Permanent monitoring systems in prestressed concrete bridges

– The case study of Lezíria Bridge –

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Federal Highway Research Institute (BASt), Bergisch Gladbach, Germany, 21st March, 2018

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    - FE model for assessment and validation
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3. The next generation of asset management supported by SHM

4. The references

0. Brisa Group

- One of the largest tolled motorway operators in the world
  - Concessions in the Netherlands
- The largest transport infrastructure group in Portugal
  - Management of transport infrastructures (roads and railways)
- Investments in SHM
  - Sorraia Bridge (A13)
  - Lezíria Bridge (A10)

1. The monitoring system : Overview

- Permanent monitoring system (construction + operational life)
- Monitoring project (as part of the bridge project)
- ≅ 400 sensors (10 different type of sensors)
- 3 different acquisition systems (static, dynamic, optic)
- > 10km cable length
- sampling-rate up to 100 Hz
- ≅ 1 000 000 records / year

1. The monitoring system : Embedded sensors

- Embedded sensors:
  Strain gauges and temperature sensors

1. The monitoring system : External sensors

- External sensors: Accelerometers

- External sensors: LVDTs

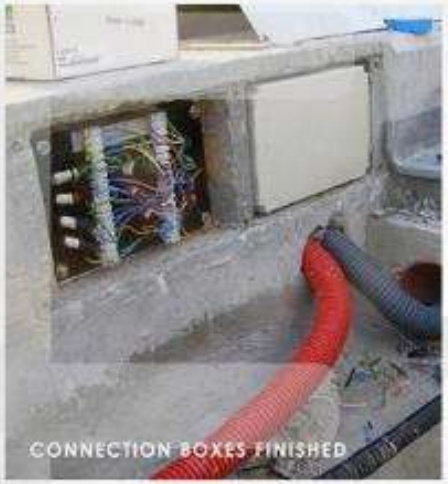
1. The monitoring system : External sensors

- External sensors: Accelerometers

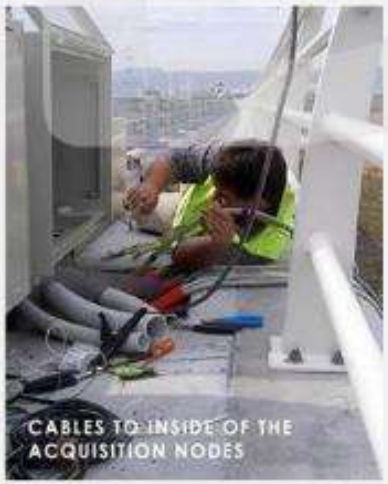
- External sensors: LVDTs

1. The monitoring system : Cables and Acquisition Nodes

❑ Cables and connections

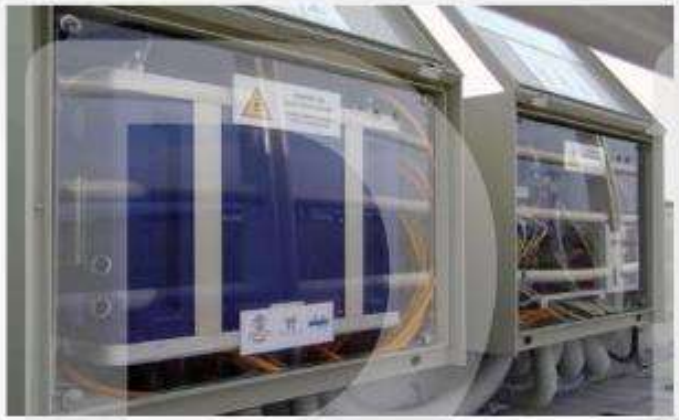


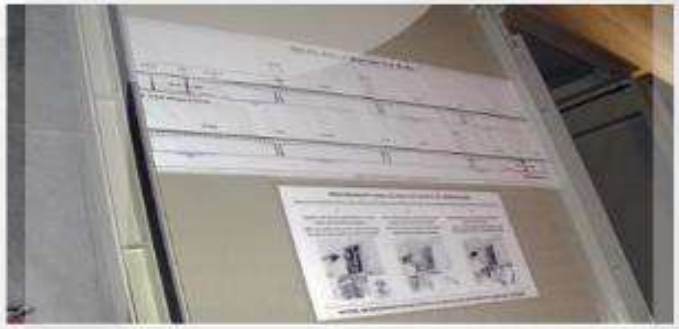
❑ Acquisition Nodes



1. The monitoring system : Labelling

❑ Labelling: Acquisition Nodes





❑ Labelling: External sensors

1. The monitoring system : Waterproofing and sealing

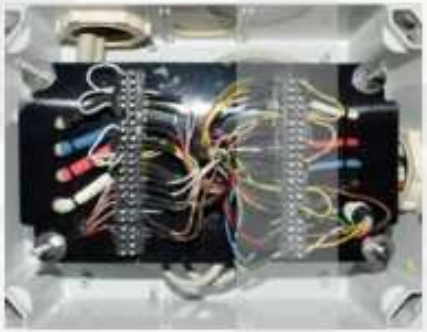
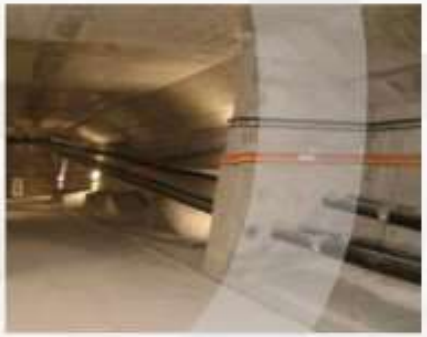
❑ Waterproofing

❑ Sealing

SOUSA, H., FÉLIX, C., BENTO, J., FIGUEIRAS, J. (2011) "Design and implementation of a monitoring system applied to a long-span prestressed concrete bridge.", Structural Concrete 12(2): 82-93.
http://onlinelibrary.wiley.com/doi/10.1002/suco.201000014/abstract

1. The monitoring system : Performance after 12 years in operation

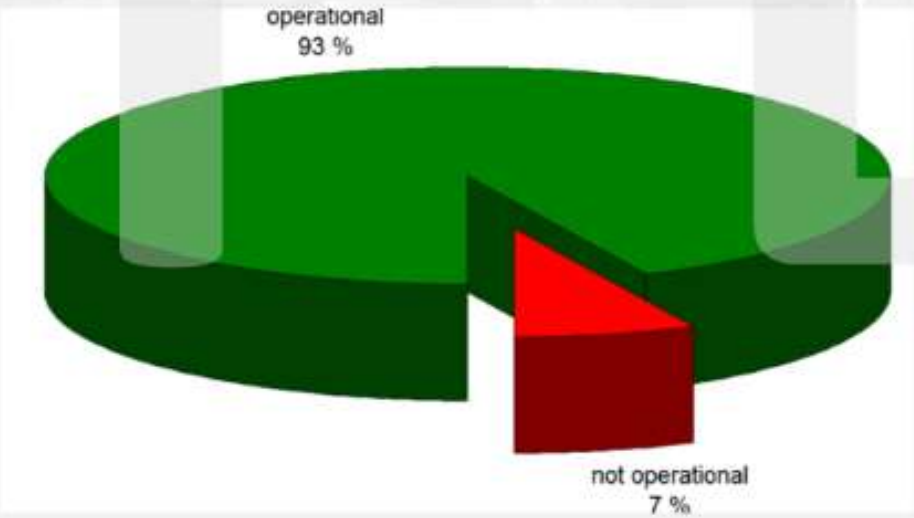
- Good condition after 9 years of operation and without signs of vandalism

	External sensors	Connection boxes	Cables path	Acquisition nodes
2007				
2014				

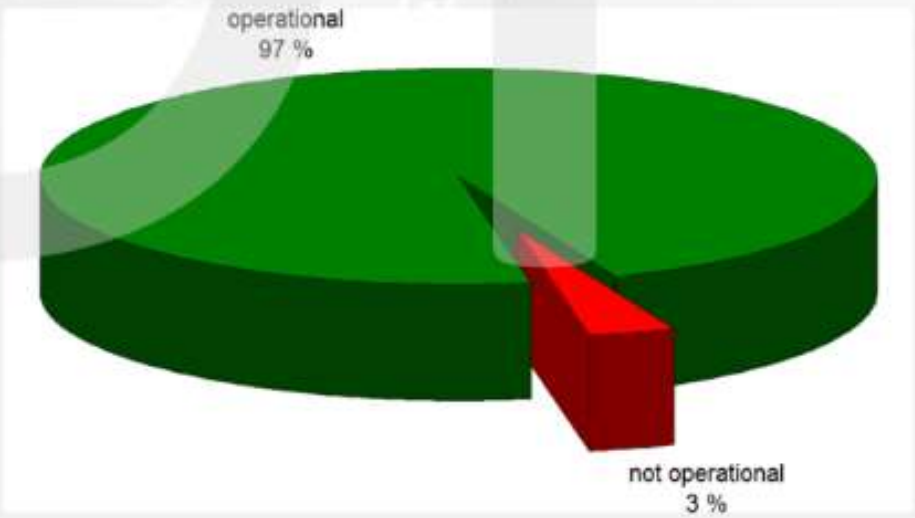
1. The monitoring system : Performance after 12 years in operation

- Good condition after 9 years of operation and without signs of vandalism
- Overall, 93 % of the embedded sensors are operational, although it is being done some work to recover up to 97 %.

Current status (in 2014)



Current objective (in 2015)



1. The monitoring system : Performance after 12 years in operation

- ❑ Good condition after 9 years of operation and without signs of vandalism
- ❑ Overall, 93 % of the embedded sensors are operational, although it is being done some work to recover up to 97 %.
- ❑ Quality of the collected measurements vs. required maintenance

Location	Best measurement stability	Requiring particular maintenance
Embedded	• Vibrating wire strain gauges • Pt100 thermometers • Fibre optic sensors	• Fibre optic sensors
External	• LVDTs • Pt100 thermometers	• LVDTs (corrosion) • Sonar altimeters

TR

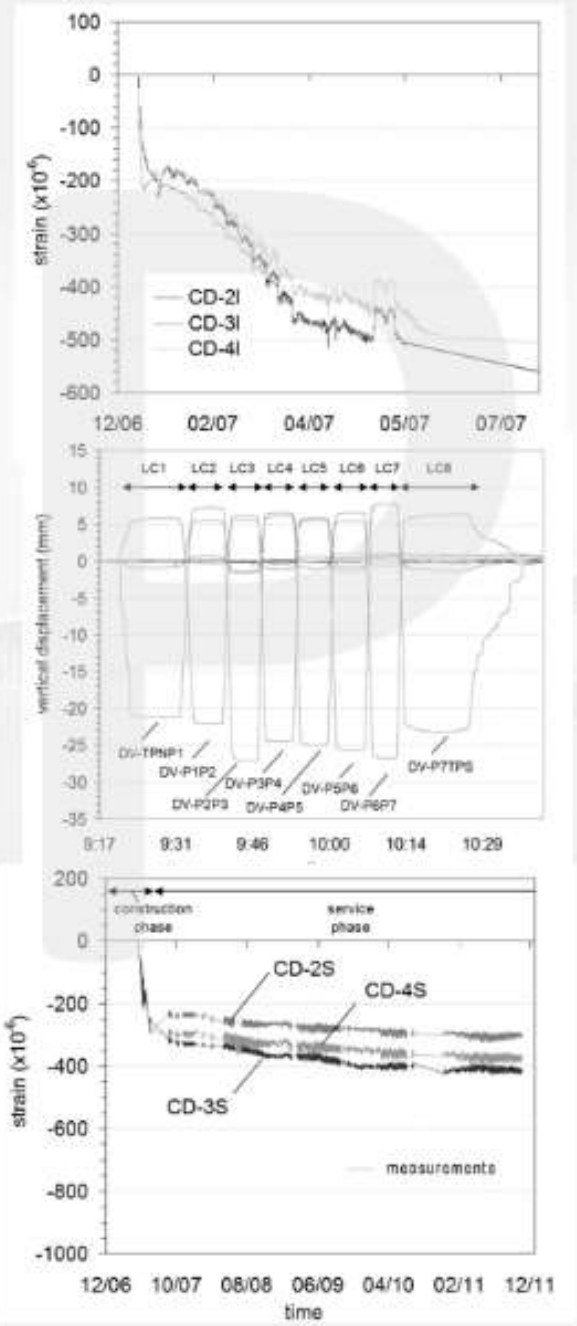
SOUSA, H., (2014) "Monitoring system of the Lezíria Bridge – Limitations & Potentialities: Technical Report", Client: BRISA Group, Lisbon, Portugal (Major Portuguese Highway Agency – private concessionaire).

