

# Design and solutions for bridge monitoring systems + loading test of bridges



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# Maintenance of structures – inspection

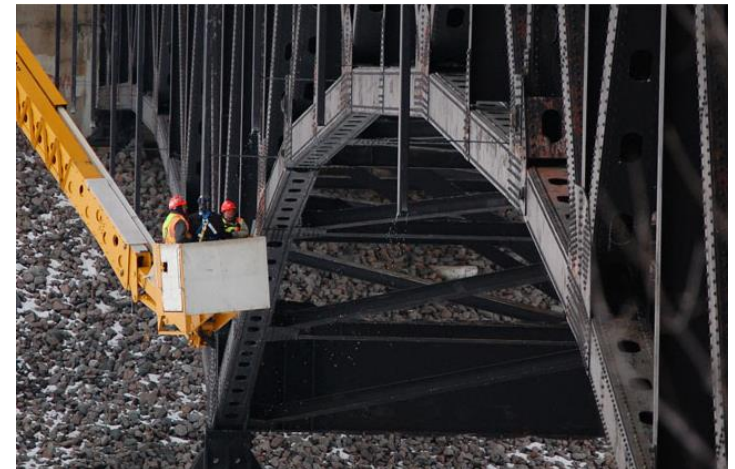
# Assesment of structure's condition

damage → exist?  
where?  
size? → Its effect?  
What to do?

## Practice: analysis on the site

prescribed check

extra/additional check



# Maintenance of structures – inspection

## Critique

subjective

uniform judgement?

re-examinable

to be considered during design

ensured always?

resource demanding

## Alternative solution?



# SHM – Structural Health monitoring

## Structural Health Monitoring – Monitoring the structural condition

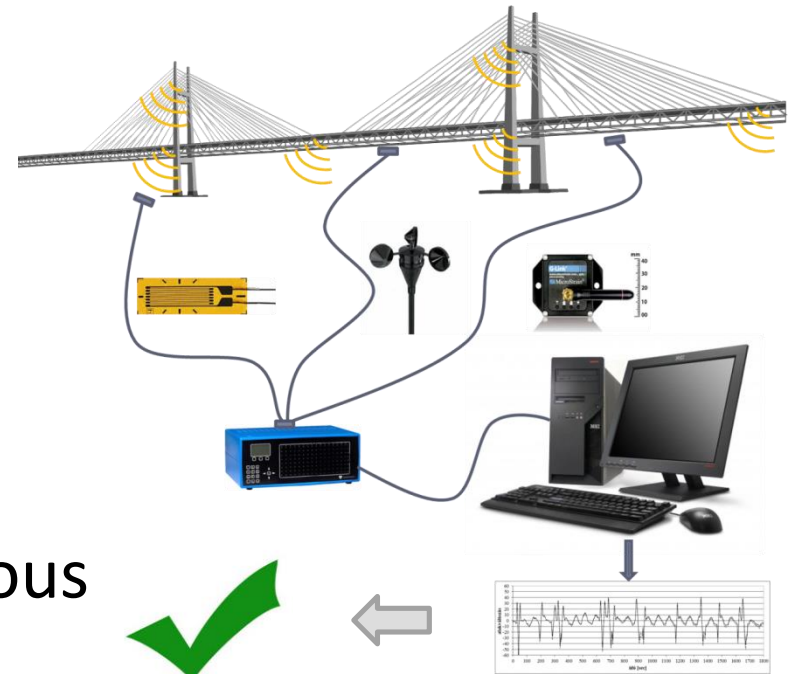
Permanent  
measurement



Permanent  
evaluation



Momentaneous  
condition

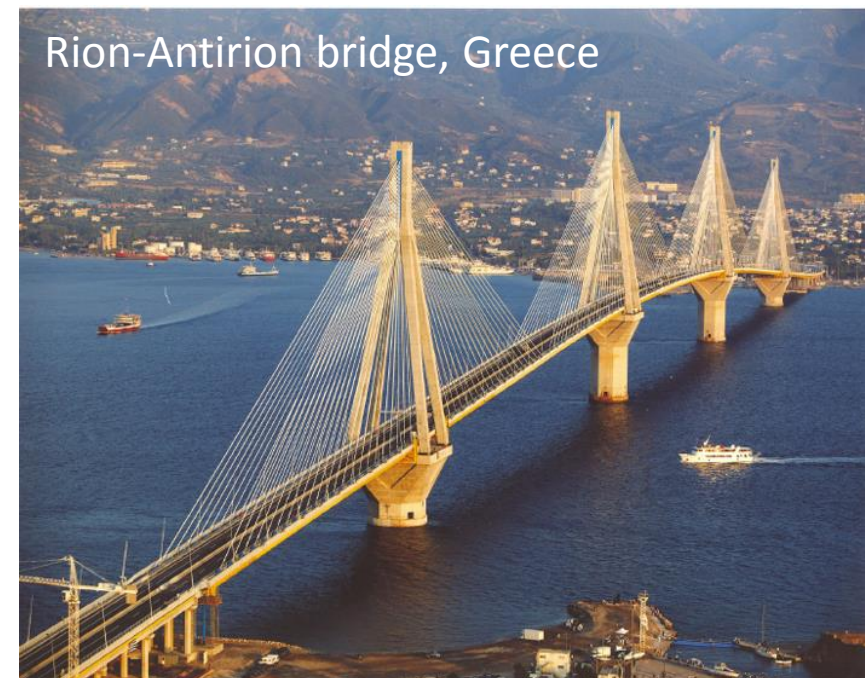


# SHM in engineering practice

Effect of natural forces – structural response

high seismicity regions

hurricane/typhoon endangered countries



# SHM in engineering practice

## Buildings

skyscrapers, facilities of accentuated importance



Millikan Library, CalTech



San Onofre Nuclear Power Plant, California

# SHM's subtasks

Measurement

Evaluation

Decision

Action

electrotechnics

informatics

engineering mechanics

civil engineer

# Global measurement



Acceleration measurement at several points  
Determination of modal characteristics  
    eigenfrequency  
    modal shapes  
    system damping

# Local measurements

## Check-up of design values

cableforce, strain

bearings, dilatation's displacement

## Monitoring of structural members

stress distribution

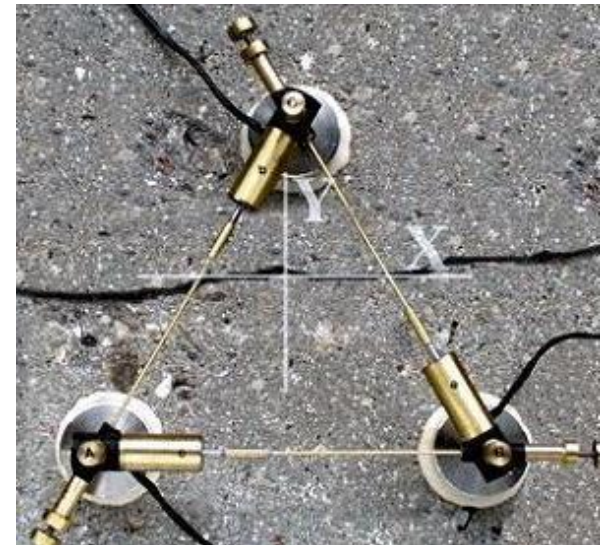
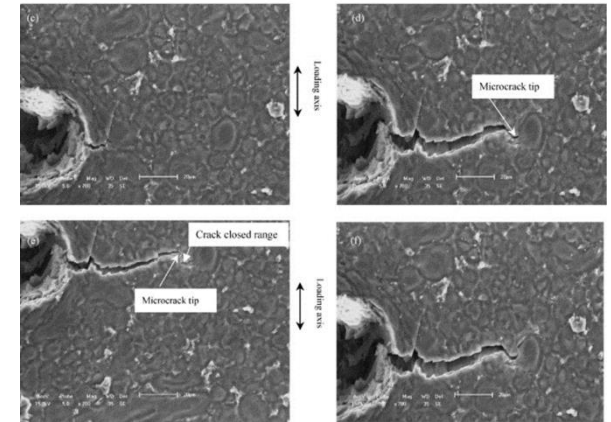
internal forces



# Local measurement

Specific analysis of a phenomenon

- corrosion
- fatigue
- cracks



# Sensors

## Traffic

camera, scale

## Weather

temperature, humidity, rainfall

## Structure

strain (strain gage, vibrating wire, optical)

displacement, inclination

cableforce

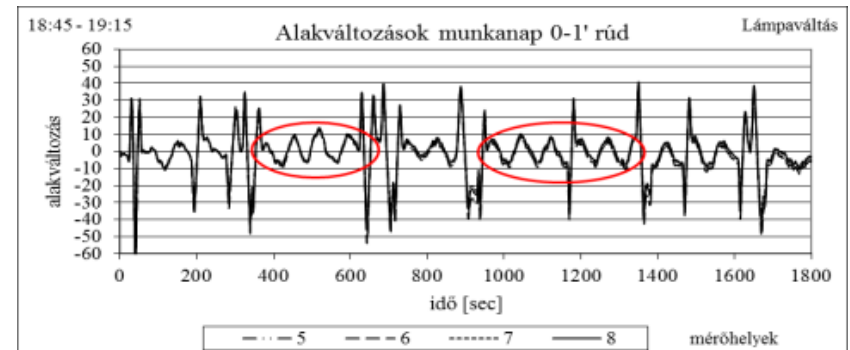
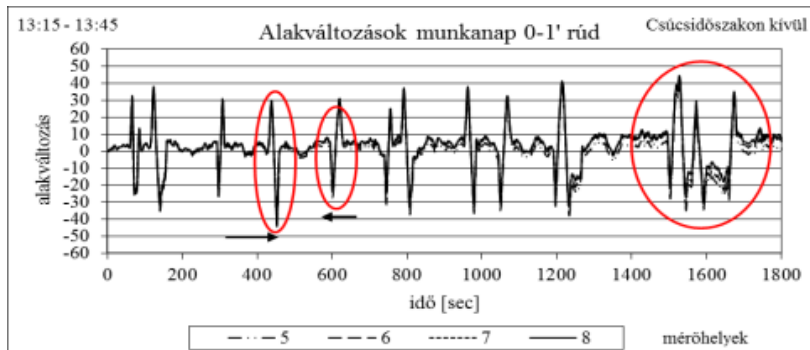
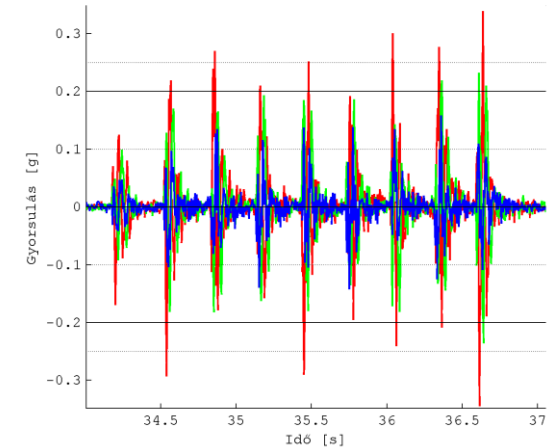
acceleration



# Evaluation methods

## Direct evaluation

global, local measurement's results  
tendencies, monitoring limit values



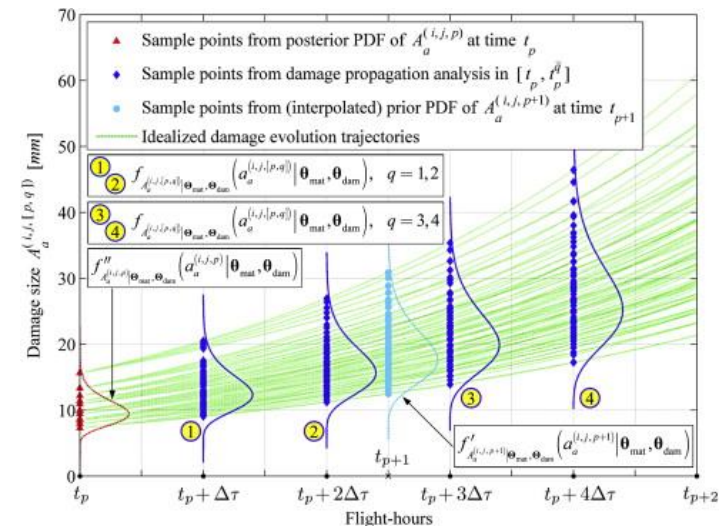
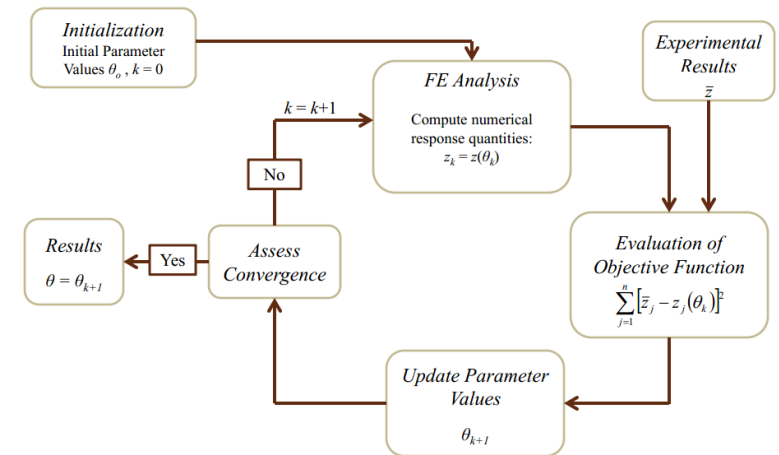
# Evaluation methods

## Modell „updating”

refinement of global model  
system identification  
identifying damage

## Probabilistic methods

reliability analysis  
lifetime estimation



# Monitoring system design - Requirements

## 1. Aim of the system

- a, traffic controll
- b, determination of traffic volume
- c, structural healt monitoring

→ inspection of the structure (evaluation of results)



decision for maintenance

## 2. Operation duration of the system

Life time of the bridge: 100 years



Guarantie for electric devices: 5-10 years

most expensive electric devices



maintenance of the system



main part of the total costs

## Operation times and durations:

- a, permanent systems: each minutes
- b, measurement periods: each month
- c, measurement periods: each years

# Monitoring system design - Requirements

## 3. Type of the system

### a, automatic post-processing

measurement result: huge database → complex evaluation method



specific softwares

### b, semi-automatic post processing

- manual start of the measurement
- only measurement of rough data (no result evaluation)
- partial post-processing (ready for detailed evaluation)

### c, alarm function

- additional automatic decision algorithm → - large reliability
- - no failure possibility
- - engineering aspects

# Monitoring system design - Requirements

## 3. Survey on typical damages of the analyzed bridge type

What to measure, where to measure, and which instruments should be used?

Examples:

|                               |   |                                        |
|-------------------------------|---|----------------------------------------|
| - fatigue of orthotropic deck | → | strain gauges on bridge deck           |
| - bearing system function     | → | displacement transducers               |
| - dilatation system function  | → | displacement transducers               |
| - global structural behaviour | → | vibration measurements / strain gauges |

## 4. Post-processing and data analysis, data management

- Huge database, server requirements (HDD)
- evaluation of the data → software tools → automatic analysis  
↓  
error handling

## 5. Application of measured data

- in the design of new bridges
- research purposes (design method / load model development)

# Tiszavirág-bridge monitoring system



# History

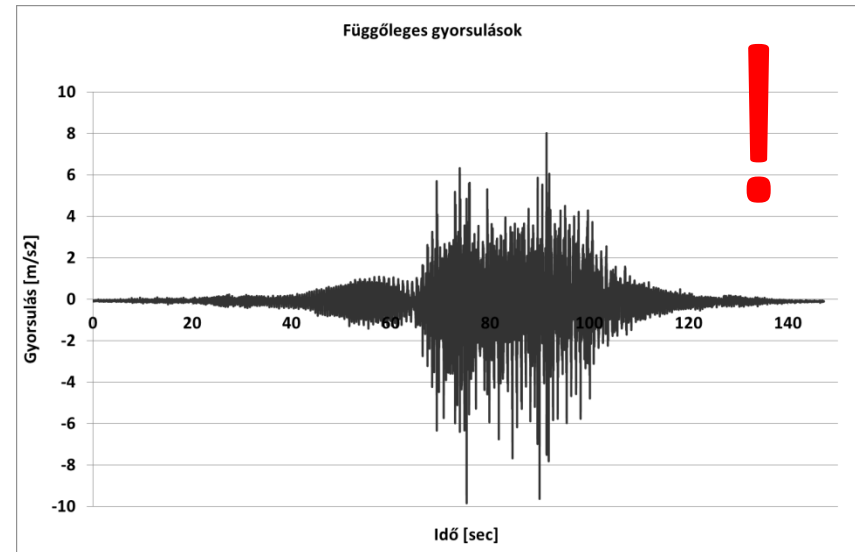
2010.

