NEW DEVELOPMENTS ON STRUCTURAL HEALTH MONITORING (SHM) OF EXISTING STRUCTURES

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MOTIVATION

One of the key issues in bridge maintenance systems is Structural Health Monitoring (SHM) as a tool to identify the existence of *Damage.*

A Damage Identification Procedure (DIP) comprises three main levels:

- ***Detection***
- ***Localization***
- ***Quantification***

When DIP is conducted effectively, it may prevent extensive rehabilitation and costs due to the execution of appropriate timely repairs.

SHM is of paramount interest for an optimum assessment and maintenance policy !!

NEW TECHNIQUES

- DISTRIBUTED FIBER OPTICS
- ACOUSTIC EMISSION
- DIGITAL IMAGE CORRELATION (DIC)
- OTHERS.....

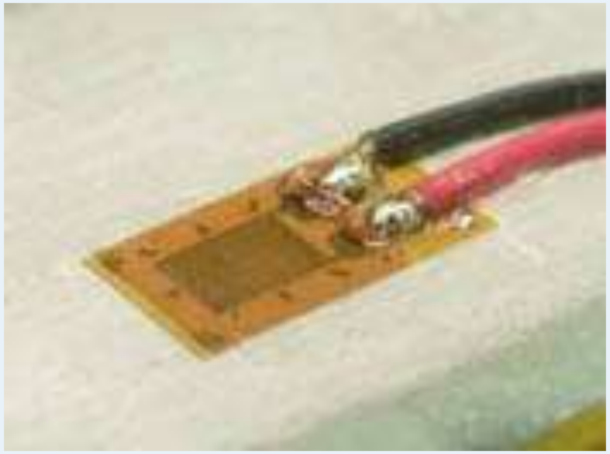
DISTRIBUTED FIBER OPTICS

Level 1 Detection (Global Identification)

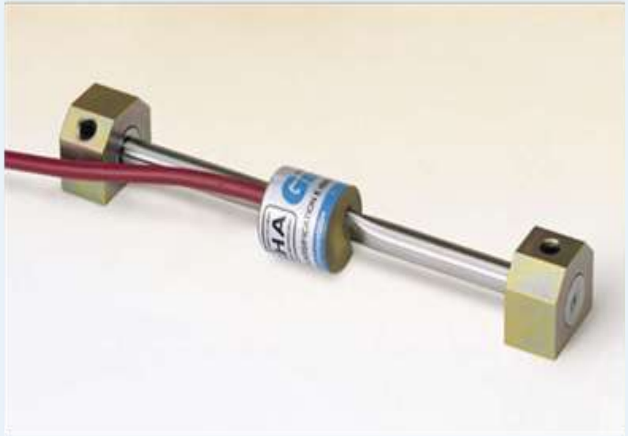
First, damage modifies the sttiffness of the structural system

Something happens: increase of deflection, change of frequencies

Discrete sensors



Strain gauge



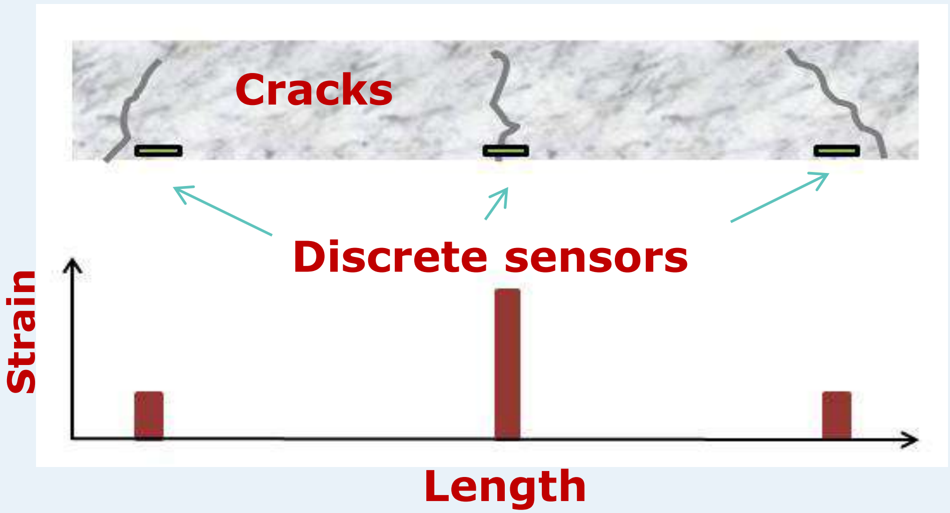
Vibrating wire

Accelerometer

Level 2 Localization (Local Identification)

Localization is an extension of damage *detection* in the process of SHM by estimating the possible damage position within the structure

Localization of damage in RC structural member (cracks) with discrete sensors is limited (*Local Identification is dificult*)



Crack detection must be based on :

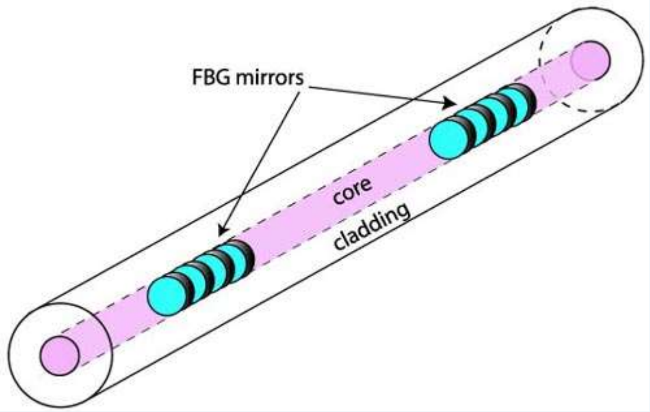
- **Visual inspection, which is time consuming, expensive and unreliable procedure.**
- **With advanced structural analysis techniques.**

►STRUCTURAL HEALTH MONITORING WITH FO SENSORS

1. **Optical instrumentation**
2. **No signal loss (5 km)**
3. **Strain accuracy (+-0.1 με)**
4. **Immunity to the EMI/RFI**
5. **Resistance to corrosive environments**
6. **Capacity to be thermally compensated**

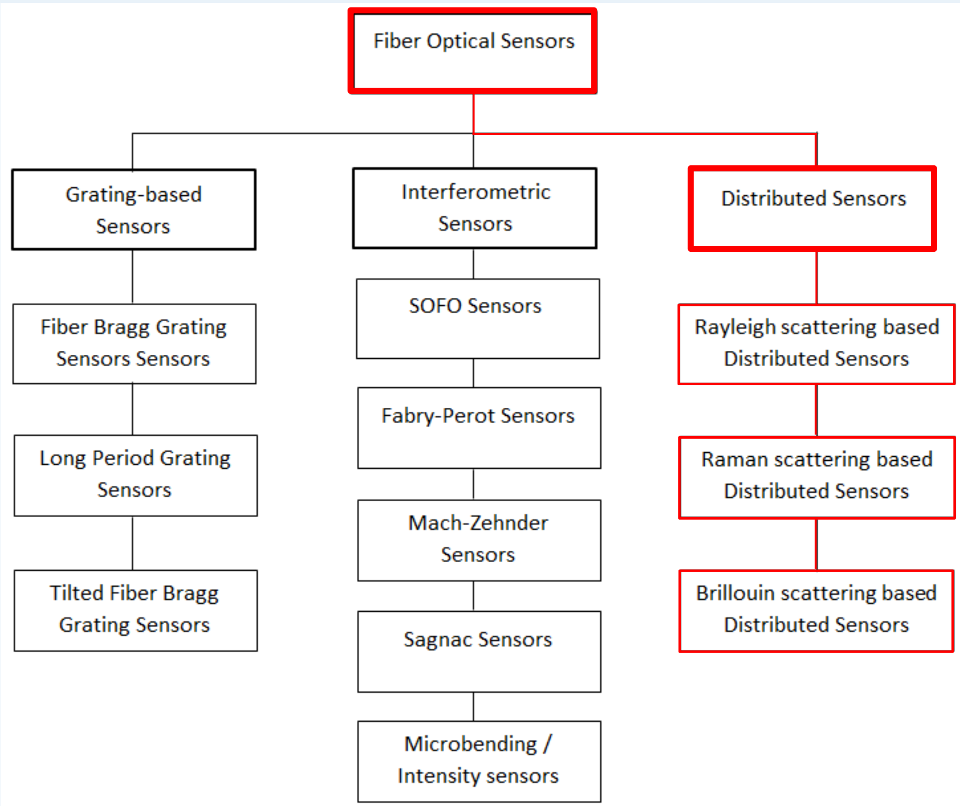
Types

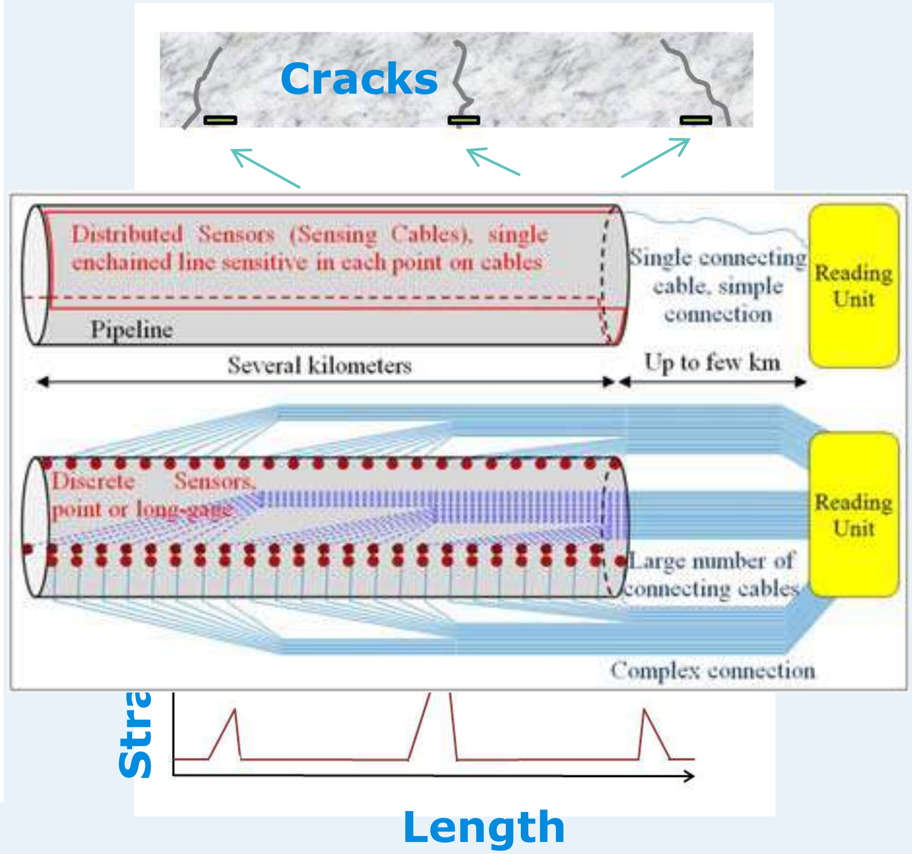
1. **Fabry-Perot**
2. **Bragg Grating**
3. **Continuous Sensors**



The optical fiber is an ideal distributed sensor by its material properties

Fiber Optic Sensors





All possible crack openings are covered by the extension of the sensor

Level 3: Quantification

Quantification is the last step to assess the damage condition: to quantitatively estimate the severity of the damage.

Example: ***Assessing damage due to cracking in concrete structures: which is the crack width ?***

Discrete sensors (very difficult/not possible)

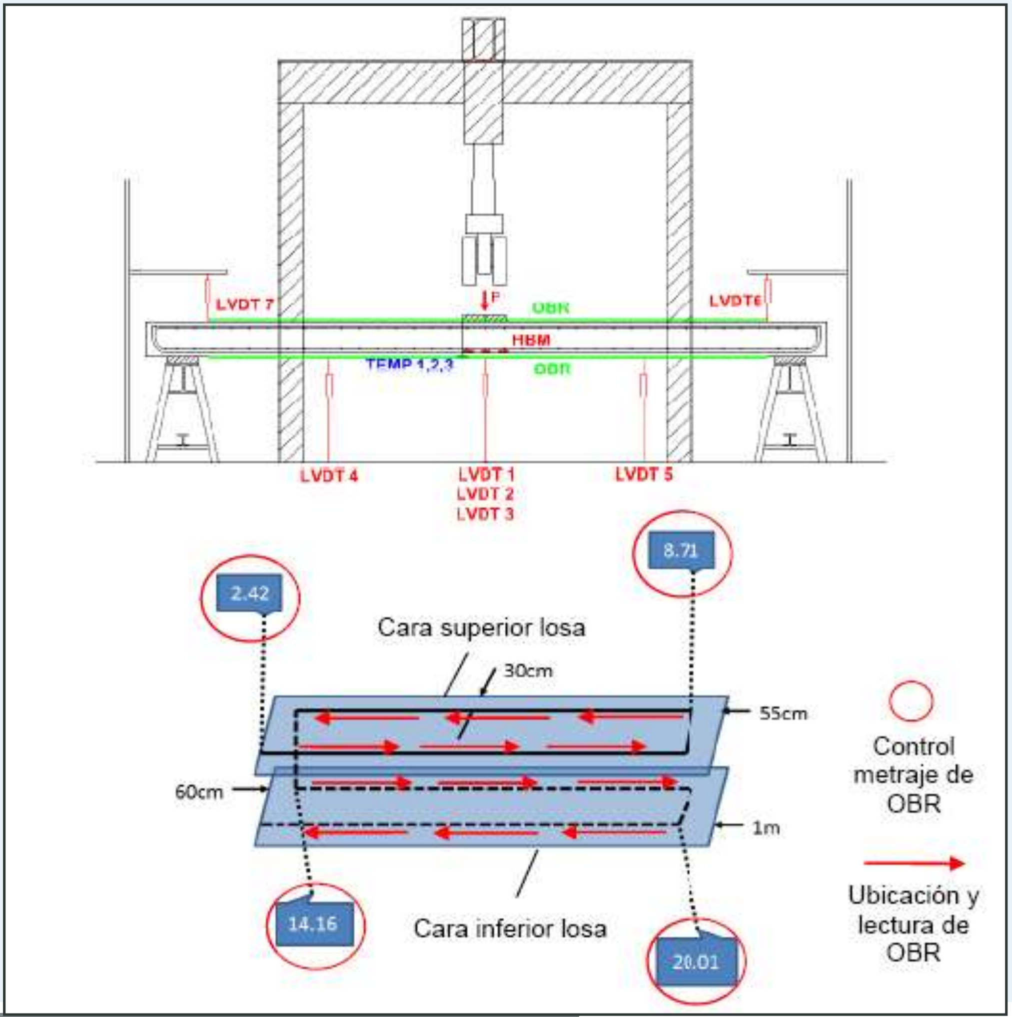
Distributed Optical fiber (OBR system) is possible

►Long term monitoring FO system

►OBR equipment – Experimental validation in reinforced concrete structures

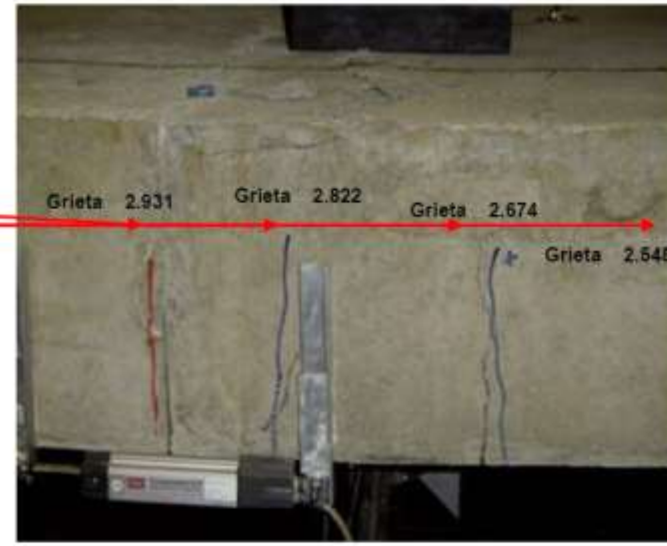
STRUCTURAL HEALTH MONITORING WITH FIBER OPTICS

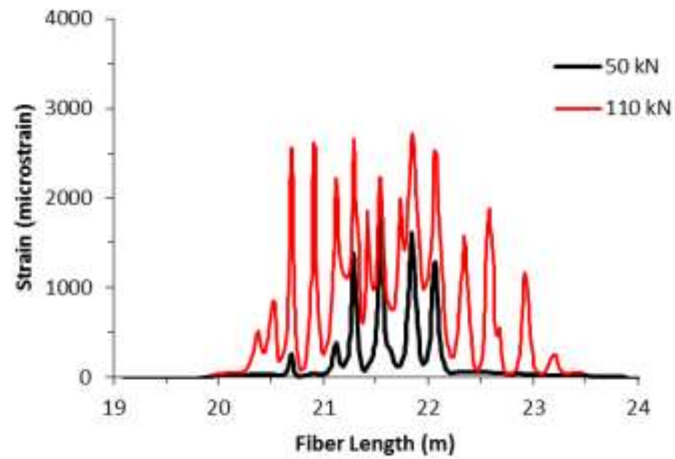
- Use **OBR BACKSCATTER REFLECTOMETER (Optical Fiber) ⇨ in slab LR1**

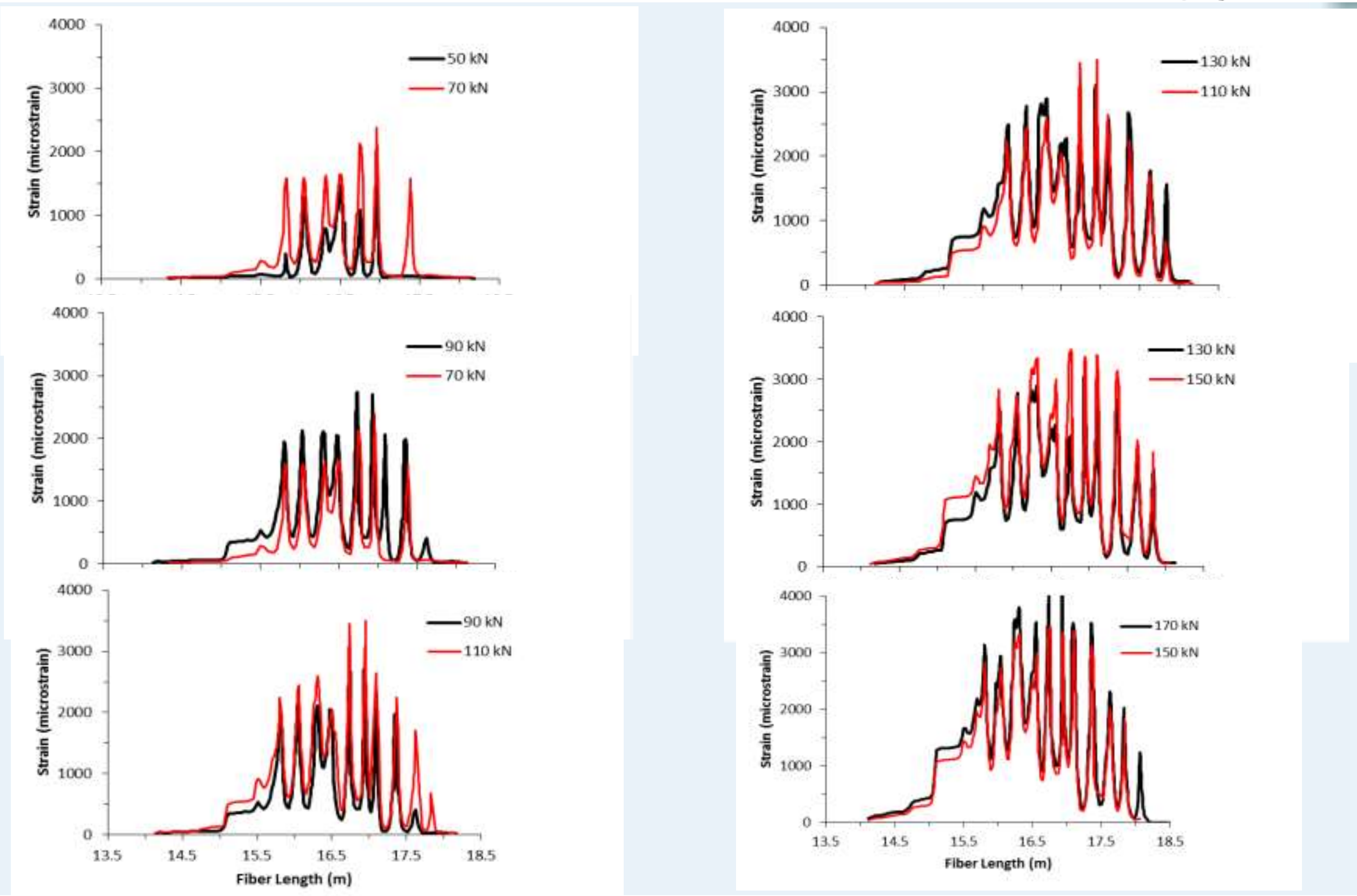


EXPERIMENTAL TEST : OBR Results

L_1 (1) (m)	L_2 (2) (m)	(με) (Q=50kN)	(με) (Q=110kN)
20,522	3,588	-	800
20,694	3,416	270	4400
20,909	2,931	-	4460
21,123	2,987	400	2250
21,288	2,822	1450	2600
21,436	2,674	-	2150
21,562	2,548	3260	4910
21,735	2,375	-	2000
21,851	2,259	1650	2700
22,064	2,046	1270	2500
22,357	1,735	-	4500
22,940	1,170	-	350





