New features on instrumentation of structures.

By Dario Rinaldis, Paolo Clemente & Michele Caponero
ENEA

- This paper aimed at illustrating some principles on which to base a complex monitoring system designed for monitoring bridge structures subjected to the influence of seismic activities.
- The system is to contain a specially prepared measuring instrumentation based on continuous monitoring principle: accelerometers and strain and deformation measuring devices - fiber optic Bragg grating (network of parallel wires) sensors.

SECTION I

Some examples

DYNAMIC TESTING OF STRUCTURES

The data bases for dynamic characteristics of building structures are sufficiently populated. However, data on dynamic characteristics of special structures such as bridges and in particular cable-stayed bridges are scarce.

The data bases are in general obtained from two sources:

- **dynamic testing of structures** (forced vibration, ambient vibration, etc),

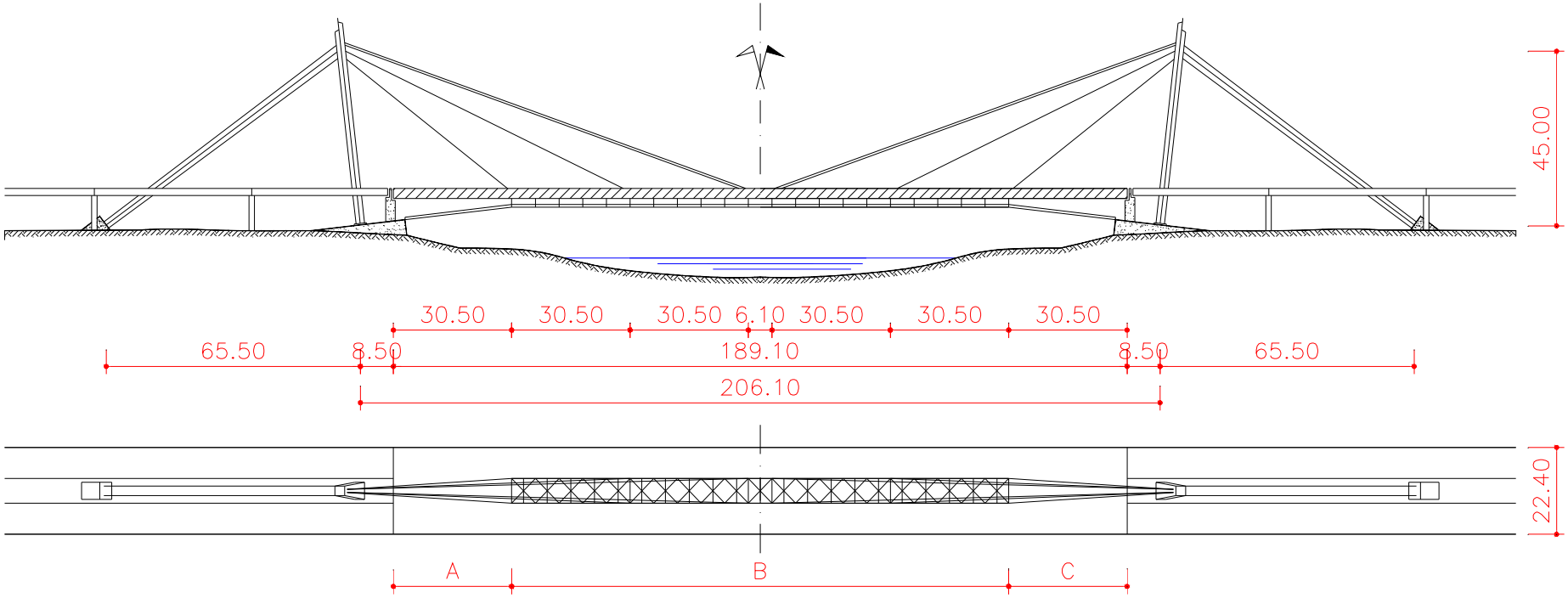
- **analyses of data from instrumented structures**. This however is dependent on strong-motion response data, which depends on a long duration project that is costly to implement and maintain.

Whenever possible, low-amplitude tests are used to verify the results of analytical studies.

The INDIANO Bridge – Florence Italy

THE STRUCTURE

The Indiano Cable-Stayed Bridge over the Arno River in Florence was completed and opened to the traffic in 1977. The main span is 189.1 *m.*

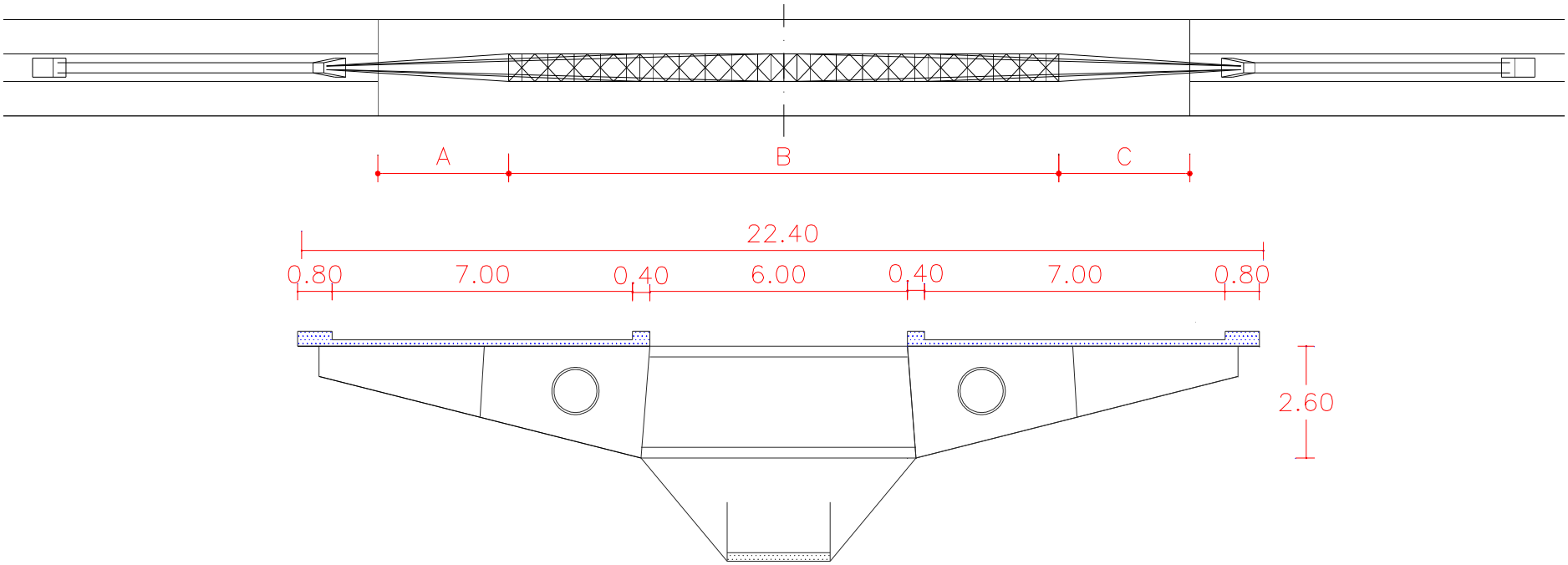


GIRDER

In the central portion of the girder (zone B), whose length is 128.1 *m*, two boxes spaced of 6.0 *m* compose the cross-section.

They are linked one to another, at the upper and lower levels, by means of truss structures. As a result, the beam is characterized by large torsional stiffness.

The boxes have a width of 4.0 *m* and a height variable from 2.6 *m* to 1.6 *m*.



PRELIMINARY TEST

The experimental analysis was organised in two phases.

A team was first dispatched to Indiano Bridge to get a first hand understanding of the approach to be taken and the constraints to be dealt with for ambient testing of Indiano Bridge.

At that time, several preliminary records were obtained using three sensors only.

The preliminary analyses of these records provided an understanding as to how to optimise the testing to be conducted during a later period.

Just after the completion of the construction, the bridge was tested.

The structure was excited by dropping a suspended mass of 0.8 $MN/(m/s^2)$ from the middle of the span. In this way only the first mode was excited.

An associated frequency of 0.61 *Hz* was estimated.

EXPERIMENTAL SET-UP

Eight Kinemetrics SS1 seismometers,

an HP3566A signal conditioner and

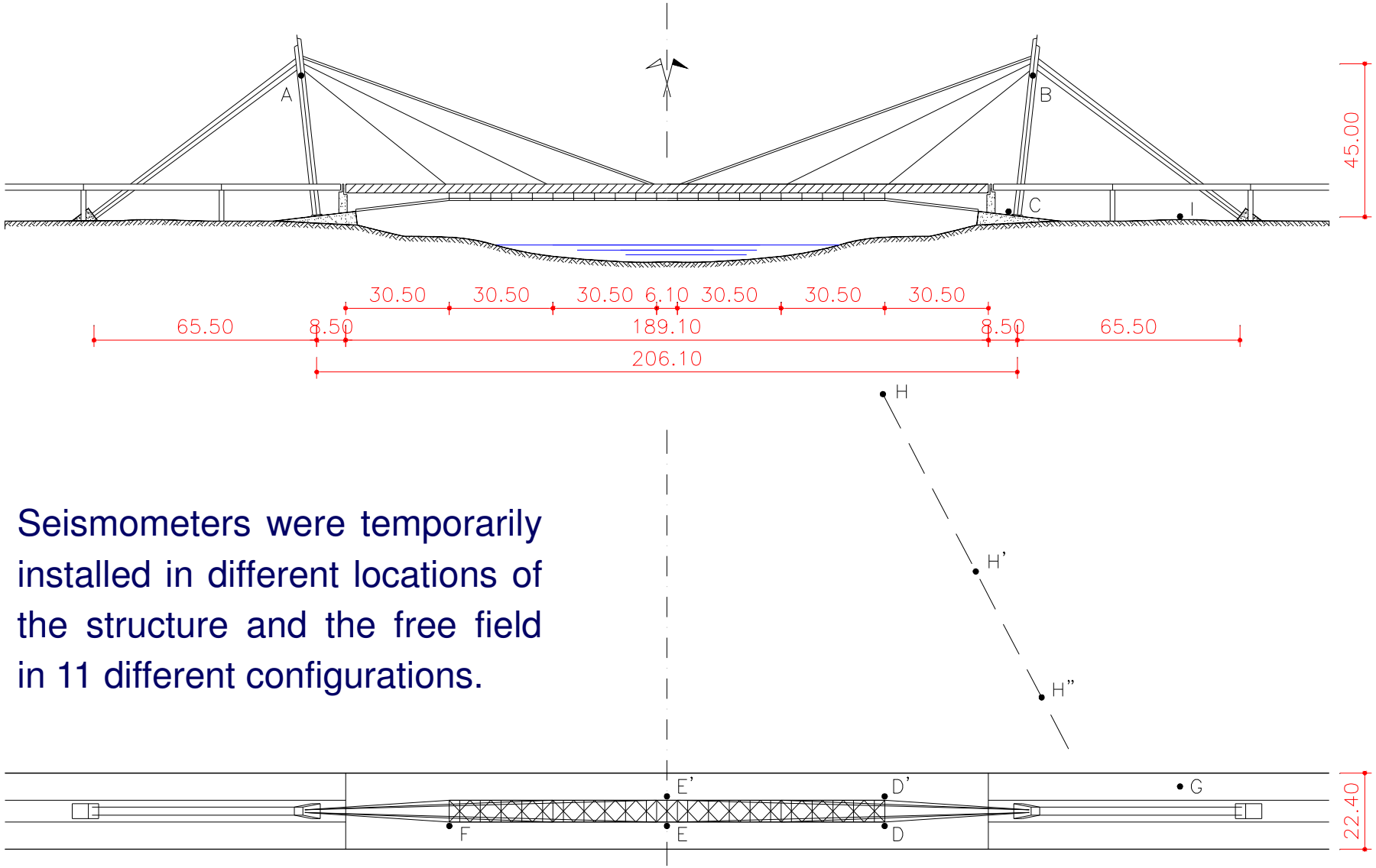
a laptop

composed the experimental set-up.