7<sup>th</sup> of December

static load testing

10<sup>th</sup> of December

dynamic load testing



# Alert- and monitoring system

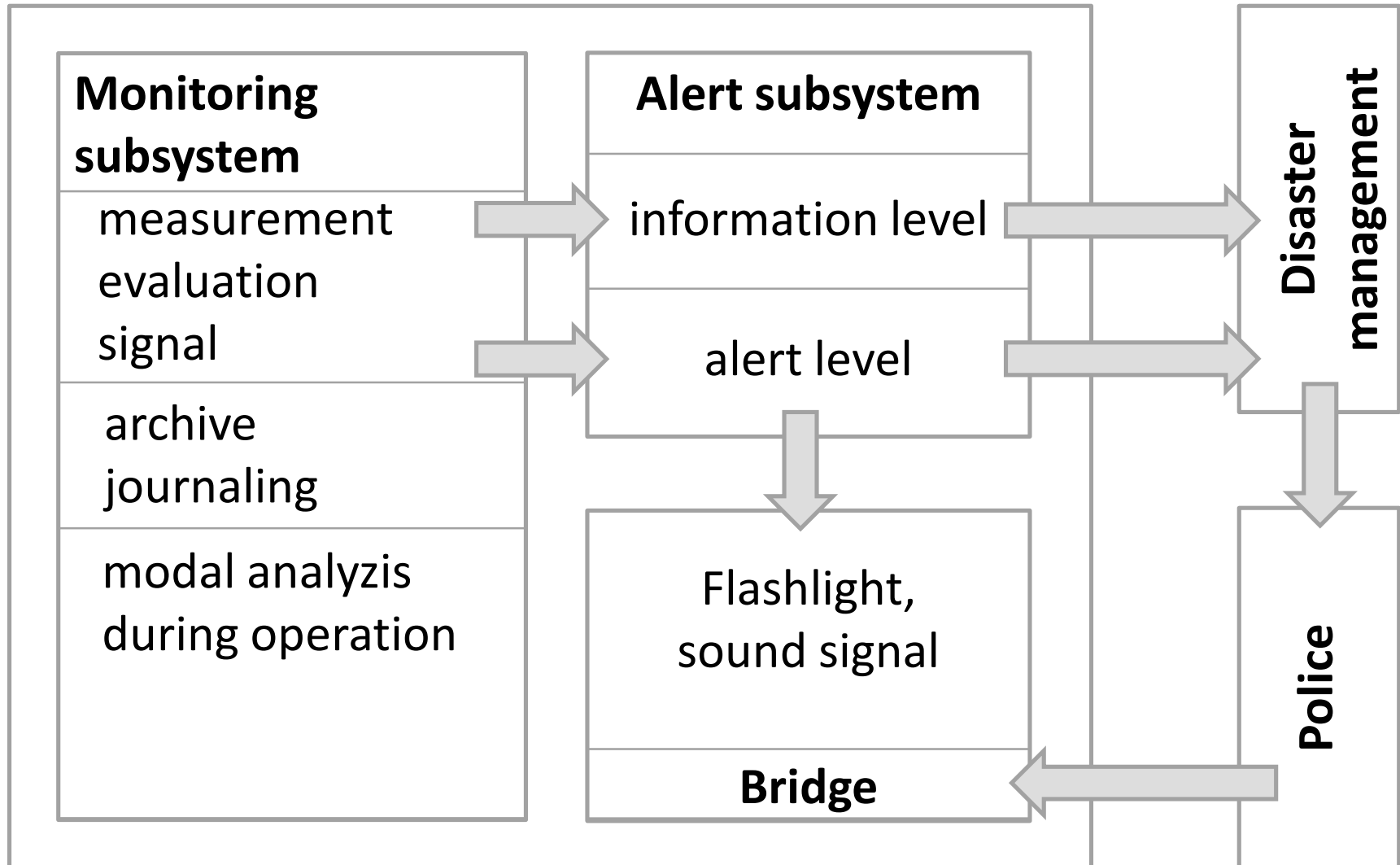
Aim: monitoring of upper structure's movements

- wind-caused excitation
  - pedestrian-caused incidents
  - detailed knowledge on the structure
  - SHM and practice
  - „on-scene laboratory”
- } alert
- } research

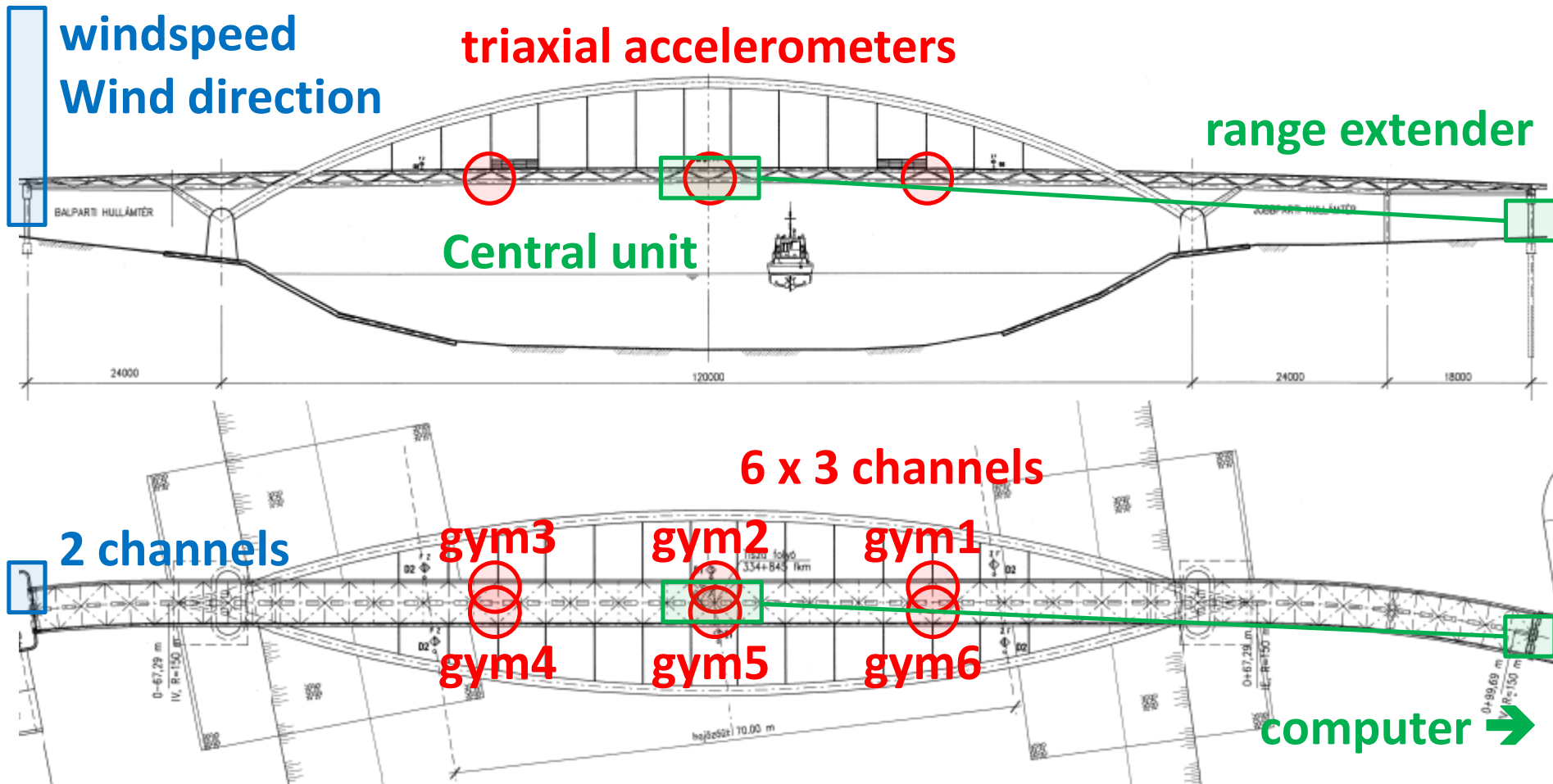
System establishment: 2011 July - October

|                              |                              |
|------------------------------|------------------------------|
| 25 <sup>th</sup> of October  | beginning of test operation  |
| 22 <sup>nd</sup> of November | calibration, official survey |
| 29 <sup>th</sup> of November | system starts                |

# System – overview



# Monitoring system overview



# System – hardware

## Sensors

accelerometers

Kriwan wind direction sensor, anemometer



## Measurement system

National Instruments extender

MOXA network devices

## Head PC

„office” configuration

2 x 3 TB storage space



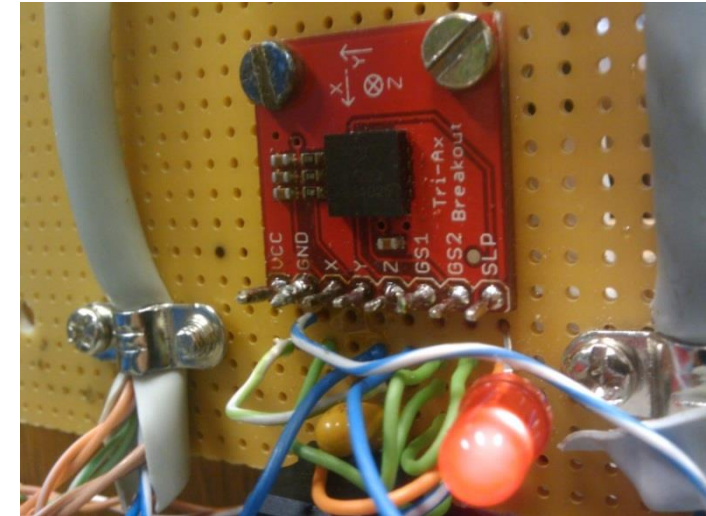
# System – sensors

BME Acel

triaxial MEMS accelerometer

Measuring limit  $\pm 1.5\text{ g}$

Sensitivity  $800\text{ mV/g}$



Kriwan INT10 anemometer

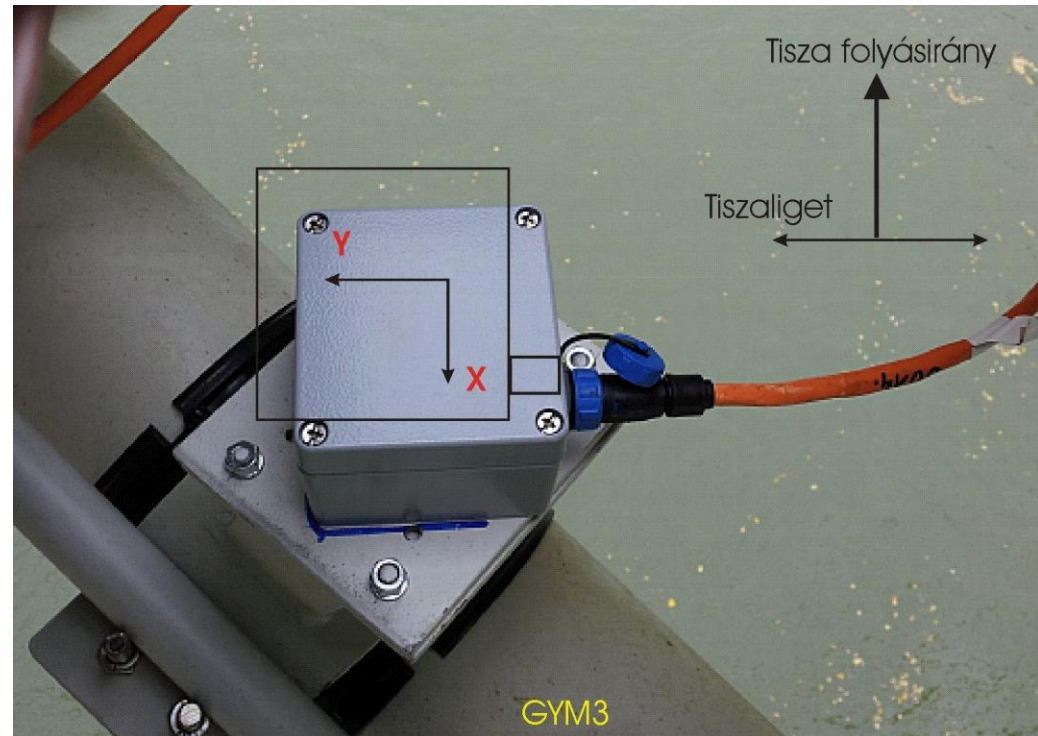
Measuring range  $0.1 - 40\text{ m/s}$

Kriwan INT30 wind direction sensor

Resolution  $5.625^\circ$

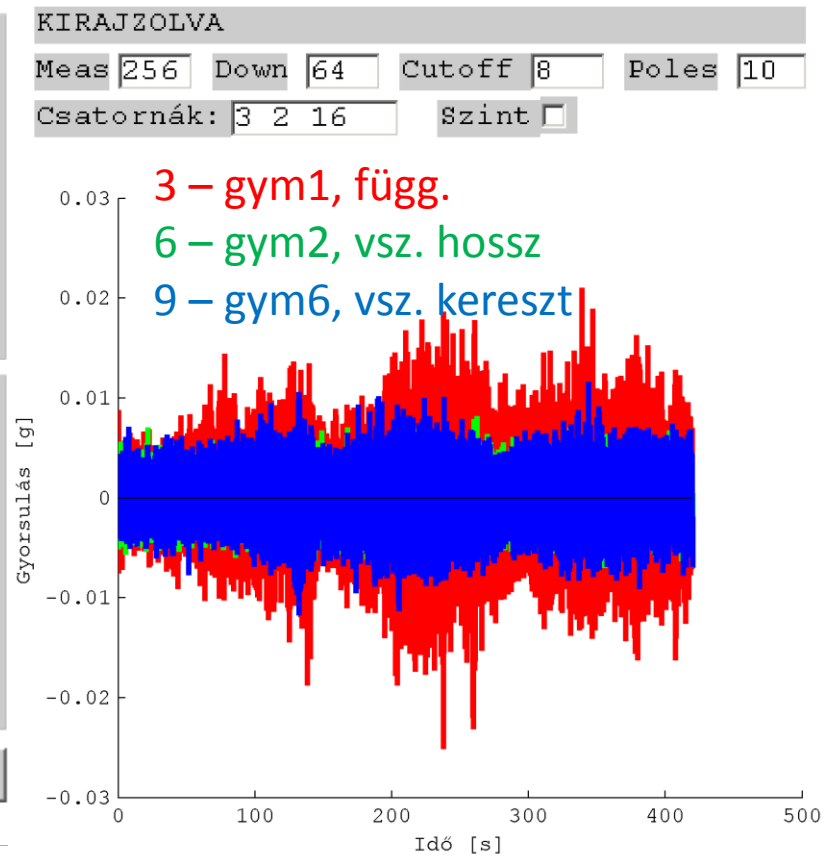
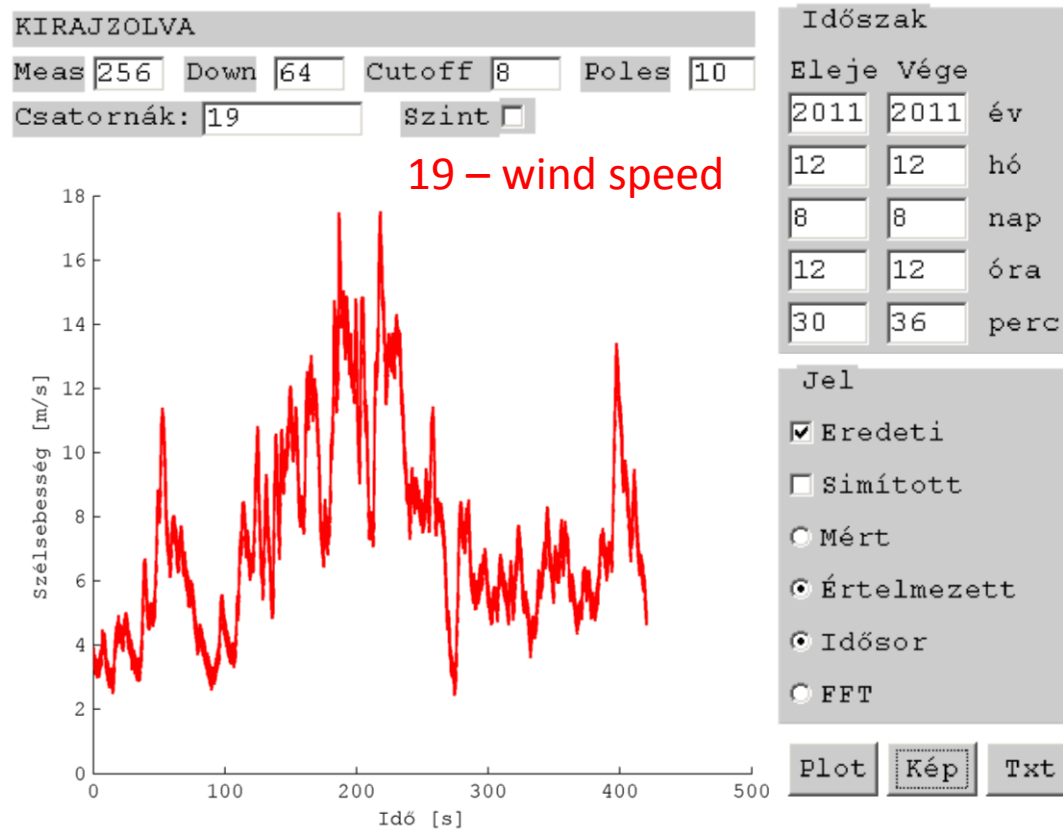


