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*Challenges and Innovations in Tunnelling*

# Tunnelling Instrumentation – Support Design, Optimization and Testing


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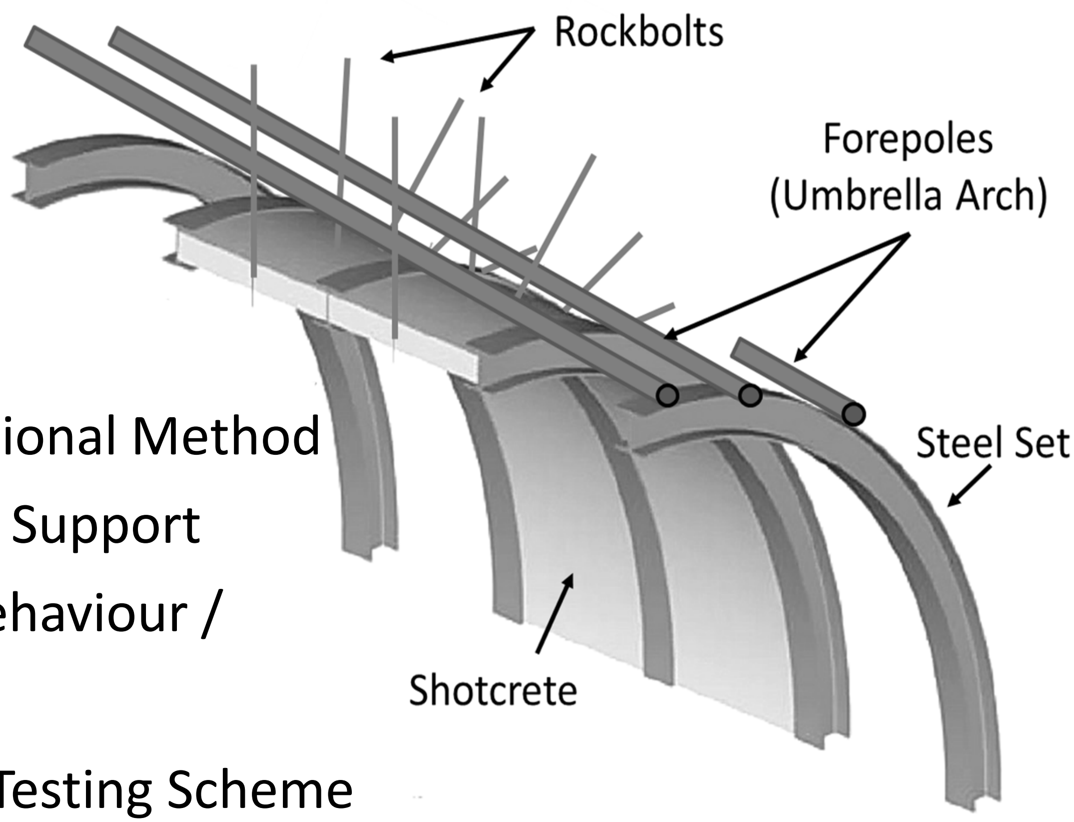
04 October 2015

Tunnelling Association of Canada
Association Canadienne Des Tunnels

# Outline




1. Introduction
2. Instrumentation & Observational Method
3. Design of Temporary Tunnel Support
4. Factors Affecting Support Behaviour / Mechanisms
5. Instrumentation & Physical Testing Scheme
    a. Outline of testing
    b. Use of fibre optics
6. Selected Results
7. Conclusions / Questions / Discussion

# Observational Method

- Equations do not yield exact behaviour of site conditions
  - Results in over-conservative design
- The observational method employs instrumentation to predict actual site conditions
  - Leads to modification of original design to suit actual ground conditions

# Observational Method

- Common concerns in field monitoring operations:
  - Too many programs are based on the number of instruments to be used rather than on the questions to be answered
  - Sophistication and Automation are substituted for patient proof testing of equipment under field conditions

# Steps to Planning an Instrumentation Plan

- Engineers tend to proceed by first selecting instruments and taking data and then wondering what to do with the data. This is a bad idea. Instead a series of steps should be completed.
- "*We need to carry out a vast amount of observational work, but what we do should be done for a purpose and be done well*".

Peck (1972)

# Steps to Planning an Instrumentation Plan

- There are 20 Steps to completing a proper instrumentation plan.
- Each step is important…

“a monitoring program is a chain with many potential weak links and breaks down with greater facility and frequency than most other tasks in geotechnical engineering”.

Franklin (1977)

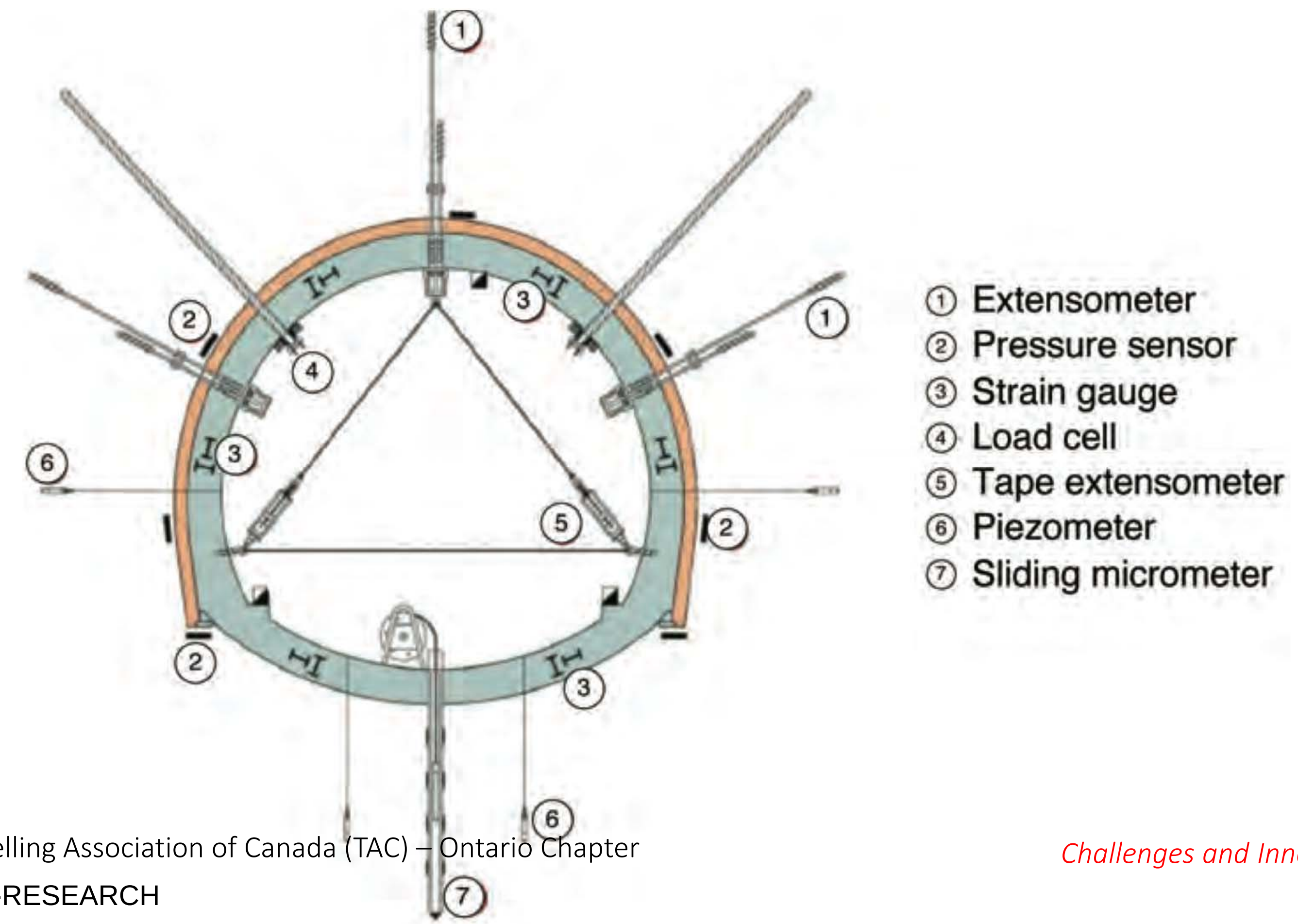
# Instrumentation and Monitoring

Objective:

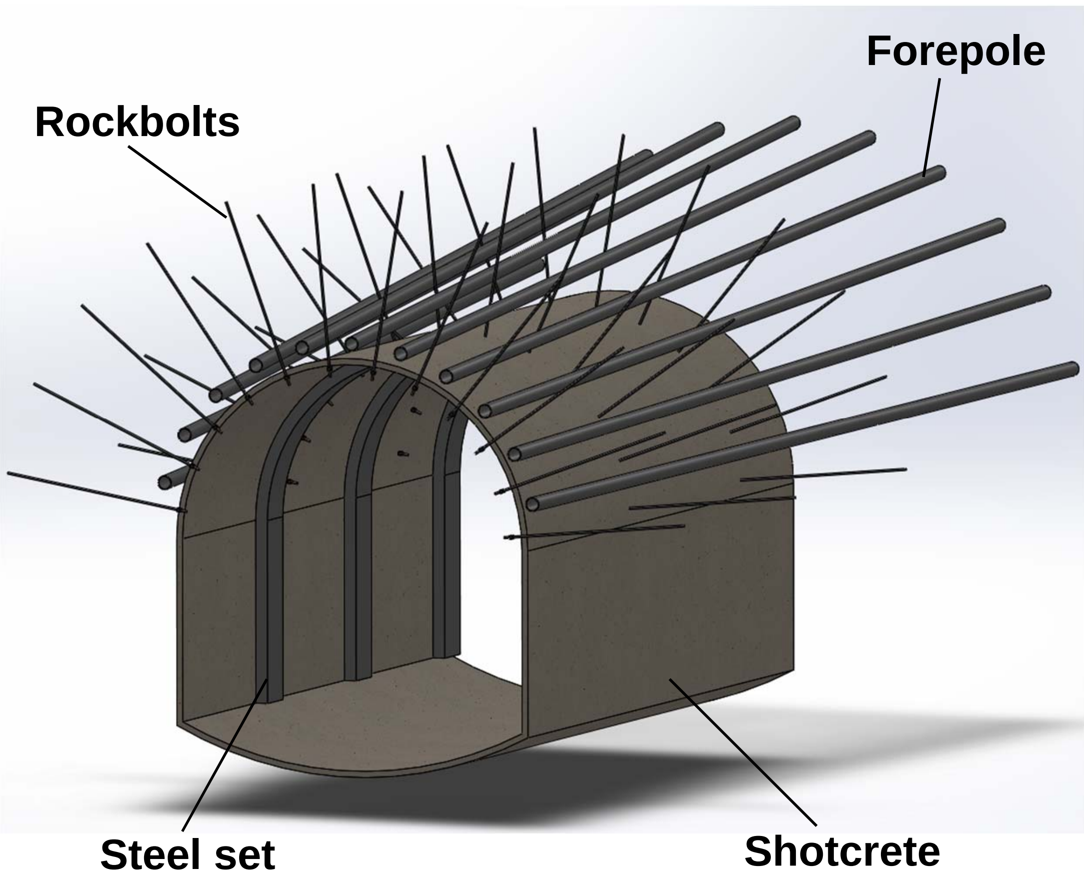
- Obtain information on ground response to tunneling
- Provide construction control
- Verify design parameters and models
- Measure performance of the lining during and after construction
- Monitor impact on the surrounding environments
- Optimization of the design and execution of safe tunneling works

# Instrumentation and Monitoring

Generally instruments employed in tunnel monitoring are as follows:



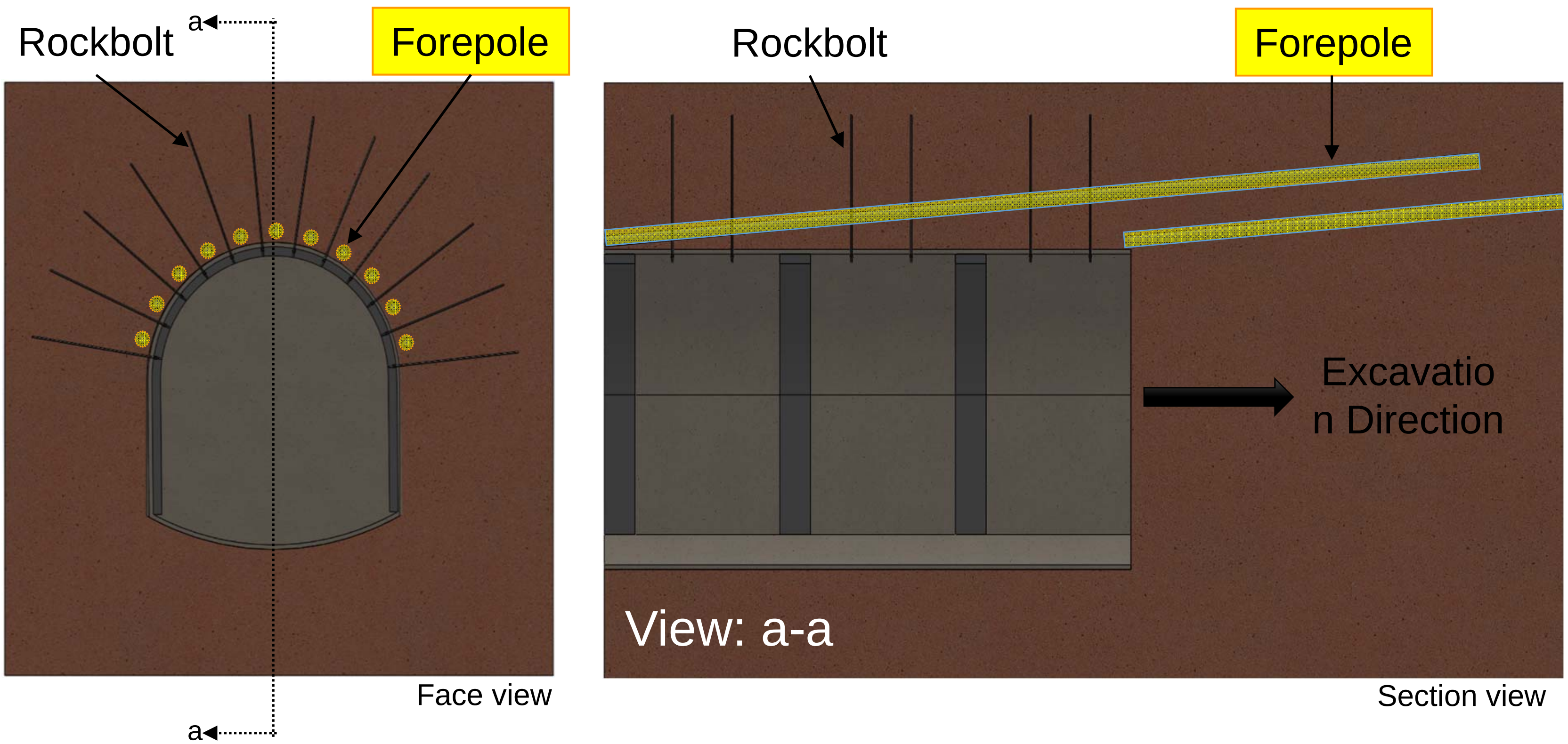
# Temporary Support Systems

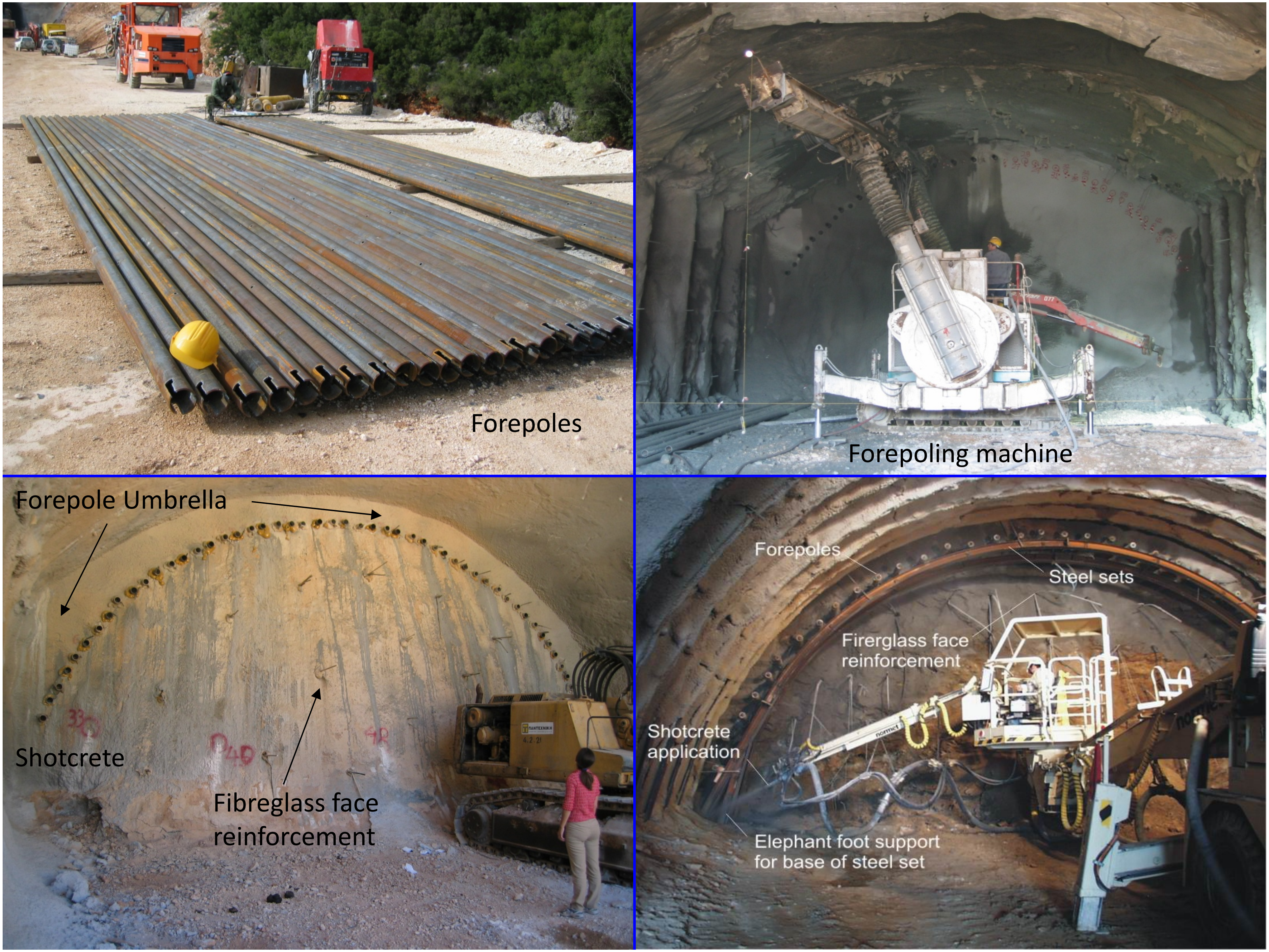





(Modified after Solotrat, 2011)