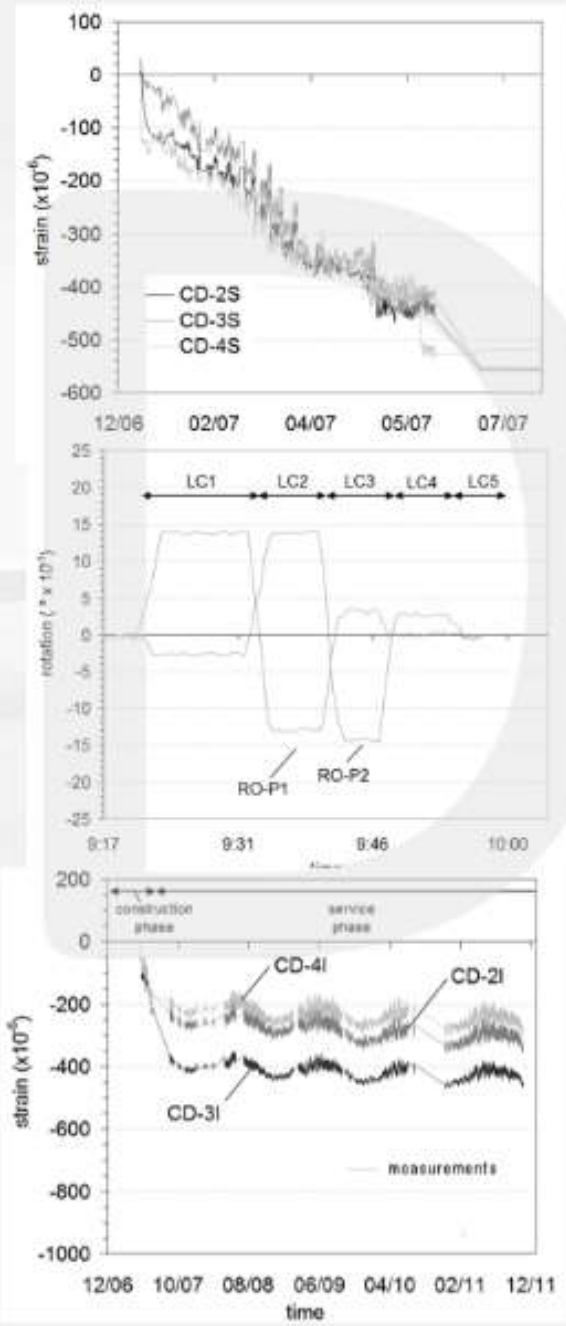
1. The monitoring system : Measurements (since construction)

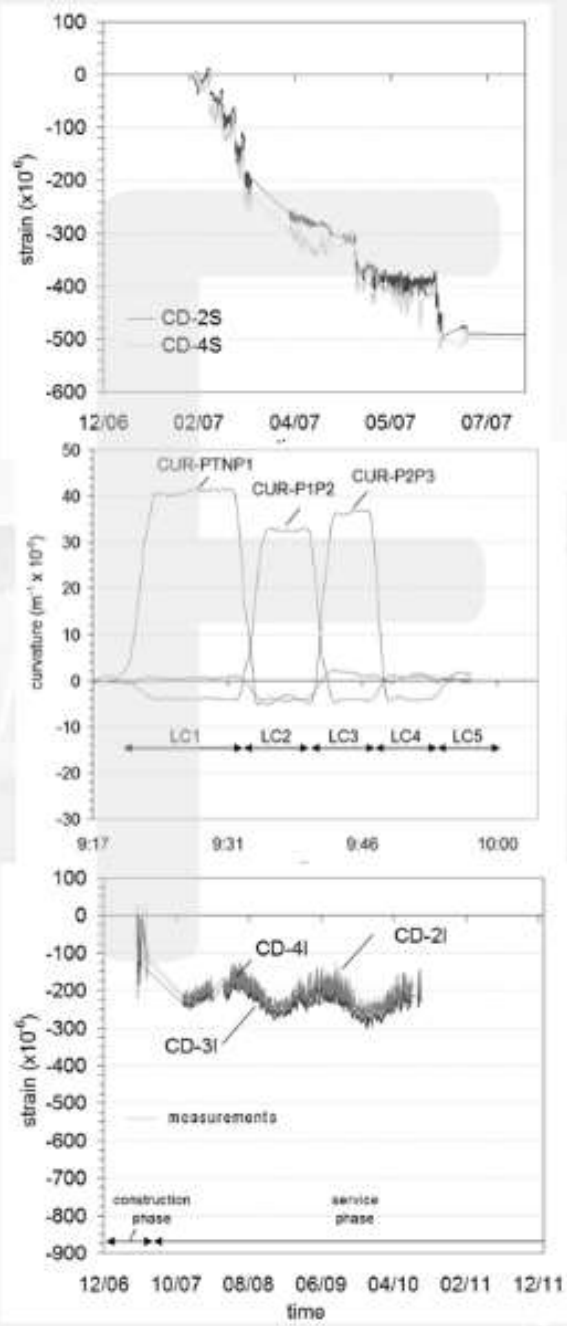
CONSTRUCTION

LOAD TEST

OPERATIONAL





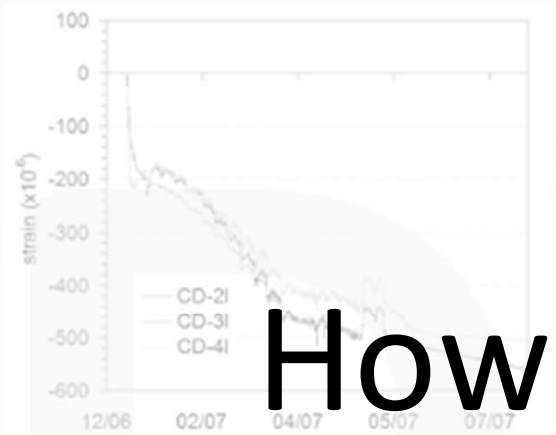


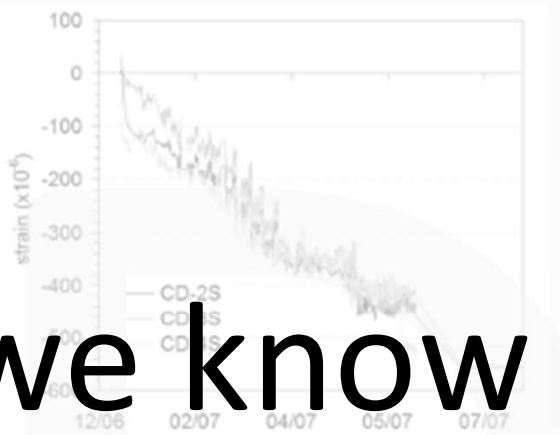
1. The monitoring system : Measurements (since construction)

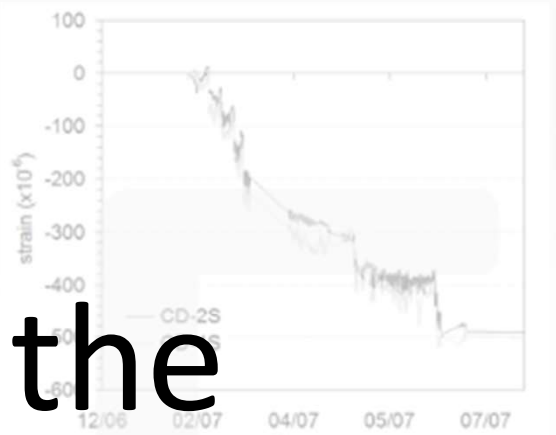
CONSTRUCTION

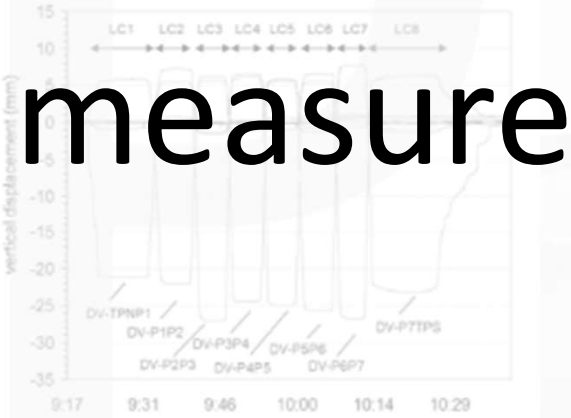
LOAD TEST

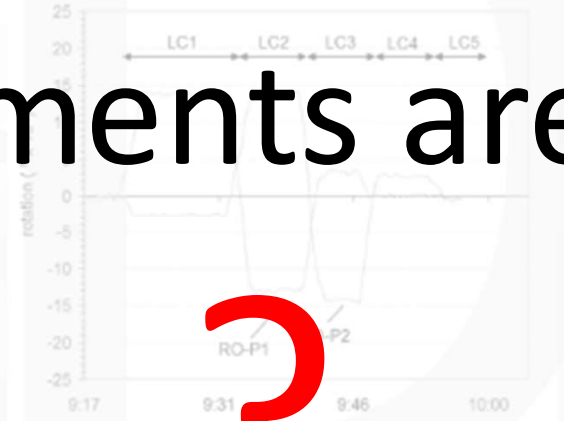
OPERATIONAL

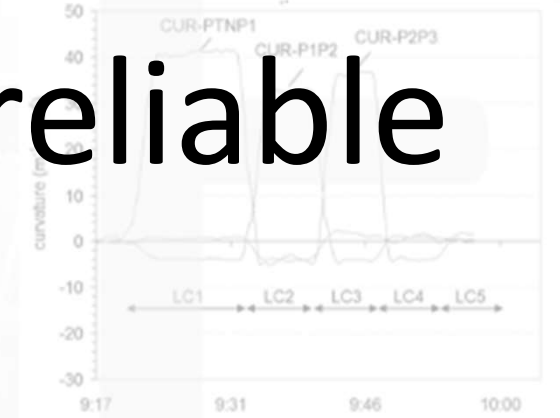


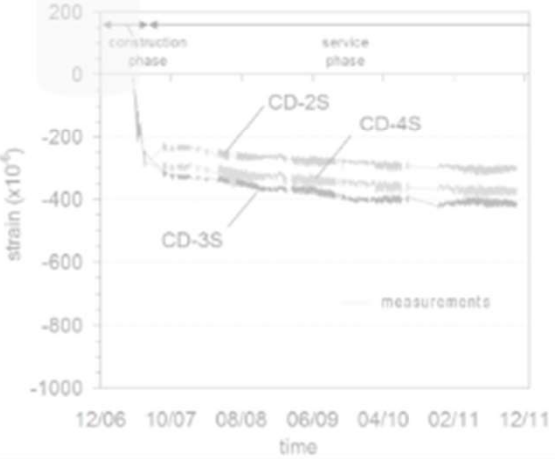


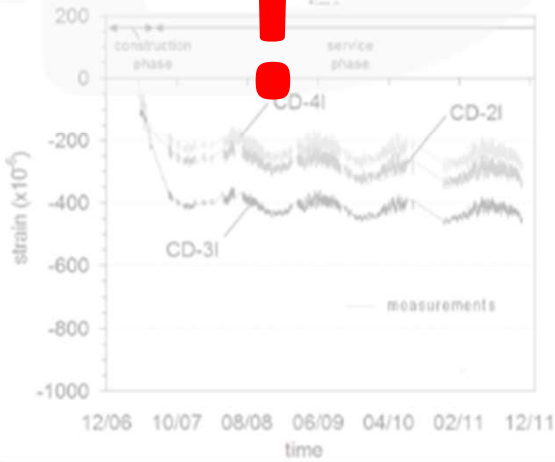


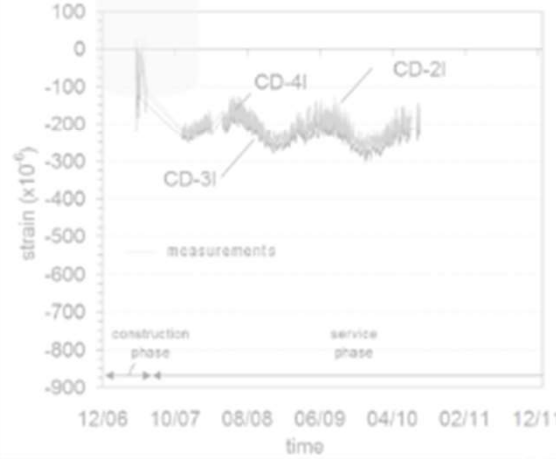












How we know if the measurements are reliable

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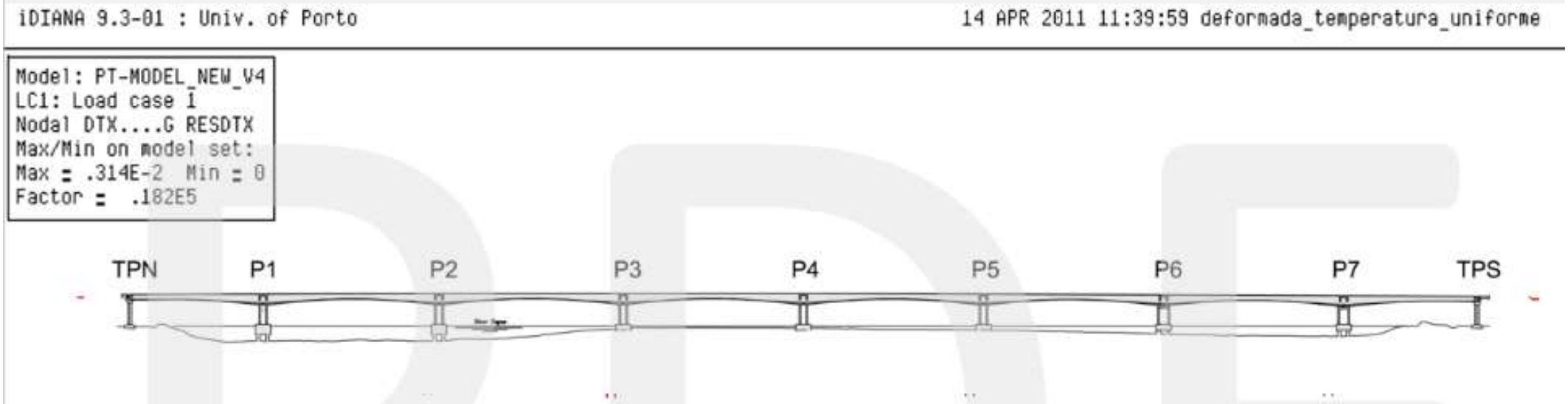
2. The results : FE model for assessment and validation