EXPERIMENTAL SET-UP

The synchronized signals from several seismometers were recorded by the acquisition system and analysed in real time in order to have a first glance at the experimental data.

SENSOR LAYOUT

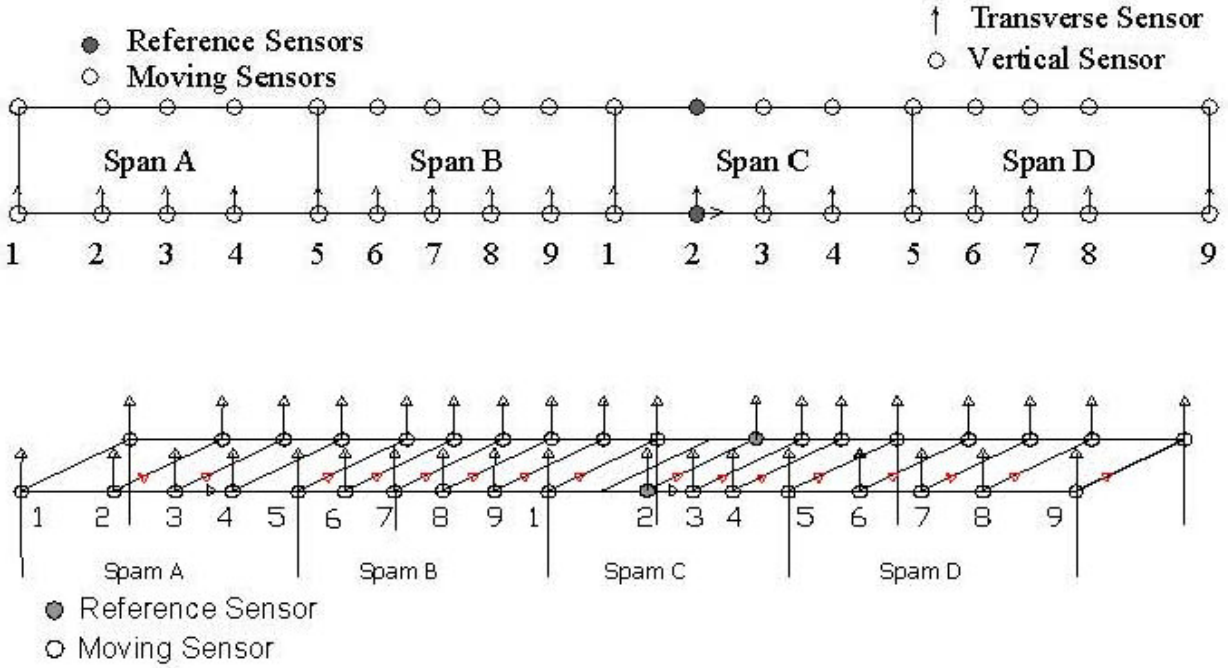


Seismometers were temporarily installed in different locations of the structure and the free field in 11 different configurations.

EXPERIMENTAL FREQUENCIES AND DAMPING

Sensor location	Freq. (Hz)								
Tower longitudinal	**0.61**					1.41	1.61	2.25	
Tower transversal				1.04	1.15				2.61
Deck vertical	**0.61**			1.04	1.15	1.41	1.61	2.25	
Deck transversal			0.87						2.61
Deck longitudinal	**0.61**	0.81				1.41	1.61		
Damping	6.5%	6%	4.5%	4.8%	-	-	3%	2.5%	-

From "INVESTIGATION OF DYNAMIC RESPONSE AND MODEL UPDATING OF INSTRUMENTED R/C BRIDGES
Vassilios LEKIDIS & al.
"



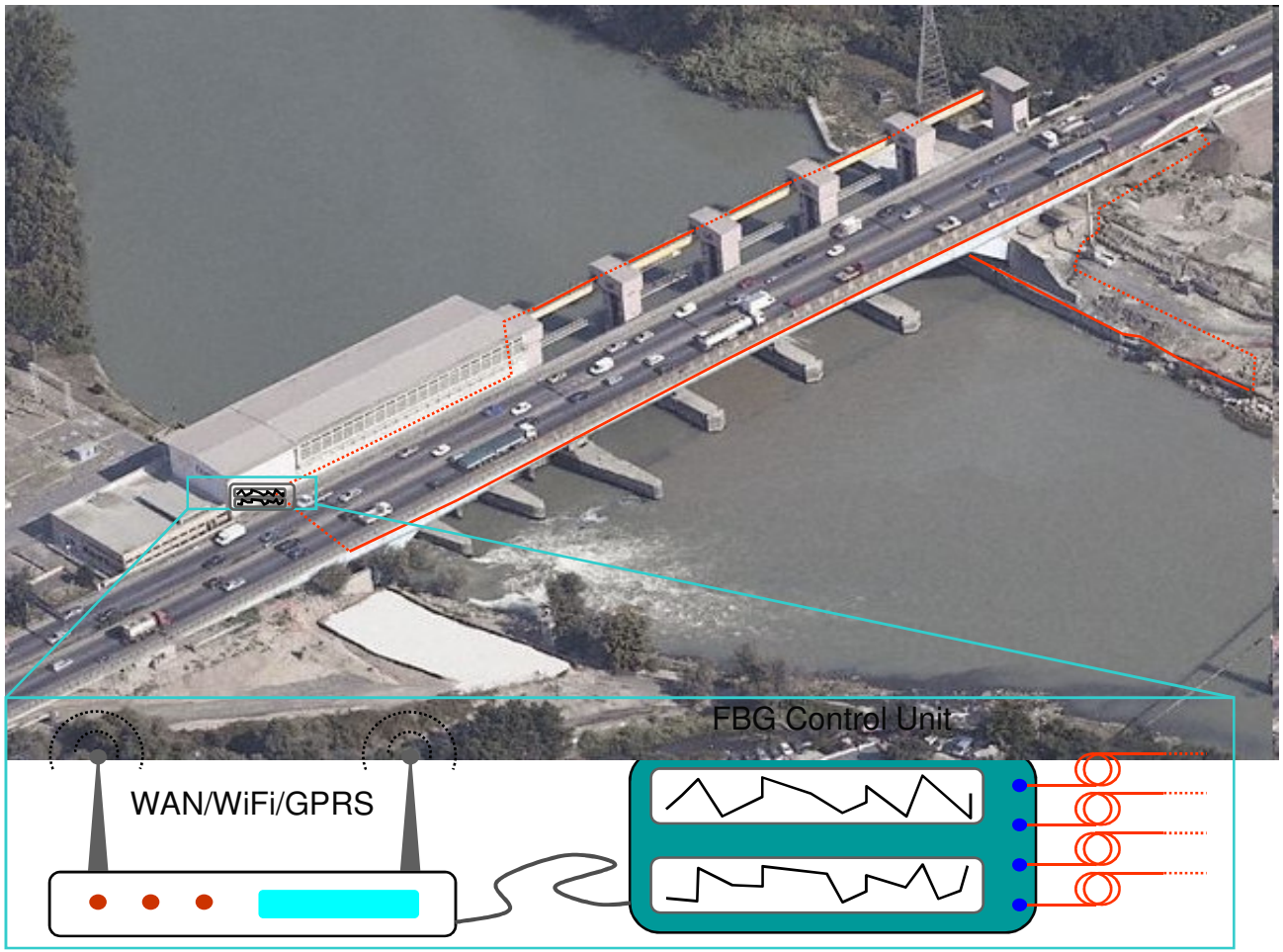
ibidem

- In order to be able to get an estimate of the mode shape with the available system of six sensors, three of the sensors were placed at fixed reference positions (two vertical and one transverse) at span C, while the other three were moved along deck of the C and D span of the bridge.
- The reference and moving positions of the sensors along with the measurement directions are shown in Figure.
- From the set of three sensors used in the reference and the moving positions, two of them monitor the vertical accelerations at the left and right side of the deck, and one of them monitors the deck acceleration in the transverse direction.

ibidem

- The special structural array used in the instrumentation was a mobile one by Kinemetrics .
- The system consists of a central recording unit (of type K2), which can support up to 12 sensors (uniaxial force balance, ± 2g full scale, accelerometers of type FBA-11).
- The recording unit has a 19-bit resolution, a sampling rate capacity of up to 200sps

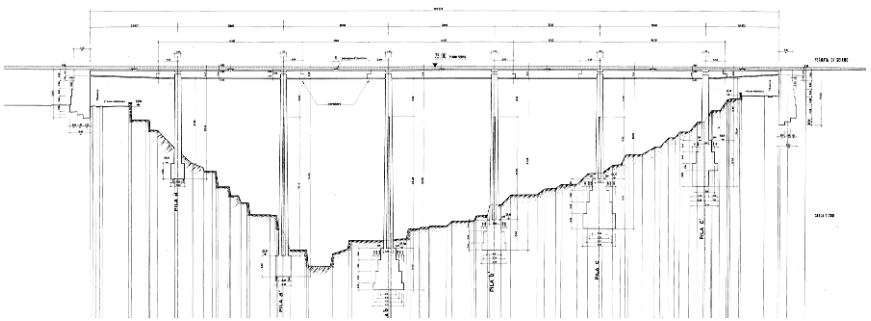
DEVELOPMENT OF STRUCTURAL MONITORING SYSTEMS BASED ON USE OF FBG SENSORS



Conceptual application of FBG sensors for remote structural monitoring of large civil engineering infrastructures

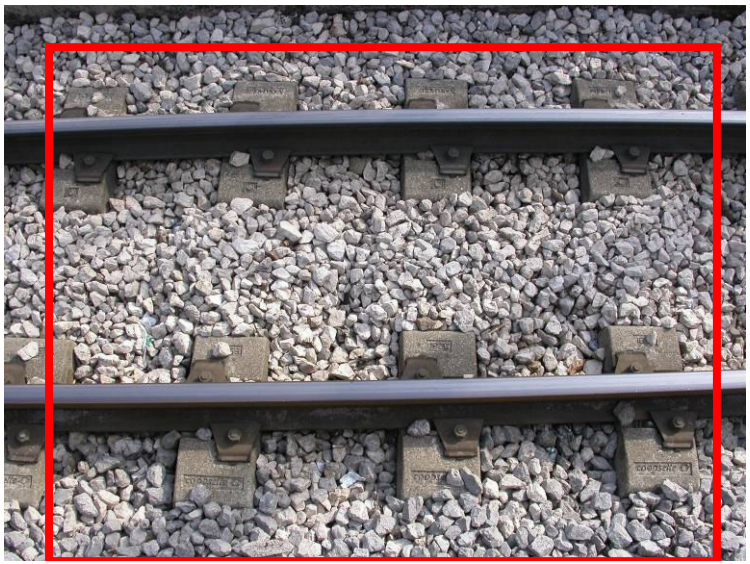
MONITORING RAILWAY INFRATRUCTURES

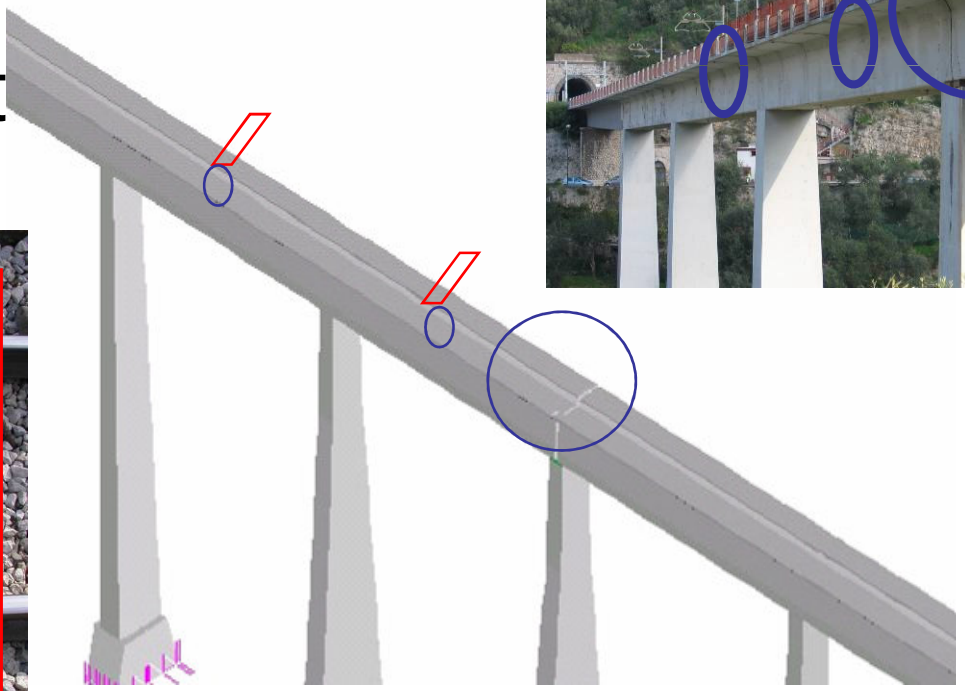
- BRIDGE ‘SEIANO’ OF THE CIRCUMVESUVIANA RAILWAY -



