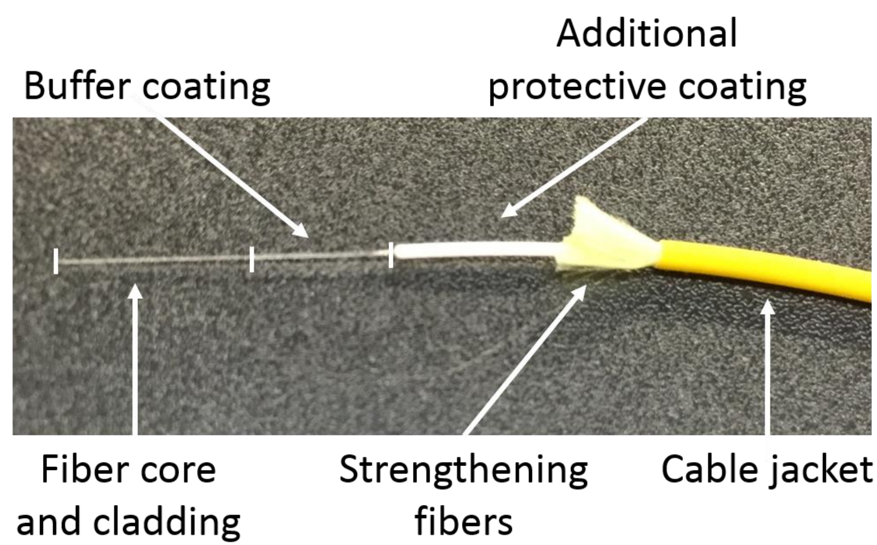
- Support may not be loaded in a continuous fashion *in situ*
- The ability to capture localized loading is contingent on the positioning and number of discrete gauges
- Limited by costs and manufacturing difficulties
- Is there solution that overcomes limitations of conventional instrumentation?



Optical Strain Sensing

- One single mode optical fiber is used as the sensing length and lead
- Optical fiber is 250 micrometers in diameter (ideal for placing along a given support element)
- Light is the transmission signal:
  - Immune to electromagnetic and radio interference
  - Inherently intrinsically safe
- Glass transmission medium implies the instrumentation will not degrade or require recalibration over time (i.e. zero-shift)



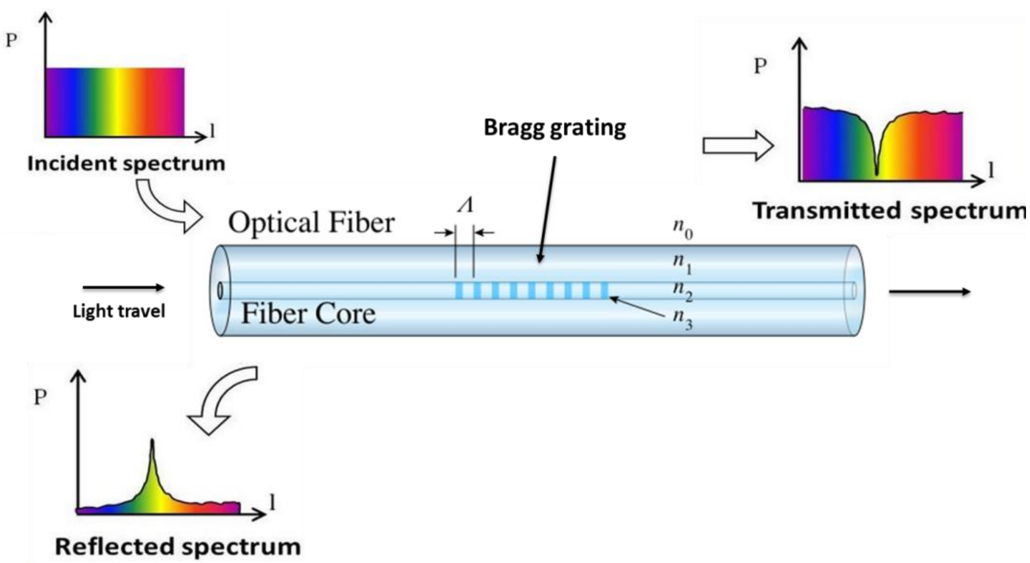


Optical Strain Sensing

Fiber Bragg Gratings

Modified after FBGS (2014)

- Bragg grating structure: fixed index modulation inscribed into the fiber core from high-intensity UV exposure
- Bragg grating will reflect a component of the incident wavelength spectrum
- Strain will change the local refractive index and periodicity of the Bragg grating
- Reflected wavelength will shift linearly with strain

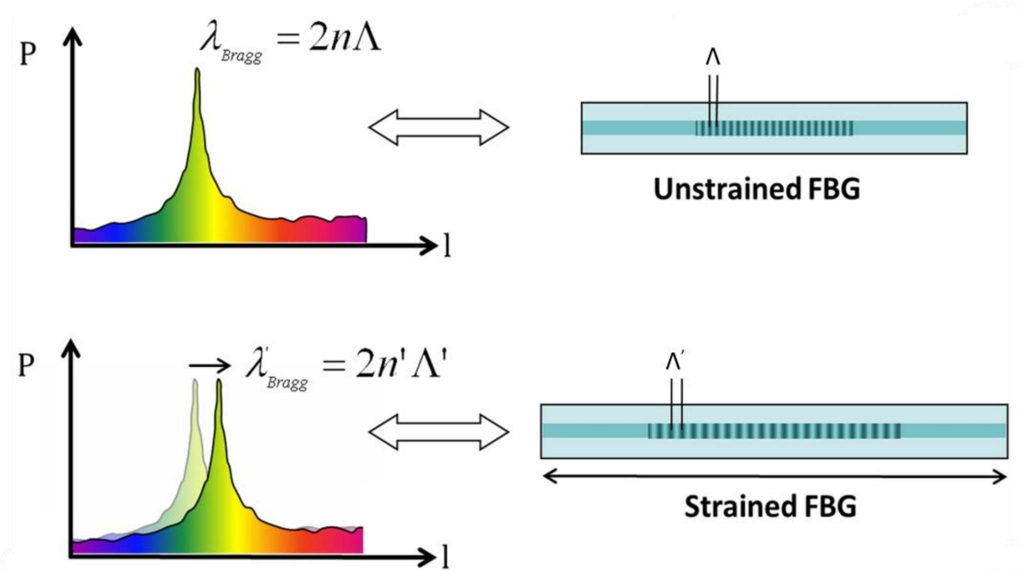


Optical Strain Sensing

Modified after FBGS (2014)

Fiber Bragg Gratings

- Bragg grating structure: fixed index modulation inscribed into the fiber core from high-intensity UV exposure
- Bragg grating will reflect a component of the incident wavelength spectrum
- Strain will change the local refractive index and periodicity of the Bragg grating
- Reflected wavelength will shift linearly with strain

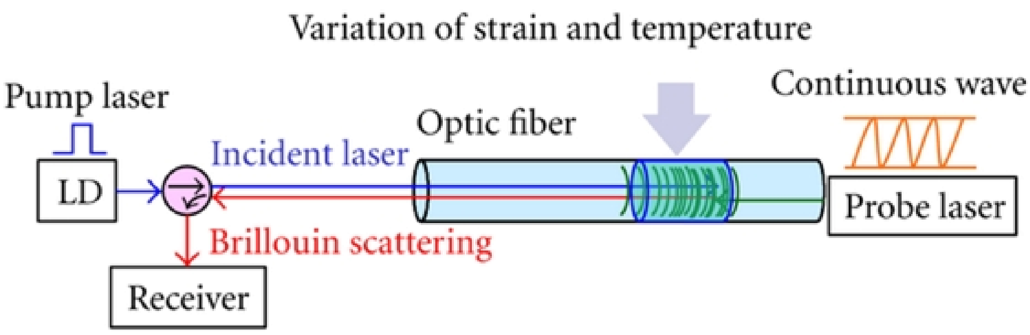


Optical Strain Sensing

Modified after Zhang & Wu (2012)

Distributed Optical Sensing (DOS)

- Monitors back scattered components of light
- Uses a standard low-cost optical fiber
- Brillouin Optical Time Domain Reflectometry (BOTDR):
  - measures Brillouin frequency shift along the optical fiber
  - frequency shift arises from interaction with acoustic waves
  - shifts linearly with strain

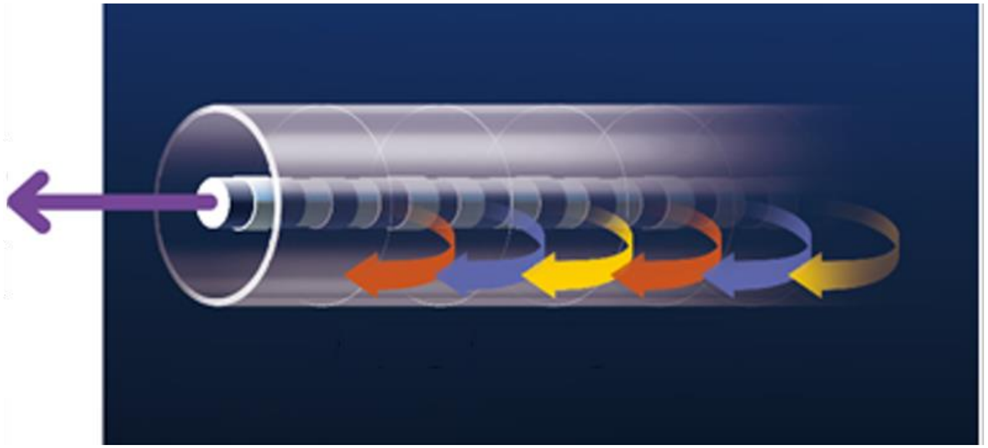


Optical Strain Sensing

Modified after Fuji Technical Research Inc.

<u>Distributed Optical Sensing (DOS)</u>

- Monitors back scattered components of light
- Uses a standard low-cost optical fiber
- <u>Rayleigh Optical Frequency Domain Reflectometry (ROFDR):</u>
    - measures Rayleigh scatter
    - scatter arises from random fluctuations in the refractive index
    - strain alters the local refractive index along the fiber

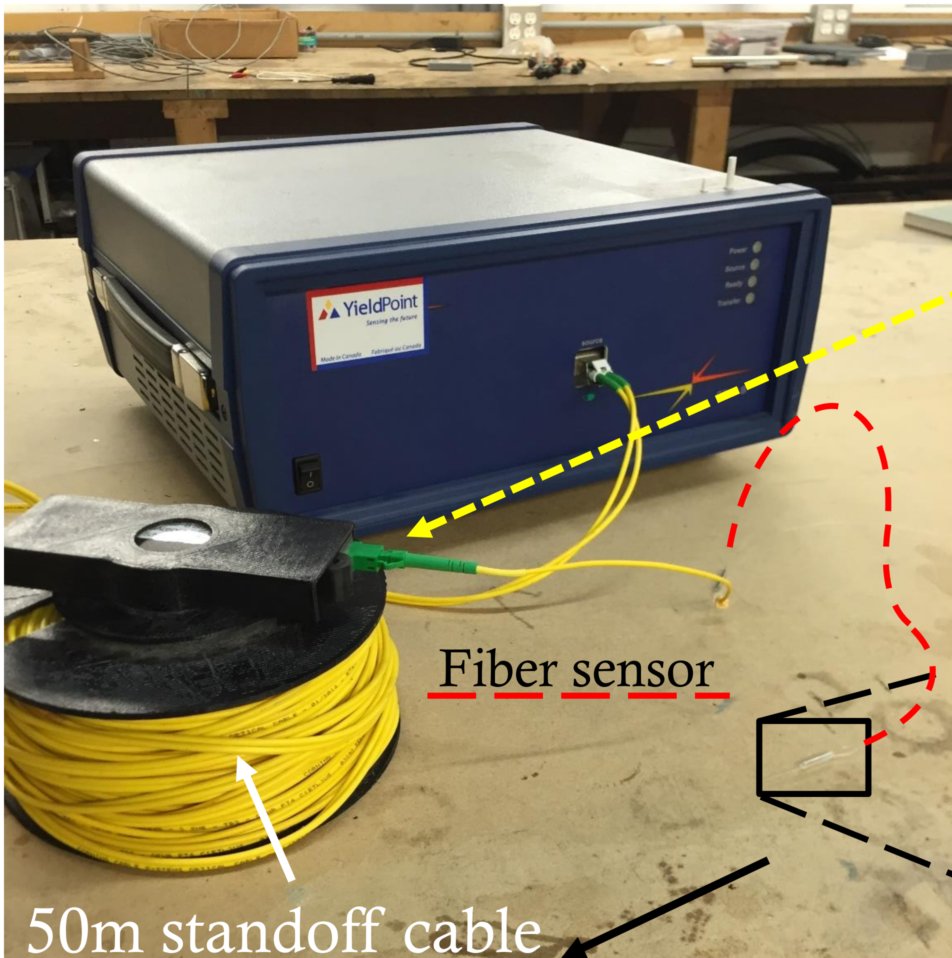


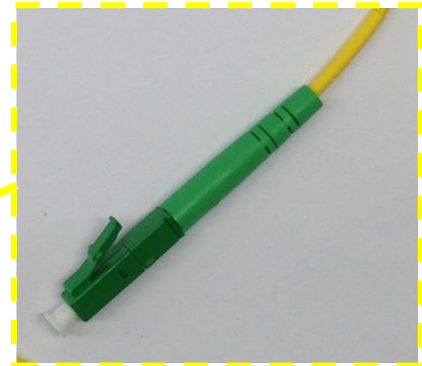
Optical Strain Sensing

Technique	FBG (Micron Optics Inc., 2012 & FBGS, 2015)	BOTDA (Omnisens, 2014)	ROFDR (Luna Innovation Inc., 2014)
Max. sensing length	> 1000 m	> 1000 m	< 40 m
Measurement repeatability	± 0.1-10 με	± 1 με	± 5 με
Spacing of measurement (i.e. spatial resolution)	10 cm (practically)	0.5 – 1 m	1.25 mm
Max. number of measurement points	10 – 20 (practically)	> 1000	> 1000