# Temporary  Tunnel Support Scheme



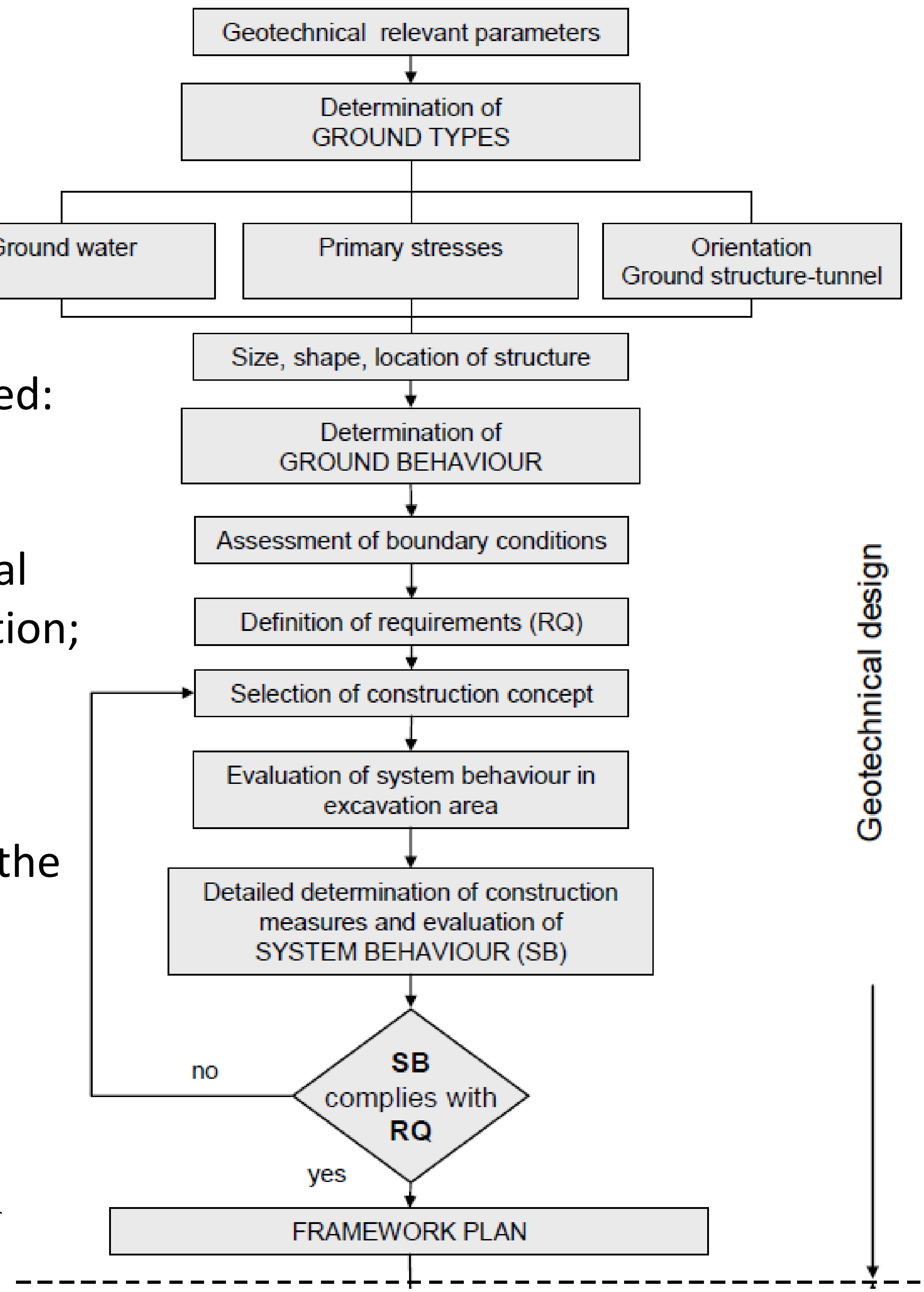

Forepoles
Forepoling machine
Forepole Umbrella
Shotcrete
Fibreglass face reinforcement
Forepoles
Steel sets
Firerglass face reinforcement
Shotcrete application
Elephant foot support for base of steel set

# Engineering Design

Two major aspects need to be addressed:

- Realistic estimate of the expected ground conditions and their potential behaviours as a result of the excavation; and,

- Design and economic and safe excavation and support method for the determined ground behaviours.

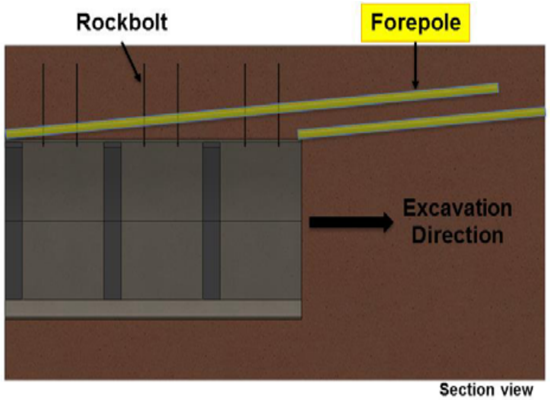


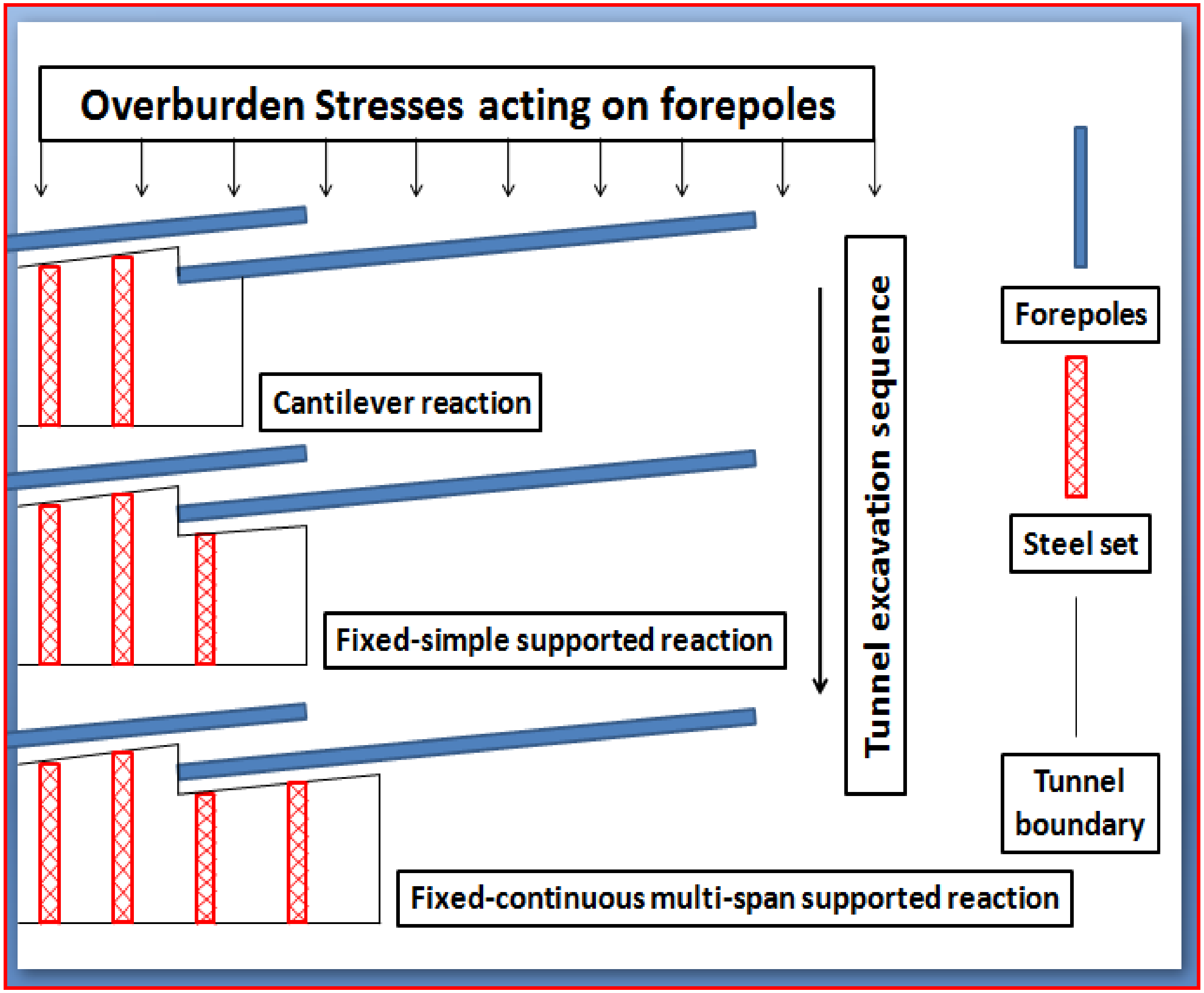
# Design of Umbrella Arches (UA)

The design of UAs is complex due to:

- 3D geometry of tunnel face;
- high number of parameters involved;
- Influence of tunnel face – stability;
- 3D analysis to take into account face position;
- Overlapping of the successive arches;
- Connection between support elements and steel sets; and,
- Stiffness and quality of steel sets.

# Mechanisms




(**Jeff Oke**, Grad Student 2013)

# Analytical Design Approaches

<u>Design Procedure</u>

1. Choice of an initial forepole spacing
2. Choice of an initial diameter and thickness of forepole
3. Choice of an initial steel set spacing
4. Choice of forepole (steel pipe)

5. Evaluation of Design Length

6. Choice of Structural Schema

7. Computation of Bending Moments
8. Computation of Stresses in forepole
9. Compare acting stress and steel yield stress

Change the Geometrical Parameters

Not adequate

10. Definition of the forepole length (machines available)
11. Definition of excavation length
12. Design of the supports and steel arch foundations

Peila, 2013

# Geo-Mechanical Understanding

“ *The rapid increase in use [of umbrella arch systems] has not been followed by an increased understanding of the interactions between the support system and the surrounding rock mass*”

“ Currently during tunnel design, as well as on site, parameters for the [umbrella arch] system… are fixed by experience or an empirical approach”

Volkmann (2003)

# Laboratory Testing

Embedded rebar specimen

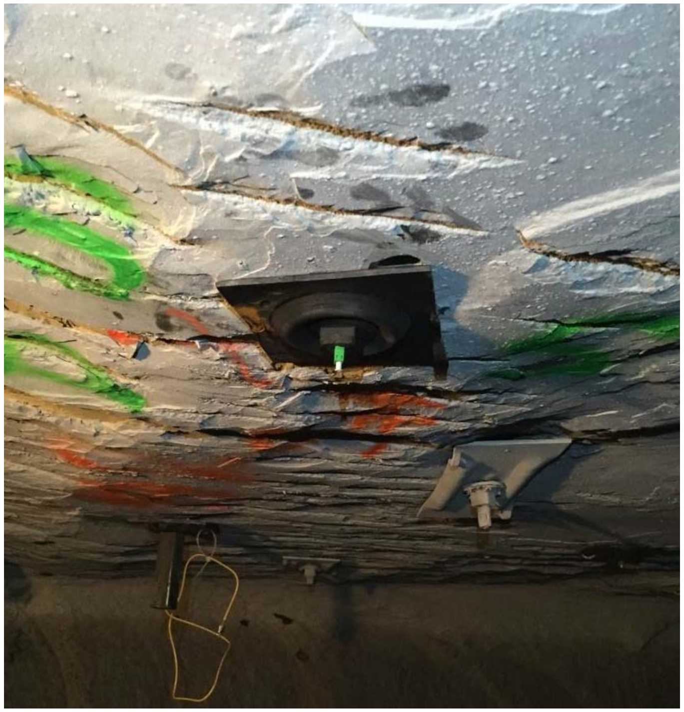

Forepole Specimen

Specimens Subjected to:

- Bending
- Axial loading
- Shearing

# Distributed Optical Sensing (DOS)

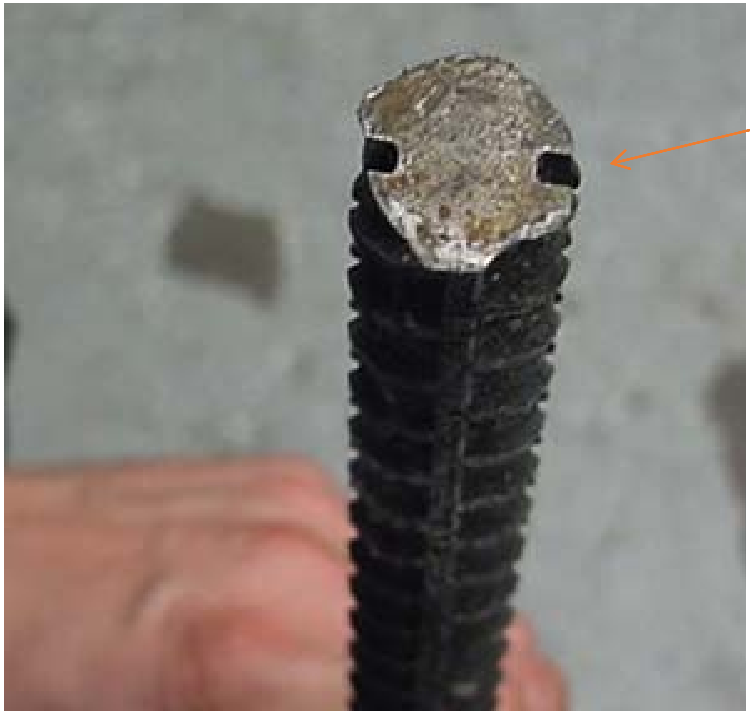
- 1.25mm spatial resolution (continuous strain profile)
- Operational accuracy is within ±10με
- Is based on low-cost, standard telecom fiber
- One transducer for thousands of measurement points