# System – sensors



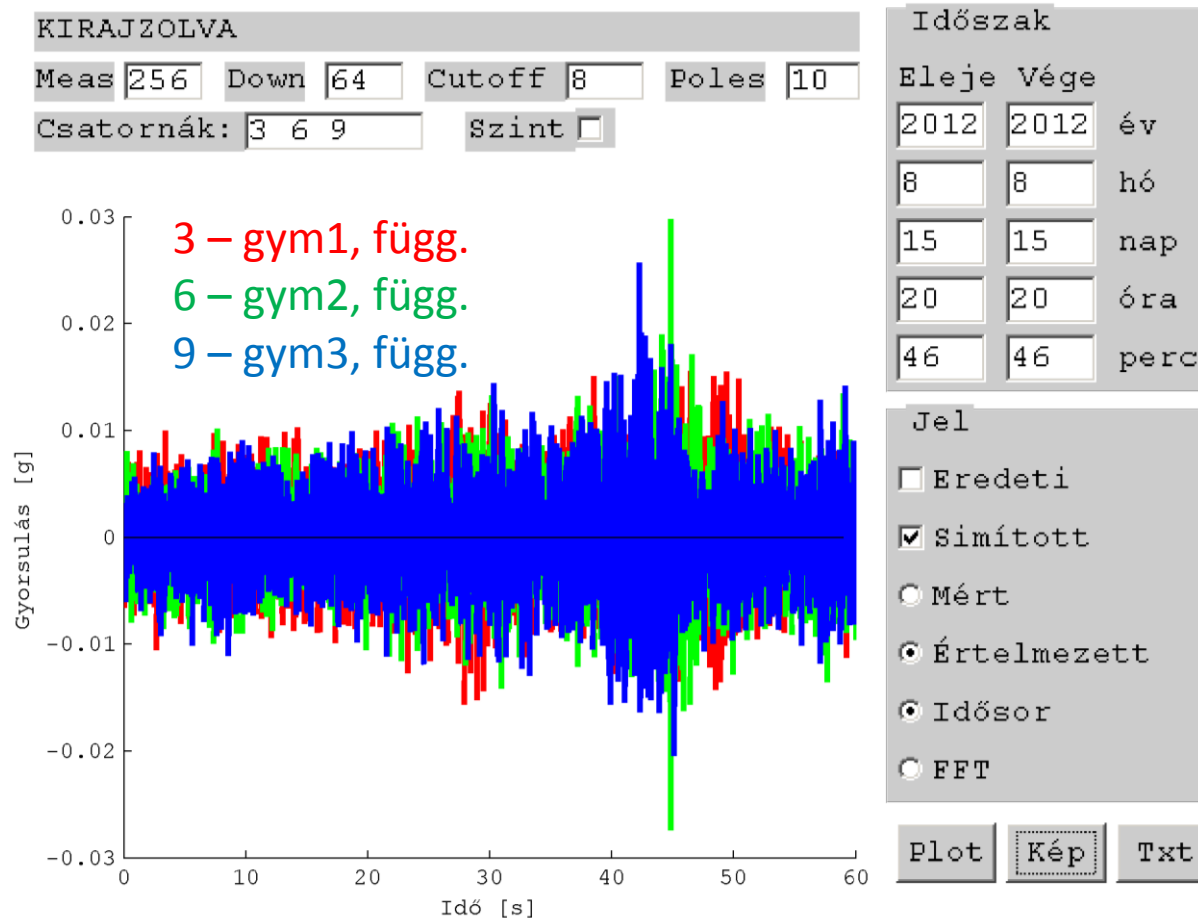
# Phenomena

## Wind effect – 7. December 2011.



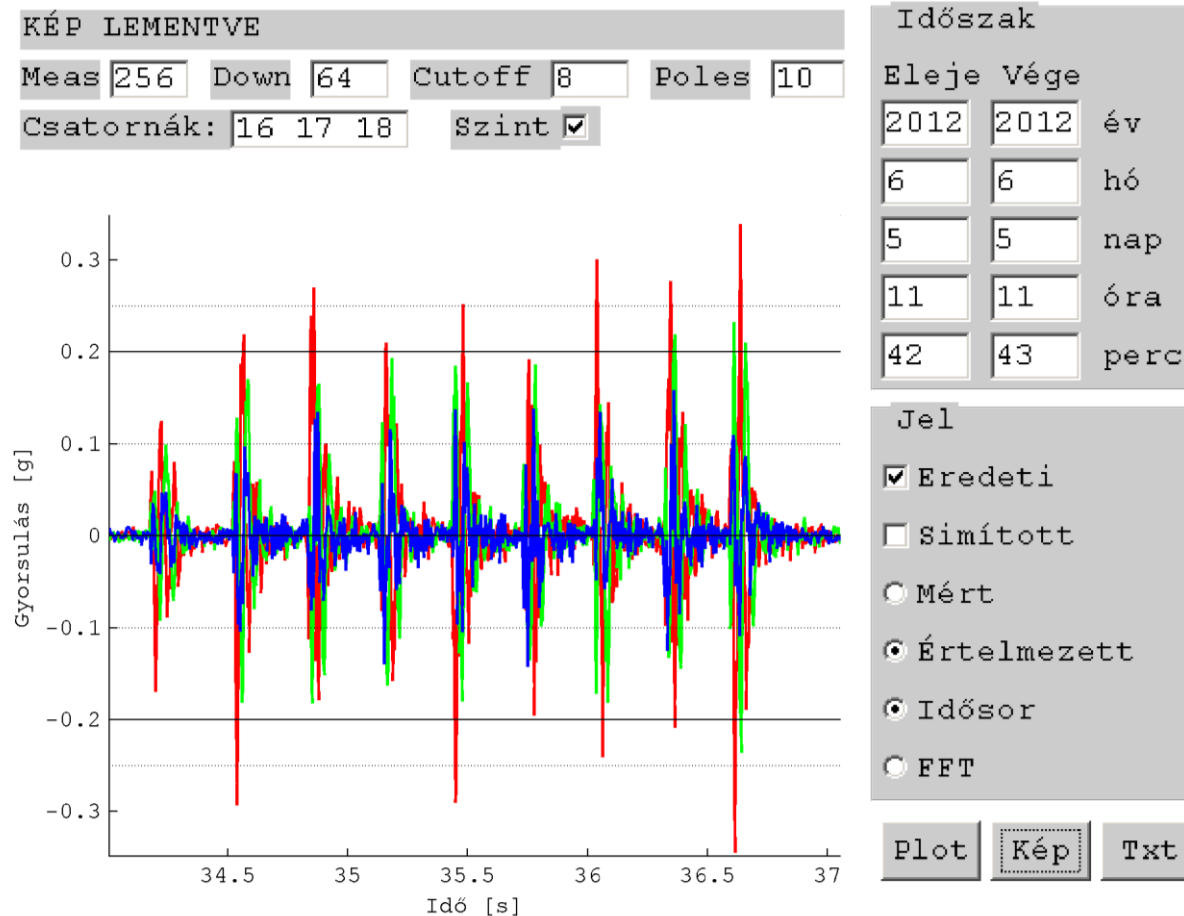
# Phenomena

## Motorbike crossing – 15. August 2012.



# Phemonena

Alert – 2012. June 5.



# M0 Hárósbirdge monitoring system



# History



# M0 Hárós bridge monitoring system

Aim: monitoring of upper structure

- measurement of bearings' displacement
- measurement of structural temperature

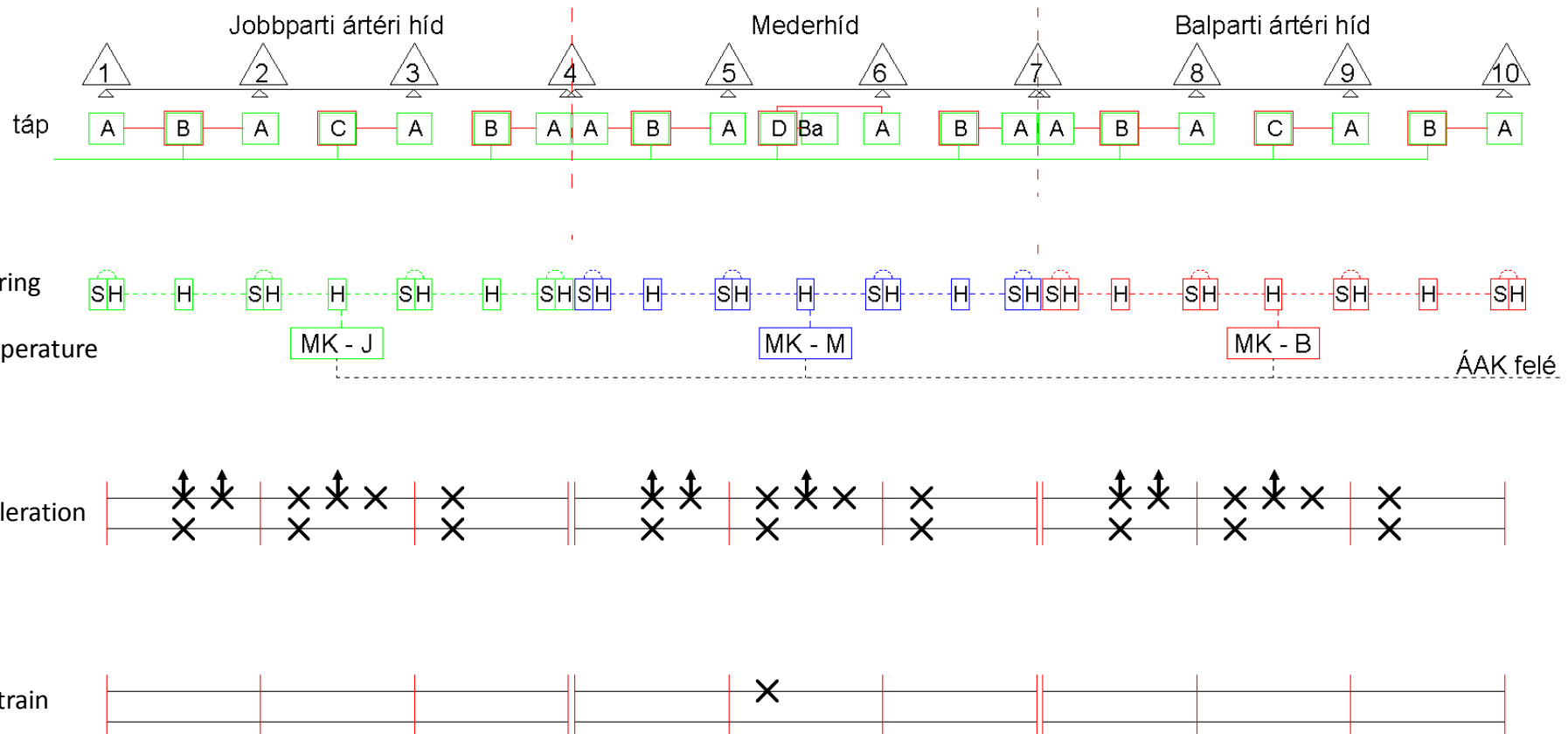
} direct  
support of  
operation

- acceleration
- strain measurement

} dynamic behaviour,  
fatigue of bridge deck

➔ research, enhancement of results

# M0 Háros – measurement system



# M0 Háros – sensors

**Bearing's displacement:** linear displacement transducers

+/- 200 mm measurement range

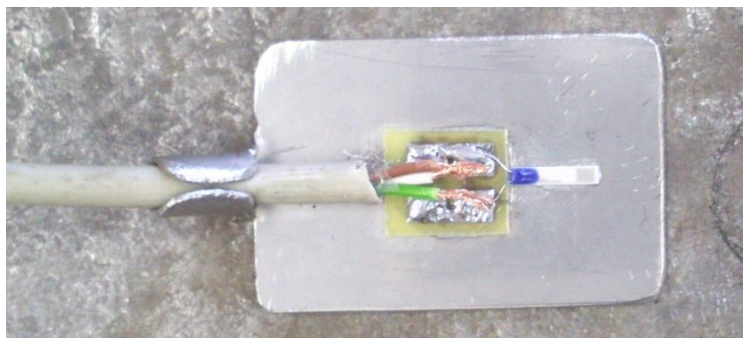
0,006 mm resolution

sampling rate: 2 Hz

**Temperature:** Pt100 thermometers

precision: 0,1 °C

sampling: 0,1 Hz



# M0 Háros – sensors

## Acceleration measurement:

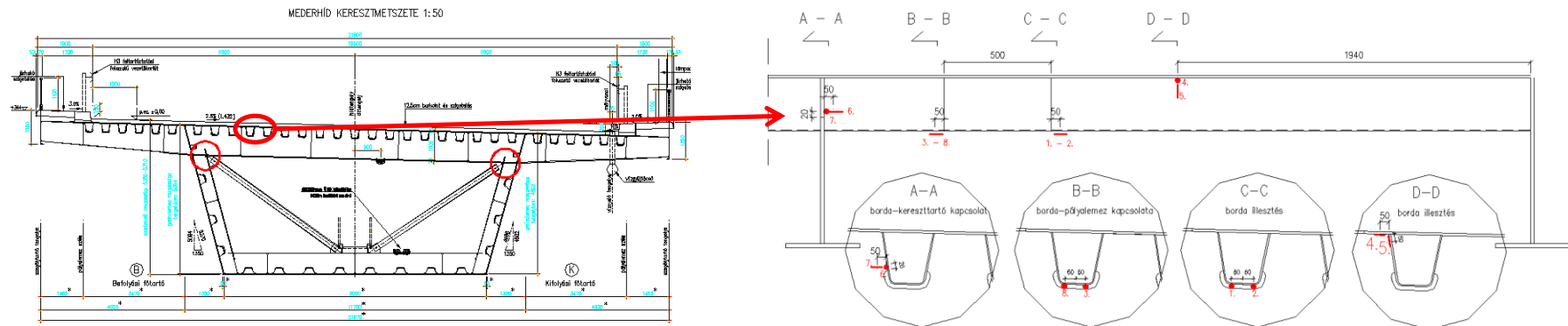
piezoelectric accelerometer

+/- 0,5 g measurement range, 10 V/g sensitivity

$8 \cdot 10^{-6}$  g noise (?)