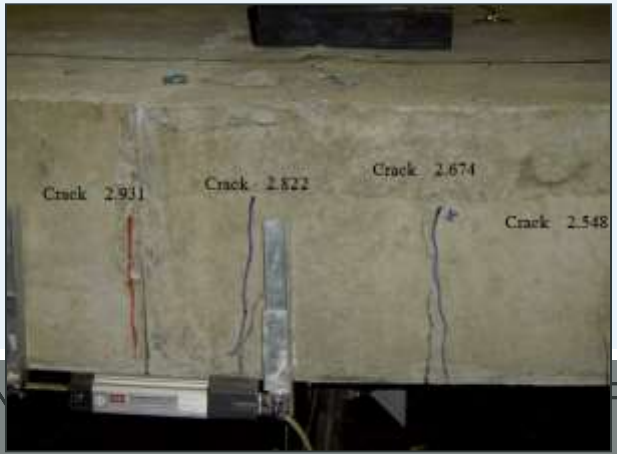

50 kN
70 kN
90 kN
70 kN
90 kN
110 kN
130 kN
110 kN
130 kN
150 kN
170 kN
150 kN
Strain (microstrain)
Fiber Length (m)
0
1000
2000
3000
4000
13.5
14.5
15.5
16.5
17.5
18.5

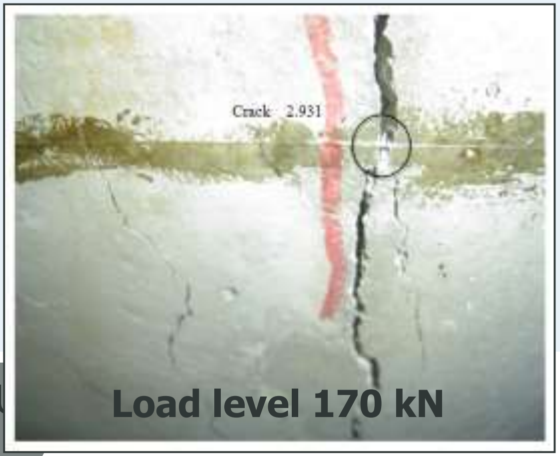
EXPERIMENTAL RESULTS

- **OBR BACKSCATTER REFLECTOMETER IN SLAB R1**

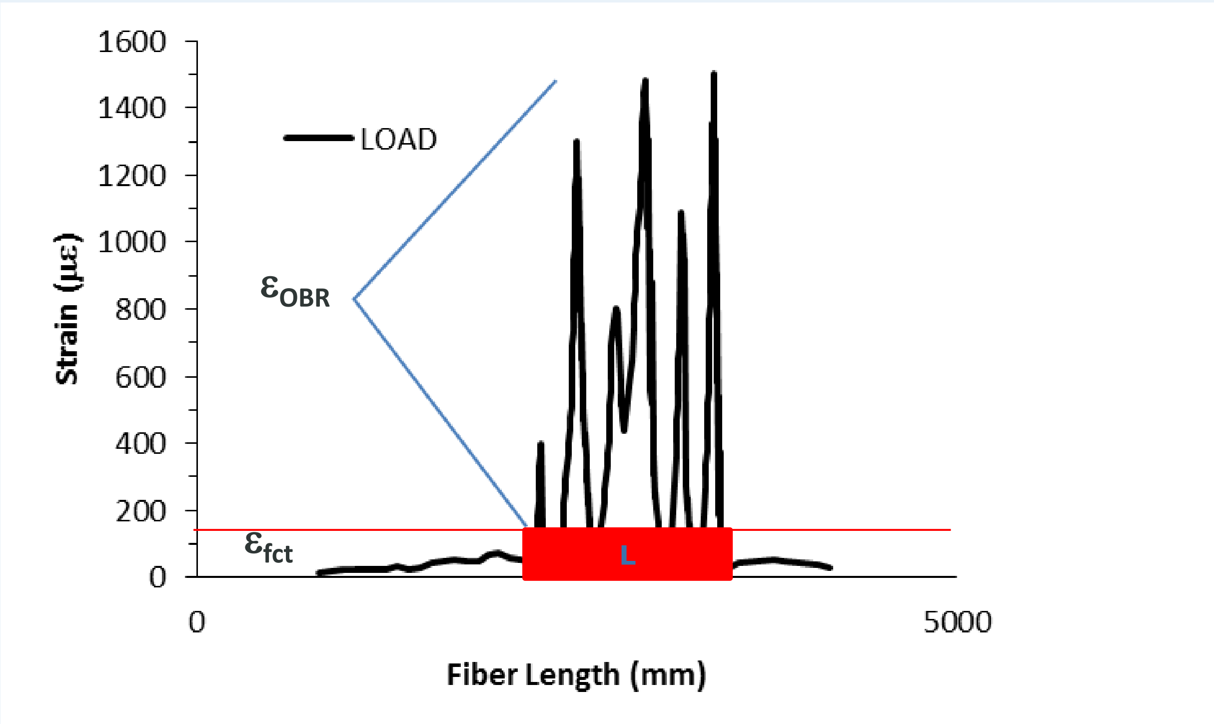
Segment	Peak location (m)	Location referenced to segment origin (m)	**Strain** (με) at **50kN**	**Strain** (με) at **110kN**
3	15.513	1.953	-	800
3	15.818	2.258	400	2250
3	16.046	2.486	1300	2450
3	16.318	2.758	800	2590
3	16.492	2.932	1480	2040
3	16.551	2.991	-	1550
3	16.745	3.185	1090	3450
3	16.942	3.382	1500	3500
3	17.085	3.525	-	2650
3	17.355	3.795	-	2240
3	17.626	4.066	-	1700
3	17.830	4.270	-	675

Segment	Peak location (m)	Location referenced to segment origin (m)	**Strain** (με) at **50kN**	**Strain** (με) at **110kN**
4	20.374	3.736	-	510
4	20.522	3.588	-	800
4	20.694	3.416	270	4400
4	20.909	2.931	-	4460
4	21.123	2.987	400	2250
4	21.288	2.822	1450	2600
4	21.436	2.674	-	2150
4	21.562	2.548	3260	4910
4	21.735	2.375	-	2000
4	21.851	2.259	1650	2700
4	22.064	2.046	1270	2500
4	22.357	1.735	-	4500





Crack width at mid-span



$$\varepsilon mean = \int_0^L \frac{\varepsilon OBR}{L} dL$$

$$\varepsilon mean = \varepsilon fct + \frac{\sum w}{L}$$

$$Wmean = \frac{\sum w}{N}$$

$$N = \ number\ of\ cracks$$

Load	magnetic_trans1_crack	magnetic_trans2_crack	ARITHMETIC MEAN	OBR stretch3	OBR stretch4
kN	mm	mm	mm	mm	mm
50	0.058	0.099	**0.079**	**0.062**	**0.065**
70	0.077	0.154	**0.116**	**0.112**	**0.101**
90	0.105	0.125	**0.115**	**0.149**	**0.127**
111	0.166	0.147	**0.157**	**0.190**	**0.163**
130	0.296	0.200	**0.248**	**0.237**	**0.209**
150	0.370	0.267	**0.319**	**0.298**	**0.246**
170	0.439	0.337	**0.388**	**0.354**	**0.213**

►Application: Can Fatjó Viaduct on the BP-1413 Highway in Cerdanyola del Vallès, Barcelona

Objectives

1. Check the feasibility and system operation in concrete structure monitoring (field test in real structure)
2. Compare the resulting data with theoretical and experimental values obtained by fleximeters installed during initial load tests.

►Viaduct on the BP-1413 Highway

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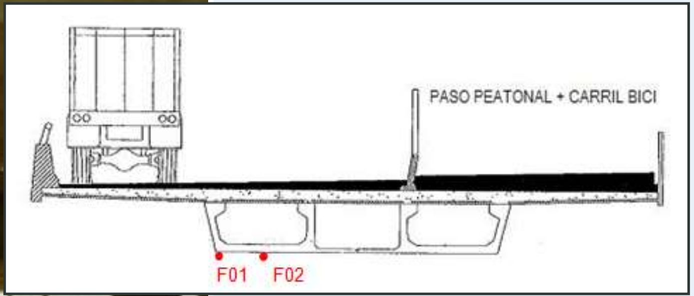
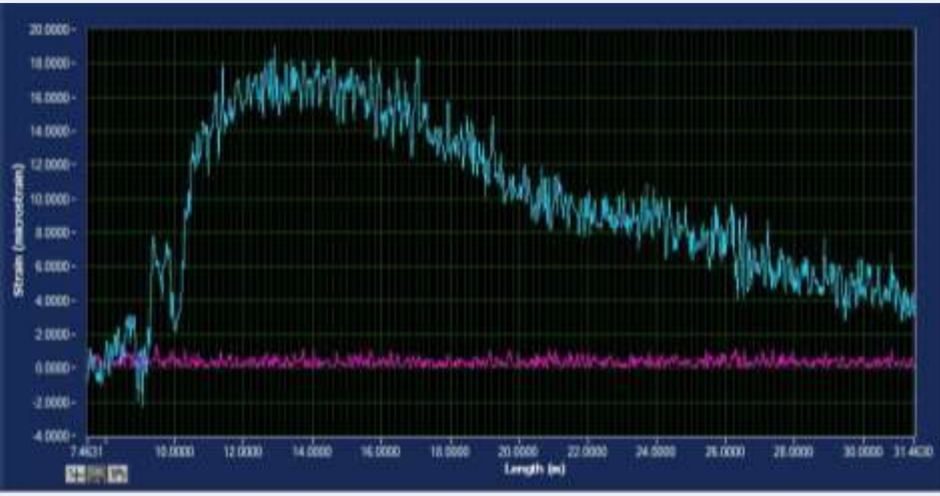
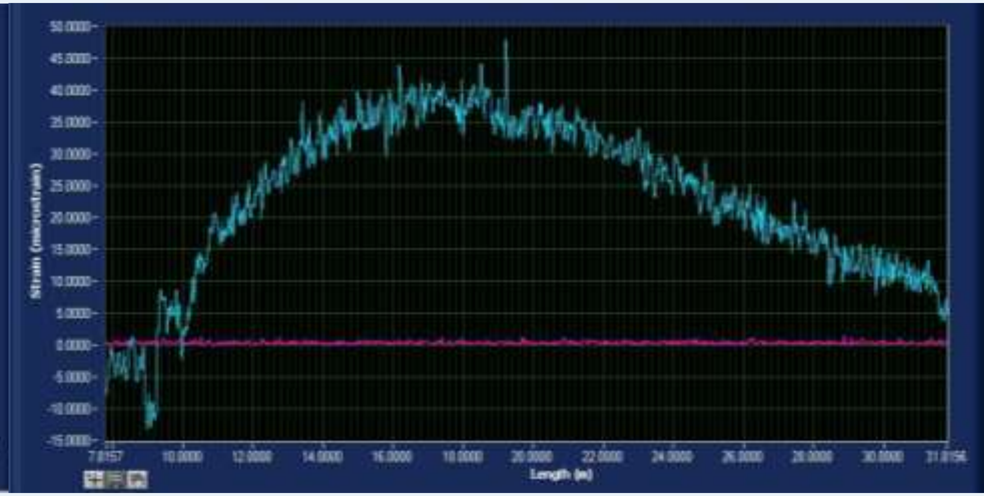


►Results - Viaduct on the BP-1413 Highway



Moving traffic – 40 T

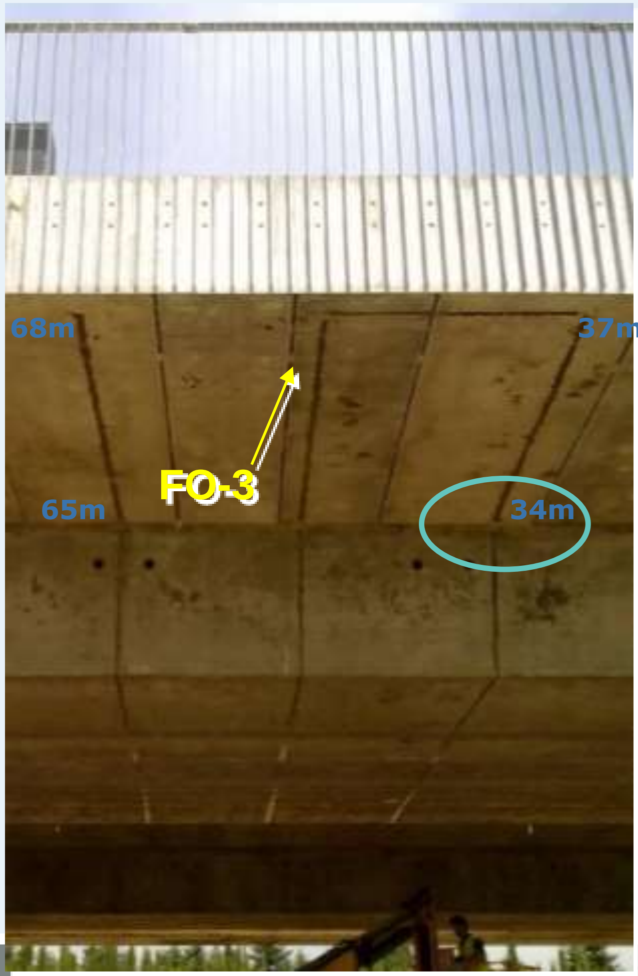


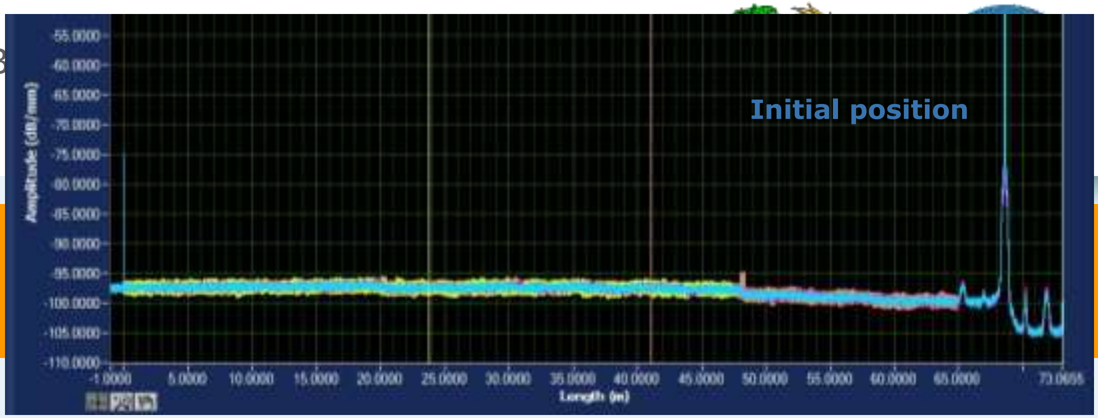
Stationary 40 T – after 1 m.

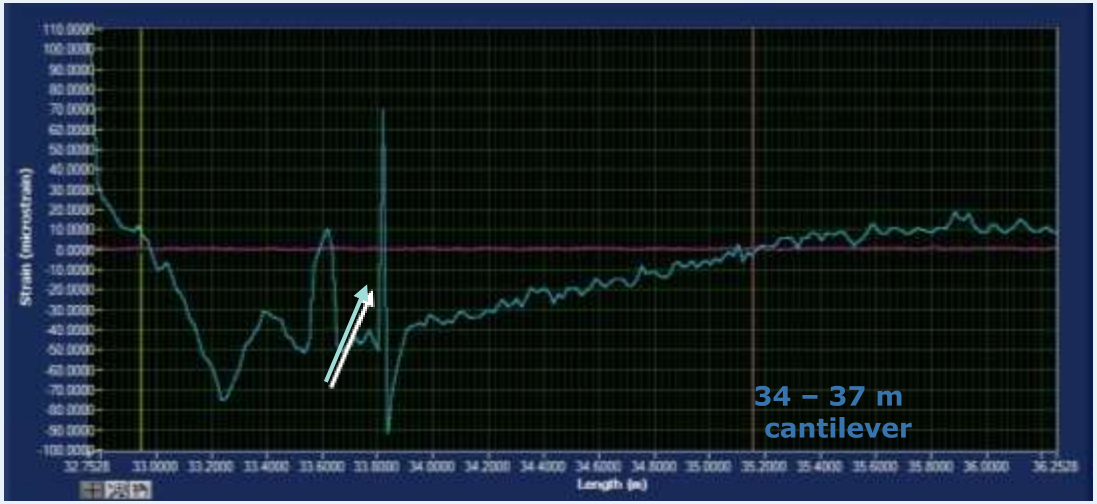
Stationary 40 T –after 5 m.

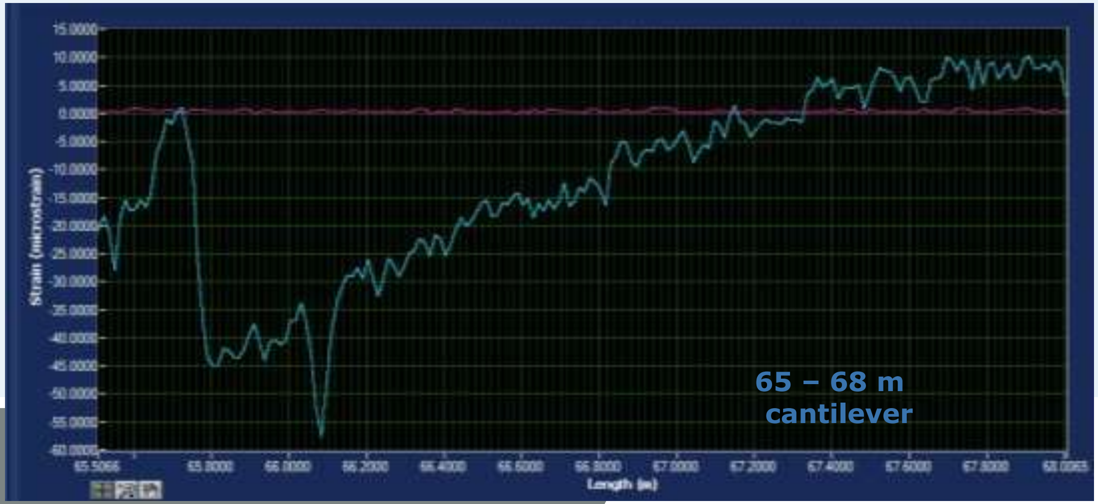
Stationary 40 T – after 10 m.

►Viaduct on the BP-1413 Highway



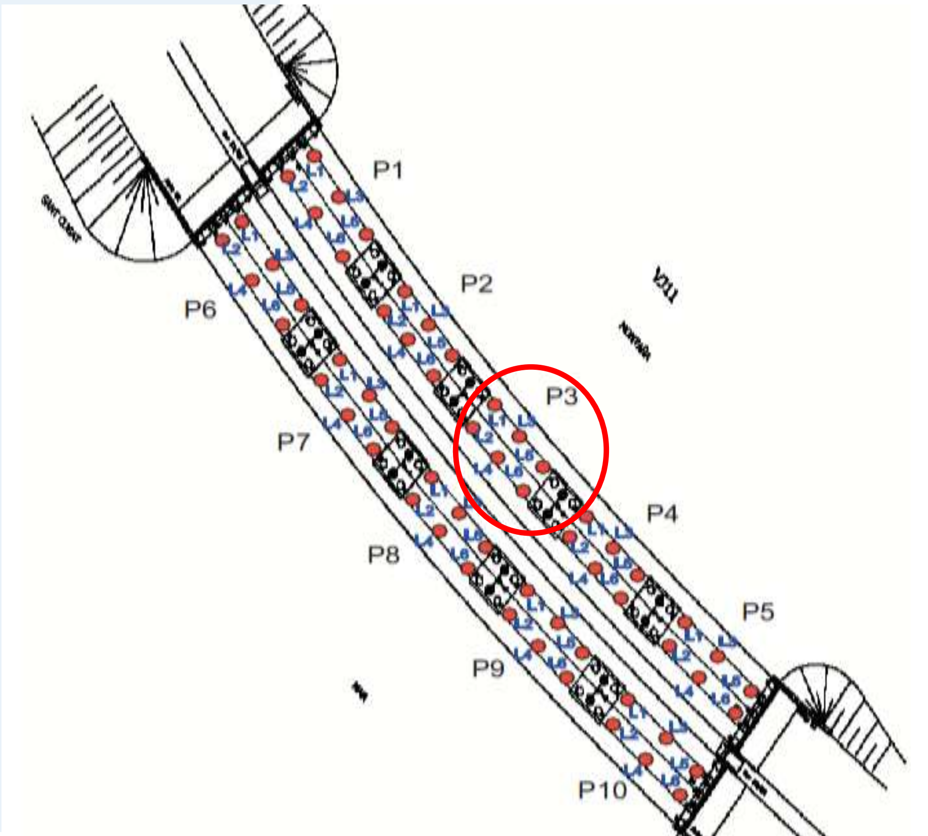






►BP-1413

PRUEBA DE CARGA: Carretera BP-1413, P3 (prueba 3)														
ESCALÓN	RAMA	TOMA DE LECTURAS	LECTURA DE COMPARADORES (mm)						FLECHAS (mm)					
			L1	L2	L3	L4	L5	L6	L1	L2	L3	L4	L5	L6
0	ORIGEN	inmediata	6,37	29,08	34,14	31,30	26,11	18,66	---	---	---	---	---	---
1	CARGA	inmediata	6,90	30,66	37,77	37,65	26,81	20,41	0,53	1,58	3,63	6,35	0,70	1,75
		10 min	6,94	30,68	37,85	37,85	26,84	20,43	0,57	1,60	3,71	6,55	0,73	1,77
2	DESCARGA	inmediata	6,44	29,48	34,23	31,77	26,12	19,08	0,07	0,40	0,09	0,47	0,01	0,42