DOS instrumented bolt installed in the roof of a coal mine

# Continual Strain Monitoring Testing – Rock Bolt

- Developed a prototype

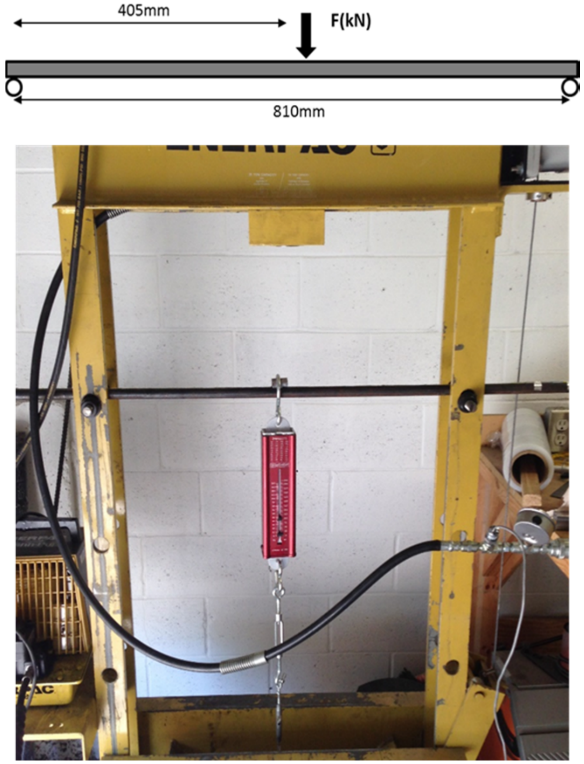


Diametrically opposed grooves along the length of a Rebar Bolt

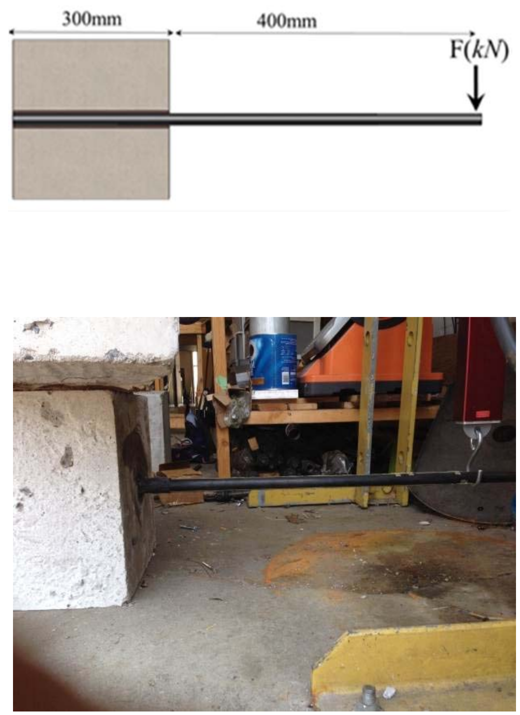
LUNA TECHNOLOGIES

Run fiber- optic instrumentation along the grooves in Rebar

- 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 instrumentation




Three Point Bending

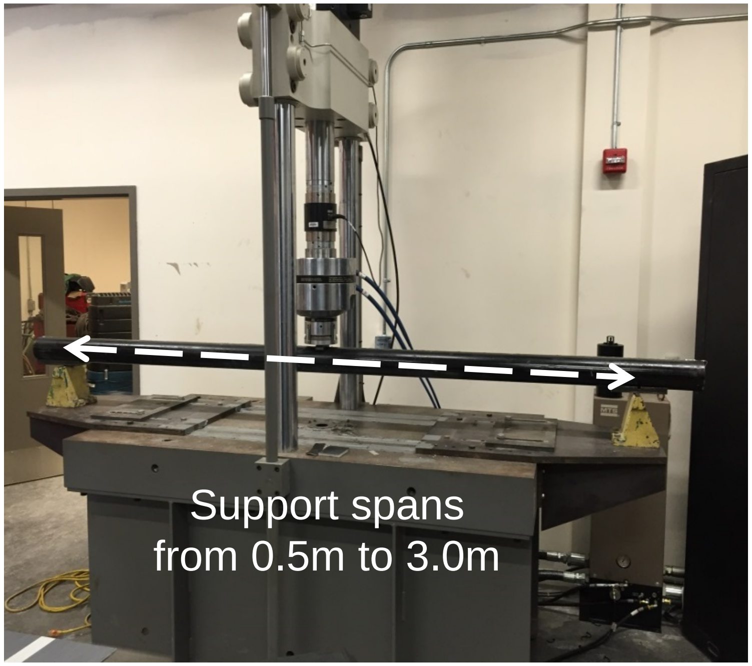


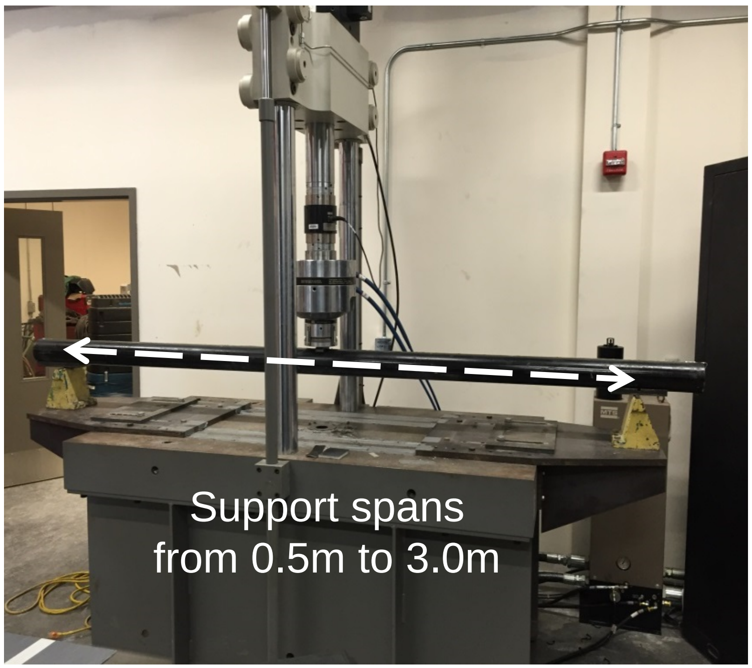

Cantilever Bending

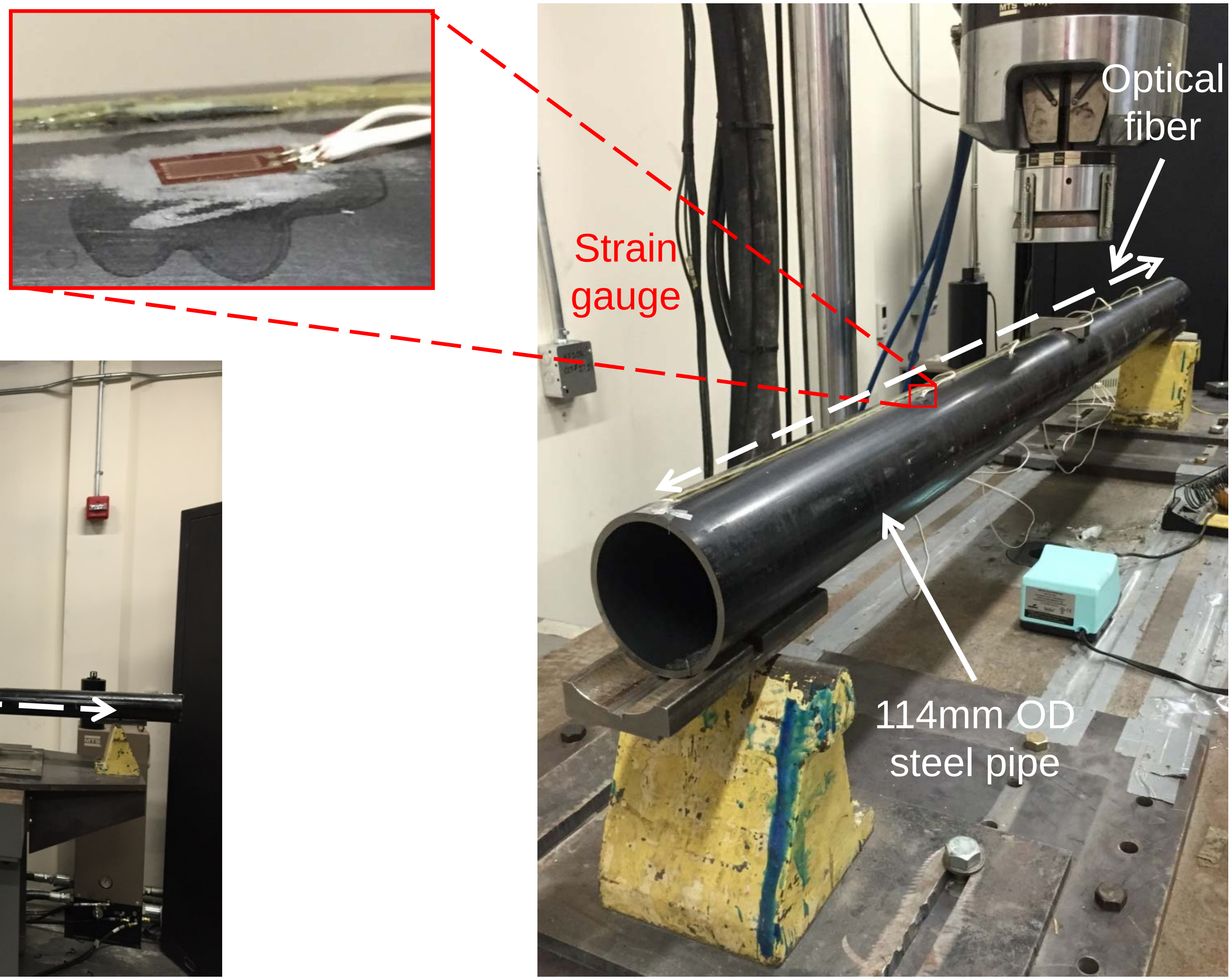

Axial Loading

(**Brad Forbes**, Grad Student 2014)

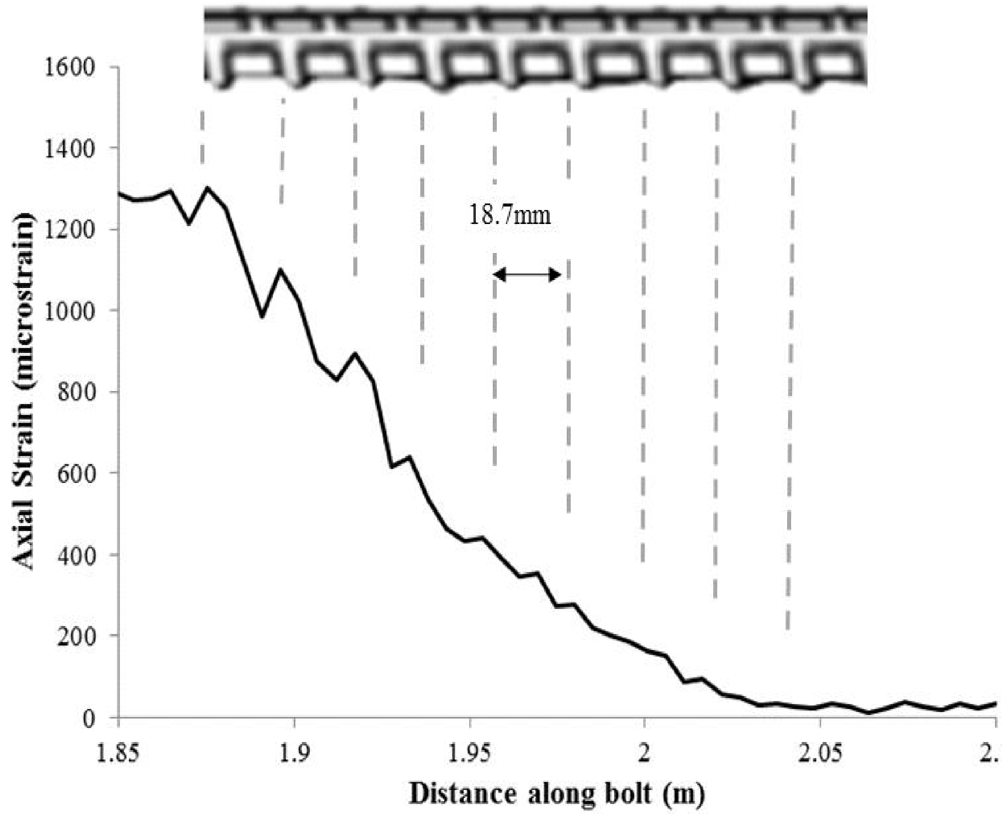
4 inch schedule 40 ASTM A53
Grade B steel pipe



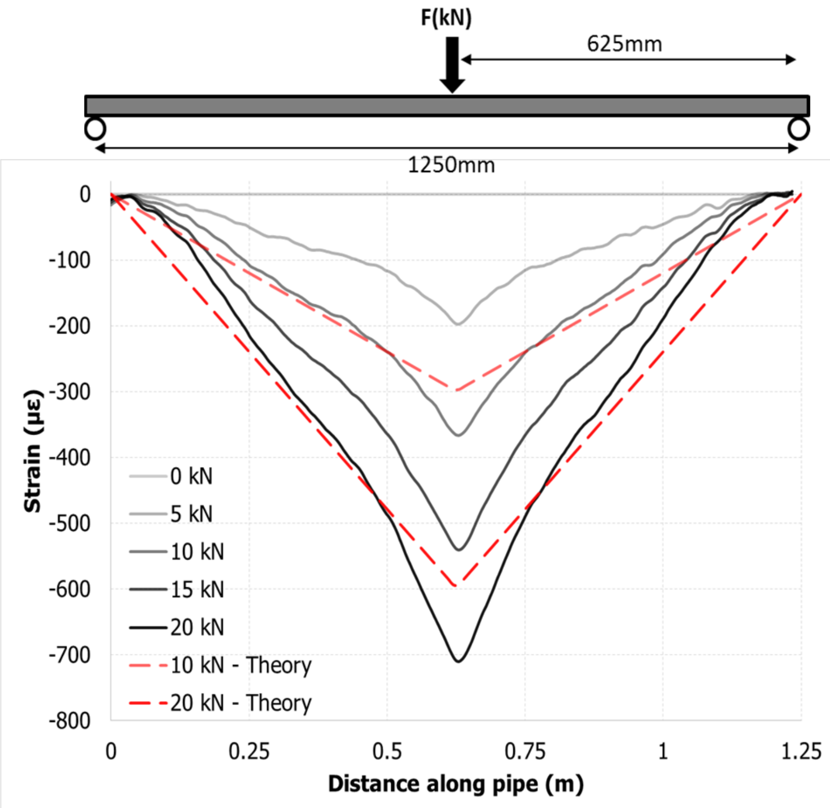


Support spans
from 0.5m to 3.0m


Strain
gauge
Optical
fiber
114mm OD
steel pipe

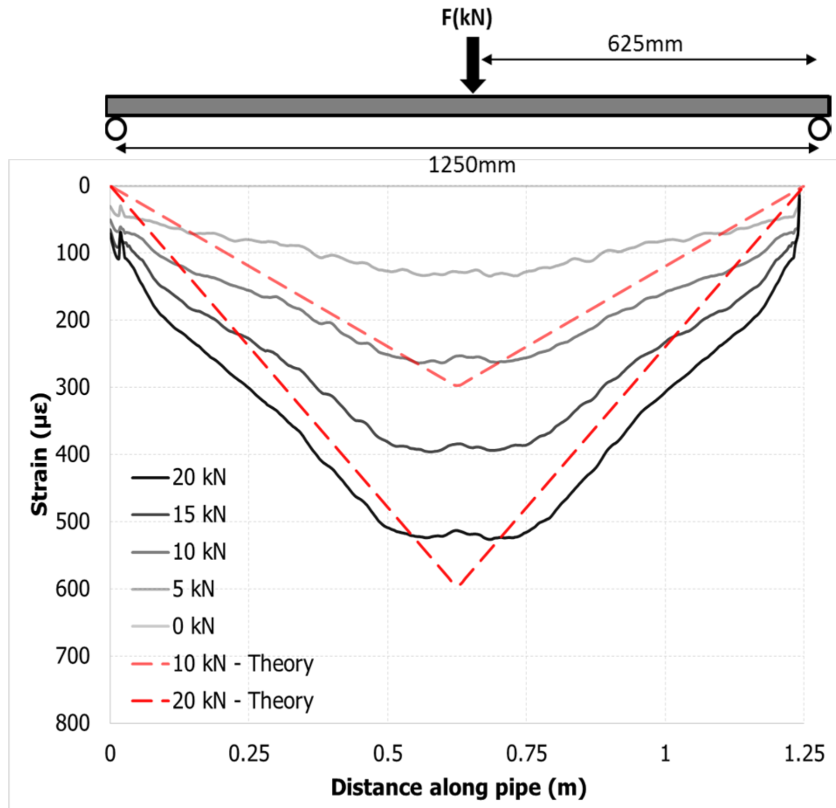
# Pullout-Test



# Bending-Test

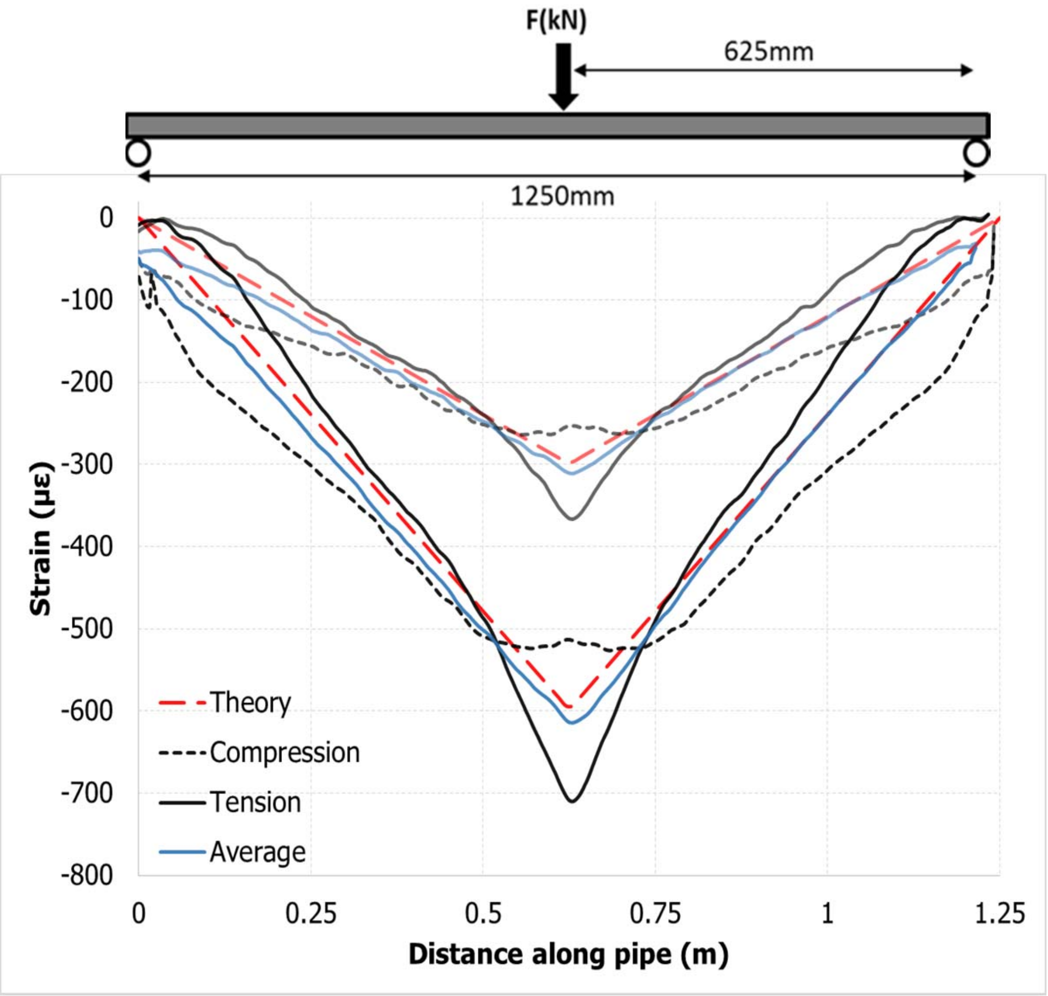



top section of the pipe in compression



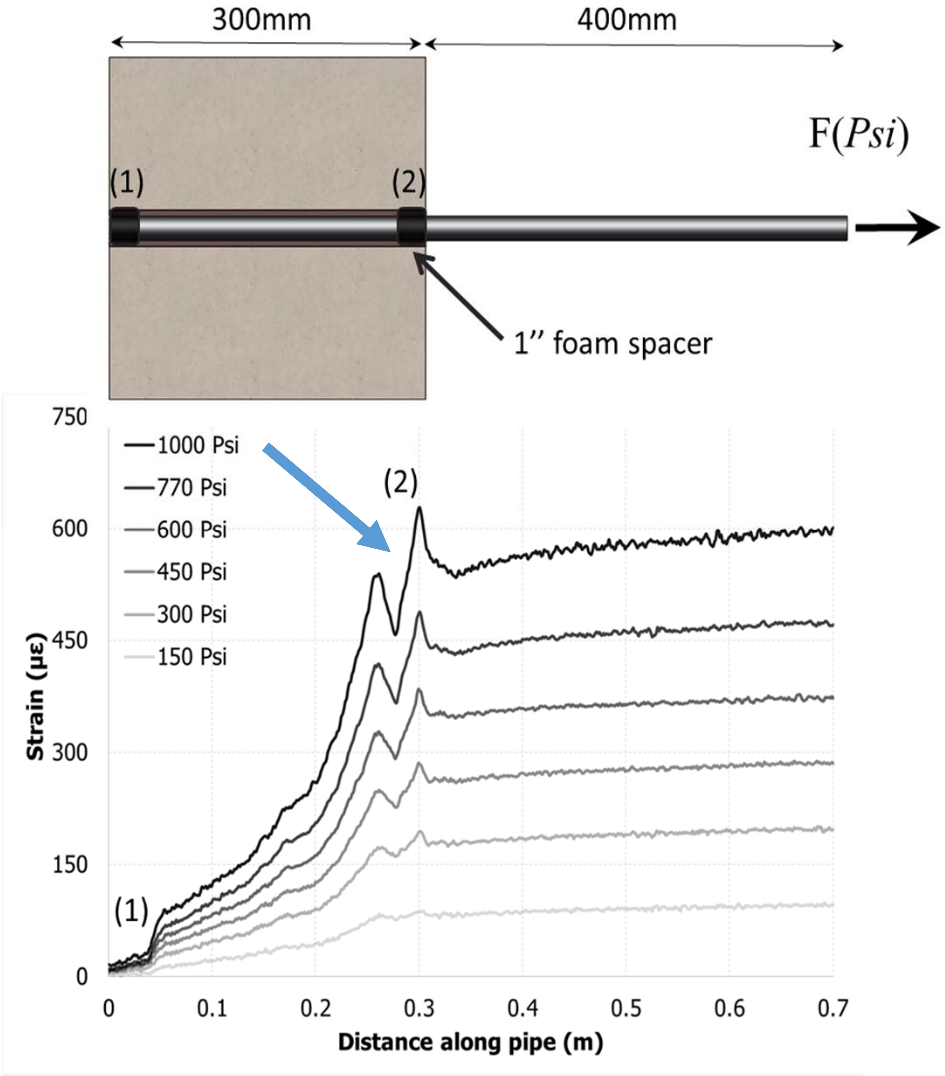

bottom section of the pipe in tension

- Absolute average of the top and bottom section of the pipe under bending
- Yields an approximately linear response