- Rayleigh OFDR is the most applicable option for monitoring support elements
- The technology remains untested in the geomechanics industry

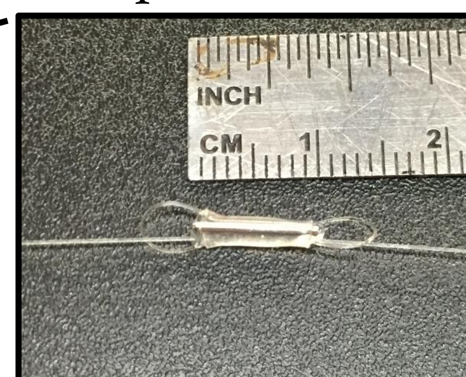
Optical Sensing Unit





LC-LC connector

Loop Termination



Rock Bolt Experimentation

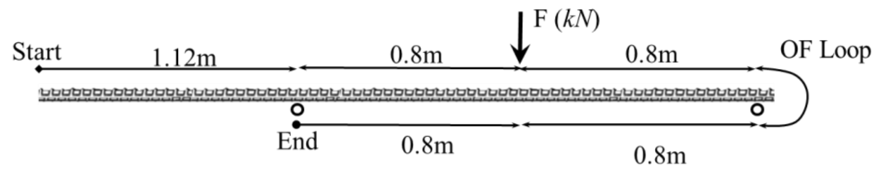
- Tested using #6 Grade 60 rebar specimens
- Diametrically opposed grooves machined along the lengths of rebar
- Optical instrumentation was embedded and encapsulated using epoxy resin

Forepole Experimentation

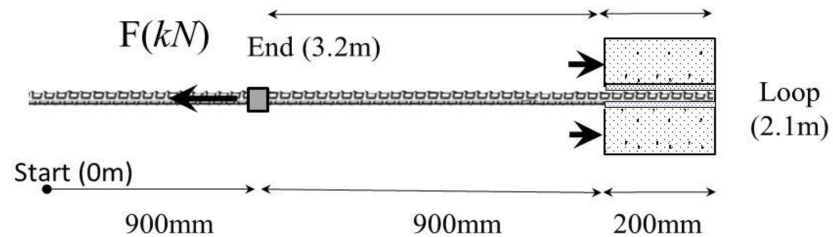
- Tests conducted on ASTM A53 steel pipe:
  - 114mm OD, 6.02mm wall
  - 21.3mm OD, 2.77mm wall
- Optical instrumentation embedded into 2mm machined groove, as well as surface mounted
- Multiple epoxy resins and adhesives experimented with to bond the instrumentation

Test Configurations

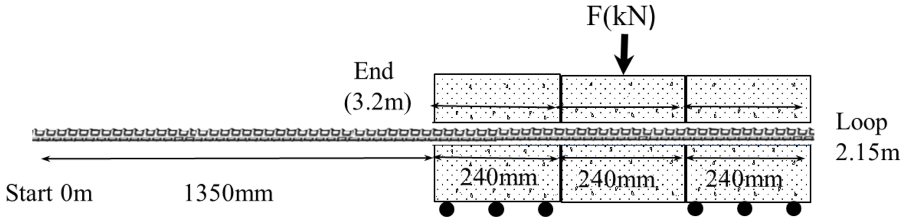
- Symmetric Point Load Bending



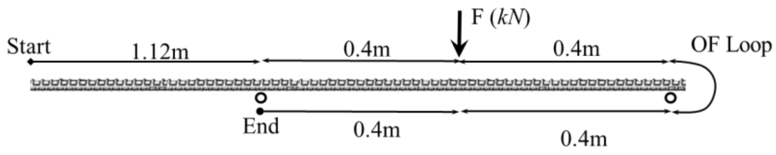
- Axial Pull-Out (Short Embedded Length)

