MONITORING AND DIAGNOSIS
OF CONCRETE BRIDGES AND TUNNELS

Speaker:
Prof. Giuseppe Mancini

Contributors: **IM-SAFE**
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MONITORING AND DIAGNOSIS OF CONCRETE BRIDGES AND TUNNELS

a. Overview on the risk-based, reliability based and semi-probabilistic assessment methods for existing structures

b. Current and future use of monitoring data in the structural assessment process and model updating methods

c. Real case studies (Sacertis Ingegneria): monitoring and diagnostics of concrete bridges and tunnels

Q&A

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Q&A

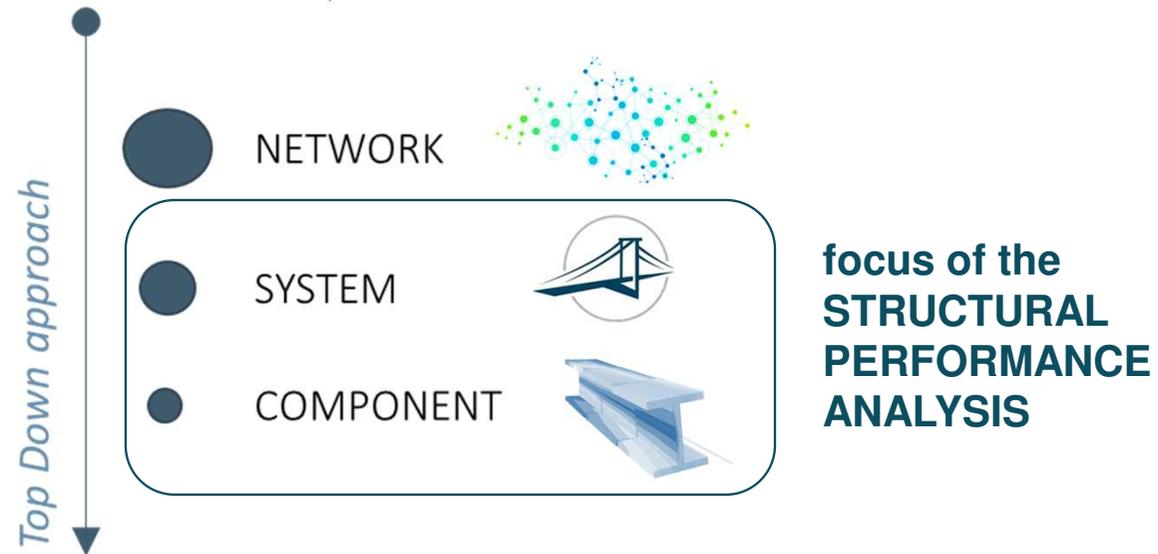# Definition of STRUCTURAL PERFORMANCE

IM-SAFE definition	The **behaviour of a structure**, a **structural component**, or a condition as a consequence of **actions**, usually classified by means of a **quantitative parameters** (e.g. reliability index, ratio between (local/overall) resistance capacity and action effect).

