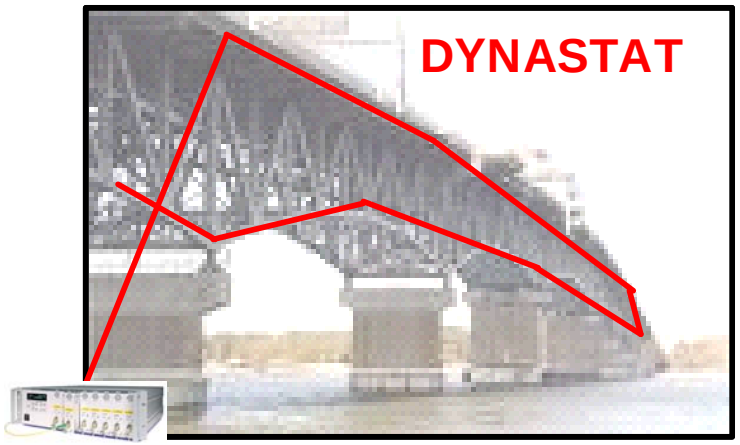
Fiber Sensing System for Civil Infrastructure Health Monitoring

T. Taylor, X. Zhang, D. Meng, and F. Ansari

Department of Civil and Materials Engineering

University of Illinois at Chicago



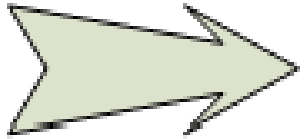
Combine Two Systems:

1. Coherent Rayleigh - - for dynamic sensing (acoustic, vibration, acceleration)
2. Brillouin Scattering- - for static sensing (simultaneous strain and temperature)

DST
Distributed Sensor Technologies

RIO
Light That Makes Perfect Sense™

Fabricate a new type of external cavity laser (PLANEX ECL)



UIC
UNIVERSITY OF ILLINOIS AT CHICAGO

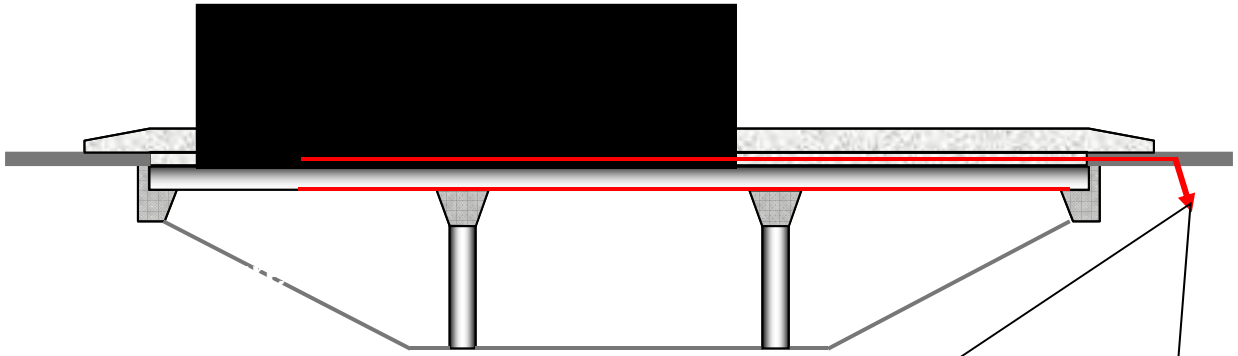
Test
Validate
Apply the Technology

OPTIPHASE®
solutions for fiber sensors

Fabricate BOTDA-CR System:

- Shared lasers
- Shared optoelectronic elements
- Shared distributed sensor fiber cable
- Integrated into a single instrument
- Use of commodity standardized fiber optic sensors

The core technologies



Brillouin Based Optical fiber sensor module:

BOTDR or BOTDA

Distributed strain and temperature: Requires two measurements (Before and After damage)

Sensor needs to have temperature compensation capability

Calibration relationships: strain; temperature

- Conversion of Brillouin data to strain
- Stability of measurements over measurement range (strain vs. deformation)

Numerical inverse analysis methods.
Identifies the location and state of the damage/cracks by using the measured strain

Scope of Studies at UIC

- Perform Calibration tests
- Perform validation tests for damage detection capability of the system
- Explore new Civil structural applications
- Employ the technology in the field

Brillouin Frequency shift – Strain - Deformation Formulations Leading to Stability Tests

$$\Delta\nu_B(\varepsilon,\Delta T) = C_\varepsilon\varepsilon + C_T\Delta T$$

$$\Delta\nu_B(\varepsilon) = C_\varepsilon\varepsilon$$

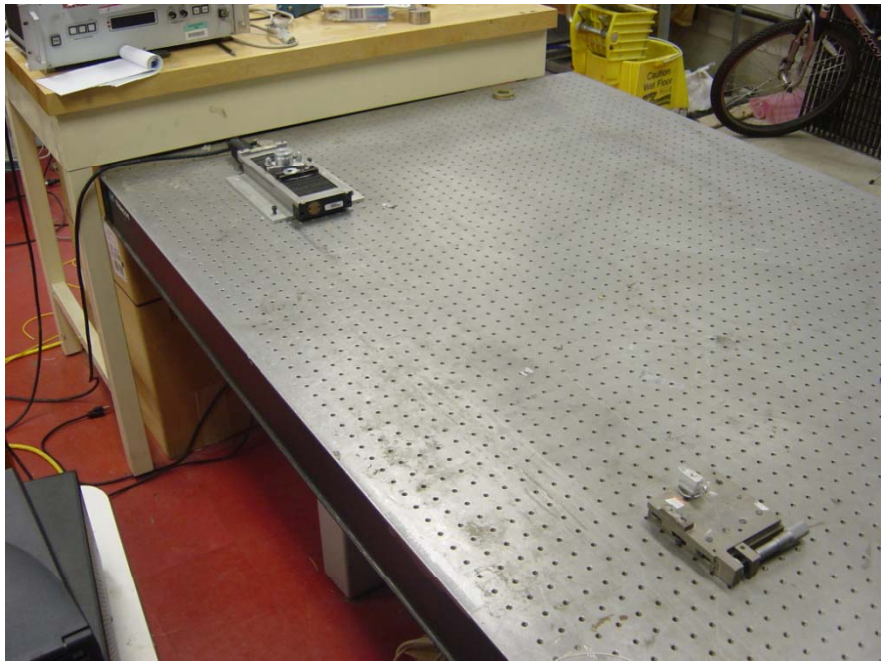
$$\Delta\nu_B(\varepsilon) = \nu_B(\varepsilon) - \nu_B(0)$$

$$\nu_B(\varepsilon) = C_\varepsilon\varepsilon + \nu_B(0)$$

$$\varepsilon = \frac{1}{C_\varepsilon}[\nu_B(\varepsilon) - \nu_B(0)]$$

$$\Delta l = \int_0^l \varepsilon(x)dx$$

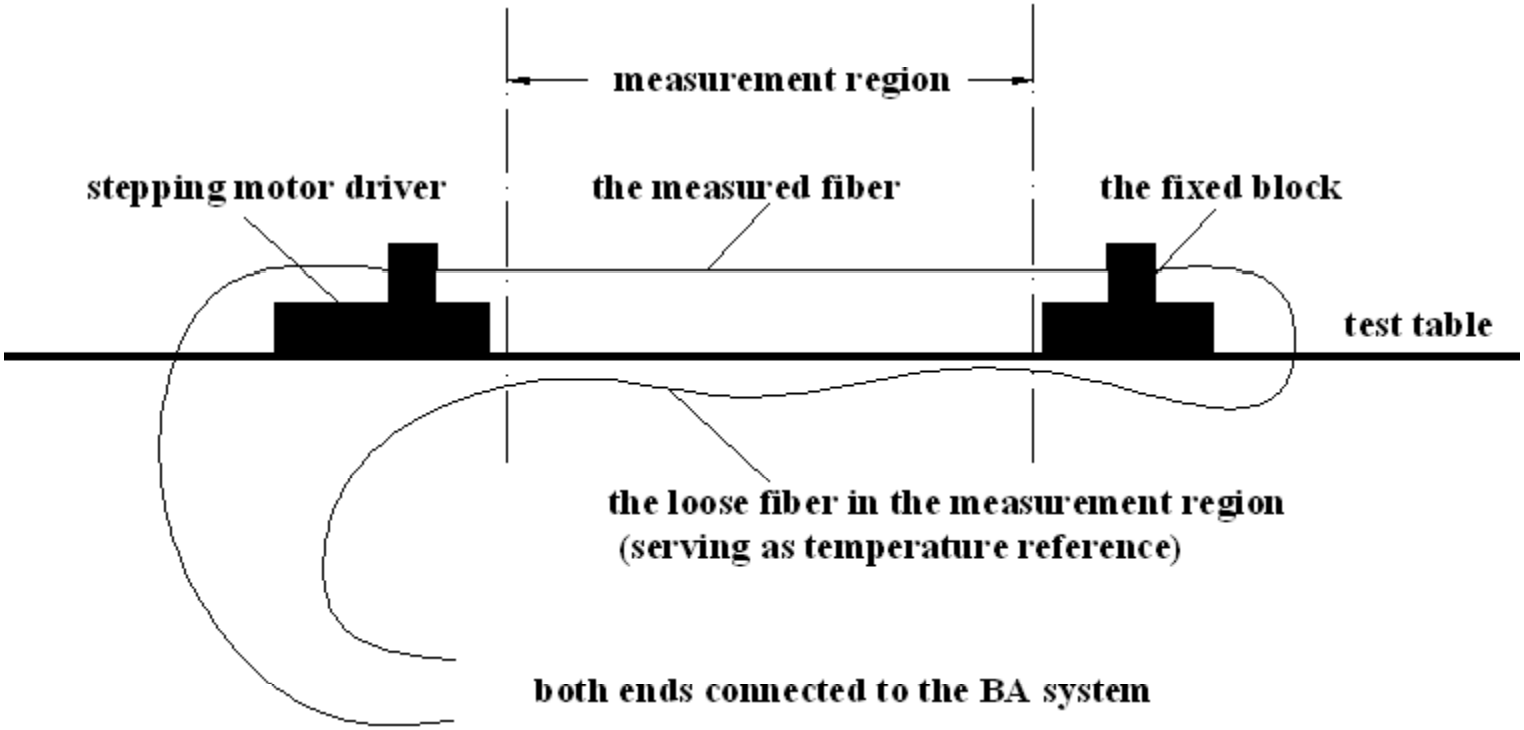
Strain Calibration Test Set-up



(a) (b)

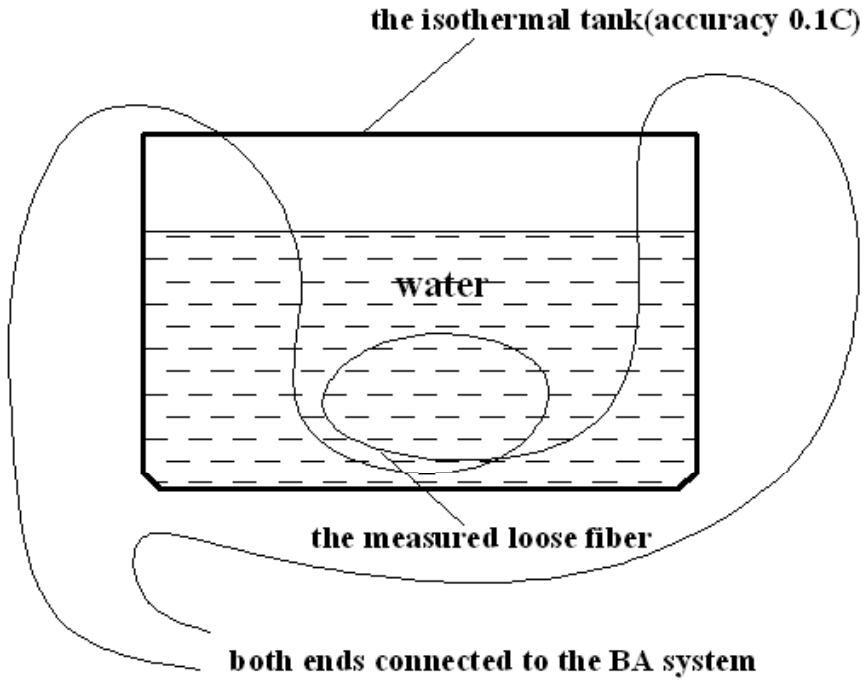
Measurement set-up for strain coefficient:(a) Stepper motor driver;
(b) Programmable controller (accuracy 1µm)