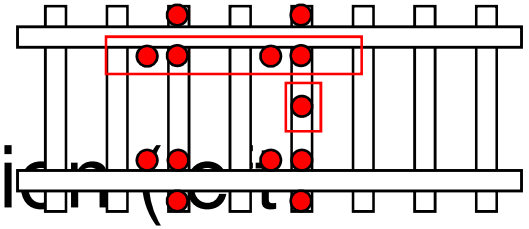
MONITORING RAILWAY INFRATRUCTURES - BRIDGE ‘SEIANO’; CIRCUMVESUVIANA RAILWAY

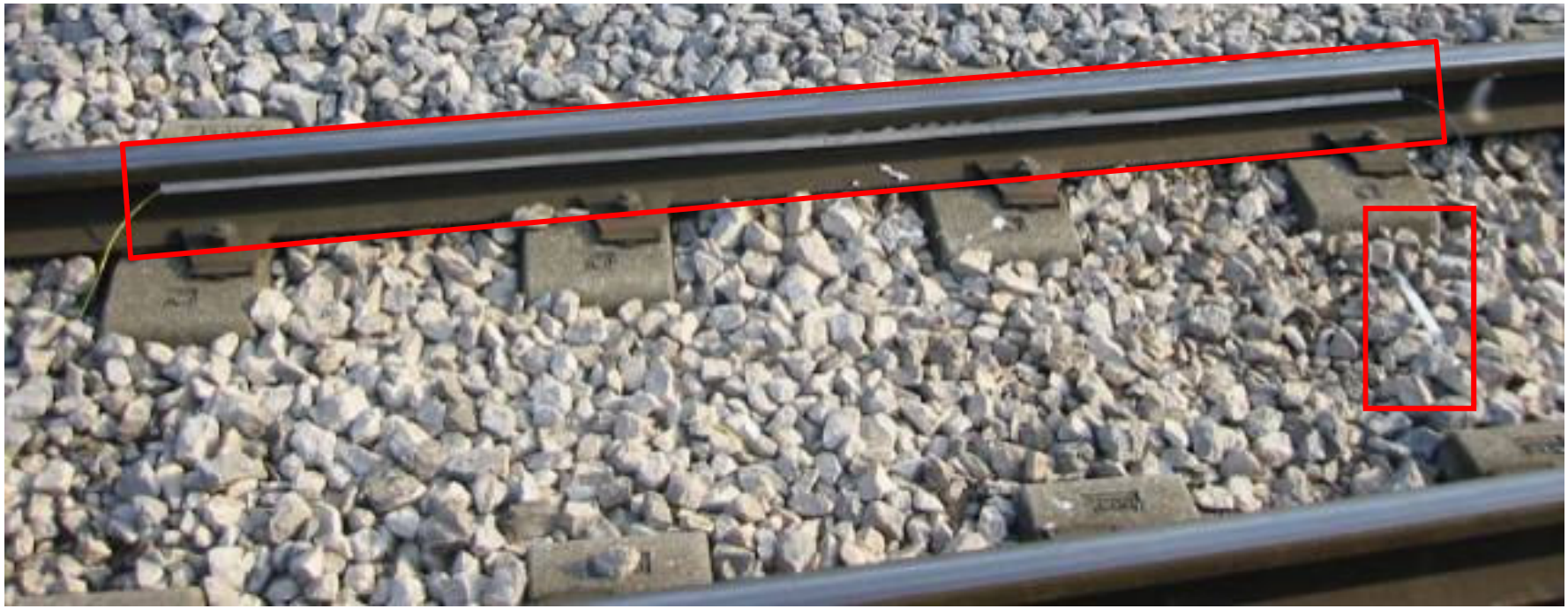
- Static and dynamic monitoring of civil and technological infrastructures:
- beam joint, concrete rebars
- rails, sleepers
- Long term monit
-



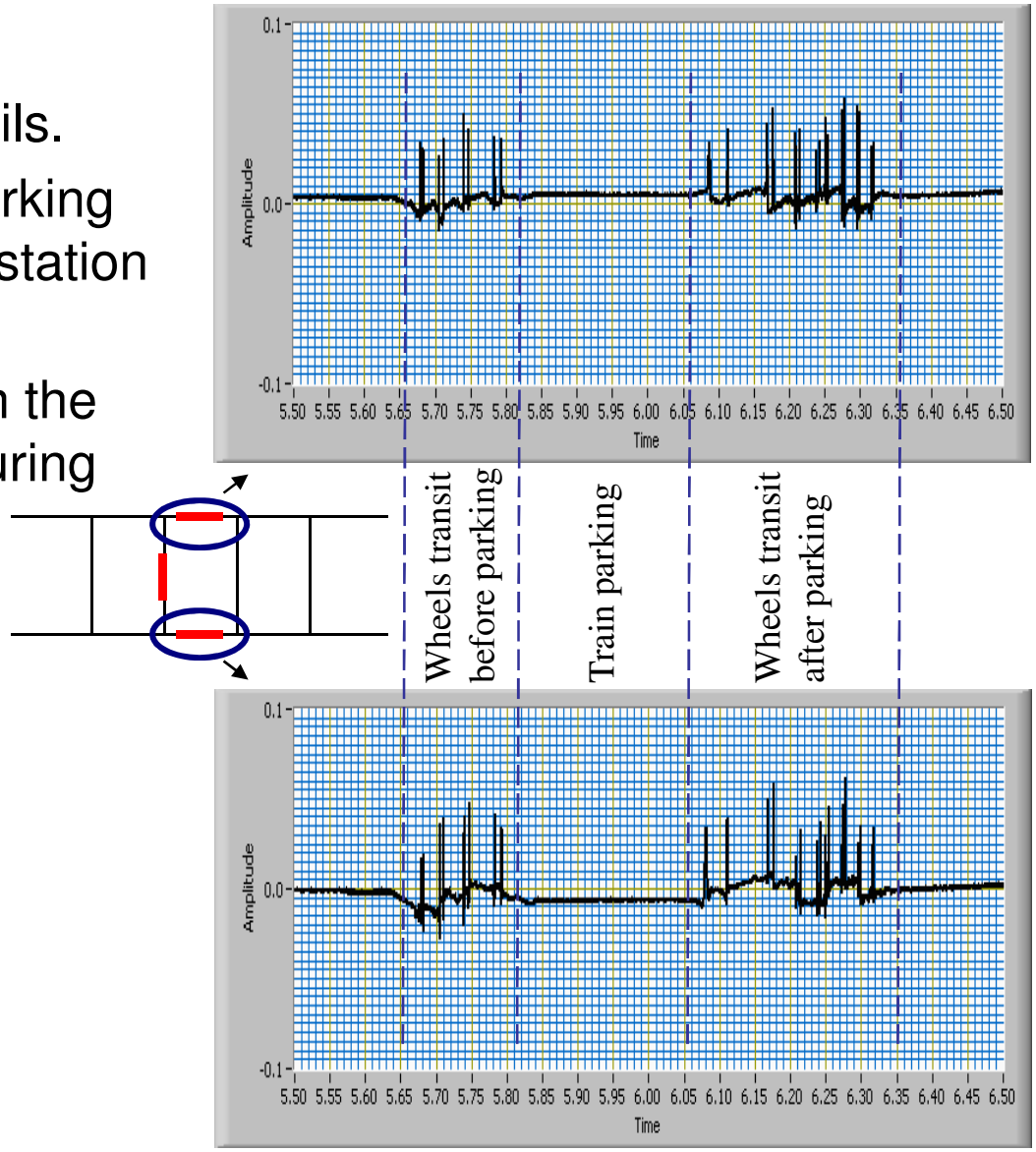


- Sensors installed on technological infrastructure devoted to monitor both track and rolling stock:
- coach dynamic-weight distribution (left)





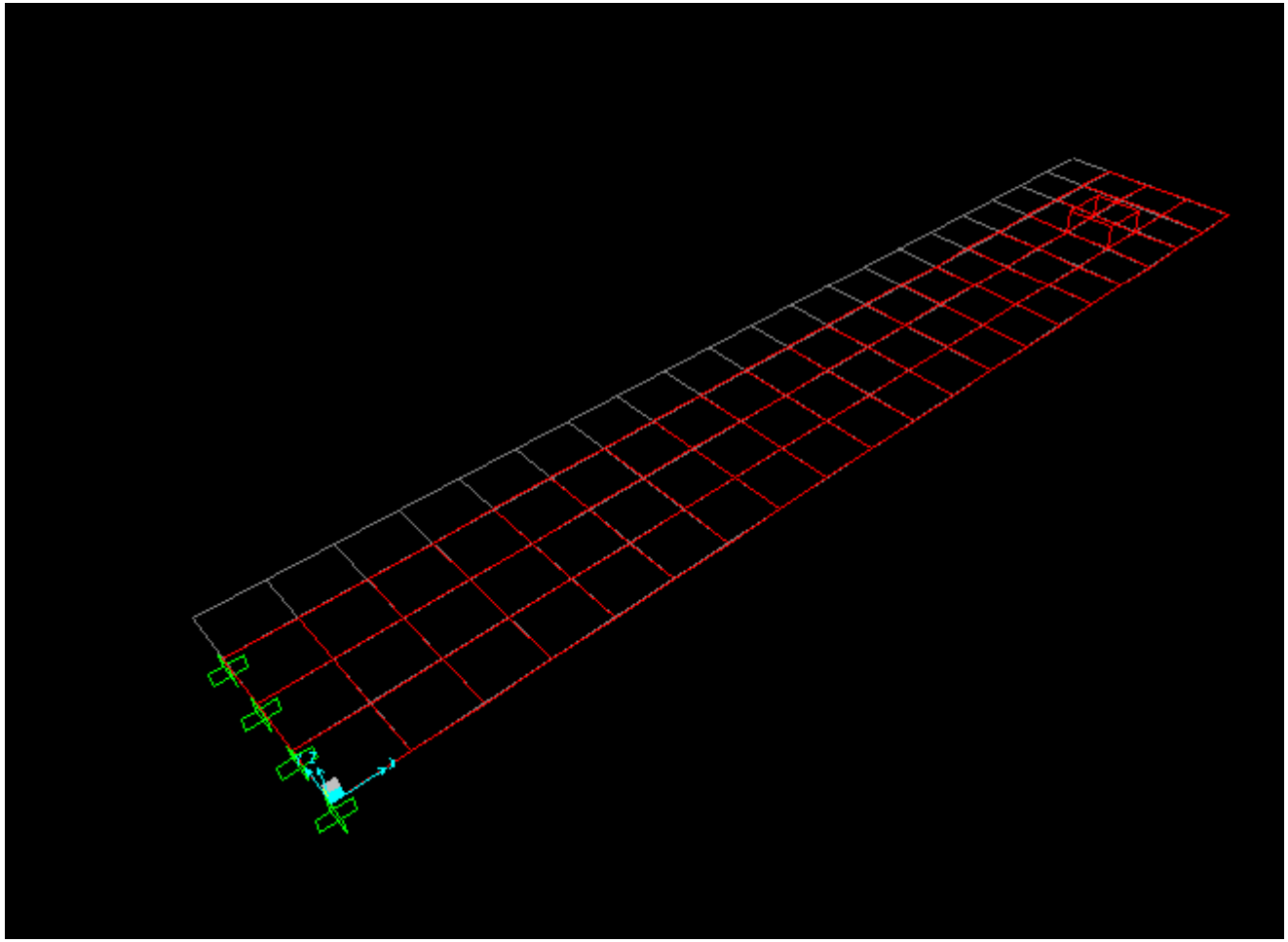
- Monitoring coach weight distribution (left-right) on rails.
- Sensors register arrival, parking an departure of train (train station located at bridge end).
- Uneven load distribution on the two rails results (evident during parking).