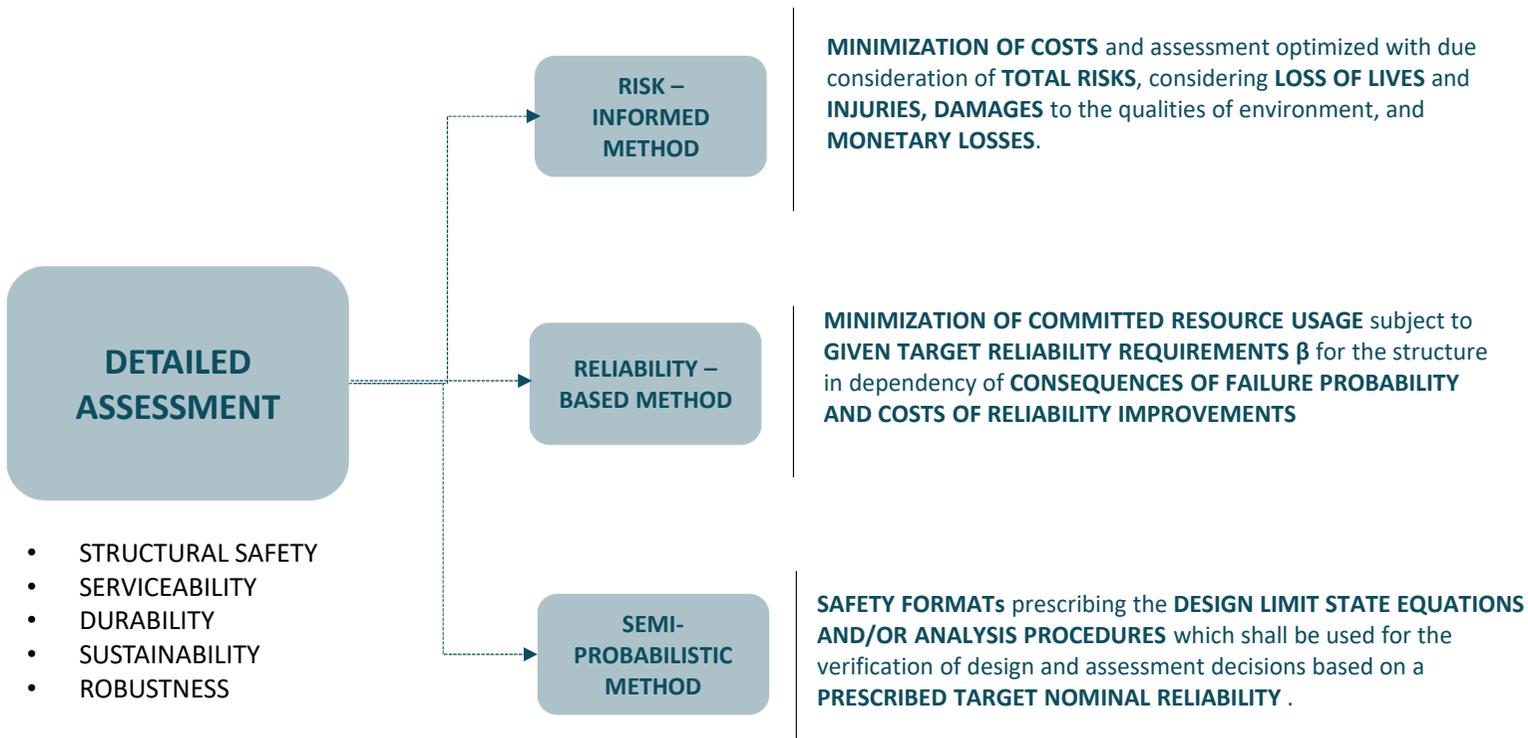| fib Model Code 2010:2013	COST TU1402	ISO 2394:2015	ISO 13822:2010	ISO 13824:2009	ISO 13824:2020
The behaviour of a structure or a structural element as a consequence of actions to which it is subjected or which it generates.[1]	Behaviour of the structure or one of its members usually quantified by means of a quantitative parameters (e.g. reliability index, ratio between resistance capacity and action effect)	Qualitative or quantitative representation of the behaviour of a structure (e.g. load bearing capacity, stiffness, etc.) related to its safety and serviceability, durability, and robustness.	Qualitative or quantitative representation of the behaviour of a structure (e.g. load bearing capacity, stiffness) in terms of its safety and serviceability.	-	-

[1]Note : In fib Model Code 2010:2013 the term structural performance is referred to as *performance*

https://im-safe-project.eu/

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING *OF LONG-SPAN BRIDGES*

Definition of STRUCTURAL PERFORMANCE

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Top Down approach

NETWORK

SYSTEM

COMPONENT

focus of the STRUCTURAL PERFORMANCE ANALYSIS

STRUCTURAL PERFORMANCE ASSESSMENT

DETAILED ASSESSMENT

- STRUCTURAL SAFETY
- SERVICEABILITY
- DURABILITY
- SUSTAINABILITY
- ROBUSTNESS

RISK – INFORMED METHOD

MINIMIZATION OF COSTS and assessment optimized with due consideration of **TOTAL RISKS**, considering **LOSS OF LIVES** and **INJURIES, DAMAGES** to the qualities of environment, and **MONETARY LOSSES**.