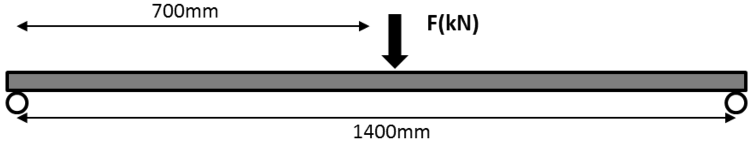


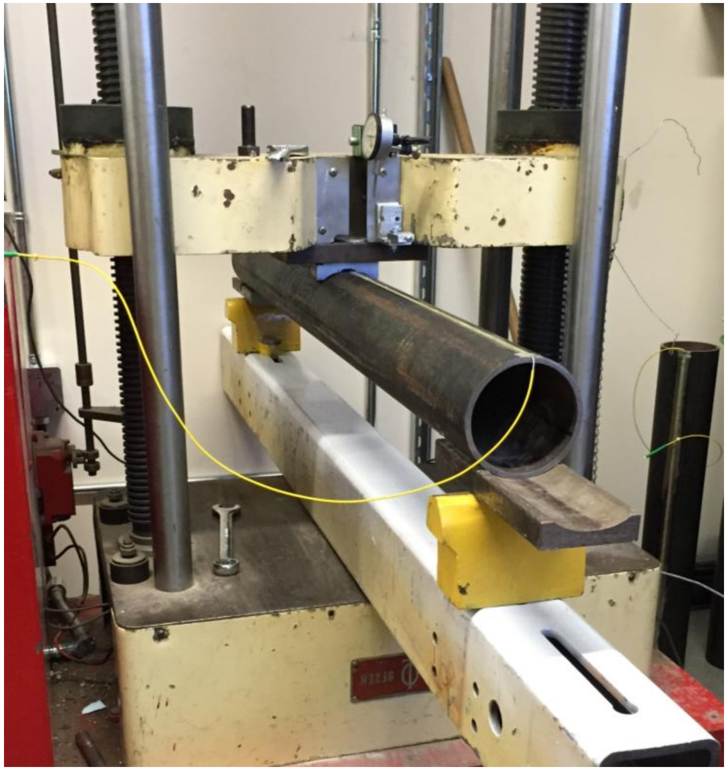
- Double Shear Configuration



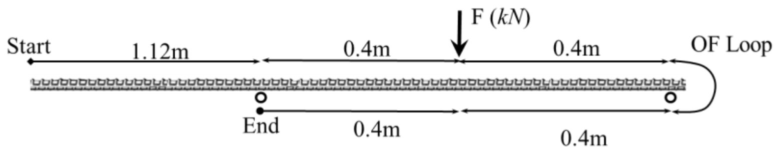
Symmetric Bending Testing

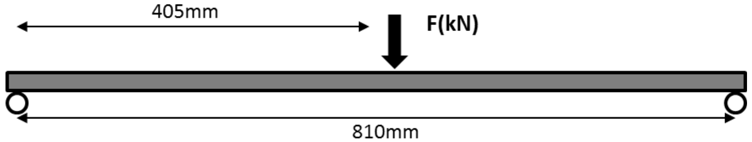


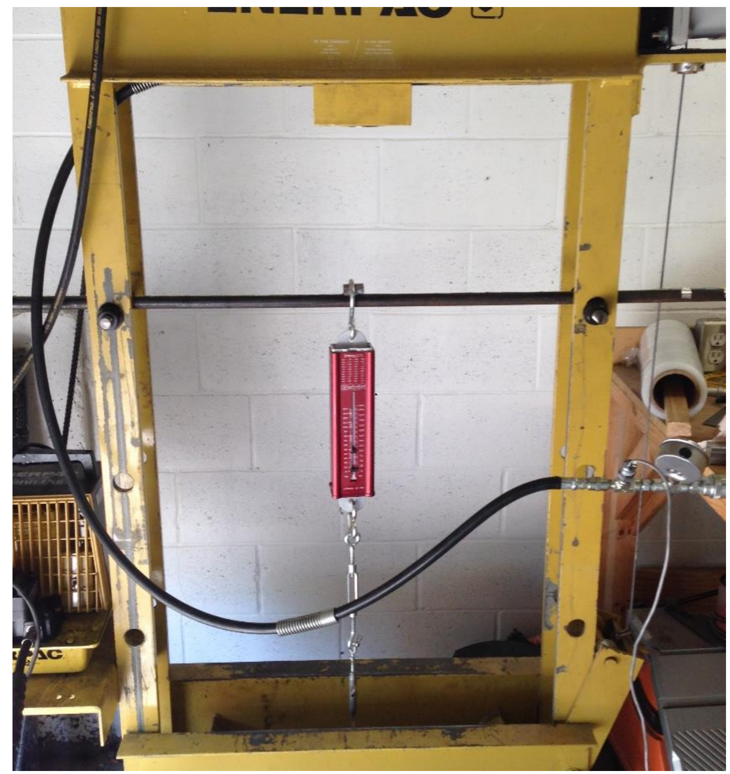




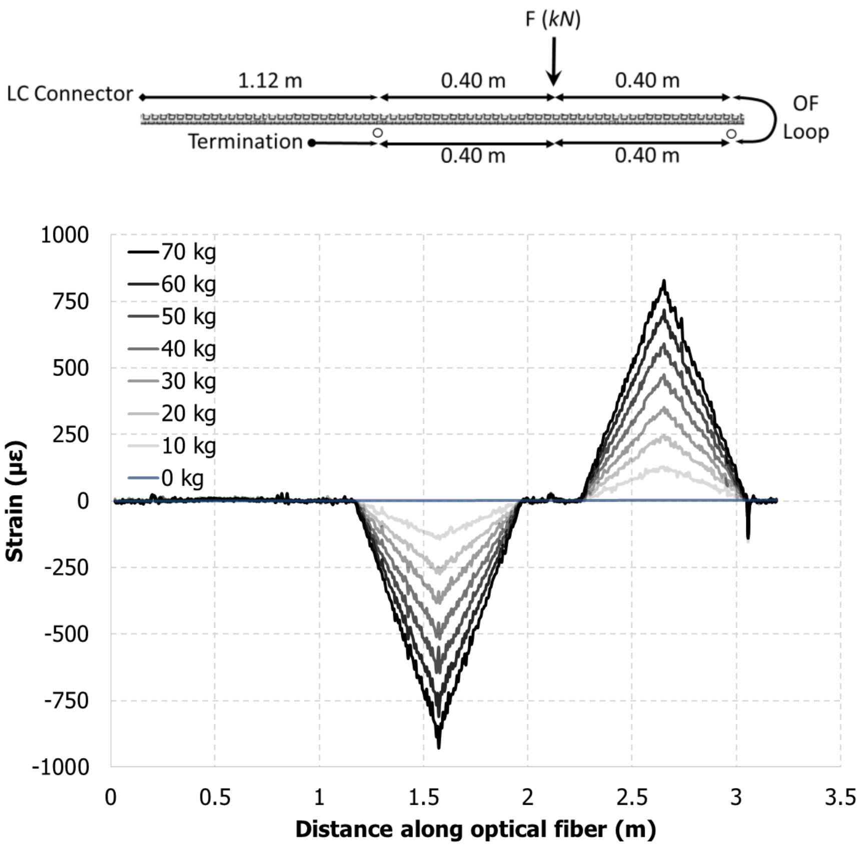
Symmetric Bending Testing





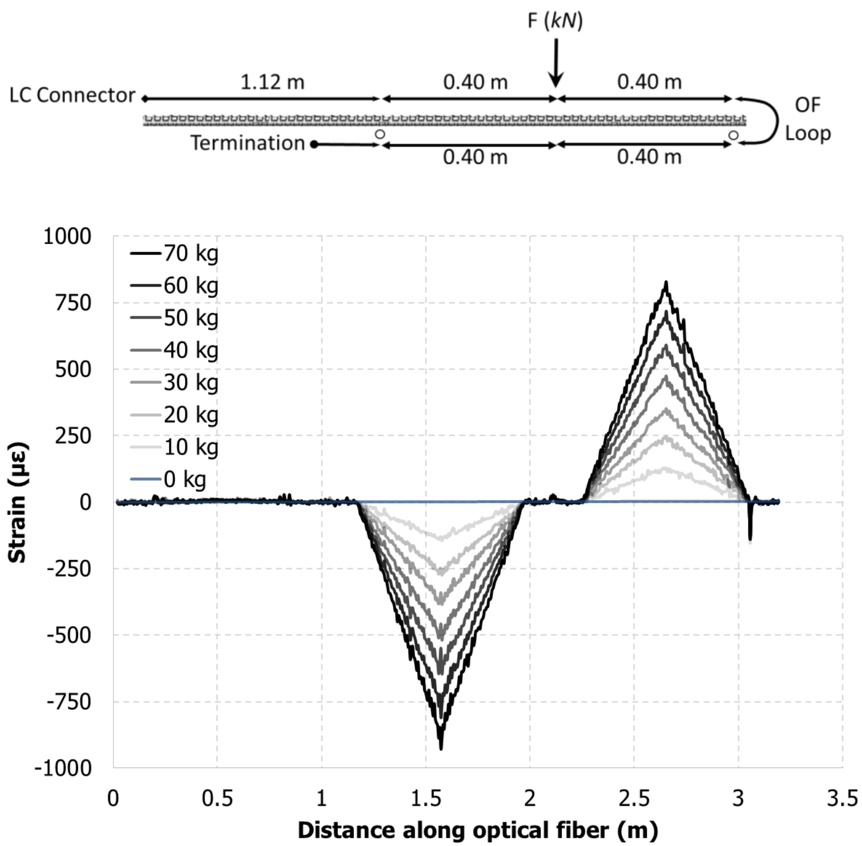


Symmetric Bending Testing

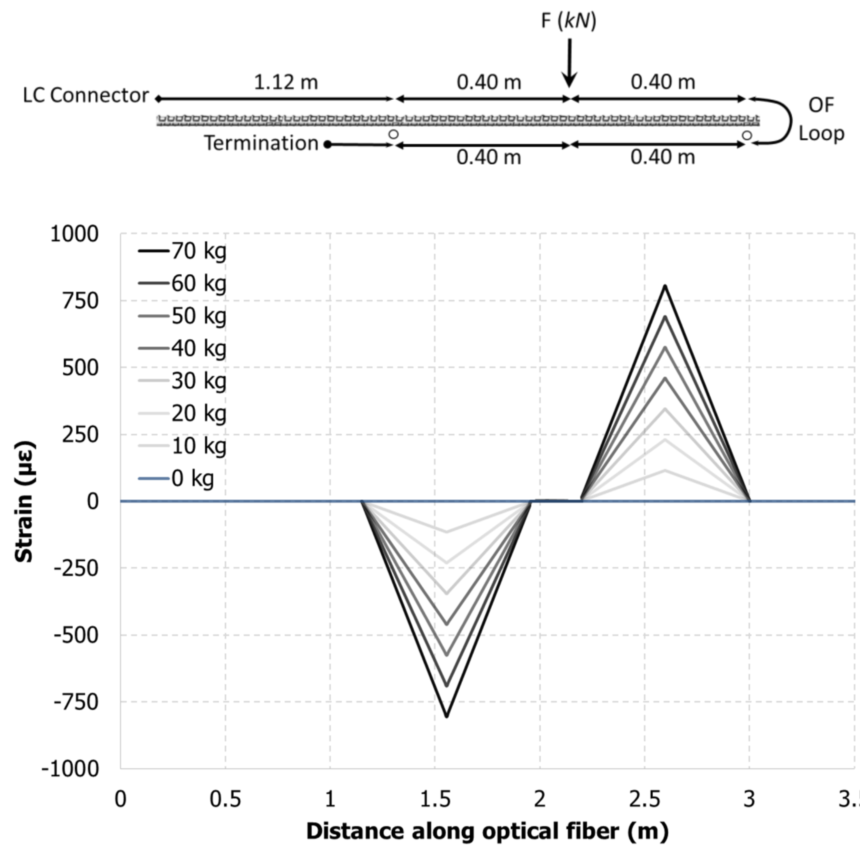


Strain Profile of Rebar Element

Symmetric Bending Testing

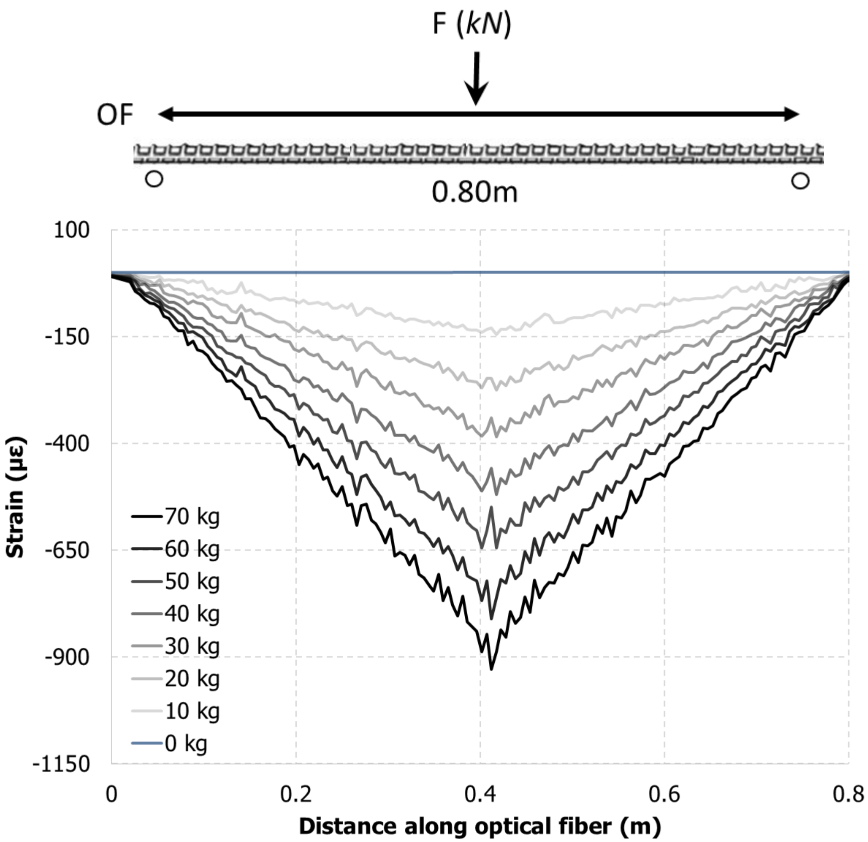


Strain Profile of Rebar Element



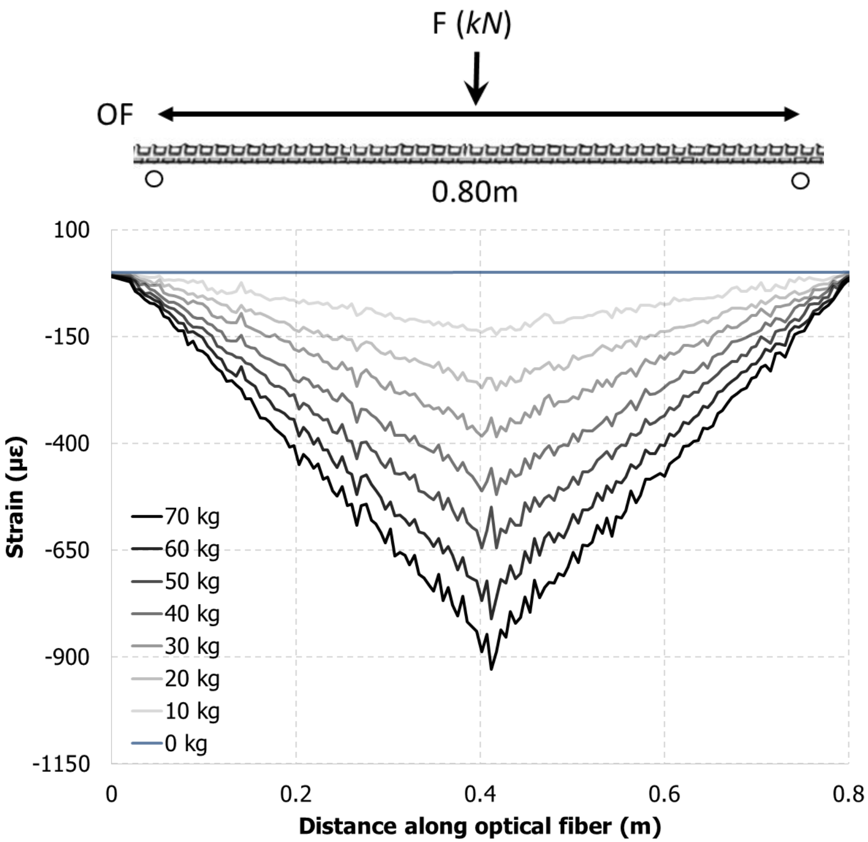
Euler Bernoulli Strain Profile

Symmetric Bending Testing

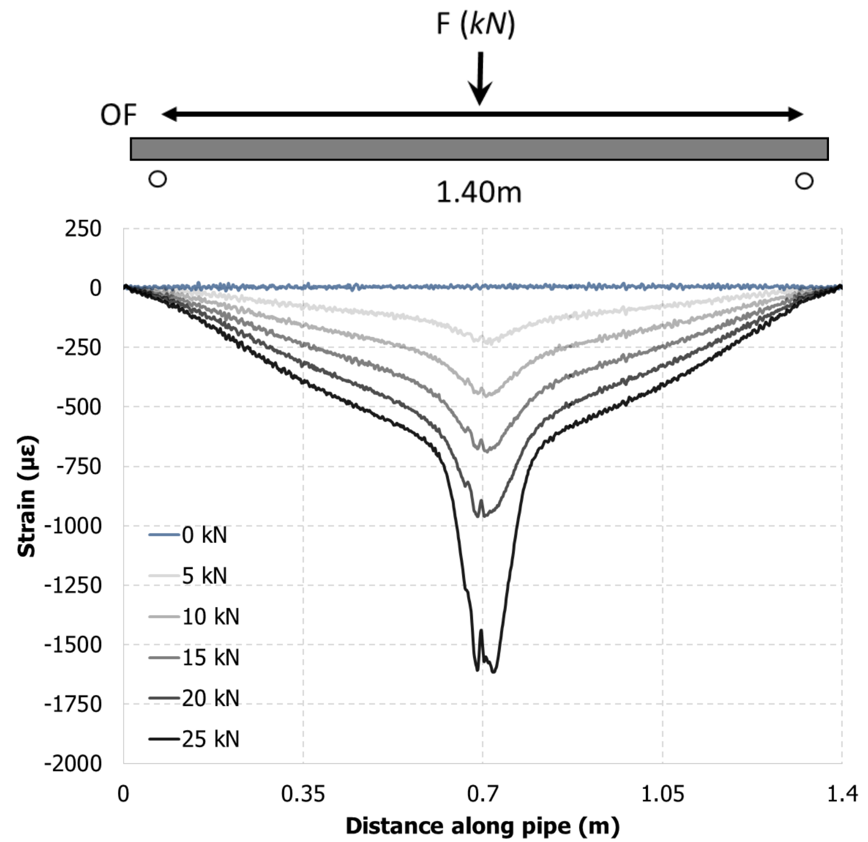


Strain Profile of Rebar Element

Symmetric Bending Testing

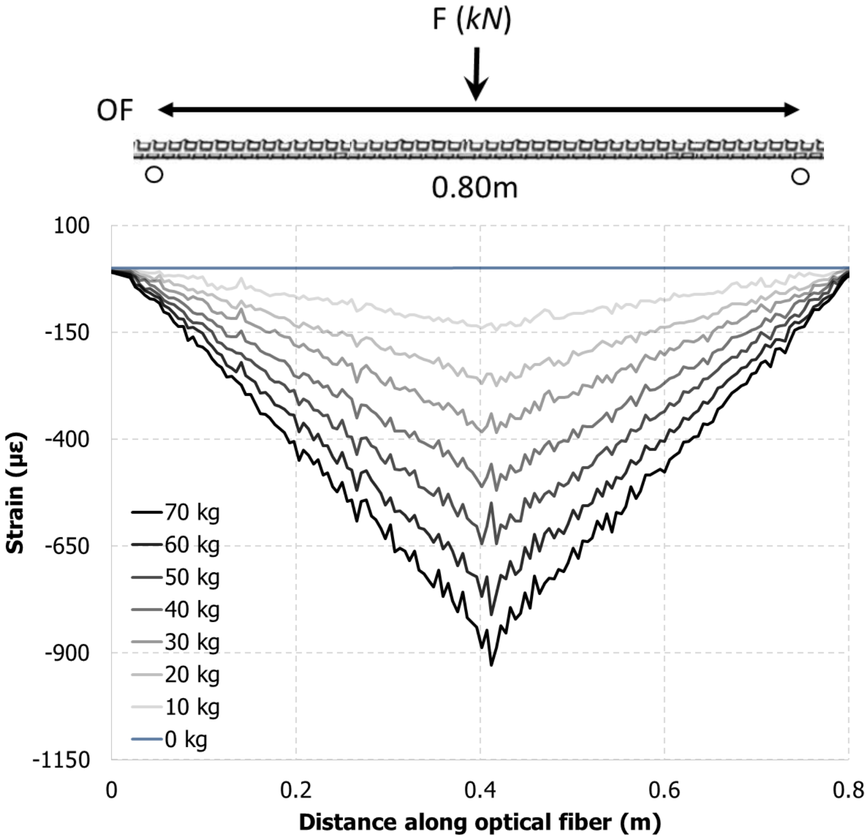


Strain Profile of Rebar Element