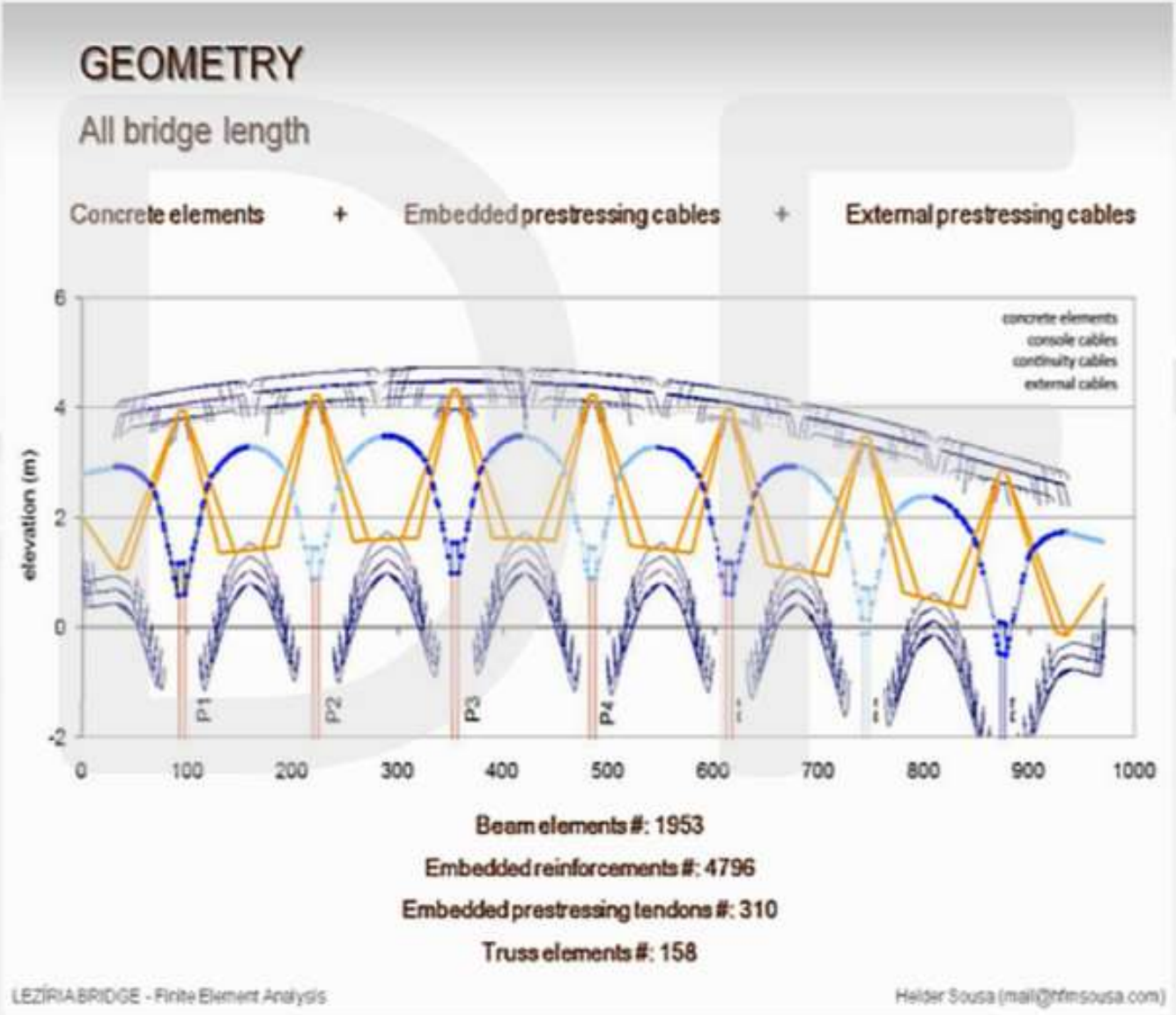


- ❑ Numerical simulation throughout the bridge lifetime (construction + service)
- ❑ Complexity of the construction process (geometry, materials and time–history)
- ❑ Time–dependent effects (shrinkage and creep)
- ❑ Loading: Self–weight, prestressing
- ❑ Model validation through load test at the end of the bridge construction
- ❑ Lifetime predictions based on a model updating supported by the collected measurements

SOUSA, H., A., BENTO, J., FIGUEIRAS, J. (2014) "Assessment and management of concrete bridges supported by monitoring data–based finite element modelling.", Journal of Bridge Engineering DOI:10.1061/(ASCE)BE.1943–5592.0000604
http://ascelibrary.org/doi/abs/10.1061/(ASCE)BE.1943–5592.0000604

2. The results : FE model for assessment and validation

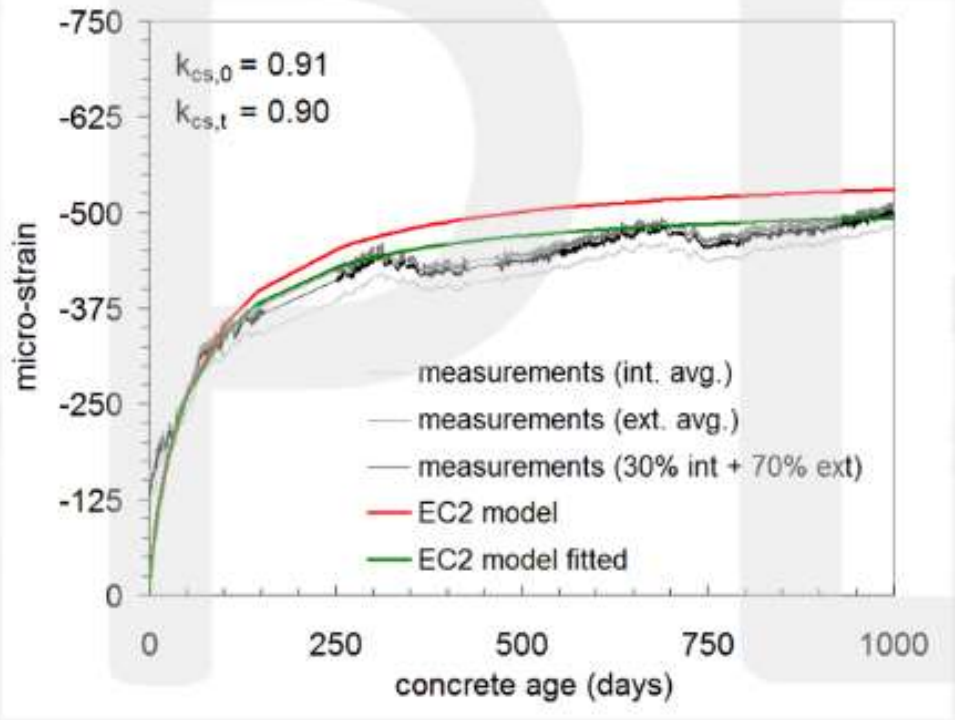
- FE model:
  - Geometry,
  - Materials
  - Boundaries
- Loading (construction phase and operational life):
  - Self-weight
  - Prestressing
  - Traffic loads
- Long-term effects:
  - Shrinkage
  - Creep
  - Thermal effects



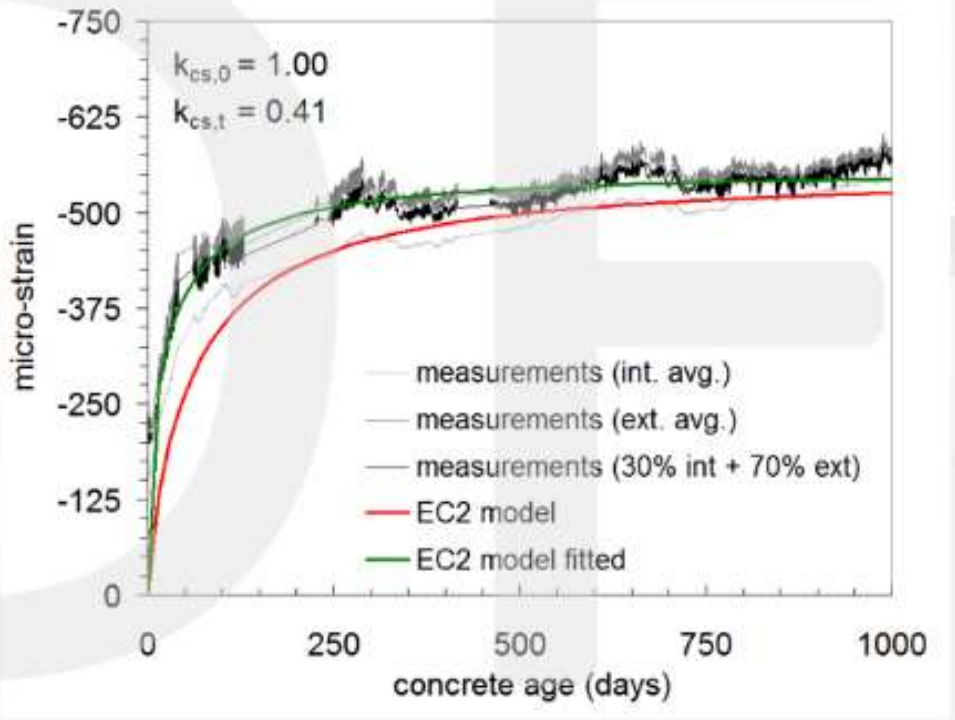
2. The results : FE model for assessment and validation

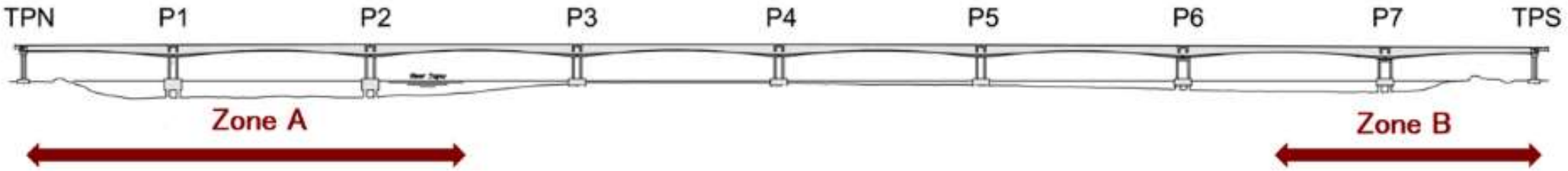
❑ **MATERIALS** (based on measurements performed in concrete prisms)

Shrinkage (Zone A)



Shrinkage (Zone B)

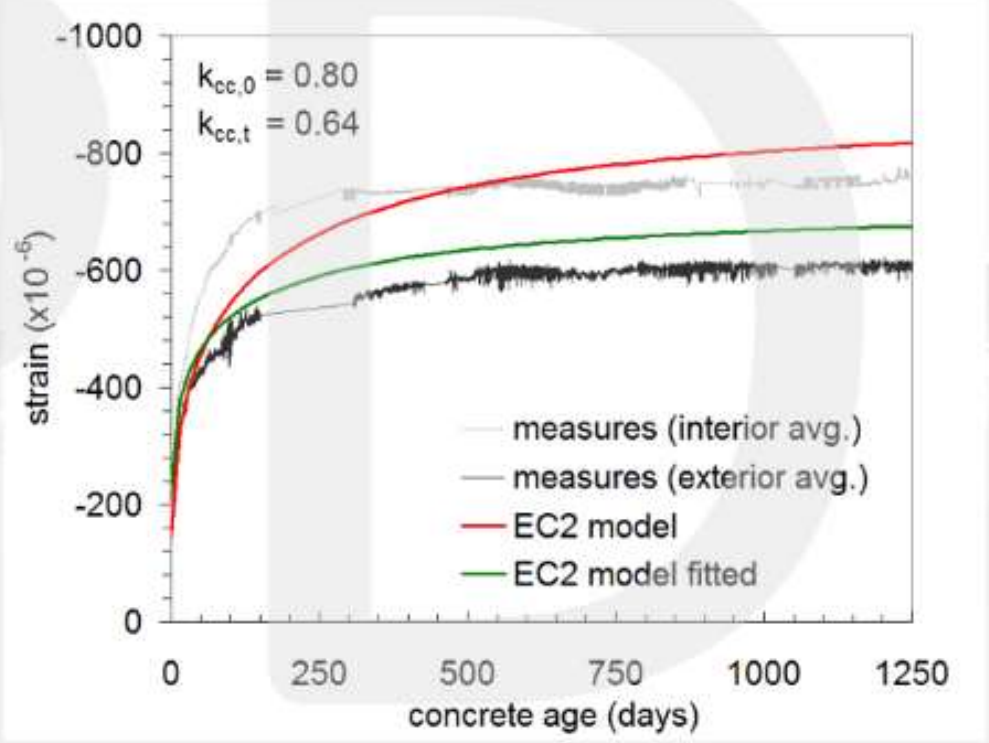


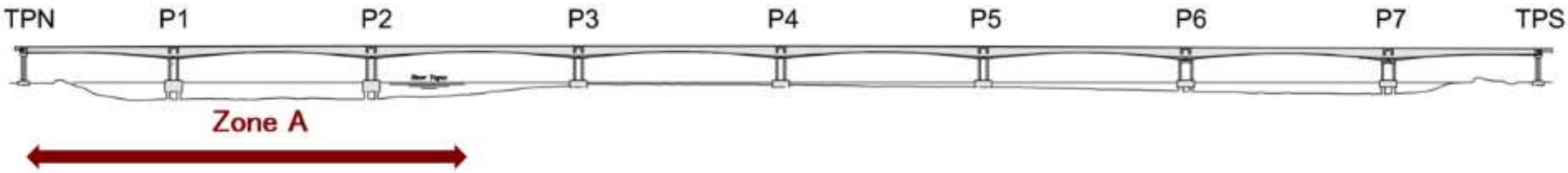


2. The results : FE model for assessment and validation

- **MATERIALS** (based on measurements performed in concrete prisms)

Creep



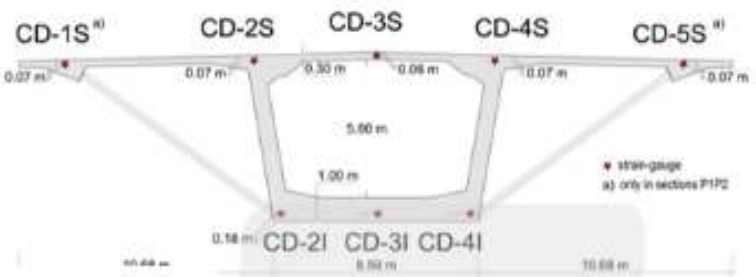


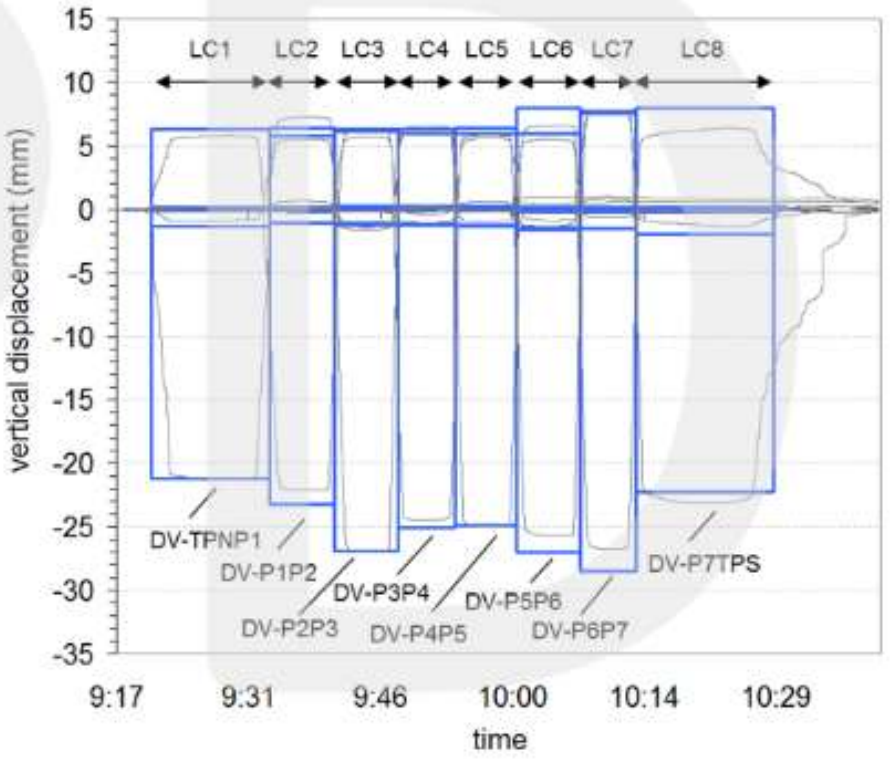
2. The results : Performance during the load test