SECTION II

Combined Monitoring
EXPERIMENTAL RESULTS

Frequenze ai vari punti di appoggio									
spessore	100	90	80	70	60	50	40	30	20
1.0mm	0,560629	0,681745	0,849757	1,093848	1,47106	2,106736	3,326359	6,220066	16,24141
1.5mm									
3.0mm									
5.0mm	3,706971	4,553921	5,734471	7,453675	10,1055	14,53087	22,80866	41,29842	96,82417

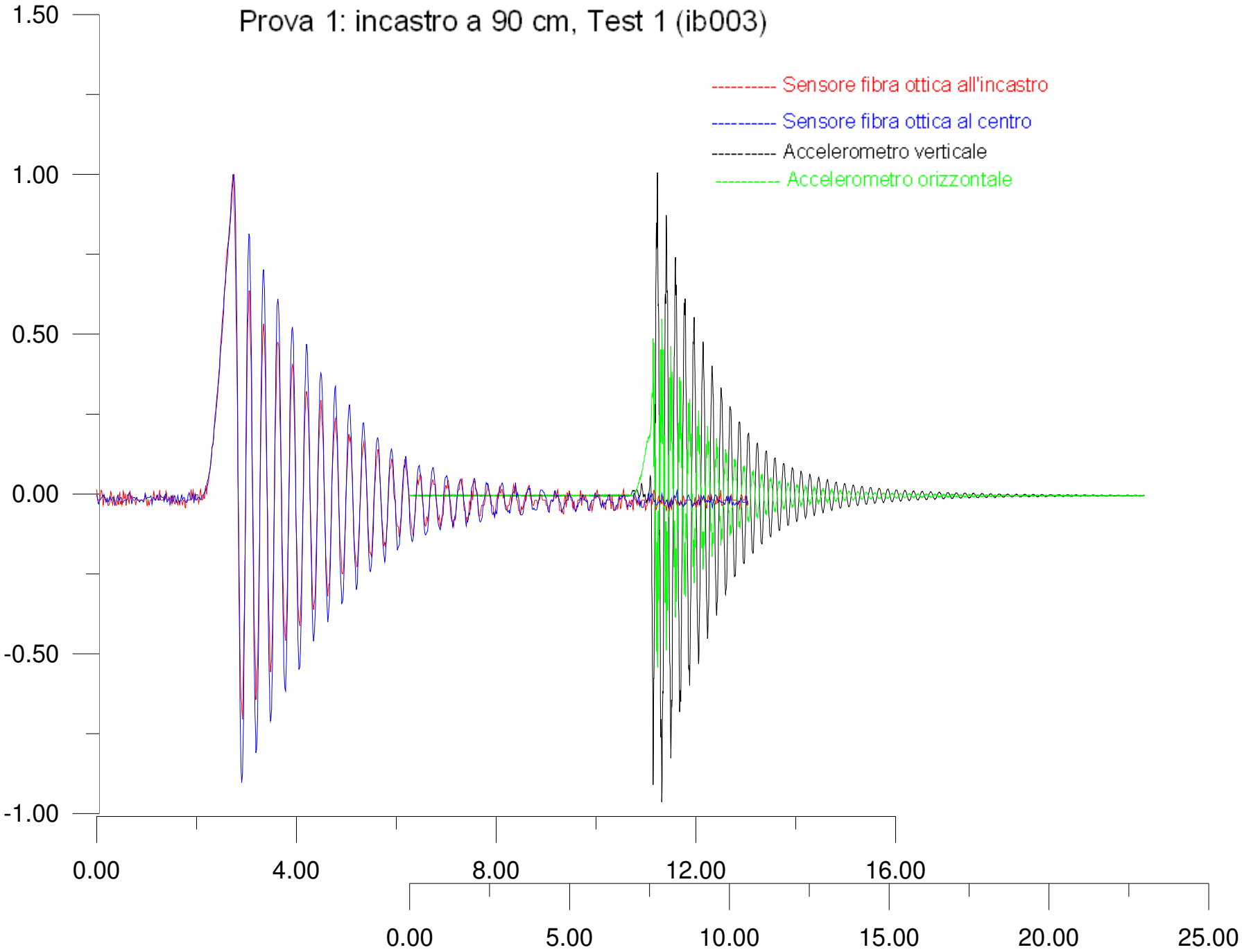


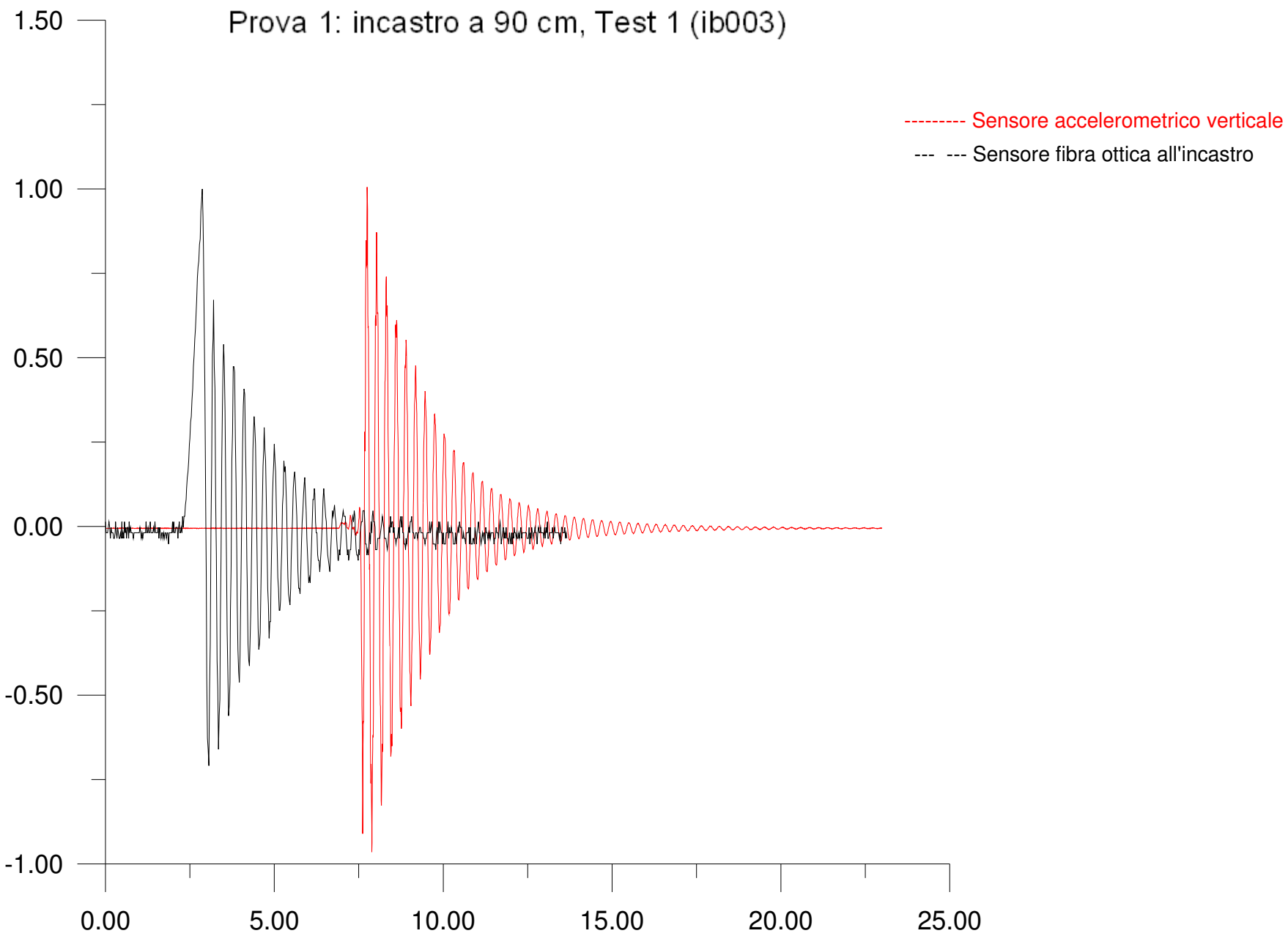
List of tests

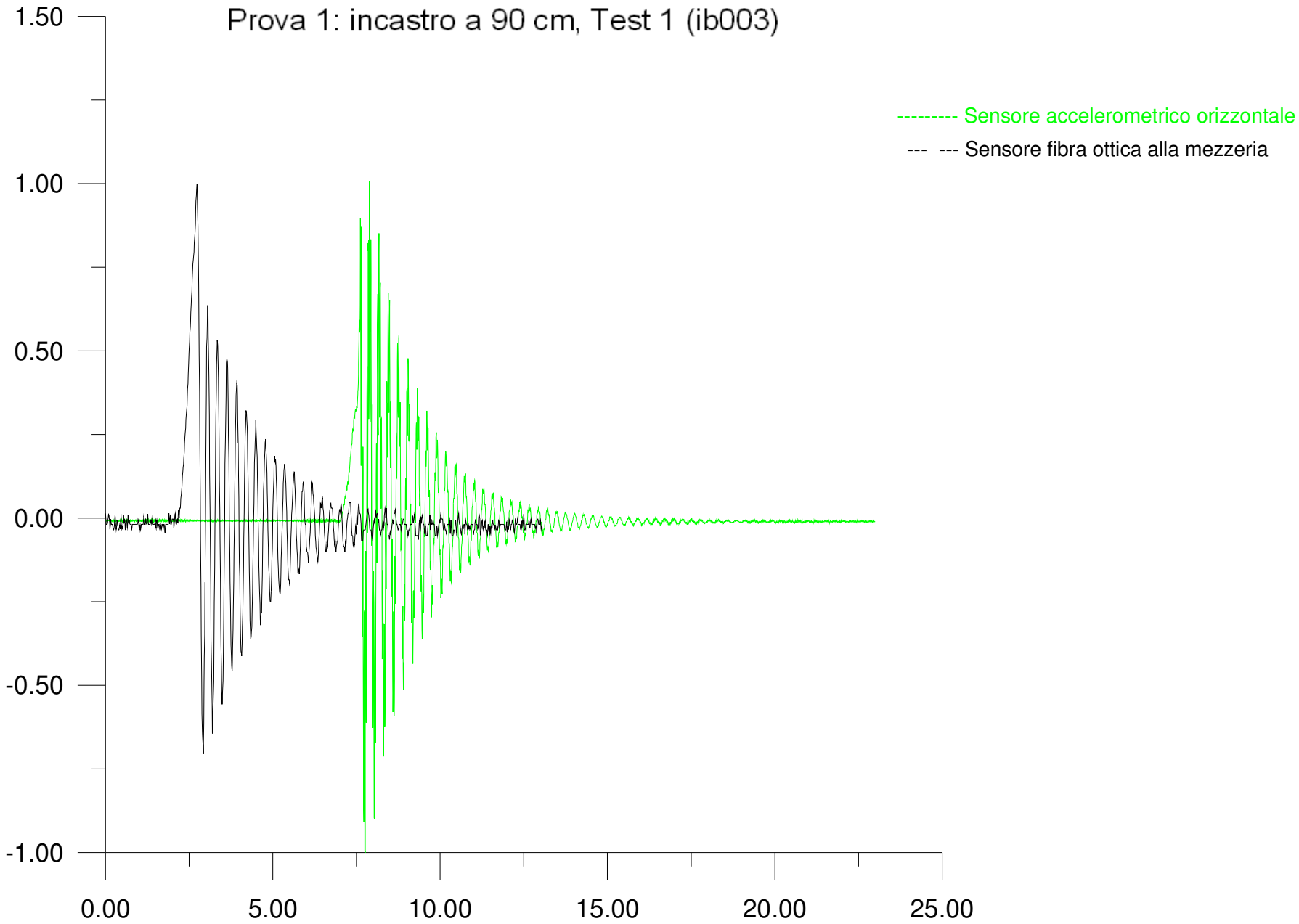
90	80	70
ib003	ib008	ib011
ib004	ib009	ib012
ib005	ib010	ib013