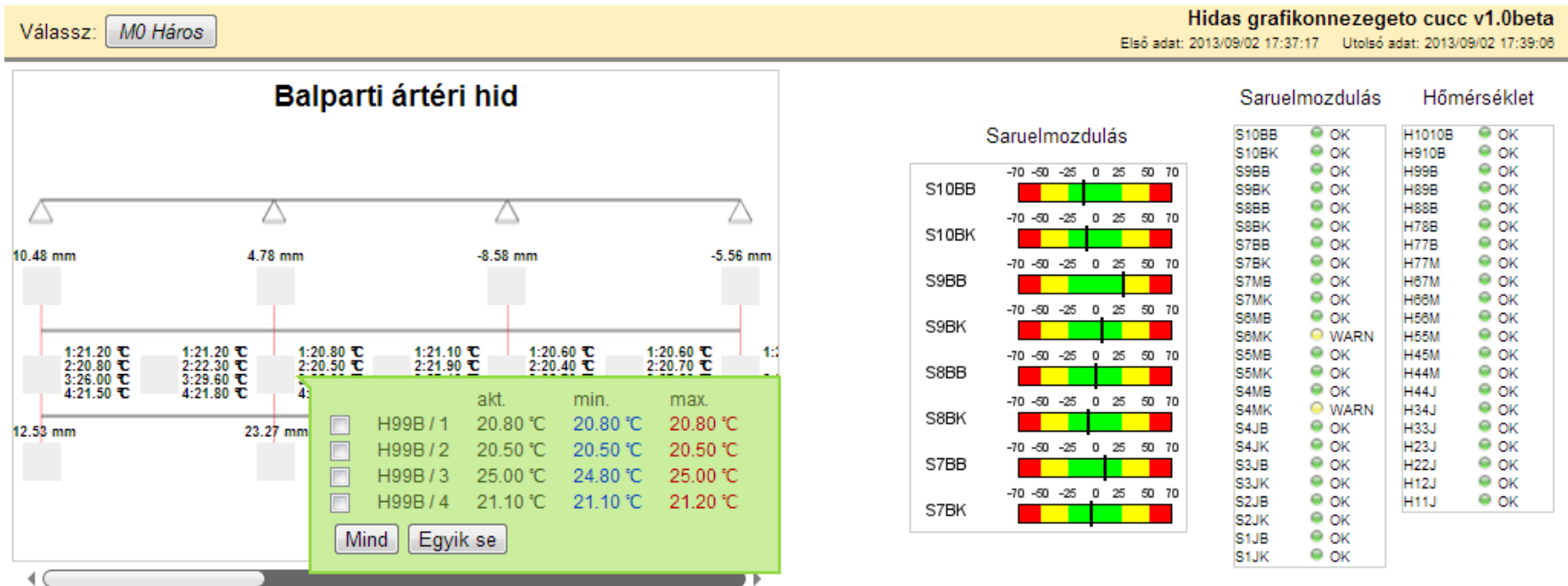
## Strain measurement:

8 + 22 db uniaxial, temperature-compensated strain gage (steel)





# M0 Háros – data acquisition



Jelenleg nincs kiválasztott hőmérsékletszenzor.

Jelenleg nincs kiválasztott elmozdulásszenzor.

# Summary – Tiszavirág-bridge

System is working for 2,5 years so far

experience acquisition: hardver, softver, operation

stabil operation, low maintenance costs

## Measurement results

wind-structure interaction safety aspects

detection of unexpected phenomena

further monitoring tasks, evaluations

## On-site laboratory

„practice field”: possibility of additional measurements

# Summary – M0 Hárós

Large amount of data, excellent quality

Direct benefit

- demand automatic processing – development
- support of bridgekeeper

- oversized vehicles, maintenance of bearings

Research

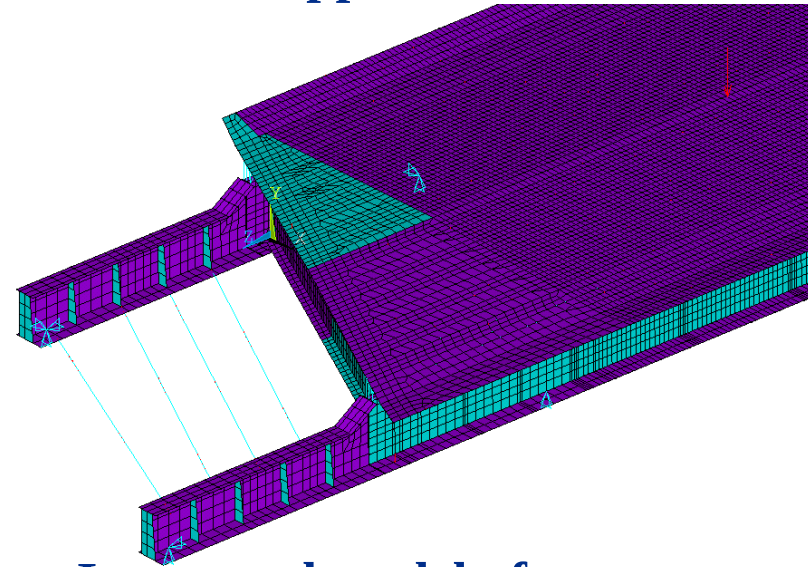
- BME – ÁAK cooperation

- fatigue, dynamic behaviour

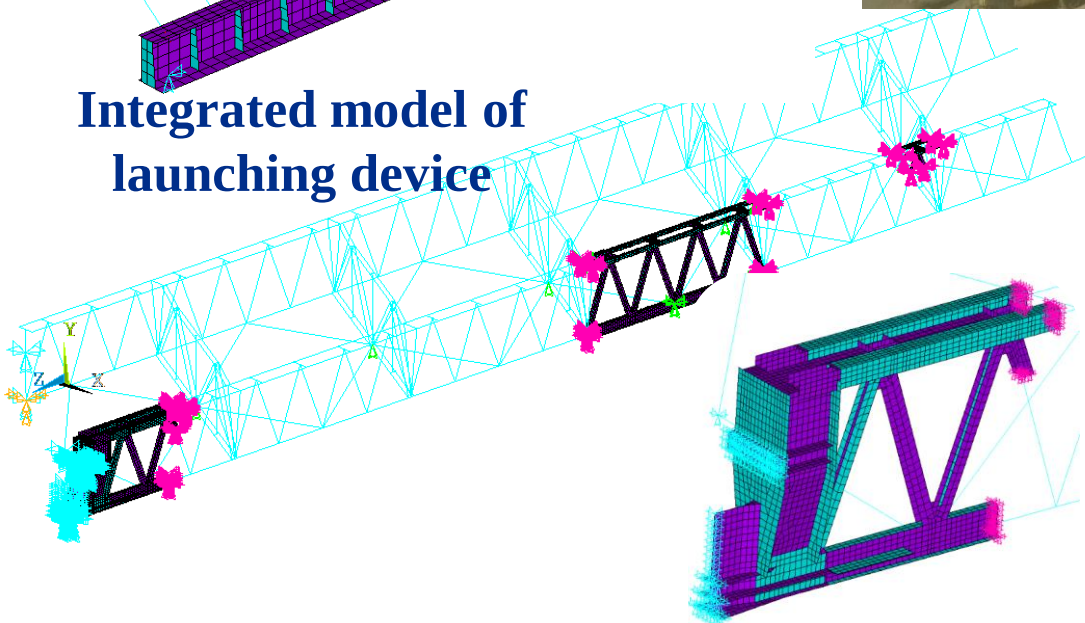
- instruments, utilization of results on other bridges

# Construction - VEM simulation

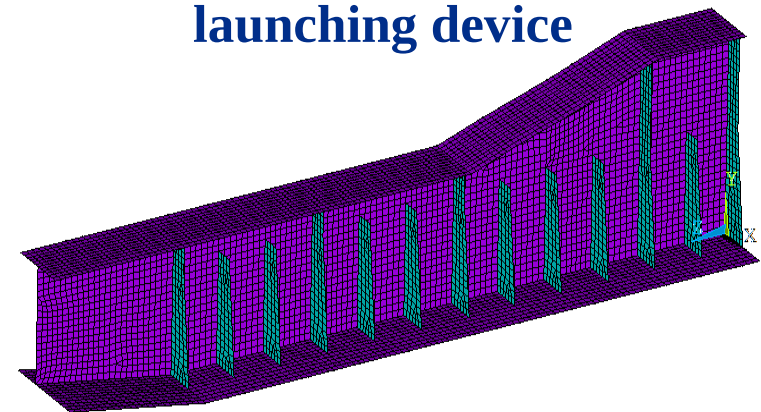
## Model of upper structure



## Integrated model of launching device

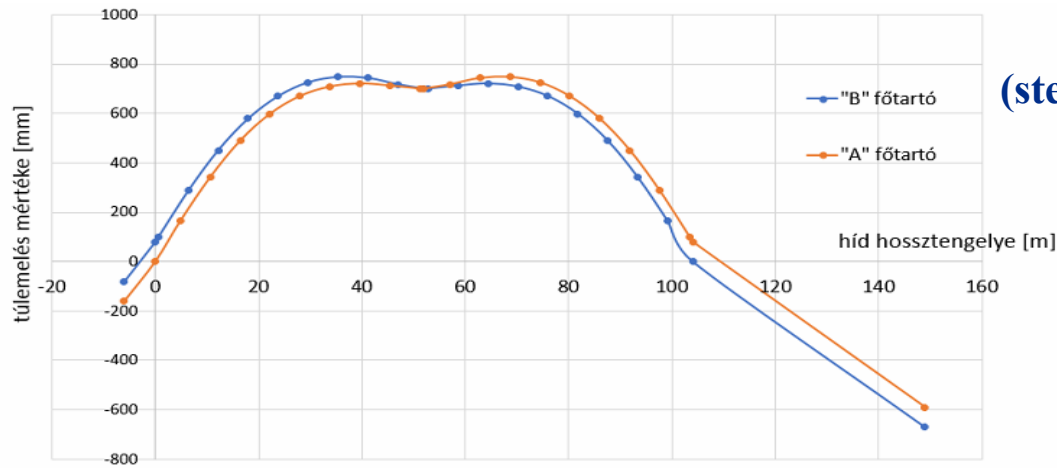


## Shell model of backward launching device



# Construction - VEM simulation

## Concrete casing stressfree shape (from the point of view of RC)



Initial shape

(steel structure's shape after construction)



Shape after concrete casing

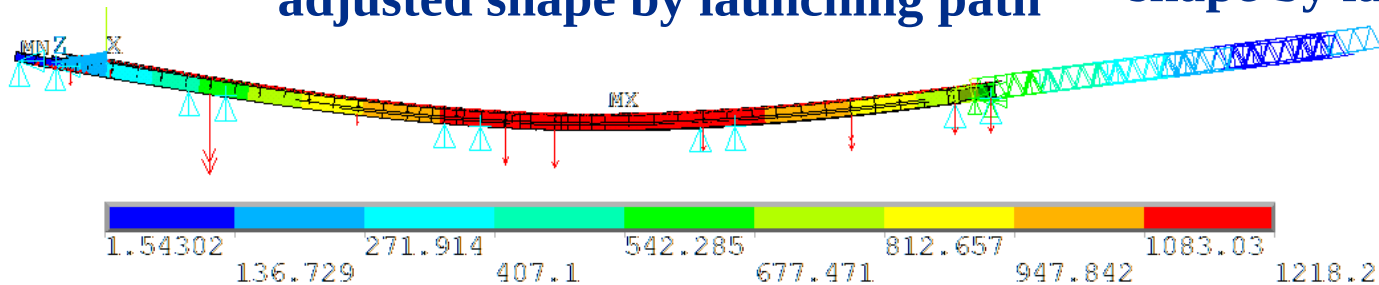


Total initial shape



constantly controlled  
shape by launching path

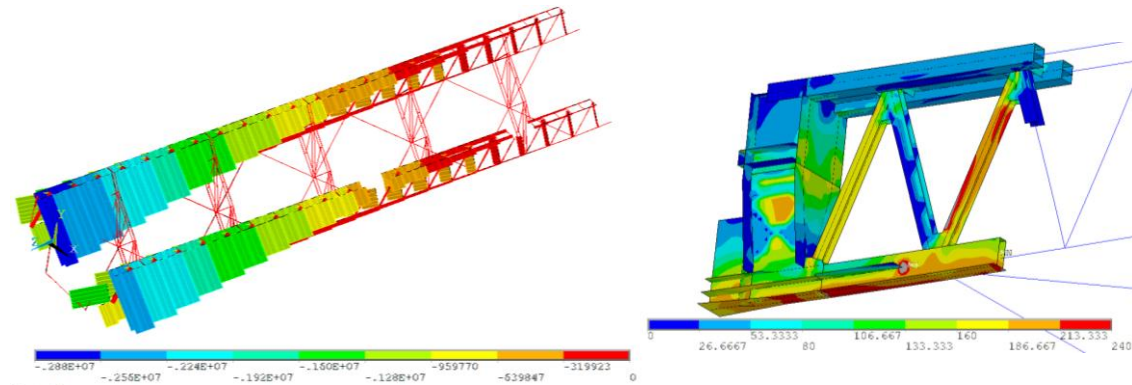
adjusted shape by launching path



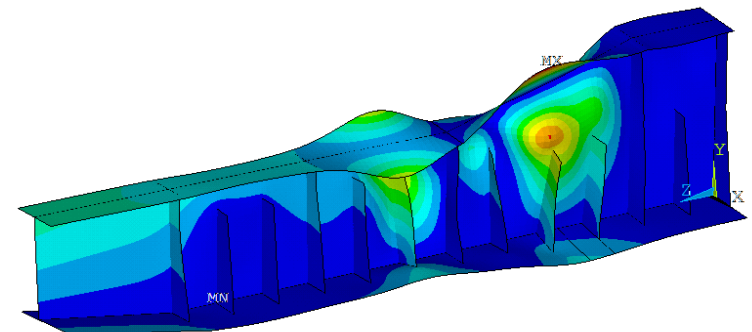
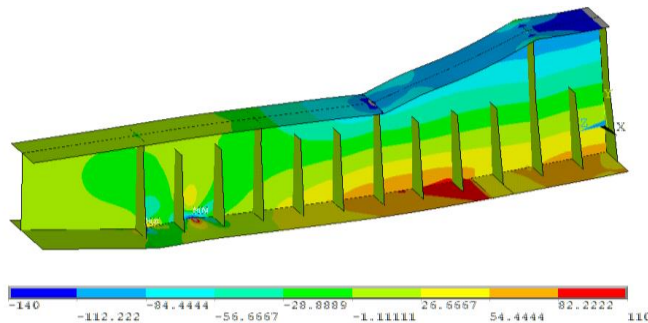
**Aim:**  
crackfree RC deck