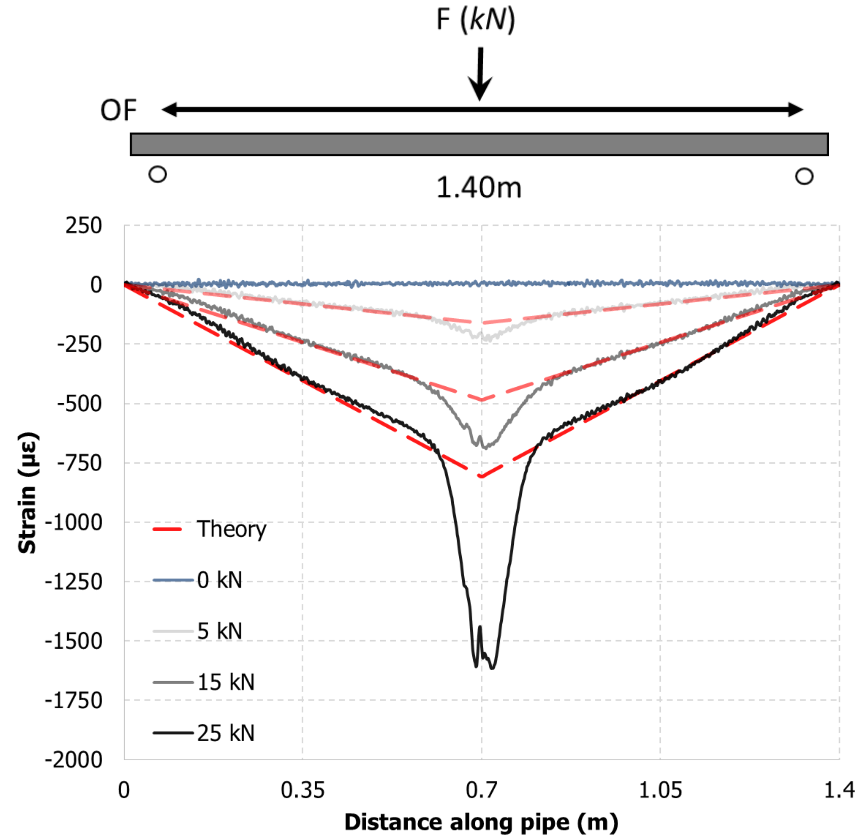


Strain Profile of Forepole Element

Symmetric Bending Testing

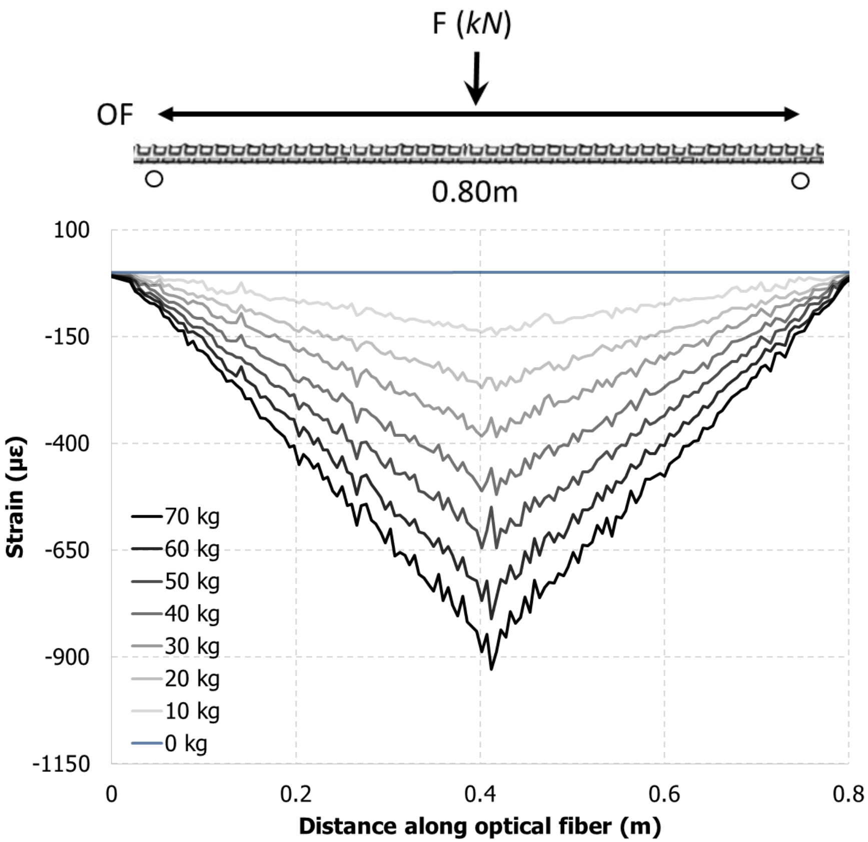


Strain Profile of Rebar Element

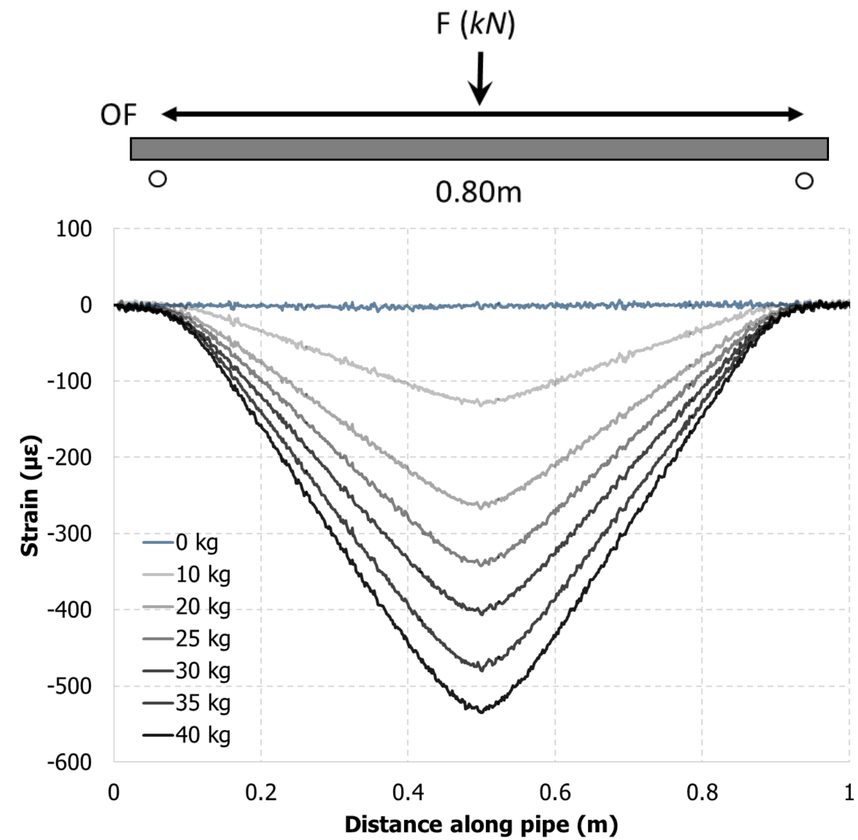


Strain Profile of Forepole Element

Symmetric Bending Testing

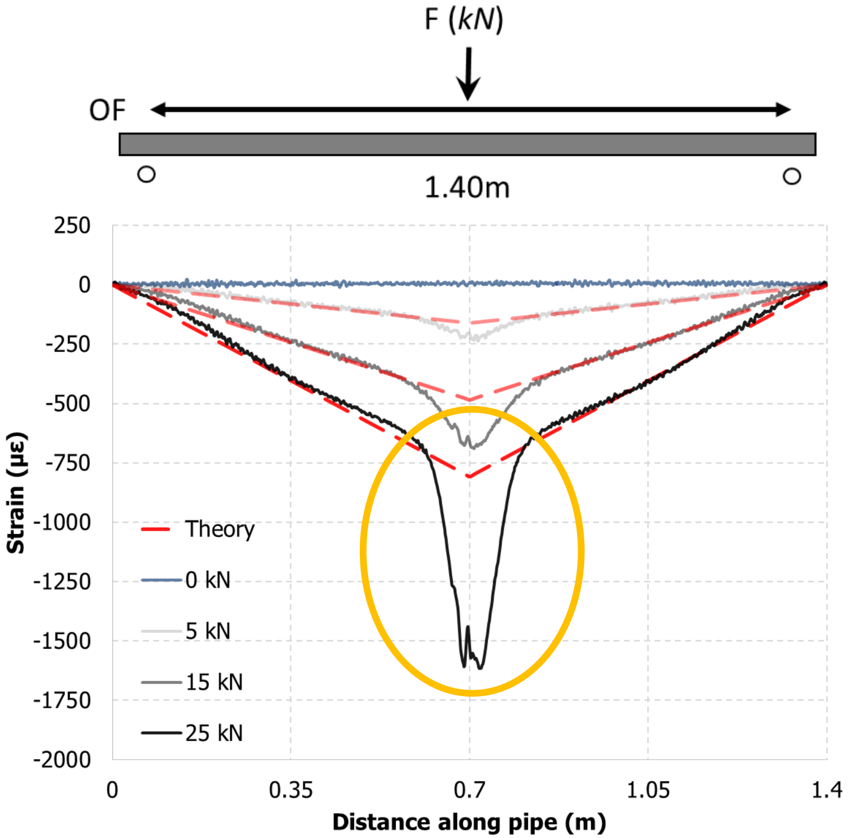


Strain Profile of Rebar Element



Strain Profile of Model Forepole

Symmetric Bending Testing

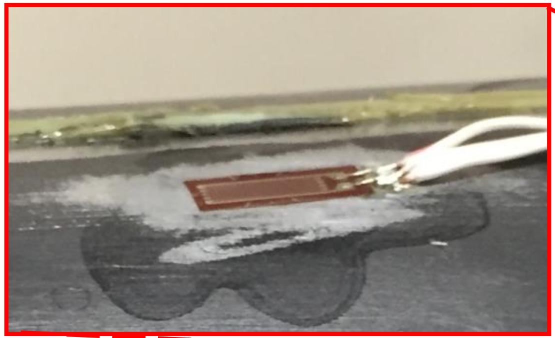


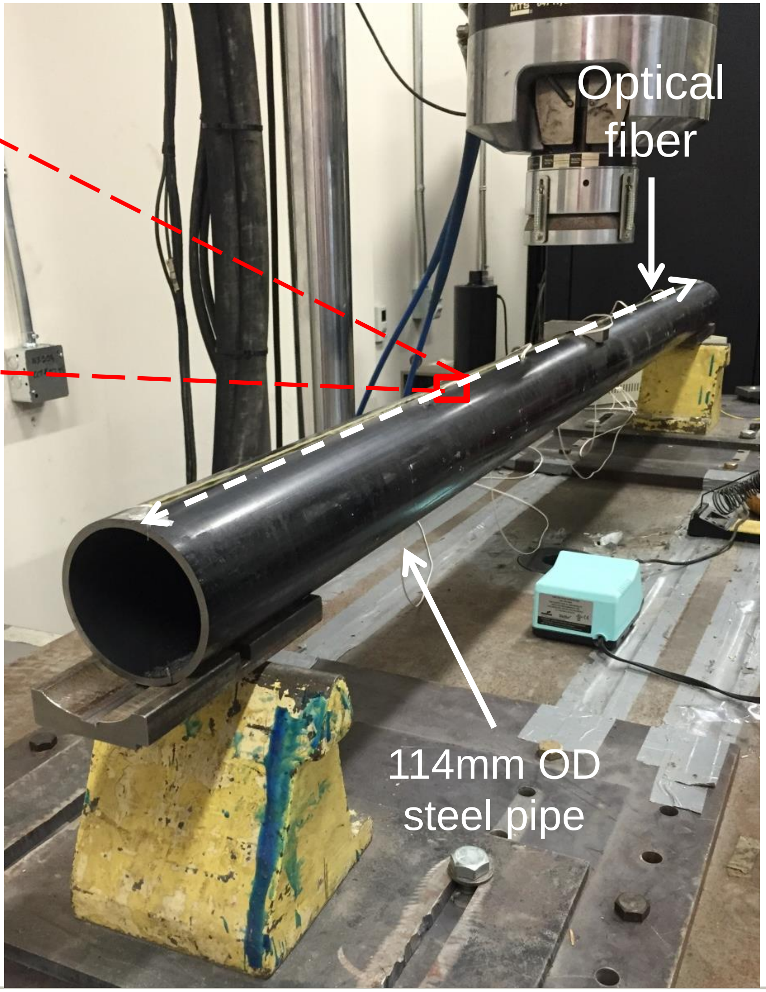
Strain Profile of Forepole

- Need to determine if this is an inherent issue with the sensing <u>technique</u> or <u>actual response</u>?
- Approach:
  - Surface mount the optical sensor using a less brittle adhesive
  - Conduct the bending test at multiple support spans (i.e. scale issues?)
  - Compare against traditional strain techniques