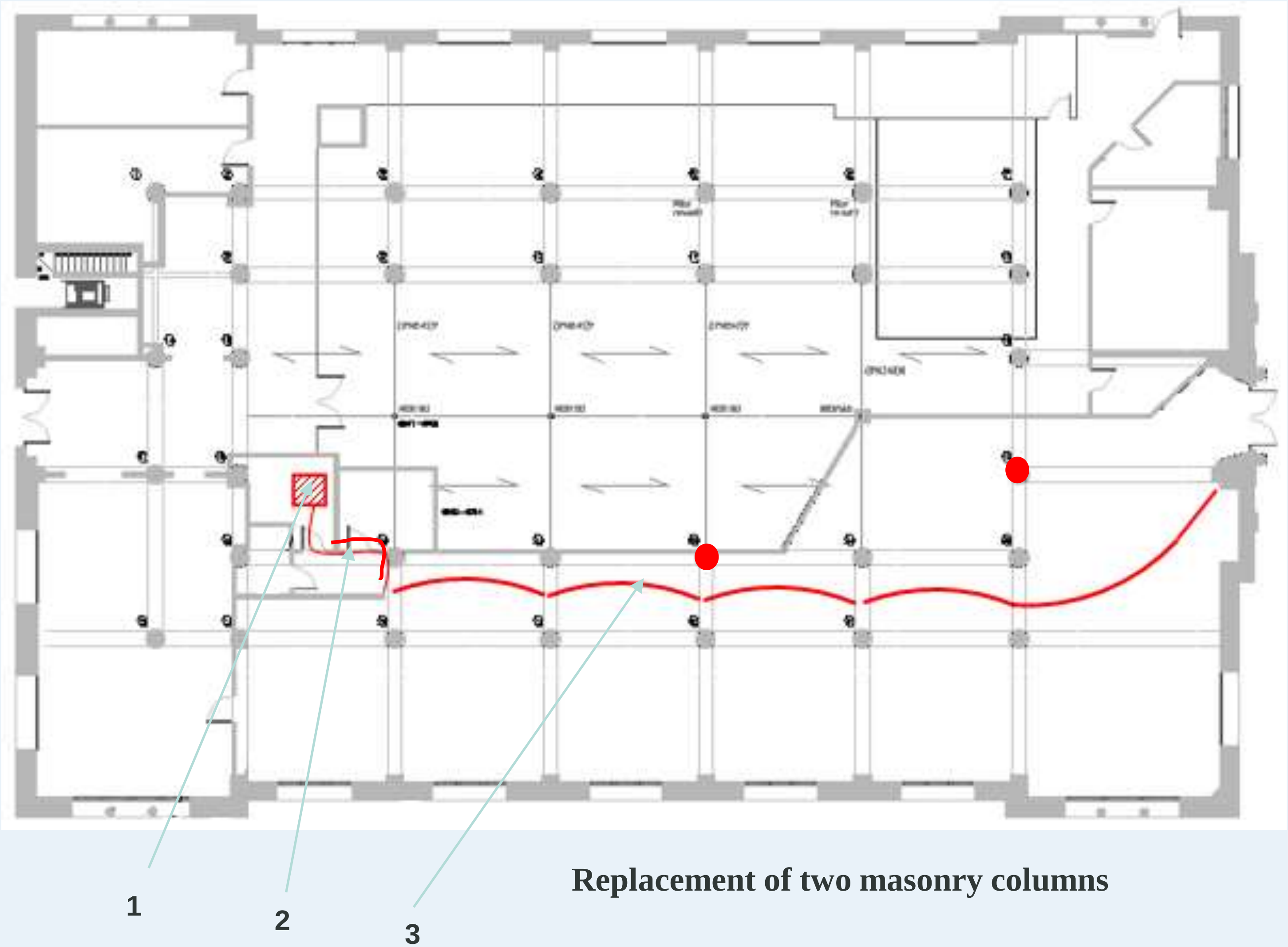


Fibra Óptica F02	Flexómetros	SAP2000
3,45	3,71	3,42

Fibra Óptica F03	Flexómetros	SAP2000
0,26	-	0,57

Hospital de Sant Pau

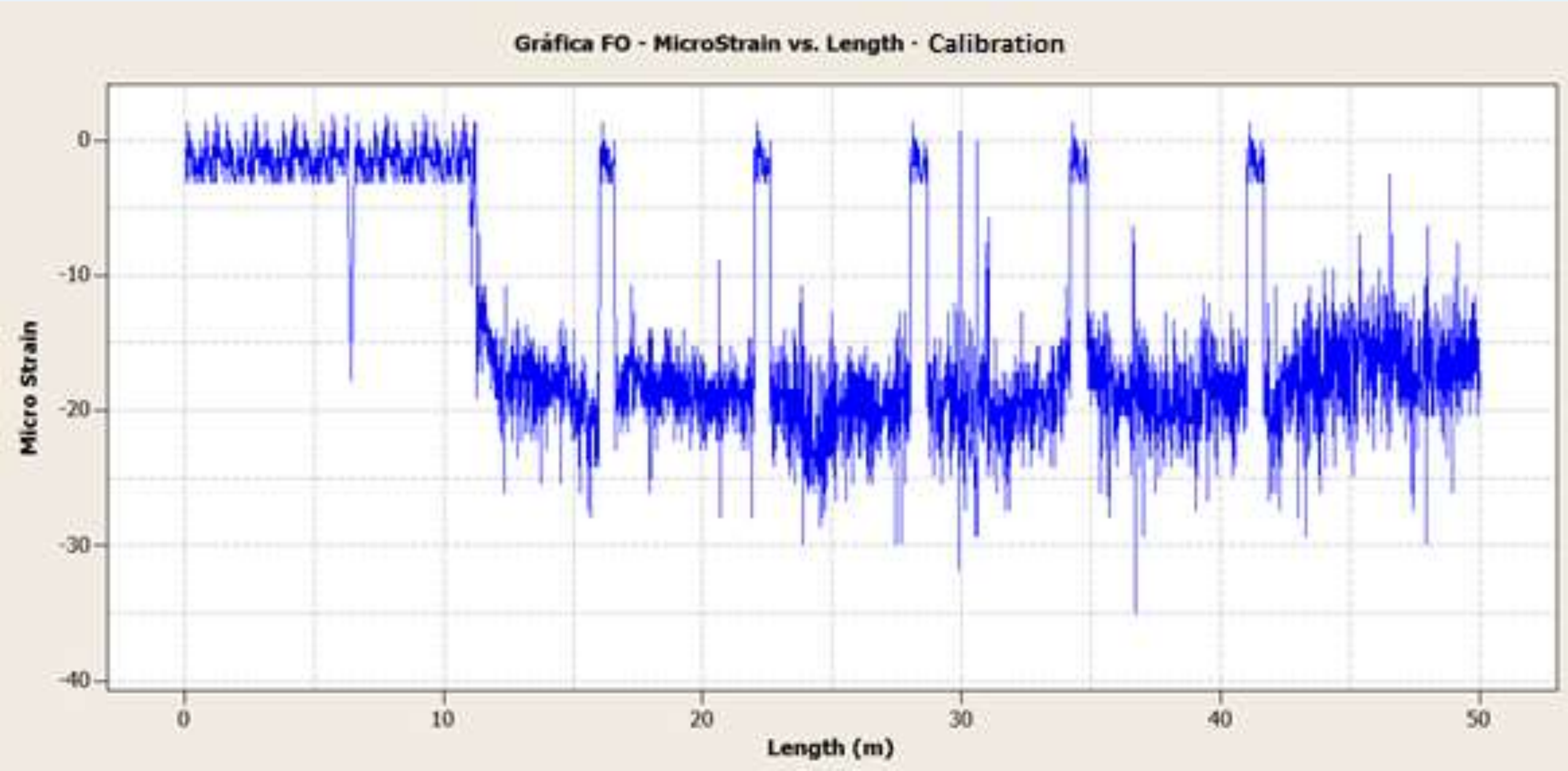
- **Early 20th century modernist building**
- **Masonry structure**
- **UNESCO World Heritage Site**



1- Work station
2- Non adherent DOFS
3- Adherent DOFS

Replacement of two masonry columns


DOFS



First reading of the sensor serves as a baseline calibration for subsequent readings

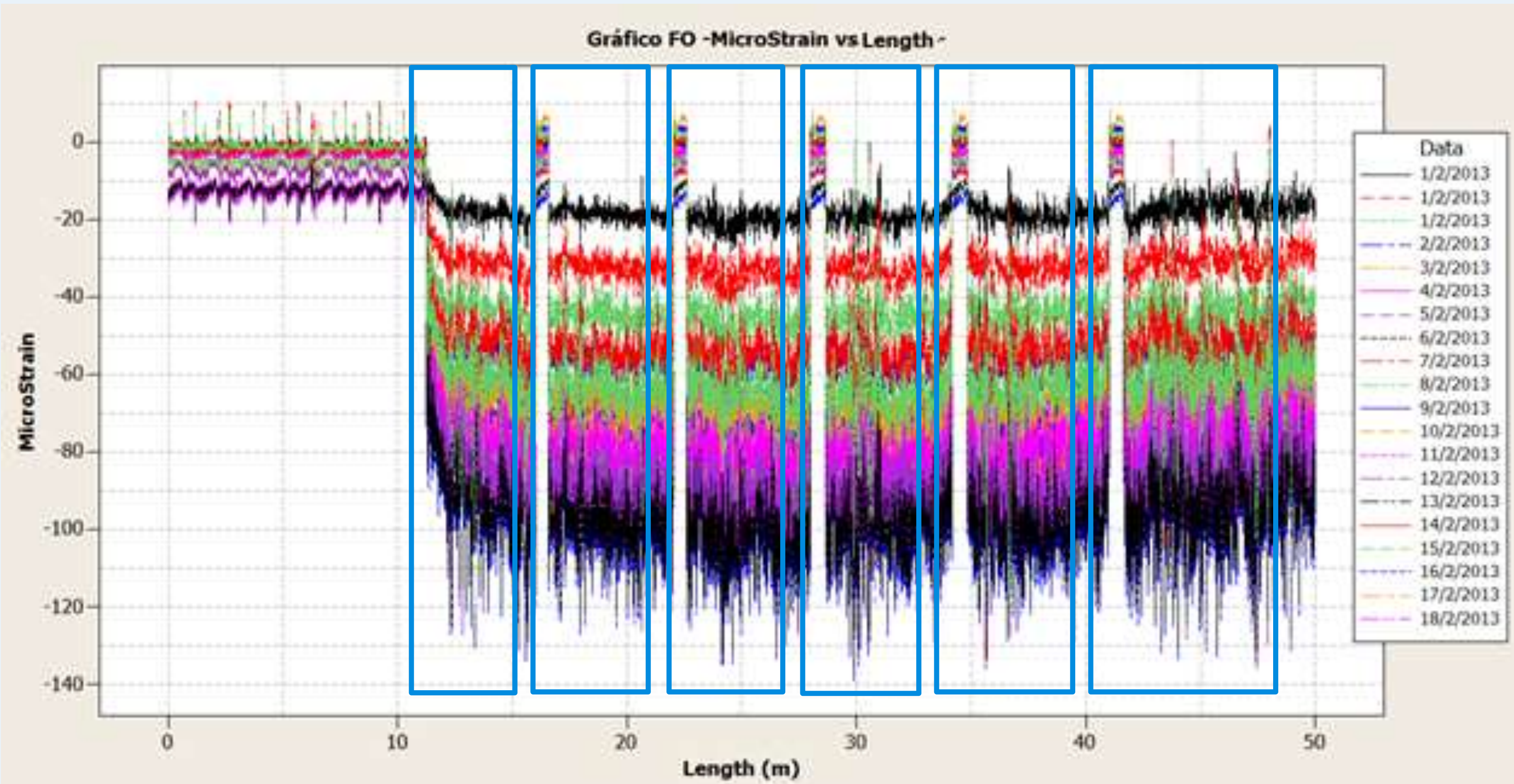


Gráfico FO -MicroStrain vs Length-
MicroStrain
Length (m)
0
-20
-40
-60
-80
-100
-120
-140
0
10
20
30
40
50
Data
1/2/2013
1/2/2013
1/2/2013
2/2/2013
3/2/2013
4/2/2013
5/2/2013
6/2/2013
7/2/2013
8/2/2013
9/2/2013
10/2/2013
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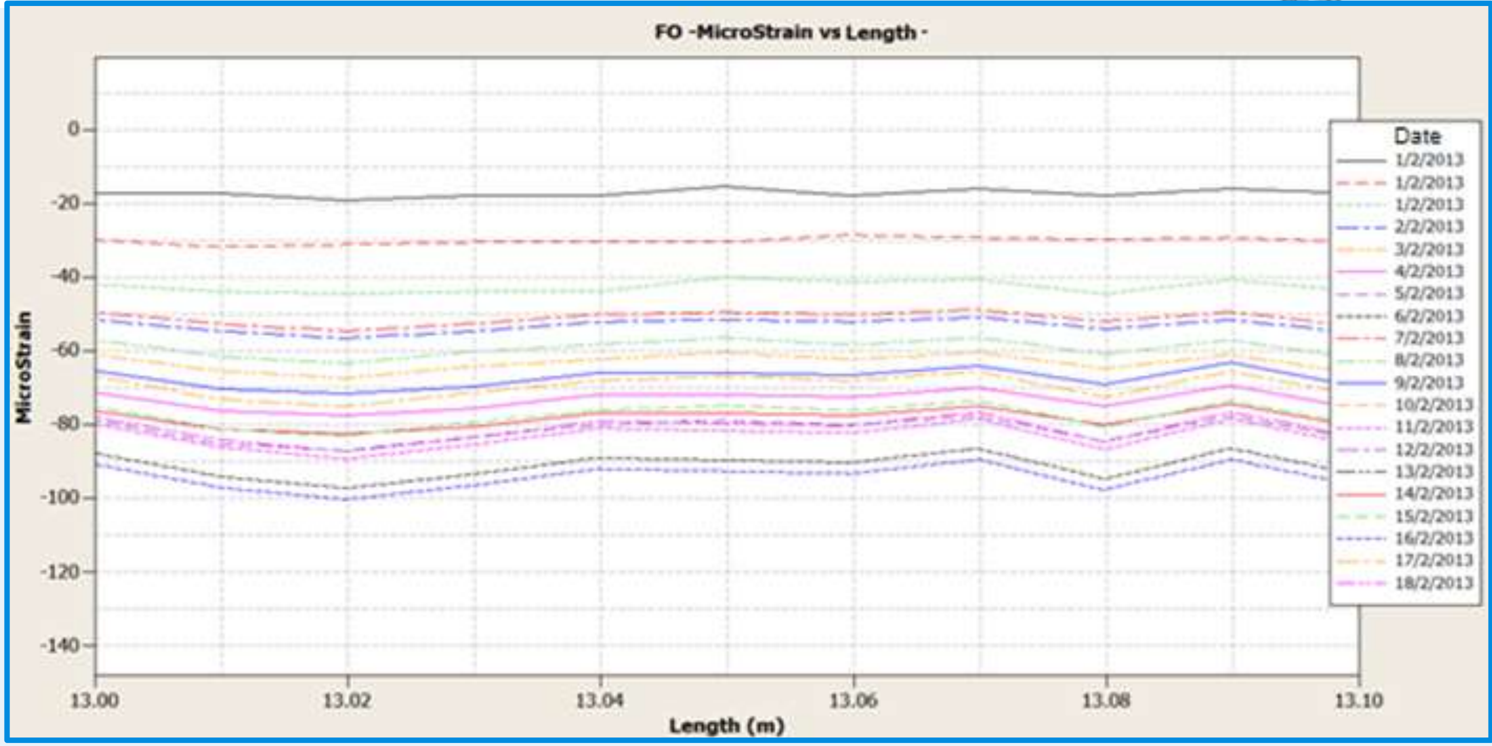
17/2/2013
18/2/2013



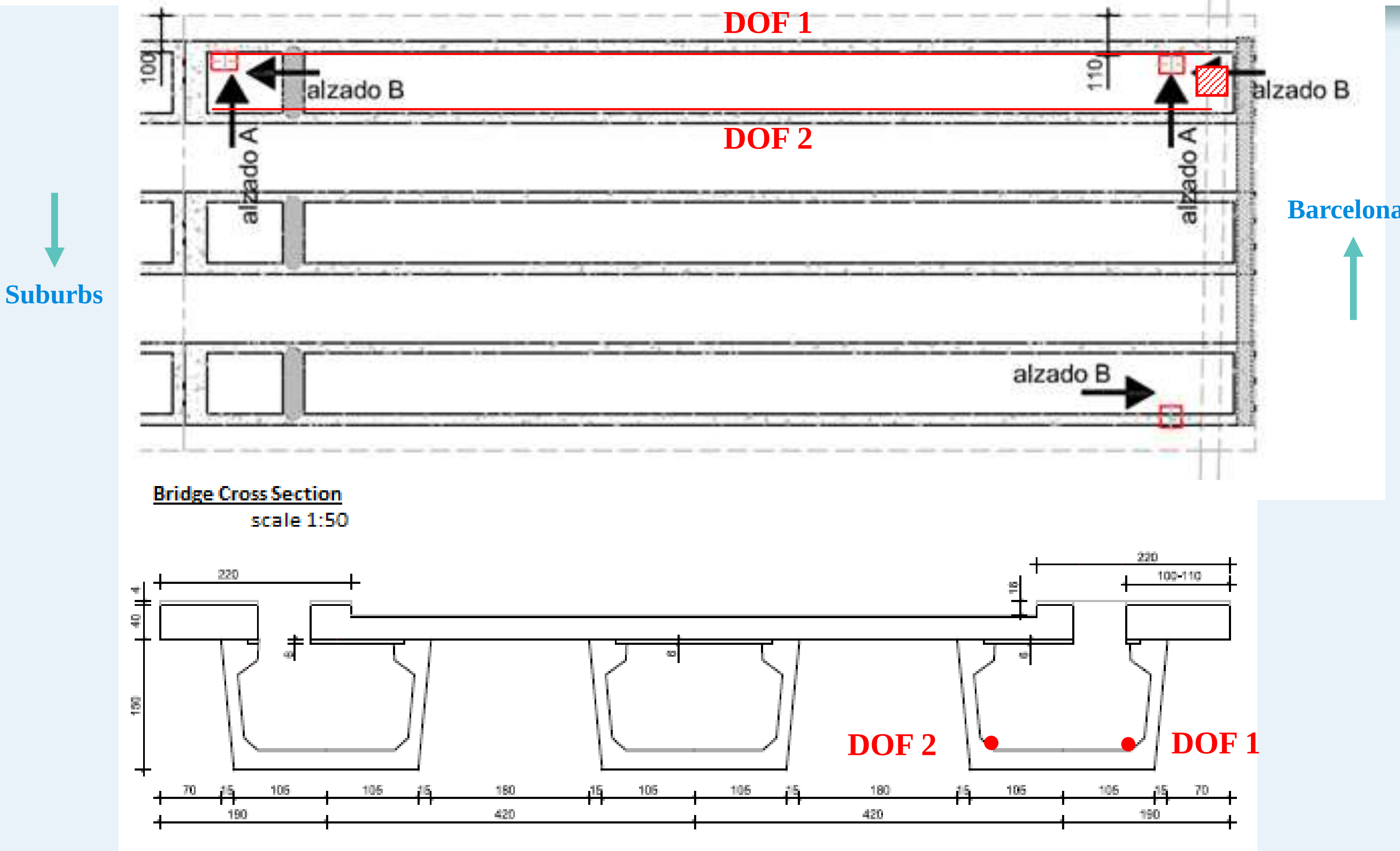
- **Micro deformations oscillation corresponds to an increase of compression**
- **Total increase due to both columns replacement is of ≈ 80 με**
- **Prevention of decompression of the vaults**
- **The formation of new cracks was not observed both by the monitoring system or by visual inspection**
- **In the last readings, it is perceived a recovery of ≈ 20 με which shows stabilization**

Sarajevo Bridge

- **Located over one of the busiest road entrances of Barcelona**
- **Two-span prestressed concrete bridge (36m and 50m span)**
- **In order to enhance the pedestrian traffic and capacity as well as aesthetics of the bridge, a deck widening procedure was proposed with the addition of a steel structure over the new sidewalks. This produces a change in the bridge permanent loads.**

Objective:

- **Detect major changes in the structural behavior of the bridge and obtain information to assess the structural safety during and at the end of this process.**