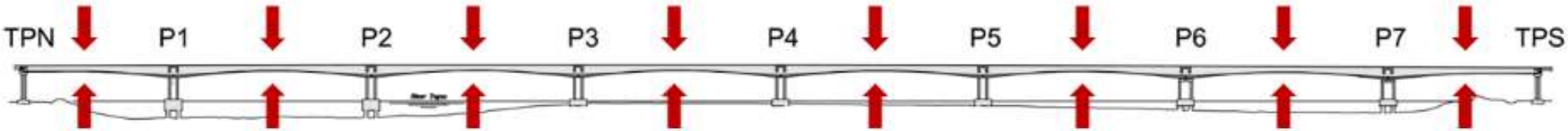
❑ LOAD TEST

(performed at the end of construction)

Vertical displacements





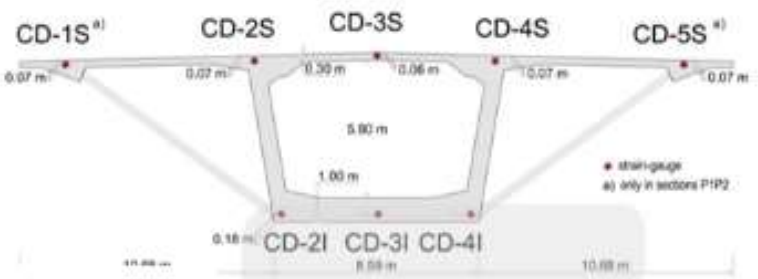


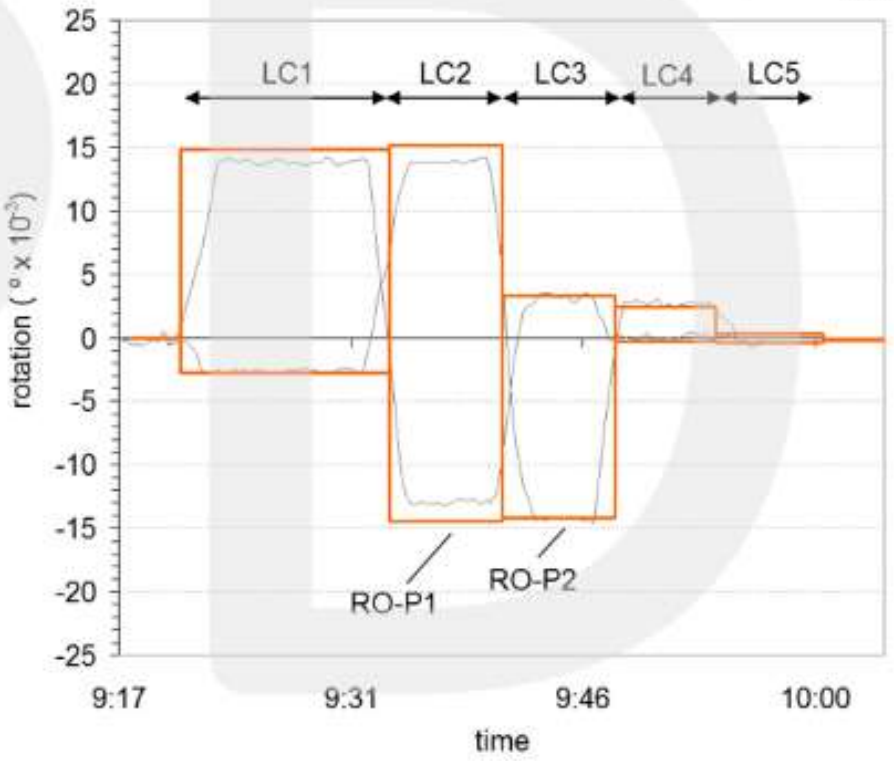
2. The results : Performance during the load test

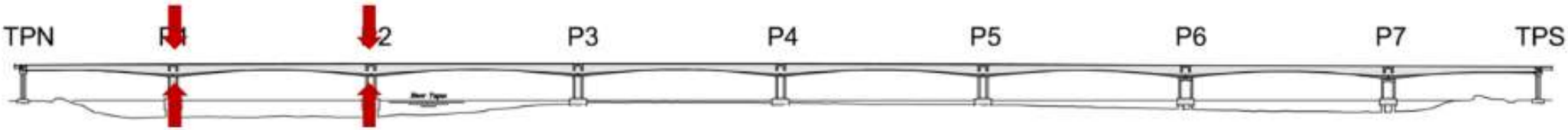
❑ LOAD TEST

(performed at the end of construction)

Rotations





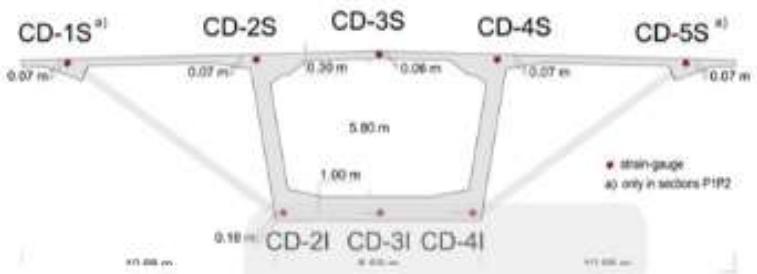


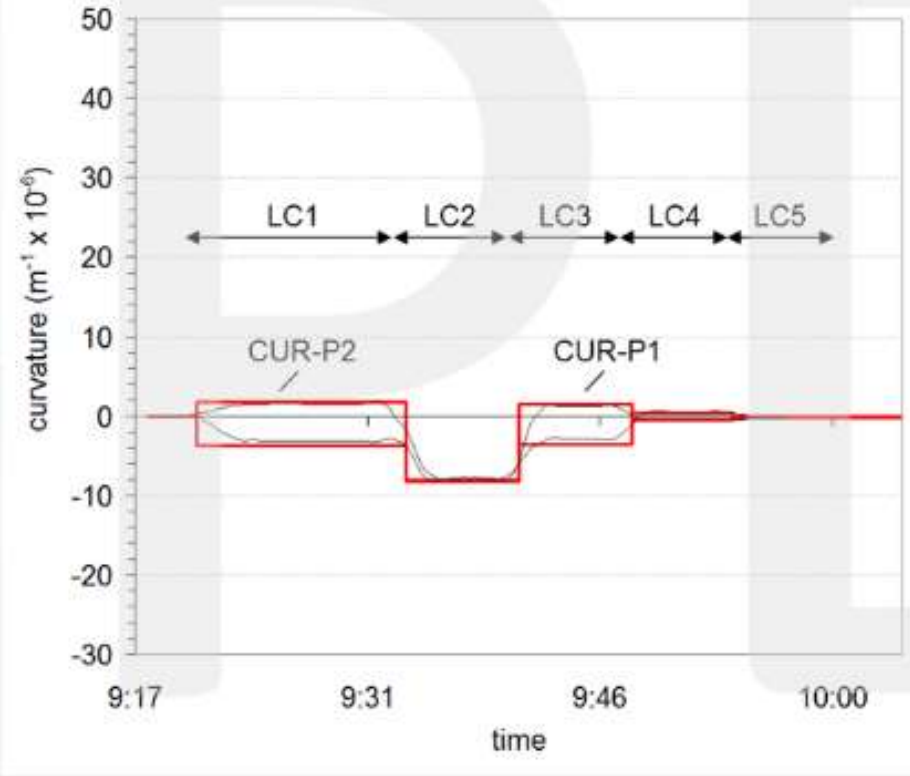
2. The results : Performance during the load test

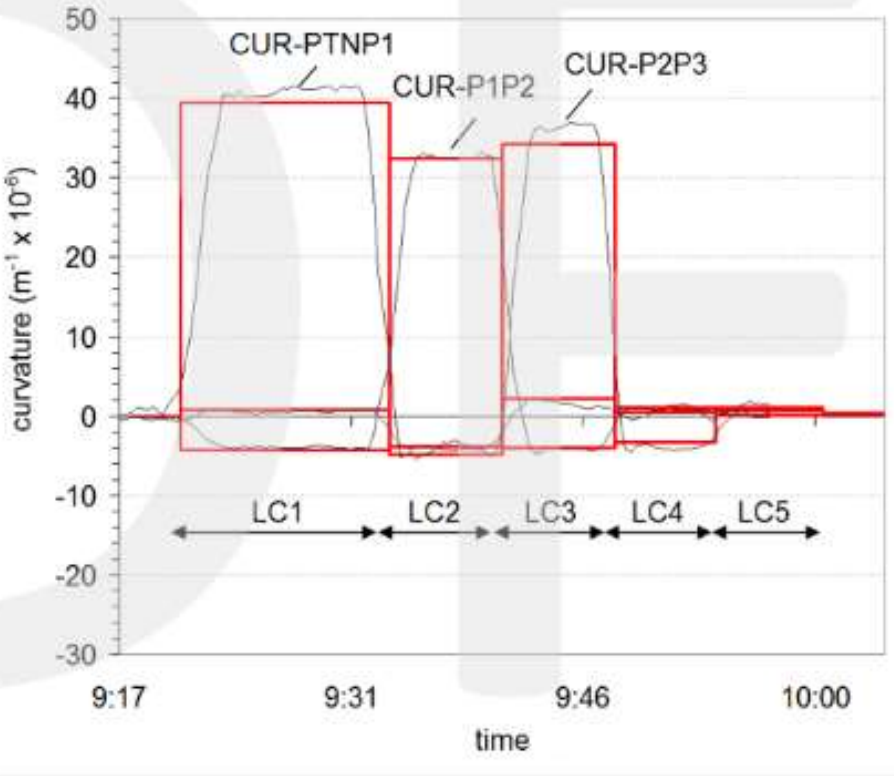
❑ LOAD TEST

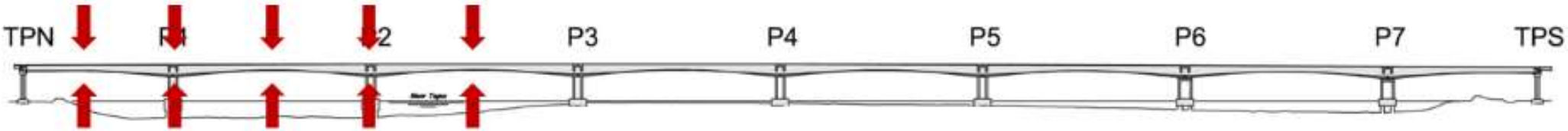
(performed at the end of construction)