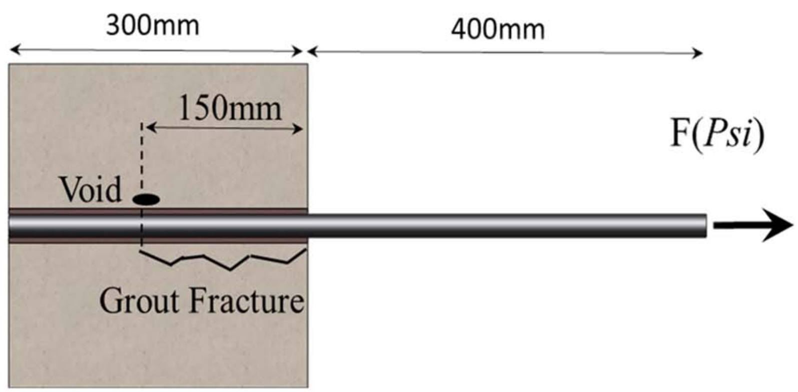


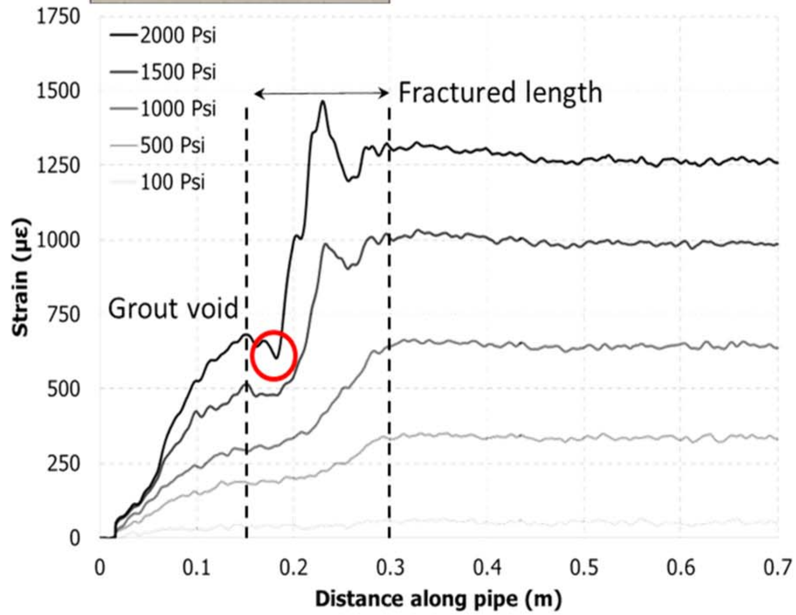
- The strain profile shows inconsistencies at the end of the grouted section.

- These correspond to 1 inch long foam spacers used to center the steel pipe while grouting

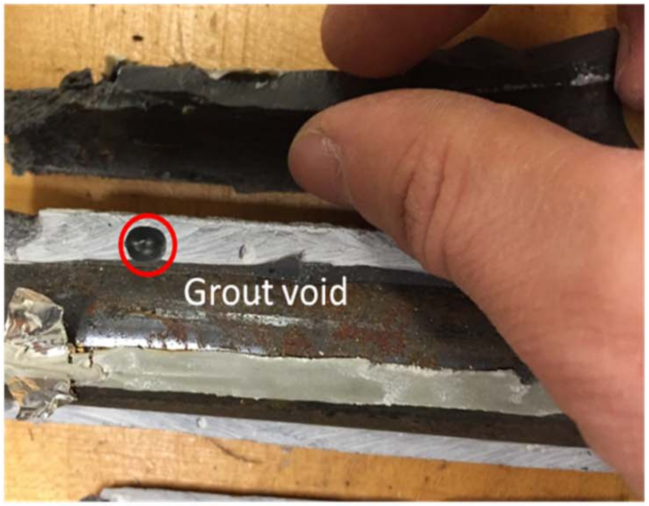


Shows the potential for the optical technique to be used to detect minor features

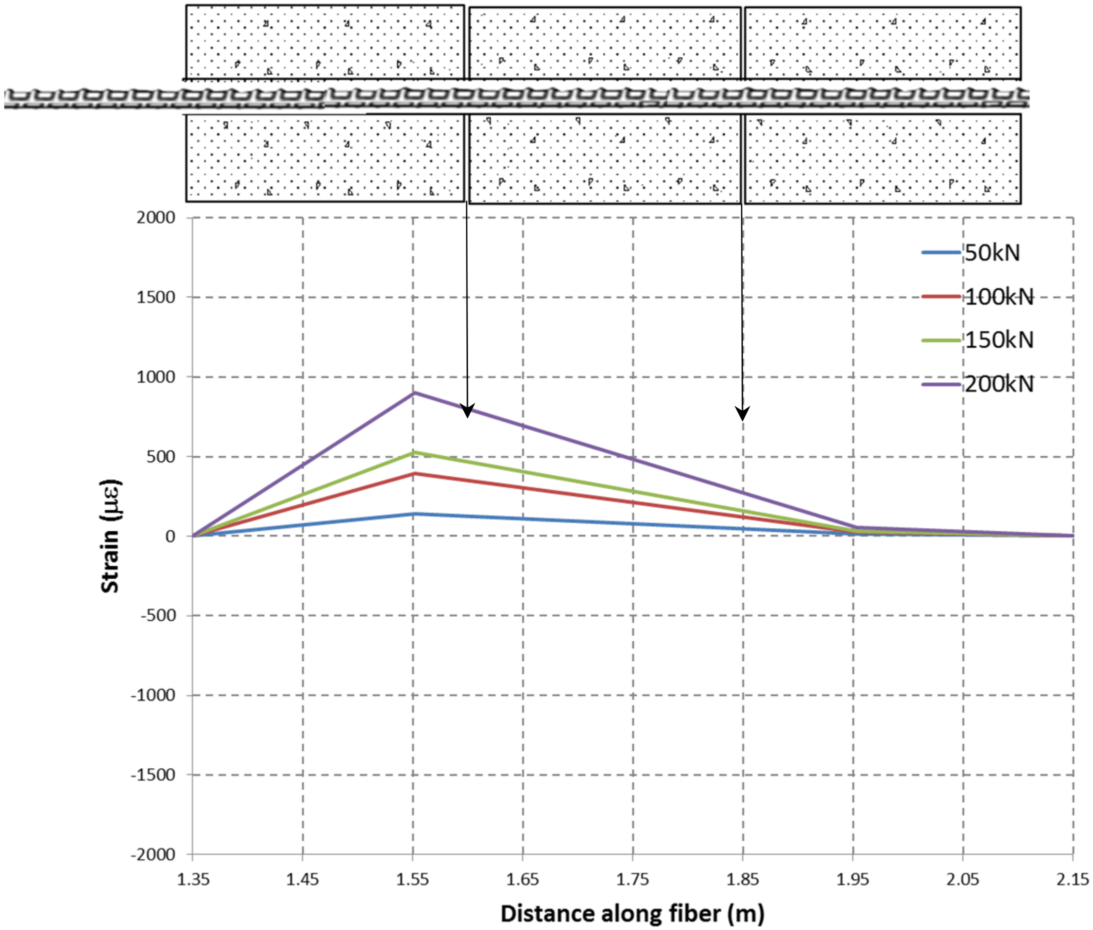






# Double Shear Configuration


Experimental Plot – Top section of rebar

**Spatial Resolution**

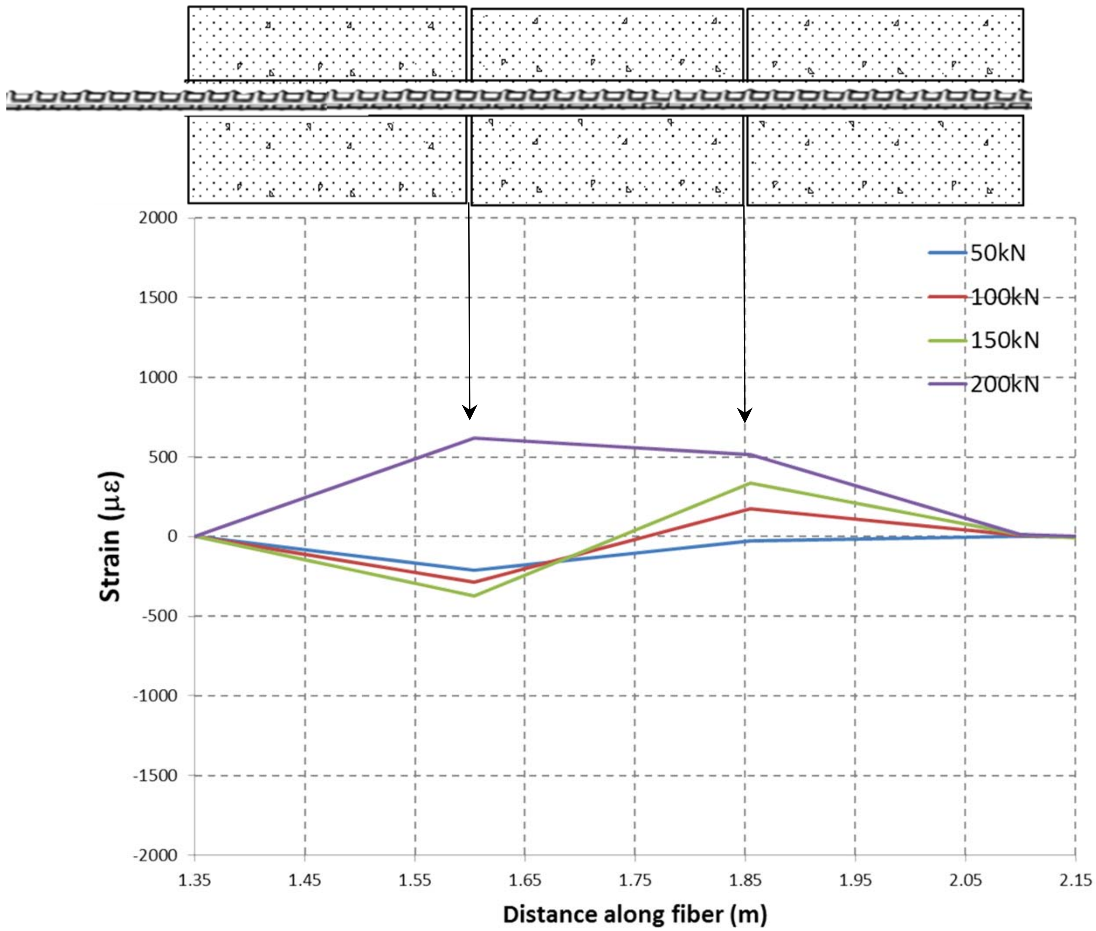
40cm

25cm

10cm

1.25mm

# Double Shear Configuration

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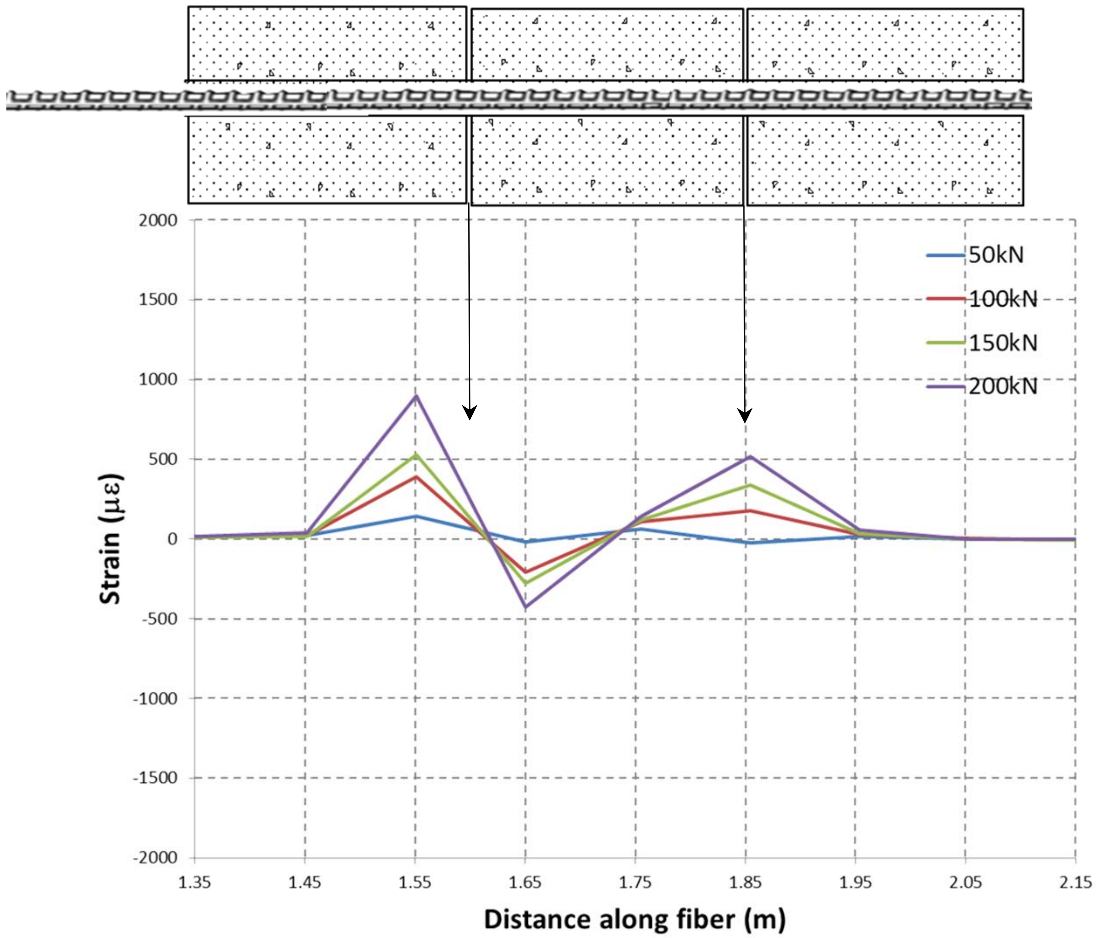


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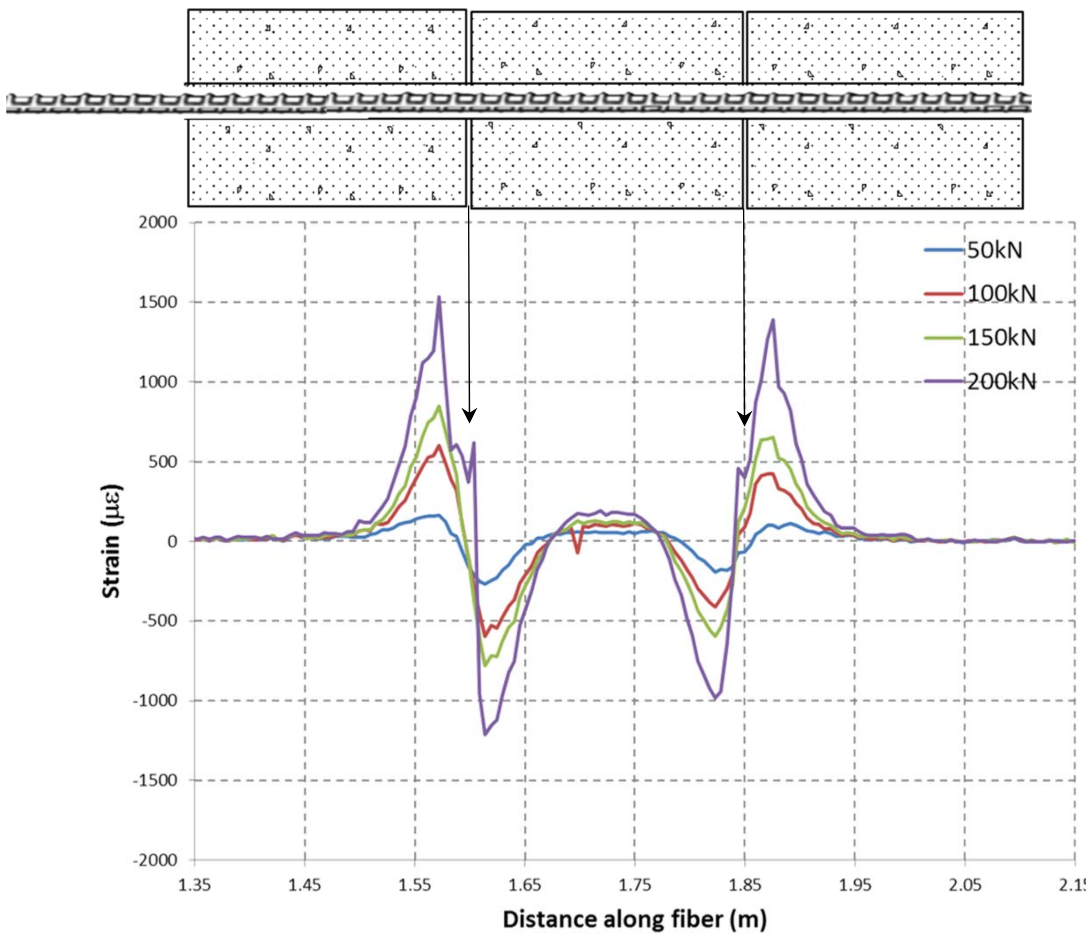