Work Station **Distributed Optical Fiber sensor**



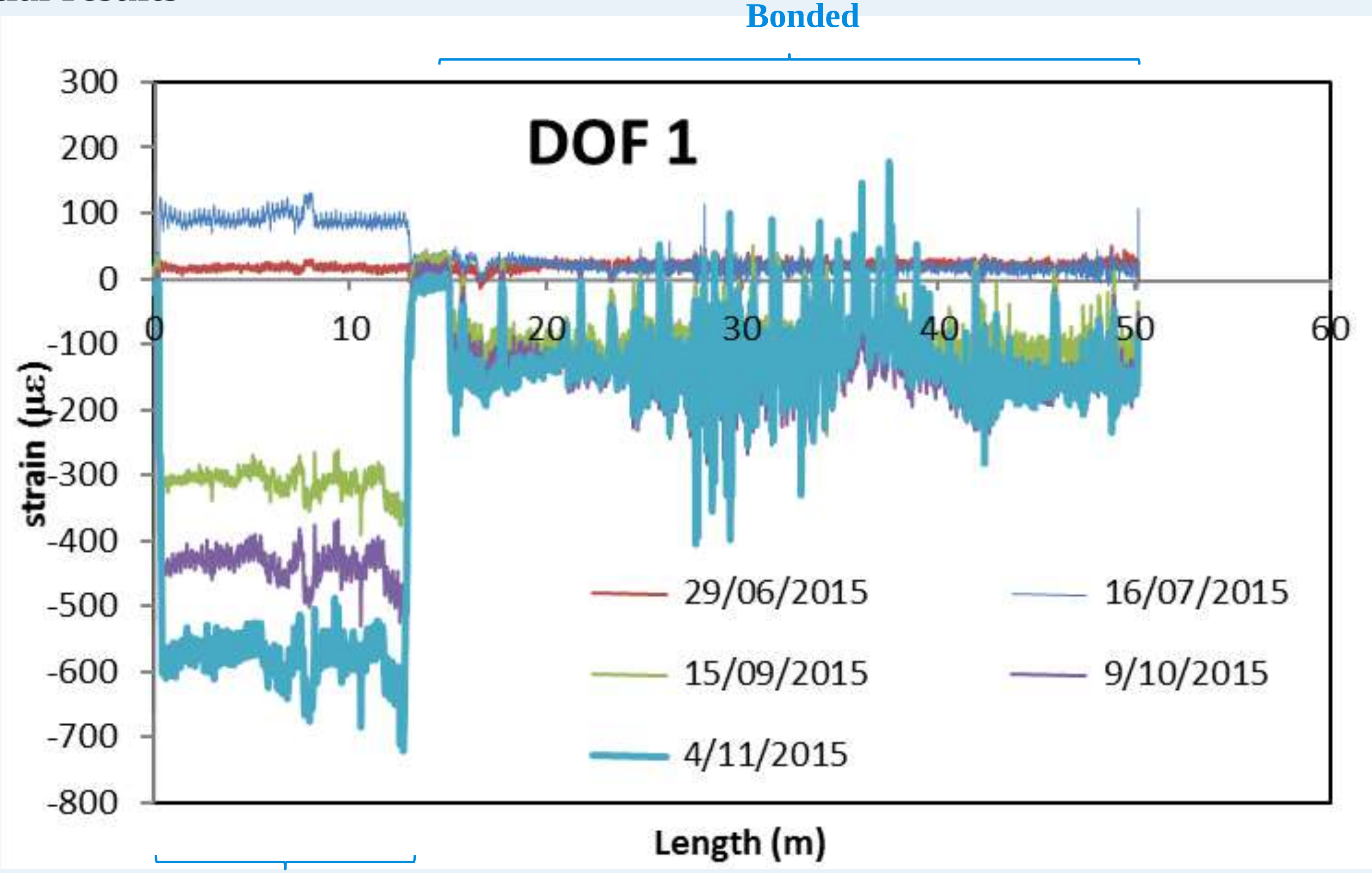

Date	Description
29/06/2015	Initial reading and calibration – 4 hours’ measurement – DOF 1 only
16/07/2015	5 hours’ measurement – DOF 1 only
06/08/2015	8 hours’ measurement – DOF 2 only
15/09/2015	5 hours’ measurement – DOF 1 only
01/10/2015	6 hours’ measurement – DOF 2 only
02/10/2015	2 hours’ measurement – DOF 2 only*
09/10/2015	6 hours’ measurement – DOF 1 only
04/11/2015	8 hours’ measurement – DOF 1 and DOF 2
10/12/2015	7 hours’ measurement – DOF 2 only
22/12/2015	3 hours’ measurement – DOF 2 only
18/01/2016	6 hours’ measurement – DOF 2 only
19/01/2016	3 hours’ measurement – DOF 2 only
20/01/2016	3 hours’ measurement – DOF 2 only

*** The two hours’ duration was due to the rupture of the cable that provided electrical power to the monitoring system**

- **DOFS data was achieved through continuous readings obtained in combined time intervals of: 1 reading each 5 minutes and 1 reading each 10 minutes.**
- **The critical values (maximum and minimum) are analyzed and used to generate envelope response graphs**

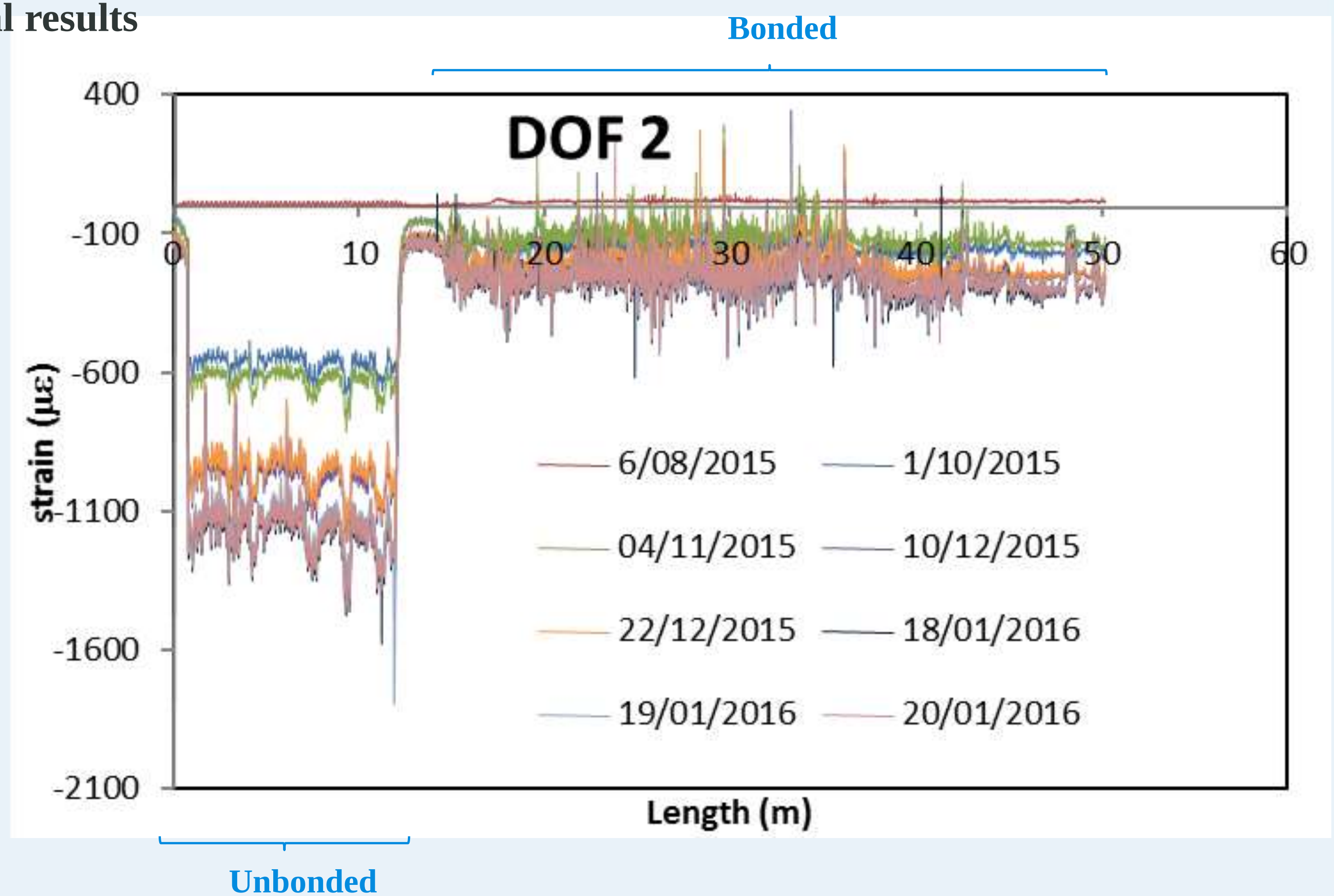
Initial results

Bonded



Unbonded

Initial results

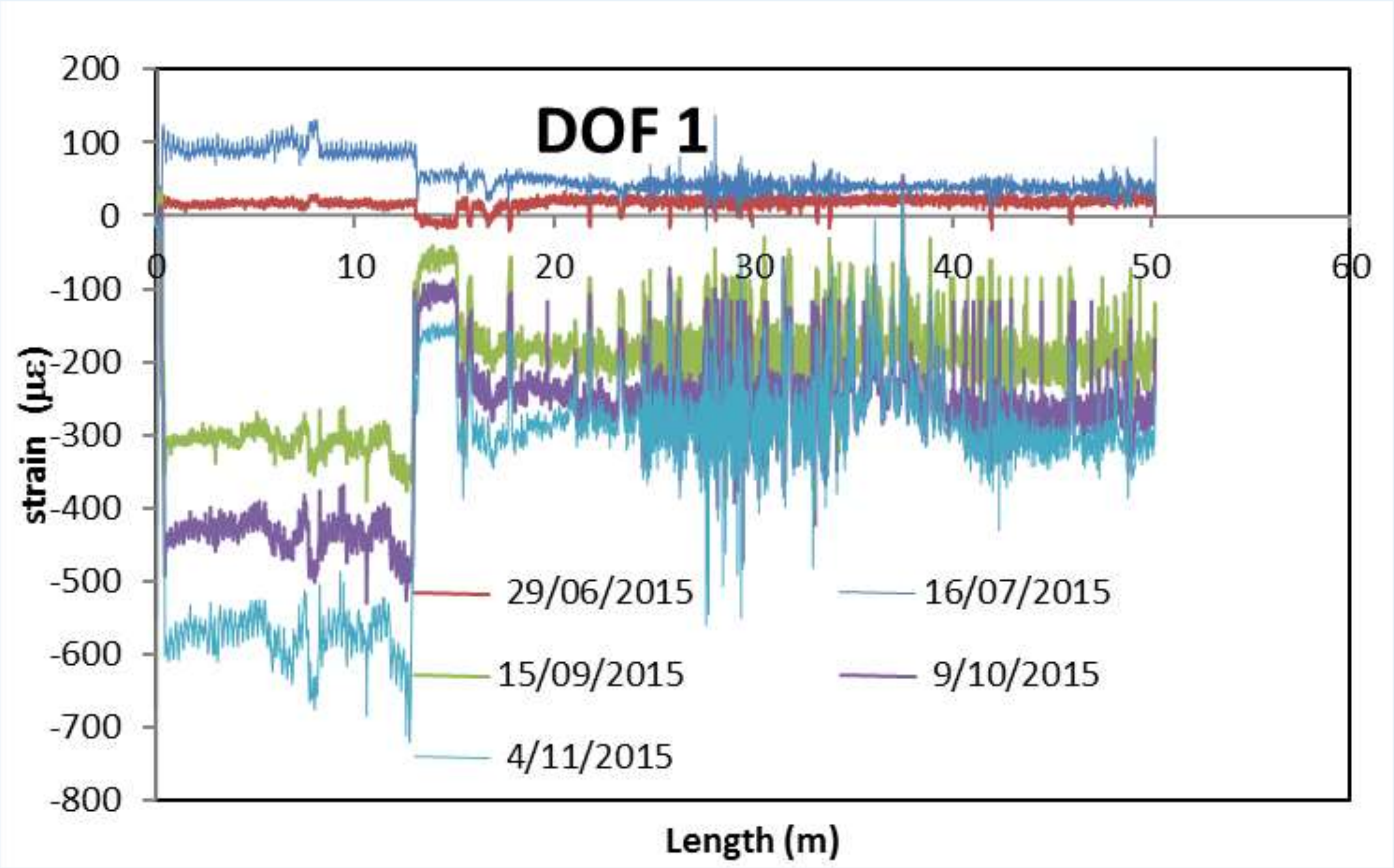


- **However, since this readings go from the beginning of summer up until winter, it's necessary to take into account the temperature effect on these initial readings.**

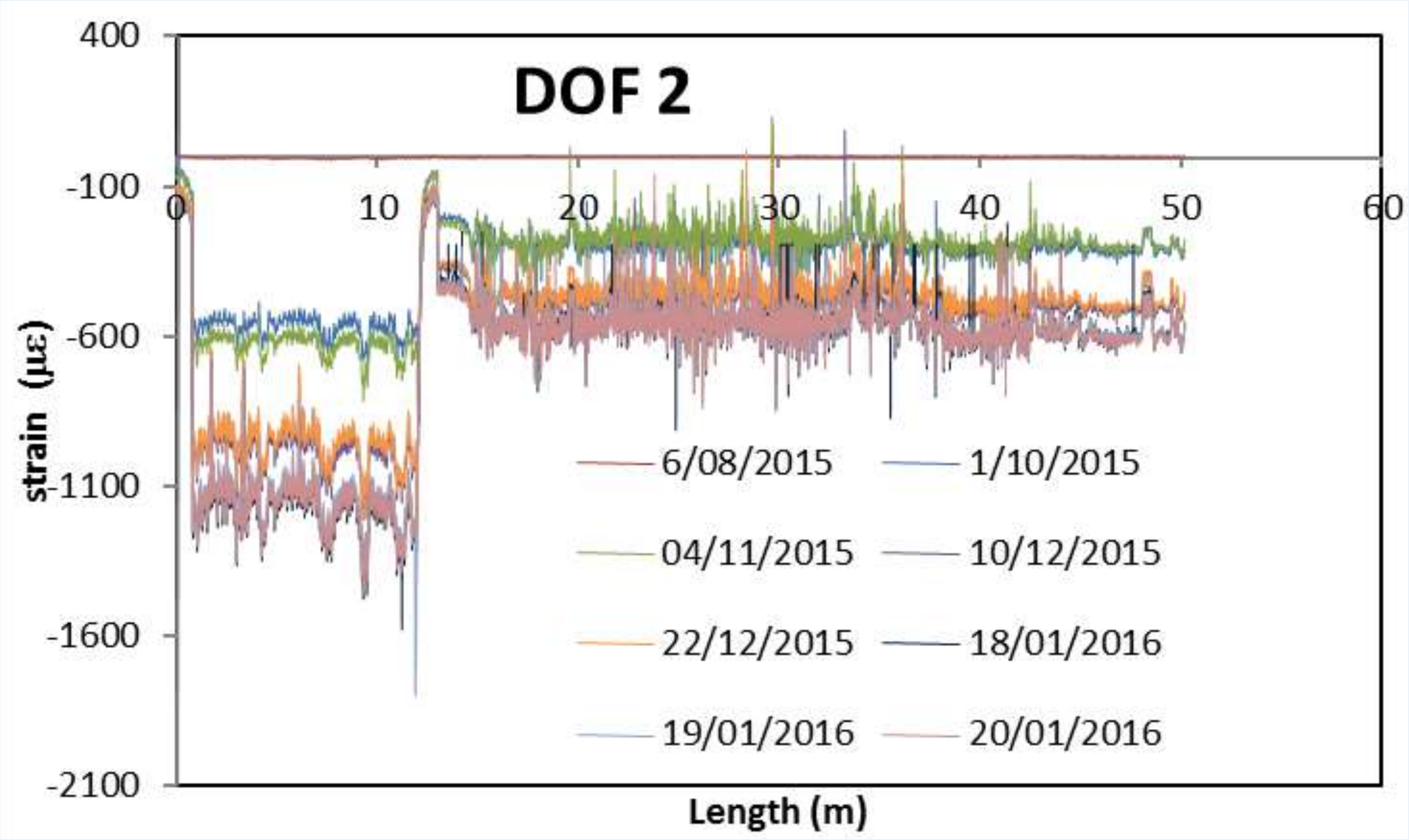
Unbonded loop of the DOF sensor

Readings in this part of the sensors are only affected by the ambient temperature variation

After temperature compensation

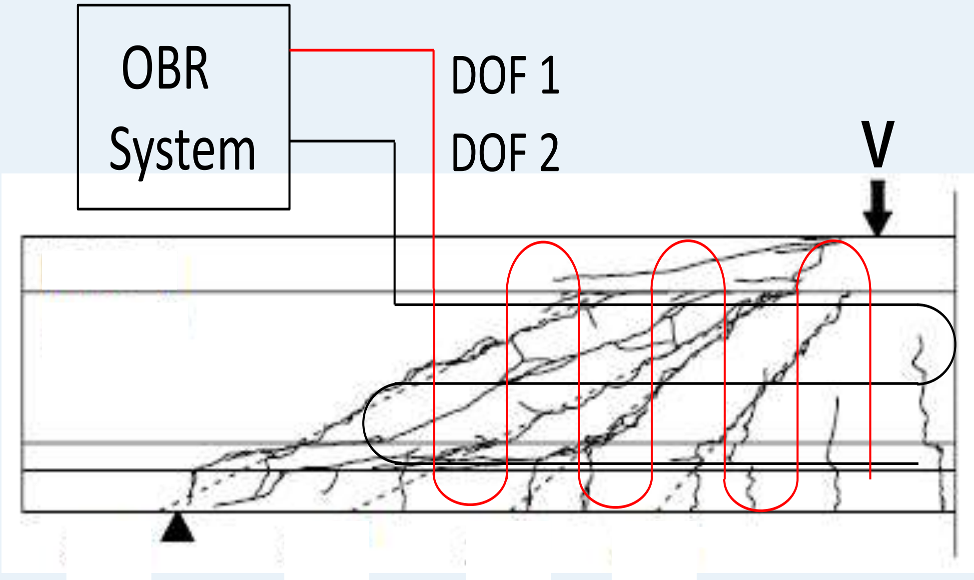


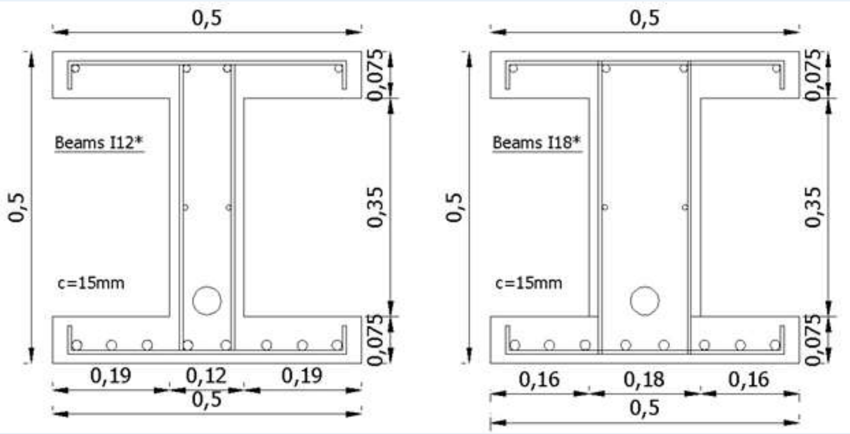
After temperature compensation

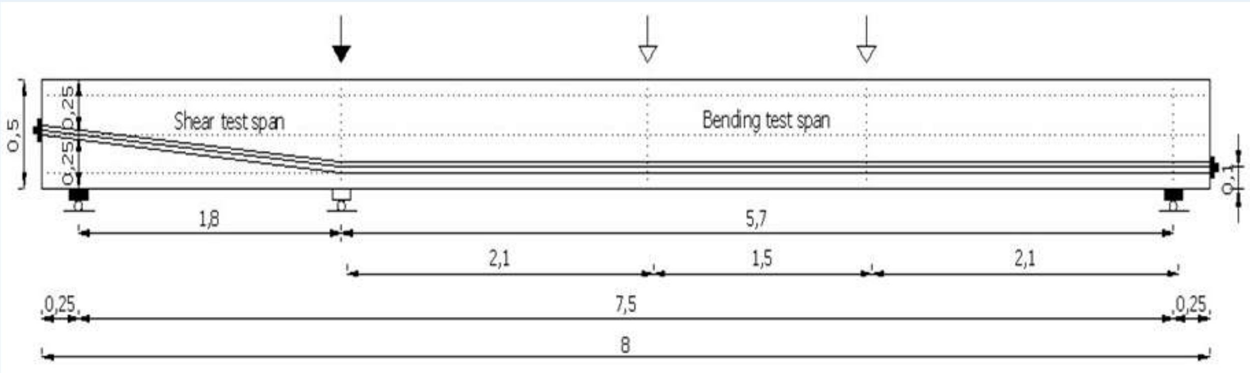


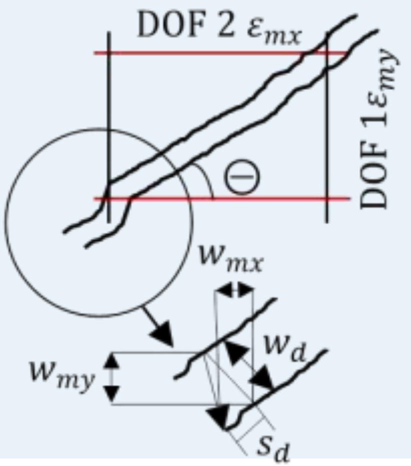

BENVINGUTS
BARCELONA

TESTS ON SHEAR CRACKING



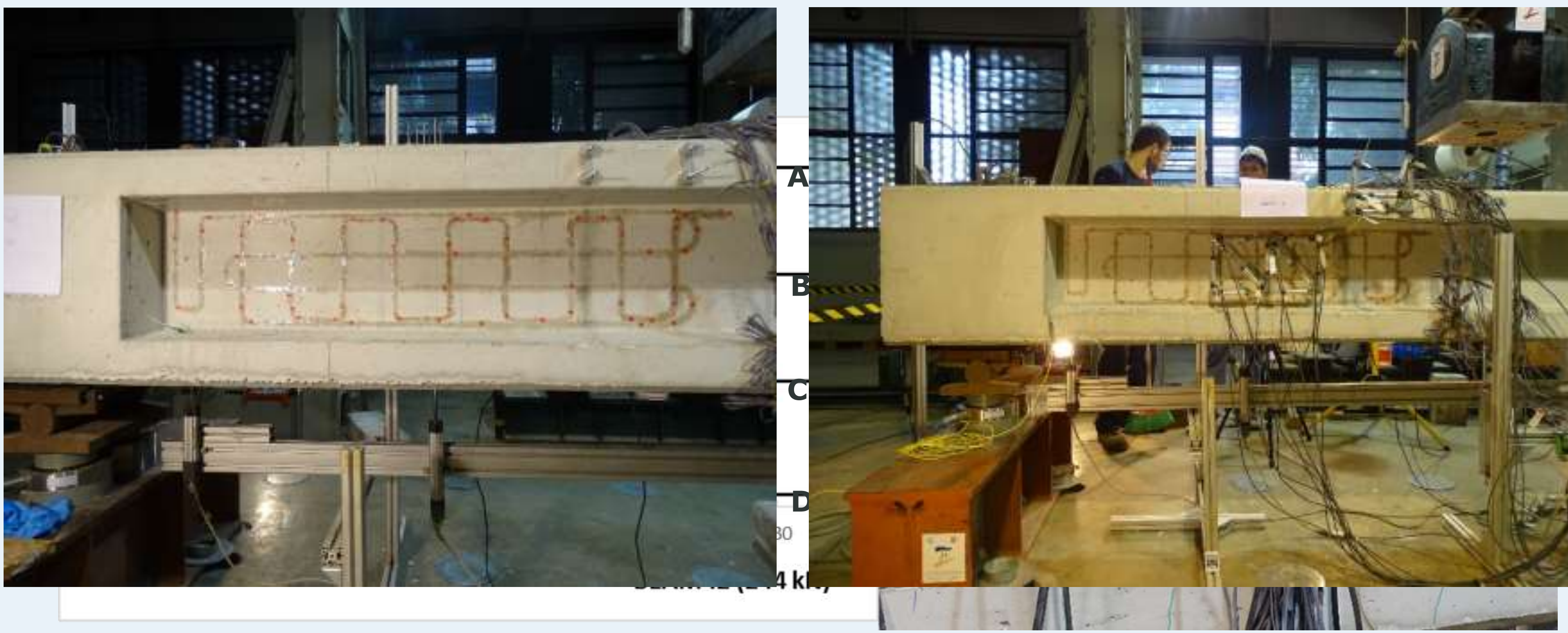




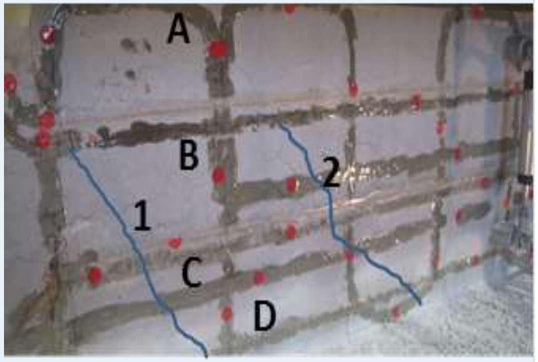


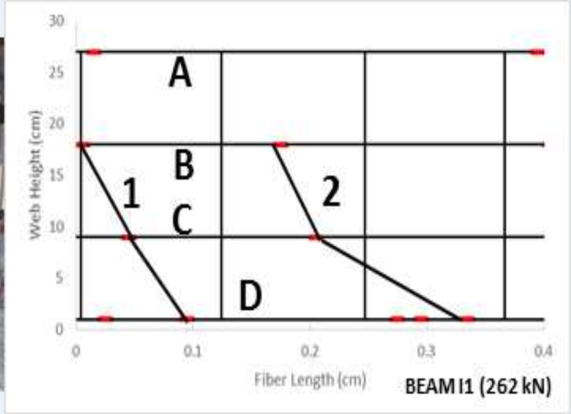
Parallel experiments within UPC’s research group:

Laboratory experiment where Partially Prestressed Concrete (PPC) beams were instrumented with DOFS

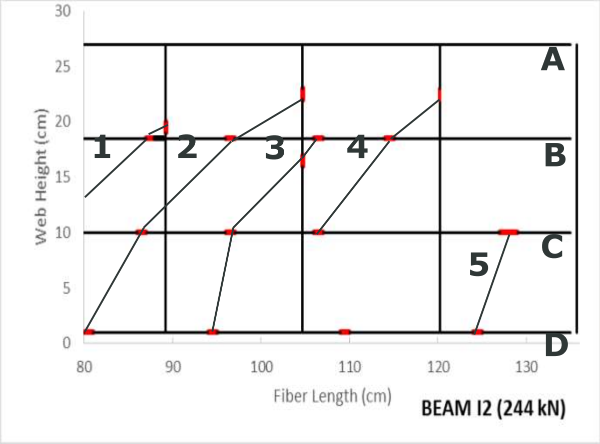


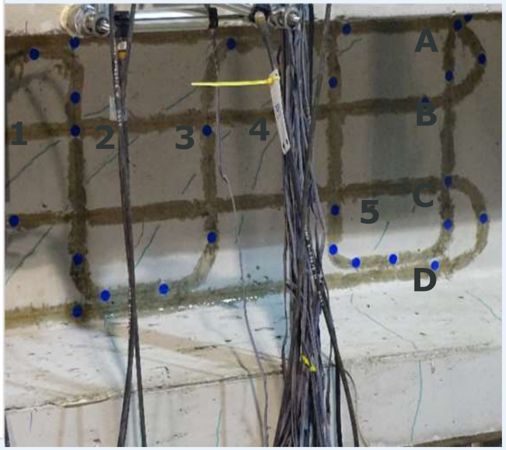
- **By converting the whole length of the fiber to a local coordinate system, the pinpointing of the cracked grid locations was possible**



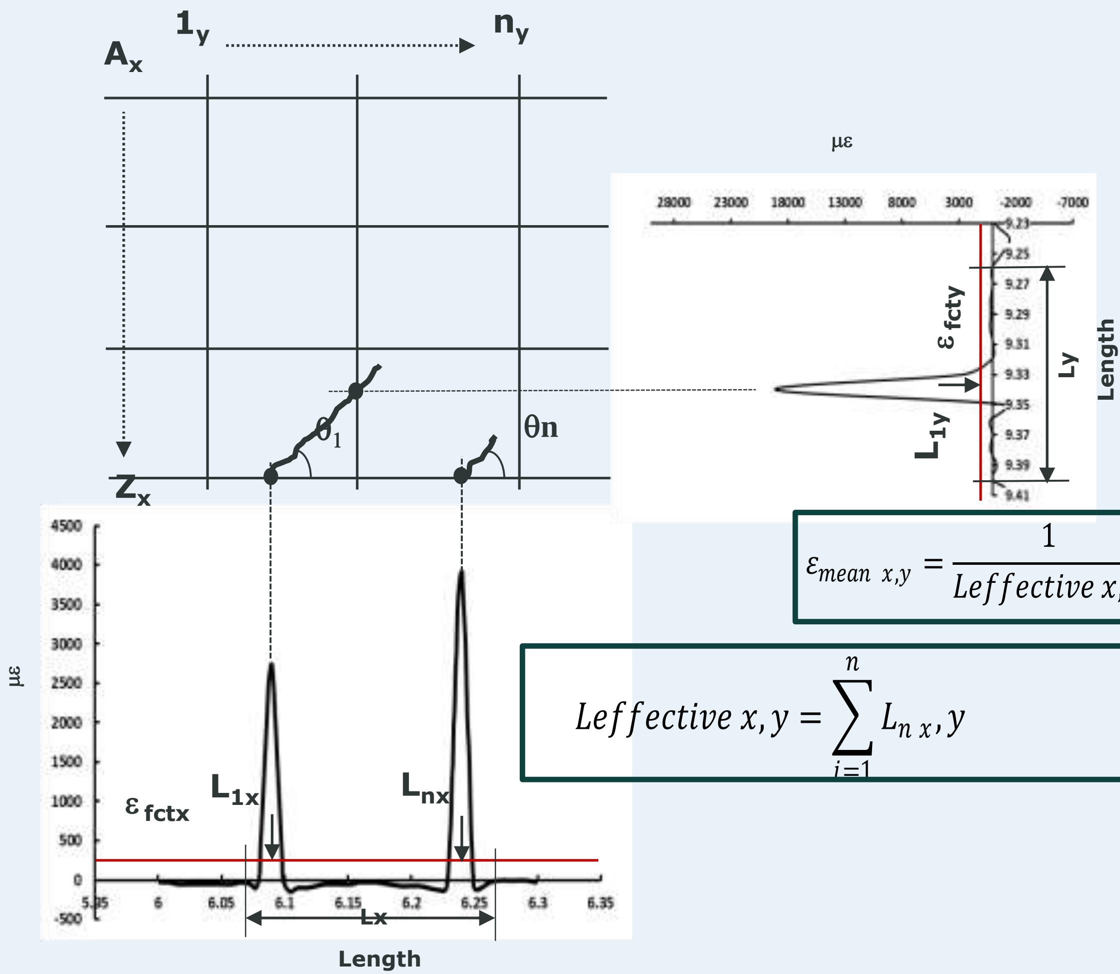


- **Comparing with the acquired photographic evidence, both patterns present a satisfactory agreement**





Calculation of Shear Crack Width



Where N is the total number of cracks

$$\varepsilon_{mean\ x,y} = \frac{1}{Leffective\ x,y}\int_0^{Leffective\ x,y} \varepsilon_{OBR}\ dLeffective\ x,y$$

$$Leffective\ x,y = \sum_{i=1}^{n} L_{n\ x}, y$$

$$\varepsilon_{mean\ x,y} = \varepsilon_{fctx,y} + \frac{\Sigma wx,y}{Leffective\ x,y}$$

$$W_{meanx\ ,y} = \frac{\sum wx,y}{N}$$

Comparison of the obtained average crack widths

Load (kN)	Crack Width (mm)	
	Strain rosette	OBR
203	0.24	0.20
213	0.27	0.21

CONCLUSIONS

• **Feasibility to assess cracking in concrete:** crack initiation and evolution with time and most important: location of cracks and dimensions

•Feasibility to measure deflections (integration of continuous curvature)

Good bonding with concrete surface (smoothing of concrete to facilitate placement).

Good bonding up to high levels of load: crack openings higher than **1 mm**.

Even for load levels higher than **60 % of failure load**, OBR is still measuring properly, providing correct values of strain an **without fiber breaks**.

BENDING

- **The OBR system deployed allowed to predict the formation of the initial cracking (even before visually observed), the location of the cracks and also their width based on the continuous monitoring of strain along the optical fiber.**

- **The obtained results compare very well with the available experimental values obtained from the rest of the sensors as well as with the visual inspection and the values predicted by the non-linear finite element models.**

SHEAR

- Proven feasibility of DOFS monitoring of shear induced cracking on concrete structures
- Continuous strain data at different loading levels were obtained with high spatial resolution by OBR system
- Detection and location of shear cracks were obtained without requiring prior knowledge of the cracked zone
- An extended method to obtain a complete shear crack pattern in concrete structures, including crack inclination and width, using DOFS is actually under development based on the results obtained in this experimental campaign

REAL STRUCTURES

- Possible to observe the evolution of strain due to structural changes with high spatial resolution along an extensive length of the structure
- Relatively simple and easy installations with the use of only one terminal and one connection cable
- Two different types of structural materials (masonry and concrete) denotes the versatility allowed by this technology and the feasibility of bonding the fiber to those materials.

BOOKS AND JOURNAL PAPERS

- BARRIAS, A.; CASAS, J.R.; VILLALBA, S. " A review of distributed optical fiber sensors for civil engineering applications". Sensors, 16, 748. 2016.

- RODRIGUEZ G.; CASAS, J.R.; VILLALBA, S.; BARRIAS, A.: "Monitoring of shear cracking in partially prestressed concrete beams by distributed optical fiber sensors". 8th International Conference on Bridge Maintenance, Safety and Management, IABMAS' 16. 2016.

- RODRIGUEZ, G.; VILLALBA, S.; CASAS, J.R. BARRIAS, A.: "Health monitoring of real Structures by distributed optical fiber". 5th Int. Symposium on Life-Cycle Civil Engineering, IALCCE 2016. 2016. Delft

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RODRIGUEZ, G.; CASAS, J.R.; VILLALBA, S. "*Structural health monitoring by distributed optical fiber in civil engineering: a review*". Structural Monitoring and Maintenance, An International Journal, Vol 2, N.4, pp. 357-382. 2015.

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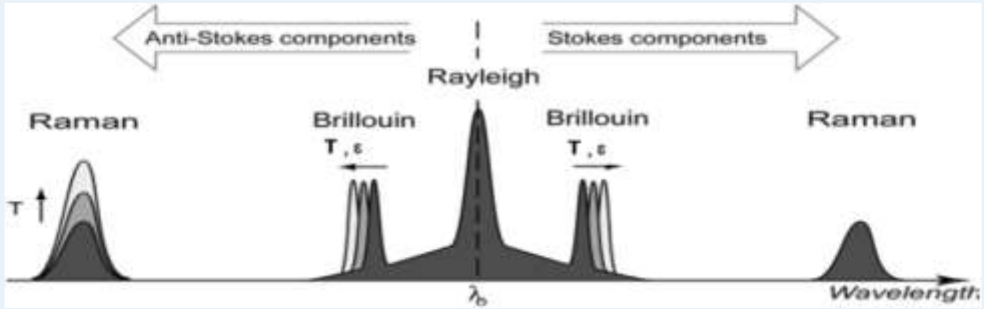
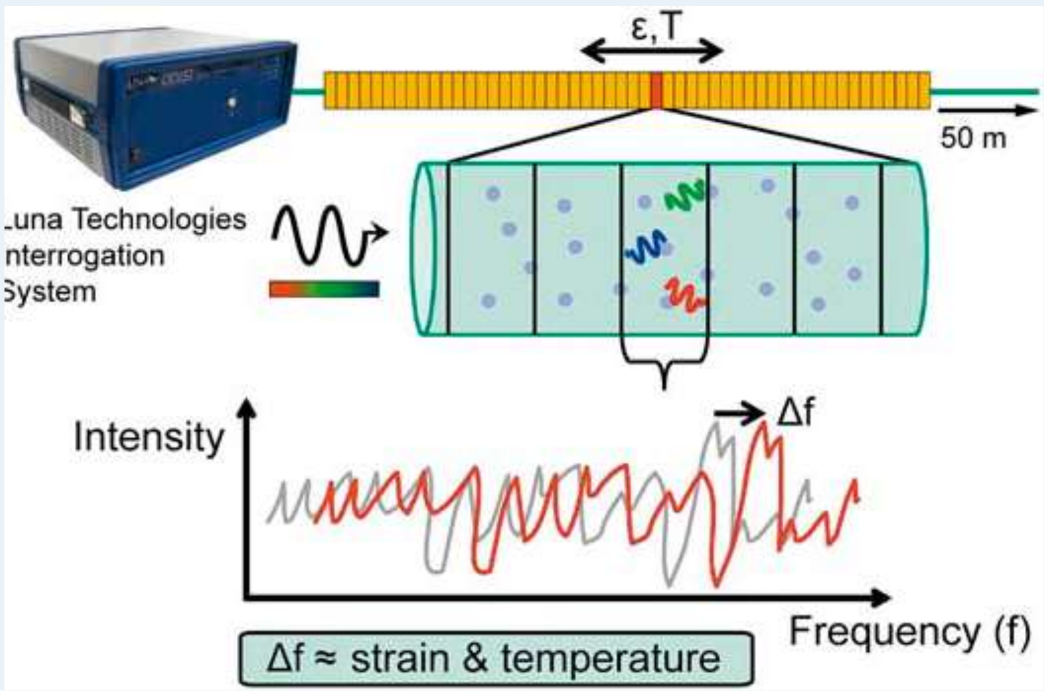
"Una manera de fer Europa"

Thank you !!

THANK YOU FOR YOUR ATTENTION !!

Optical Backscattered Reflectometer (OBR) : Description





In this way, we can use the following expression:

Mechanical strain in bonded fiber i = Strain measured in bonded fiber i – (Index-dependent apparent strain + CTE-dependent apparent strain)

Mechanical με (mean) | με (mean) bonded fiber | RIAS με (mean) | TEAS με (mean)

$$\varepsilon_{L_i} = (\Delta\nu_{B_i} \times k_\varepsilon) - ((k_{nT} \times \Delta\nu_U \times k_\varepsilon) + (\Delta\nu_U \times k_T \times \alpha_S))$$

RIAS – Refractive index apparent strain

TIAS – Thermal expansion apparent strain

$\Delta\nu_B$ = Spectral shift in bonded fiber

$\Delta\nu_U$ = Spectral shift in unbonded fiber

$k_{nT} = \frac{dn}{dT}$ effect – approximately 0.95

Sarajevo Bridge

Temperature compensation

Temperature compensation of DOF 1

Date	με (mean) bonded fiber	RIAS με (mean)	TEAS με (mean)	**Mechanical με (mean)**
29/06/2015	11	-1	1	**11**
16/07/2015	16	90	-114	**40**
15/09/2015	-89	-321	405	**-173**

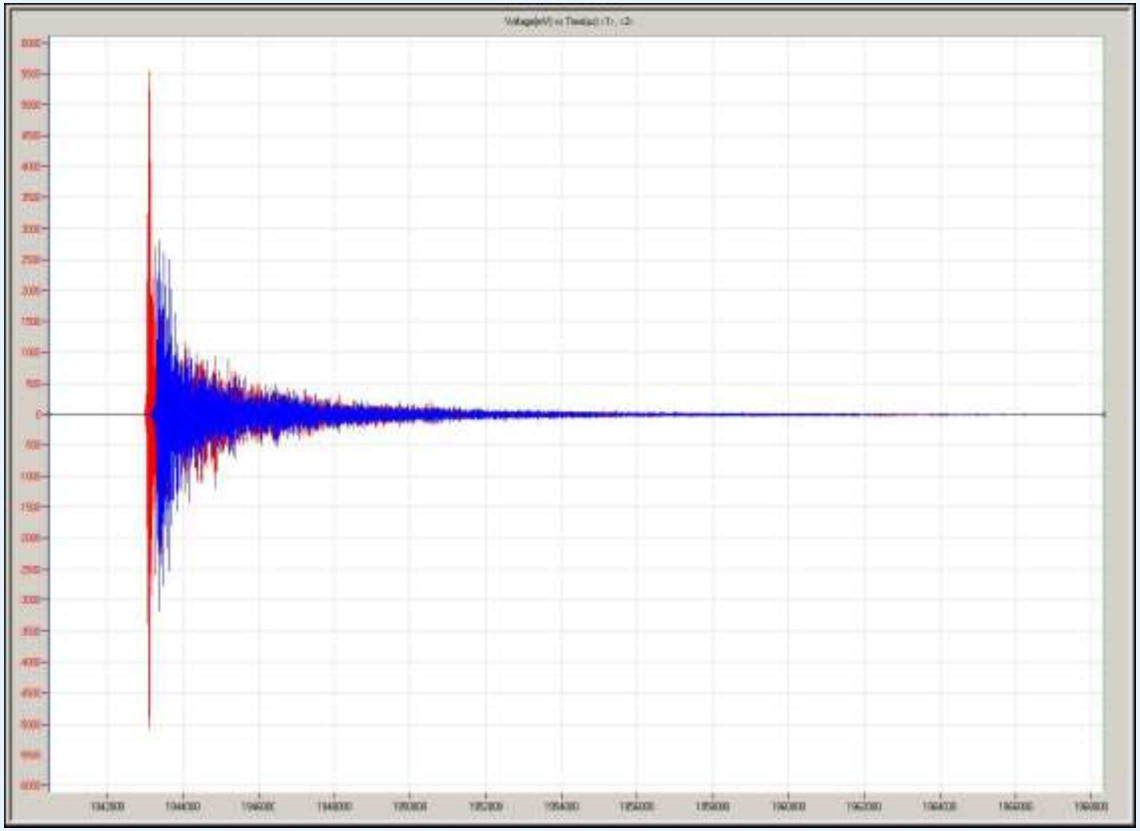
Temperature compensation of DOF 2

Date	με (mean) bonded fiber	RIAS με (mean)	TEAS με (mean)	**Mechanical με (mean)**
06/08/2015	0.23	-6.00	7.58	**-1.35**
01/10/2015	-152	-568	718	**-302**
04/11/2015	-117	-630	796	**-283**
10/12/2015	-209	-976	1234	**-467**
20/12/2015	-202	-953	1205	**-454**
18/01/2016	-270	-1112	1406	**-563**
19/01/2016	-252	-1143	1445	**-554**
20/01/2016	-253	-1160	1466	**-559**

In this way we can implement this average in order to update our previous graphs

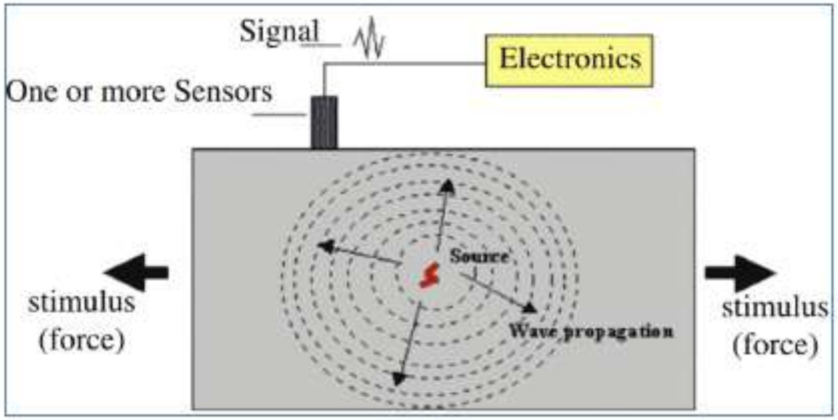
La Barqueta bridge, Sevilla (Spain)

ACOUSTIC EMISSION



Acoustic Emission (AE) techniques

- Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden **redistribution of stress in a material** (≅ earthquake)
- Uses signals generated **within** the structure, which are due to
  - crack growth under stress
  - secondary emissions due to e.g. friction of crack interfaces

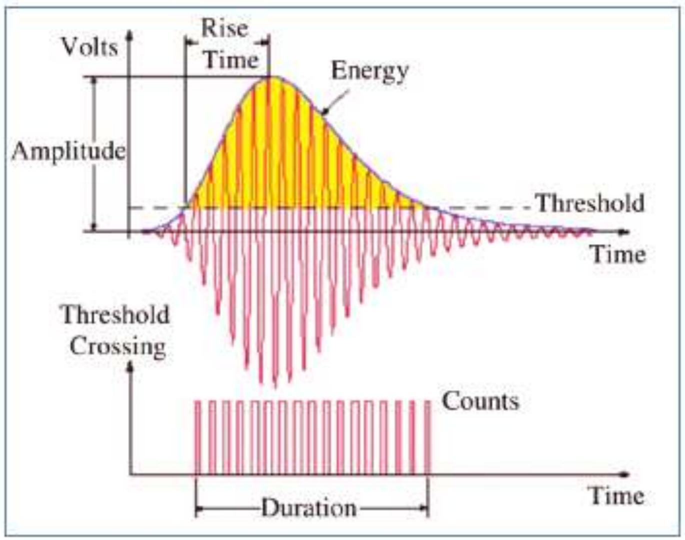


Pros & Contras AE

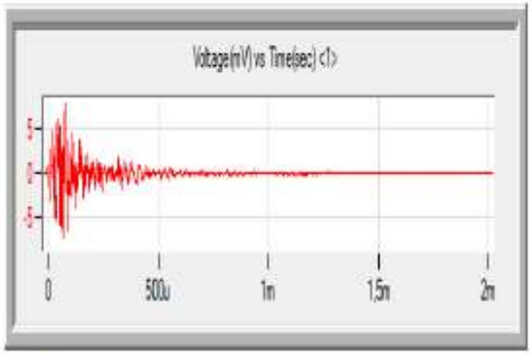
ADVANTAGES	DISADVANTAGES
Distant events can be detected	The structure has to be loaded
The whole structure can be tested all at once	AE activity depends on microstructure of the material
Measuring equipment is easy to use	Ambient noise can disturb the measurement
Access to the whole structure is not required	Localization is not completely precise
Active cracks can be detected	Demanding interpretation of measurements requiring skilled personnel