Test Set-up



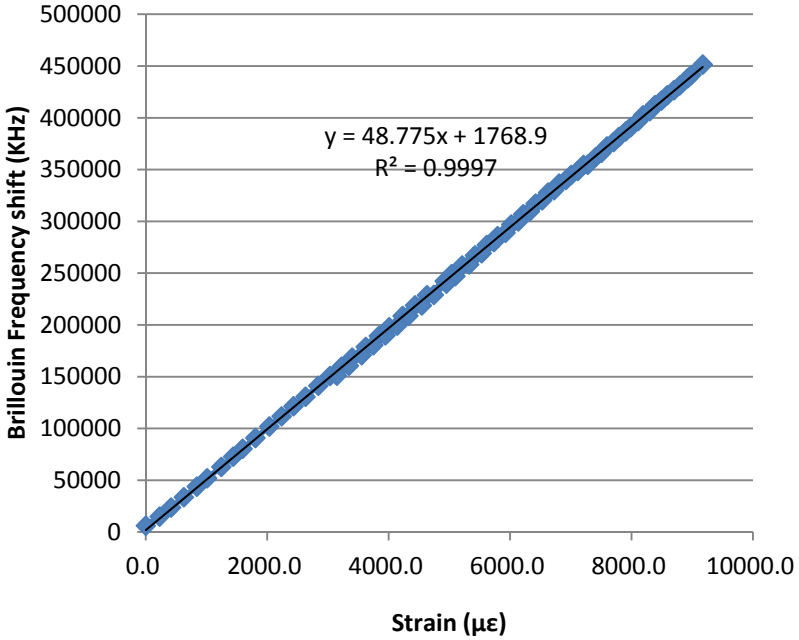
Schematic of the measuring set-up
for strain coefficient

Temperature Calibration Test Set-up

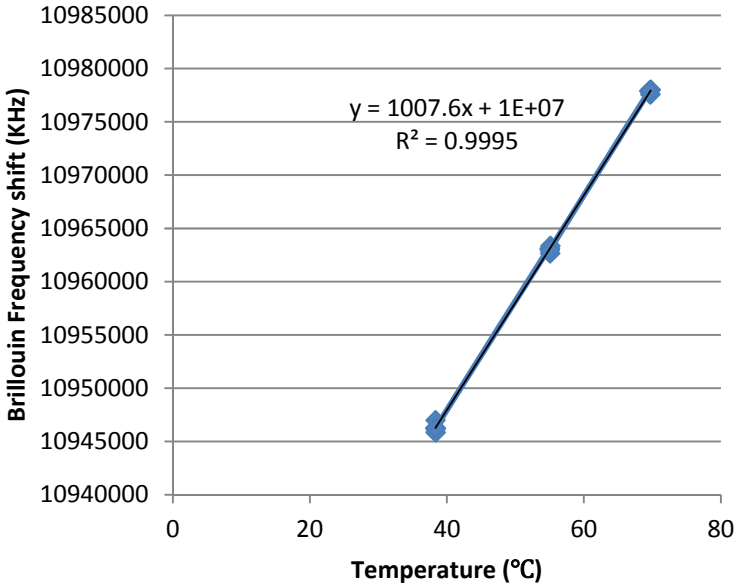


Measurement set-up for temp. coefficient

Results for Calibration Test



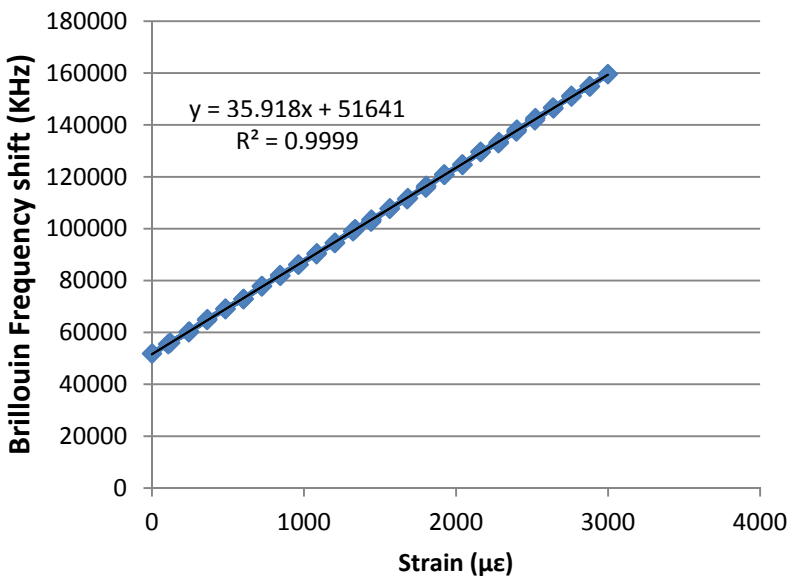
(a)

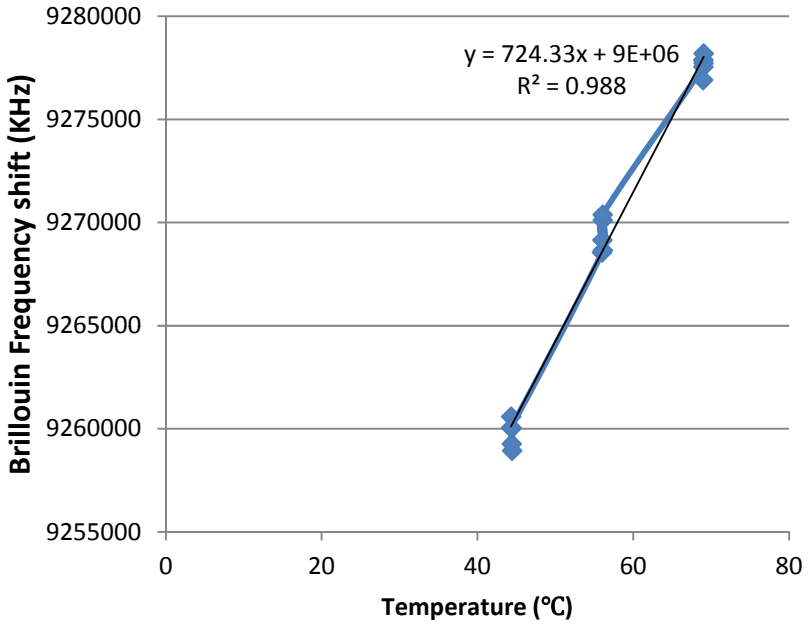


(b)

Calibration results for the SMF28 fiber
(a) Strain coefficient;(b) Temp. coefficient

Results for Calibration Test

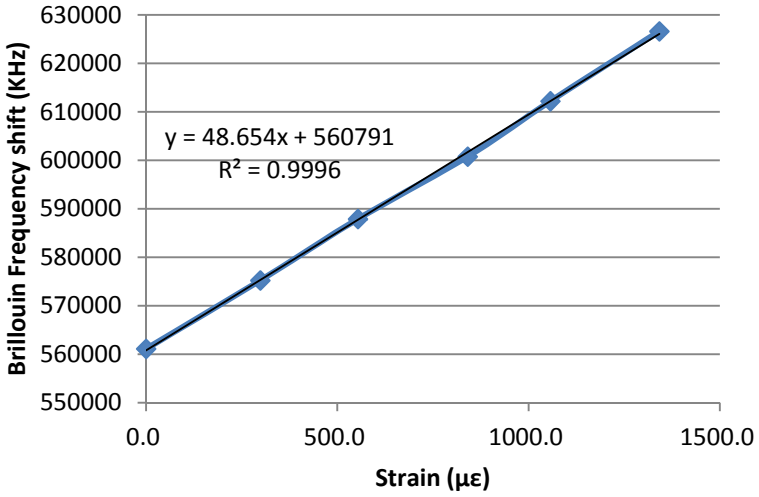




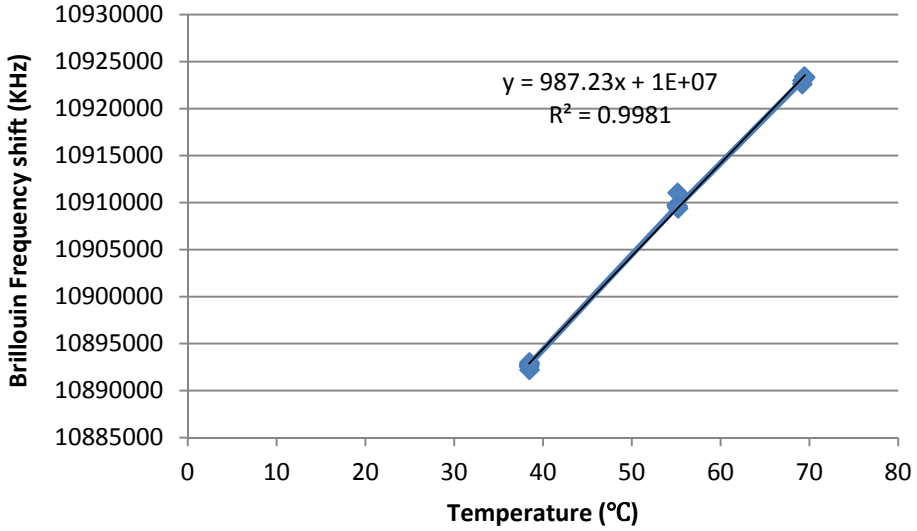
(a) (b)

Calibration results for the HN fiber
(a) Strain coefficient;(b) Temp. coefficient

Results for Calibration Test



(a)



(b)

Calibration results for the PM1550-HP fiber
(a) Strain coefficient;(b) Temp. coefficient

Results for Calibration Test

Fiber types	Strain Coefficient (kHz/με)	Temperature Coefficient (kHz/T)
SMF 28	48.77	1007
HN fiber	35.91	724.3
PM1550-HP	48.65	987.2

BOTDR TEST

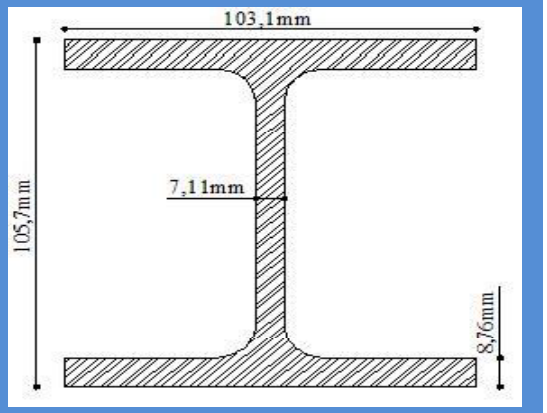
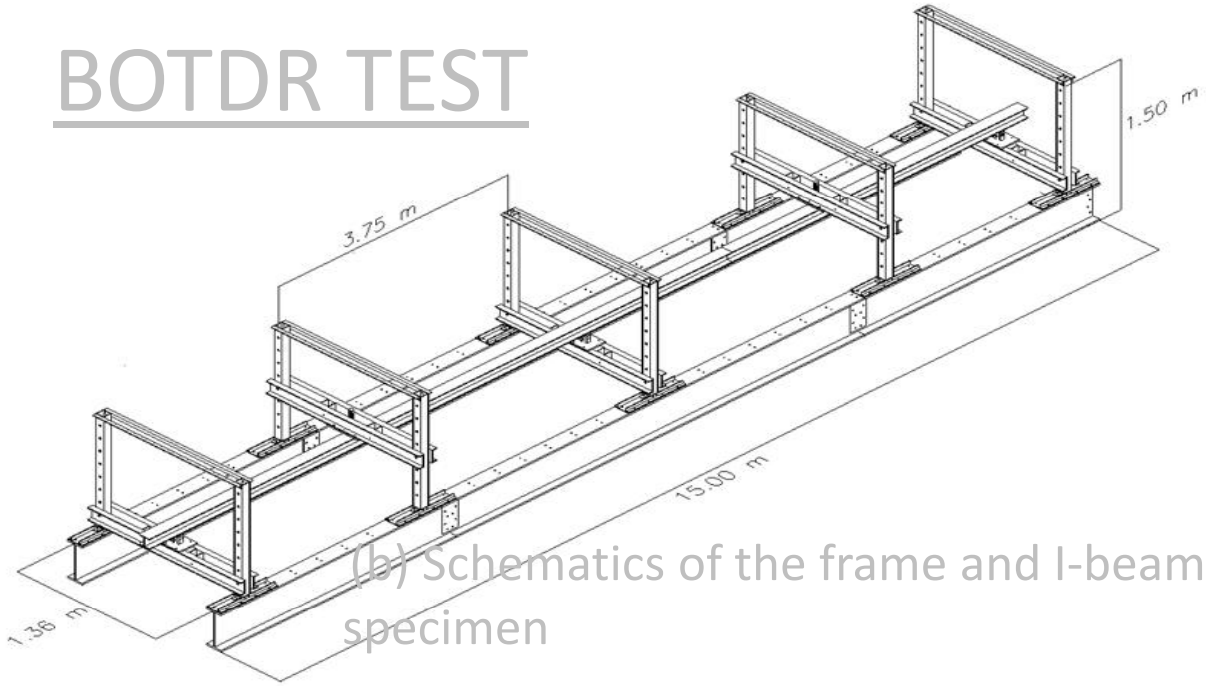
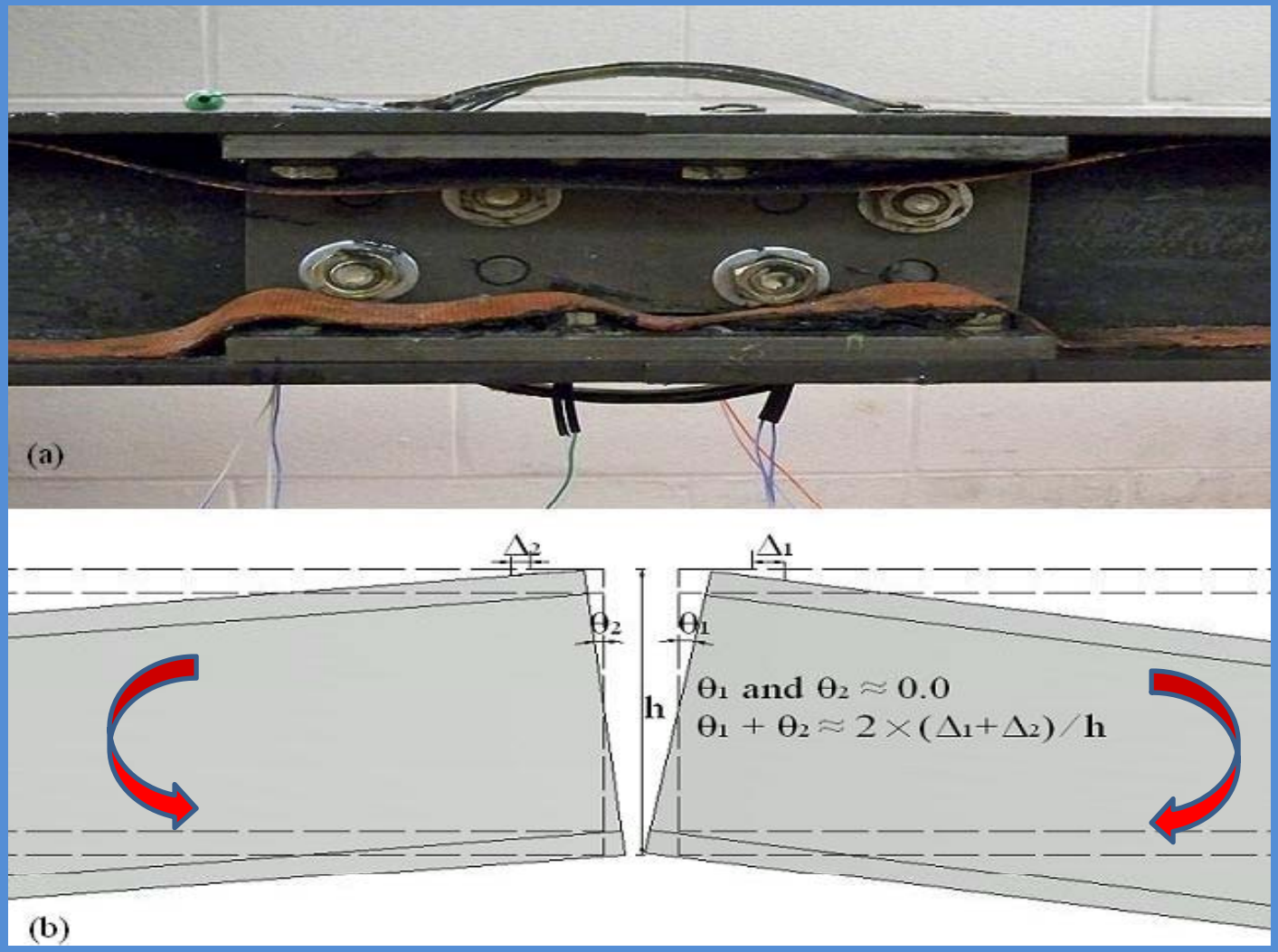