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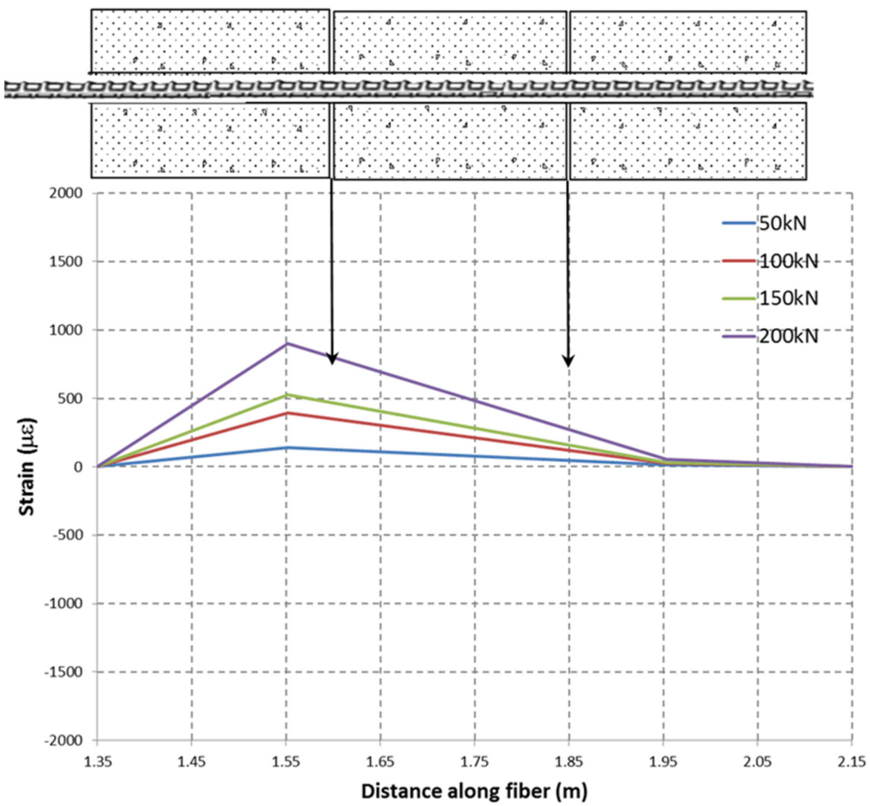
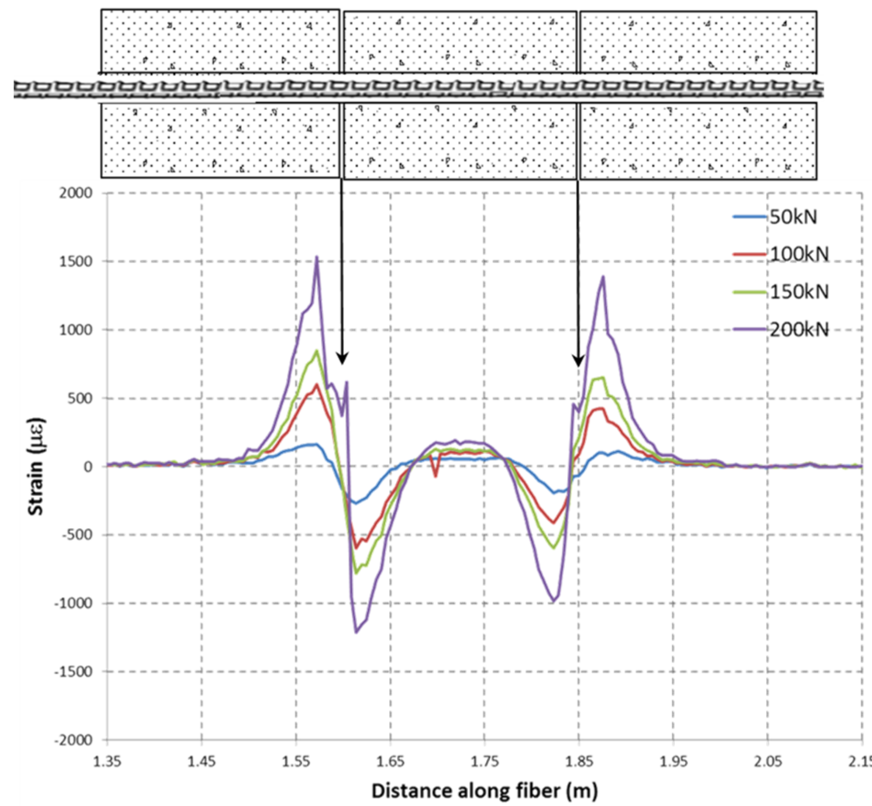
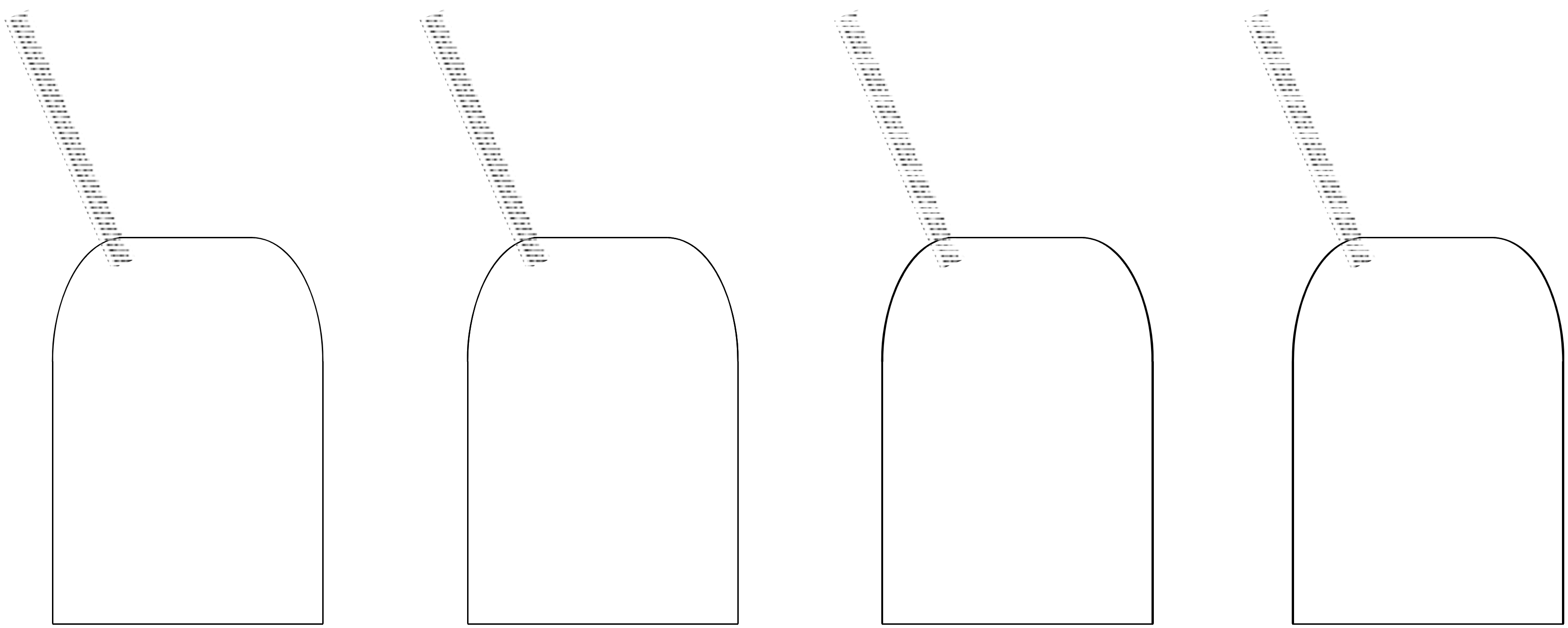



1.25mm




Experimental Plot – Top section of rebar

# Is Continuous Monitoring Necessary?



(1) (2) (3) (4)

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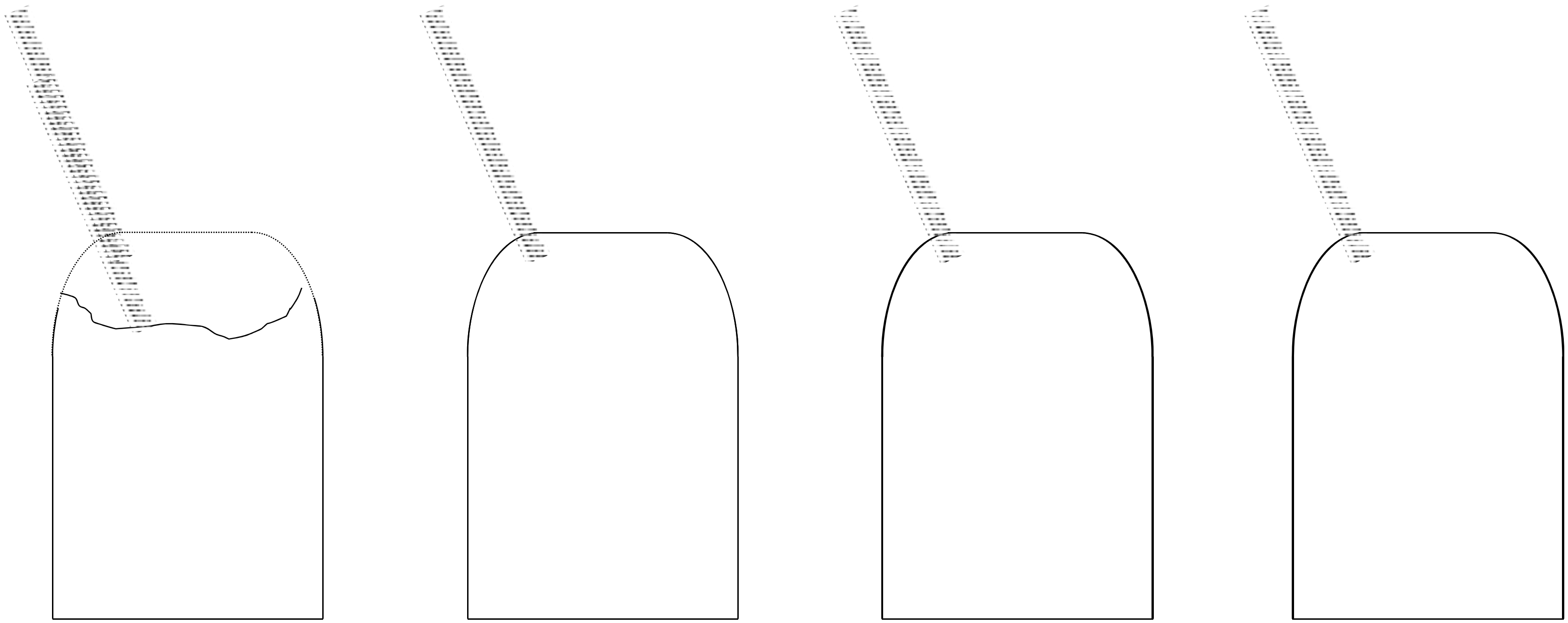

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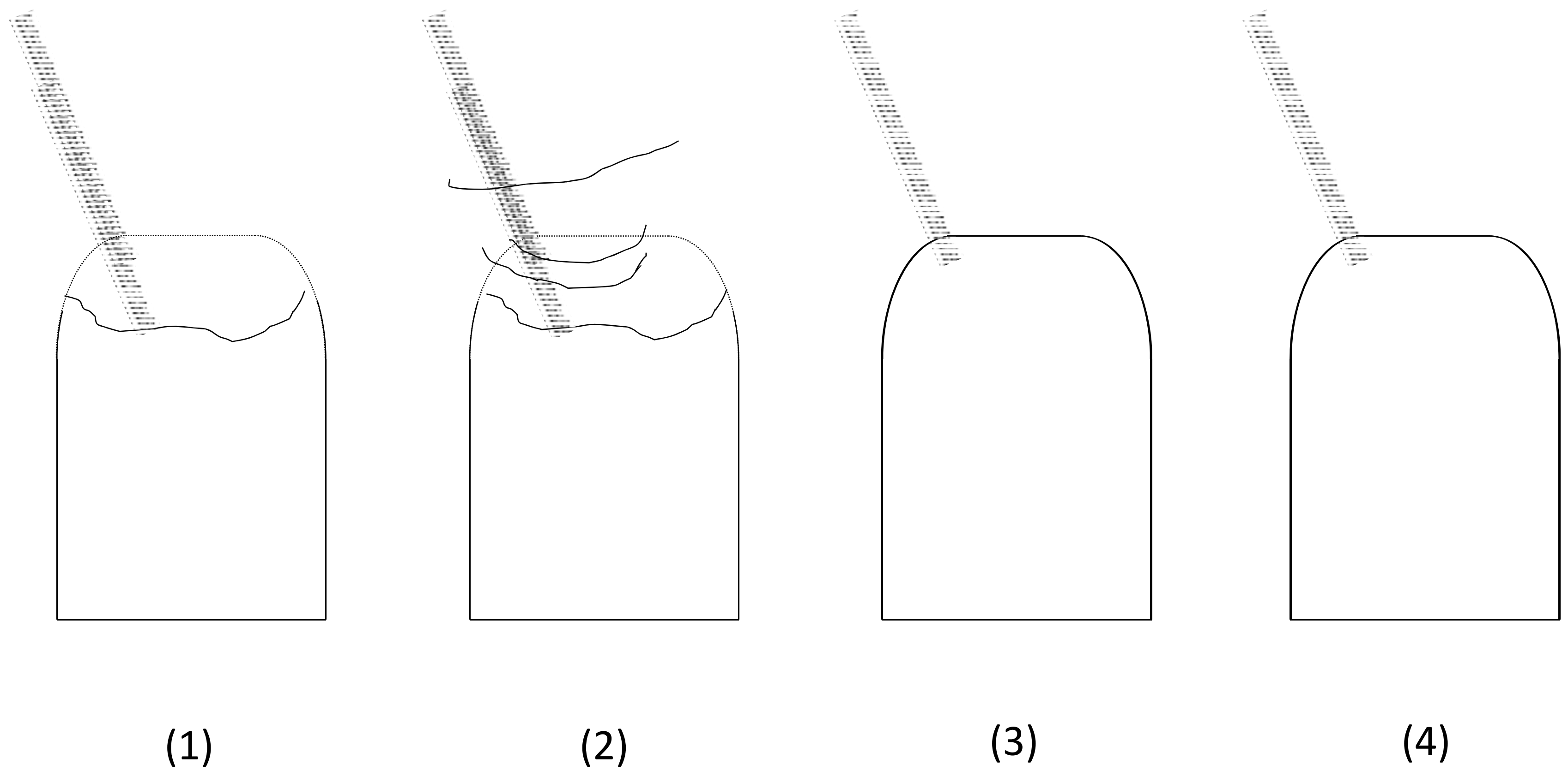

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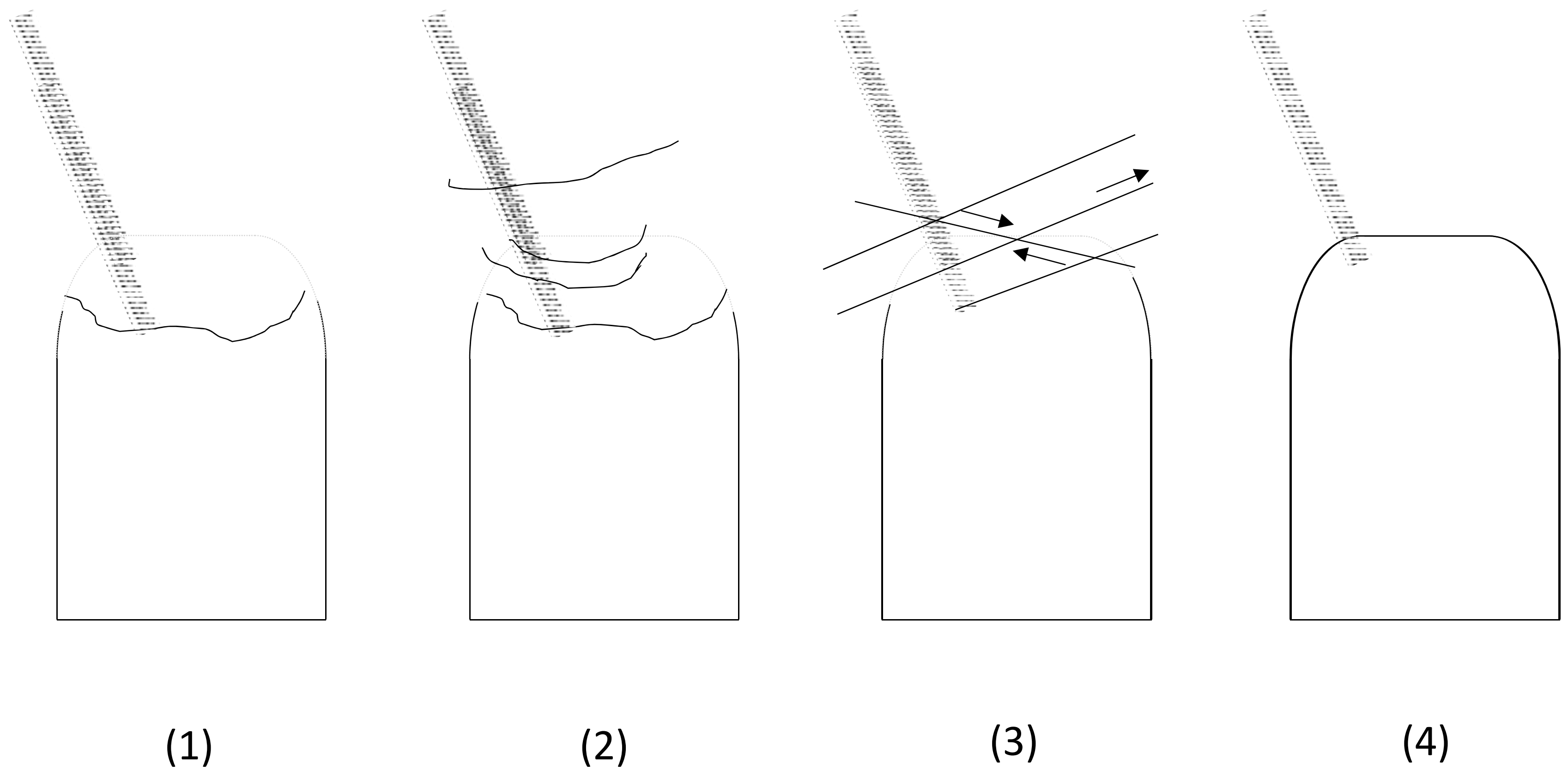