Level 1: Damage detection

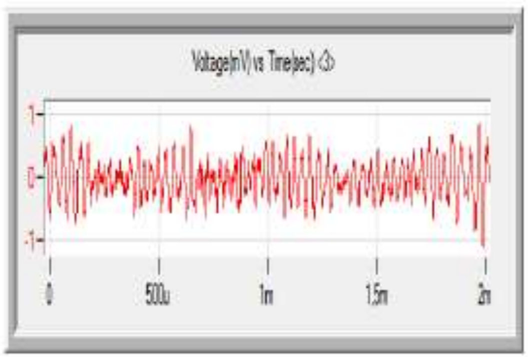
AE signal – basic expressions



Theoretical burst AE signal



Typical burst AE signal



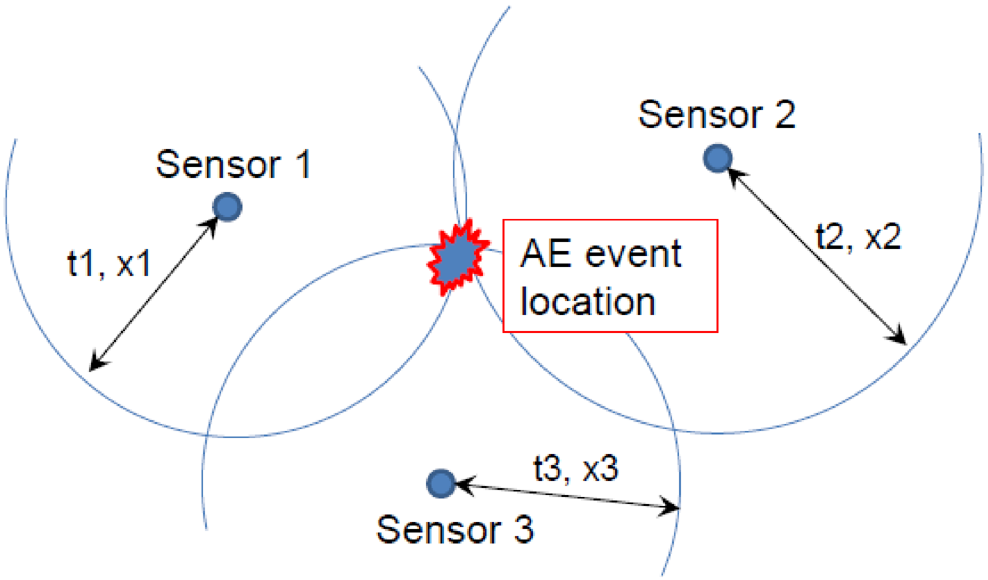
Typical "continuous" AE signal

Level 2: Damage localization

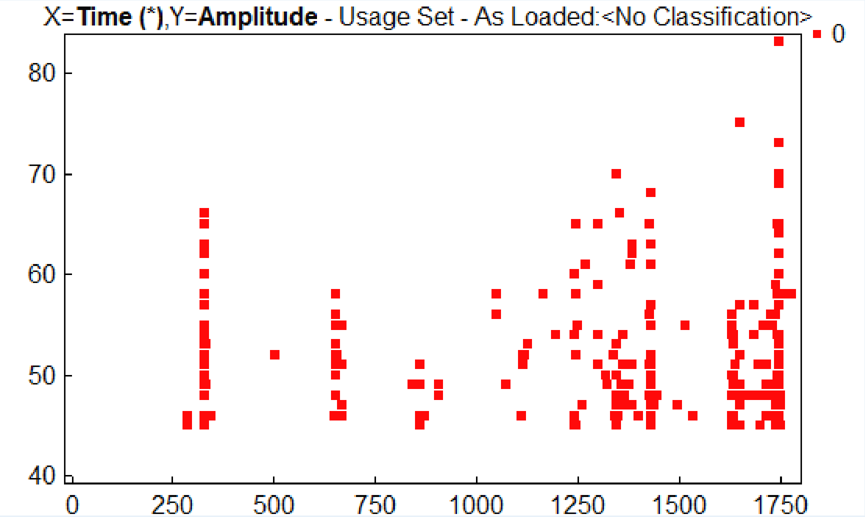
Interpretation of AE data

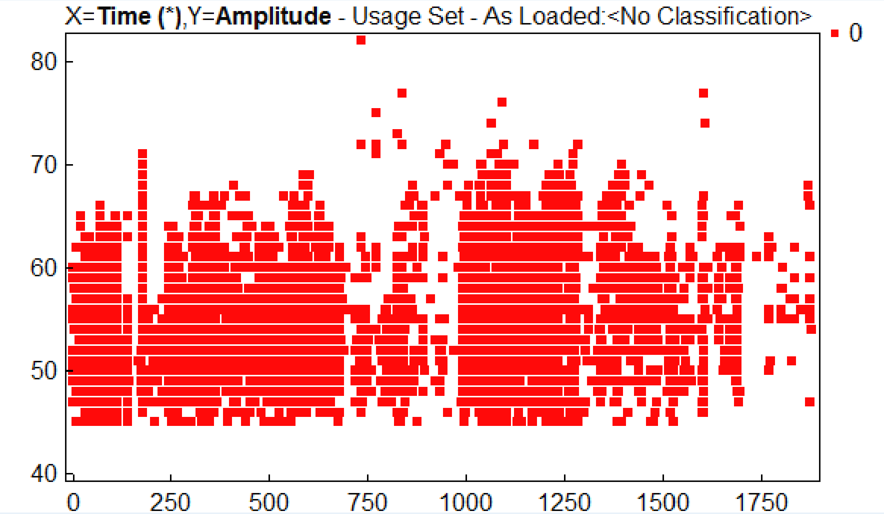
AE event **location determination**

- An AE measuring system can be used to determine the location of the AE event



Level 3: Damage quantification

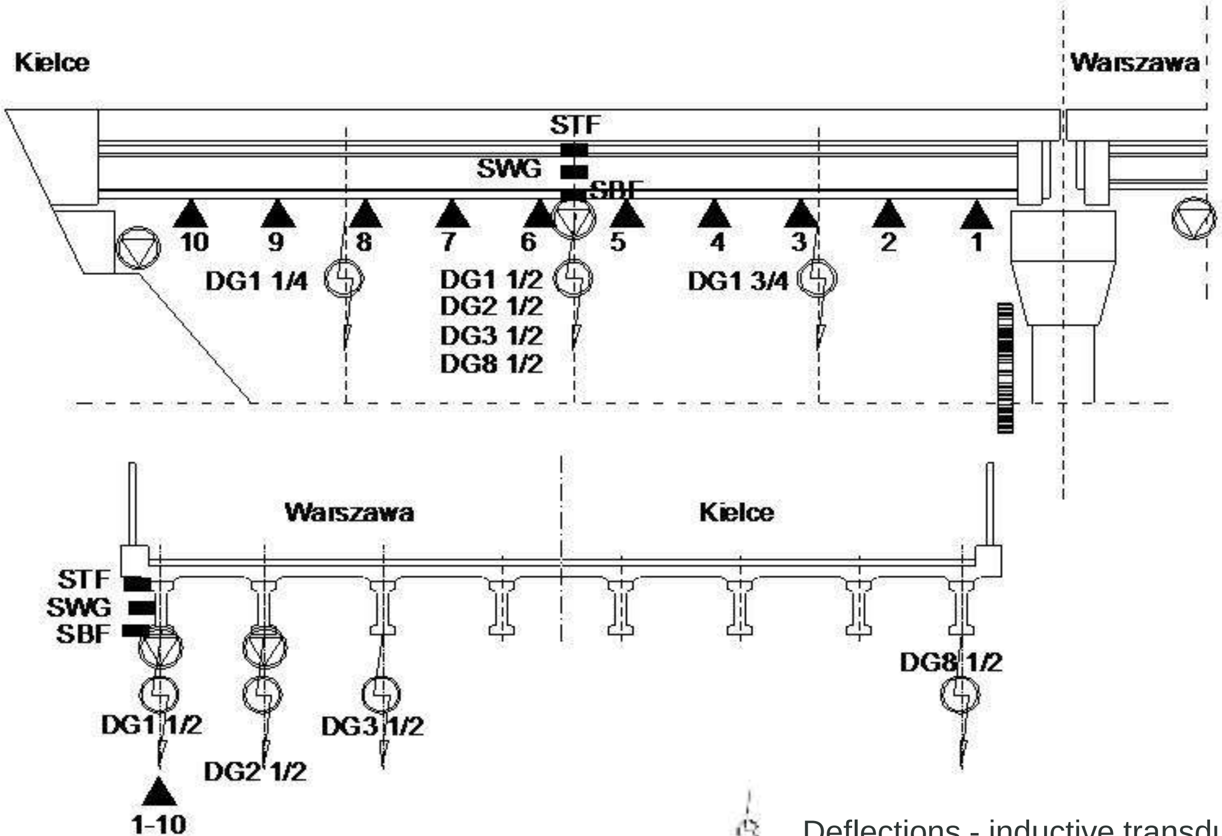




- **History and Severity index**
- **Load ratio and Calm ratio**
- **b- Value**

Proof load test: Barcza bridge (Poland)

- **The bridge** - should be removed in the next future
- **The lateral span** - to not interact with the railway traffic
- **The end girder** - load possibility (short span)



Deflections - inductive transducers

Deflection/Support displacement – Total Station

Strain/stress - electric resistance wire strain gauges

Acoustic emission - sensors

Support displacement – leveling staff


13.11.2008


13.11.2008

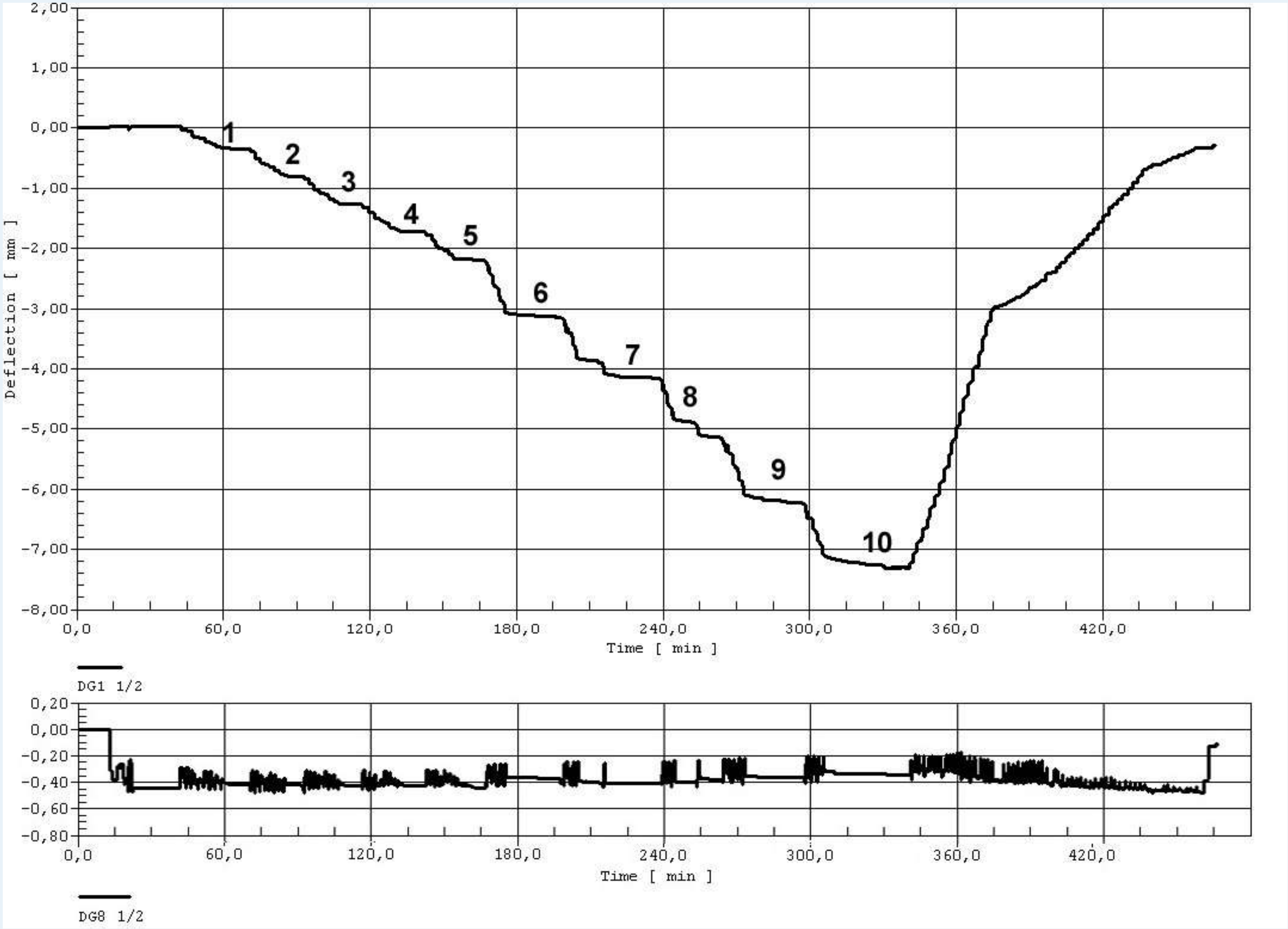

13.11.2008


13.11.2008

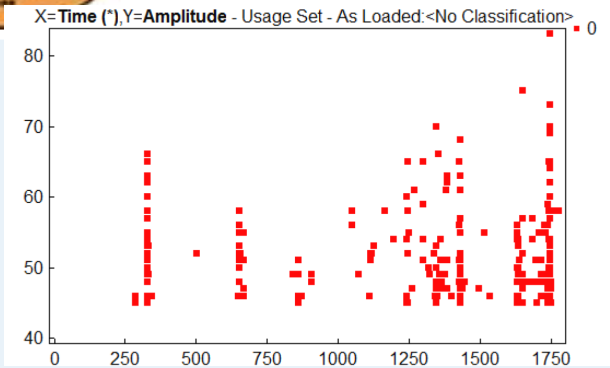

13.11.2008


13.11.2008

Proof load testing - Test results - Deflections/Time

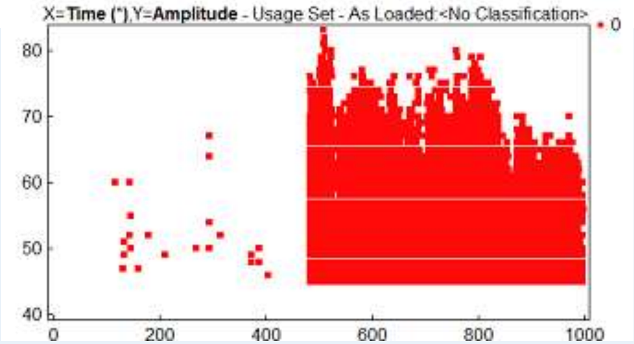


Proof load testing - Test results - Acoustic emission



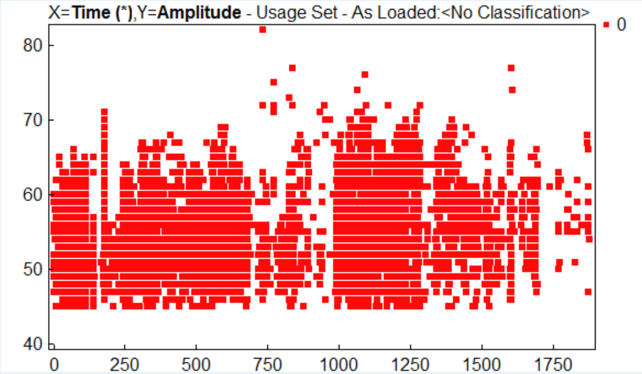
Phase No. 6: five concrete slab layers + one steel layer

Cracking in concrete under bearing



Phase No. 7: five concrete slab layers + two steel layers

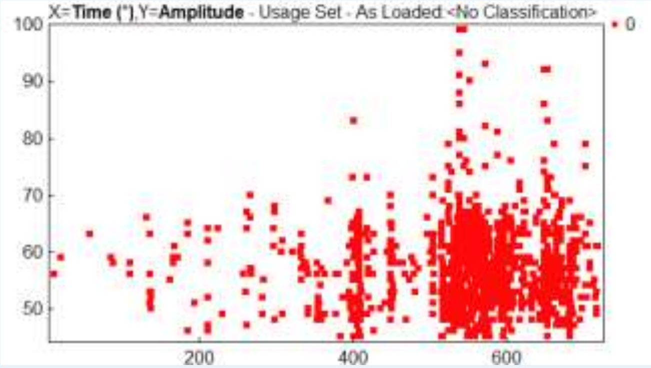
Cracking in concrete under bearing and in transverse beam



Phase No. 8: five concrete slab layers + three steel layer

The most increase of AE signal in the girder midpoint

The visual inspection – no cracks near the girder midpoint

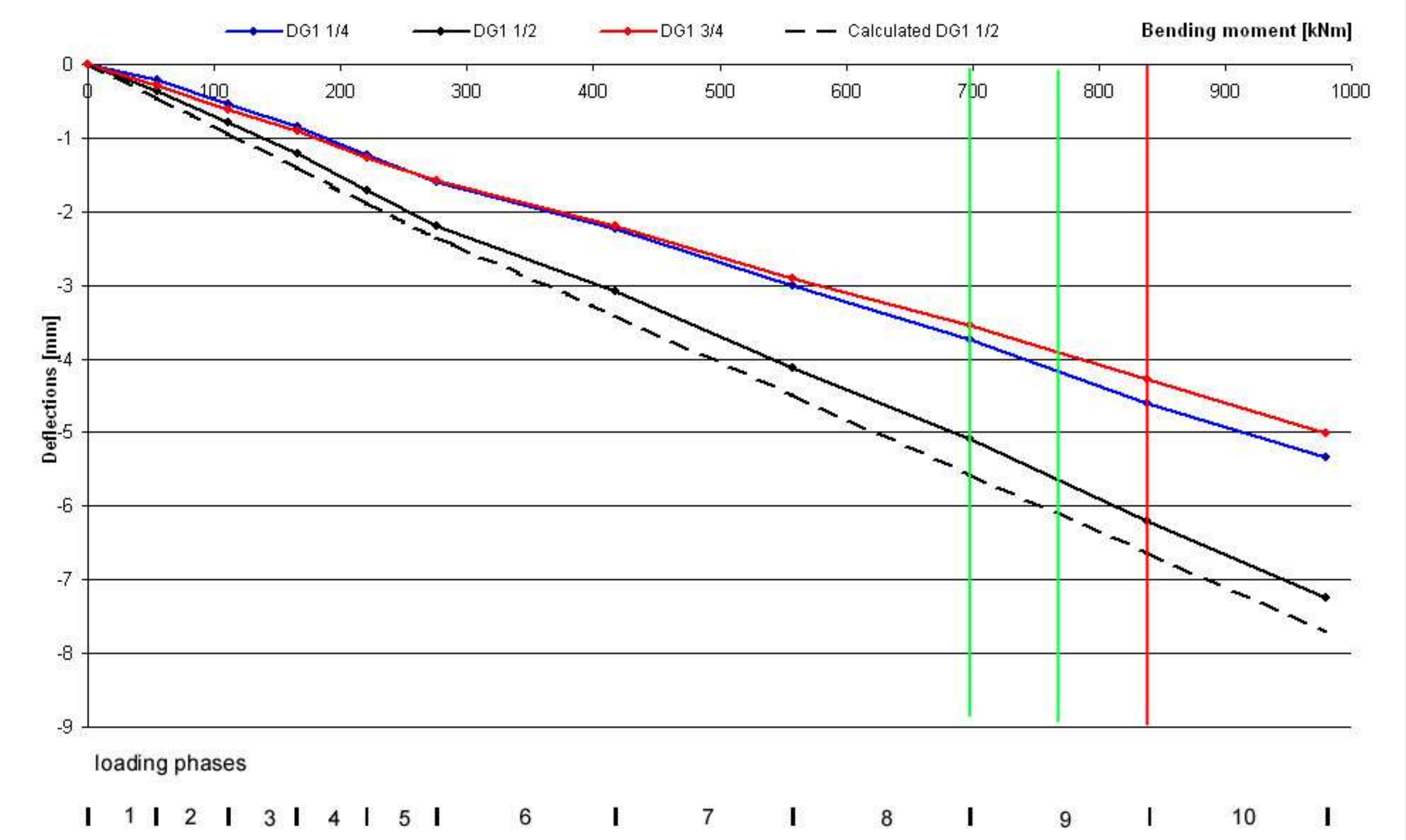


Phase No. 9: five concrete slab layers + four steel layer

The fast increase of AE signal in the girder midpoint - development of existing cracking processes

The visual inspection –the crack near the girder midpoint

Proof load testing - Test results – Deflections/Bending moment



Green lines - loading level where load testing should have been stopped on the base of AE signals

The red line - loading level where the cracking was detected by visual inspection

CONCLUSIONS

Non-linearity in the response of the structure to high loads was successfully detected by the increased AE activity during a proof load test.

The change in AE signal characteristics was recorded beyond the point of the linear response of the structure, proving that the source of the AE waves changed too.

The AE system can successfully be used to detect AE active zones in the structure. These zones could be related to damaged or damage-active zones.