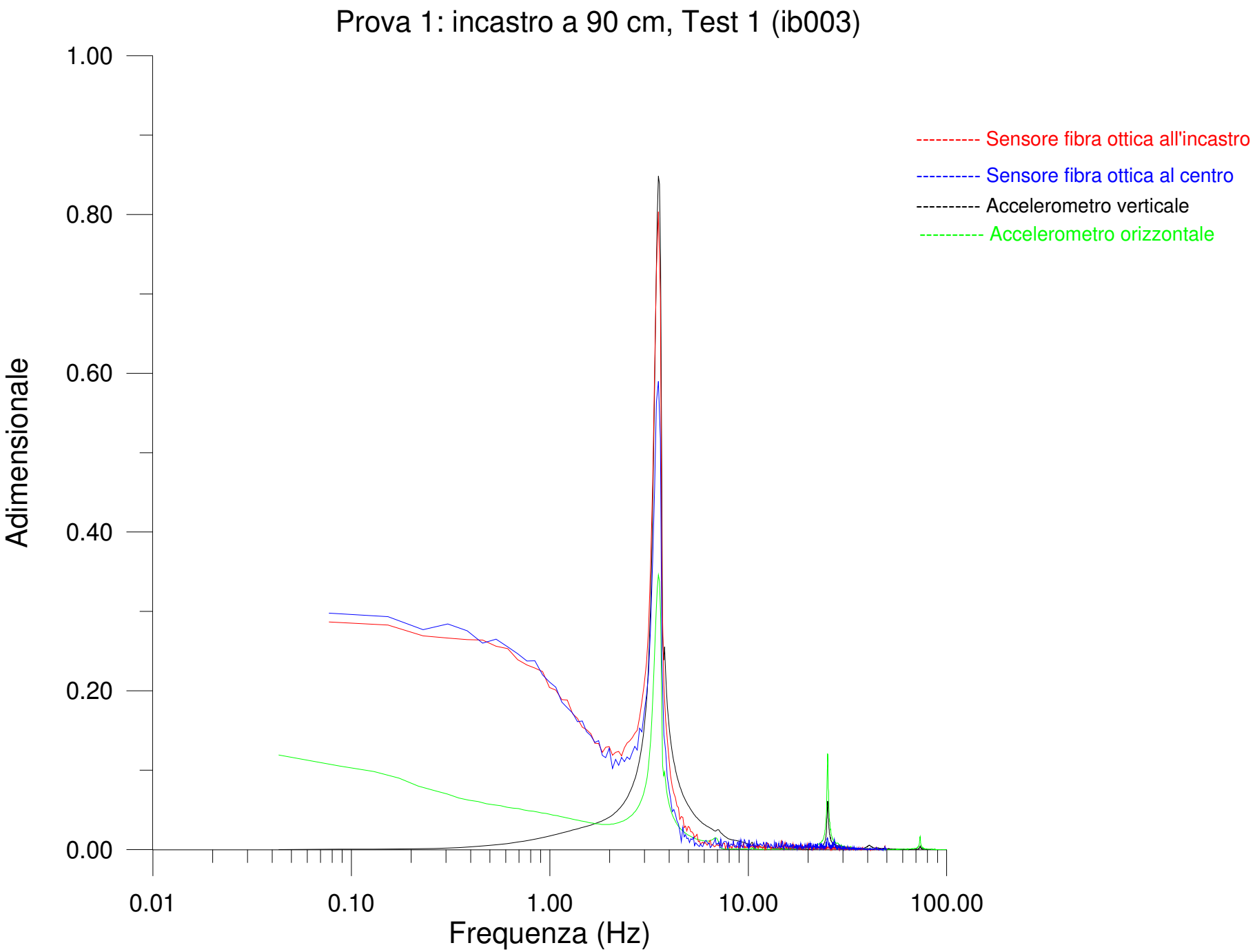
Test a 90 cm ib003

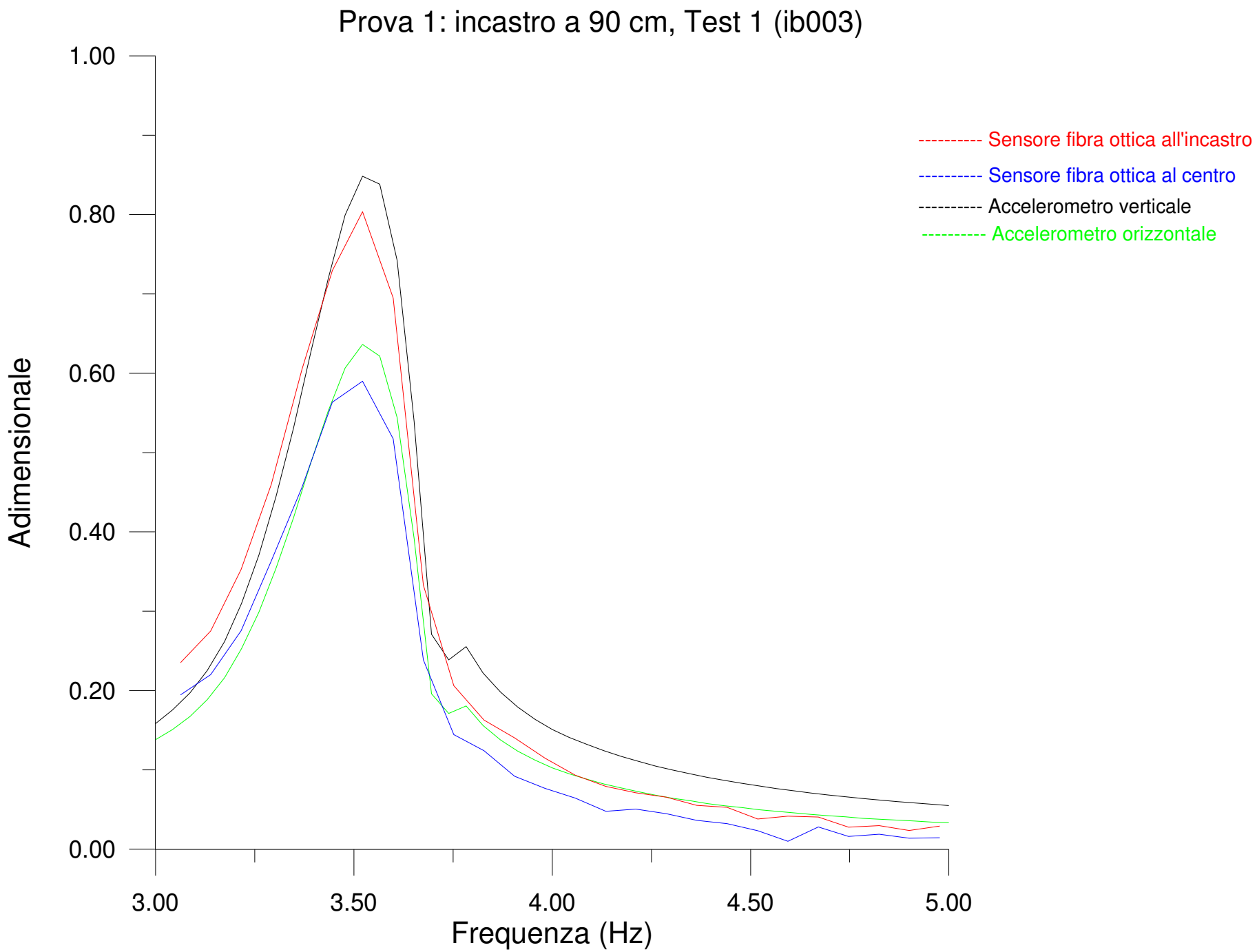
- All records were normalized to the peak.
- All records from the FBG sesnsors were linearly interpoled at 100 Hz.


Prova 1: incastro a 90 cm, Test 1 (ib003)
---------- Sensore fibra ottica all'incastro
---------- Sensore fibra ottica al centro
---------- Accelerometro verticale
---------- Accelerometro orizzontale
1.50
1.00
0.50
0.00
-0.50
-1.00
0.00
4.00
8.00
12.00
16.00
0.00
5.00
10.00
15.00
20.00
25.00


Prova 1: incastro a 90 cm, Test 1 (ib003)
--------- Sensore accelerometrico verticale
--- --- Sensore fibra ottica all'incastro
1.50
1.00
0.50
0.00
-0.50
-1.00
0.00
5.00
10.00
15.00
20.00
25.00


Prova 1: incastro a 90 cm, Test 1 (ib003)
--------- Sensore accelerometrico orizzontale
--- --- Sensore fibra ottica alla mezzeria
1.50
1.00
0.50
0.00
-0.50
-1.00
0.00
5.00
10.00
15.00
20.00
25.00

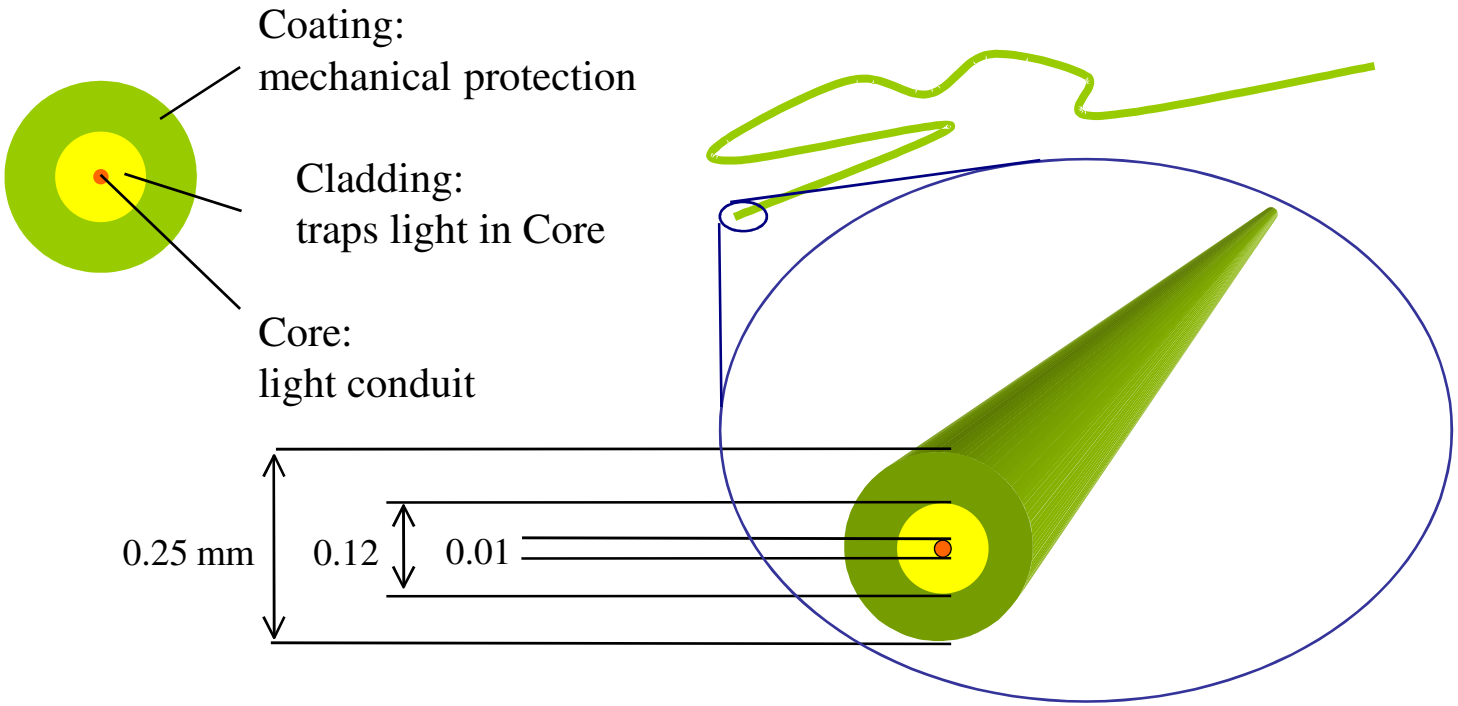

Prova 1: incastro a 90 cm, Test 1 (ib003)
1.00
0.80
0.60
0.40
0.20
0.00
Adimensionale
0.01
0.10
1.00
10.00
100.00
Frequenza (Hz)
---------- Sensore fibra ottica all'incastro
---------- Sensore fibra ottica al centro
---------- Accelerometro verticale
---------- Accelerometro orizzontale