Fig.3 (a) Cross section of test specimen

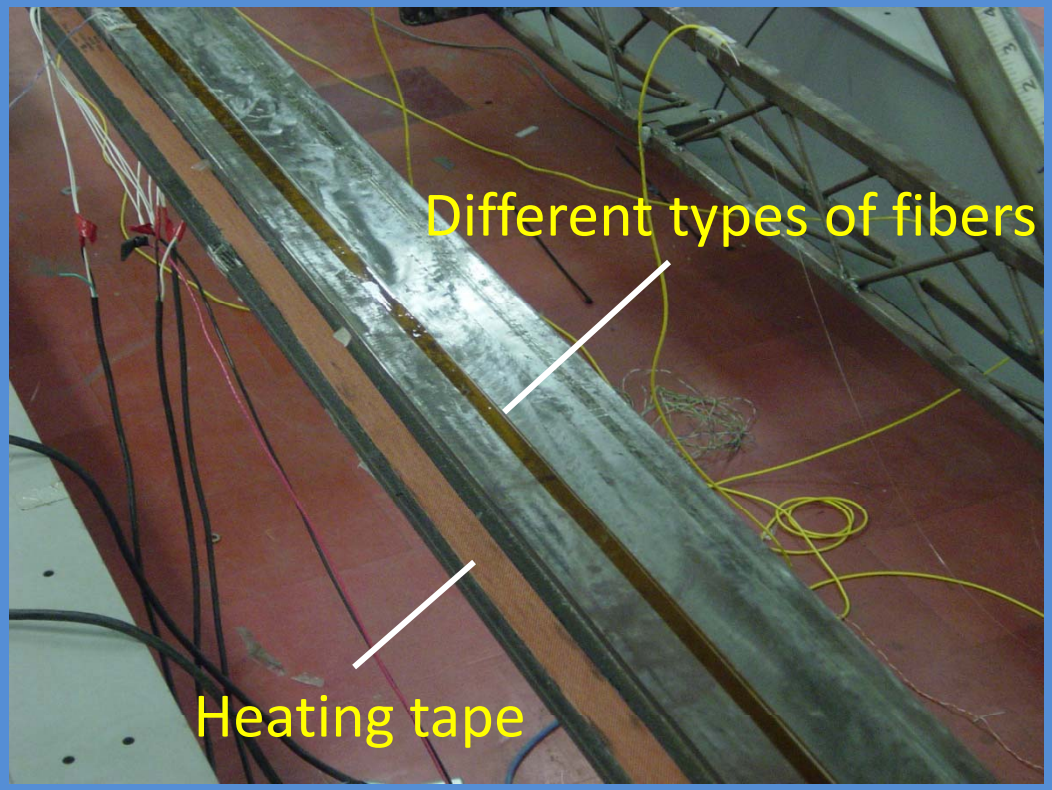


(b) Schematics of the frame and I-beam specimen

(c) The manufactured frame


(a)
Δ2
Δ1
θ2
θ1
h
θ1 and θ2 ≈ 0.0
θ1 + θ2 ≈ 2 × (Δ1+Δ2) / h
(b)

Beam test on different types of fibers

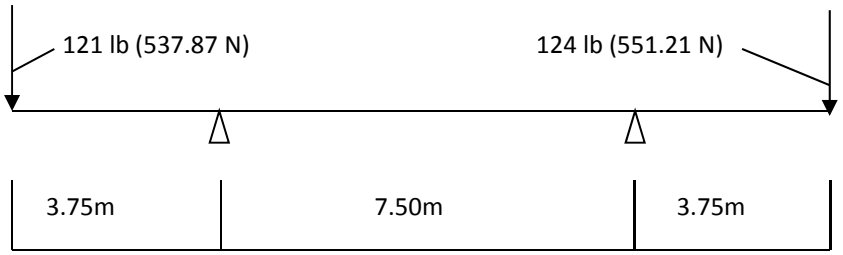


Tested fibers on the upper surface of beam

Test cases

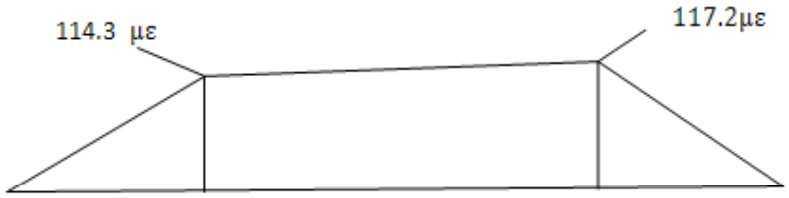
No.	loading pattern	loading forces F1,F2(lbs)	temperature (℃)	spatial resolution (cm)	sensor	remarks
1	4 point bending	0,0	25	20	design 2 PM fiber	room temperature
2		121,124				
3		263,255				
4		0,0	42,25			the beam was partially heated
5		113,107				
6		256,262				
7		0,0				
8		0,0	62,25			
9		110,117				
10		248,270				
11		0,0				

Some initial results (1) - room Temp. at Low Load

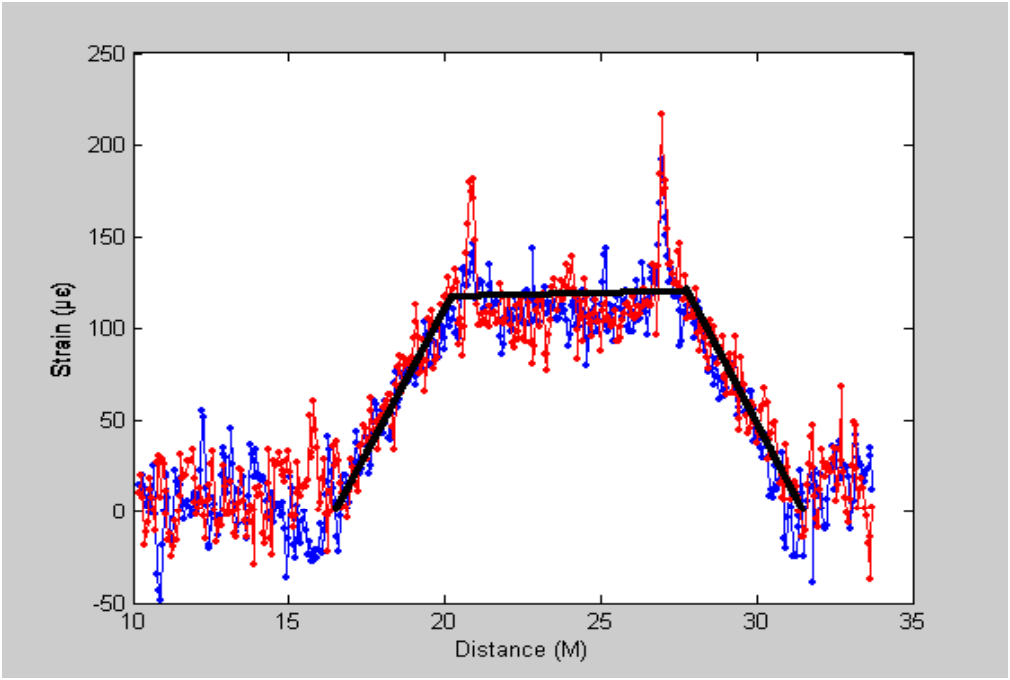


the loading plot

the moment plot

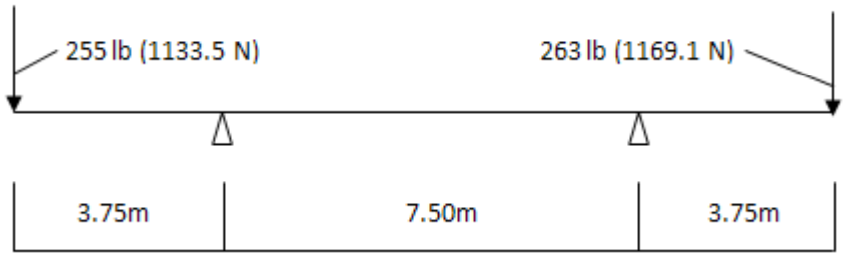


the axial strain distribution along the beam

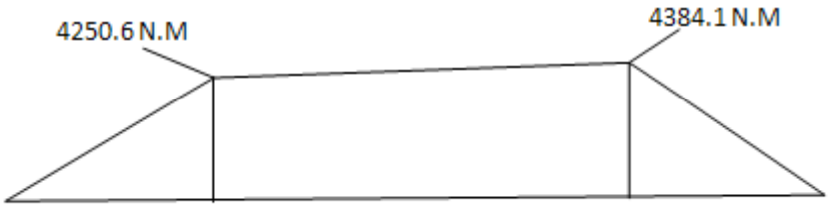


blue line is for SMF28 fiber while the red line for PM fiber (HN) with 20cm spatial resolution;

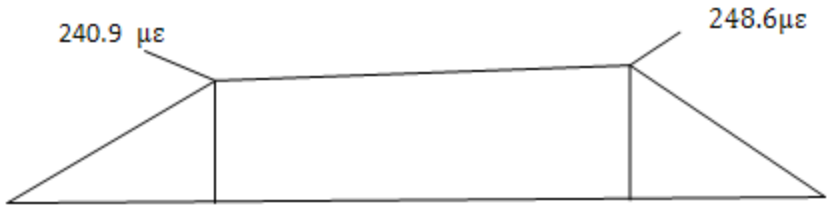
Some initial results (2) - room Temp.
At Higher Load