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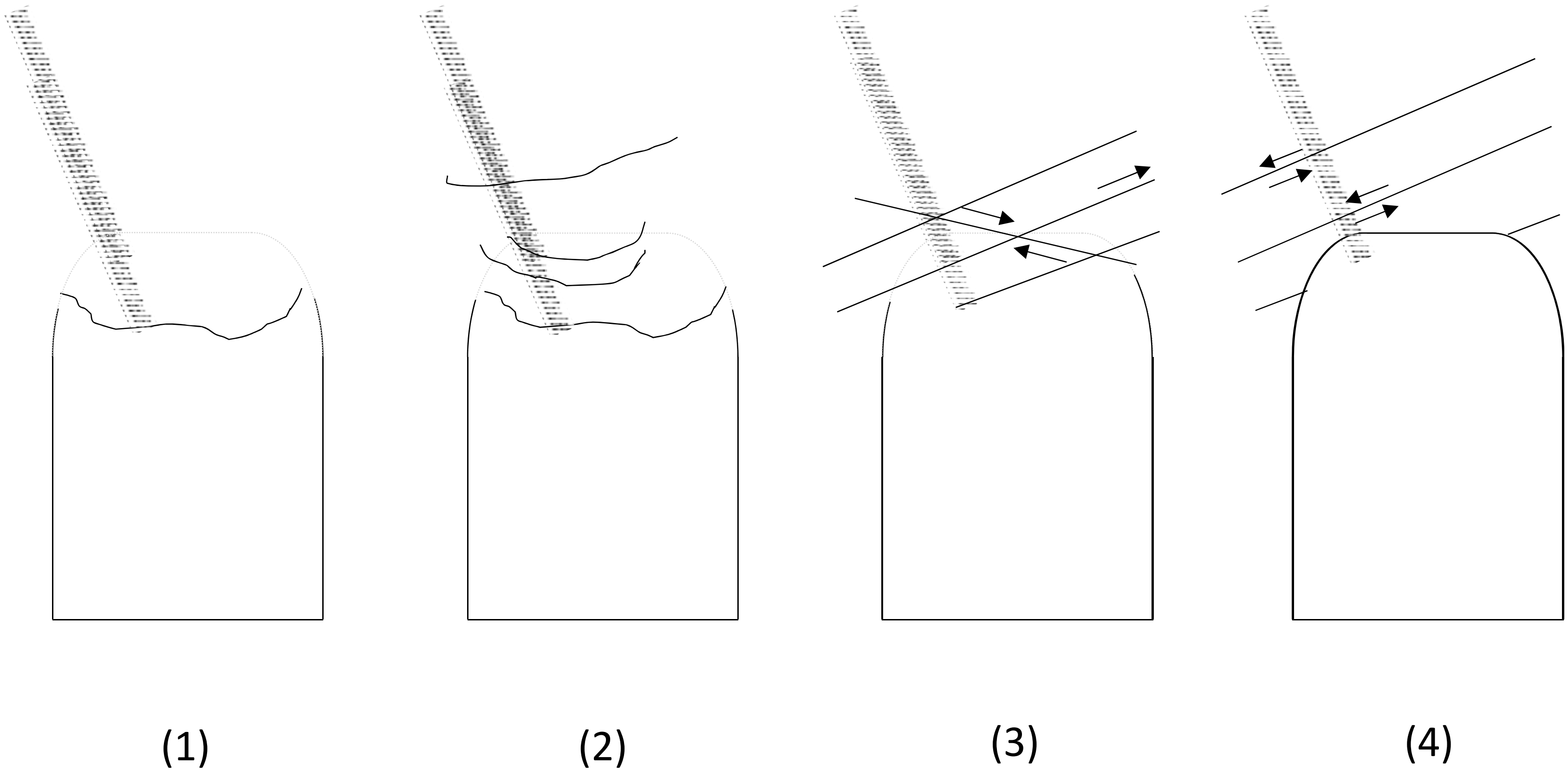

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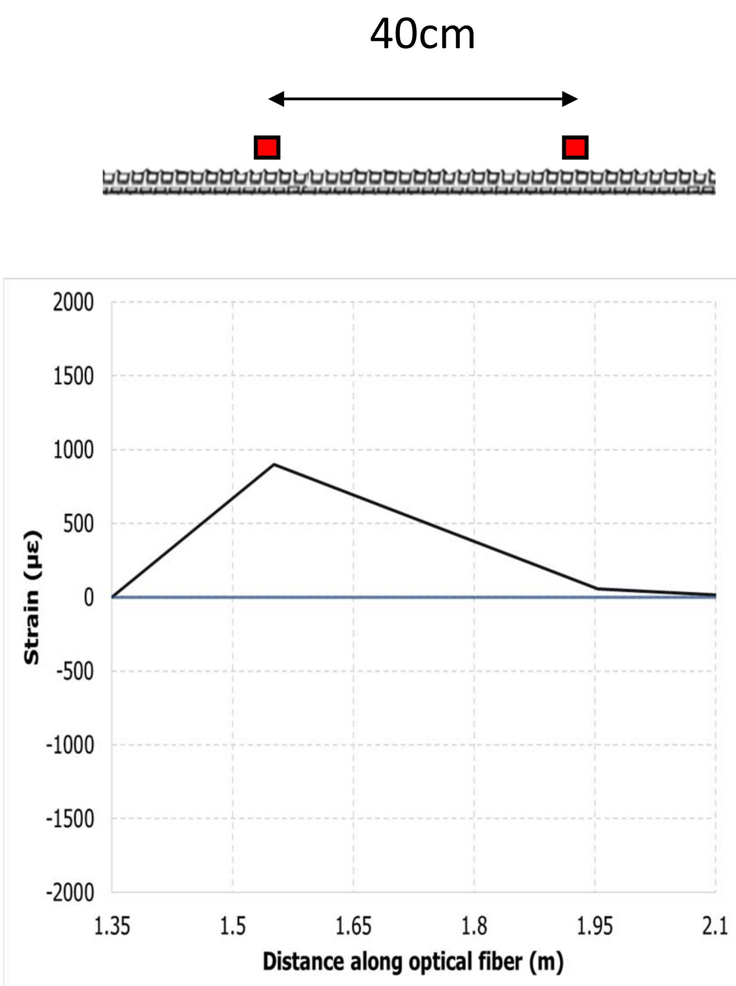


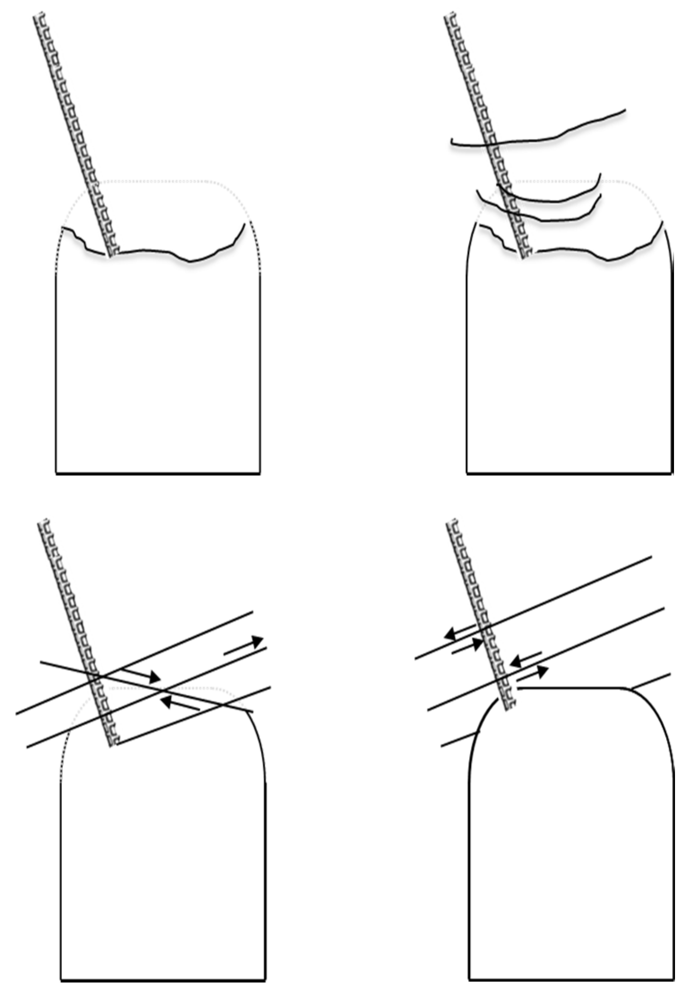

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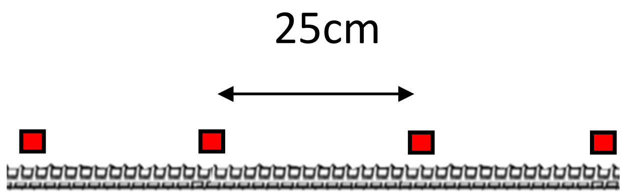


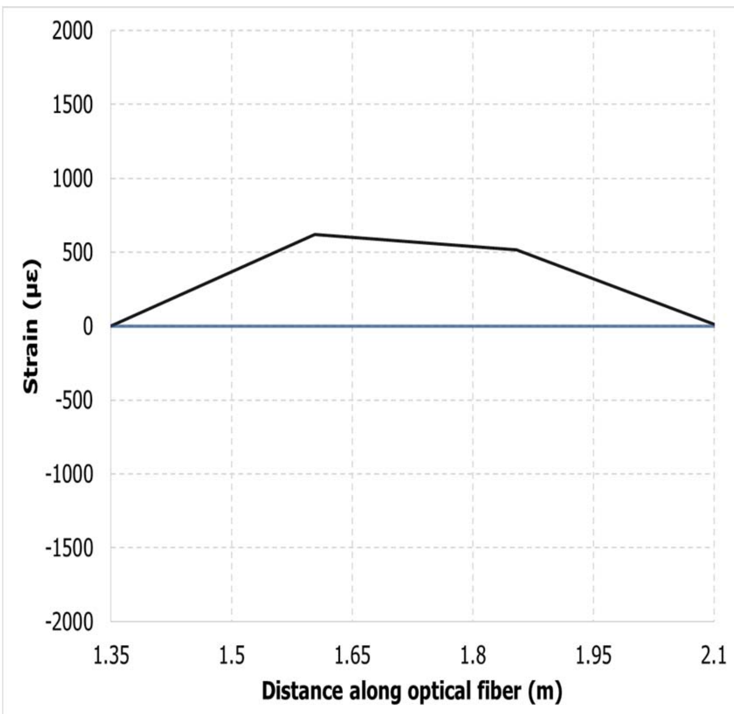


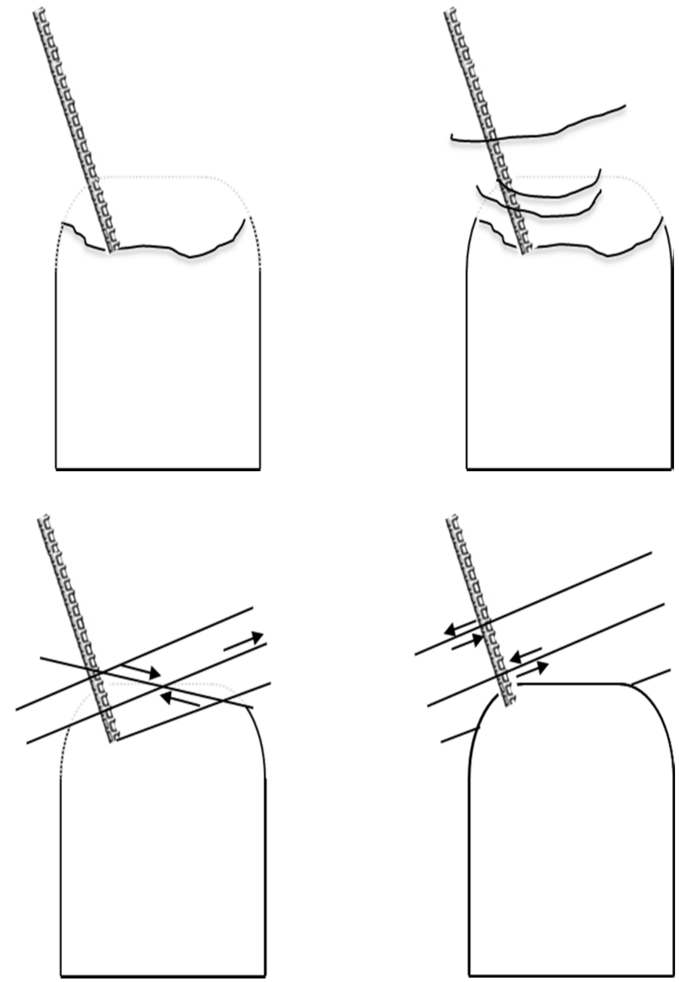

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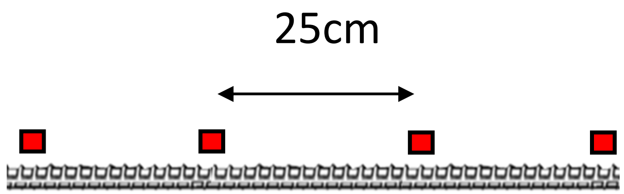


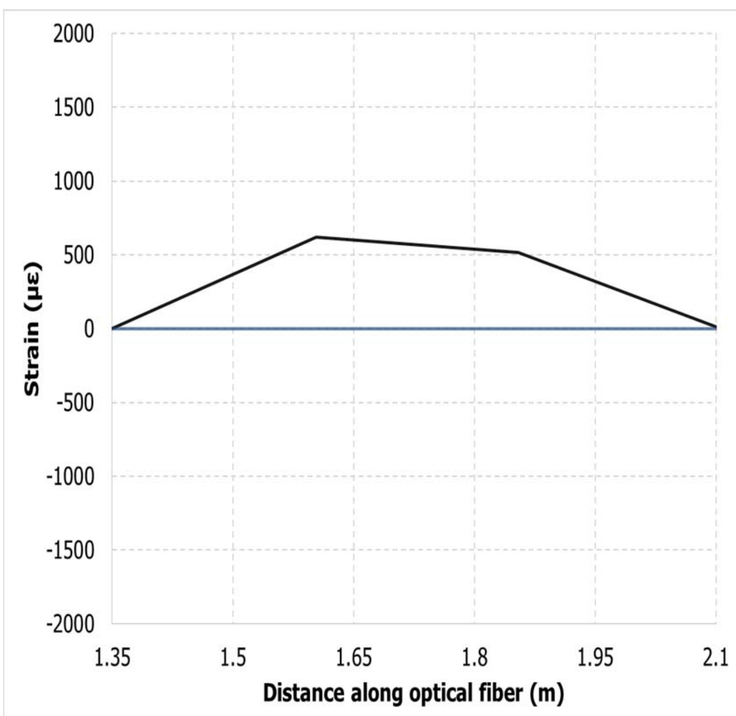


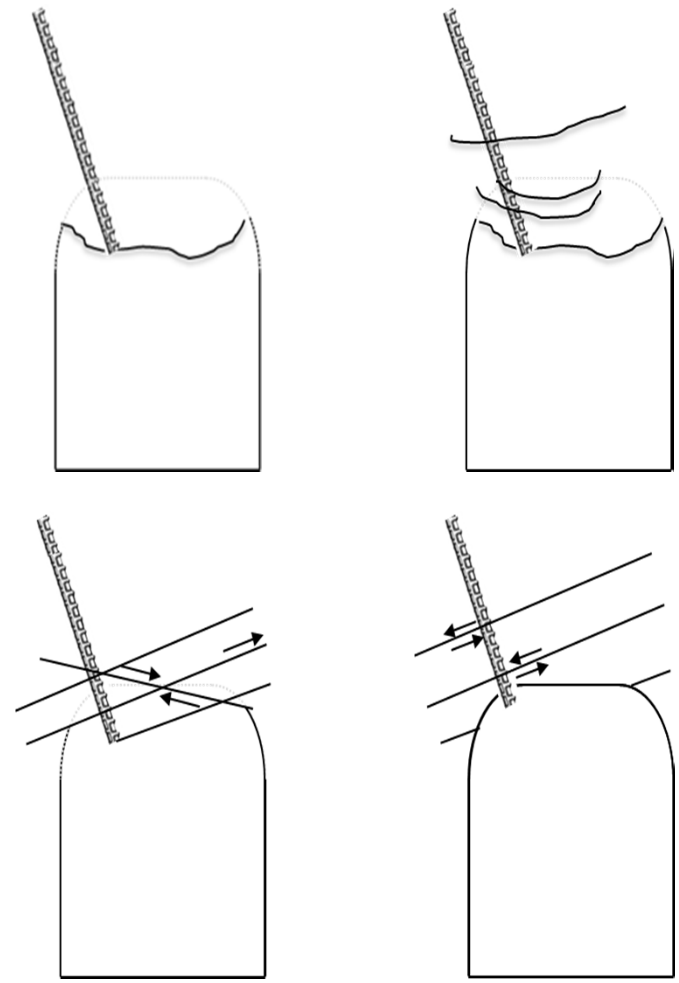

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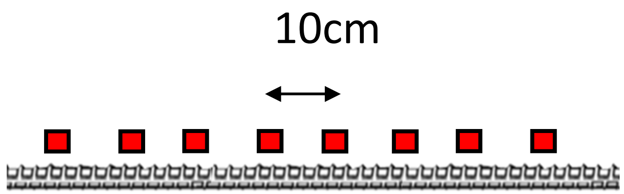