Exceptional situations for uncertainties and consequences

RELIABILITY – BASED METHOD

MINIMIZATION OF COMMITTED RESOURCE USAGE subject to **GIVEN TARGET RELIABILITY REQUIREMENTS β** for the structure in dependency of **CONSEQUENCES OF FAILURE PROBABILITY AND COSTS OF RELIABILITY IMPROVEMENTS**

Unusual situations for uncertainties

SEMI-PROBABILISTIC METHOD

SAFETY FORMATs prescribing the **DESIGN LIMIT STATE EQUATIONS AND/OR ANALYSIS PROCEDURES** which shall be used for the verification of design and assessment decisions based on a **PRESCRIBED TARGET NOMINAL RELIABILITY** .

Usual situations

Analysis Method Simplification

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING **OF LONG-SPAN BRIDGES**

Differentiation between NEW | EXISTING STRUCTURES

SUBSTANTIAL COSTS OF INTERVENTIONS on existing structures in order to increase performance levels

ADJUSTED β TARGET PERFORMANCE LEVELS IN ASSESSMENT TO BE CONSIDERED

EXISTING STRUCTURES

DETERIORATION MECHANISMS are to be taken into account

Verification assisted by **NLFEA and MODEL UPDATING**

REMAINING WORKING LIFE and **REFERENCE PERIOD** often smaller than design life of 50 years

ADJUSTED REFERENCE PERIOD in assessment to be considered

TESTING, INSPECTION AND MONITORING can be done in order to increase **KNOWLEDGE LEVEL**

adjusted **TREATMENT OF UNCERTAINTIES, BASIC VARIABLES DISTRIBUTION** and **UPDATED MODELS** to be considered

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING OF LONG-SPAN BRIDGES

Differentiation between NEW | EXISTING STRUCTURES

Fig. 3.3-1: Reliability index resulting from individual risk criterion for buildings.

[Fib Bulletin 80]

- **RELIABILITY:** Ability of a structure or structural element to fulfil the specified requirements over a specific reference period, including working life for which it has been designed

- **TARGET RELIABILITY:** Specified average acceptable failure probability that is to be reached over a reference period

- **REFERENCE PERIOD:** timeframe used as a basis for assessing the statistical parameters of time dependent variables and of the target reliability.

EXISTING CONCRETE STRUCTURES:

Recommended target reliability levels for structural design (ULS)			
Annual target β-values for structures to be designed, based on economic optimisation			
Relative cost of safety measure	Consequence Class		
	CC1	CC2	CC3
Large (A)	3.1	3.3	3.7
Normal (B)	3.7	**4.2**	4.4
Small (C)	4.2	4.4	4.7
Informative target reliability indices β for structures to be designed, related to a 50-year reference period			
Relative cost of safety measure	CC1	CC2	CC3
Normal (B)	3.3	**3.8**	4.3
Recommended annual target reliability levels for assessment of existing structures (ULS)			
Relative cost of safety measure	CC1	CC2	CC3
Large (A)	3.1	3.3	3.7
Recommended target reliability levels for upgrade of existing structures (ULS)			
While slightly lower values can be normally justified for β_{up}-levels in comparison to design target levels, it is common and reasonable to require the compliance with the design levels when upgrading the structure.			