Symmetric Bending Testing

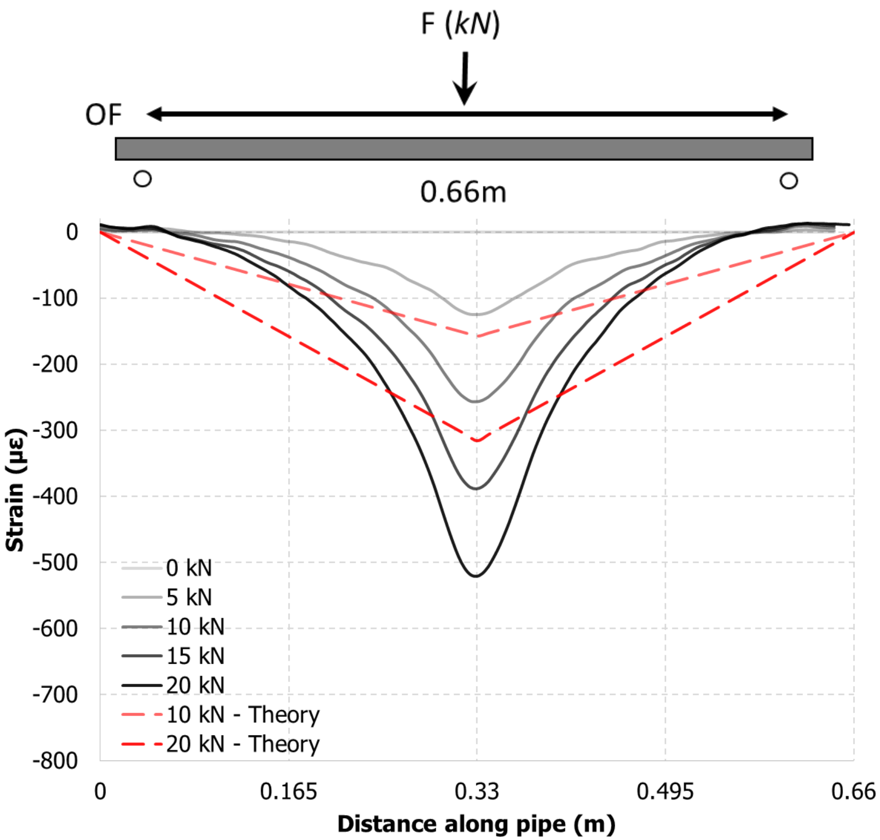
Strain gauge



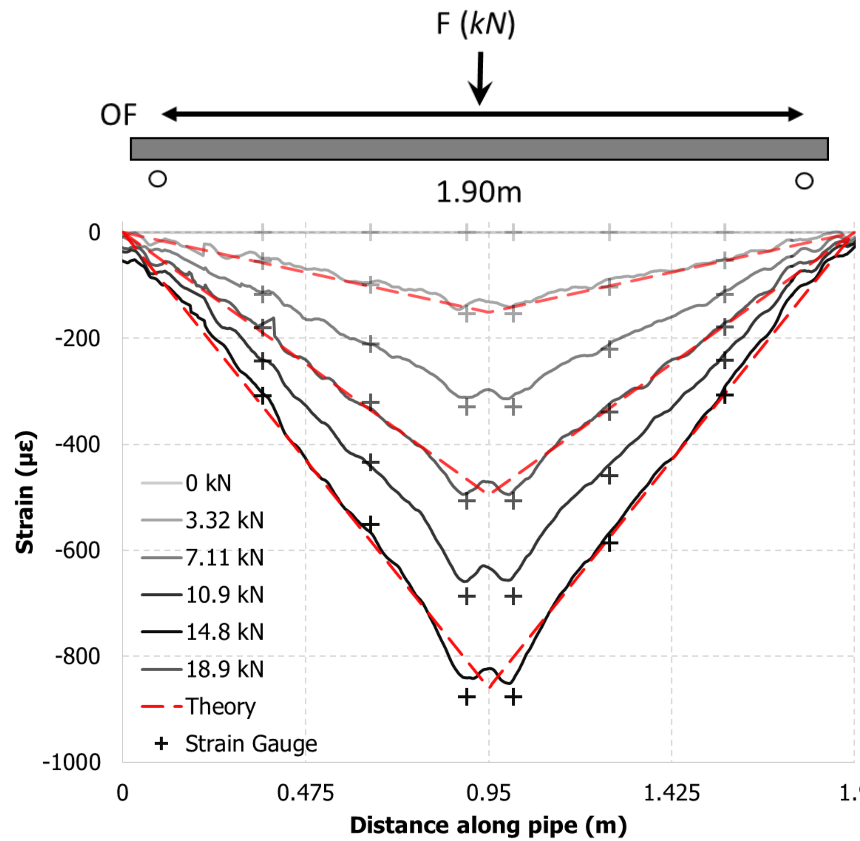


- Optical sensor surface mounted using a metal bonding adhesive
- Adjust support span spacing from 0.5m to 3.0m

Symmetric Bending Testing

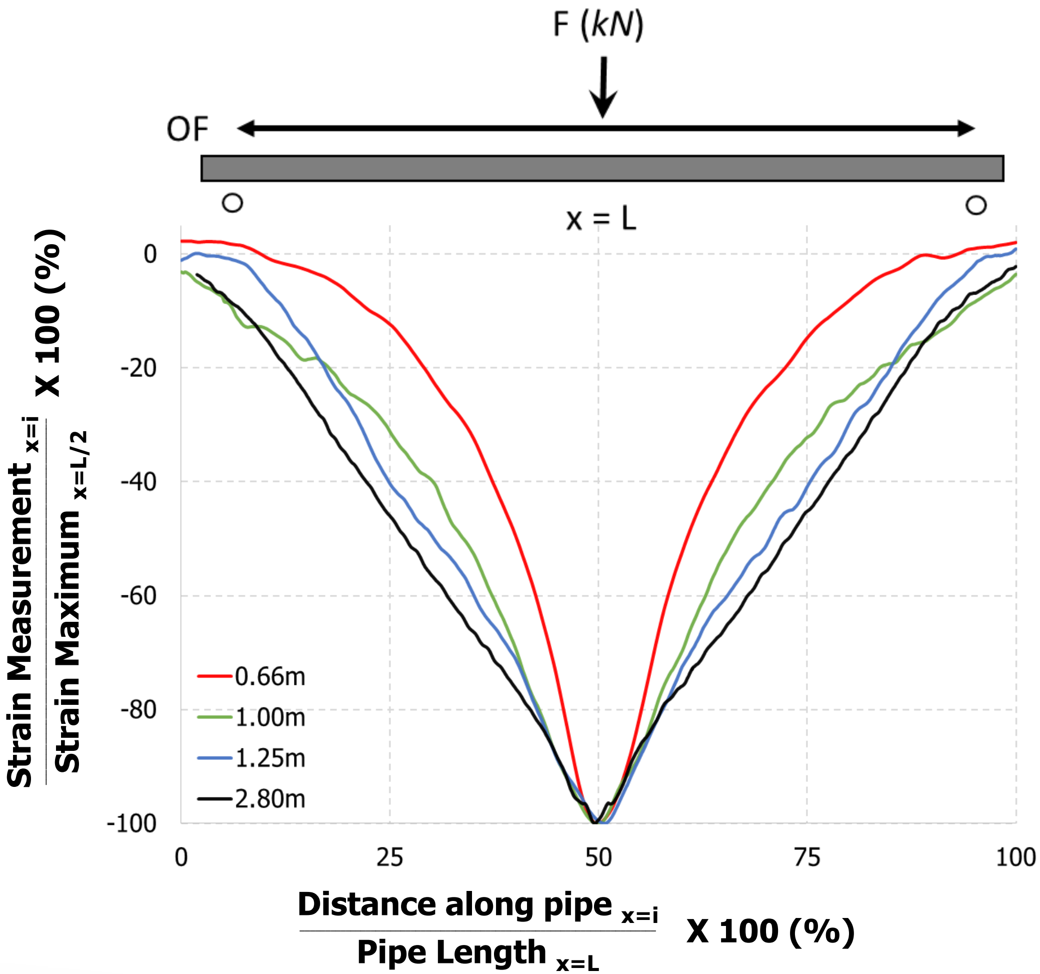


Strain Profile: 0.66m Support Spacing



Strain Profile: 1.90m Support Spacing

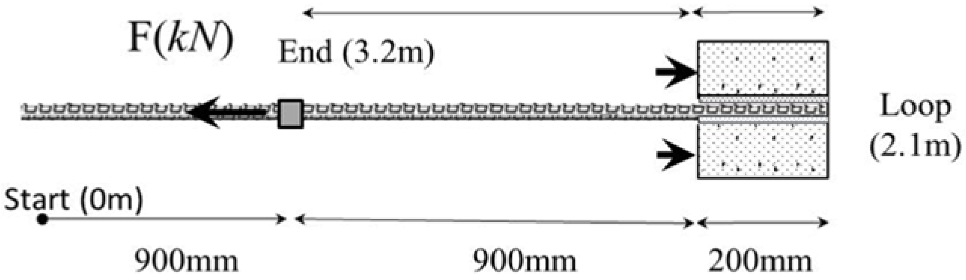
Symmetric Bending Testing



Summary of Symmetric Bending

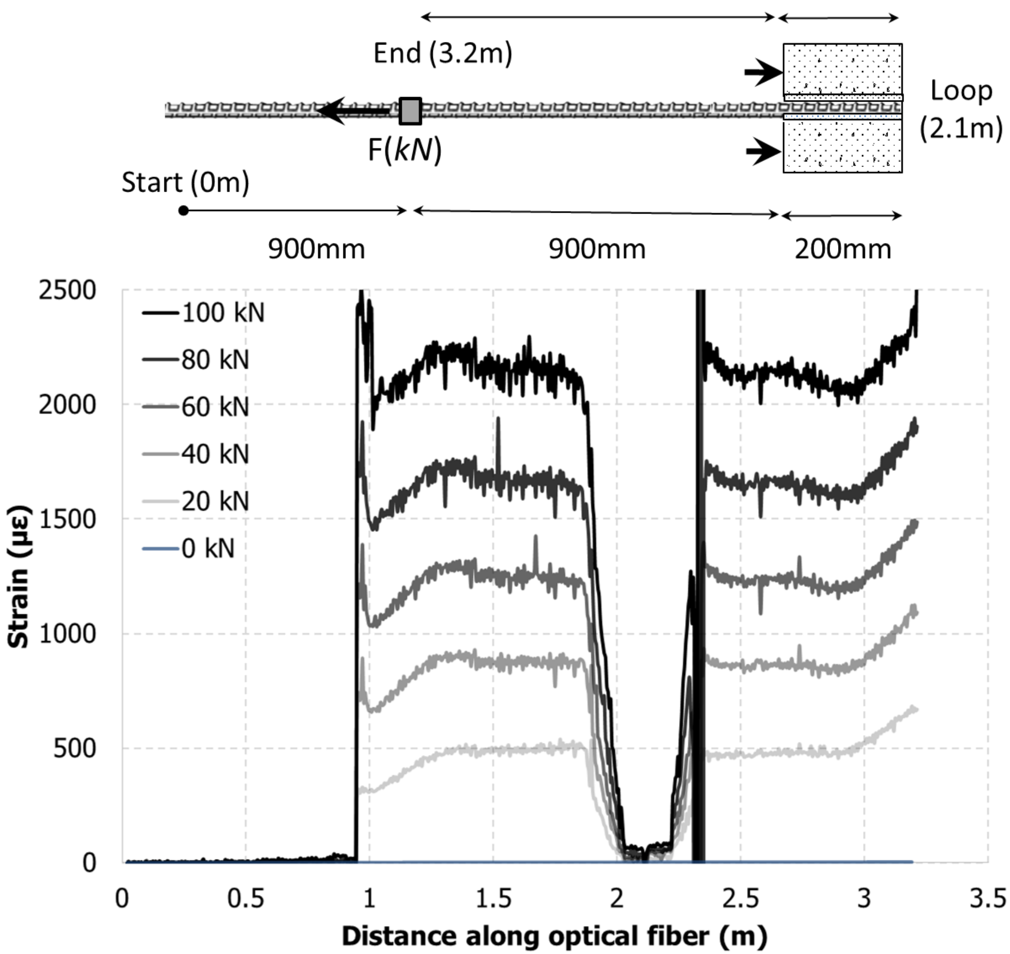
- DOS verified against conventional strain gauges
- Strain profiles become linear with increased support spacing.
- Metal bonding adhesive is the preferred bonding compound.
- Use the small diameter model forepole to avoid large loading apparatus for other loading mechanisms.