Curvatures





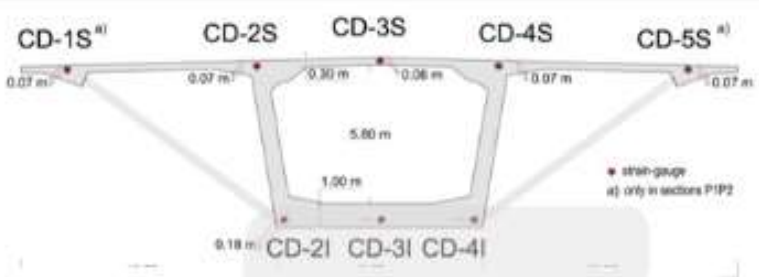


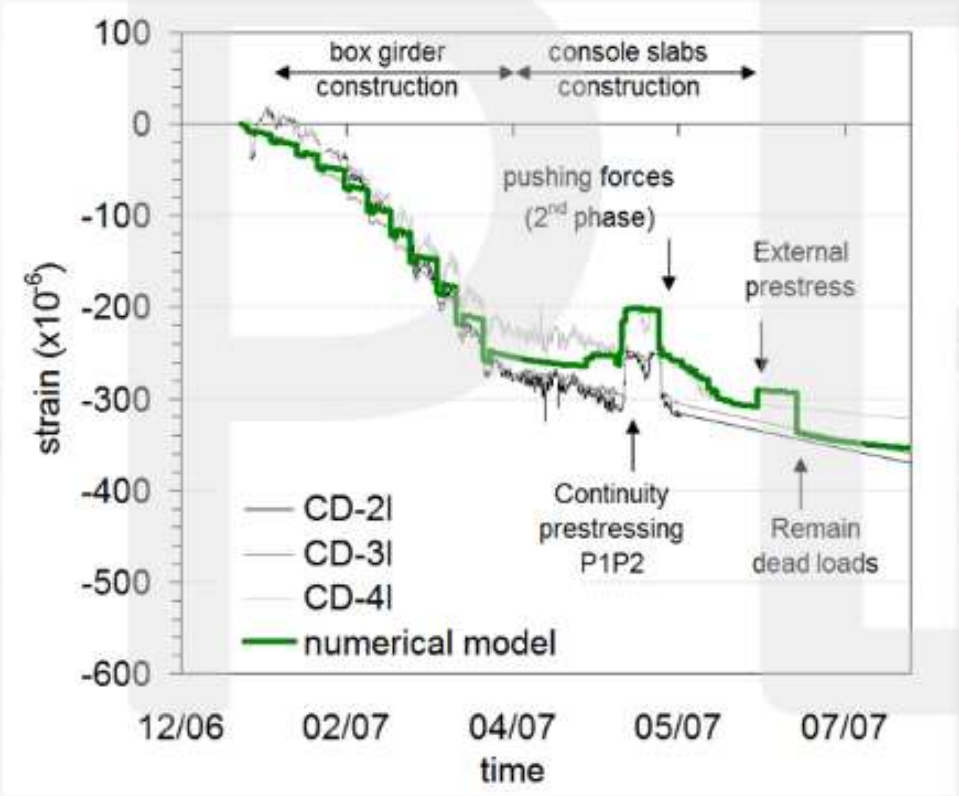


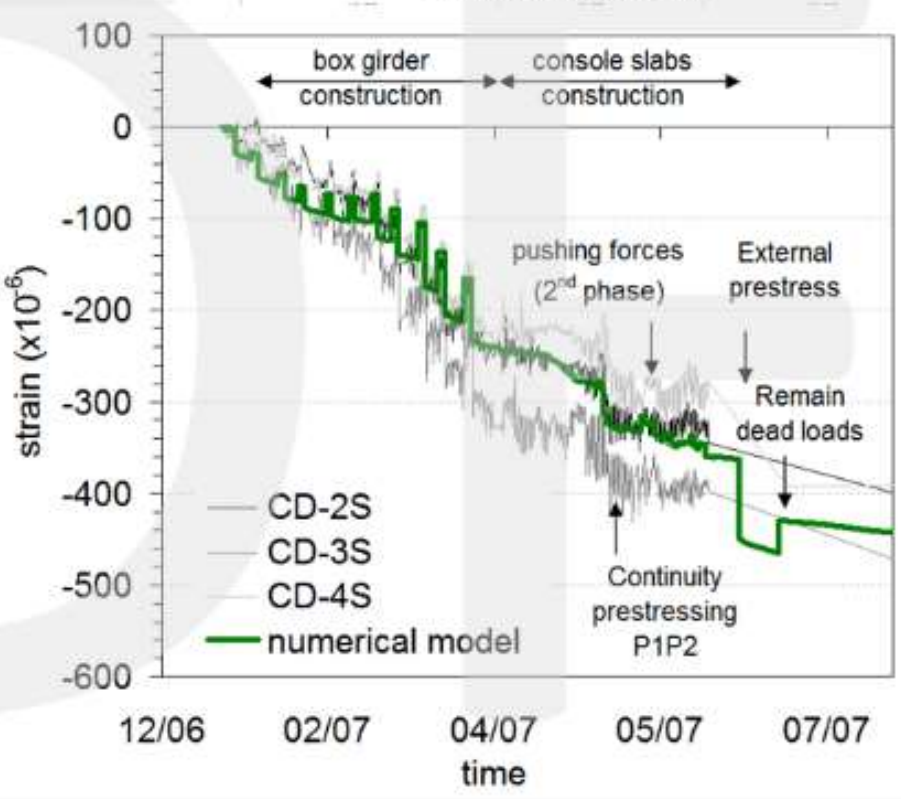
2. The results : Performance during the cantilever construction

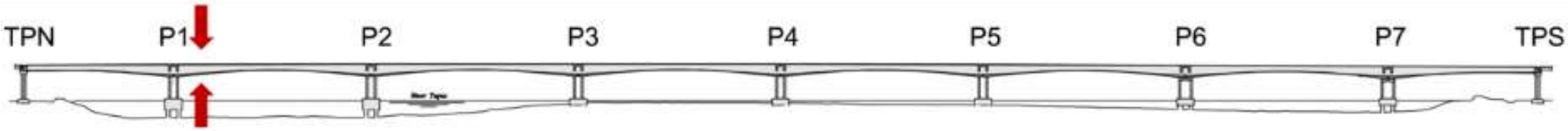
❑ CONSTRUCTION PHASE

Section P1





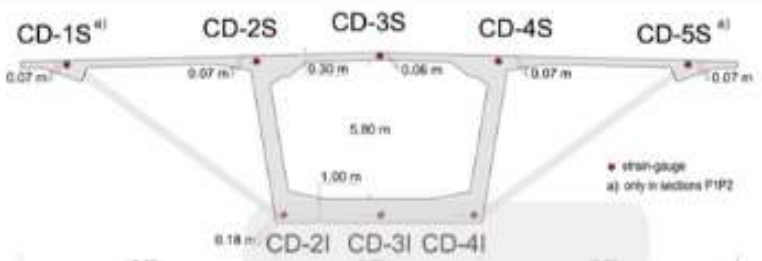


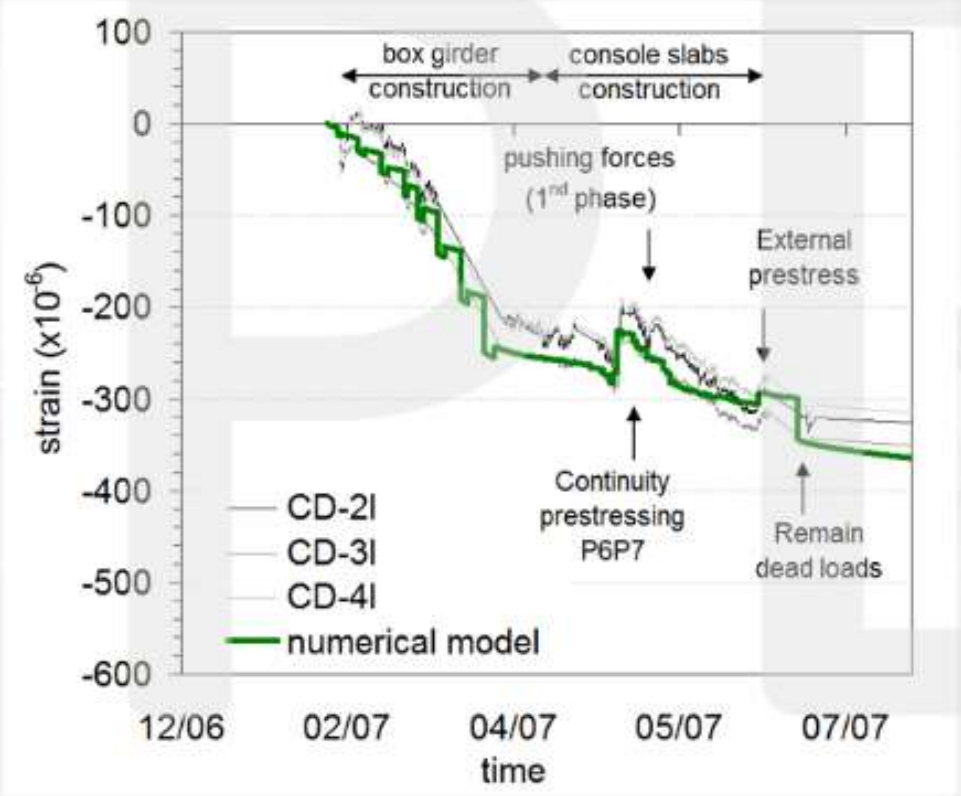


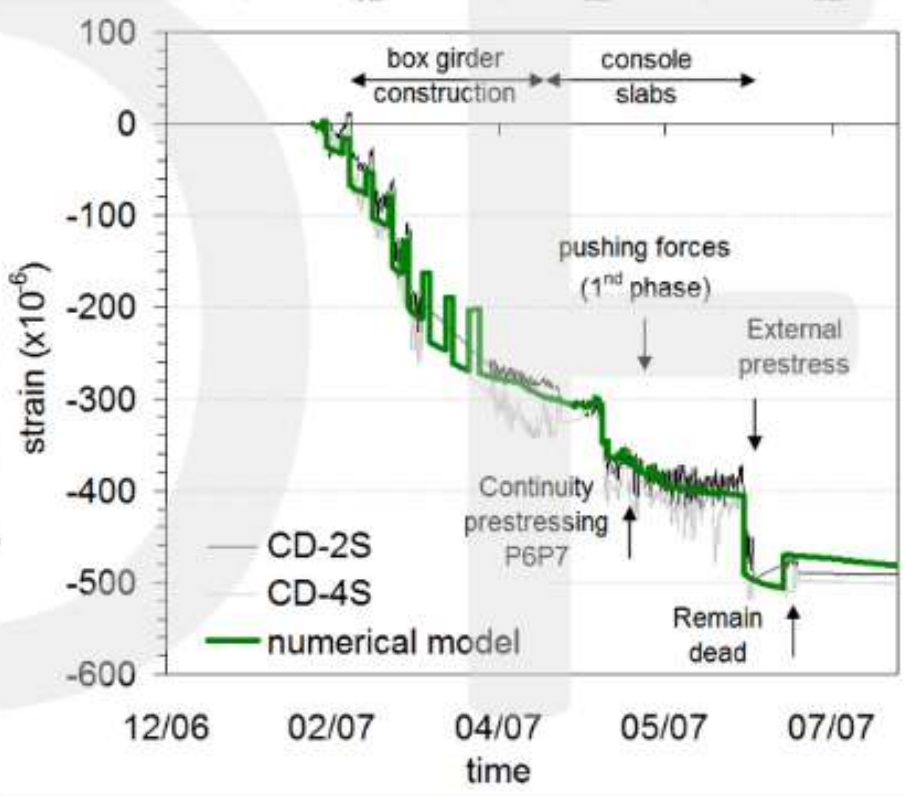
2. The results : Performance during the cantilever construction

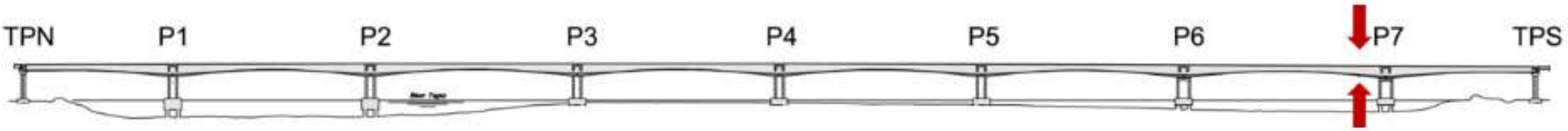
❑ CONSTRUCTION PHASE

Section P7







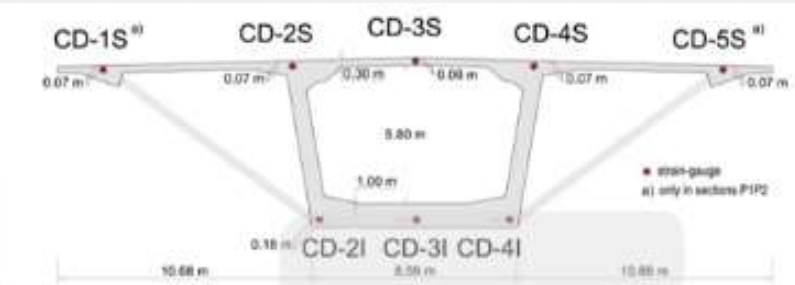


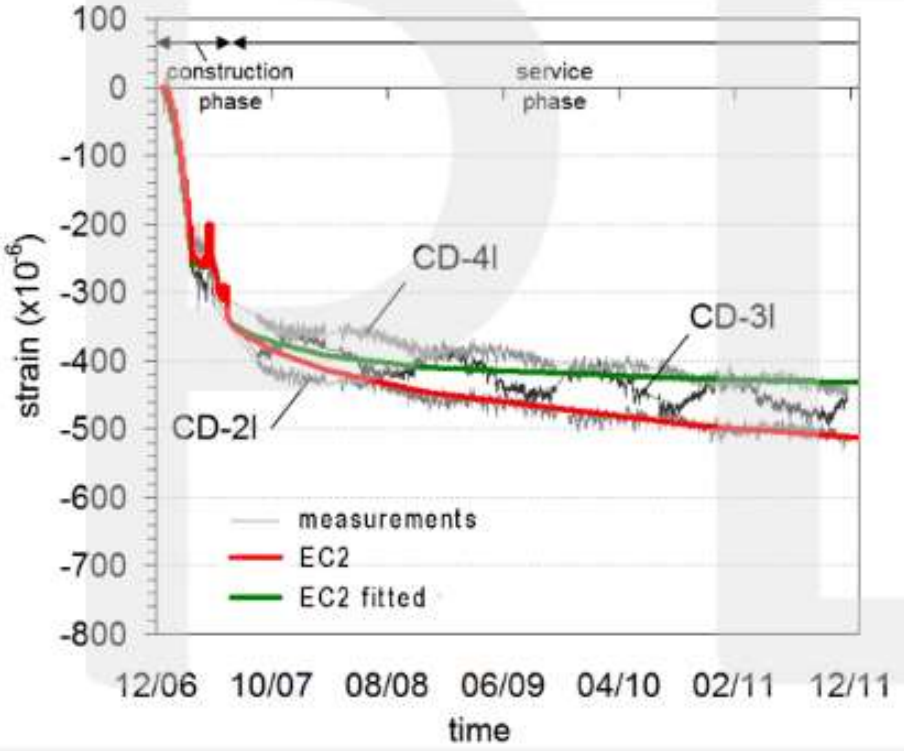
2. The results : Long-term performance (operational life)