Prova 1: incastro a 90 cm, Test 1 (ib003)
1.00
0.80
0.60
0.40
0.20
0.00
Adimensionale
3.00
3.50
4.00
4.50
5.00
Frequenza (Hz)
---------- Sensore fibra ottica all'incastro
---------- Sensore fibra ottica al centro
---------- Accelerometro verticale
---------- Accelerometro orizzontale

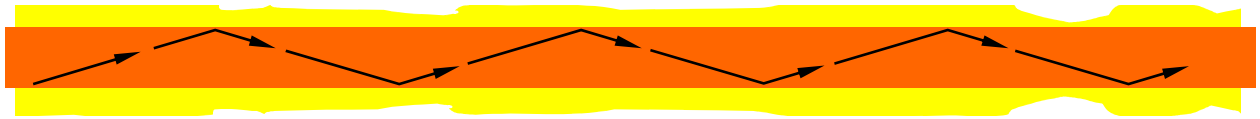
SECTION III

FBA & FBG

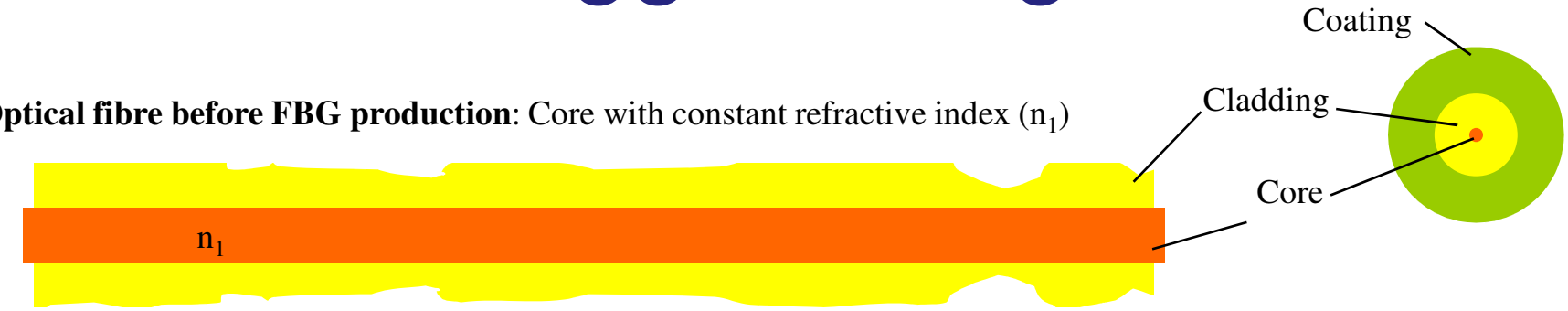
Optical fibre: thin and flexible light delivery ‘pipe’.



Light is trapped in Core by total internal reflection at Core-Cladding interface.

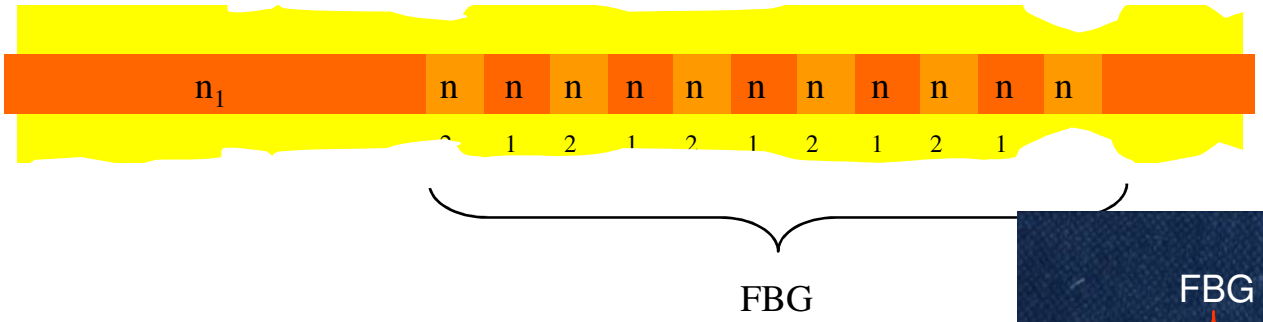


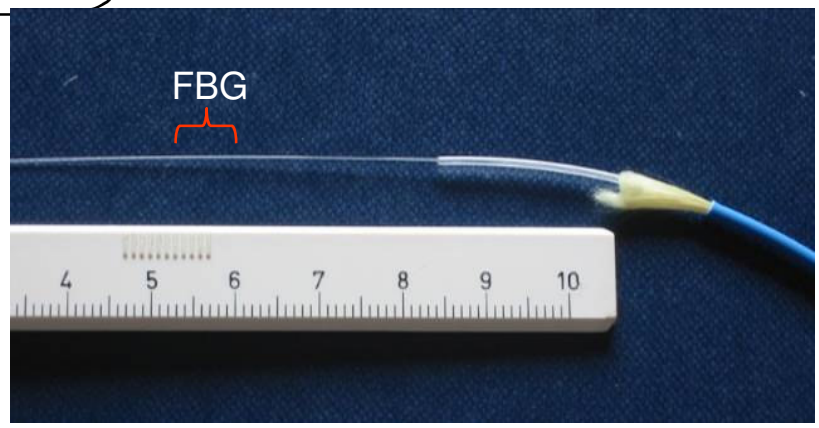
Fibre Bragg Grating sensors



Optical fibre before FBG production: Core with constant refractive index (n_1)

Optical fibre after FBG production: Short segment of Core with modulated refractive index (n_1; n_2)



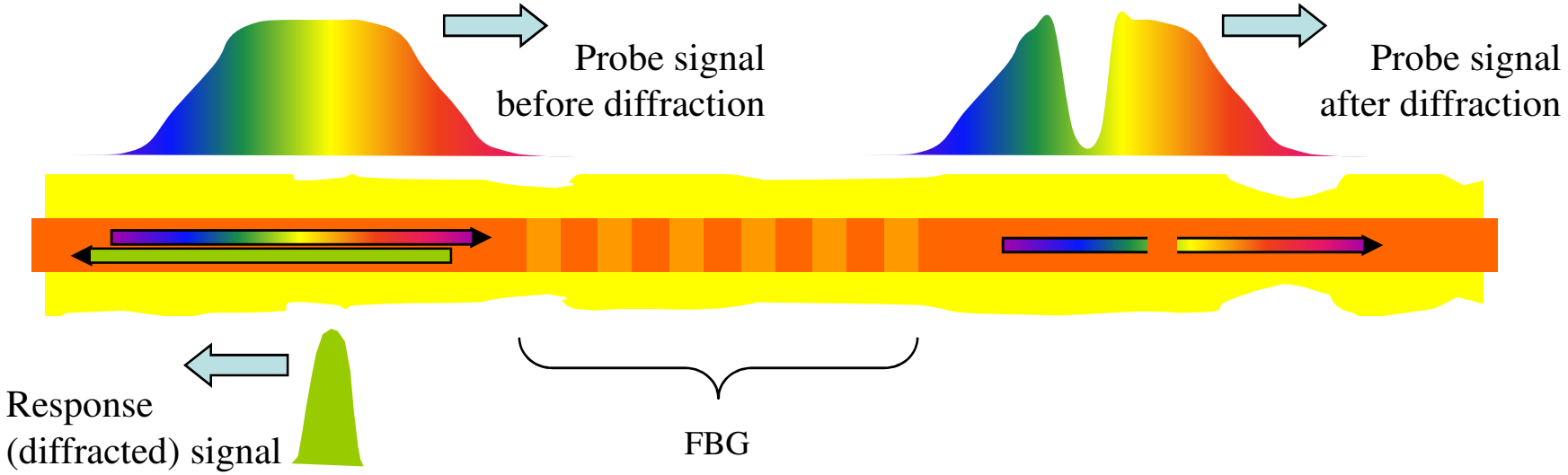


Fibre Bragg Grating (FBG) sensor: diffraction grating along the fibre axis.

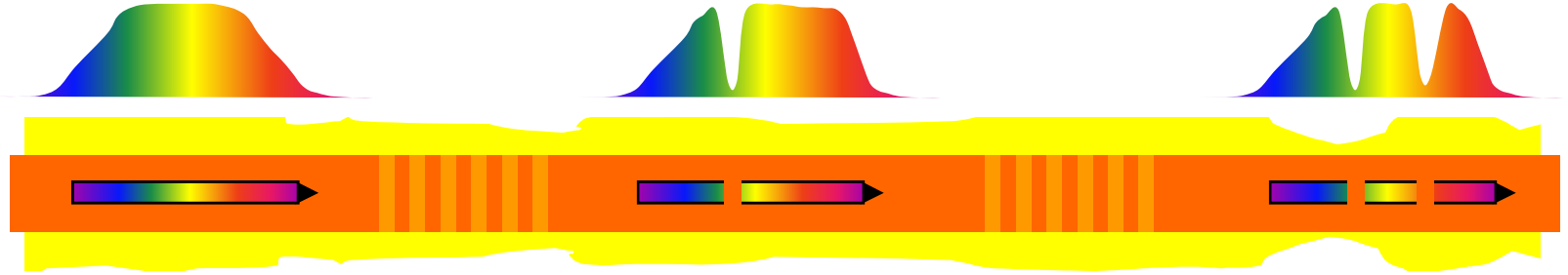
Diffraction grating is produced by modulation of the Core refractive index.

Fibre Bragg Grating sensors

Light propagating along the optical fibre is diffracted (back-reflected) by FBG



Many FBGs at different λ_{BRAGG} can be arranged along one optical fibre



Fibre Bragg Grating sensors

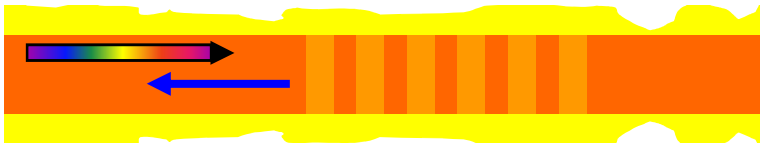
Diffracted wavelength depends on FBG geometry, that is affected by Temperature and Stress.