Using a sufficient number of sensors (which is problem specific) the AE system enables exact determination of source location.

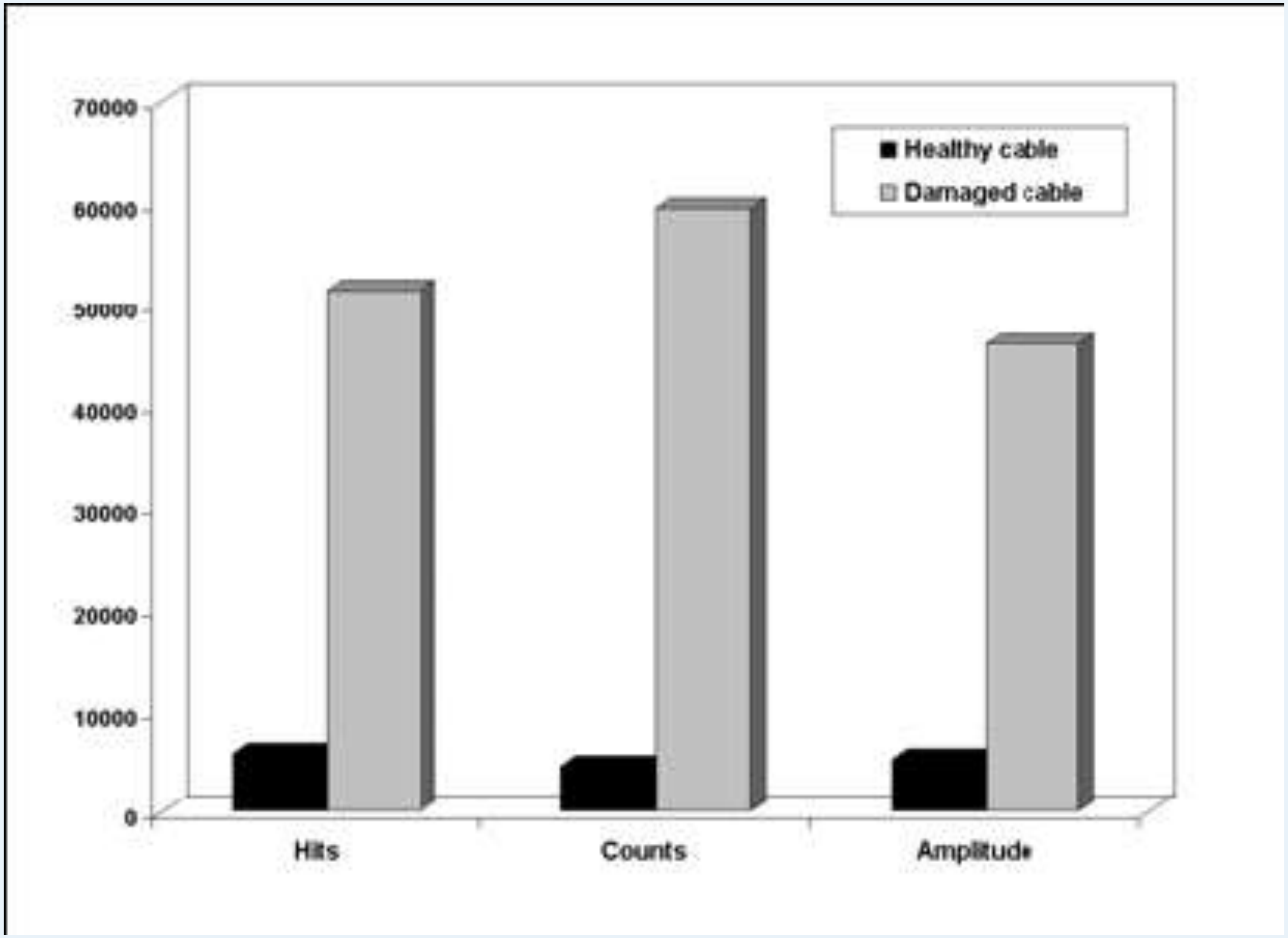
JOURNAL AND CONFERENCE PAPERS

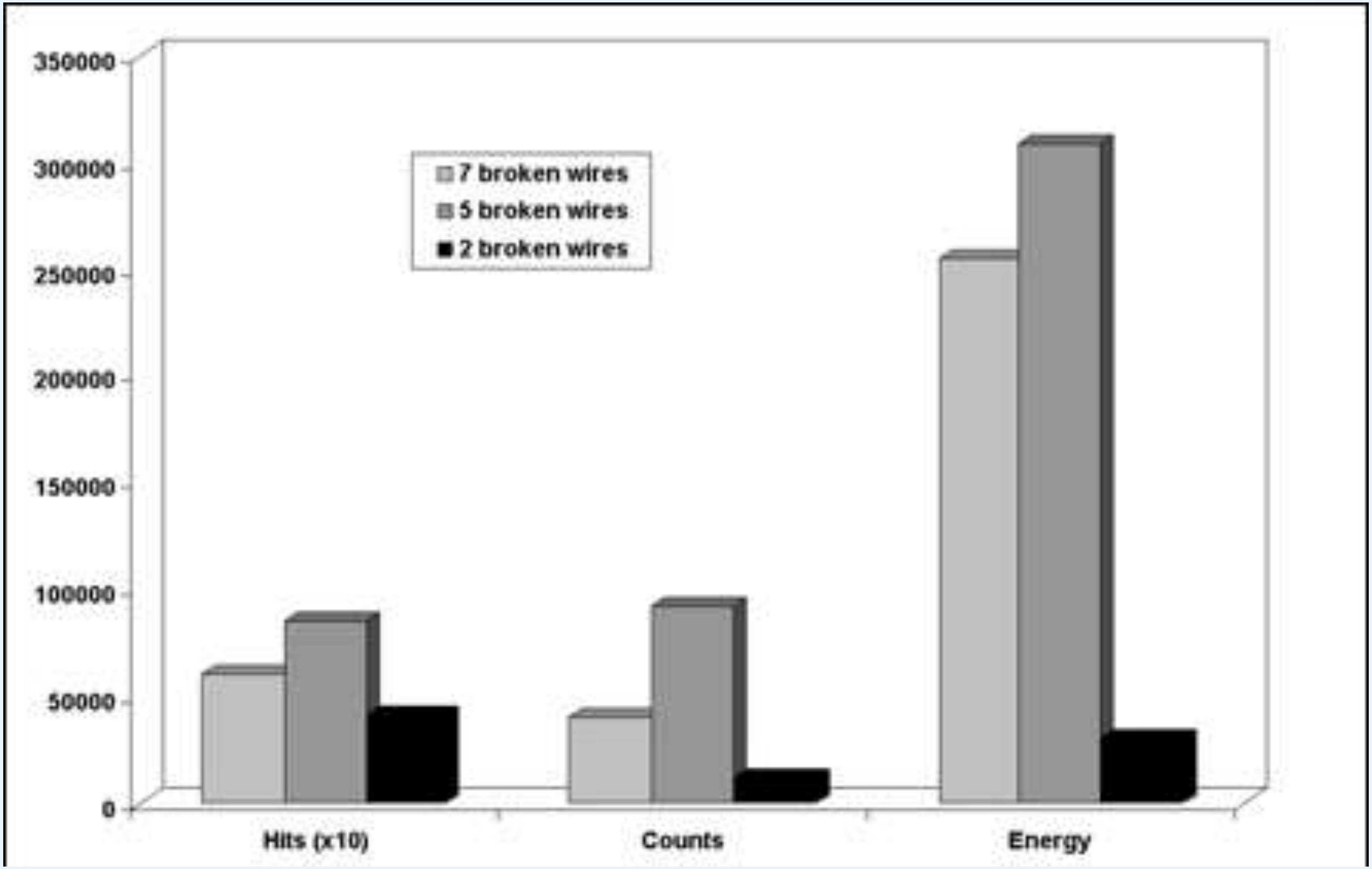
OLASZEK, P.; CASAS, J.R., SWIT, G.: "*On-site assessment of bridges supported by acoustic emission*". Proceedings of the Institution of Civil Engineers (ICE), Journal of Bridge Engineering, in press

OLASZEK, P.; LAGODA, M.; CASAS, J.R. " *Diagnostic load testing and assessment of existing bridges. Examples of application*". Structure and Infrastructure Engineering, Vol. 10, N.6, pp. 834-842, 2014.

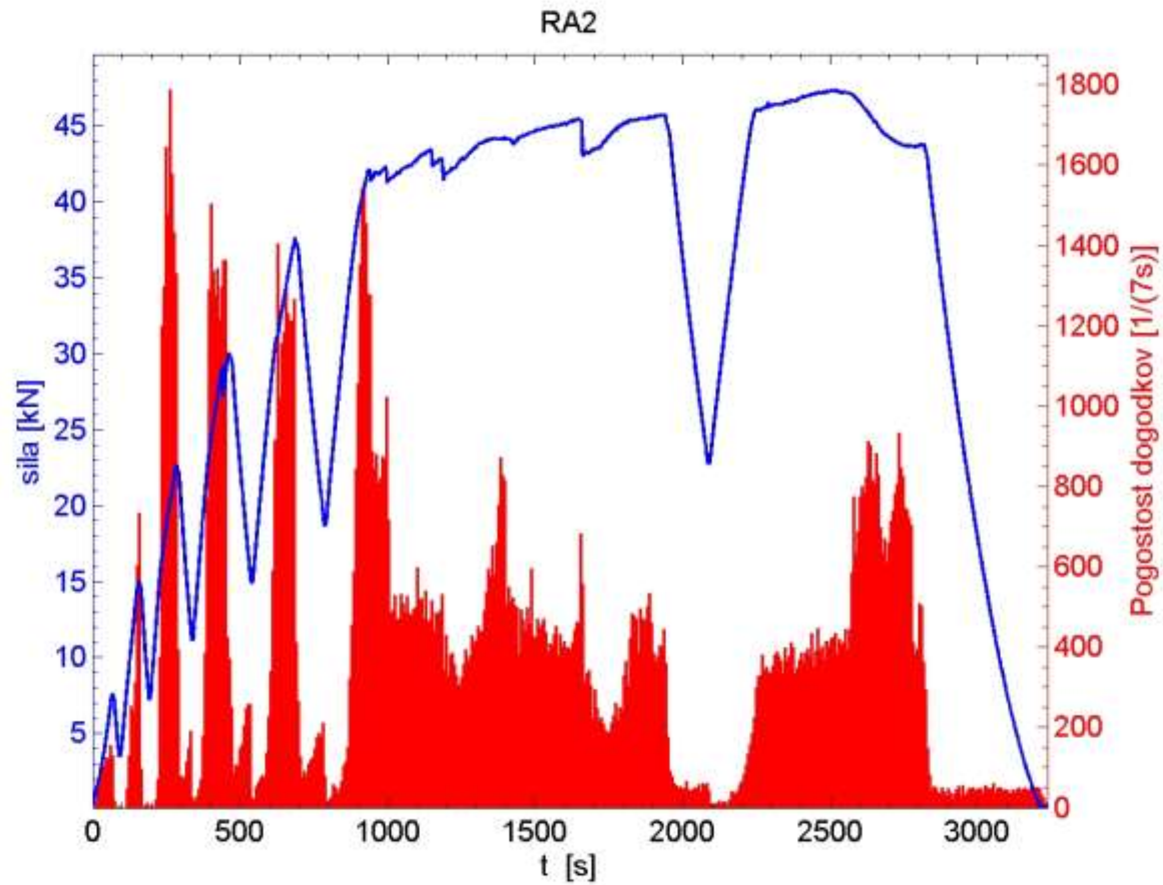
OLASZEK, P.; SWIT, G.; CASAS, J.R. : *Proof load testing supported by acoustic emission. An example of application.* V International Conference on Bridge Maintenance, Safety and Management, IABMAS' 10. Philadelphia, 2010

Steel: cable elements



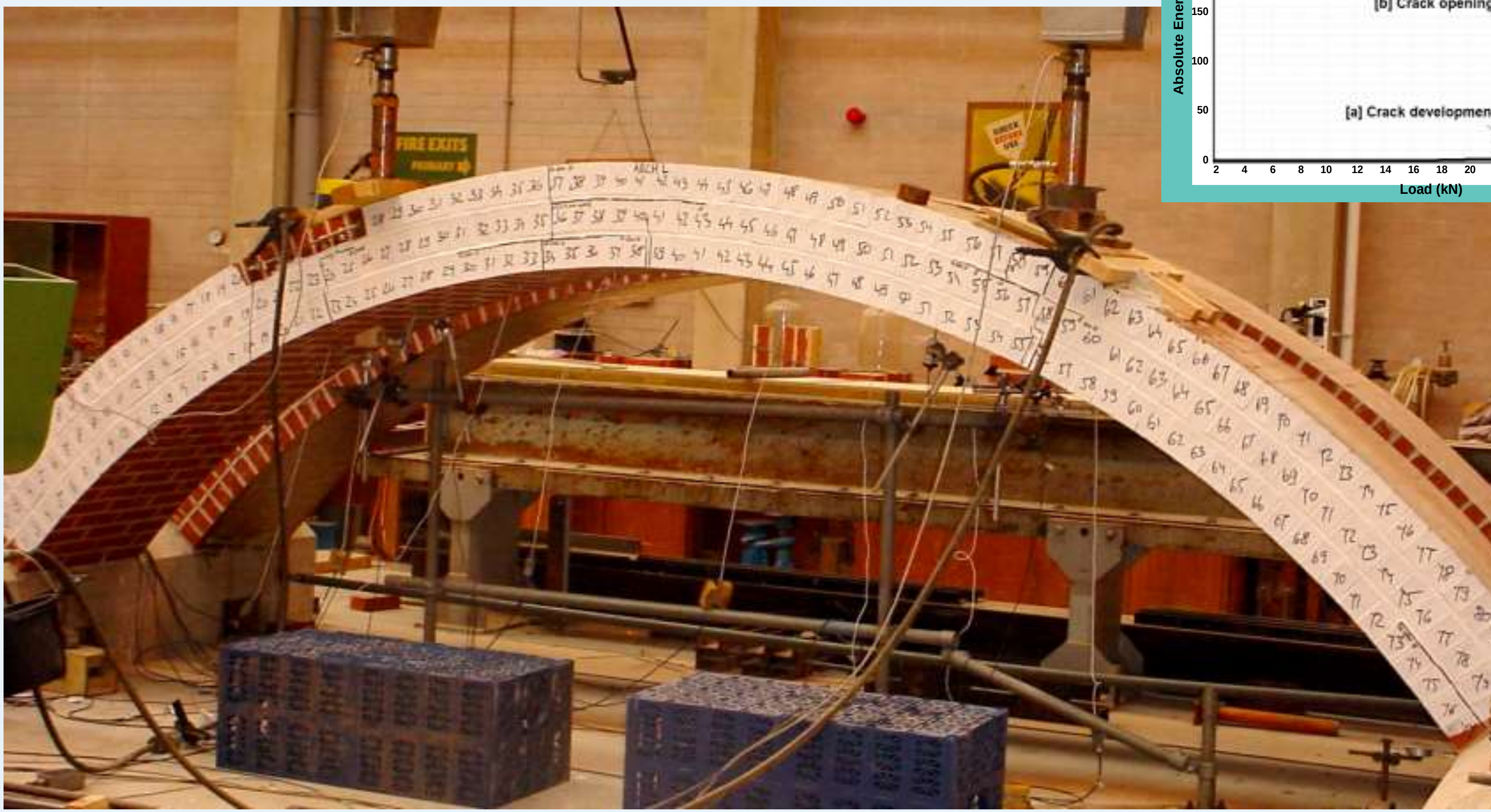

350000
300000
250000
200000
150000
100000
50000
0
7 broken wires
5 broken wires
2 broken wires
Hits (x10)
Counts
Energy

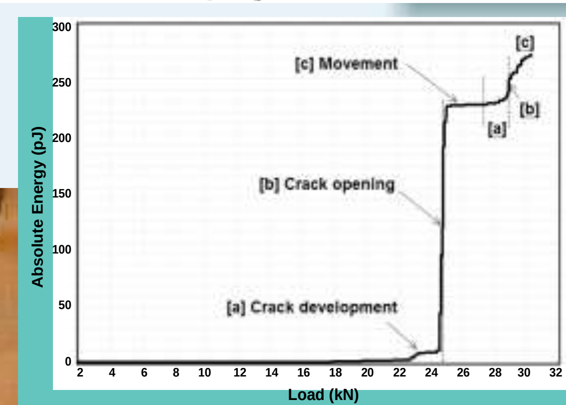
Concrete



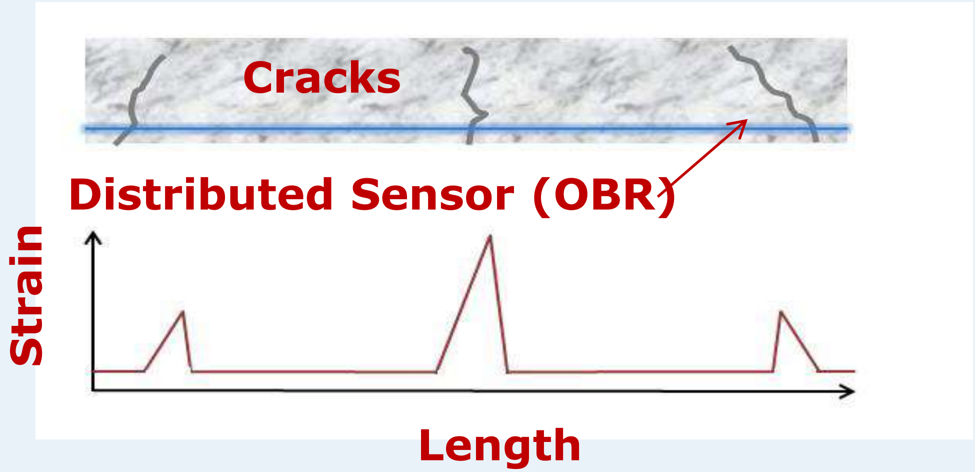
Kayser effect

Masonry




Absolute Energy (pJ)
Load (kN)
[a] Crack development
[b] Crack opening
[c] Movement
[a]
[b]
[c]
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

Why Distributed Fiber Optic Sensors (DOFS) ?



CHARACTERISTICS

Practical solution to measured cracks

Continuous (in space) monitoring

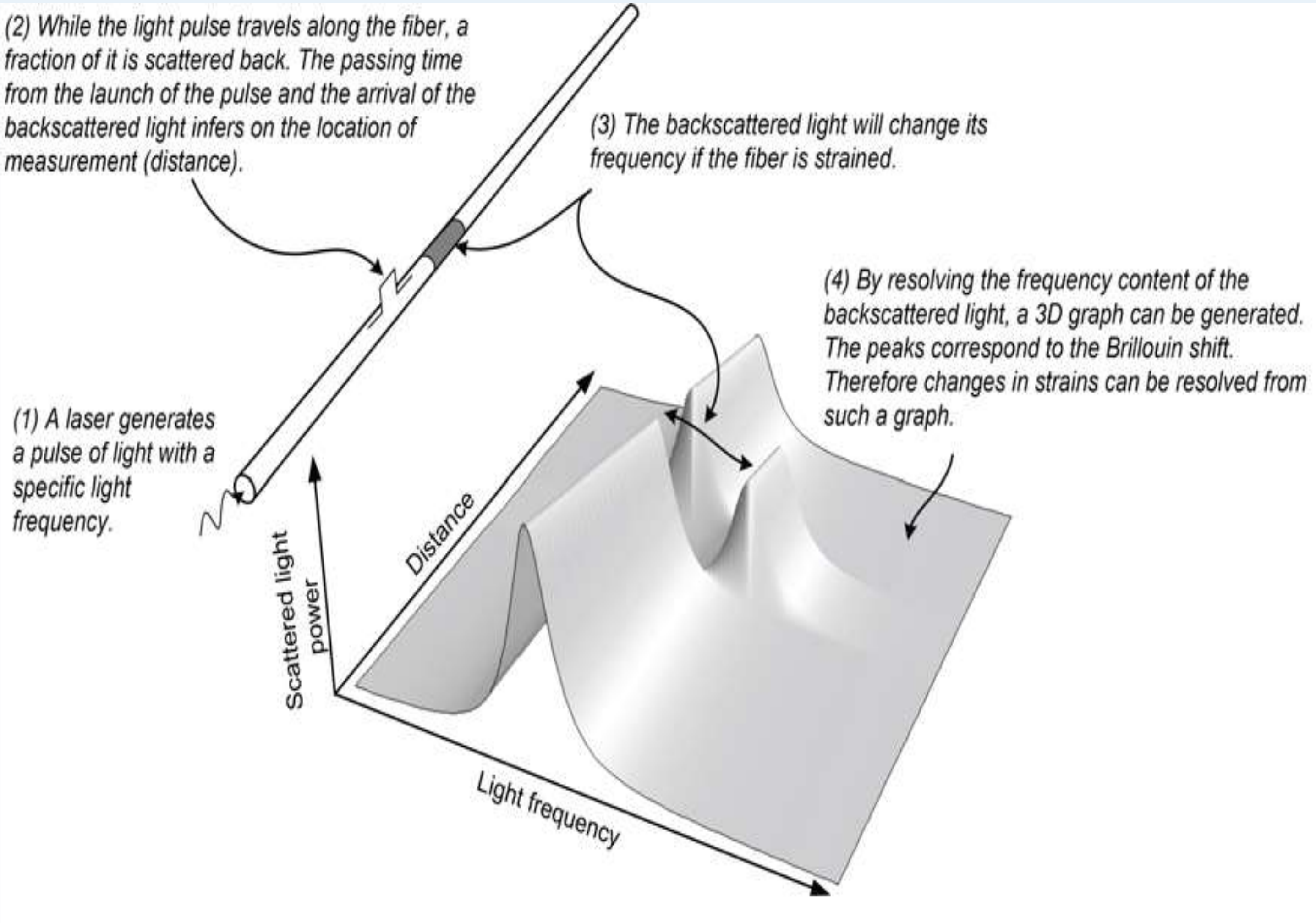
high spatial resolution (mm): we do not have to know in advance where the damage will appear