Axial Pull-out Testing



- 200mm section of the rebar resin/steel pipe grouted into a 31mm preformed and reamed borehole
- Optical instrumentation looped at the end of the grouted section

Axial Pull-out Testing: Rebar

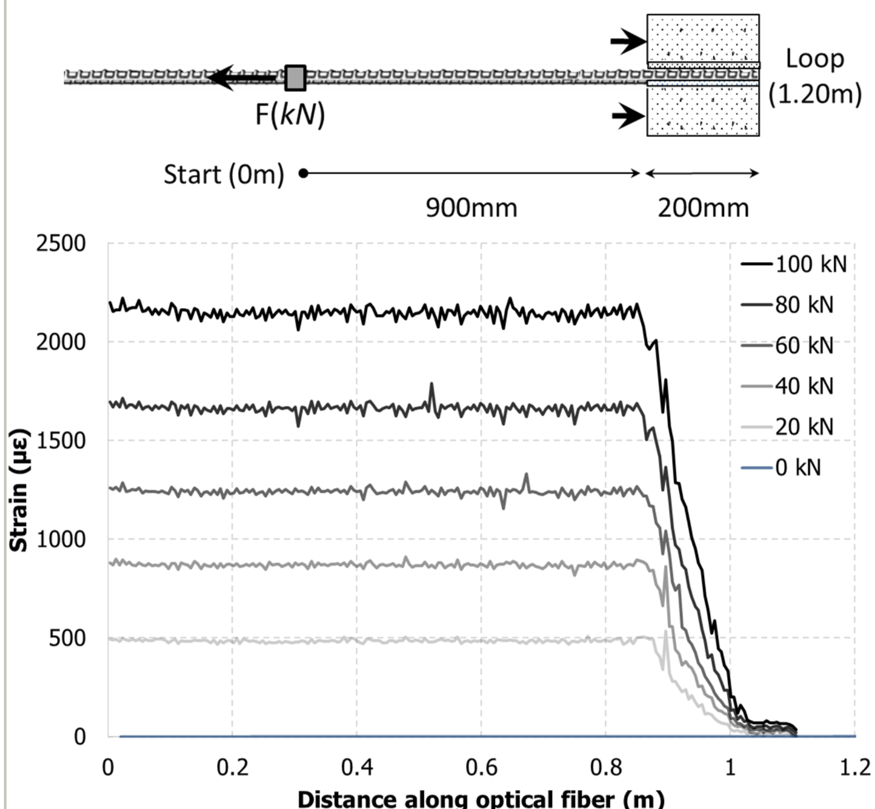


Strain Profile: Opposing Sides

Axial Loading Difficulties

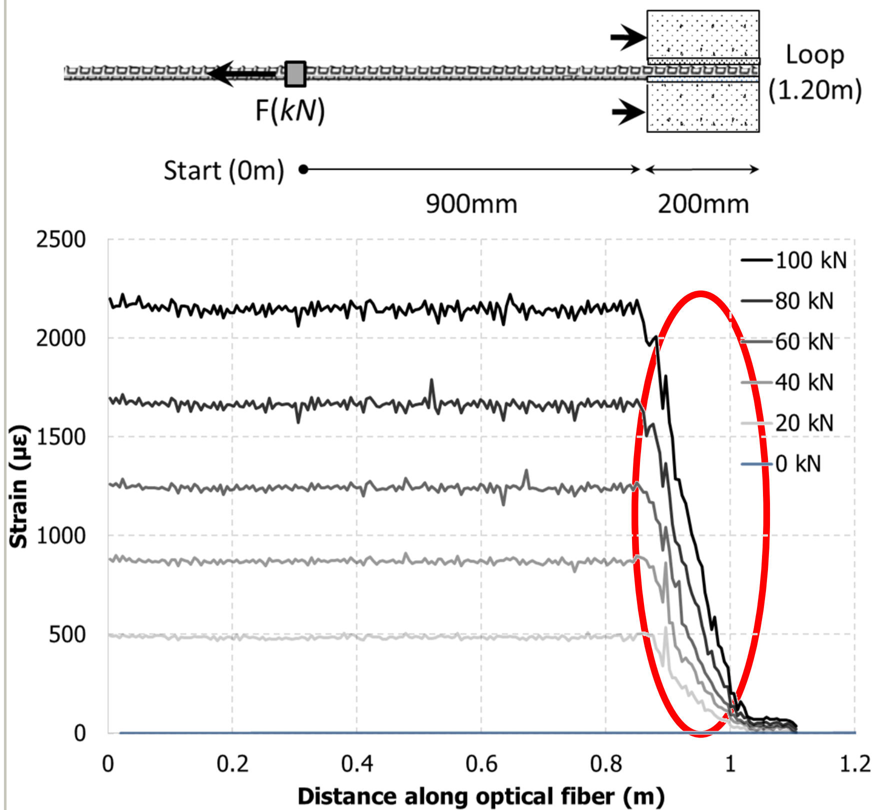
- Inherently difficult to apply a purely axial load.
- Initial seating, straightening of the rebar, and misalignment will cause a component of bending.
- Spherical washers and wedges were used to reduce bending.
- Can take an average of the strain distribution along opposing sides to remove bending component.

Axial Pull-out Testing: Rebar



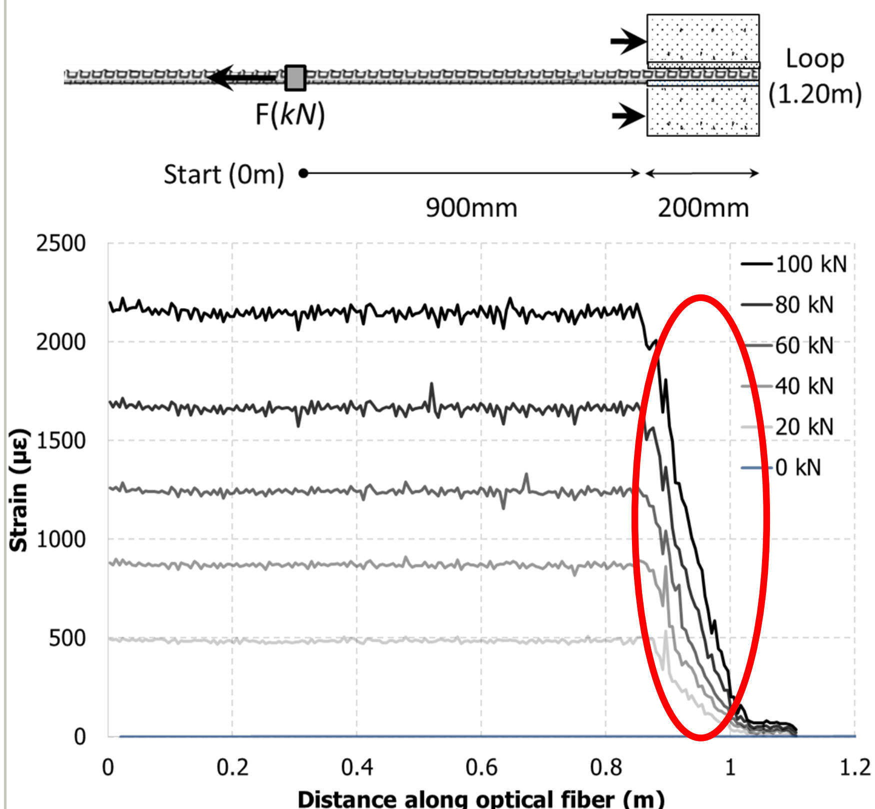
Strain Profile of rebar

Axial Pull-out Testing: Rebar

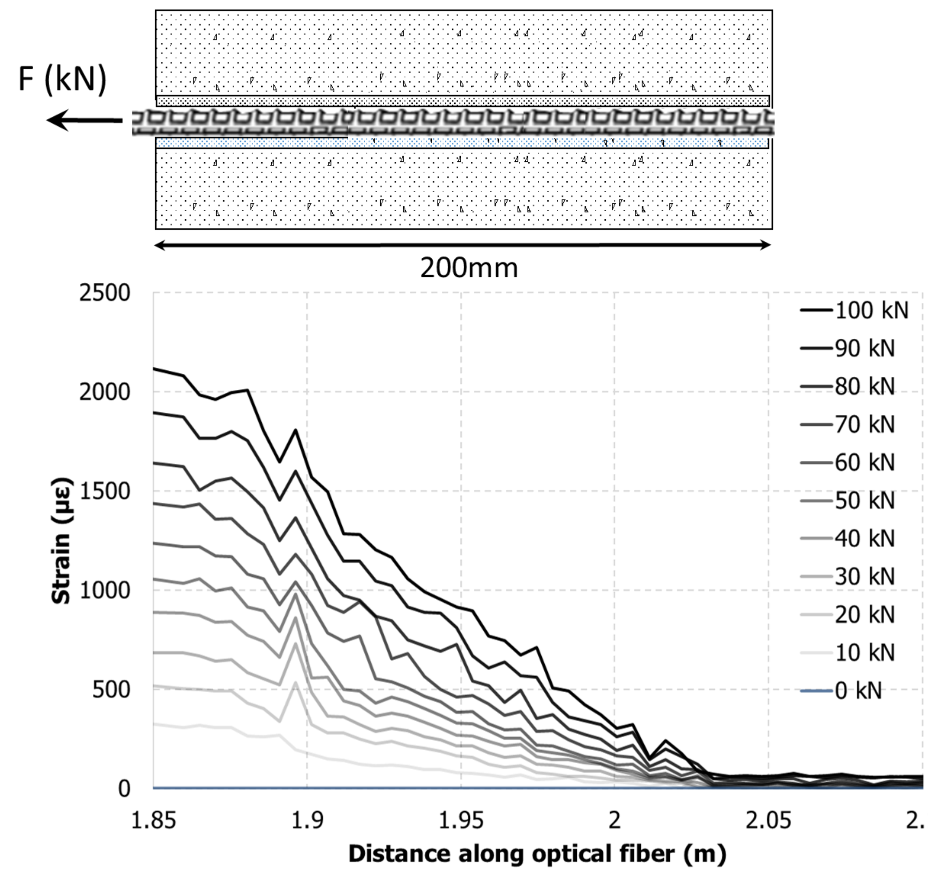


Strain Profile of rebar

Axial Pull-out Testing: Rebar

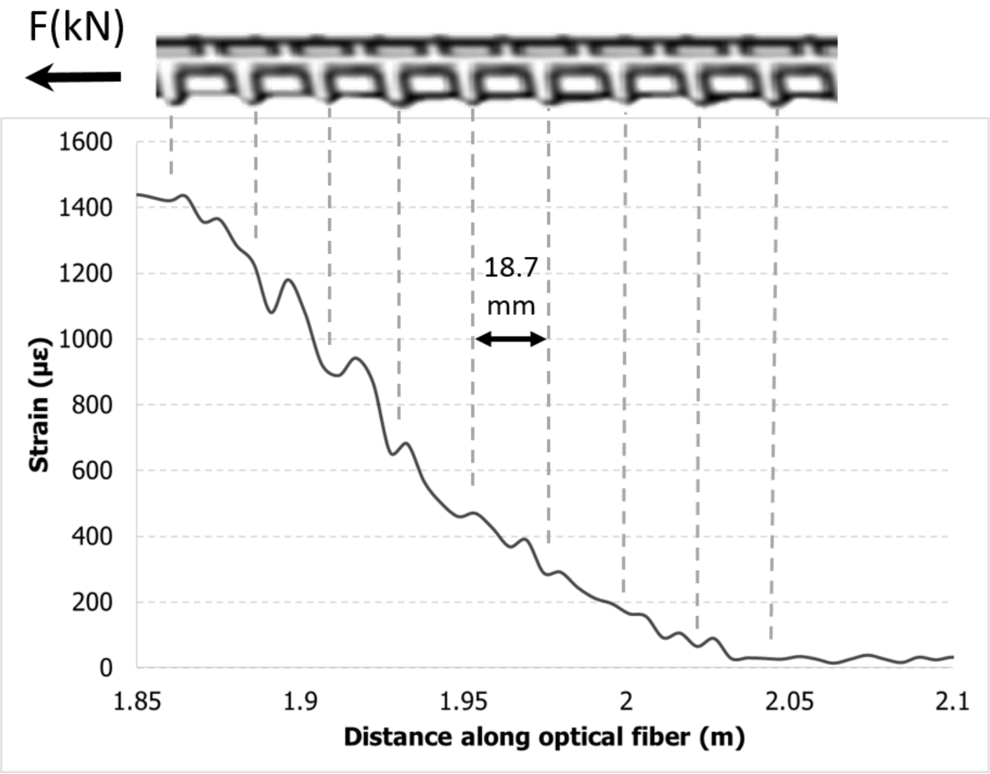


Strain Profile of rebar



Grouted Section (concrete block section)

Axial Pull-out Testing: Rebar



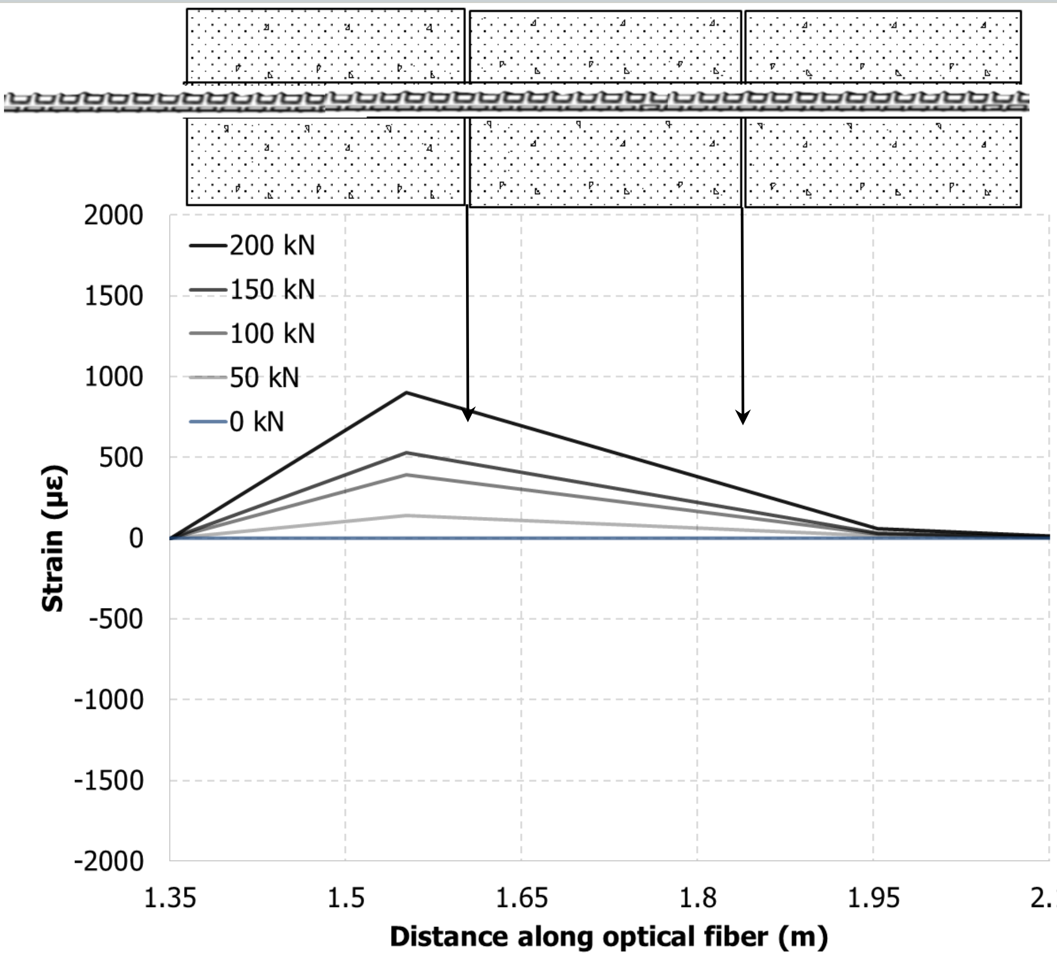
Grouted Section of rebar at 70kN

- Periodic disturbances match with the spacing of rebar ribs.
- Corresponds to the anchoring effect of rebar ribs within the resin grout.