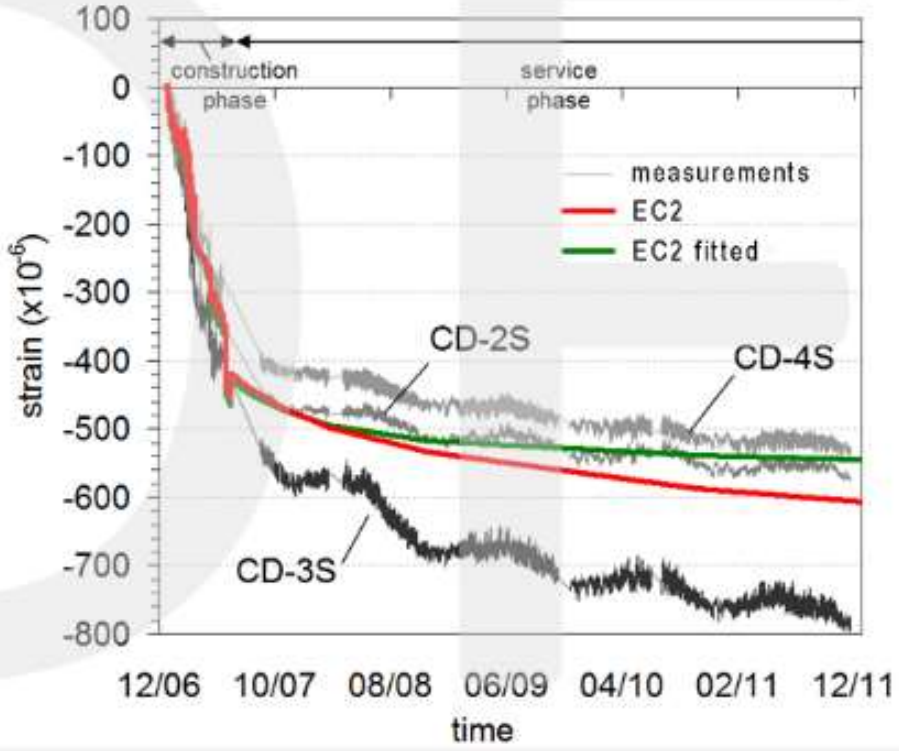
❑ LONG-TERM

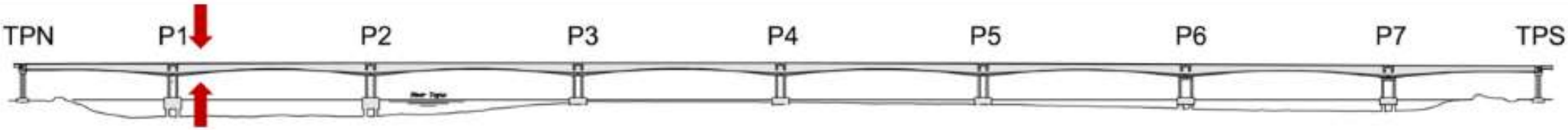
(support sections)

Section P1







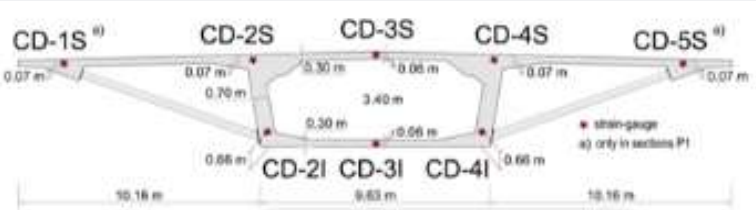


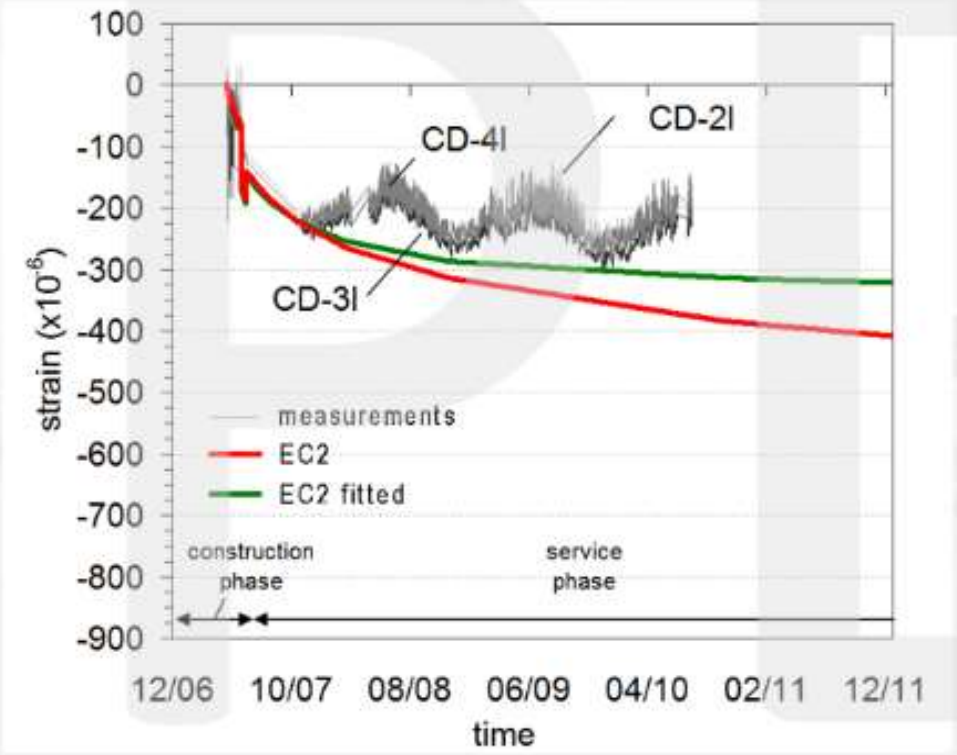
2. The results : Long-term performance (operational life)

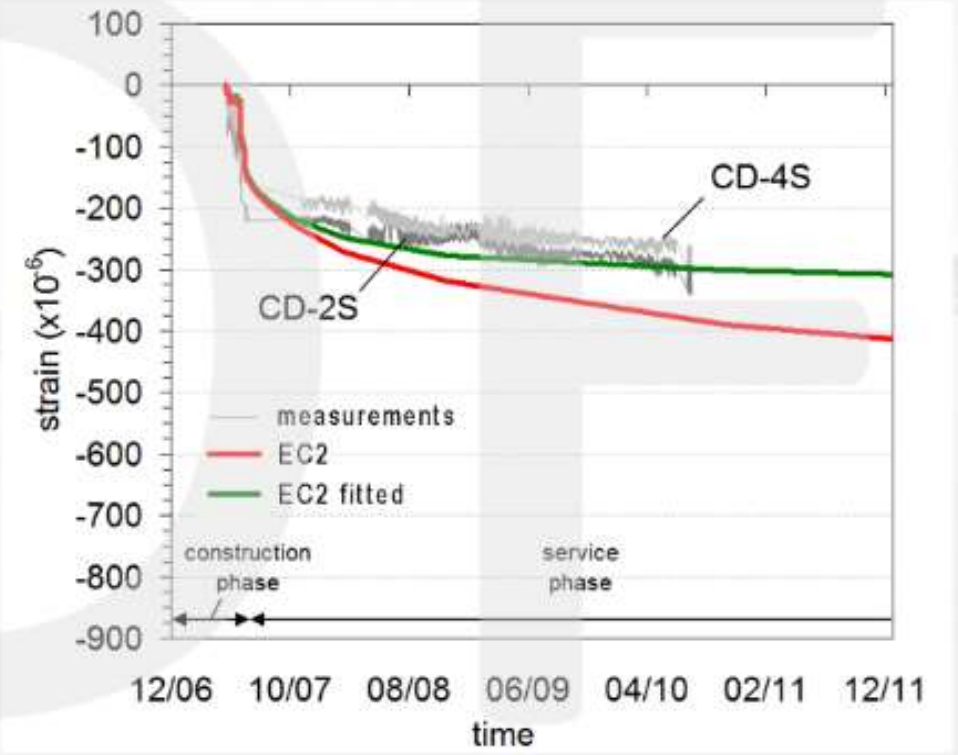
- LONG-TERM

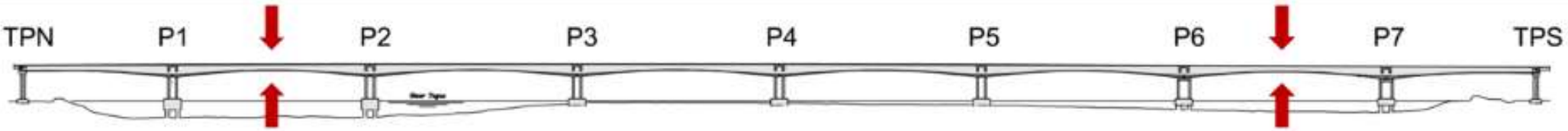
  (mid-span sections)

  Section P6P7







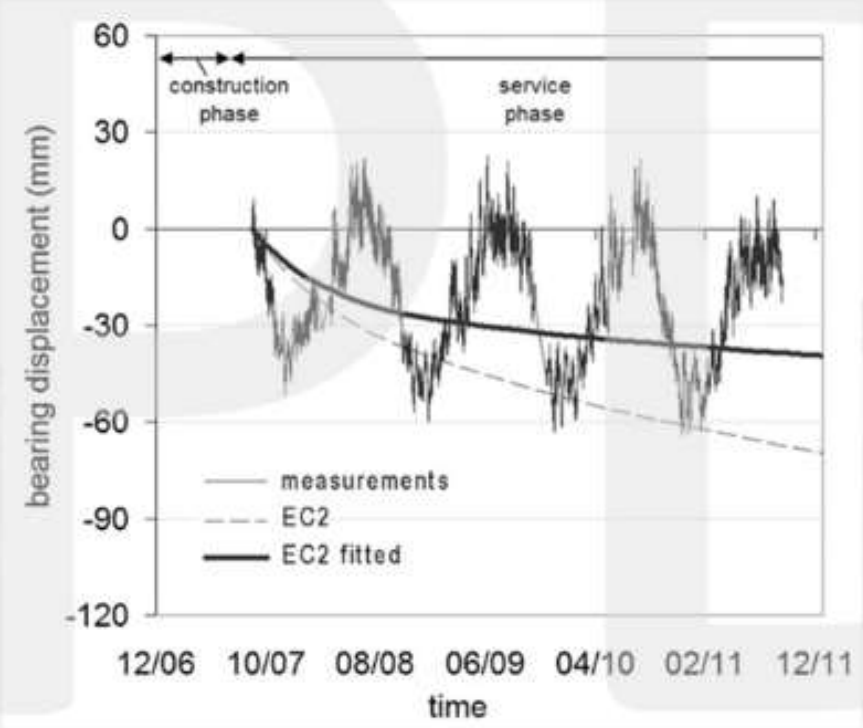


2. The results : Long-term performance (operational life)

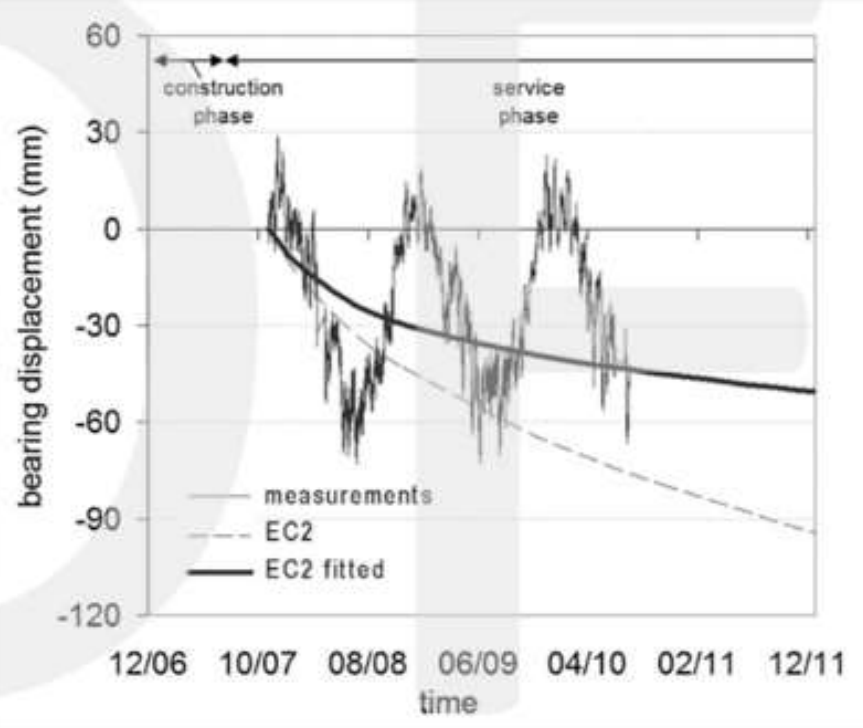
❑ LONG-TERM

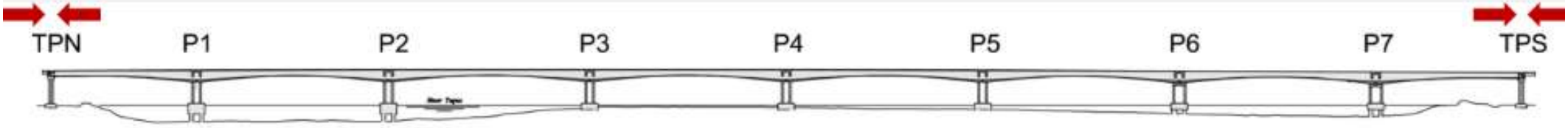
(bearing displacements)

Section TPN

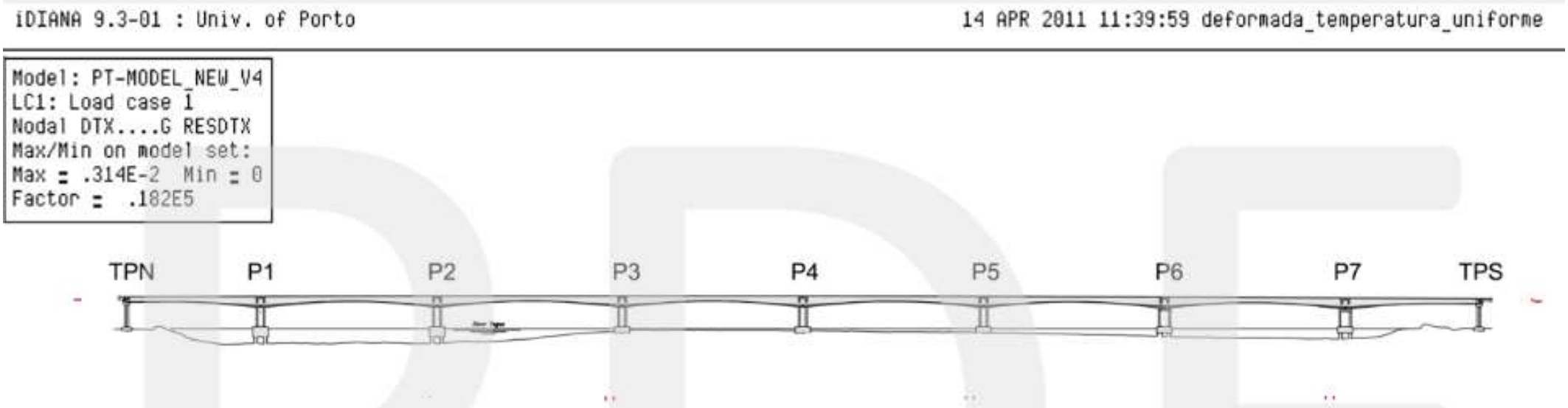


Section TPS





2. The results : FE model for assessment and validation



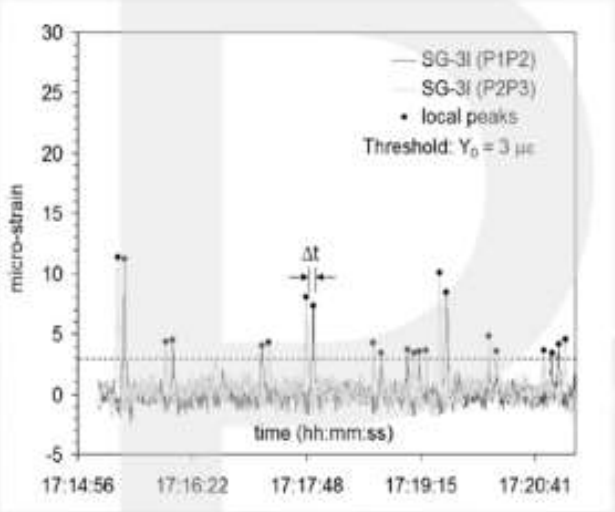
- ❑ Numerical simulation for extreme load events, i.e. effective traffic loads crossing the bridge.
- ❑ Loads were calculated based on the strain measurements.
- ❑ Elastic behavior and cracking checked.
- ❑ Loading: Traffic loads.
- ❑ Model validation through load test at the end of the bridge construction.
- ❑ Lifetime predictions for the expected maximum deflections due to extreme loads due to traffic.