# Construction - VEM simulation

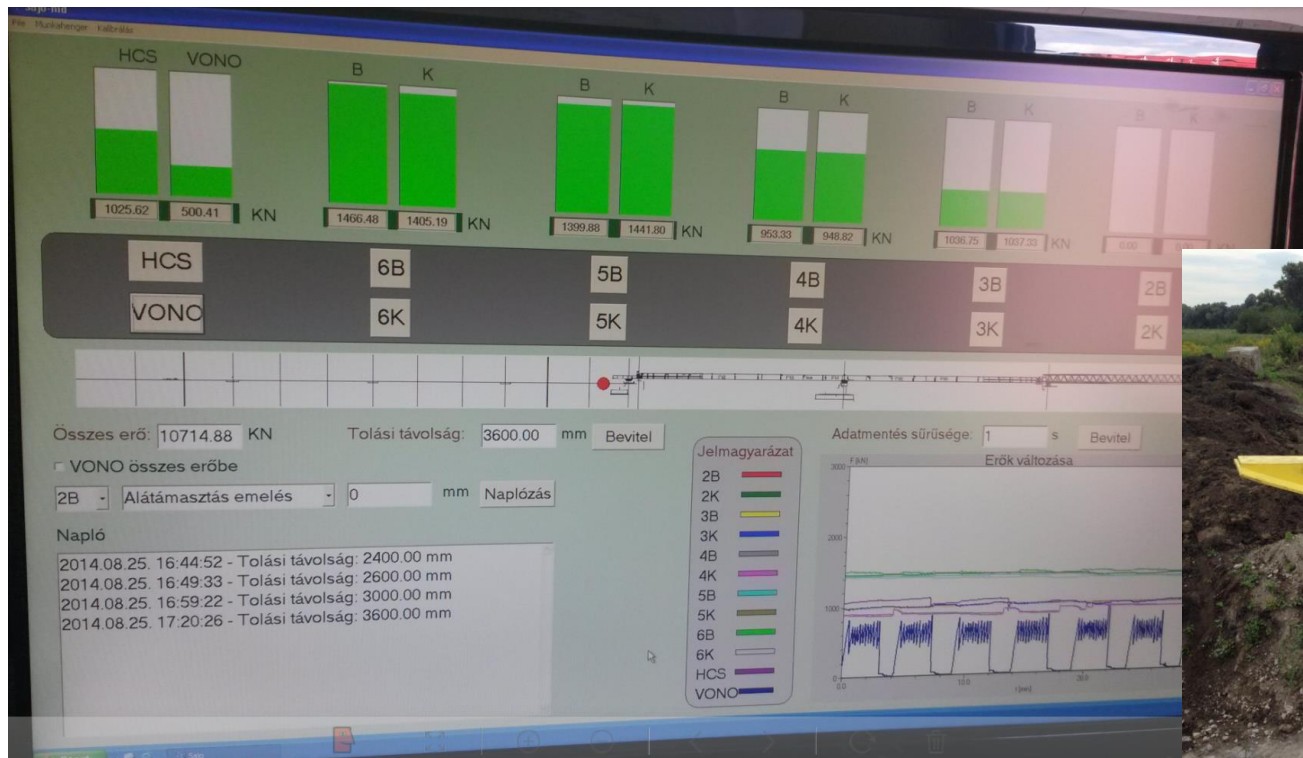


**max. reaction force: 800 kN**

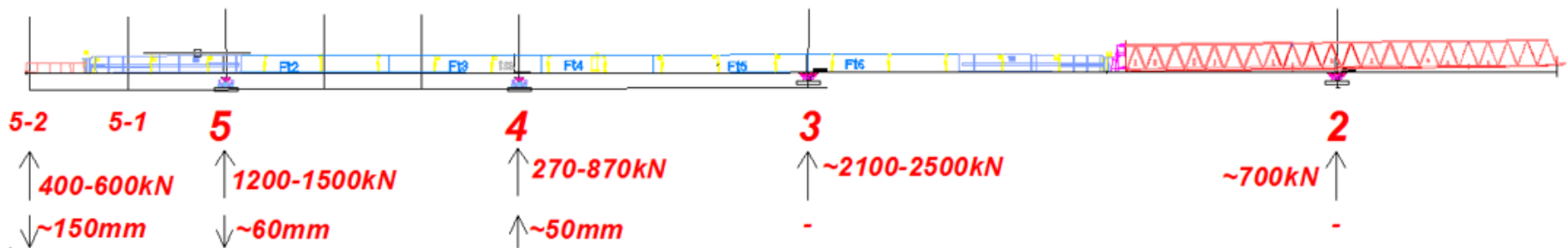


**critical load multiplier: 9,46**

# On-site monitoring check



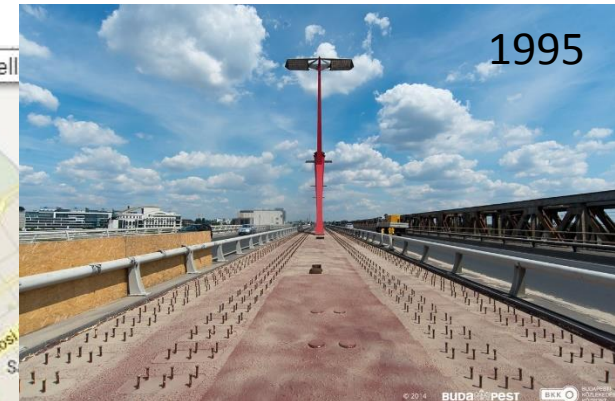
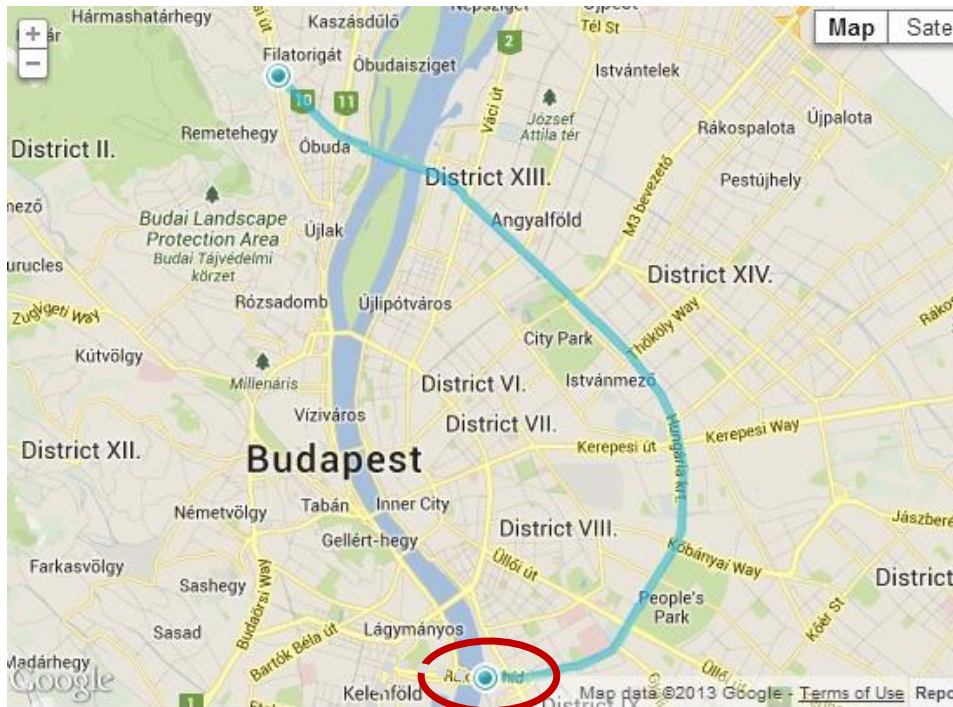
## Measured and calculated reaction forces



# Loading test of the Rákóczi bridge

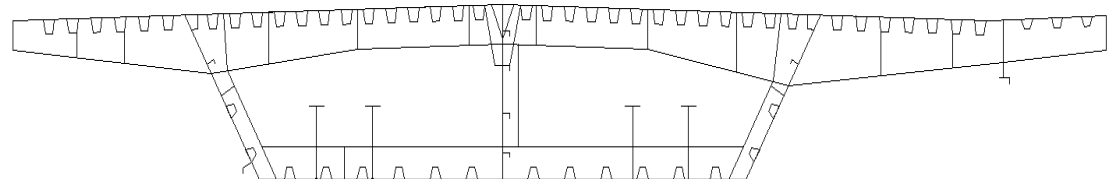


# Aim of the loading test



- tramway network development in Budapest,
- new tram line crosses the Danube,
- Rákóczi bridge opened to traffic in 1995 – no tram,
- new Combino tram heavier → bridge verified by calculation and loading test.

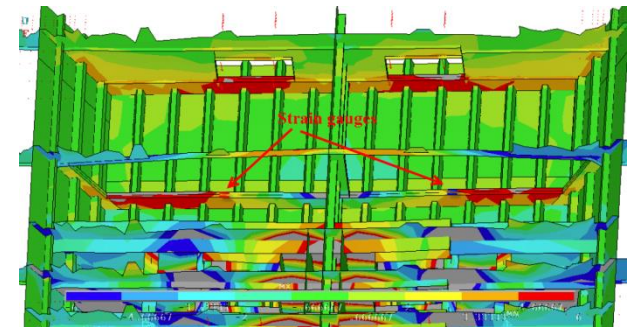
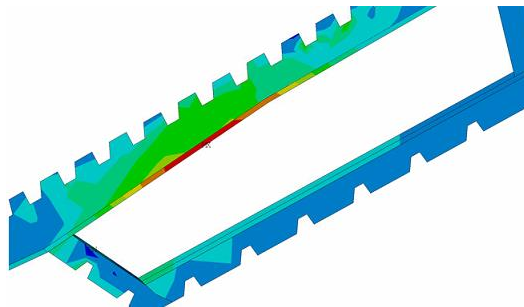
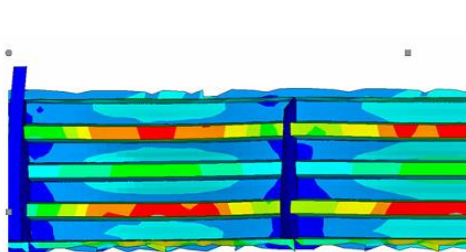
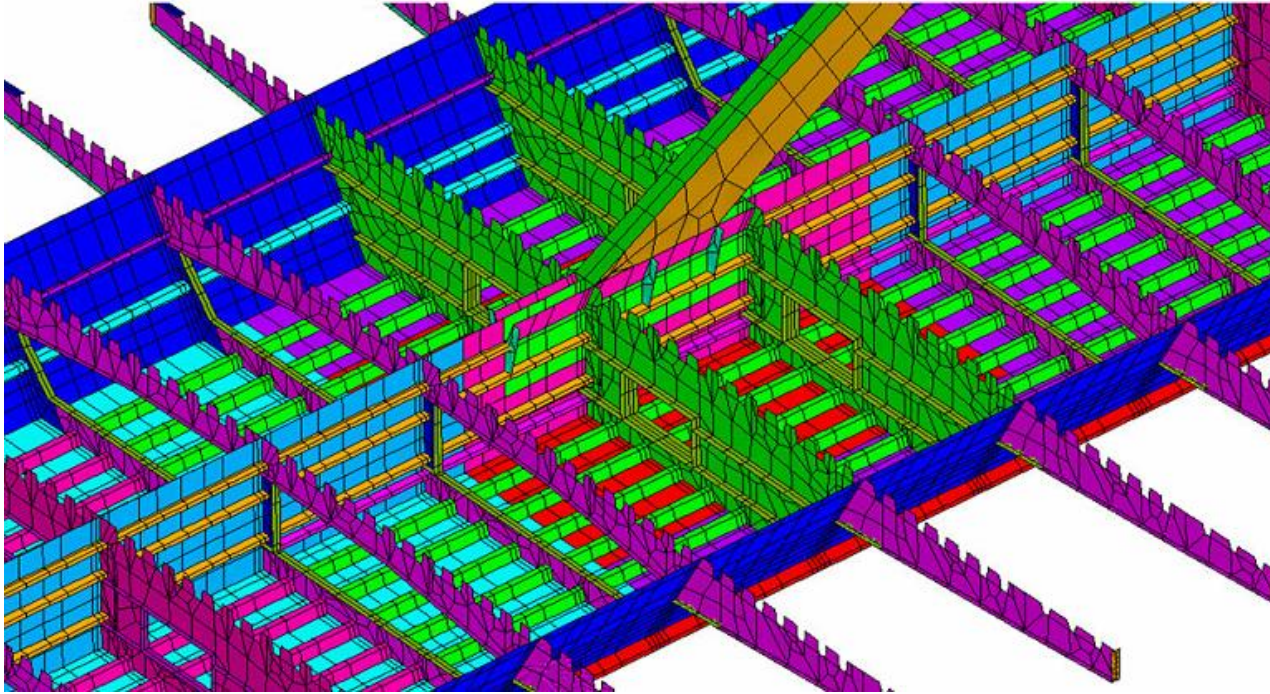
# Rákóczi bridge - structure



- continuous girder, 6 spans
- total length 492,6 m,
- double cell box section, with trapezoidal longitudinal stiffeners,
- tapered cross-girders.

# FE model

Full shell model, contains all plates of the drawings.



# Strategy of the loading test<sup>t</sup>

Loading test: 14-15th of February 2015.

## Step 1: local (transversal) measurements

- aim: analysis of structural details under tramway tracks (middle web plate, cross-girders, stiffeners)



not investigated in 1995 test loading

## Step 2: global (longitudinal) measurements

- aim: study the global structural behaviour under combination of tram and truck and vehicular traffic



tested under in 1995 equivalent tram load

Program:

33 static load cases (15 local, 18 global)

- deformation in (2x32 points),
- 109 strain gages.

Eigenfrequencies

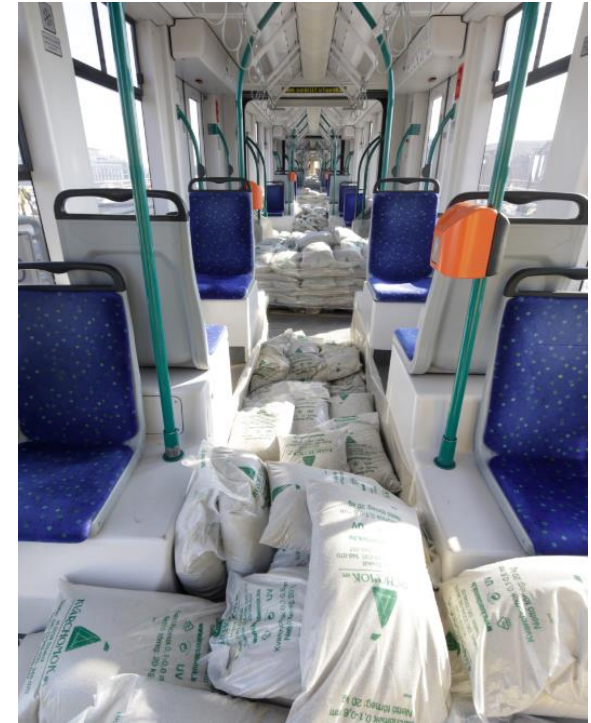
Complex dynamic loading by trams and by trucks.

# Vehicles of the loading test

4 Combino trams 850 kN each



Combino selfweight + 221 passengers  
17,0 kN/m distributed load



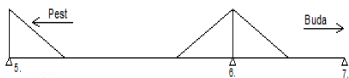
20 trucks with 4 axles, 350 kN each



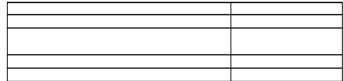
71% of total load level  
(concentrated to structures under the  
tramway track)

# Static loading – local

## 15 load cases



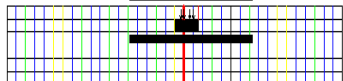
1. teherállás (üres)



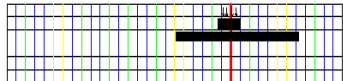
2. teherállás 8 2 kt.



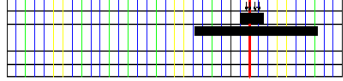
3. teherállás 6 1 kt.



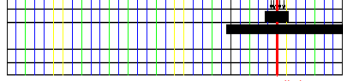
4. teherállás 4 3 kt.



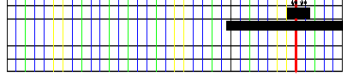
5. teherállás 3 2 kt.



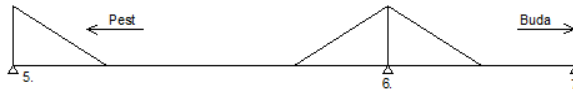
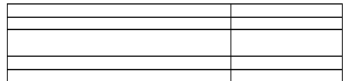
6. teherállás 2 2 kt.



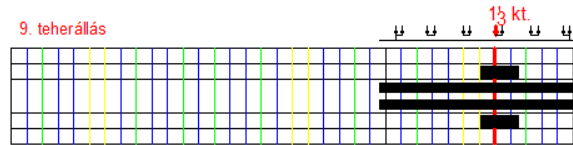
7. teherállás 1 3 kt.