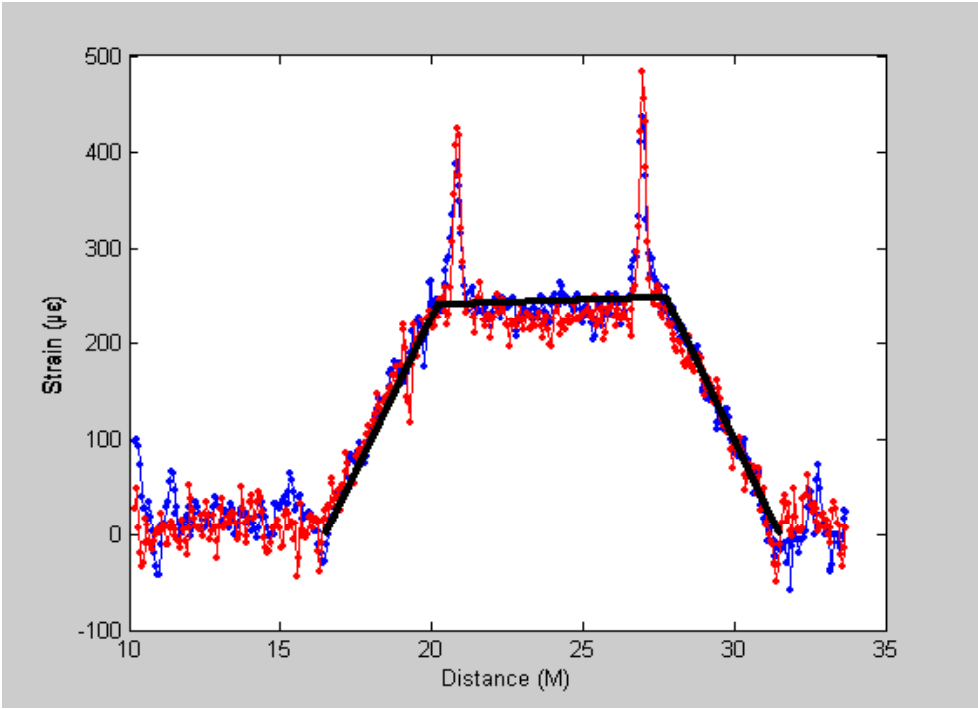
the loading plot



the moment plot

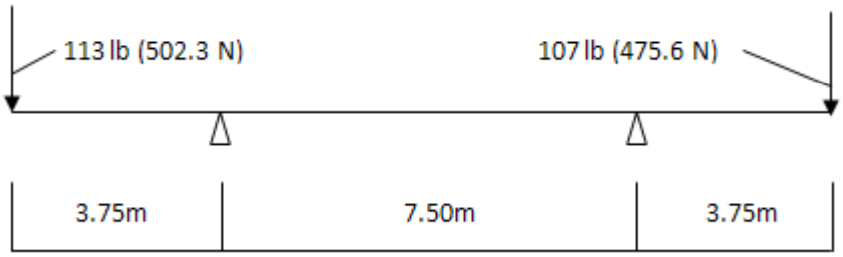


the axial strain distribution along the beam

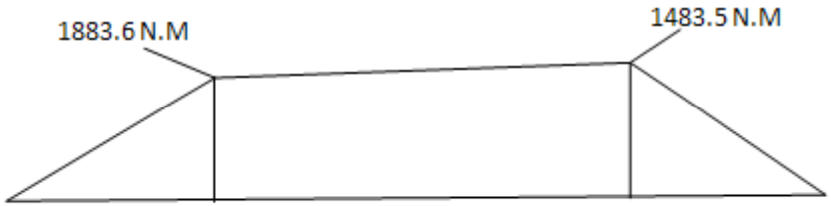


blue line is for SMF28 fiber while the red line for PM fiber(HN) <u>with 20cm spatial resolution</u>;

Some initial results (3) - partial temp. shift(from 25° C - 43.17° C) at Low load

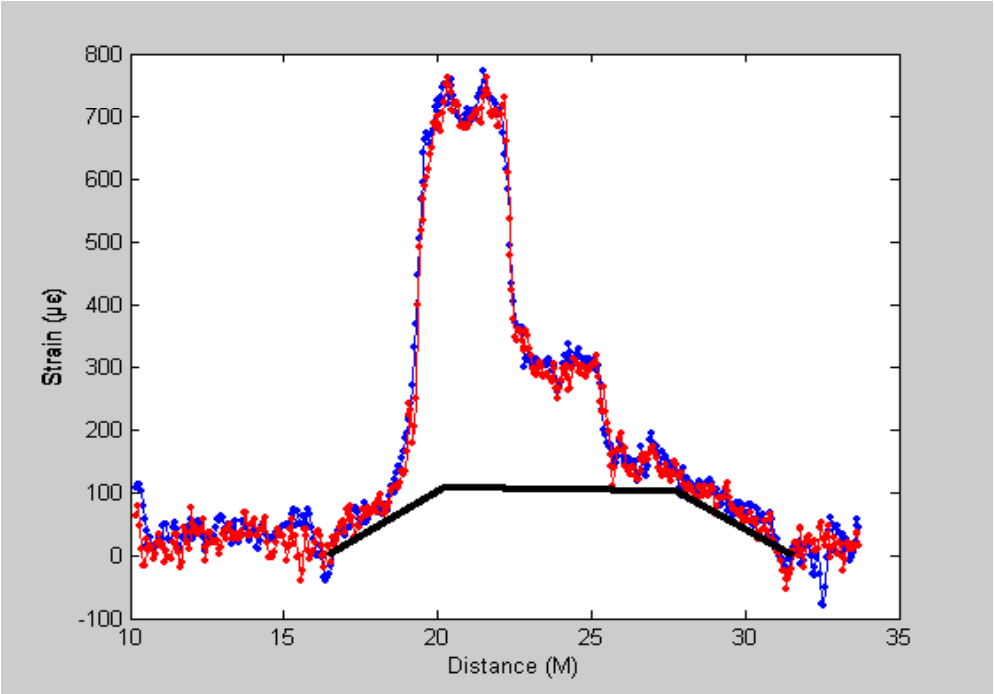


the loading plot



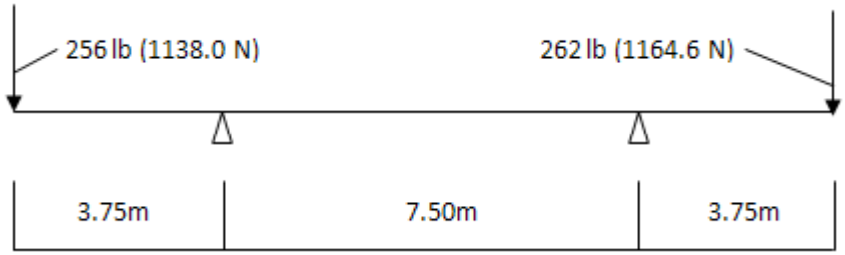
the moment plot

the axial strain distribution along the beam

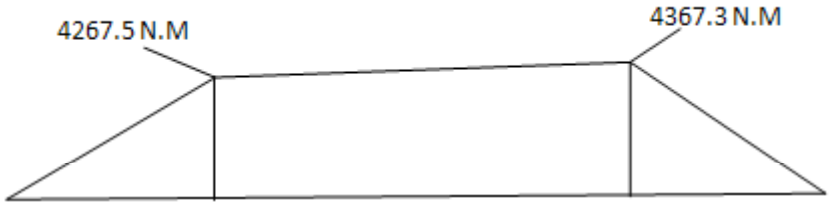


, the blue line is for SMF28 fiber while the red line for PM fiber(HN) with 20cm spatial resolution;

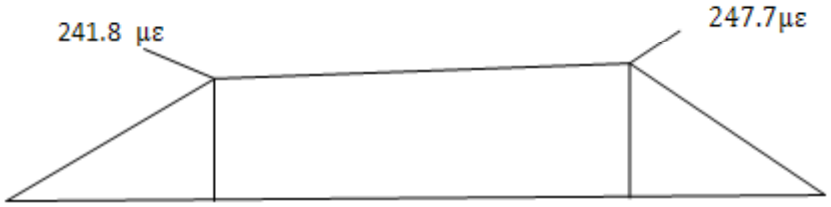
Some initial results(4)-partial temp. shift(from 25°C-43.64°C) at Higher Load