Double Shear Configuration

- Rebar resin grouted into three concrete blocks separated by thin vertical planes
- Outer two blocks are fixed in the vertical direction
- Uniformly distributed load is applied vertically onto the centre block

Double Shear Configuration



Spatial Resolution

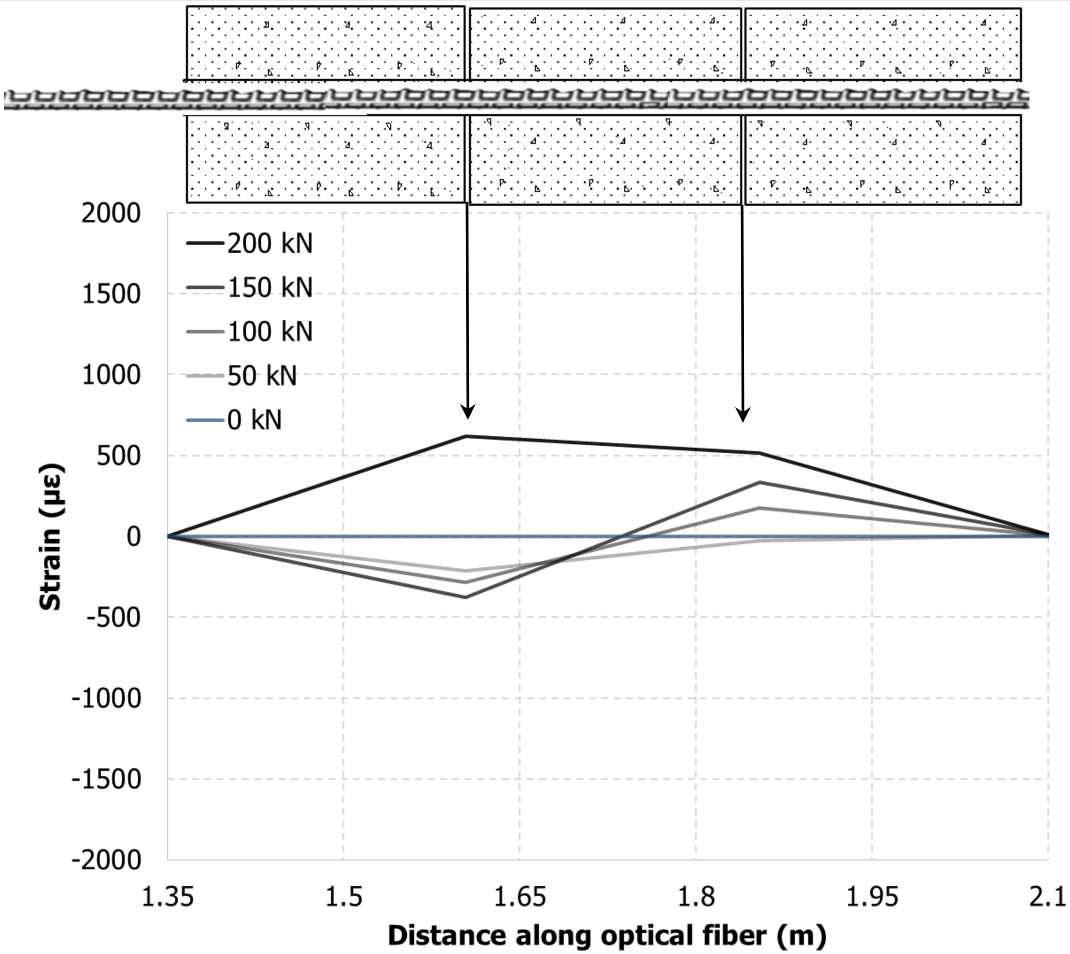
40cm

25cm

10cm

1.25mm

Double Shear Configuration



Spatial Resolution

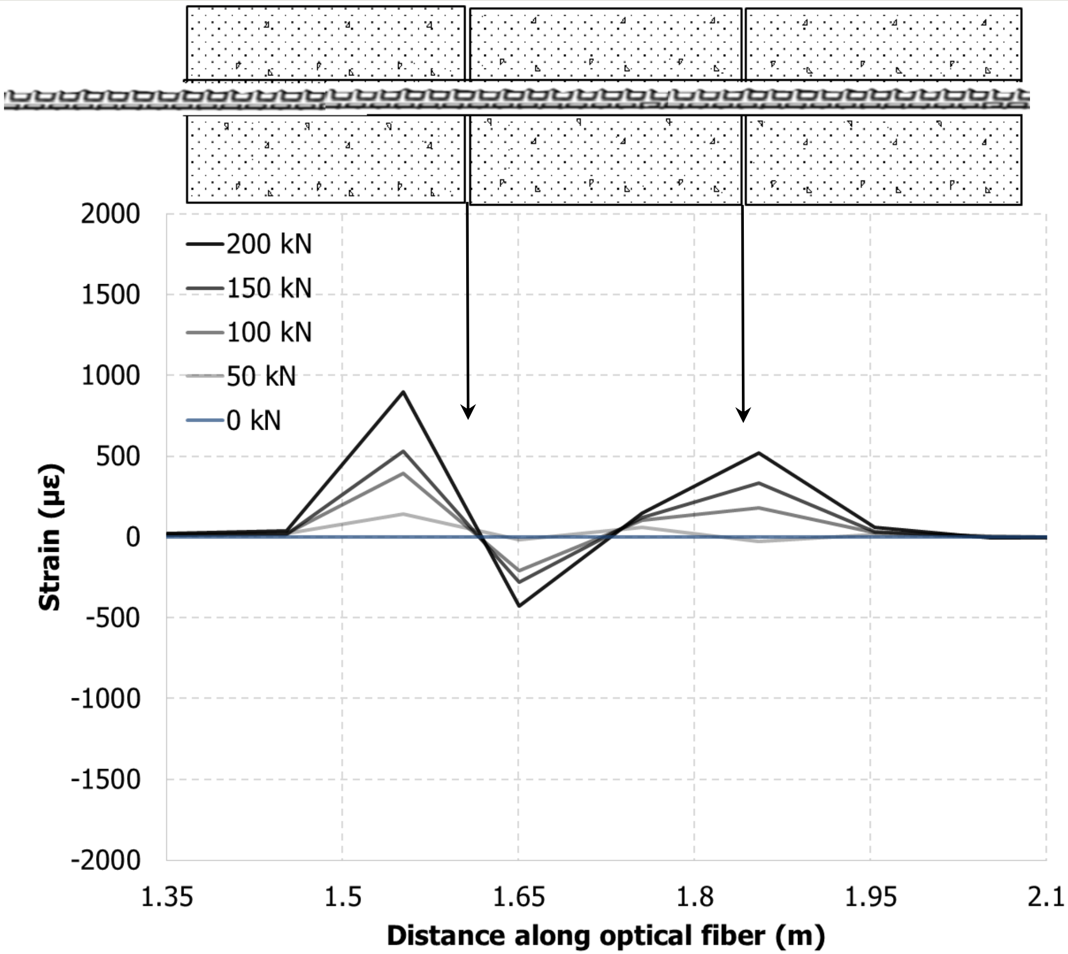
40cm

25cm

10cm

1.25mm

Double Shear Configuration



<u>Spatial Resolution</u>

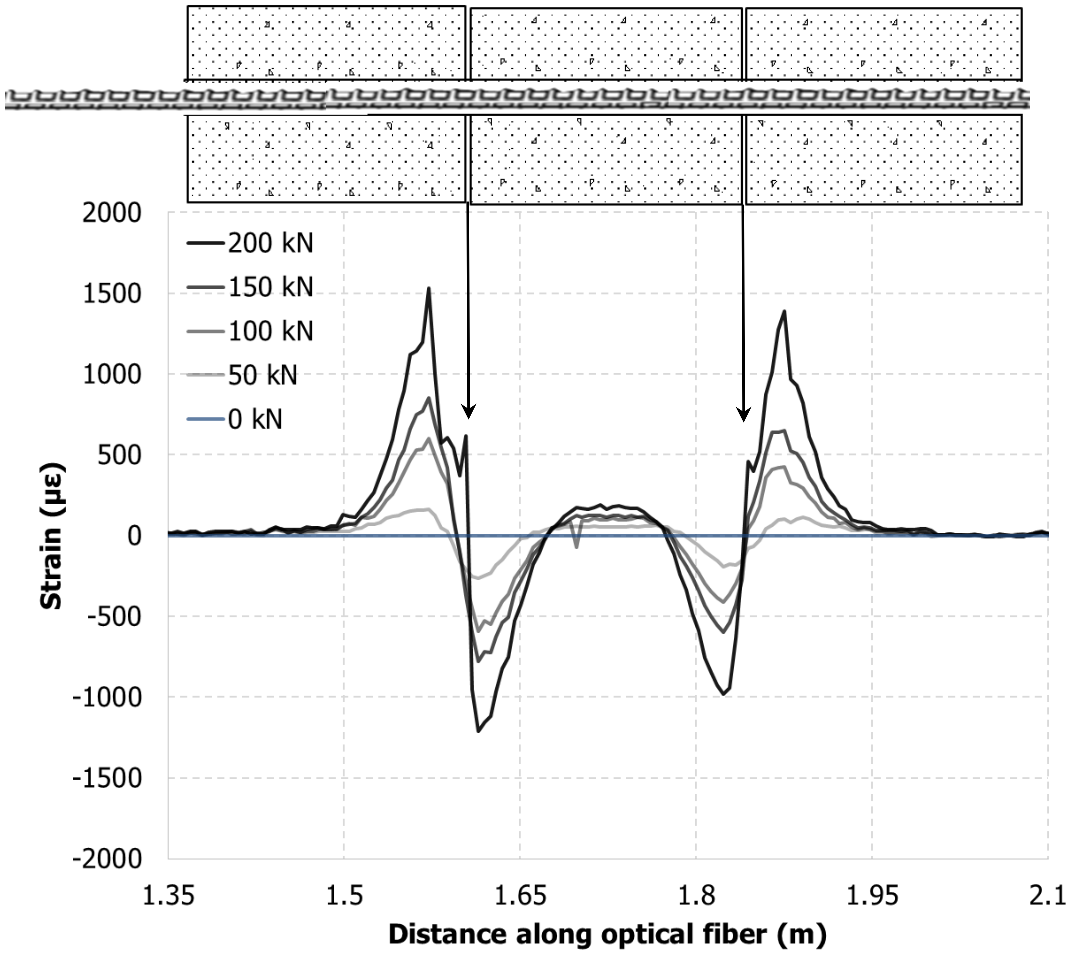
40cm

25cm

10cm

1.25mm

Double Shear Configuration



Spatial Resolution

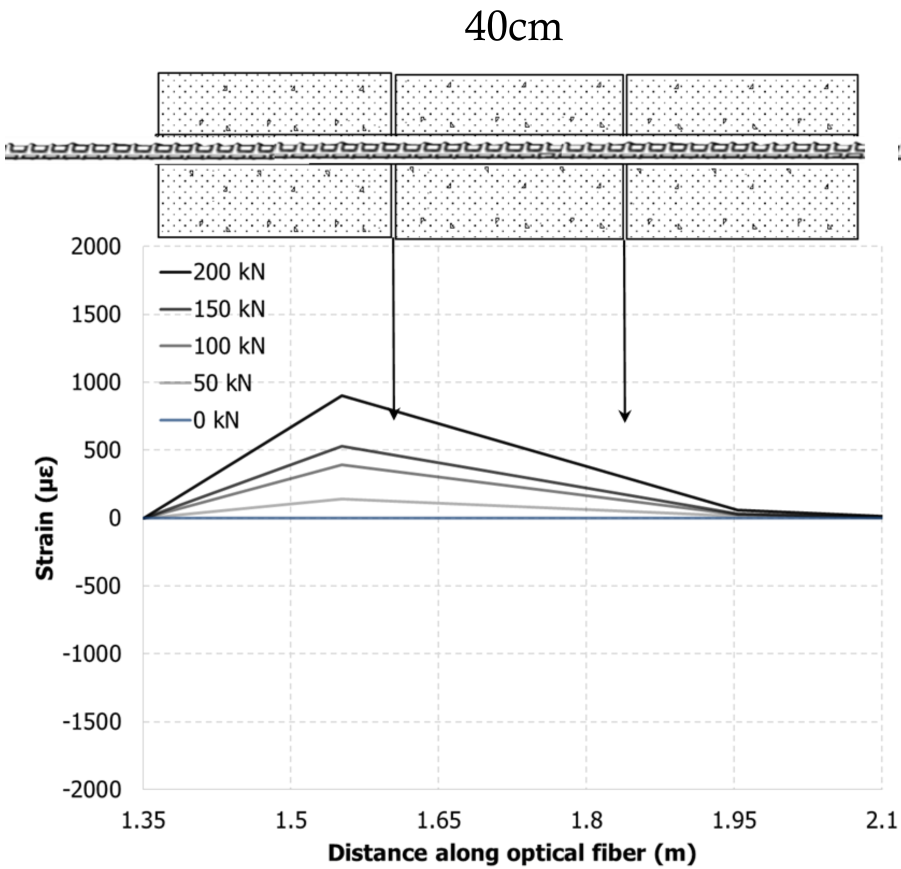
40cm

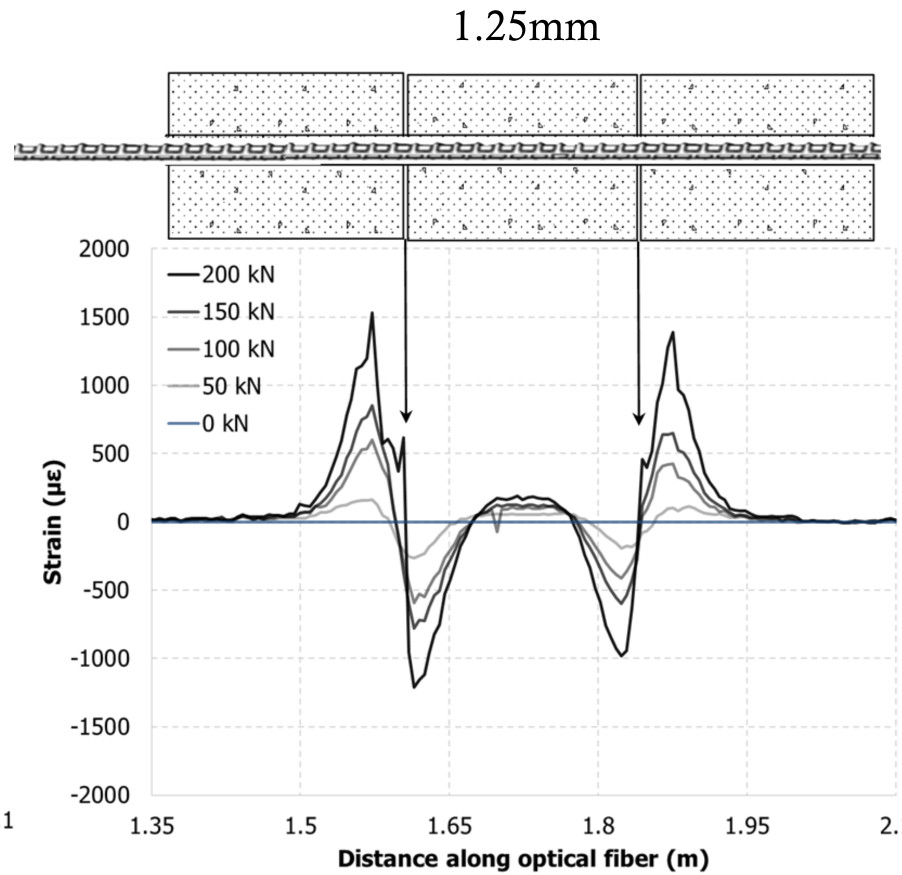
25cm

10cm

1.25mm

Double Shear Configuration





In Situ Operation

- Successfully implemented the optical technique with rock bolts in operating coal mines
- The sensors and interrogator survived harsh installation procedures and operation
- Capability of the technique best demonstrated at the laboratory scale

DOS instrumented bolt installed in the roof of a coal mine

Conclusions

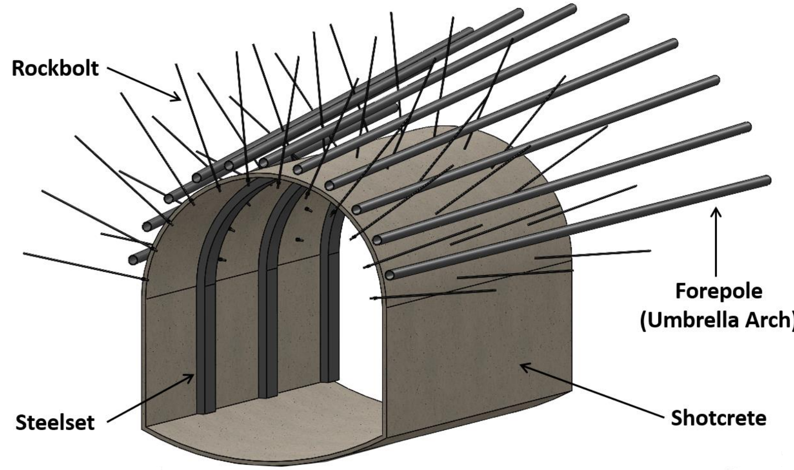
- An optical sensing technique has been developed for rock bolt and forepole support members (laboratory and *in situ*).
- The technique was demonstrated to capture expected loading mechanisms of support at an unparalleled resolution and accuracy.
- Low-cost per sensor offers an economical solution for monitoring a cluster of instrumented support specimens.
- The optical solution can be realized as a novel monitoring tool with the capability to "see" and "sense" into the ground ahead of the excavation face

Conclusions

- An optical sensing technique has been developed for rock bolt and forepole support members (laboratory and *in situ*).
- The technique was demonstrated to capture expected loading mechanisms of support at an unparalleled resolution and accuracy.
- Low-cost per sensor offers an economical solution for monitoring a cluster of instrumented support specimens.
- The optical solution can be realized as a novel monitoring tool with the capability to "see" and "sense" into the ground ahead of the excavation face

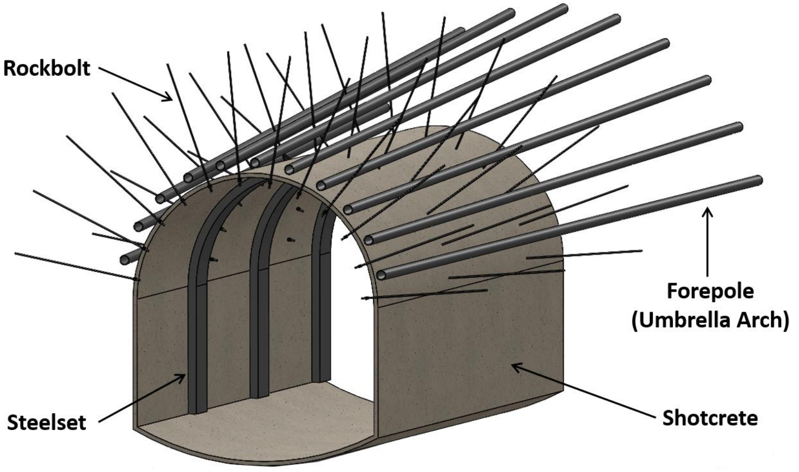
Conclusions

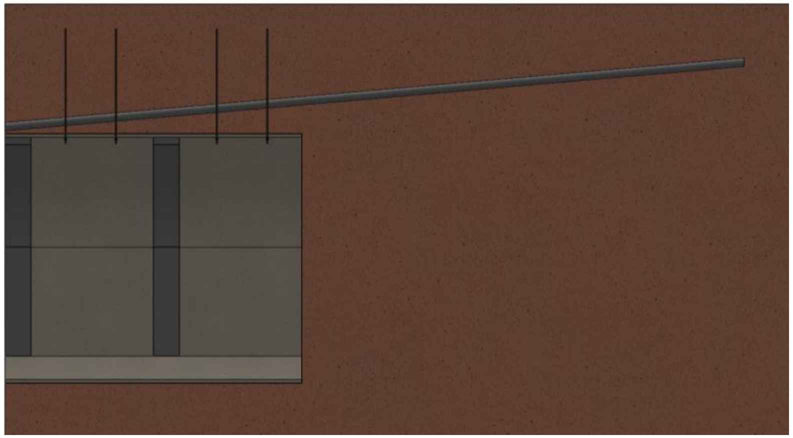