8. teherállás (üres)



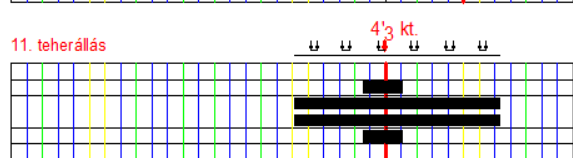
9. teherállás



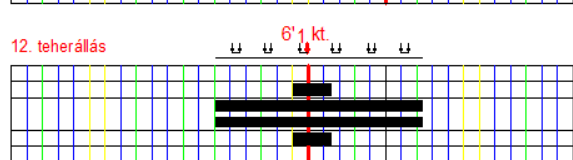
10. teherállás



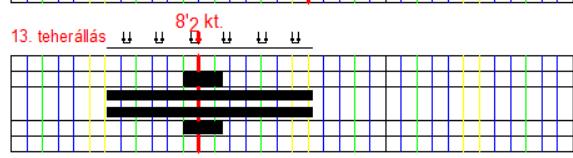
11. teherállás



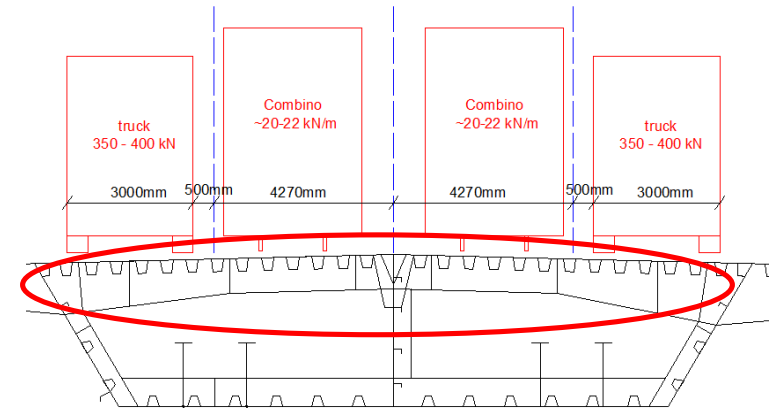
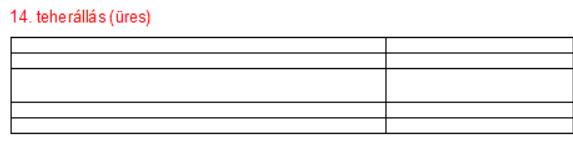
12. teherállás



13. teherállás



14. teherállás (üres)

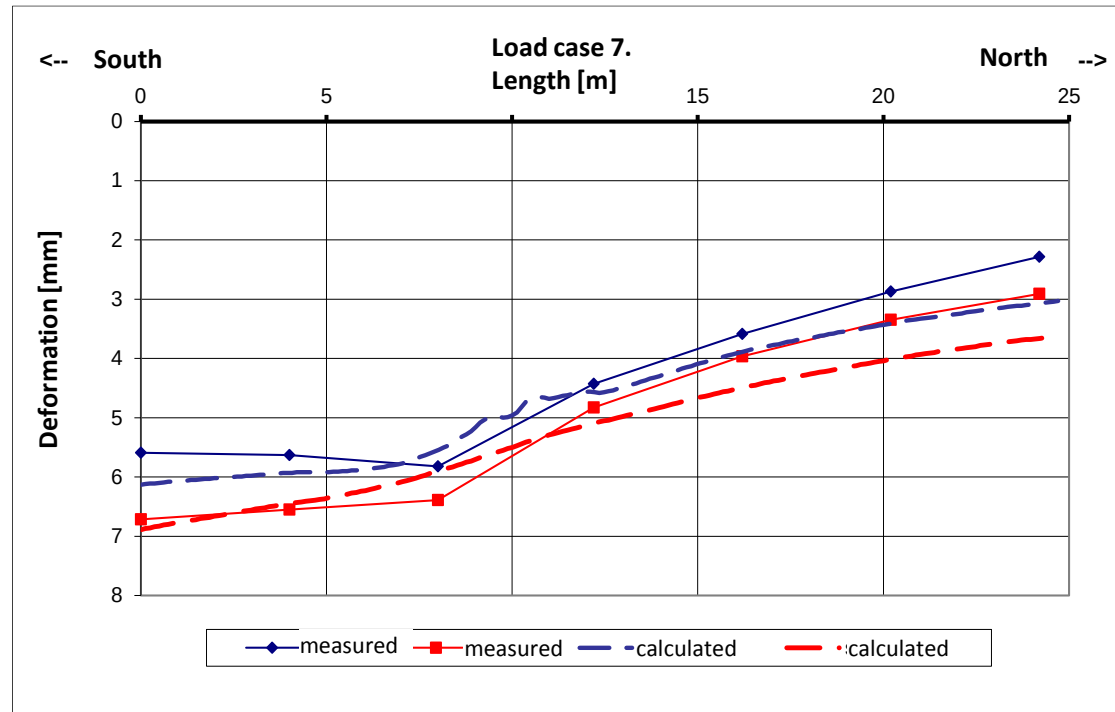
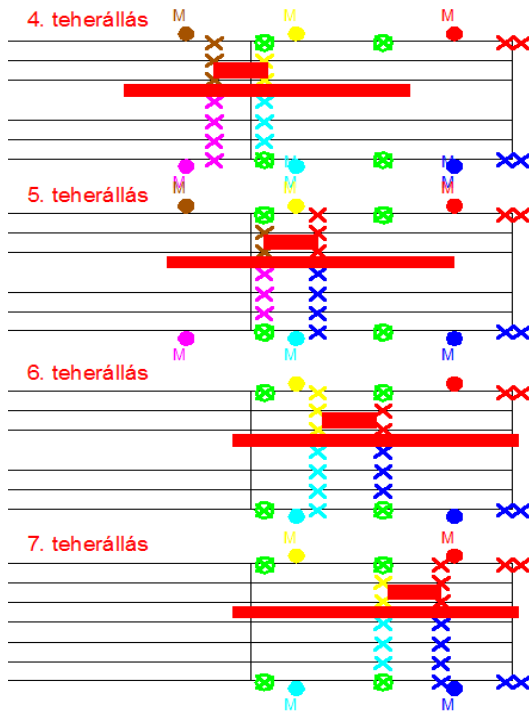


Aim: analyse structures under the tramway track



Measured: Stresses + deformations in transversal direction

# Static loading – local



Measured:

- deformations in transversal directions
- stresses in the cross-girders and steel track

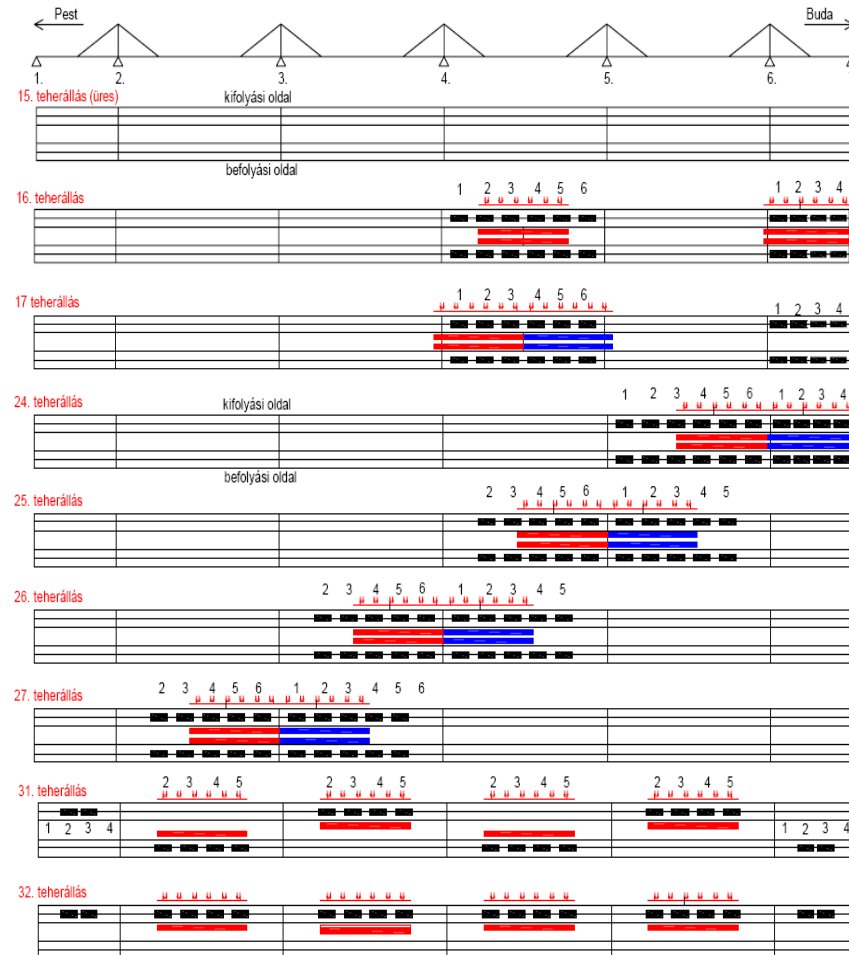


The structural behaviour under the tramway is verified.

# Static loading – global

Aim: study global structural behaviour under combined vehicular and tram loading

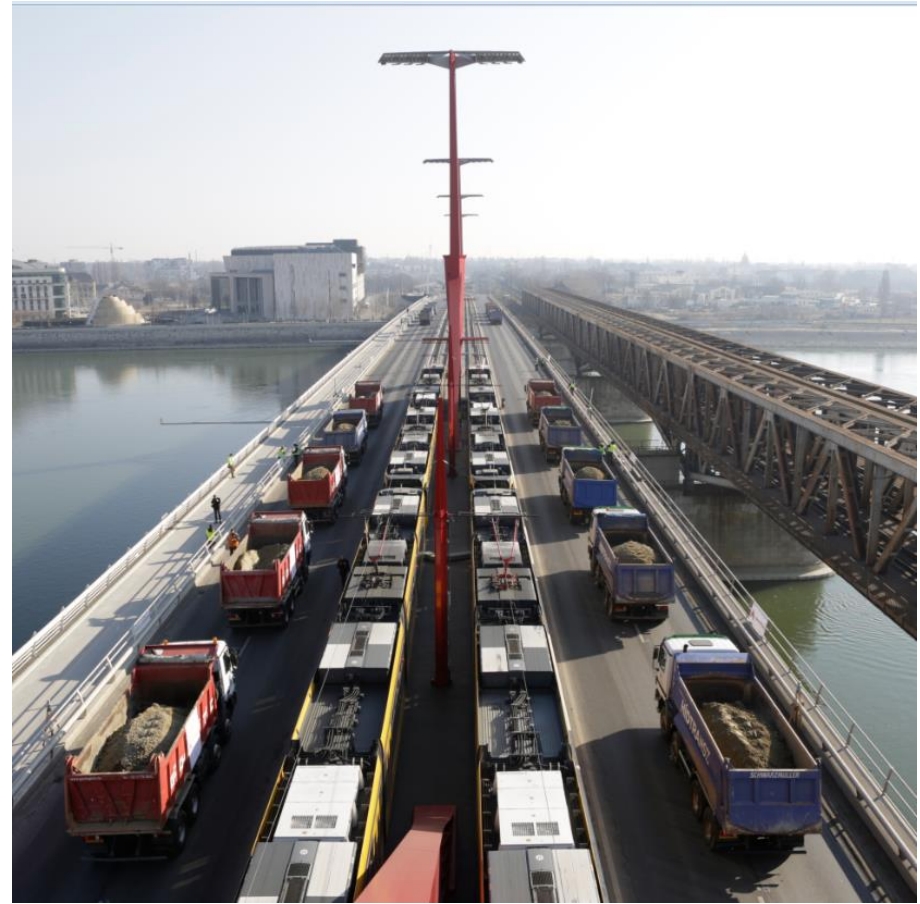
- 18 load cases,
- 20 trucks and 4 trams,
- loaded all spans,
- vehicle positions for maximum + and – bending moment, and
- maximum reaction forces.
- comparable by the 1995 load test program.



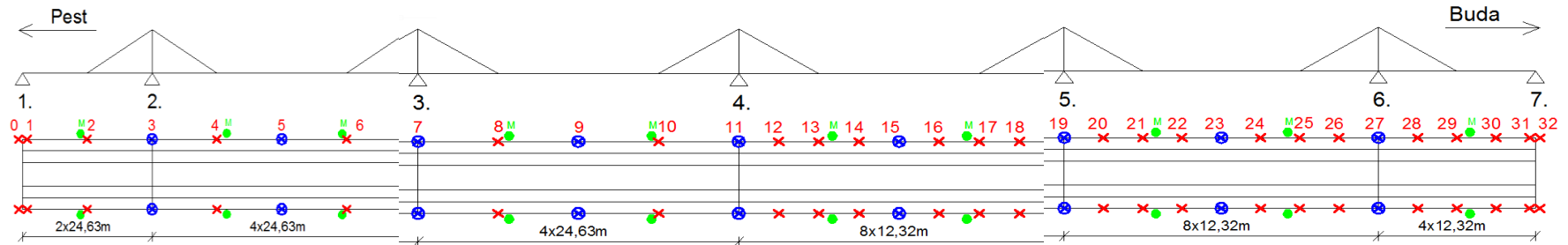
Measured: Stresses + deformations in longitudinal direction

# Static loading – global

## Load cases



# Static loading – global deformations

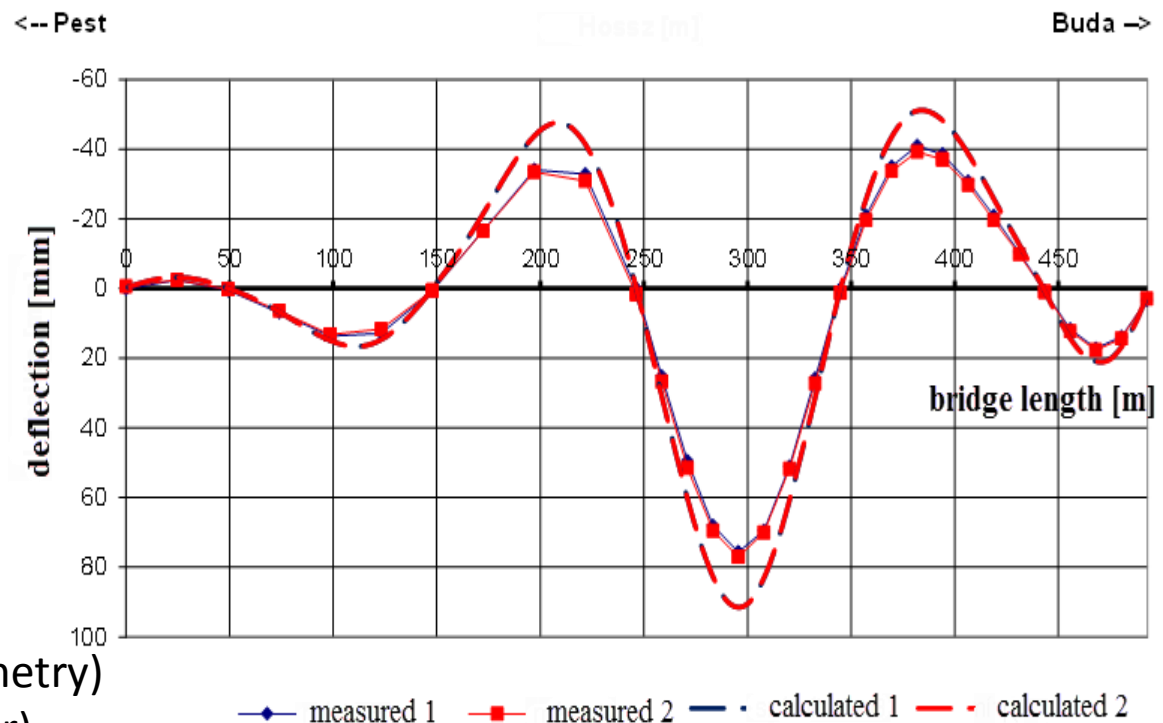


## Global deformations:

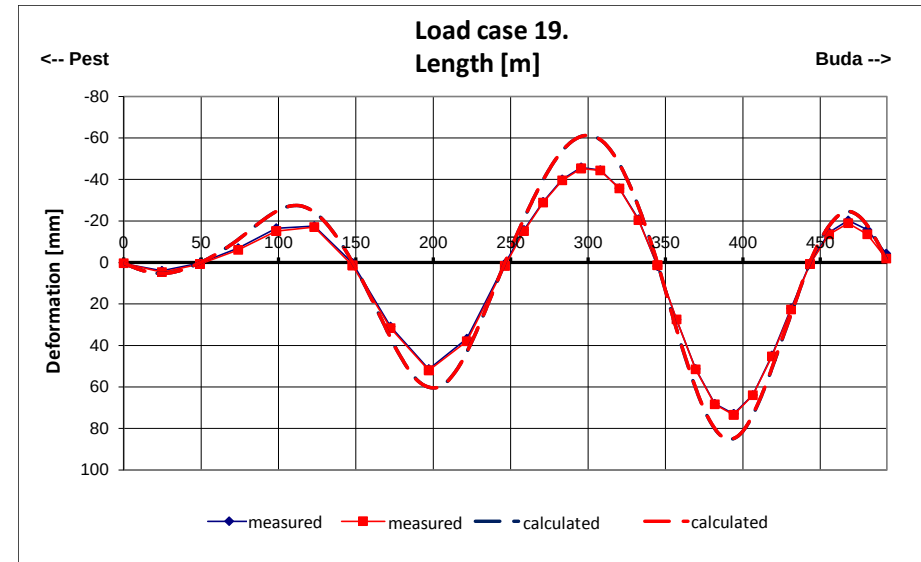
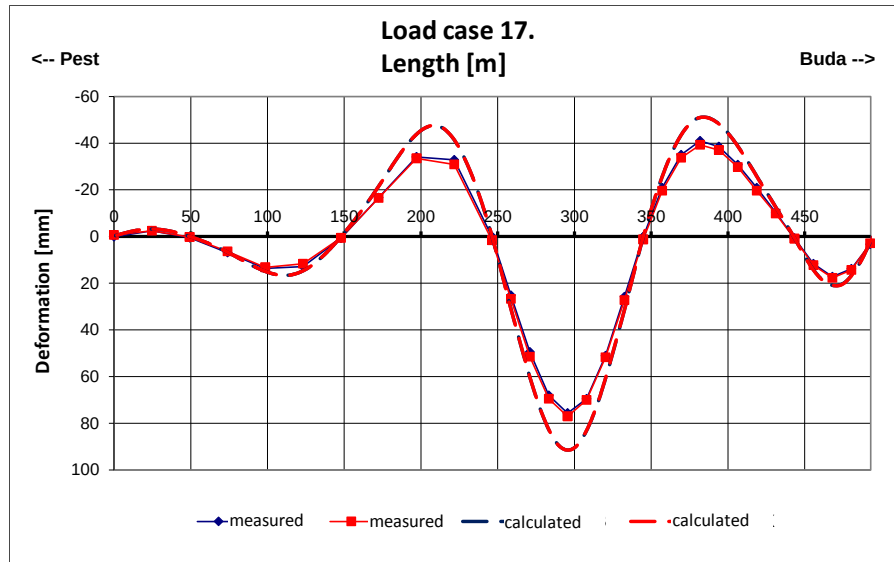
- measured in 2x32 points,
- between supports 1 and 4 measure in 3 points of each span,
- between supports 4 and 7 more dense measuring locations.