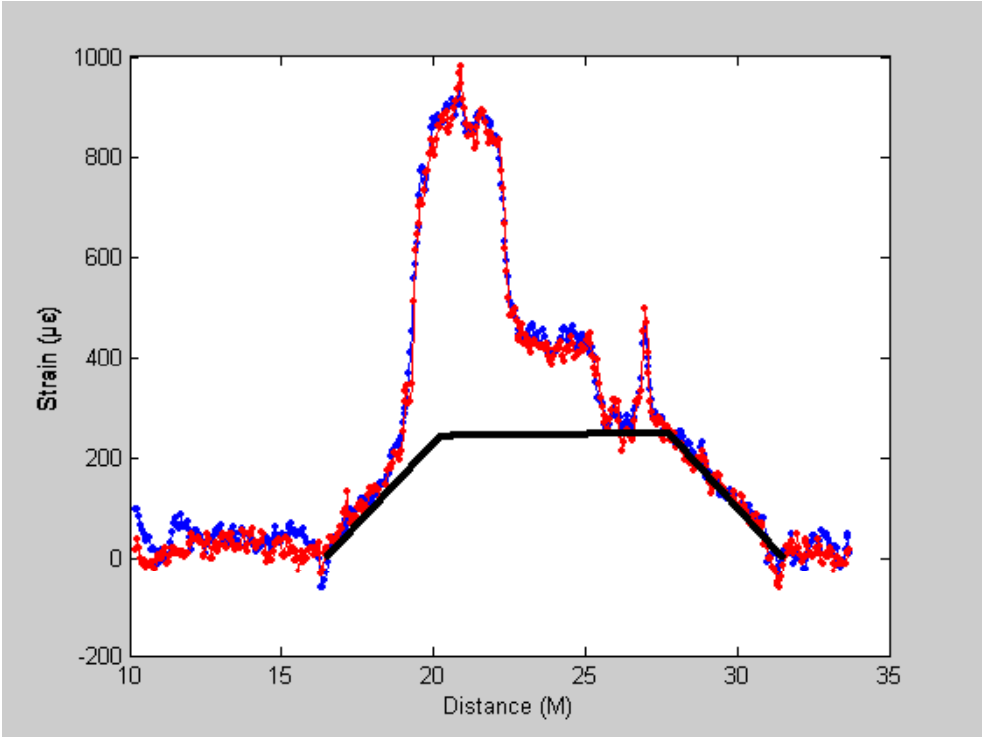
the loading plot



the moment plot

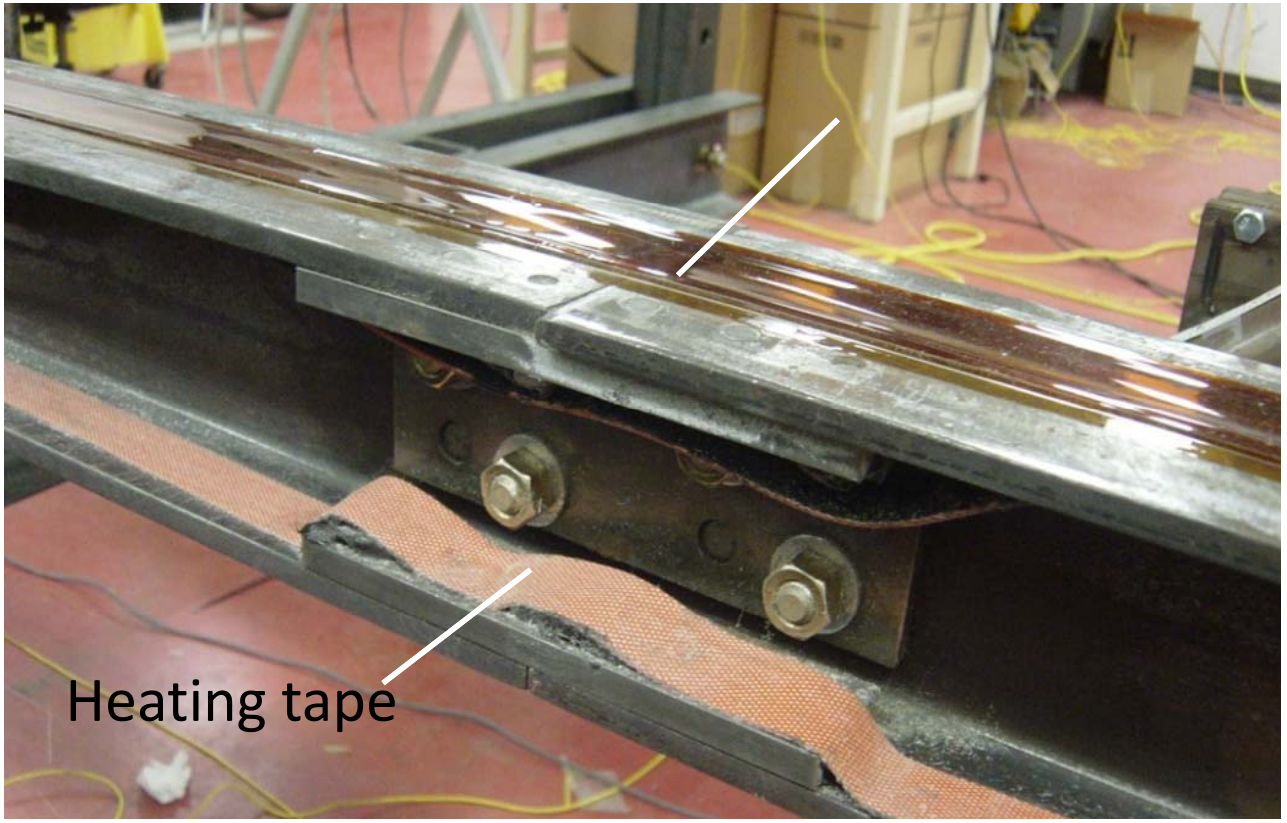


the axial strain distribution along the beam



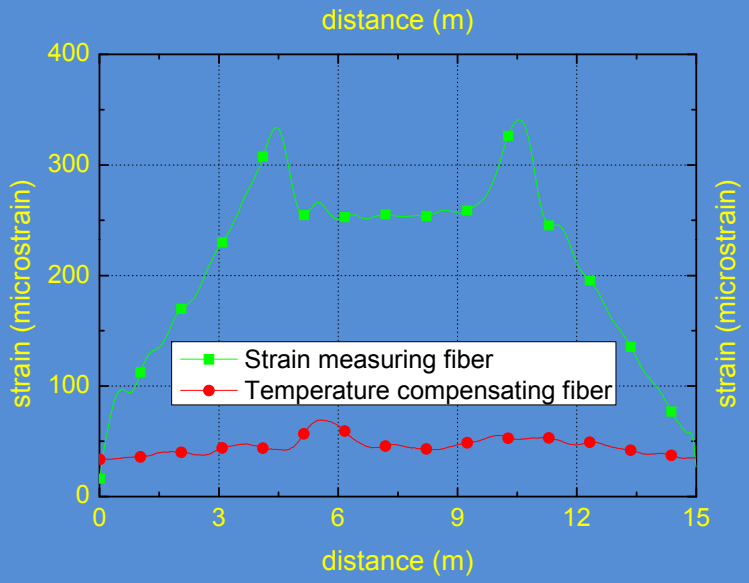
the blue line is for SMF28 fiber while the red line for PM fiber(HN) with 20cm spatial resolution

Beam test with
with Loose Fiber Temperature Compensation

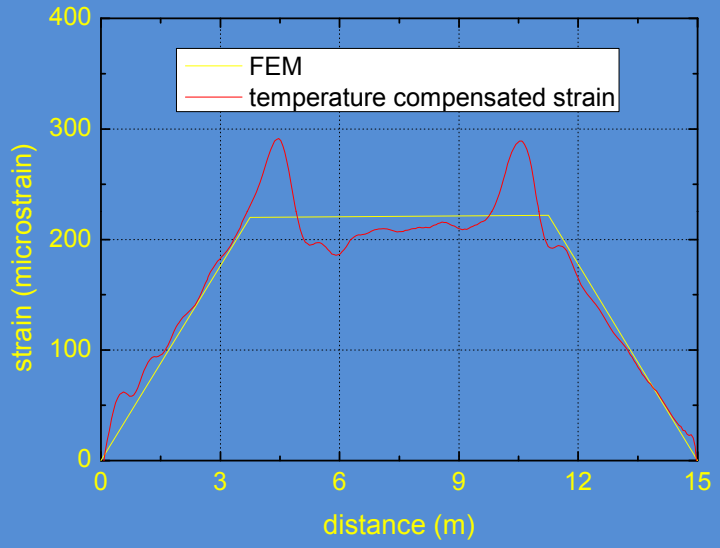


Temp compensated sensor

Test result 1 – no Temp. Gradient



(a)

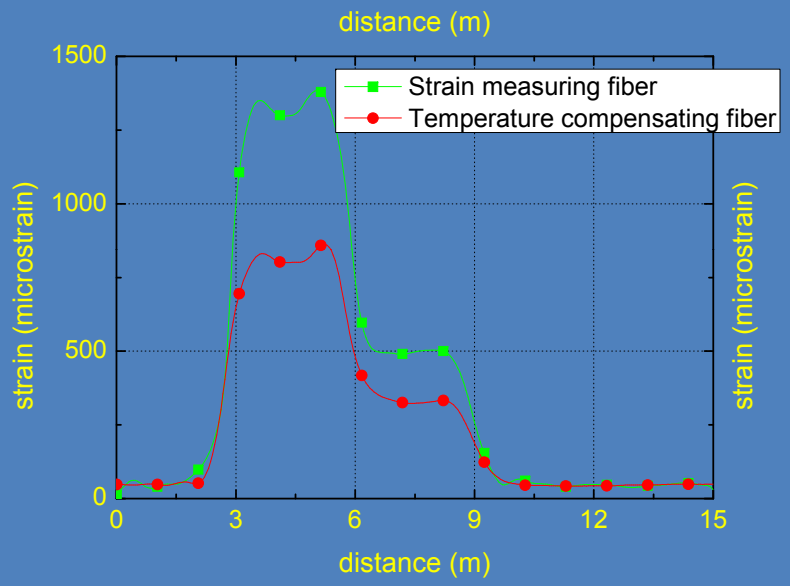


(b)

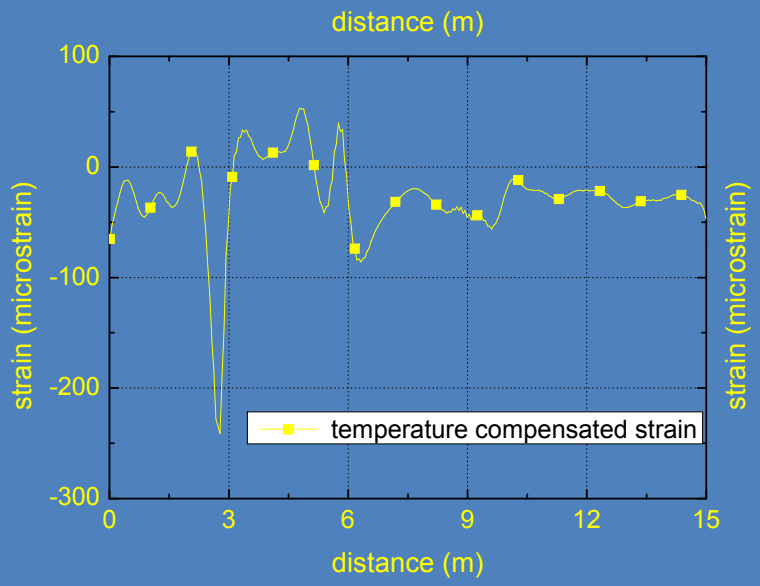
Beam-test result, loading only, without heating (random room temp. fluctuation) conditions:

(a) results of both the strain fiber and the temperature compensating fiber;
(b) temperature compensated strain distribution

Test result 2 – Only Thermal Gradients -no loads applied



(a)



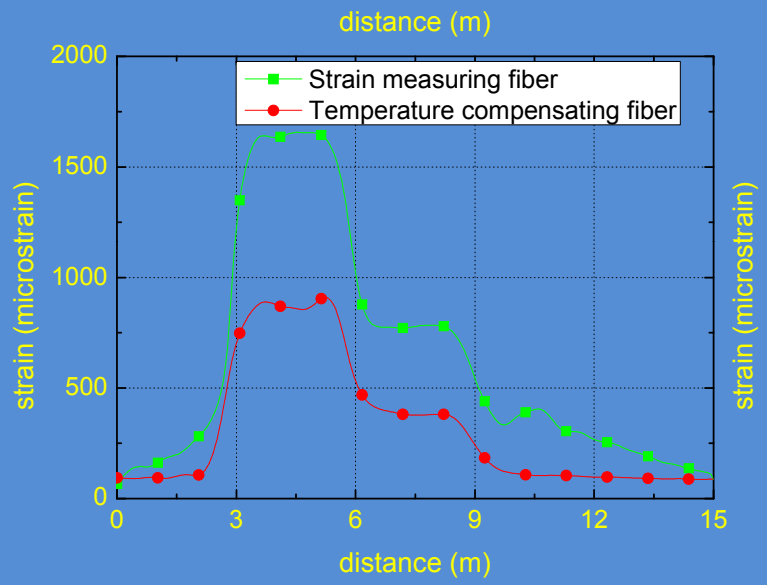
(b)

Beam-test result, heating only, without load:

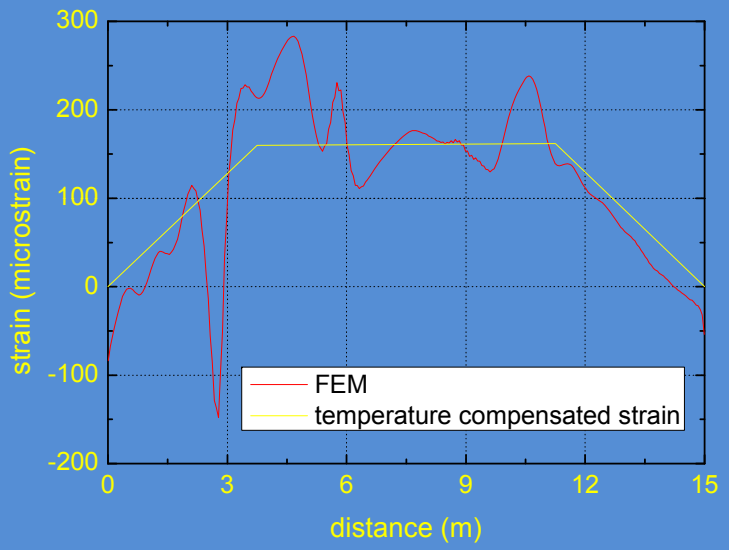
(a) results of both the strain fiber and the temperature compensating fiber;

(b) temperature compensated strain distribution

Test result 3 – load & Temp.



(a)