- An optical sensing technique has been developed for rock bolt and forepole support members (laboratory and *in situ*).
- The technique was demonstrated to capture expected loading mechanisms of support at an unparalleled resolution and accuracy.
- Low-cost per sensor offers an economical solution for monitoring a cluster of instrumented support specimens.
- The optical solution can be realized as a novel monitoring tool with the capability to “see” and “sense” into the ground ahead of the excavation face



Conclusions

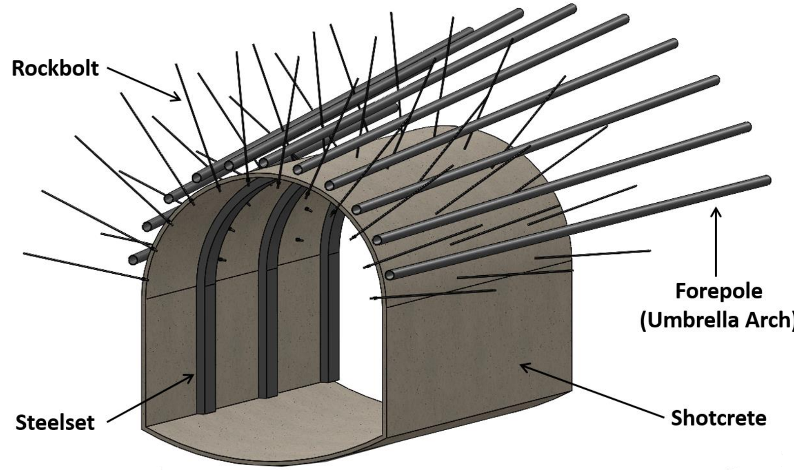
- An optical sensing technique has been developed for rock bolt and forepole support members (laboratory and *in situ*).
- The technique was demonstrated to capture expected loading mechanisms of support at an unparalleled resolution and accuracy.
- Low-cost per sensor offers an economical solution for monitoring a cluster of instrumented support specimens.
- The optical solution can be realized as a novel monitoring tool with the capability to “see” and “sense” into the ground ahead of the excavation face

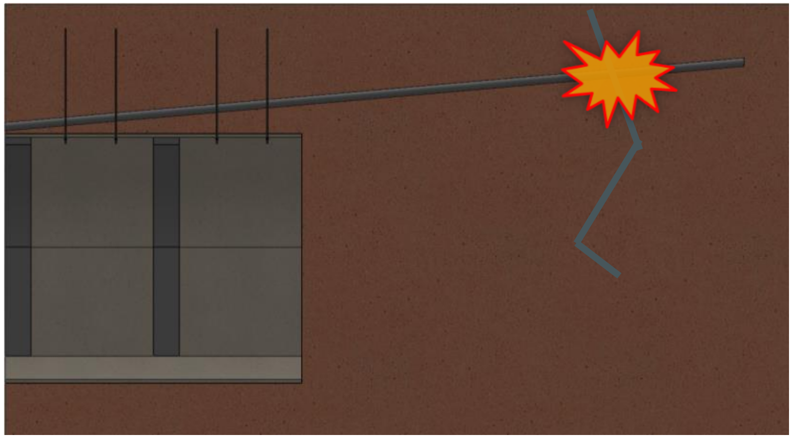




Conclusions

- An optical sensing technique has been developed for rock bolt and forepole support members (laboratory and *in situ*).
- The technique was demonstrated to capture expected loading mechanisms of support at an unparalleled resolution and accuracy.
- Low-cost per sensor offers an economical solution for monitoring a cluster of instrumented support specimens.
- The optical solution can be realized as a novel monitoring tool with the capability to “see” and “sense” into the ground ahead of the excavation face





Acknowledgments

- Co-supervision of Dr. Nicholas Vlachopoulos & Dr. Mark S. Diederichs
- Technical support and guidance provided Dr. Andrew J. Hyett of YieldPoint Inc.
- Current and Past Queen's Geomechanis Group: Special thanks to Dr. Jeffrey Oke & Ioannis Vazaios
- The Department of Geological Sciences and Geological Engineering at Queen's University
- The Department of Civil Engineering at the Royal Military College of Canada
- Funding support provided by: Natural Sciences and Engineering Resource Council of Canada (NSERC), Department of National Defence (DND), & Nuclear Waste Management Organization (NWMO)

The Application of Distributed Optical Sensing for Monitoring Support in Underground Excavations

Bradley J. Forbes

Thank You