SOUSA, H., COSTA, B., HENRIQUES, A., BENTO, J., FIGUEIRAS, J. (2016) "Assessment of traffic load events and structural effects on road bridges based on strain measurements", Journal of Civil Engineering and Management DOI:10.3846/13923730.2014.897991. http://dx.doi.org/10.3846/13923730.2014.897991

2. The results : Short-term performance (operational life)

❑ EXTREME LOADS (estimation based on strain measurements)

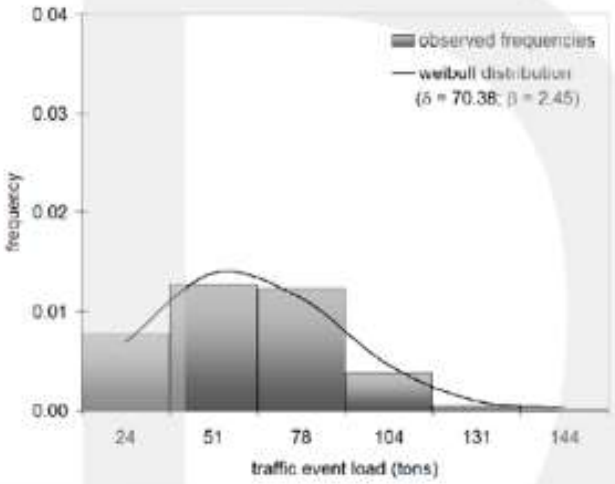
Observations



$$P_i(t) = k_2(t) \cdot k_0 \cdot \varepsilon_{i,peak}(t) \quad (1)$$

$$\begin{cases} k_0 = P_{ref} / \varepsilon_{ref} & (2) \\ k_1 = \varepsilon / \varepsilon_{ref} & (3) \\ k_2(t) = E_{c,ref} / E_c(t) & (4) \end{cases}$$

Load Histogram

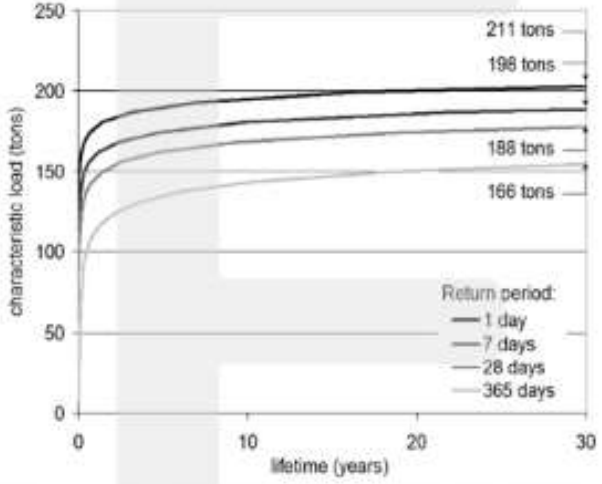


$$f(x) = \frac{\beta}{\delta} \cdot \left(\frac{x}{\delta}\right)^{\beta-1} \cdot e^{-\left(\frac{x}{\delta}\right)^{\beta}}$$

$$x > 0; \delta > 0; \beta > 0$$

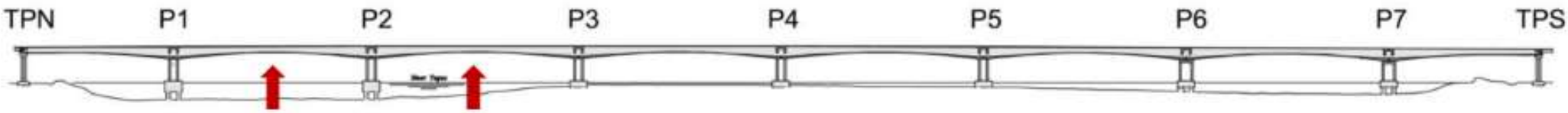
$$\bar{f}(x) = \begin{cases} 0 & x \le x_0 \\ \dfrac{f(x)}{\int_{x_0}^{+\infty} f(x)dx} & x > x_0 \end{cases}$$

Extreme Loads



$$R_p(x) = \frac{\tau}{\alpha}, \begin{cases} \tau - observation\ period \\ \alpha = 1 - F(x) \end{cases}$$

$$R_p = -\frac{T_{lifetime}}{\ln(1-\alpha)}, \quad \alpha = 0.05$$



2. The results : Short–term performance (operational life)

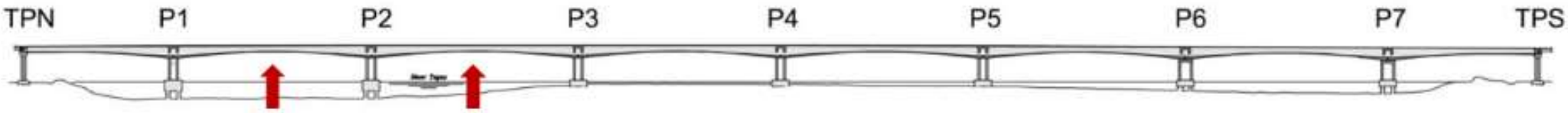
❑ ASSESSMENT OF THE BRIDGE BEHAVIOR

Safety level for the Serviceability Limit Sates

Return period	Characteristic load (tons)	Vertical displacement (mm)		Safety level
		Project	Predicted	
1 day	211	55*	44.8	1.23
7 days	198		43.9	1.25
28 days	188		43.1	1.27
365 days	166		41.7	1.32

* Value determined for the characteristic combination of actions, with a lower limit of L/1200.

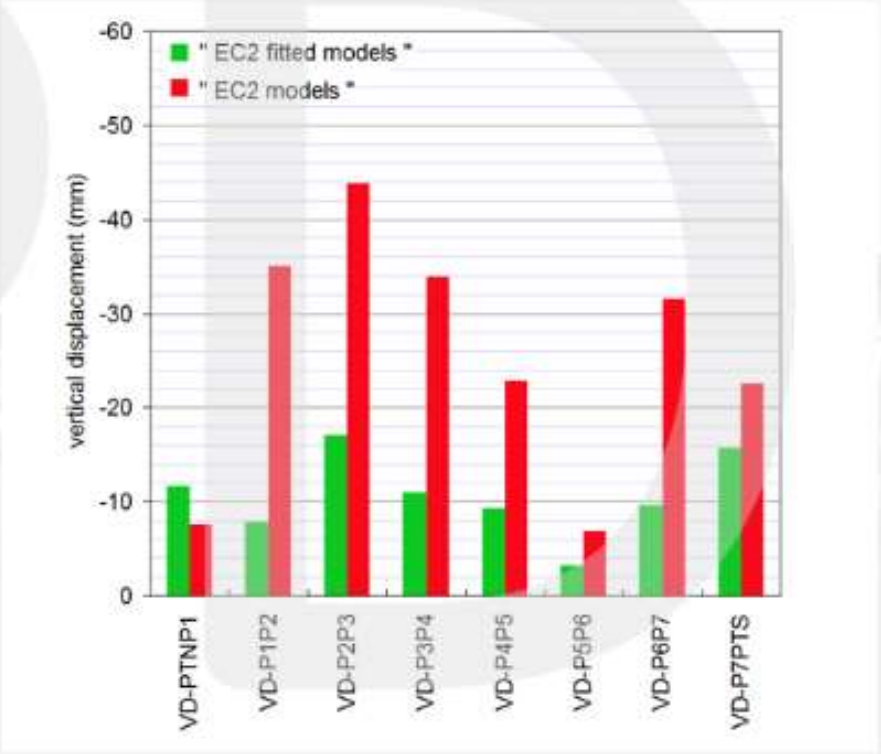
Obs. : deflections and concrete stresses checked