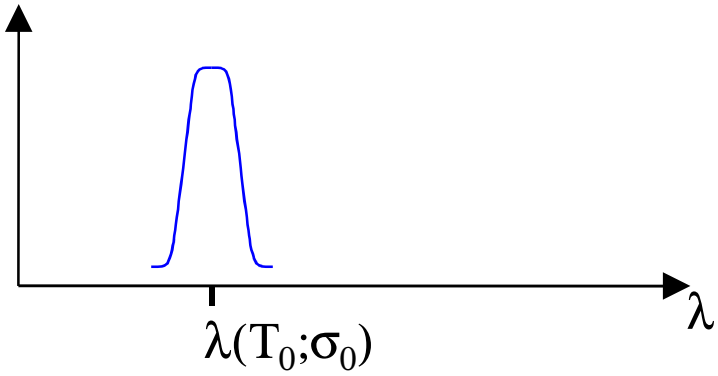
Typical values:

$\Delta\sigma = 1 \quad \mu\varepsilon \quad \Rightarrow \quad \Delta\lambda = 1$ pm

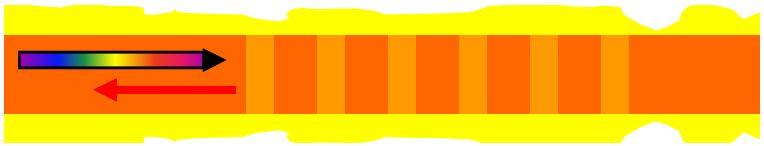
$\Delta T = 1 \quad °K \quad \Rightarrow \quad \Delta\lambda = 10$ pm

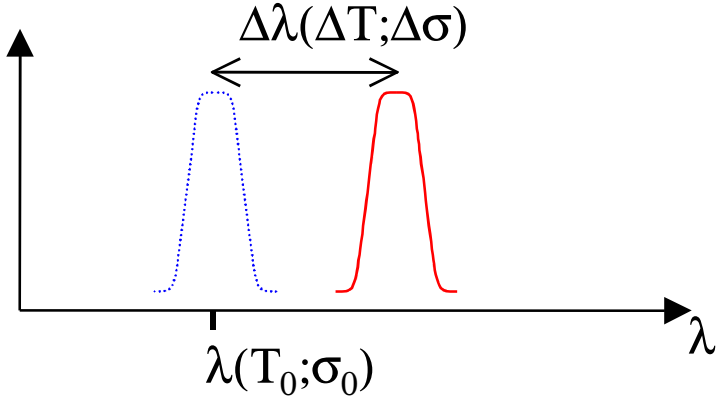
Fibre 'at rest' $(T_0;\sigma_0)$





Fibre stressed $(T_0+\Delta T;\sigma_0+\Delta\sigma)$

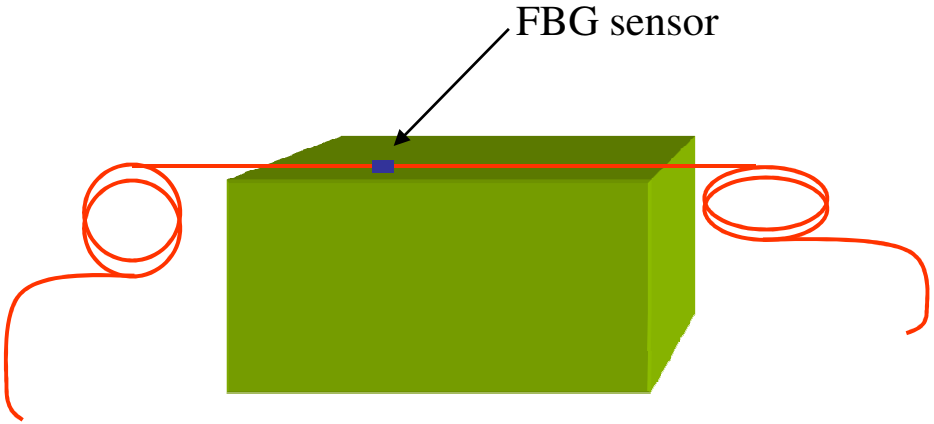


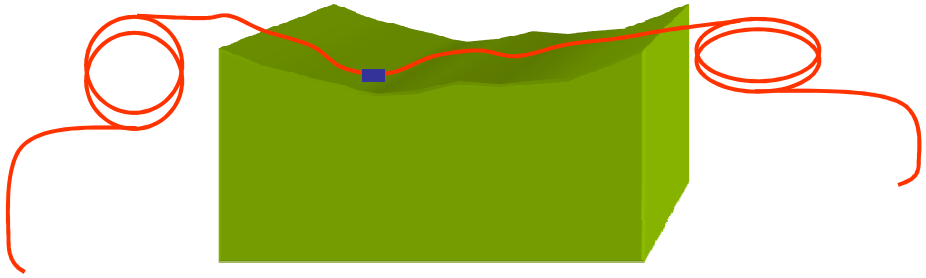


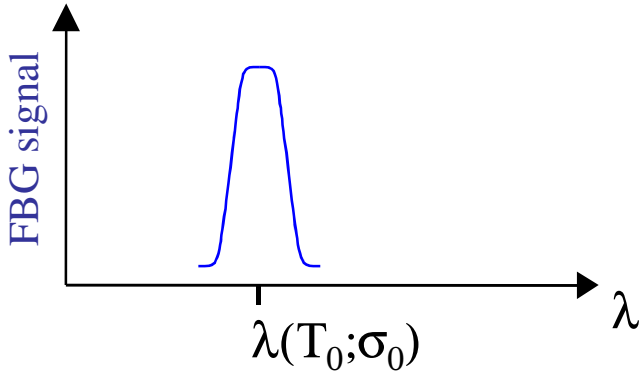
FBG

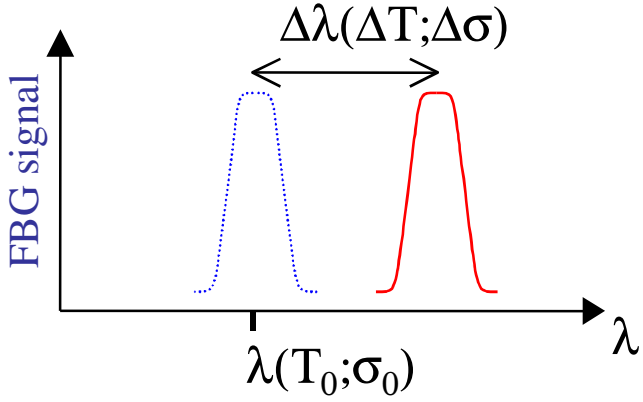
Fibre Bragg Grating sensors

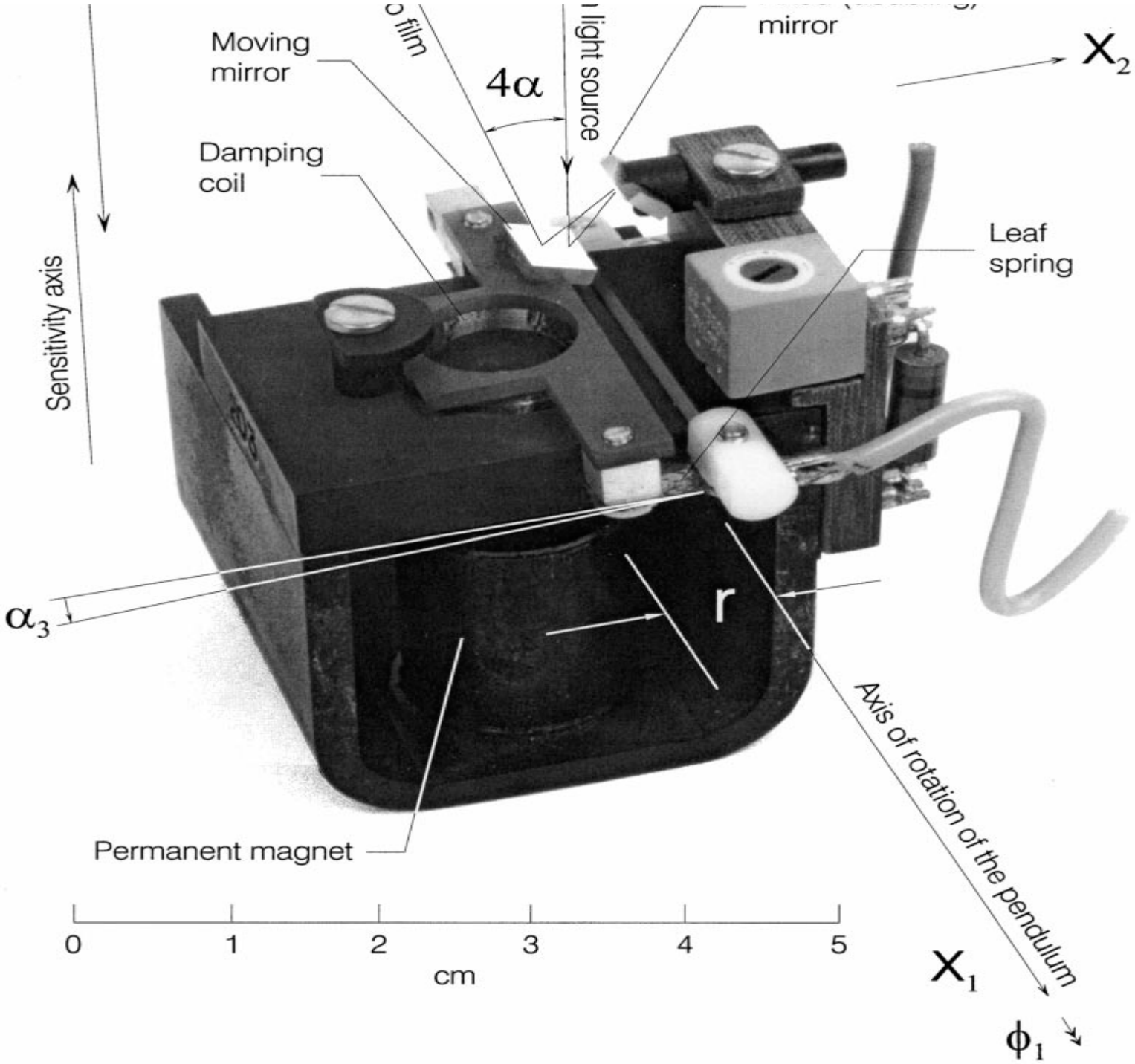
Deformation and temperature of a structure can be monitored by stuck/embedded FBGs.

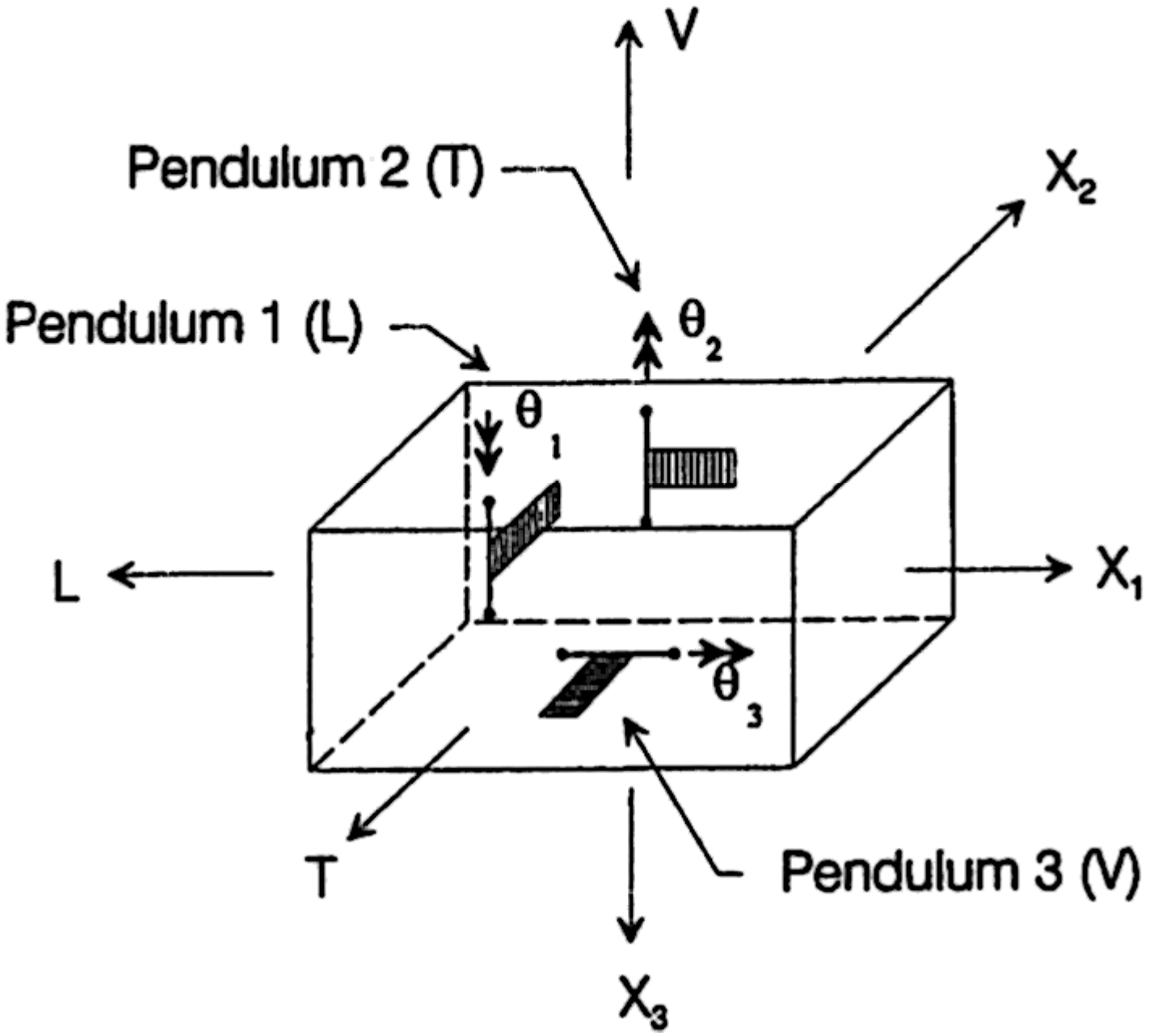









Moving mirror
4α
light source
mirror
X2
Damping coil
Leaf spring
Sensitivity axis
α3
r
Permanent magnet
Axis of rotation of the pendulum
0
1
2
3
4
5
cm
X1
ϕ1