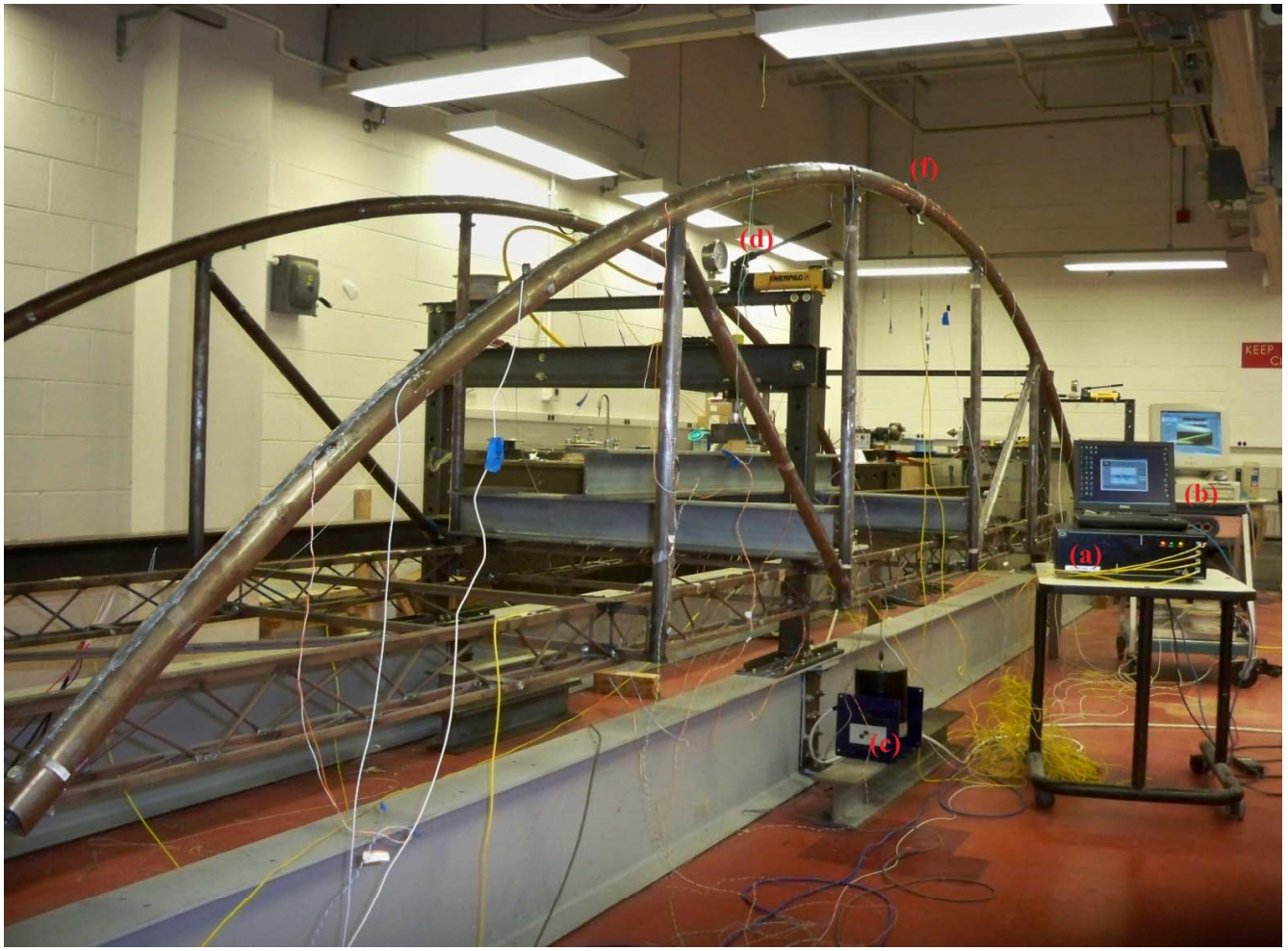


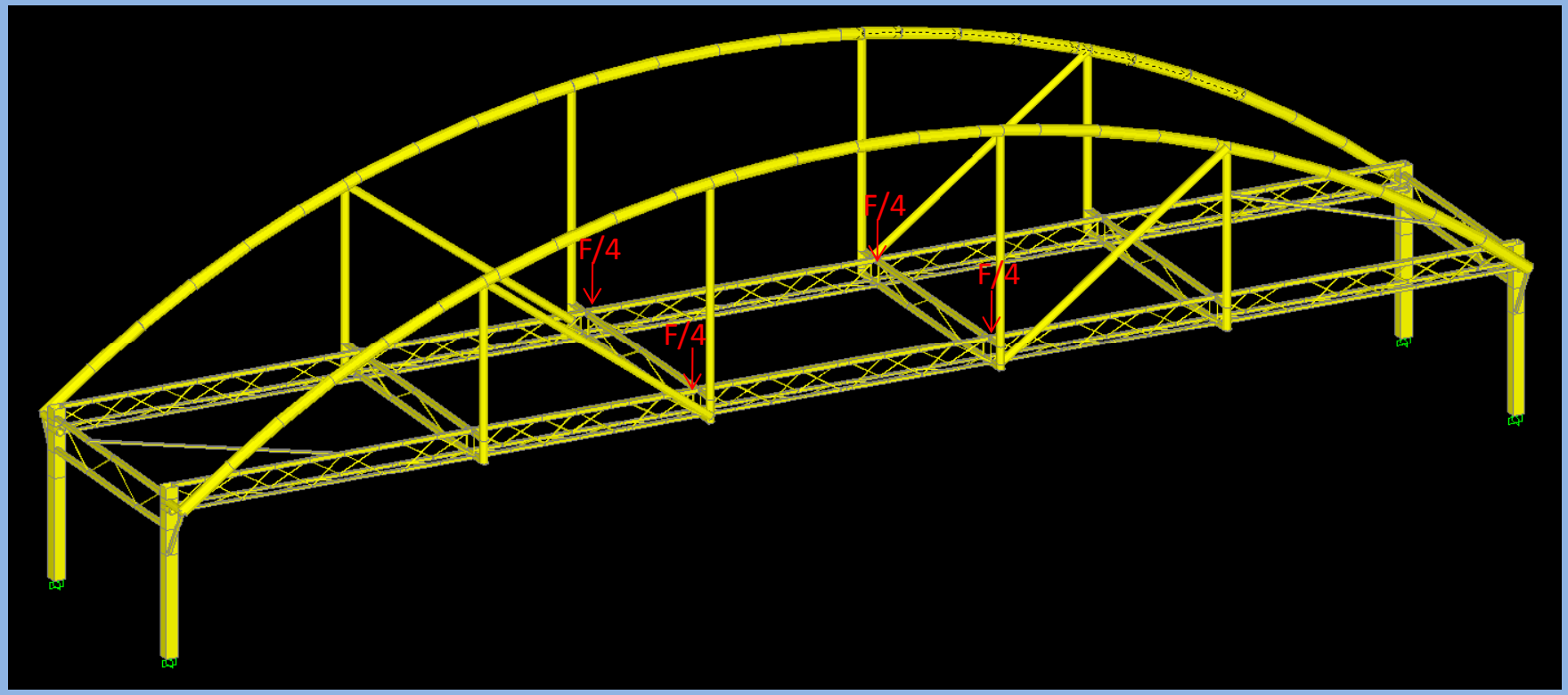
(b)

Beam-test result, both heating & load applied:

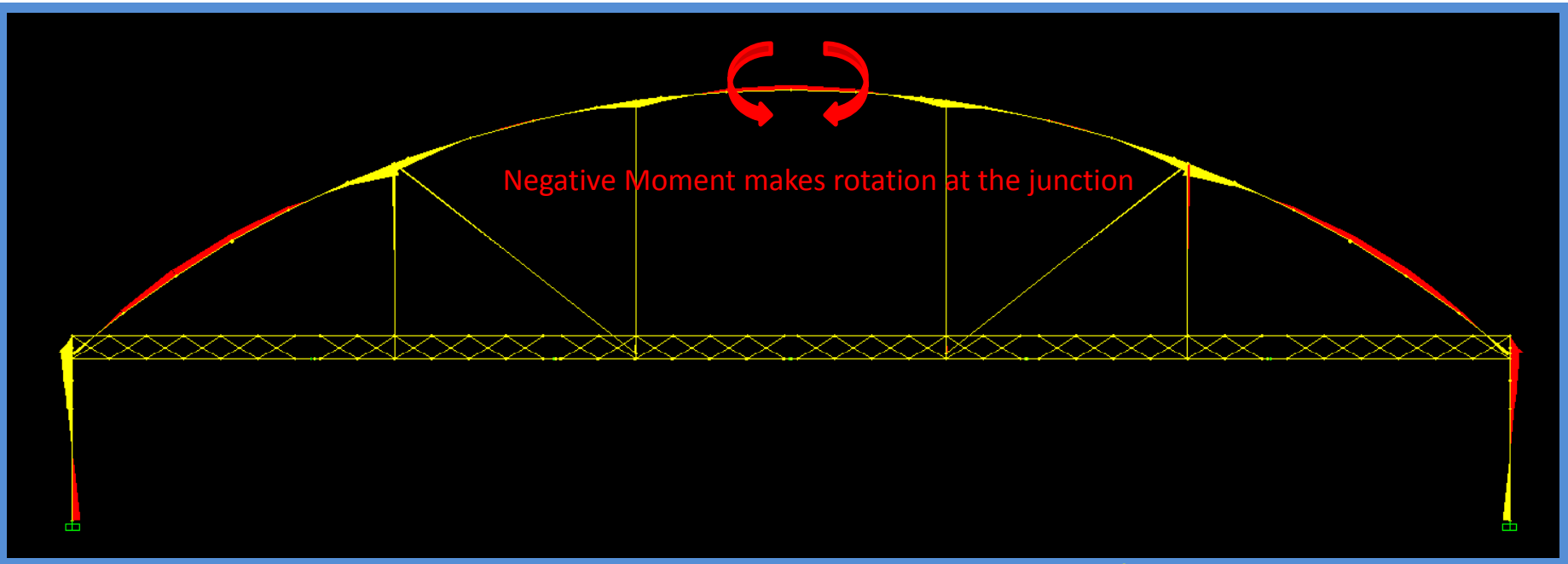
(a) results of both the strain fiber and the temperature compensing fiber; (b) temperature compensated strain distribution

Steel Arch Truss Bridge:



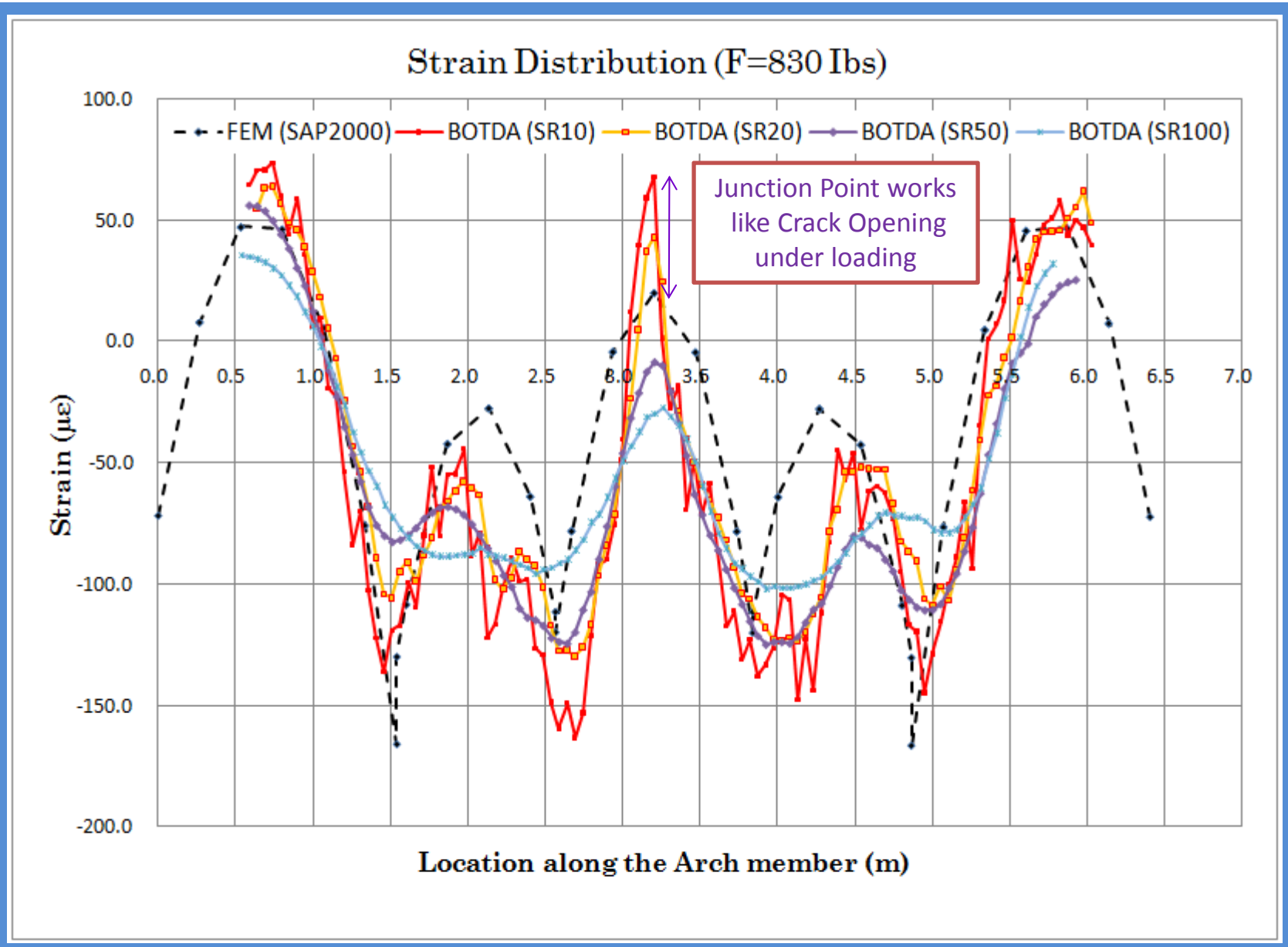


Finite element Model of Steel Arch Bridge

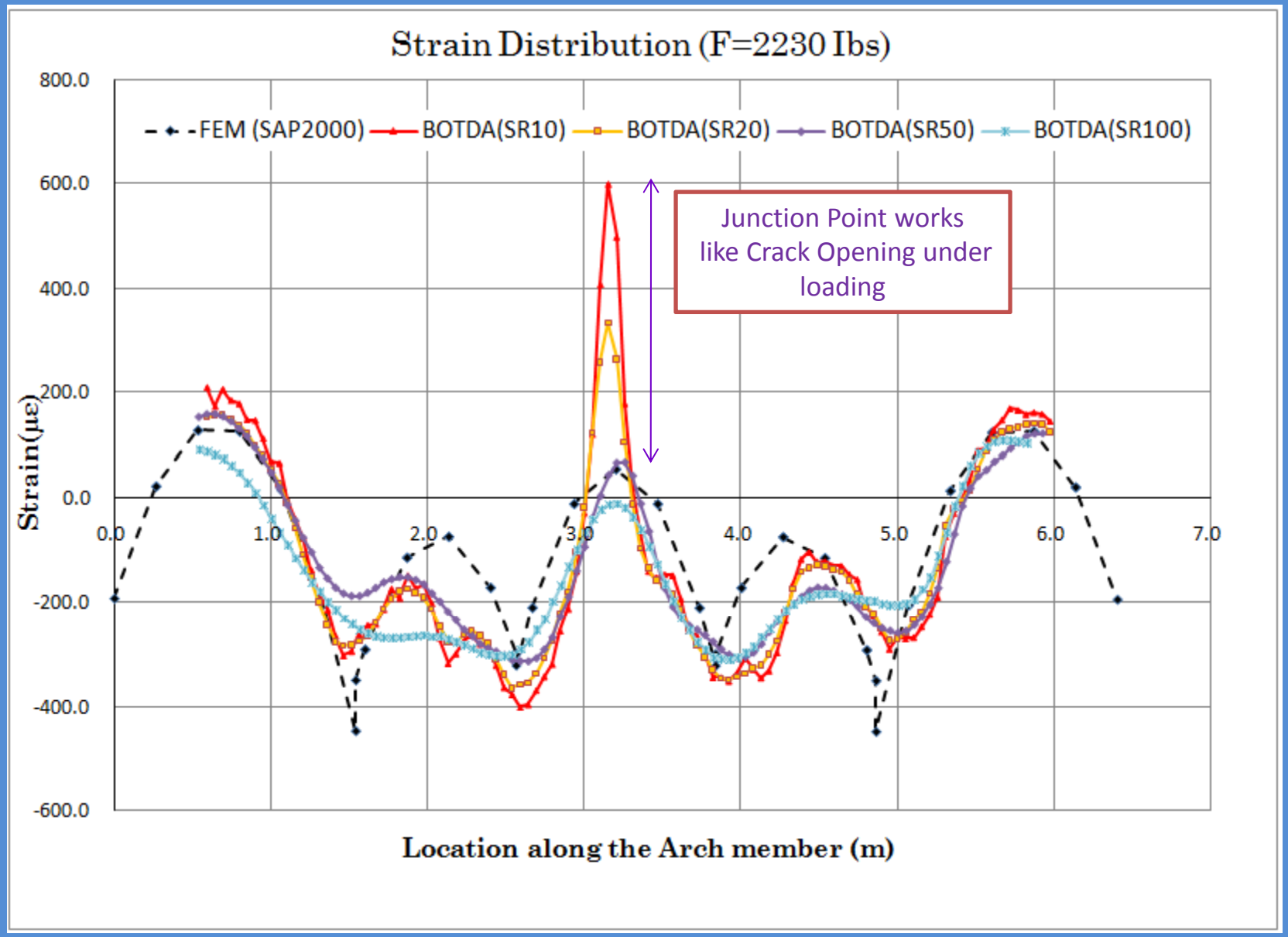


Moment Distribution along the Arch member of bridge (Finite Element Model, with solid junction assumption)