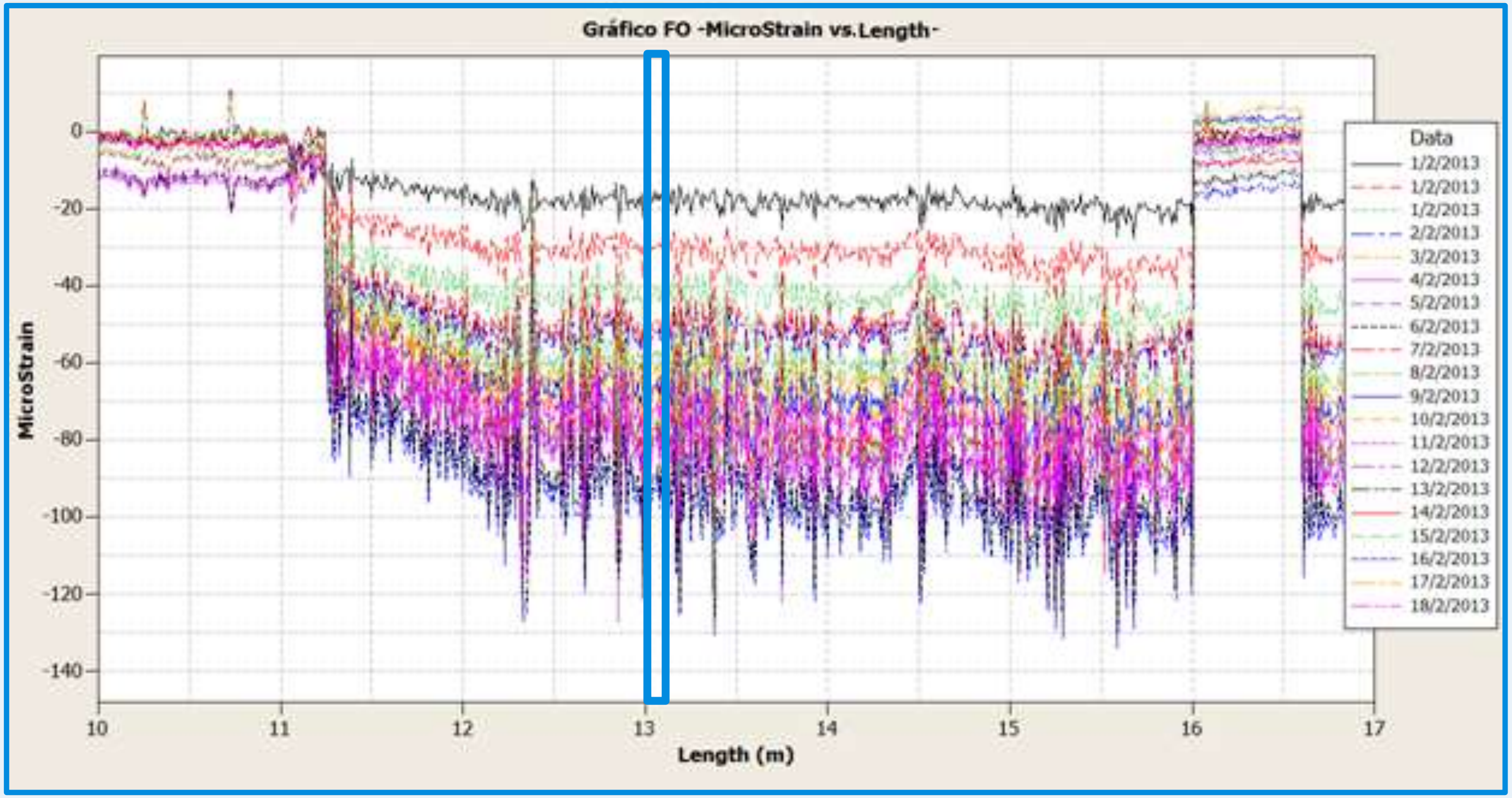
High sensitivity

Fast and easy instalation

Improvement of SHM systems

Optical Backscattered Reflectometer (OBR) : Background





Segment between 11 and 16 meters as an example

Tests results and discussion

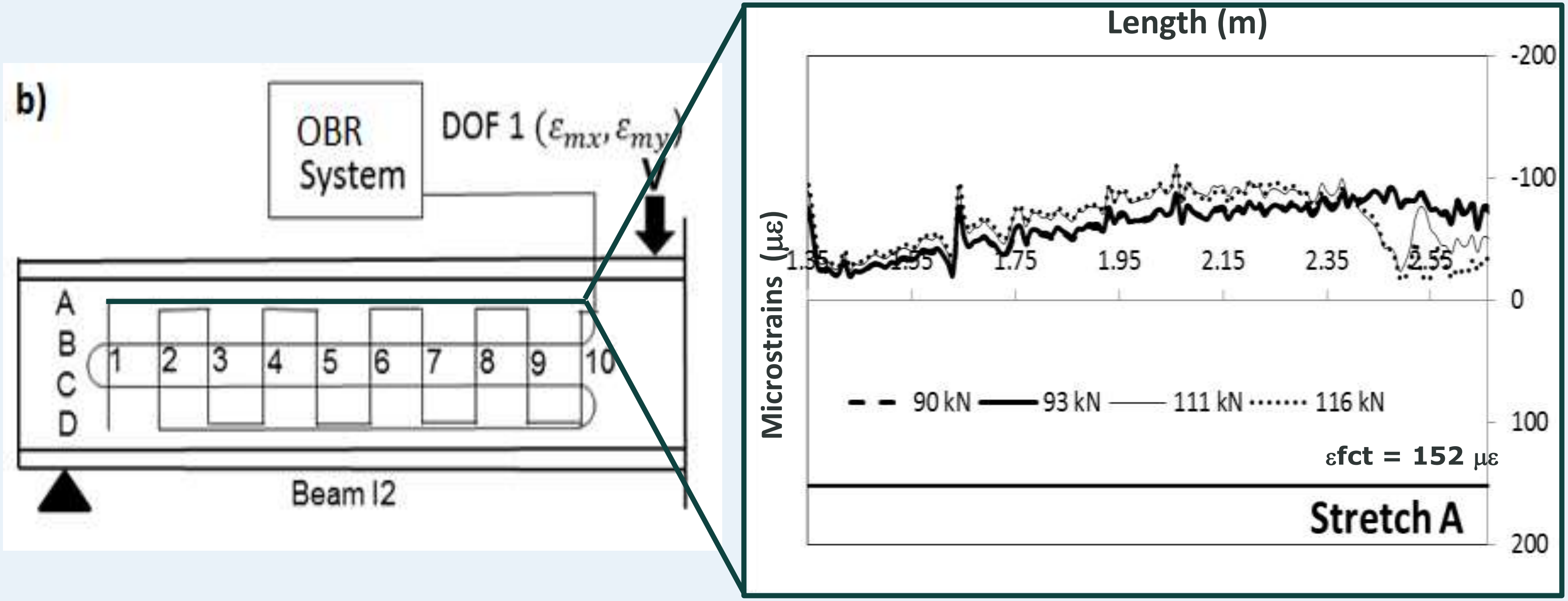
Material properties

Specimen	f_{cm}	f_{ct}	E	εfct
	(MPa)	(MPa)	(MPa)	με
Beam I1	325	4.6	36440	126
Beam I2	293.5	4.15	27264	152

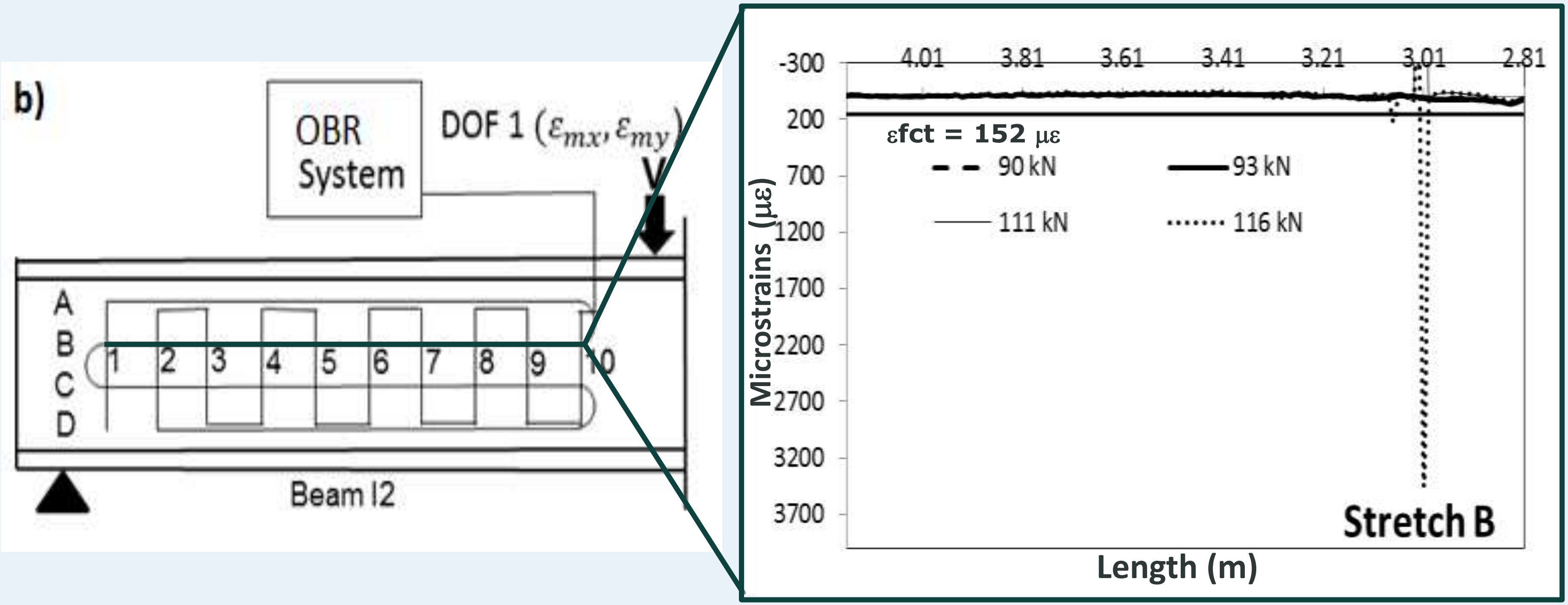
Level of extension that originates cracking of the concrete

Tests results and discussion

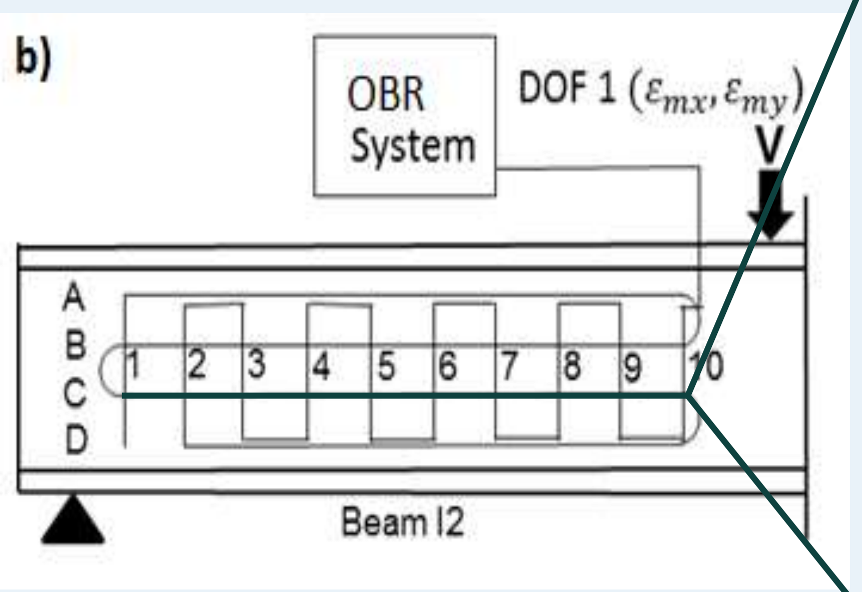
Beam I2 – Horizontal Sections

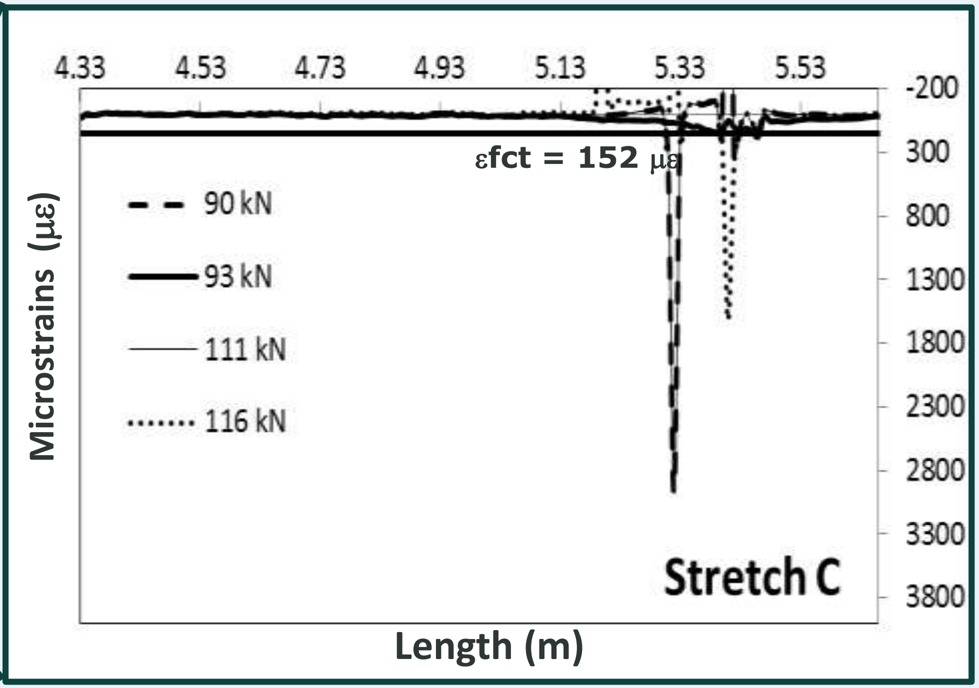


Beam I2 – Horizontal Sections

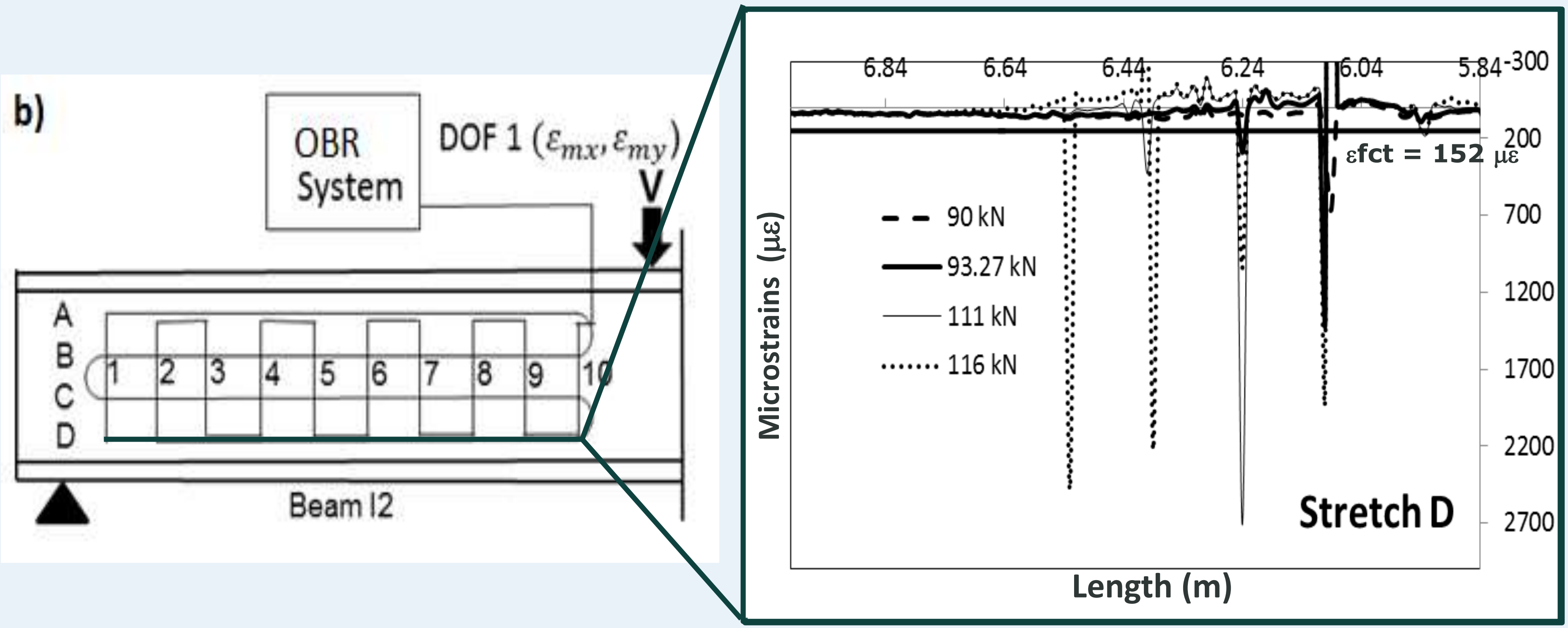


Beam I2 – Horizontal Sections

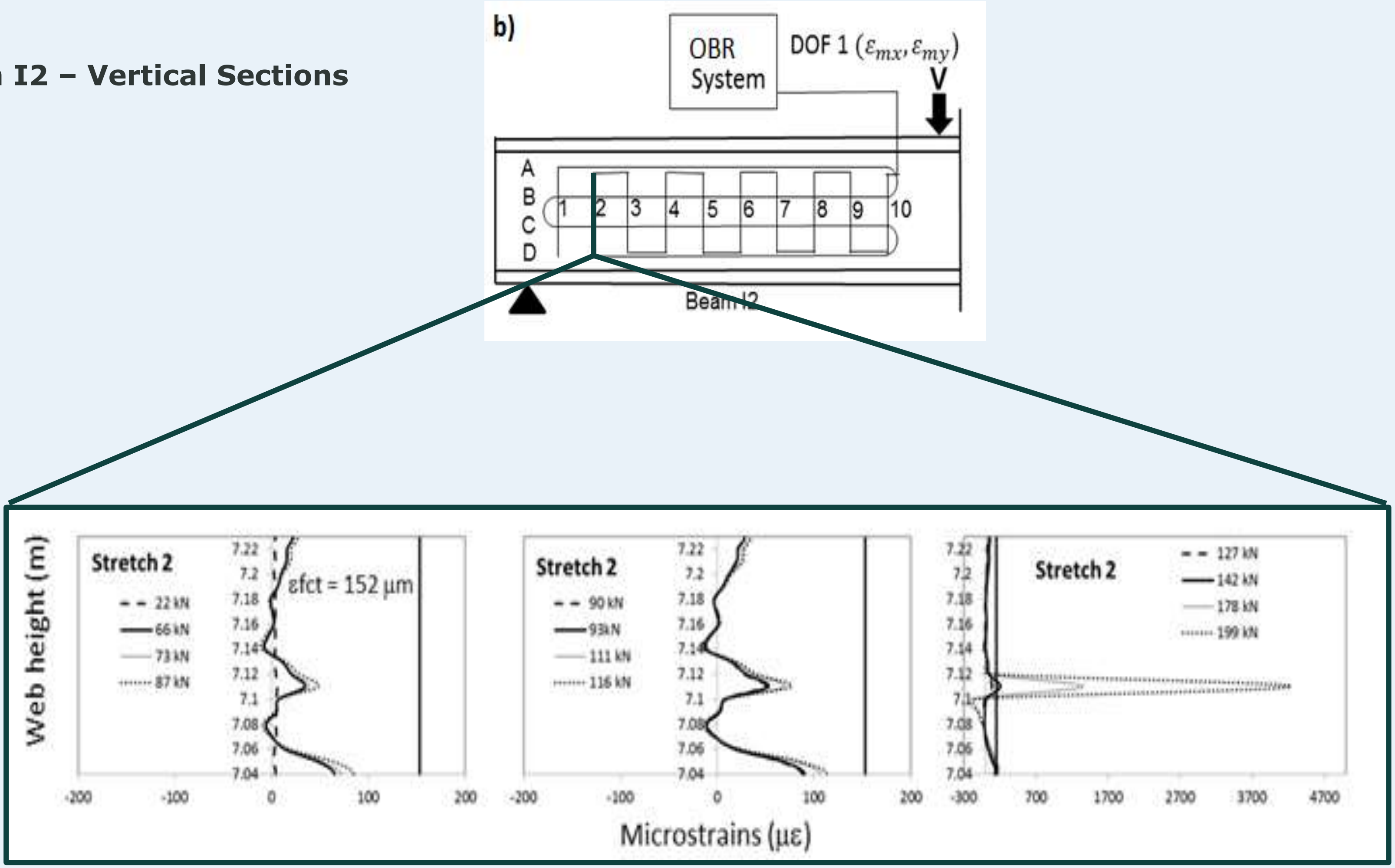




Beam I2 – Horizontal Sections



Beam I2 – Vertical Sections



- **The effect of the general unloading that the bridge suffered due to the removal of the slabs, pavement and the milling of the agglomerate, when compared to the loading at the time of calibration, is detected**

- **Furthermore, the continuous increase of compression at the bottom fiber of the monitored span can also be explained by the increase of load verified by the adjacent span that ended up having a greater new load than the one imposed on the monitored span**

- **In this way, from the constitutive equations, and the stress-strain diagram of the material, it is possible to obtain a maximum stress increment for DOF1 of -11.42 MPa and for DOF2 of -21.16 MPa**

- **So, it is possible to conclude that the actions conducted in this period did not posed an harmful impact for the monitored structure**