V
Pendulum 2 (T)
X2
Pendulum 1 (L)
θ2
θ1
L
X1
θ3
T
Pendulum 3 (V)
X3

Equation of accelerometric sensor motion

- $L: y_1'' + 2\,\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\psi_2 - \psi_3'' l_1 + x_2'' \theta_1$
- $T: y_2'' + 2\,\omega_2 D_2 y_2' + \omega_2^2 y_2 = -x_2'' + g\psi_1 + \psi_3'' l_2 + x_1'' \theta_2$
- $V: y_3'' + 2\,\omega_3 D_3 y_3' + \omega_3^2 y_3 = -x_3'' + g\psi_1^2/2 + \psi_1'' l_3 + x_2'' \theta_3$
- yi is recorded response of the instrument,
- θi is the angle of pendulum rotation,
- li is the length of pendulum arm,
- $yi = \theta i\ li$,
- ωi and Di are respectively the natural frequency and fraction of critical damping of the ith transducer,
- g is acceleration due to gravity,
- xi'' is ground acceleration in ith direction,
- ψi is a rotation of the ground surface about xi axis.

Force-balance accelerometer

with $$\ddot{X}_a = \ddot{X}_r + \ddot{X}_g \quad (1)$$

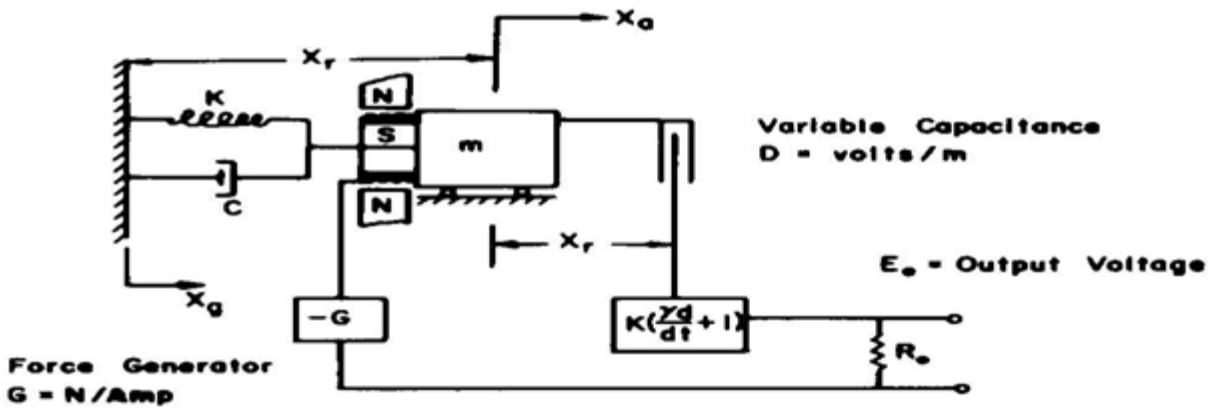
$$m\ddot{X}_r + \left(C + \frac{DKG\gamma}{R_o}\right)\dot{X}_r + \left(K + \frac{DKG}{R_o}\right)X_r = -m\ddot{X}_g \quad (2)$$

or

$$\ddot{X}_r + 2\omega_n\zeta\dot{X}_r + \omega_n^2 X_r = -\ddot{X}_g \quad (3)$$

where

$$2\omega_n\zeta = \left(\frac{C}{m} + \frac{DKG\gamma}{mR_o}\right) \quad (4)$$



Force balance accelerometer block diagram

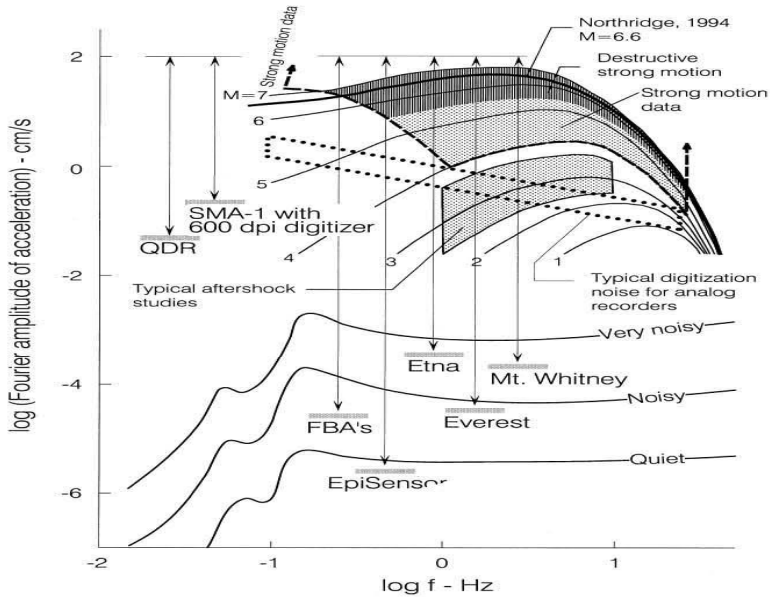


Fig. 2. Comparison of Fourier spectrum amplitudes of strong earthquake ground motion with those of typical aftershock studies and microtremor and microseism noise, threshold recording amplitudes of selected accelerographs, and typical digitization noise for analogue recorders.

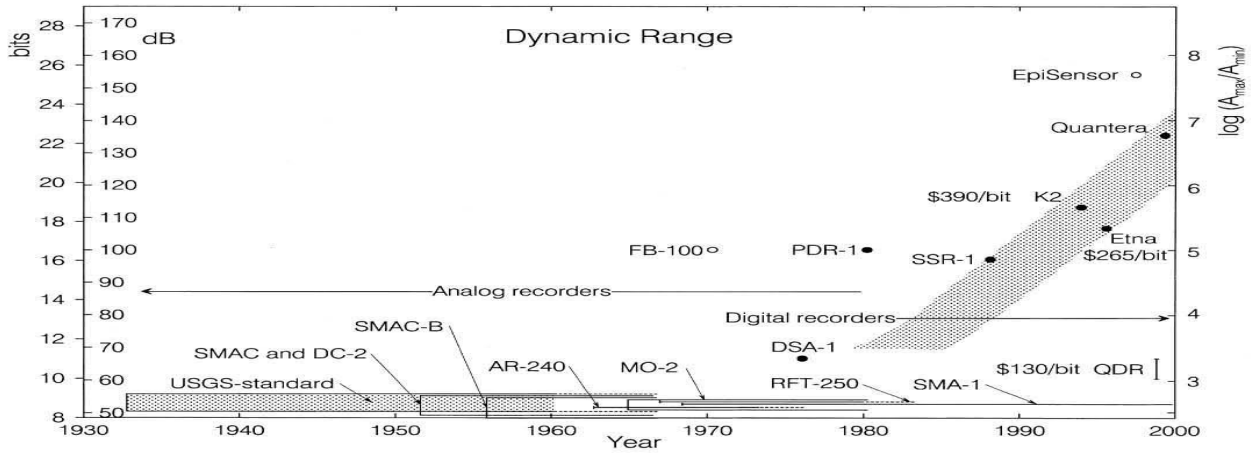


Fig. 3. Comparison of selected strong motion accelerographs and digital recorders in terms of resolution (in bits), dynamic range in dB ($= 20 \log (A_{max}/A_{min})$), and the ratio A_{max}/A_{min}, between 1930 and 2000.

ACQUISITION AND PROCESSING OF ANALOGUE AND DIGITAL ACCELEROMETRIC RECORDS

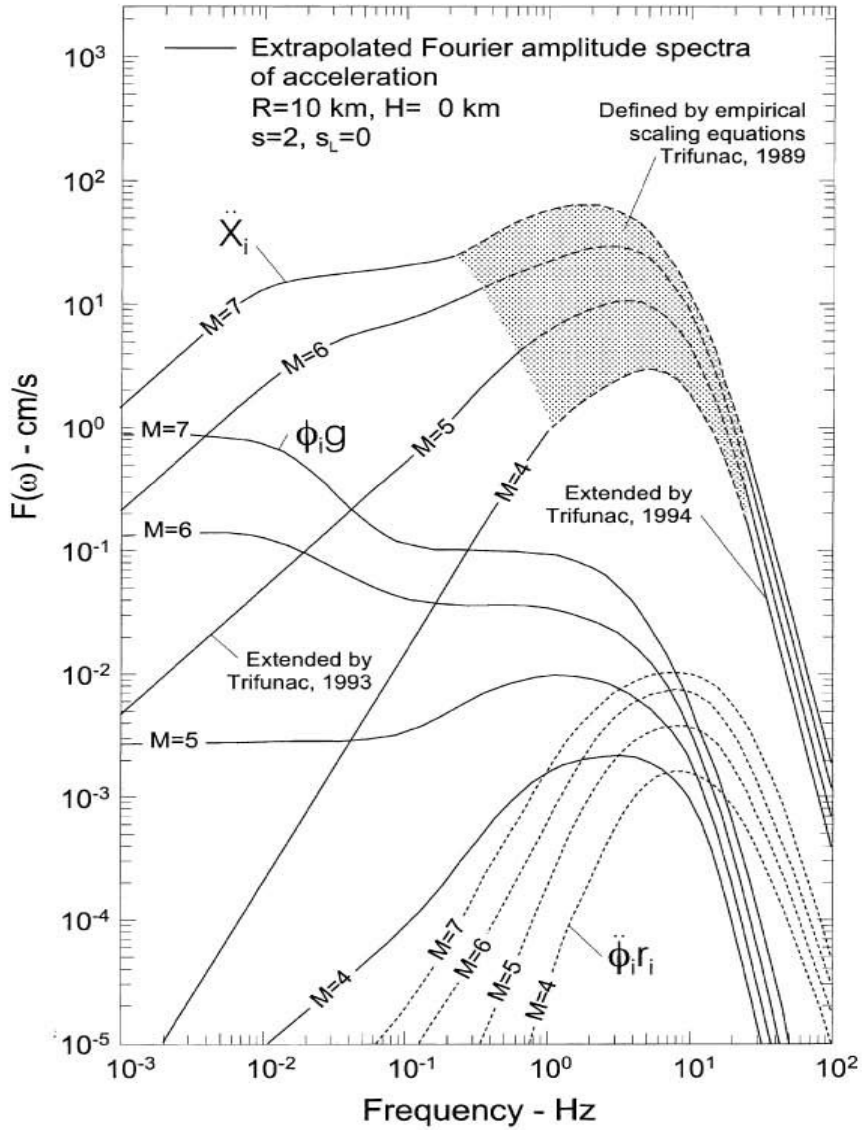


Fig. 5. Fourier amplitude spectra of ground acceleration, $\ddot{X}_i$, normalized

CONCLUSIONS & REMARKS

- FBG sensors provide dynamic deformation monitoring (500dss), allowing measurement of various parameters: quasi-static thermal deformation (day/night and winter/summer cycles), long term structural settling (ground settling, concrete aging), fatigue of structures (amplitude vibration at vehicle transit), structural integrity (change of dumping and natural frequency).
- FBA sensors provide acceleration recordings to the evaluation of structural dynamic parameters.
- FBA & FBG integrated measurements will help to improve the knowledge of all parameters.