## Supplementary measurements:

- deformed shape (photogrammetry)
- bearing system (interferometer)



# Static loading – global deformations

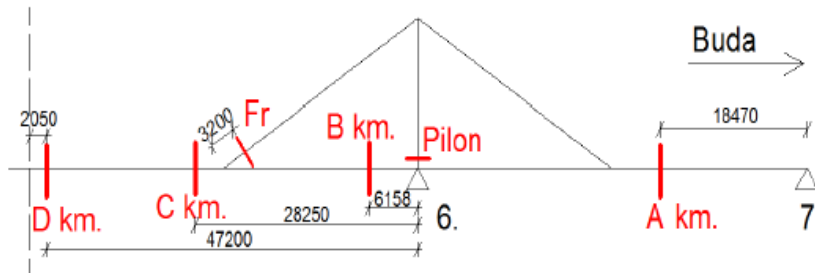


## Results:

1. The measured deformations follows the calculated values with small discrepancy.
2. Local study:
  - maximal deformation of the cross-girders is 9,2 mm (88 % of the calculated value)
  - residual deformation maximum 10 %.
3. Global study:
  - maximum deformation in mid-span is 20-78 mm (75-88% of the calculated value),
  - residual deformation 4-10 %.

# Static loading – stresses

## Global structural behaviour



- 4 cross sections investigated
- Pilon
- Inclined rod

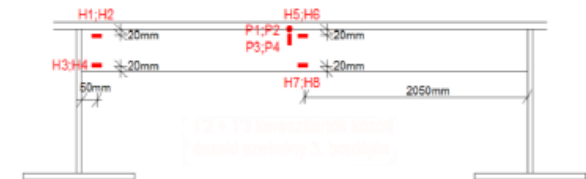
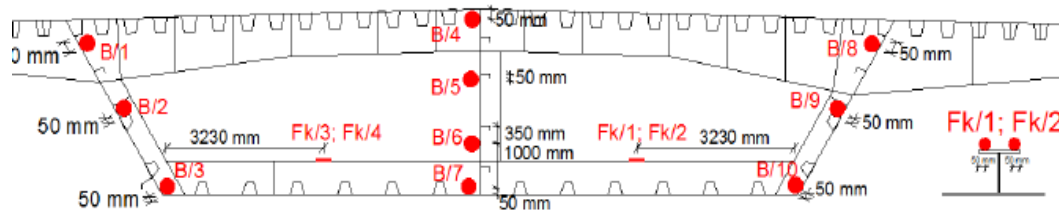
57 strain gauges

## Local structural behaviour

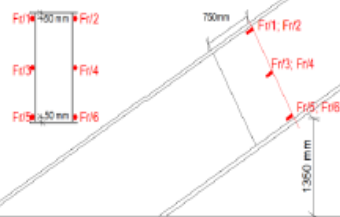


- cross girder
- longitudinal stiffeners
- bridge deck plate

52 strain gauges

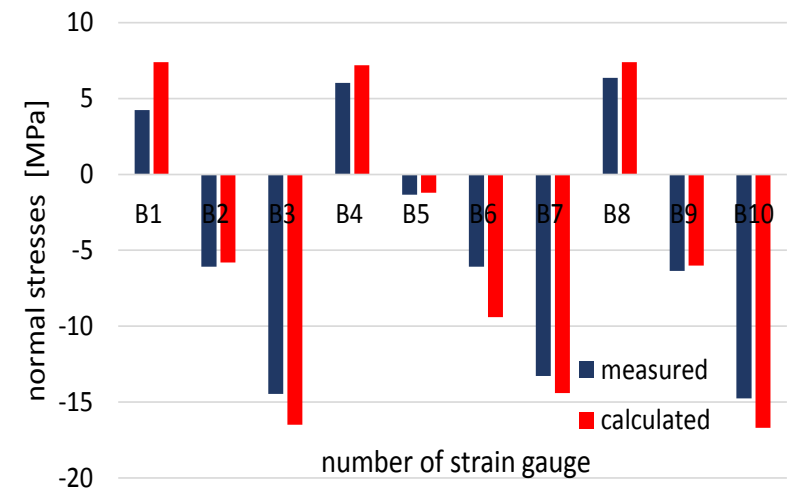
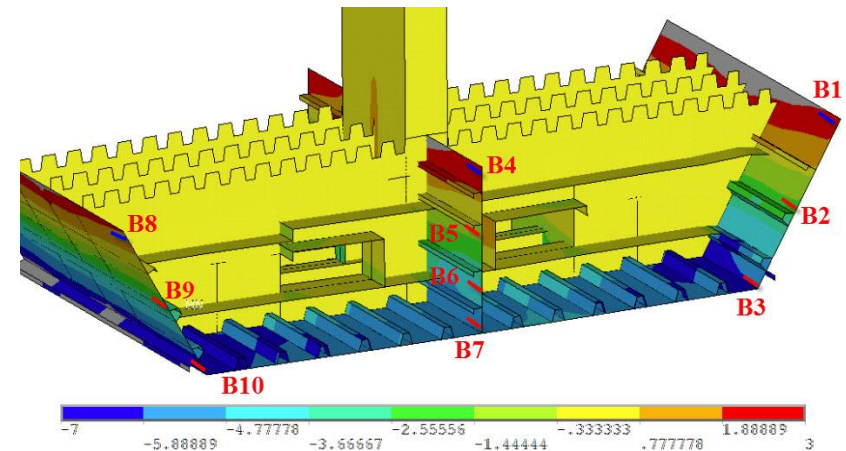
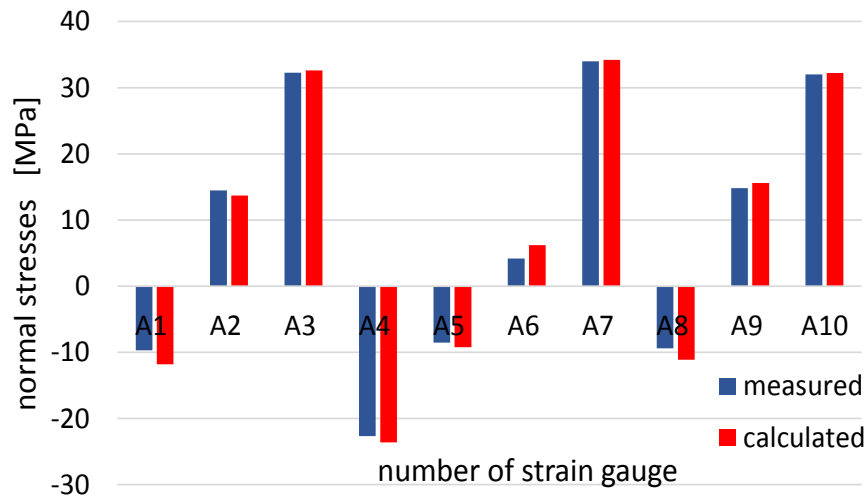
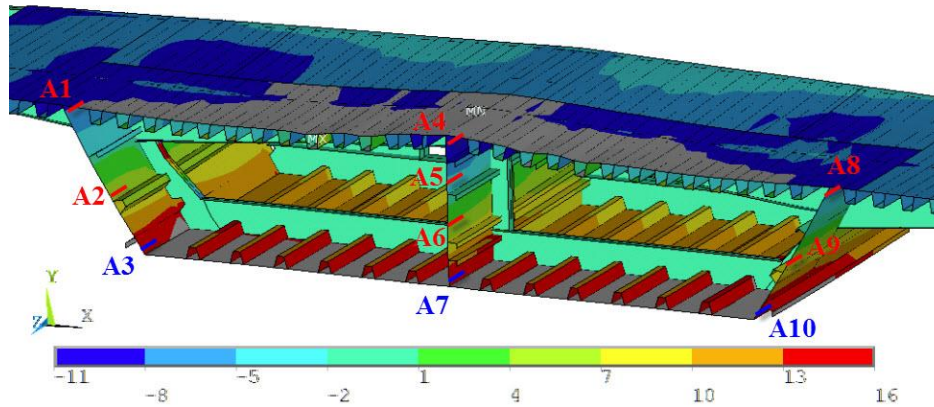


## 6 - 7. nyílásban

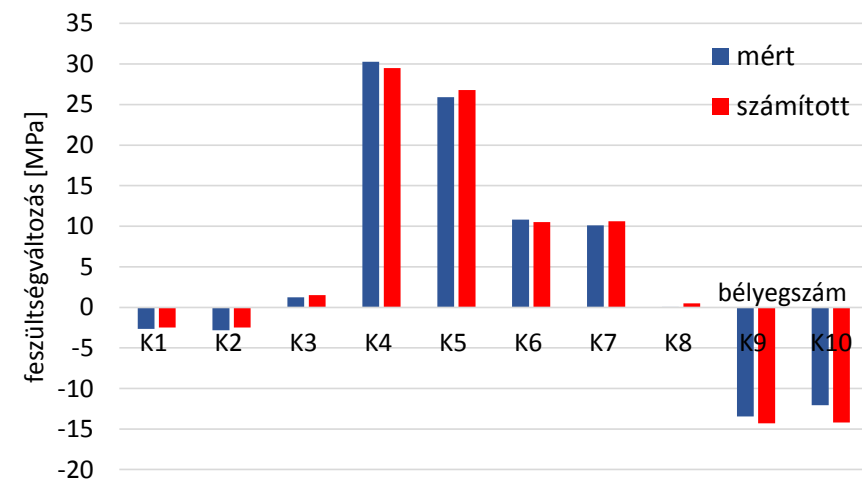
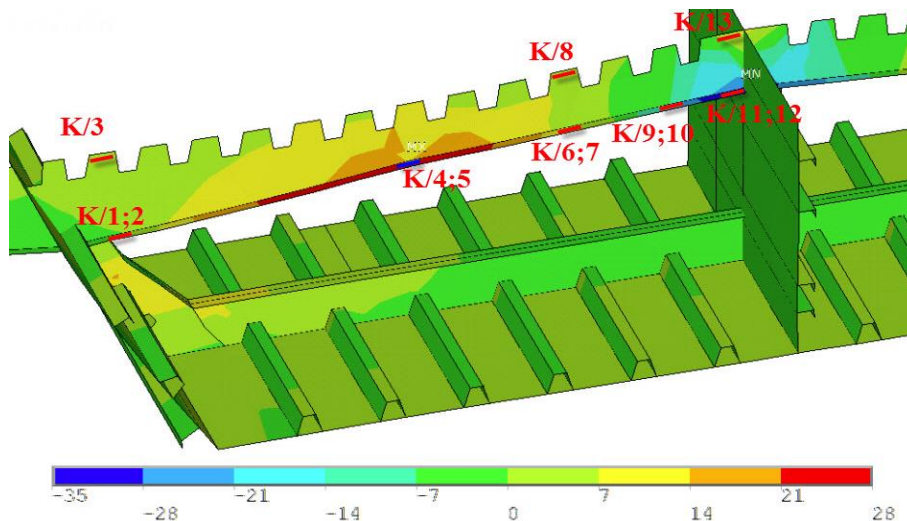
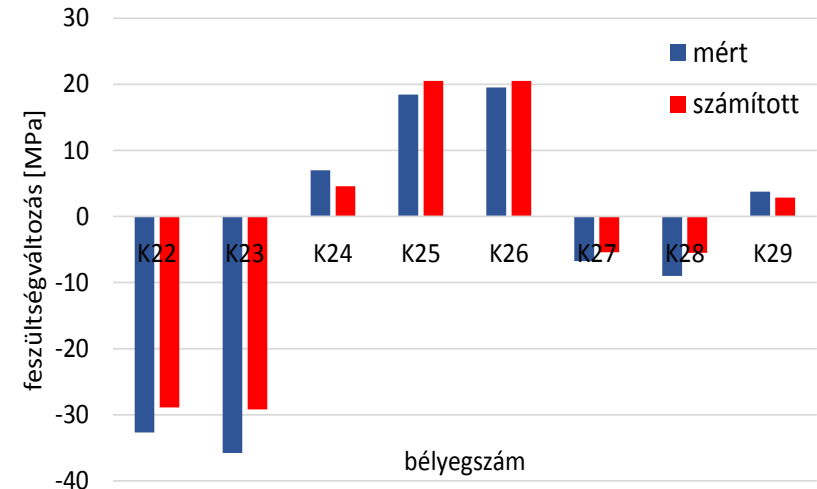
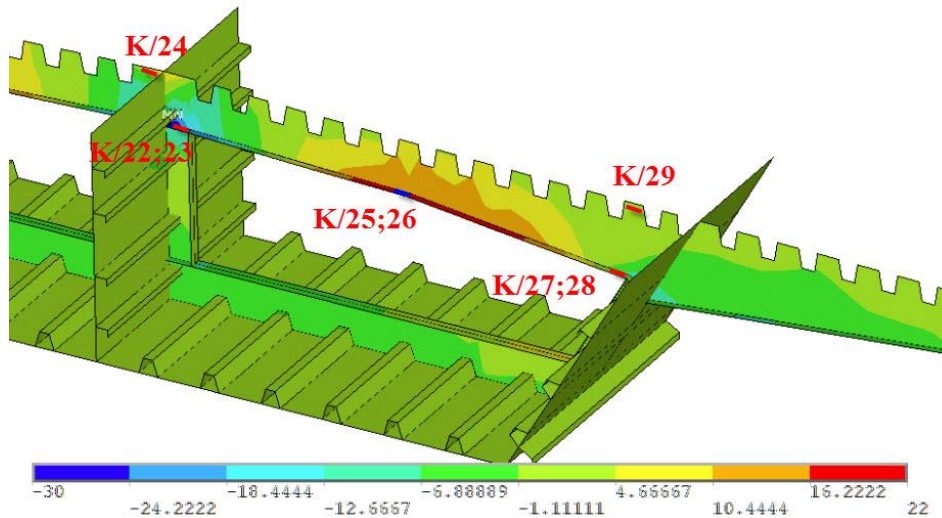


Total number of 109 strain gauges.