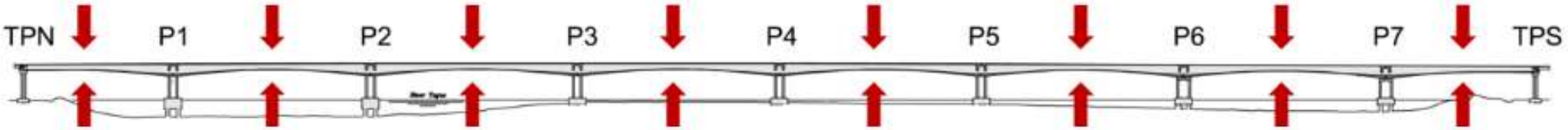


2. The results : Reference values for the measurements in 2030

- PREDICTIONS FOR THE END OF THE OPERATIONAL LIFE（100 years）

  Vertical displacements

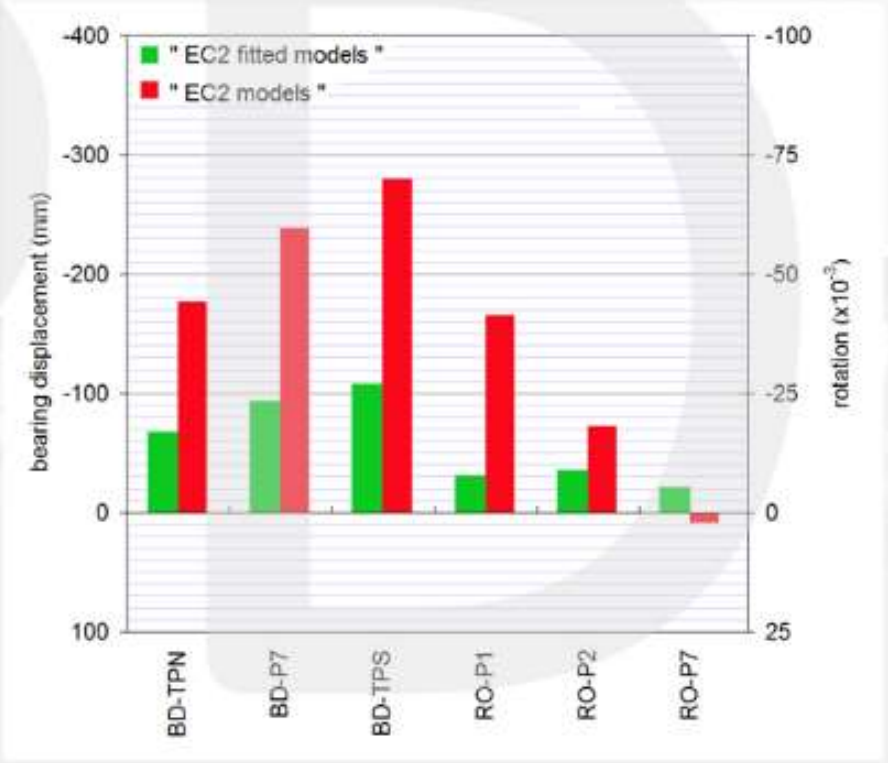


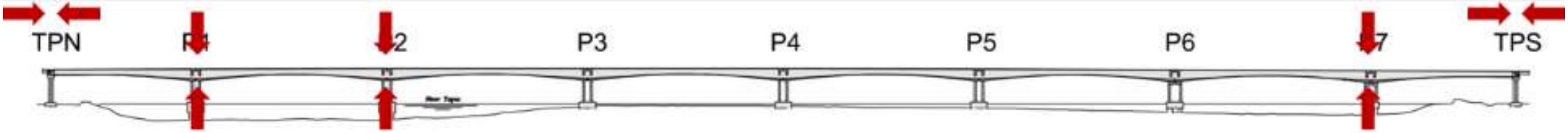


2. The results : Reference values for the measurements in 2030

- PREDICTIONS FOR THE END OF THE OPERATIONAL LIFE （100 years）

  Bearing displacements and rotations

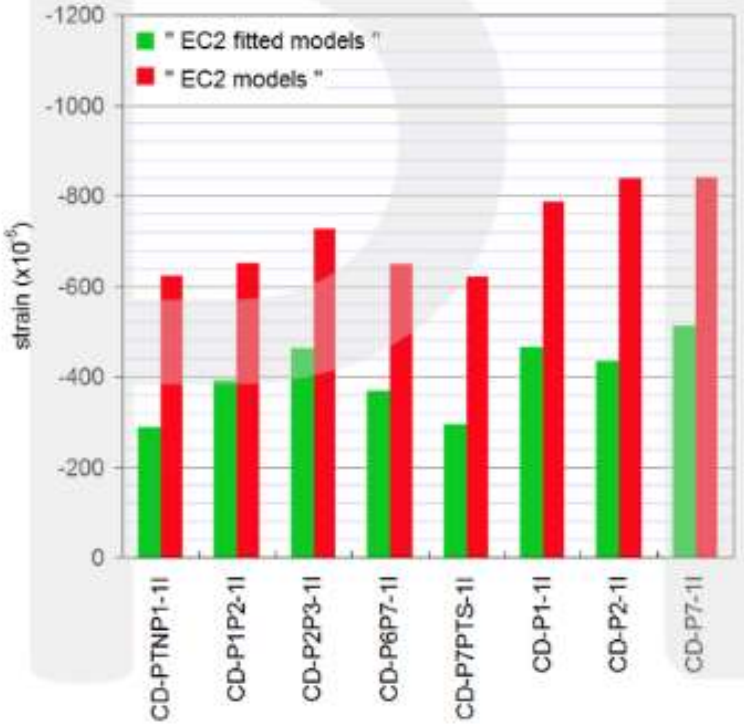


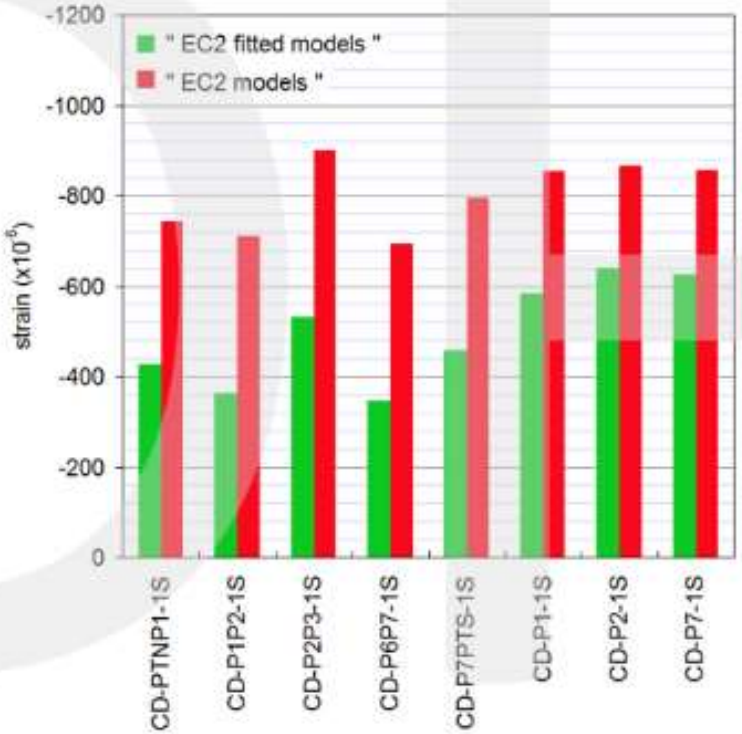


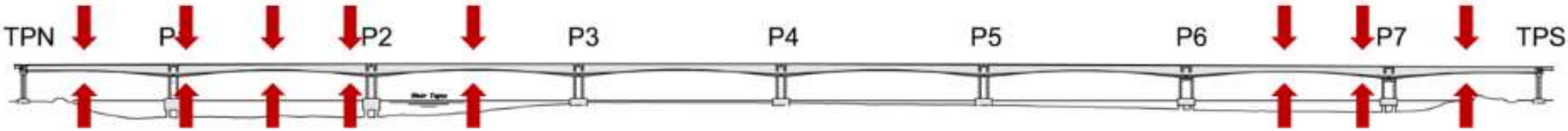
2. The results : Reference values for the measurements in 2030

❑ PREDICTIONS FOR THE END OF THE OPERATIONAL LIFE (100 years)

Concrete deformations





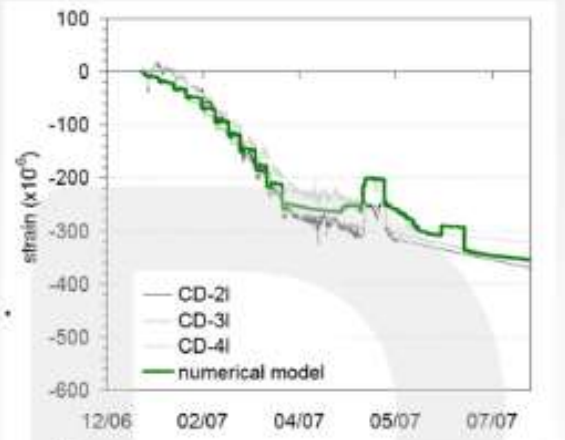


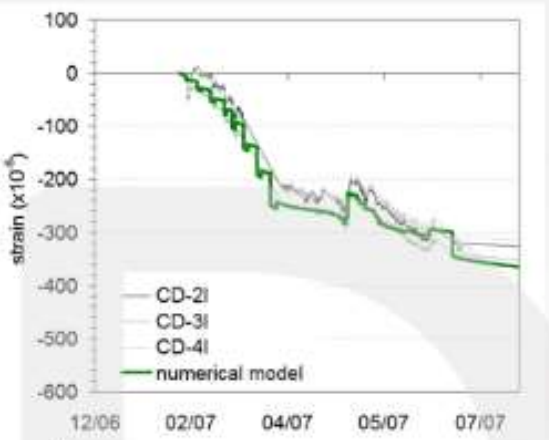
2. The results : Measurements and FE results

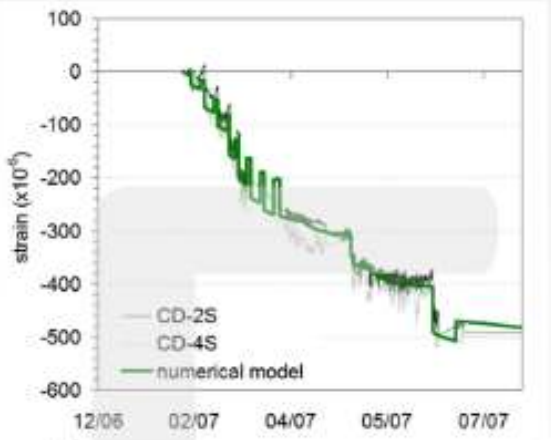
CONSTRUCTION

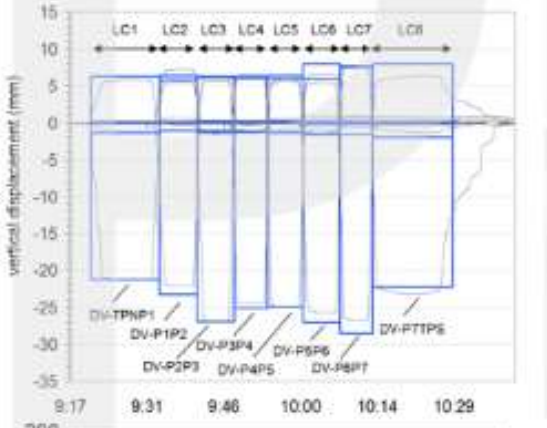
LOAD TEST

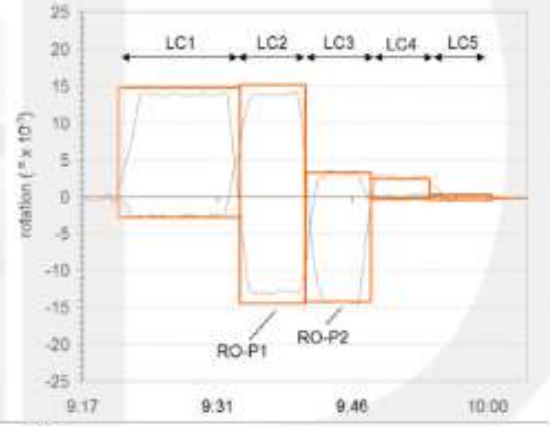
OPERATIONAL

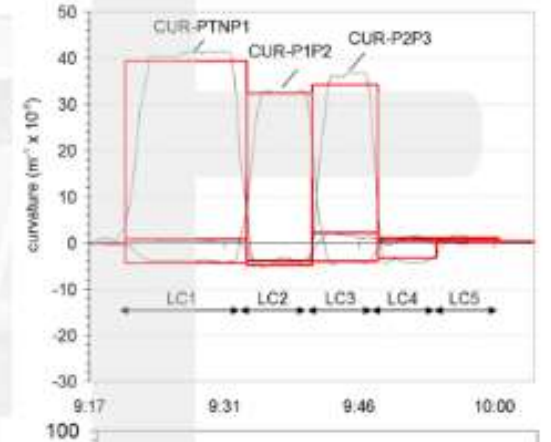


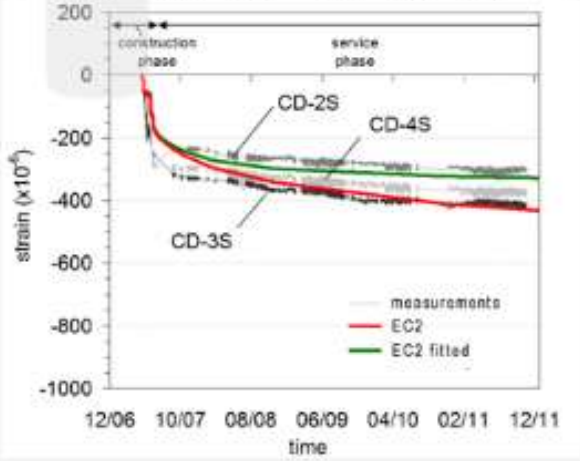


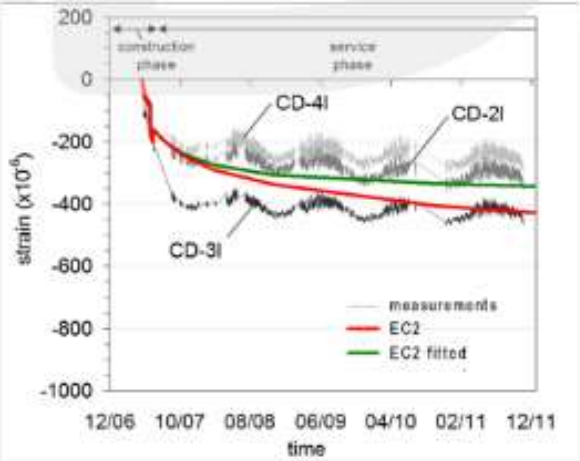


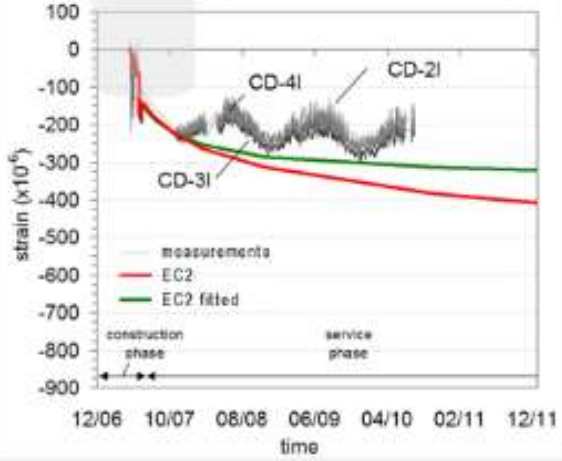












2. The results : Measurements and FE results

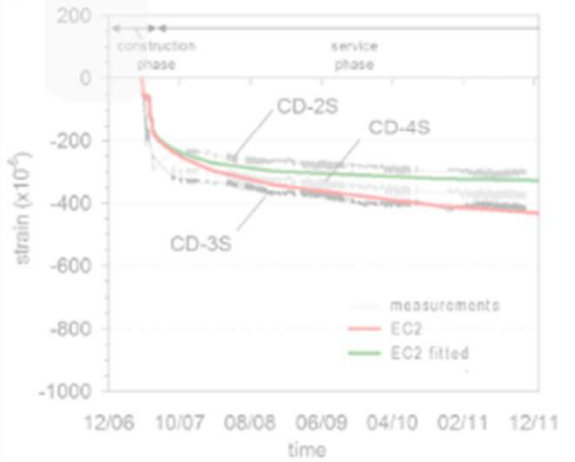
CONSTRUCTION

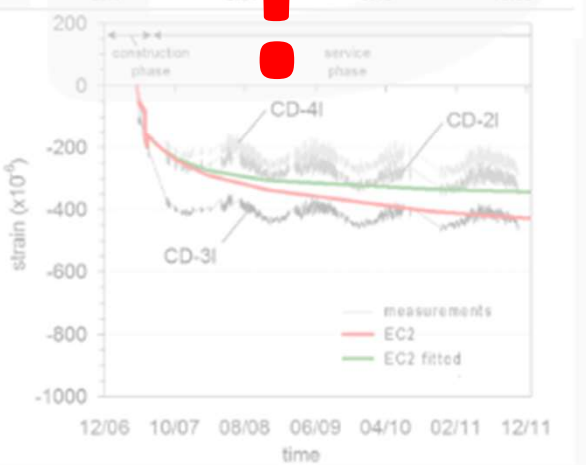
LOAD TEST

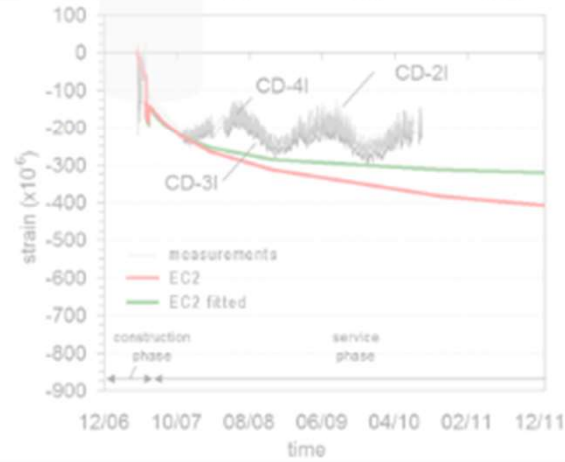
OPERATIONAL

How all this information can be delivered to the bridge owner

?







3. The next generation of asset management supported by SHM

- Dedicated data processing tools towards asset management

4. The references

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http://dx.doi.org/10.3846/13923730.2014.897991

Thank you for your attention

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Federal Highway Research Institute (BASt), Bergisch Gladbach, Germany, 21st March, 2018