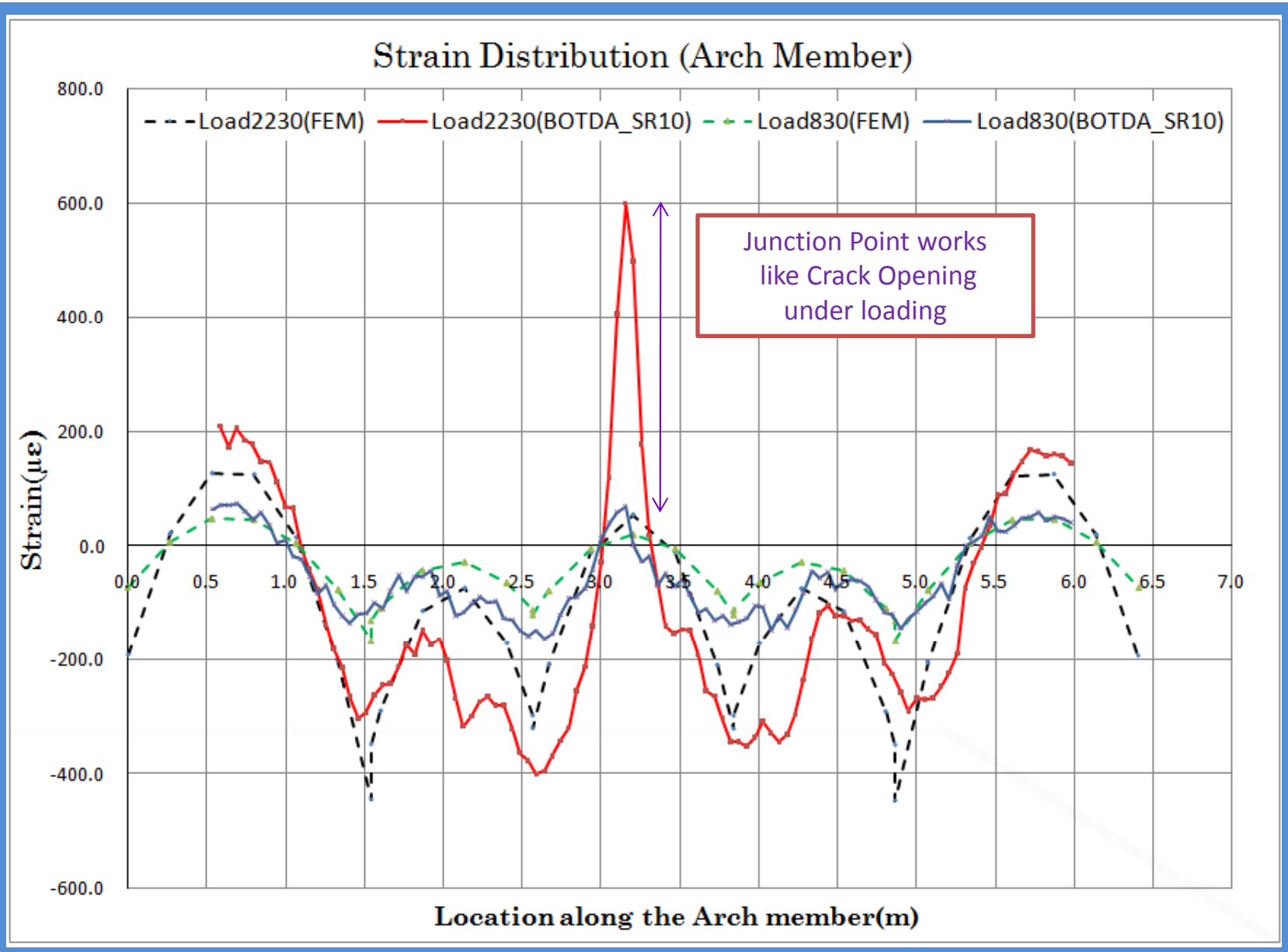
Junction Point ,which works
like Crack due to Loading in reality,
at the Arch Crown



Strain Distribution of the Arch member for Different Spatial Resolution= 10, 20, 50, 100 cm



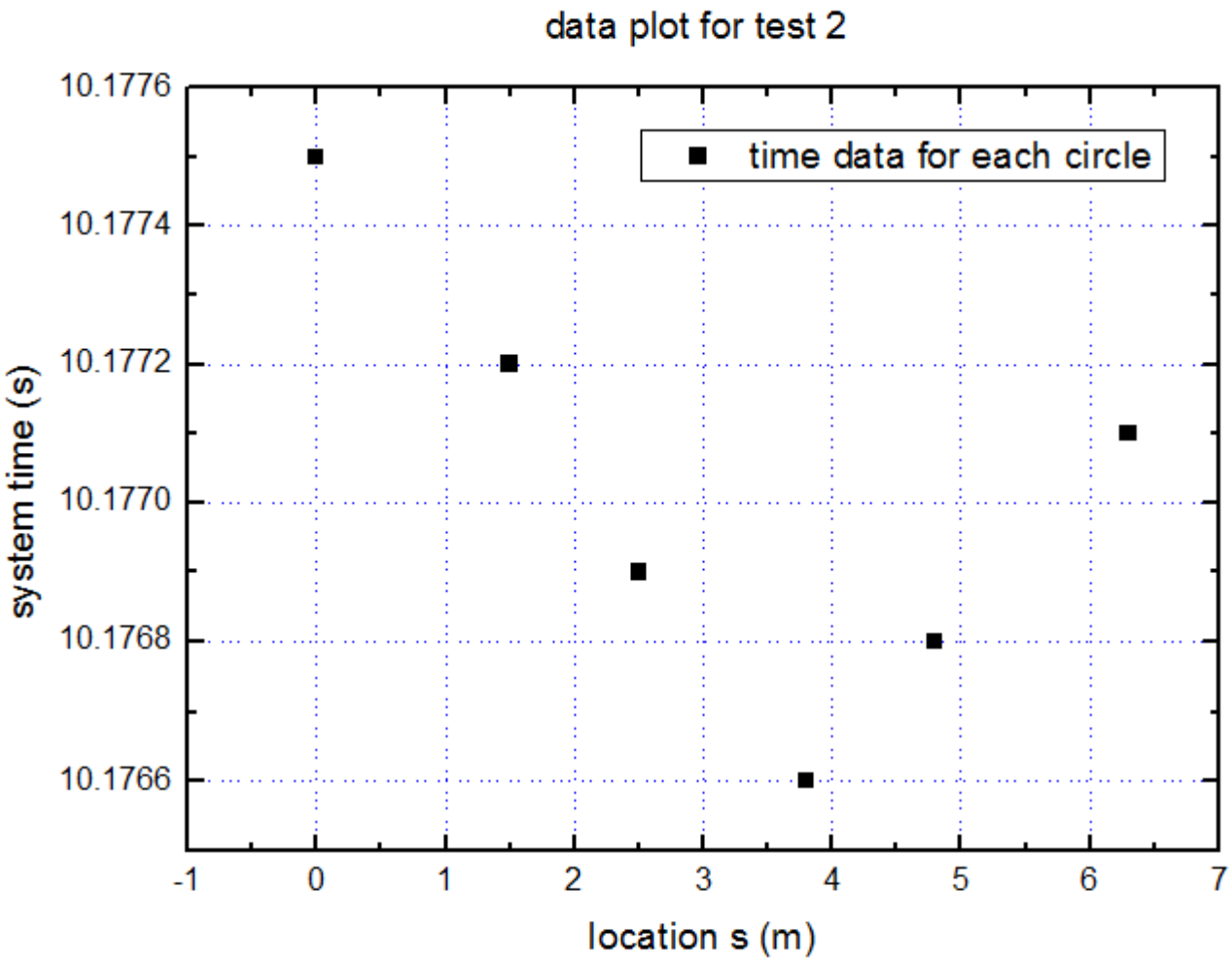
Strain Distribution of the Arch member for Different Spatial Resolution= 10, 20, 50, 100 cm



Strain Distribution of the Arch member for Spatial Resolution= 10 cm

CR Test, Crack Detection with coiled fiber optic sensors

Model Bridge Test, Crack location detection:



Salt Creek Bridge in Elmhurst Illinois

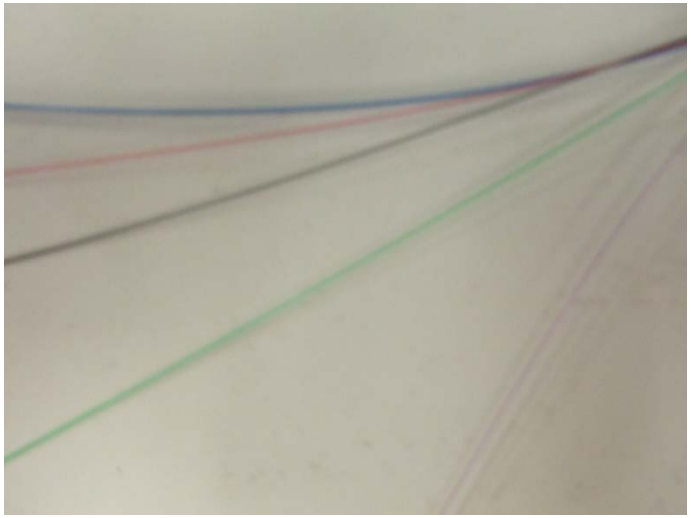
Sensor Installations – Scaffolding -Nema Enclosure- Electrical - Conduits, Junction boxes, etc.