# Static loading – stresses



# Comparison of measured and calculated stresses



# Static measurement results – fatigue analysis

Measurement results



COMBINO trams

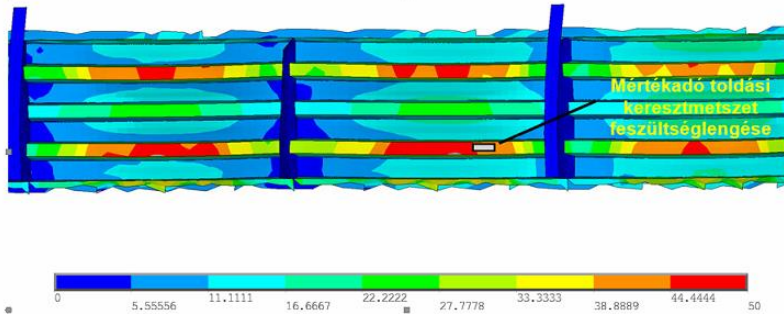


Measurements validated the static check results of the independent static check



COMBINO and new CAF trams are used

*Joint of longitudinal stiffener*



*Alsó öv keresztirányú tompavarrata:*

$$\text{közúti forgalom esetén: } \gamma_{Ff} \cdot \lambda \cdot \phi \cdot \Delta\sigma_p = 1.0 \cdot 2.5 \cdot 1.0 \cdot 27.5 = 68.75 \text{ MPa} \leq \frac{\Delta\sigma_c}{1.00} = 71 \text{ MPa}$$

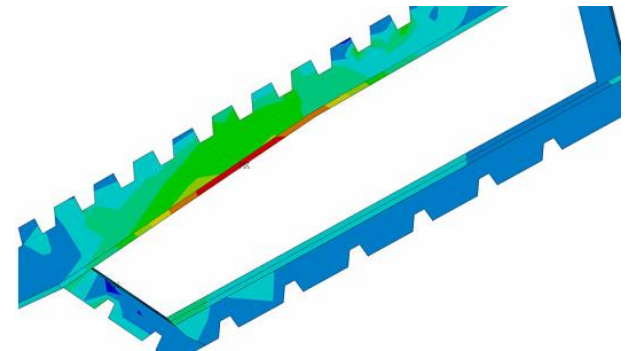
$$\text{villamos forgalom esetén: } \gamma_{Ff} \cdot \lambda \cdot \phi \cdot \Delta\sigma_p = 1.0 \cdot 1.4 \cdot 1.0 \cdot 27.1 = 37.94 \text{ MPa} \leq \frac{\Delta\sigma_c}{1.00} = 71 \text{ MPa}$$

*Kereszttartó nyakvarrata:*

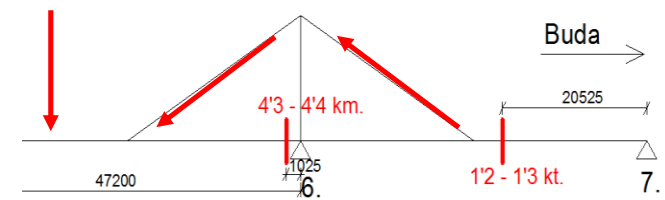
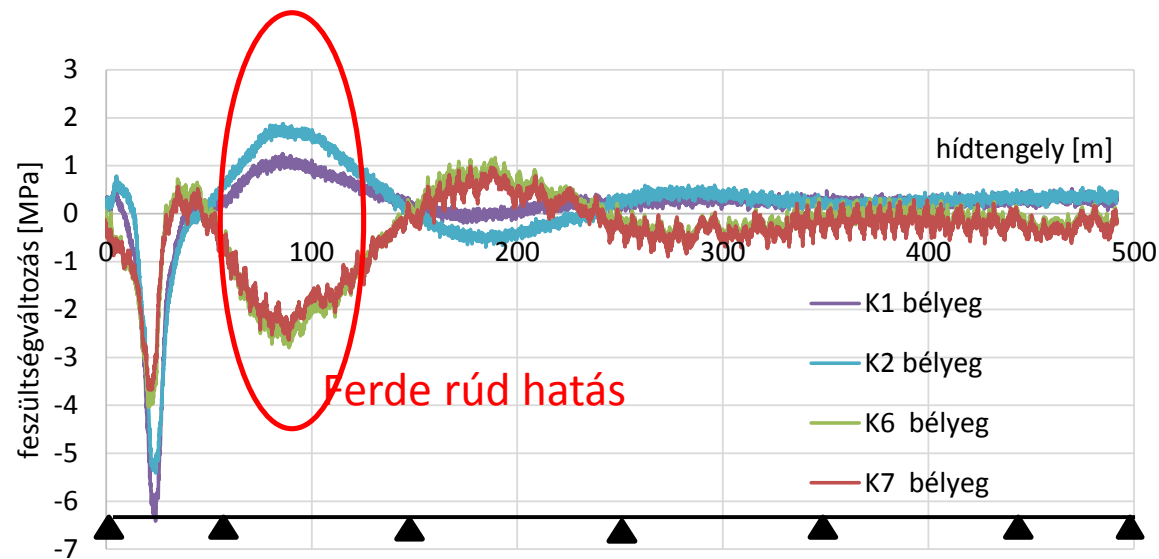
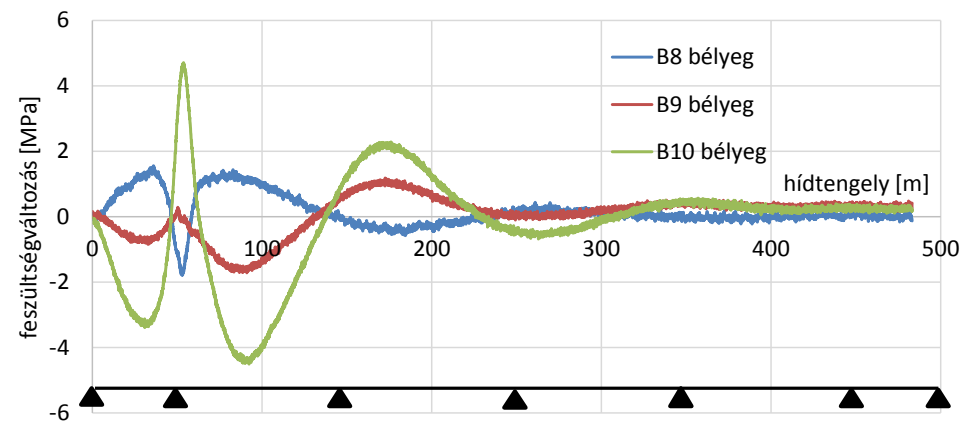
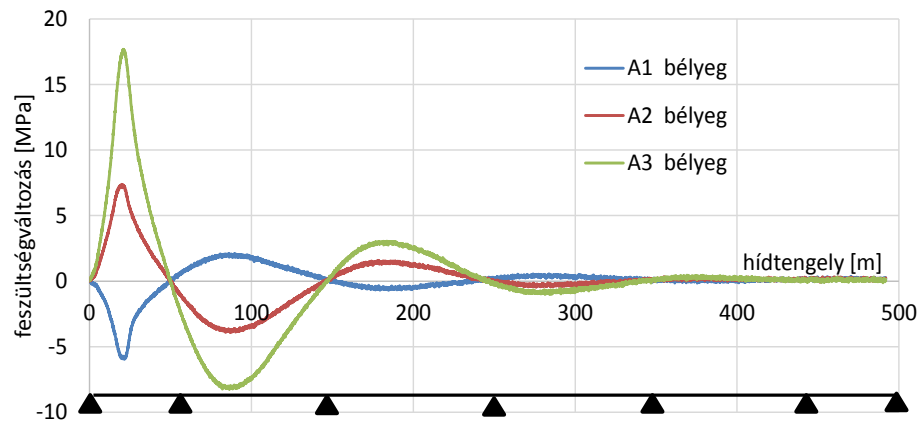
$$\text{közúti forgalom esetén: } \gamma_{Ff} \cdot \lambda \cdot \phi \cdot \Delta\sigma_p = 1.0 \cdot 2.5 \cdot 1.0 \cdot 33.6 = 84 \text{ MPa} \leq \frac{\Delta\sigma_c}{1.00} = 100 \text{ MPa}$$

$$\text{villamos forgalom esetén: } \gamma_{Ff} \cdot \lambda \cdot \phi \cdot \Delta\sigma_p = 1.0 \cdot 1.4 \cdot 1.0 \cdot 36 = 50.4 \text{ MPa} \leq \frac{\Delta\sigma_c}{1.00} = 71 \text{ MPa}$$

*Check of the cross girder*

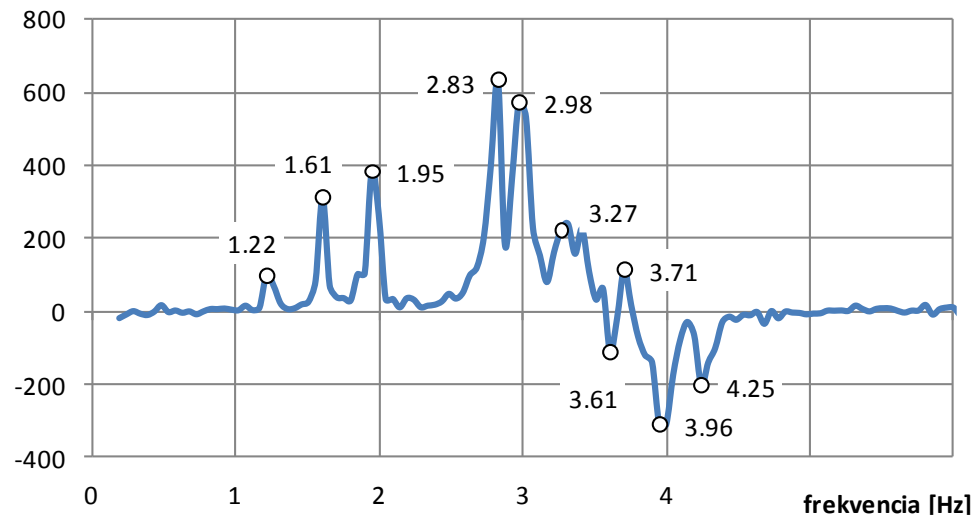


# Influence lines of the bridge



# Eigenfrequencies

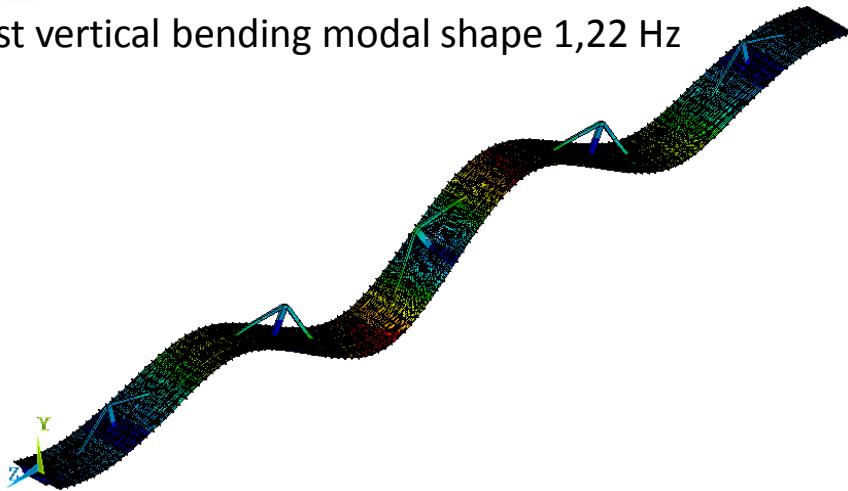
## Results of the measurements



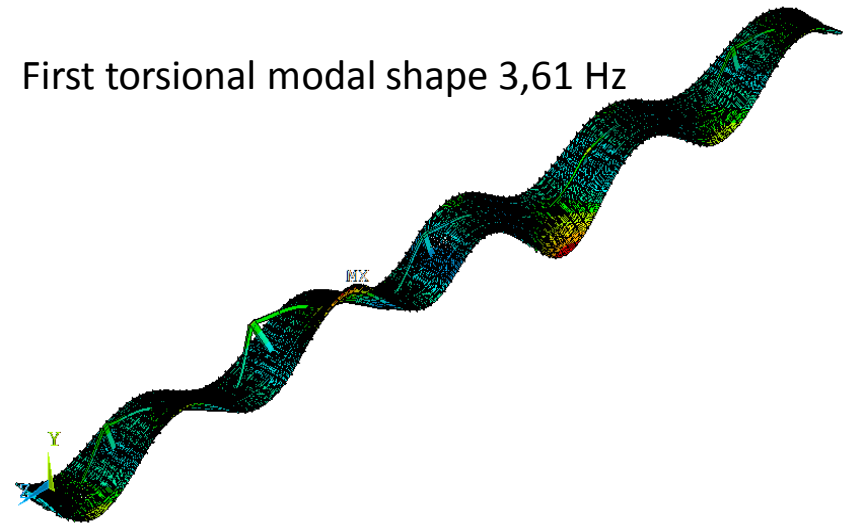
## Comparison with numerical calculations

| mért | számított | jelleg                  |
|------|-----------|-------------------------|
| 1,22 | 1,07      | 1. → függőleges hajlító |
| 1,61 | 1,46      | 2. → függőleges hajlító |
| 1,95 | 1,92      | 3. → függőleges hajlító |
| 2,54 | 2,42      | vízszintes hajlító      |
| 3,61 | 3,04      | csavaró                 |

First vertical bending modal shape 1,22 Hz



First torsional modal shape 3,61 Hz



# Dynamic loading

| 4 trucks running parallel        |                    |                |
|----------------------------------|--------------------|----------------|
| 1. run                           | 5 km/h             | from Buda side |
| 2. run                           | 20 km/h            | from Pest side |
| 3. run                           | 40 km/h            | from Buda side |
| 4. run                           | 50 km/h            | from Pest side |
| 5. run                           | 40 km/h + bracking | from Buda side |
| 1 Combino tram                   |                    |                |
| 1. run                           | 5 km/h             | from Buda side |
| 2. run                           | 20 km/h            | from Pest side |
| 3. run                           | 40 km/h            | from Buda side |
| 4. run                           | 60 km/h            | from Pest side |
| 2 Combino trams running parallel |                    |                |
| 1. run                           | 5 km/h             | from Buda side |
| 2. run                           | 40 km/h            | from Pest side |
| 3. run                           | 40 km/h + bracking | from Buda side |

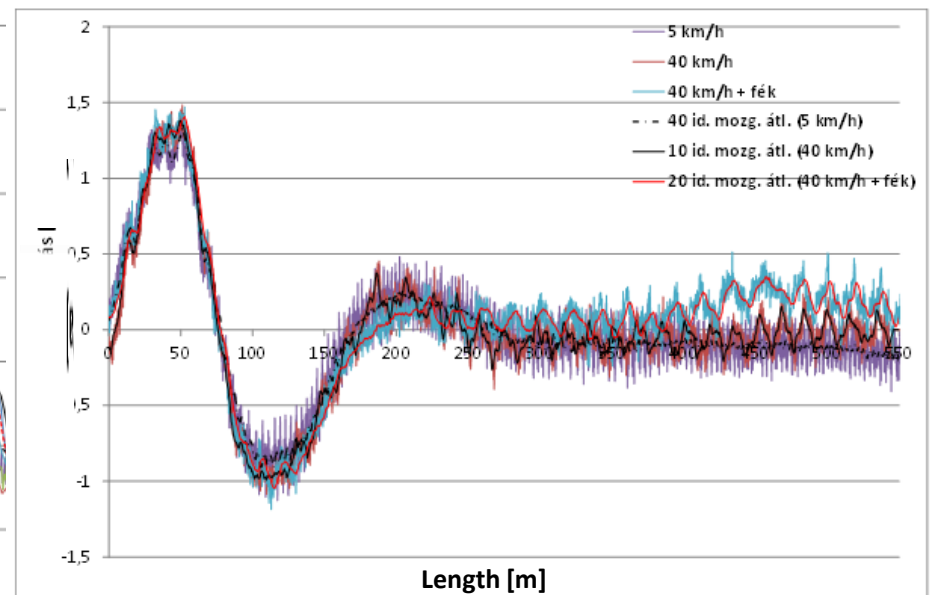
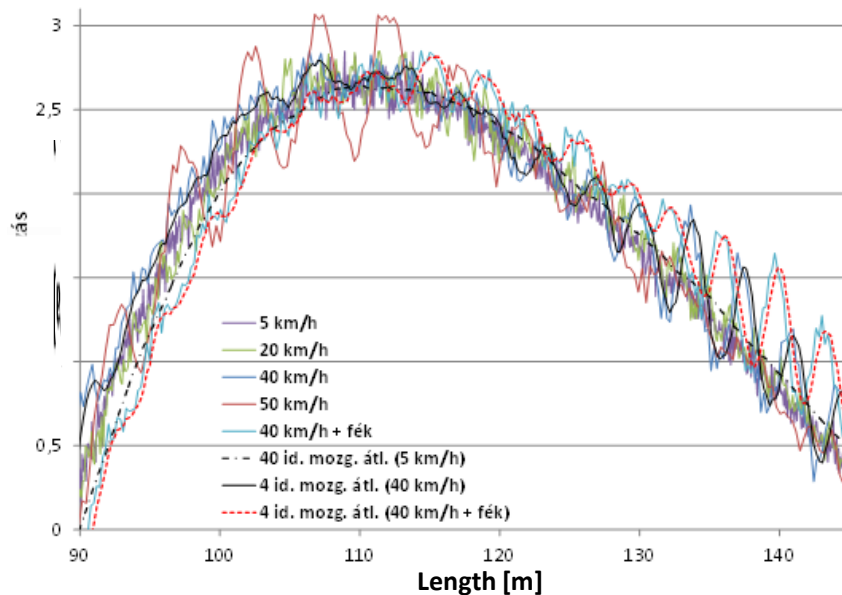
4 truck ~350 kN each

1 Combino tram

2 Combino trams

109 strain gages

50 Hz sampling frequency



## Dynamic factors

Main girders: 50 km/h run

- truck  $v = 1,10$
- Combino tram  $v \in 1,05$

Cross-girders: 50 km/h run

- truck  $v = 1,10$
- Combino tram  $v \in 1,06$

Support region: - truck  $v = 1,17 - 1,24$

- Combino tram  $v \in 1,03 - 1,08$

Results:

1. The **dynamic effect of the Combino** trams is always **smaller than the** dynamic effect of the **trucks**.
2. The **measured dynamic factor** is **smaller** the standard dynamics factor.



The Rákóczi bridge satisfies all standard criteria to open for mixed vehicular and tram traffic.



Thank you for the attention!