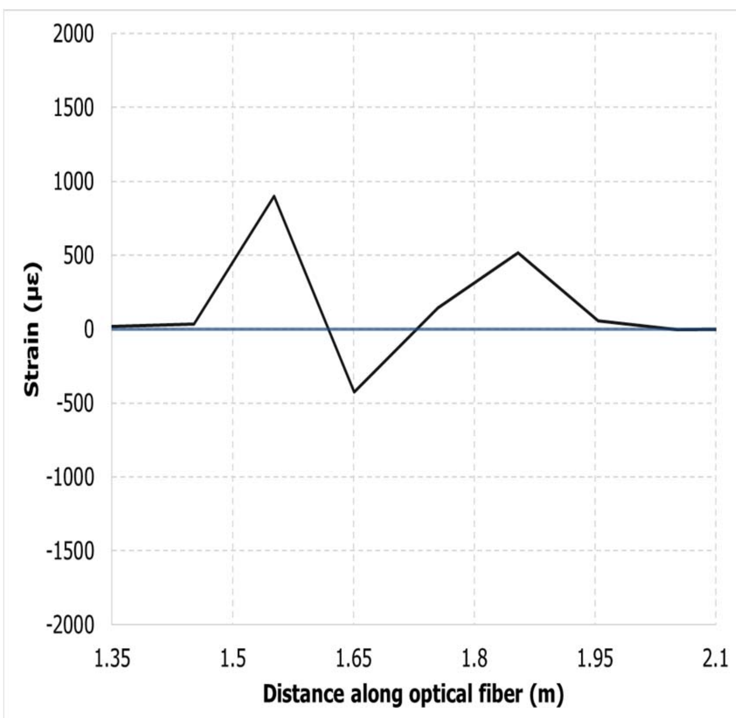


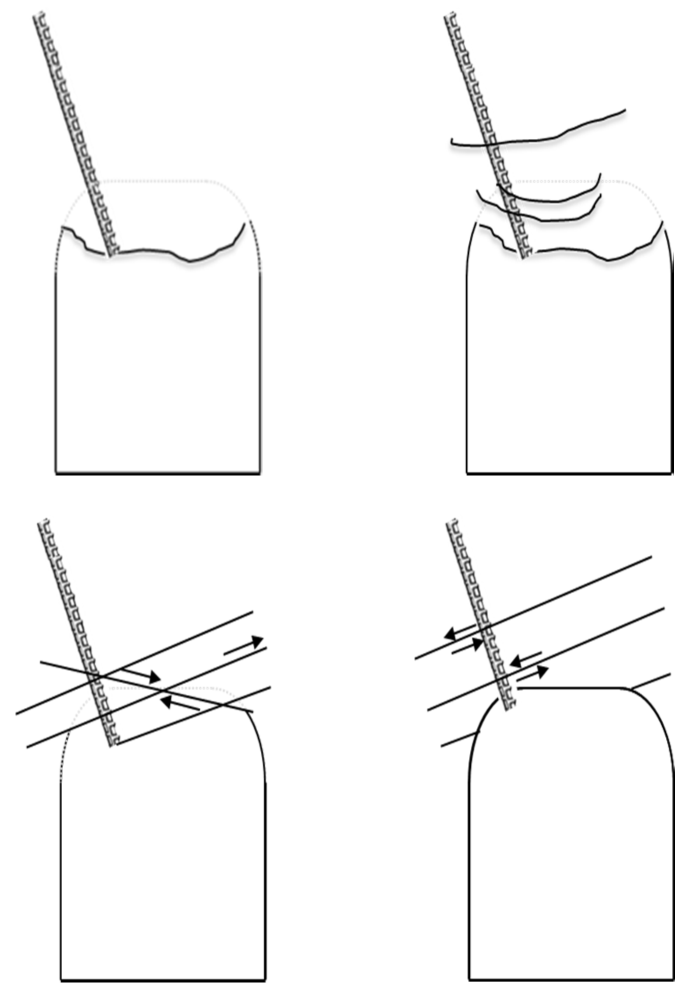

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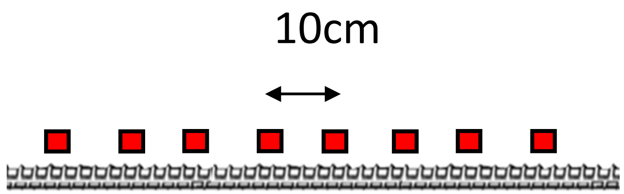
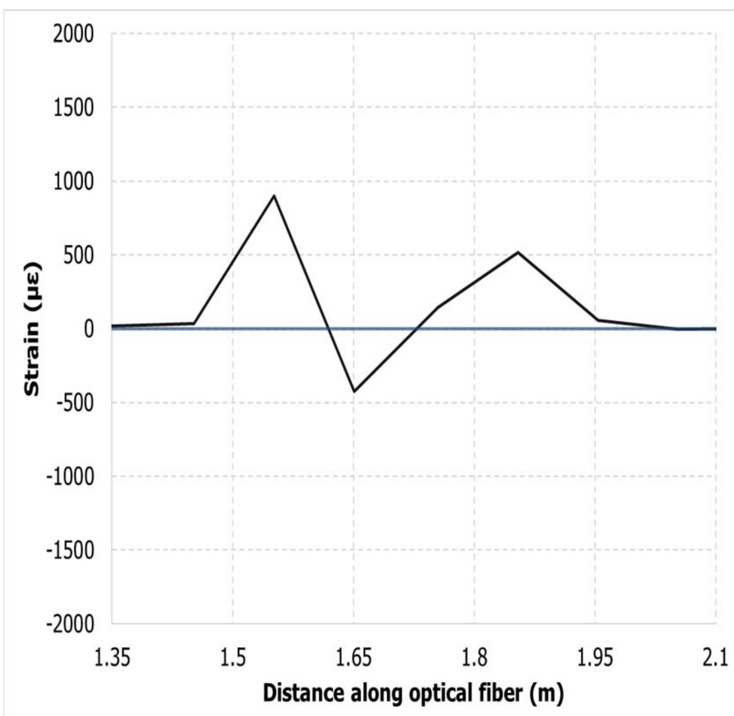
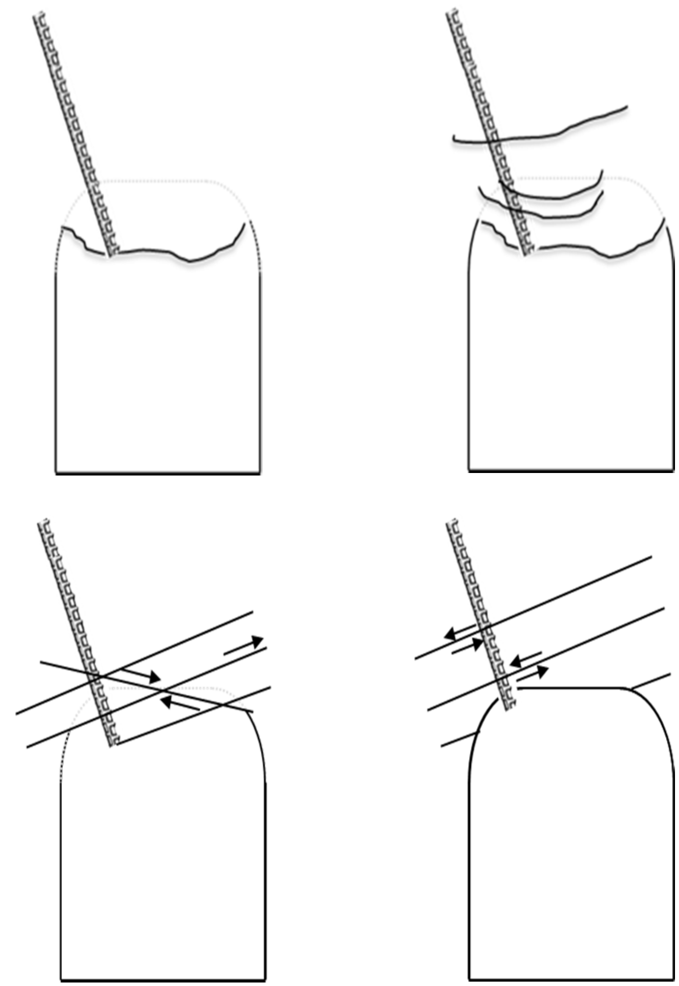
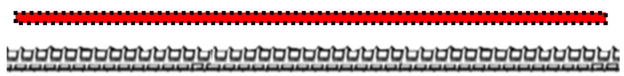


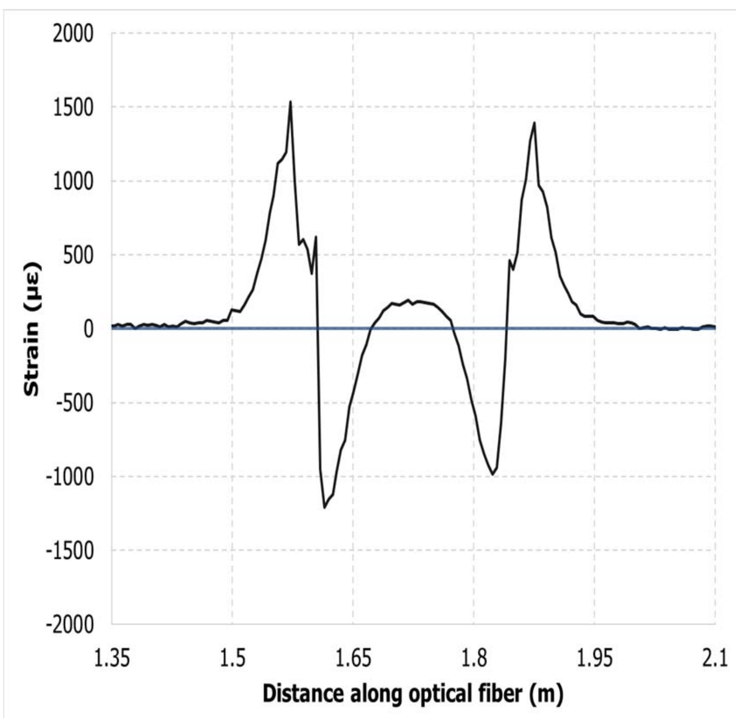



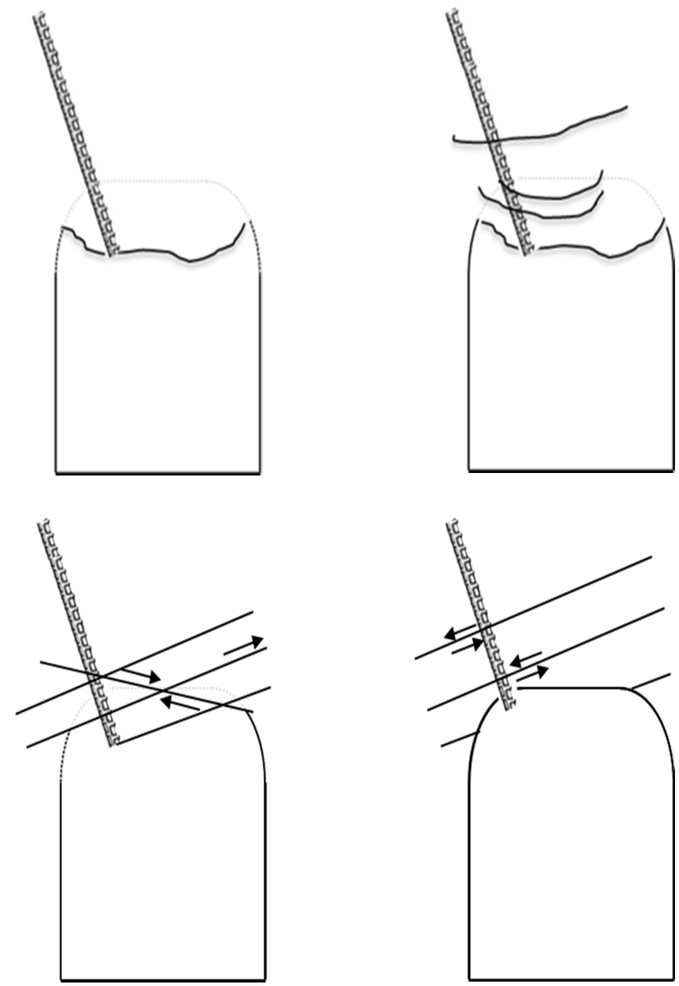



# Is Continuous Monitoring Necessary?

1.25mm





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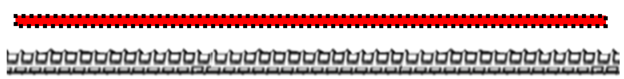

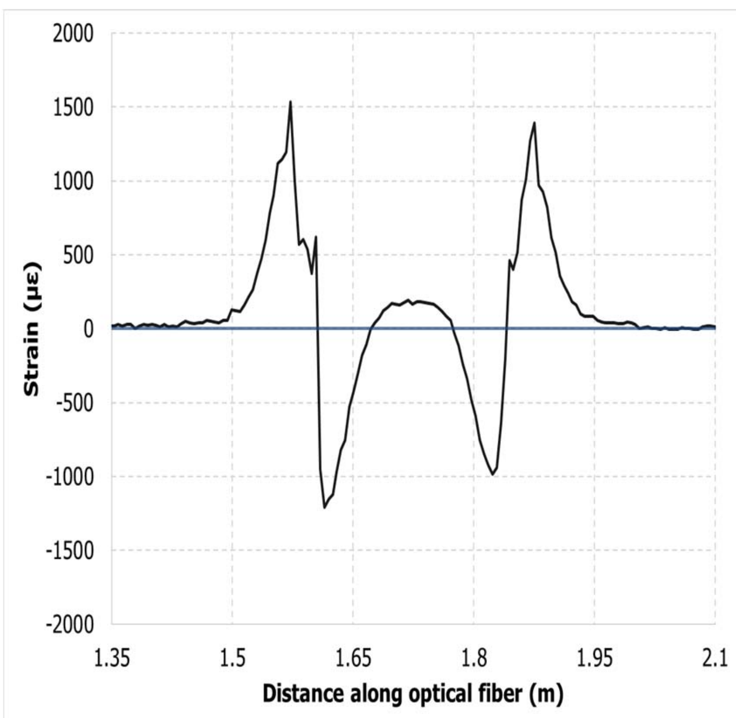


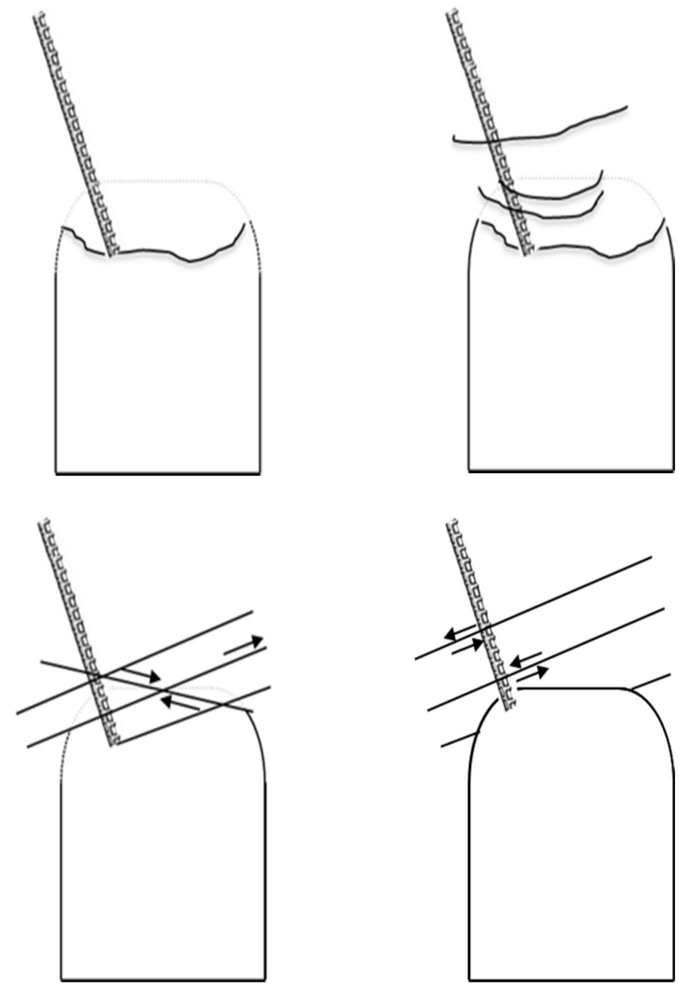

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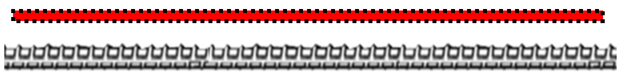
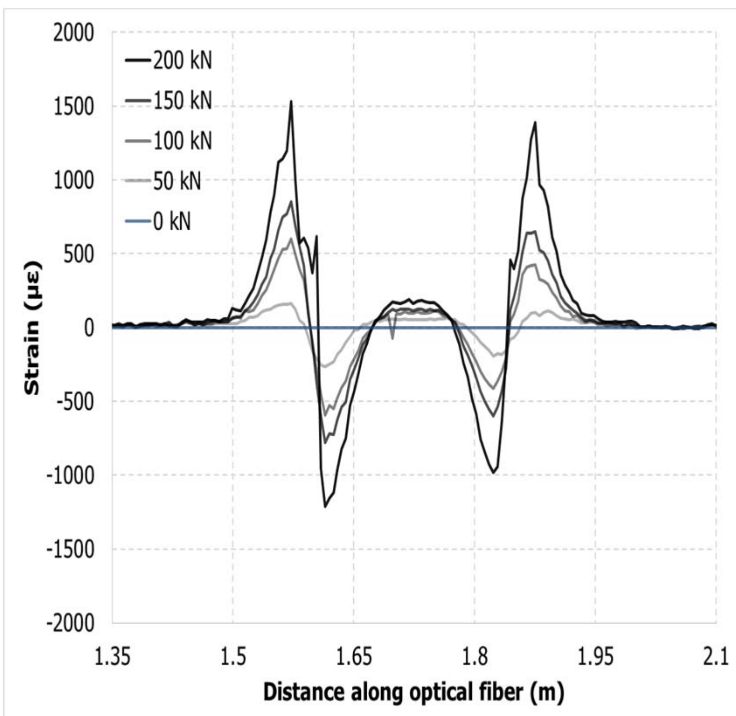