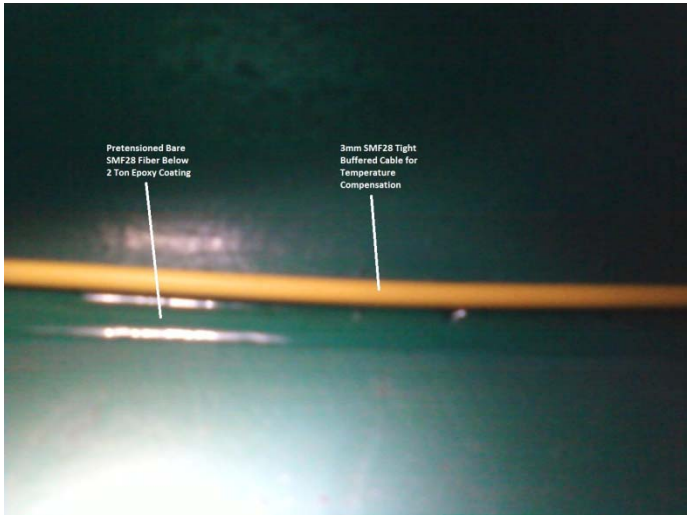
FBG Sensors

BR2 in the Field

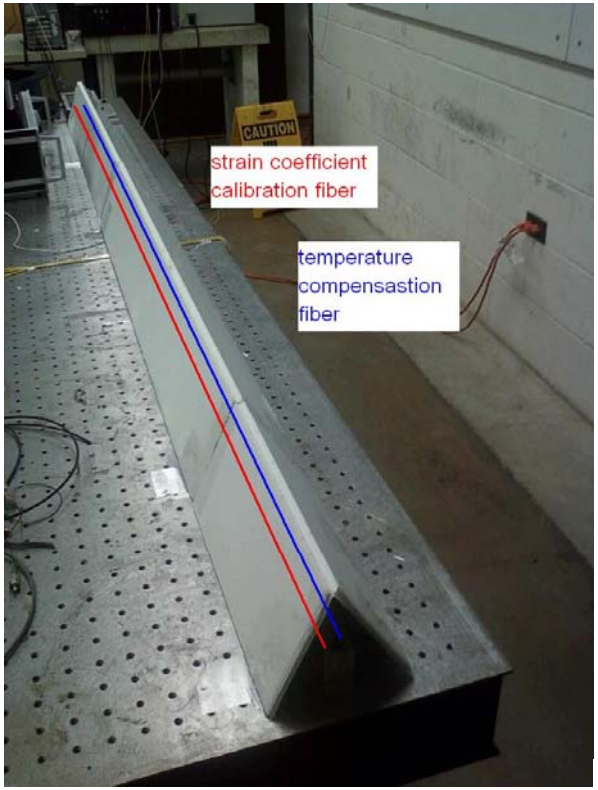
Sensors and details

- Special Fibers (‘red’ and ‘violet’ provided by Optiphase)
- Corning’s Single Mode Fiber SMF-28





Laboratory tests on Optiphase Ribbon Fibers

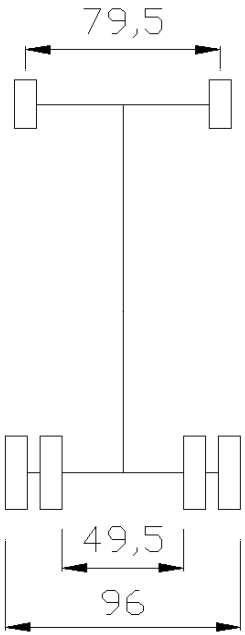


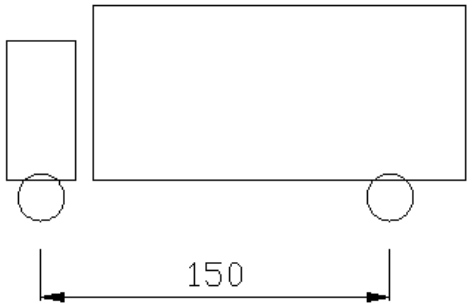
Calibration Tests:
Strain Calibration factor (left)
Temperature Calibration Factor (right)

Red: 0.0518MHz/με	1.25MHz/°C
Violet: 0.0468MHz/με	0.94MHz/°C
SMF28: ~0.05MHz/με	~1.0MHz/°C

Weigh Station at the Bridge

Calibrated Truck details

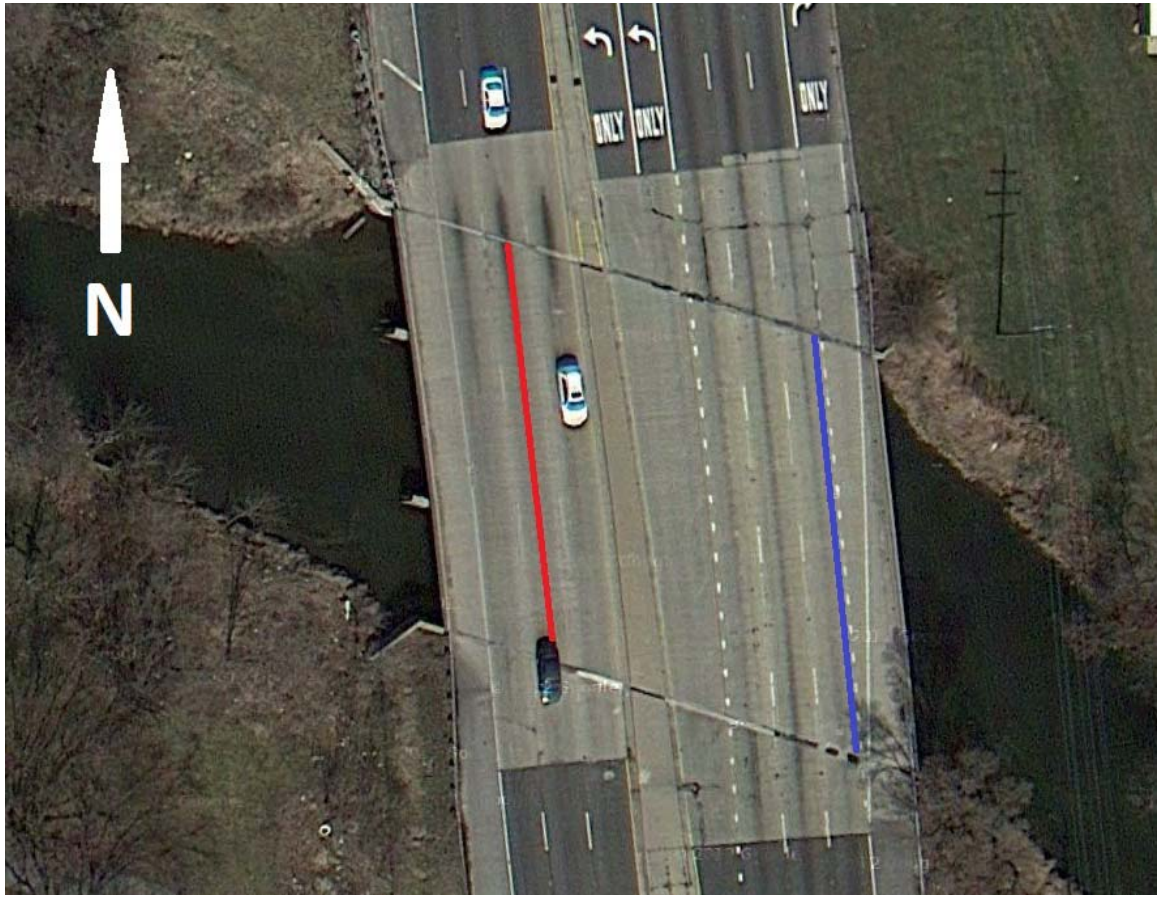




Unit: inch.

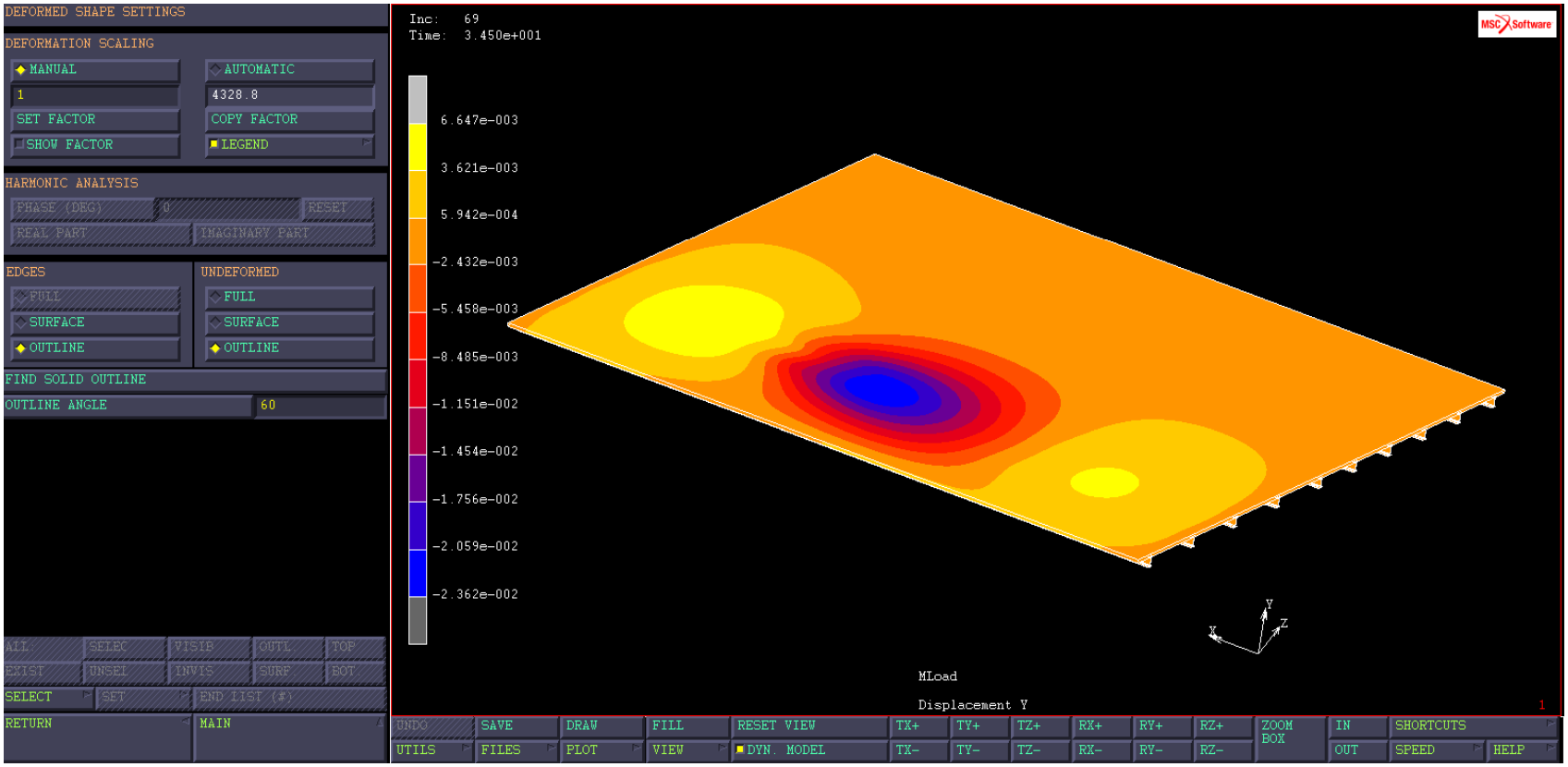
Front axle weight: 7940lbs
Rear axle weight: 11260lbs

Plan view of the Bridge

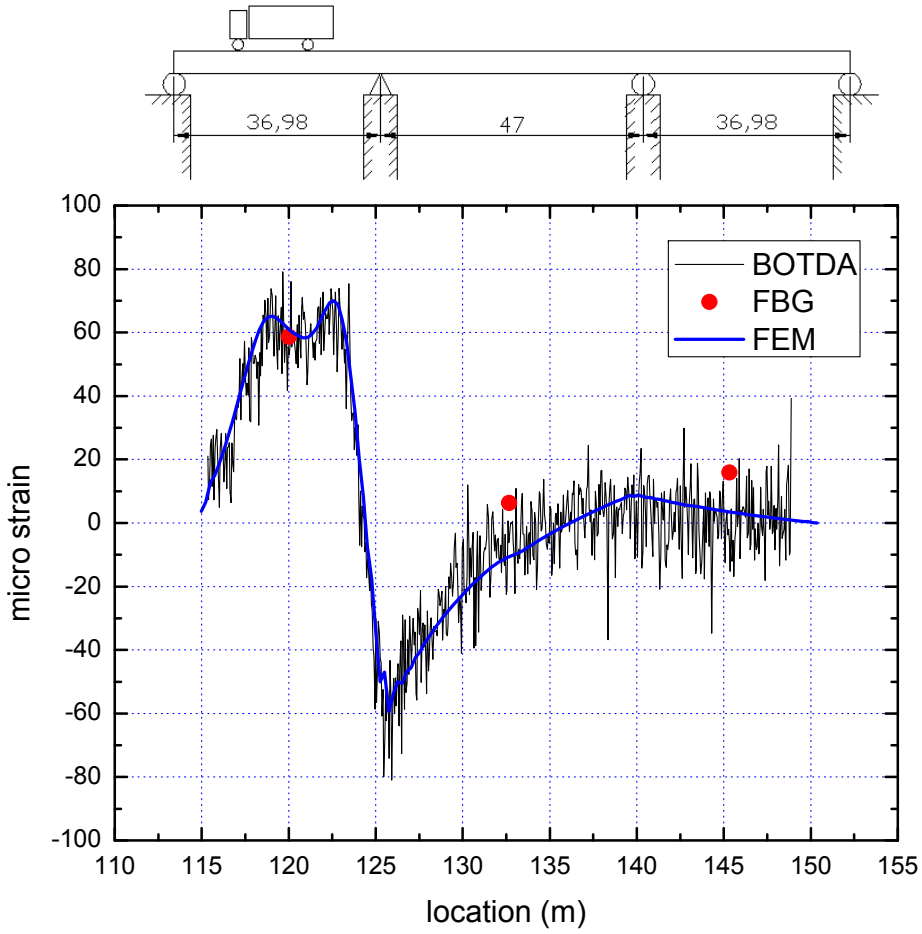


The red line and blue line are the two girders where distributed sensors and FBG sensors are installed.

FEM Analysis



Load case 3:


36,98
47
36,98
BOTDA
FBG
FEM
micro strain
location (m)
100
80
60
40
20
0
-20
-40
-60
-80
-100
110
115
120
125
130
135
140
145
150
155