Double shear test




# Field Trials

Depth of ore body approx. 725ft

3-groove DOS instrumented bolt installed in shale roof of a coal mine

# Conclusions

- DOS provides a novel opportunity in support monitoring:

  - Provides a very sensitive spatial resolution (1.25mm)

  - Has a high operational accuracy

  - Optical fiber is extremely cheap (implement an array of DOS elements)

- Validated for further development with temporary support system(s):

  - improve understanding of individual components of the umbrella arch system and the system as a whole with a view to improving design

  - potential tool for predicting ground conditions ahead of the tunnel face

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Tunnelling Association of Canada
Association Canadienne Des Tunnels

# Research Support

Golder Associates

RMC CMR

NSERC
CRSNG

YieldPoint
Sensing the future

National Defence
Défense Nationale

Mitacs

RockSense
GEOSOLUTIONS


GEOMECHANICA

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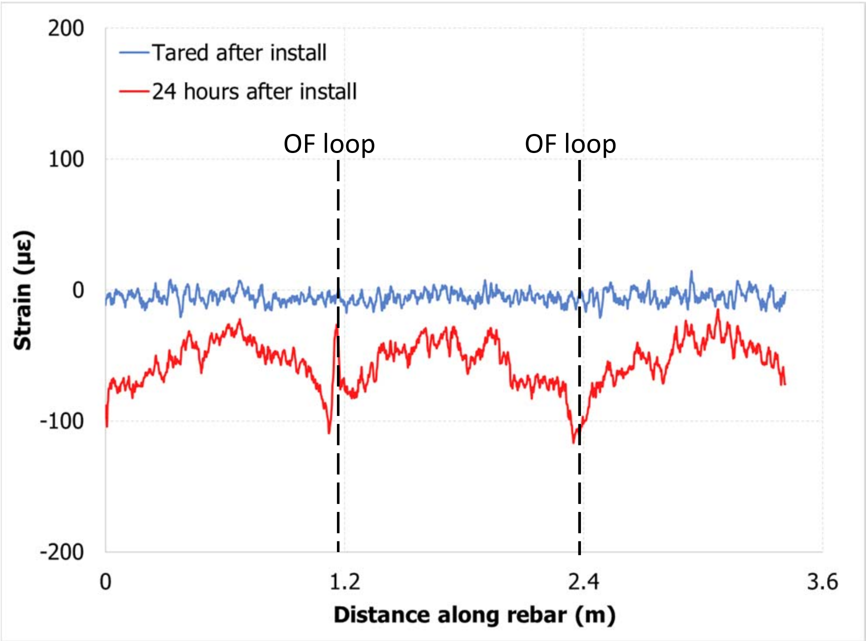
GLENCORE

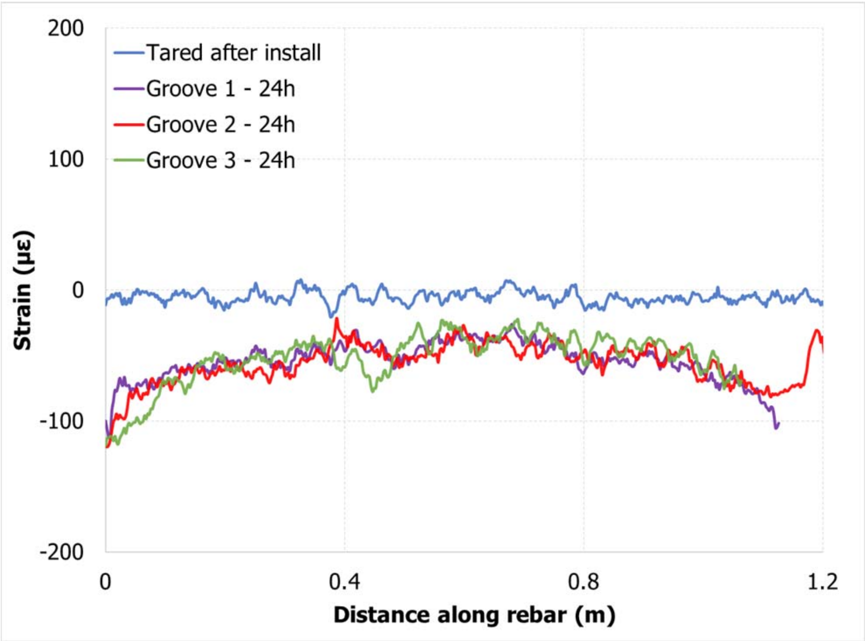
# Field Trials




Depth of ore body approx. 725ft

3-groove DOS instrumented bolt installed in shale roof of a coal mine

# Field Trials




Depth of ore body approx. 725ft

DOS instrumented bolt installed in the roof of a coal mine

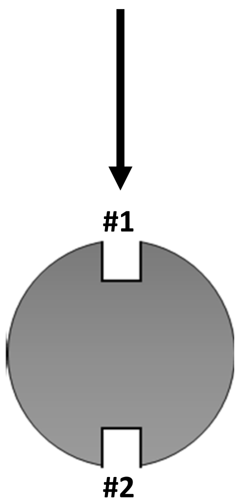
# Field Trials

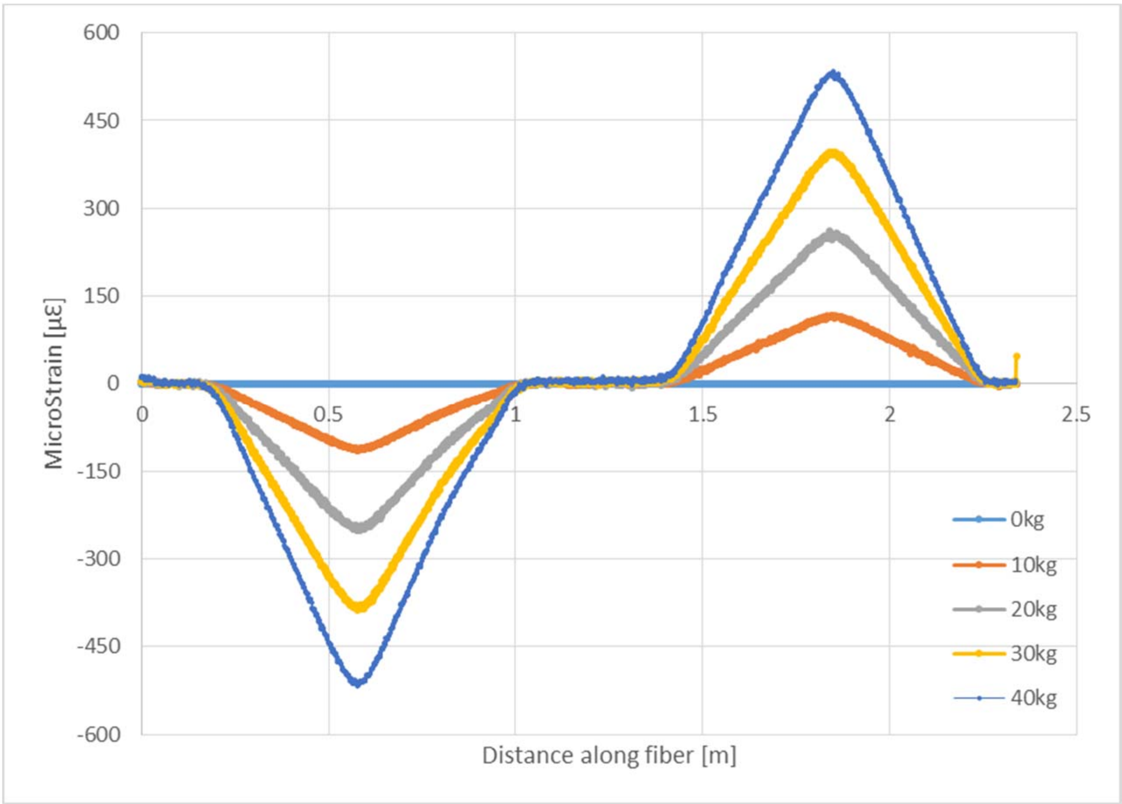
# Orientation of bending

- Developed a DOS rebar element with three lengths of optical fiber (i.e. three machined out grooves)
- Fiber lengths are orientated at approx. 120 deg. from each other
- Determine the direction of maximum bending, in turn allowing the magnitude of bending to be calculated, and ultimately the axial component separate from bending
- Signal loss overcome at loops by using a specialized low-bend loss optical fiber

# Orientation of bending

Why we need 3 grooves!

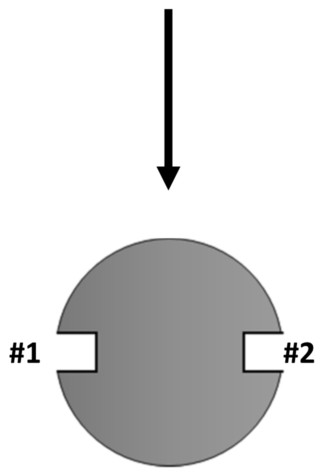


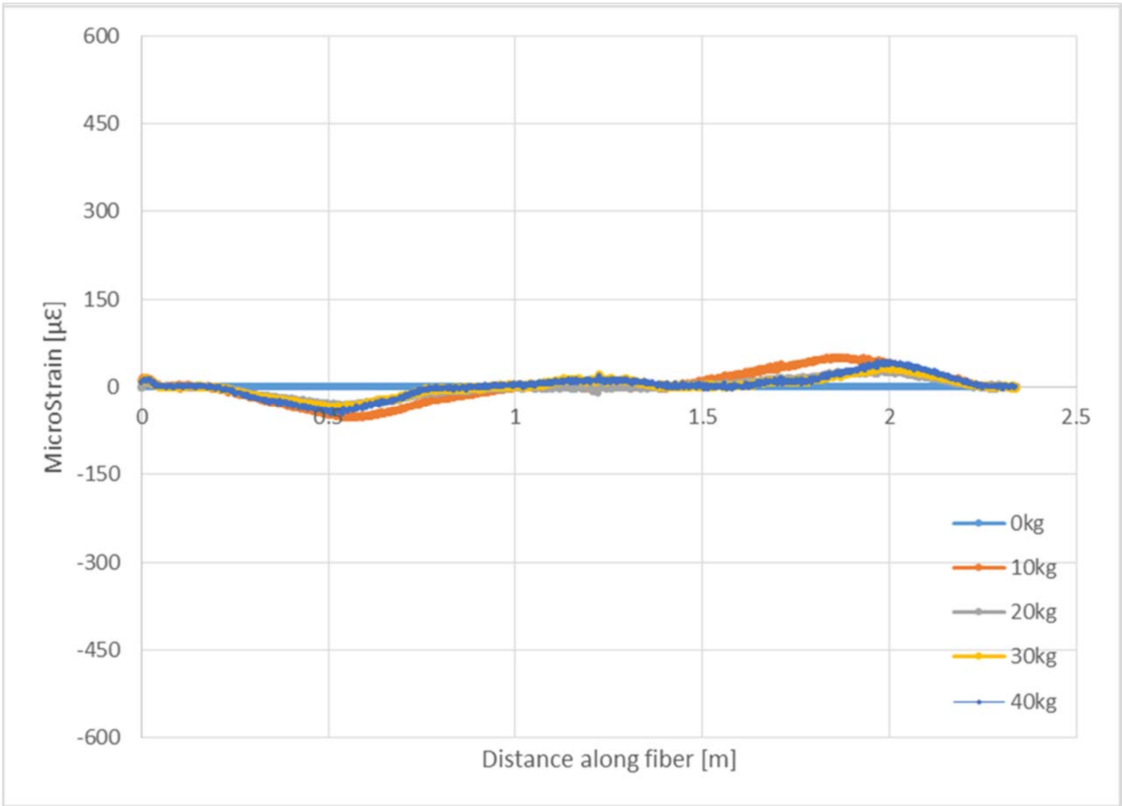




- Two grooves aligned with bending direction

# Orientation of bending

Why we need 3 grooves!



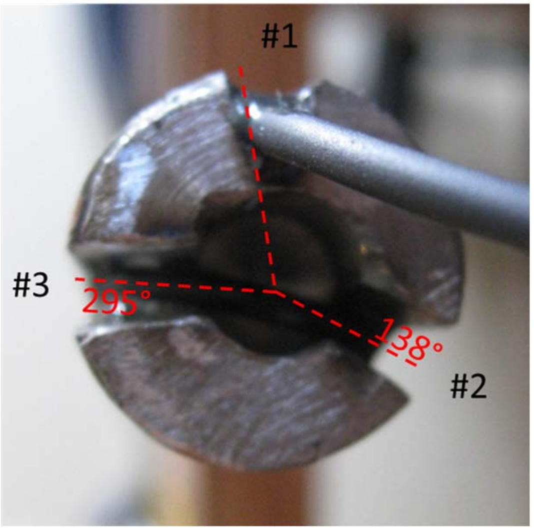




- Two grooves aligned 90 deg. from bending direction (i.e. neutral axis)

# Orientation of bending

$\theta$: Orientation (degrees) of maximum bending from length 1

$\varphi$: Orientation (degrees) of specified length from length 1




$$\varepsilon^i_{Total} = \varepsilon^i_{axial} + \varepsilon^i_{bending}$$

$$\varepsilon^i_{bending} = \varepsilon_{bending}\cos(\theta + \varphi)$$

$$\varepsilon^i_{Total} = \varepsilon^i_{axial} + \varepsilon_{bending}\cos(\theta + \varphi^i)$$

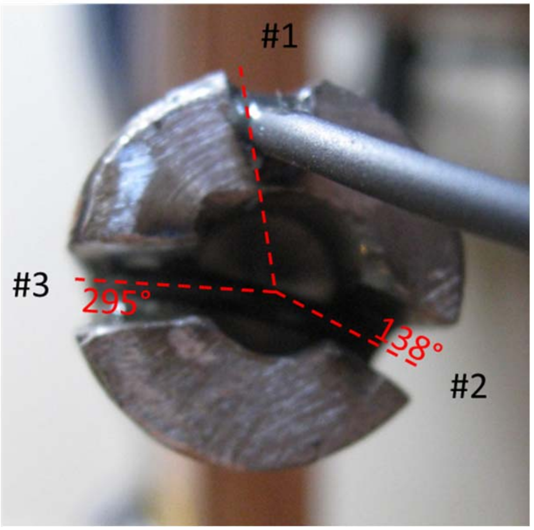
$$E = \left\{\frac{\varepsilon^1_{Total} - \varepsilon^3_{Total}}{\varepsilon^1_{Total} - \varepsilon^2_{Total}}\right\}$$

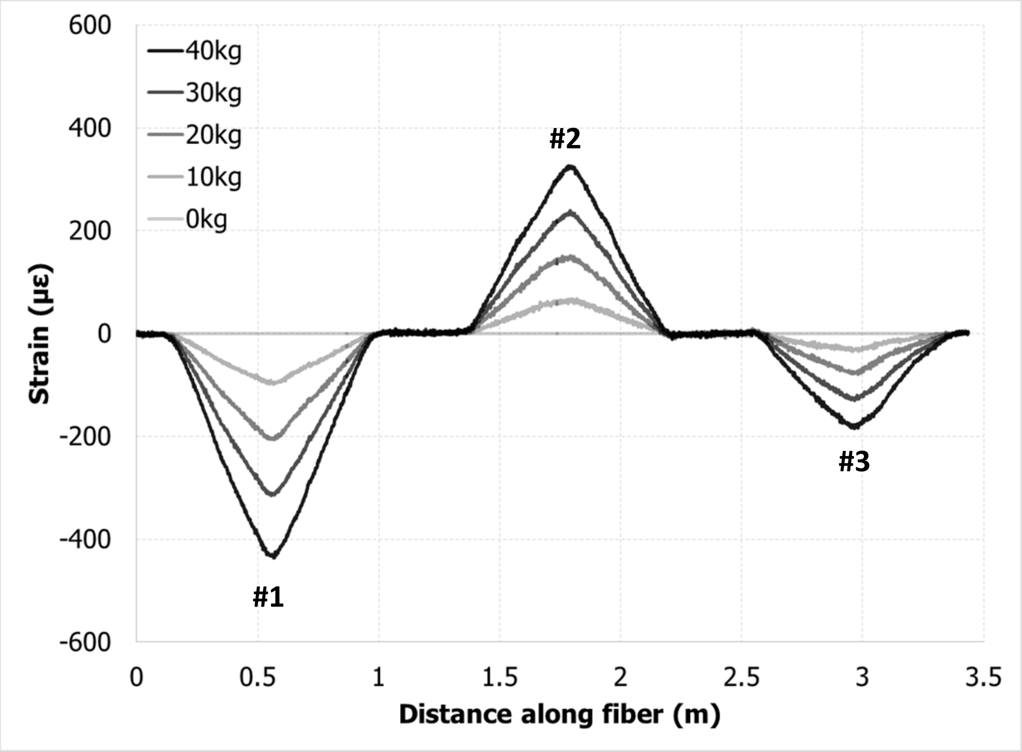
$$= \left\{\frac{\cos(\theta) - \cos(\theta)\cos(\varphi^3) - \sin(\theta)\sin(\varphi^3)}{\cos(\theta) - \cos(\theta)\cos(\varphi^2) - \sin(\theta)\sin(\varphi^2)}\right\}$$

$$\sin(\varphi^3)\tan(\theta) - E\sin(\varphi^2)\tan(\theta) = 1 - \cos(\varphi^3) - \mathrm{E} + \mathrm{E}\cos(\varphi^2)$$

$$\theta = tan^{-1}\left\{\frac{1 - \cos(\varphi^3) - \mathrm{E} + \mathrm{E}\cos(\varphi^2)}{\sin(\varphi^3) - E\sin(\varphi^2)}\right\}$$

# Orientation of bending



# Orientation of bending