[A.J. Bigaj-van Vliet (TNO), JCSS Workshop on Assessment of Existing Structures, 28th - 29th Jan 2021]

Differentiation between NEW | EXISTING STRUCTURES

New **MODEL CODE 2020** recommends principles of probabilistic structural limit state design with a possibility for differentiating the **RELIABILITY LEVEL PROMOTING THE ANNUAL APPROACH**:

NEW

βnew - level indicating desired reliability for design of new structures

FITTNESS FOR PURPOSE

β_0 - level below which the existing structure is considered unreliable and should be upgraded

REPAIR / UPGRADE

β_{up} - level indicating an optimum upgrade strategy while upgrading of existing structures

EXISTING CONCRETE STRUCTURES:

Recommended target reliability levels for structural design (ULS)			
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[A.J. Bigaj-van Vliet (TNO), JCSS Workshop on Assessment of Existing Structures, 28th - 29th Jan 2021]

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING OF LONG-SPAN BRIDGES

Differentiation between NEW | EXISTING STRUCTURES

New **MODEL CODE 2020** recommends principles of probabilistic structural limit state design with a possibility for differentiating the **RELIABILITY LEVEL PROMOTING THE** ANNUAL APPROACH:

- ➤ COMPLIES WITH CONCEPT OF **SYSTEMATIC REPAIRS**
- ➤ **COST OPTIMISATION**
- ➤ MORE SUITABLE FOR **RAPID DEGRADATION** (FATIGUE)
- ➤ **RECALCULATION OF γ PARTIAL FACTORS**
- **PROS**
- ➤ MORE CONSISTENT WITH REGULATIONS/ **ACCEPTANCE CRITERIA RELATED TO LIFE SAFETY**
- ➤ VALID FOR EXISTING STRUCTURES WITH **DIFFERENT SERVICE LIVES**

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Q&A

EXISTING STRUCTURES | Need for assessment

[CEN/TS 17440]

NEED FOR ASSESSMENT IN TIME EXTERNAL CAUSE	STRUCTURAL ISSUES	N – S – C LEVEL*	ASSESSMENT TYPE	AVAILABLE / REQUIRED INFOs
	CONSTRUCTION ERRORS	S | C	DETAILED	• ORIGINAL DESIGN DOCUMENTS • AS-BUILT & CONSTRUCTION DETAILS (BIM)
SCHEDULED ASSESSMENT for ASSET MANAGEMENT PROGRAMME		N | S | C	PRELIMINARY | DETAILED	• PERIODIC/DETAILED INSPECTION, SURVEYS OUTCOMES
	DETERIORATION PROCESSES	N | S | C	PRELIMINARY | DETAILED	• DEFECTS, DETERIORATION CHARACTERIZATION
CHANGE OF DESIGN LOADS		N | S | C	PRELIMINARY | DETAILED	
CHANGE OF HAZARDS (e.g. landslide, accidental actions)*		S | C	DETAILED	INSPECTION AND TESTING RESULTS ON: • MATERIAL PROPERTIES • HAZARDS
RETROFITTING		S | C	DETAILED	DISCRETE/CONTINUOUS (IN SPACE AND TIME) DATA FROM: • NDT/DT
NEED FOR EXTENSION OF WORKING LIFE		S | C	DETAILED	• MONITORING SYSTEMS

Working life

Incremental level of knowledge

[IM-SAFE integration to CEN/TS 17440]

[*N=Network
S=System
C=Component]

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING OF LONG-SPAN BRIDGES

INFORMATION FROM INSPECTION, MONITORING, TESTING

The proposed framework for the DATA INFORMED PERFORMANCE ASSESSMENT allows to incorporate:

ALTERNATIVE TARGET RELIABILITY LEVELS

REMAINING WORKING LIFE

ADDITIONAL INFORMATION FROM INSPECTION, MONITORING AND TESTING

DIRECT INFORMATION = quantity of interest

- **BASIC VARIABLES**: updating of probability distributions, mean values or assessment values of basic variables

INDIRECT INFORMATION = indicator of the quantity

- **PROBABILITY OF FAILURE**: updating of the probability of the structural failure by using information from load testing or about the past performance
- **MODEL UPDATING**: deterministic or probabilistic methods to update numerical structural models

MEASUREMENT & MODEL UNCERTAINTIES

Decisions concerning structures shall account for all uncertainties of relevance for their performances such as:

UNCERTAINTIES	INFLUENCE OF INSPECTION, MONITORING & TESTING
ALEATORIC UNCERTAINTIES inherent natural variability	-
STATISTICAL UNCERTAINTIES lack of data	Reduced with **INCREASED NUMBER OF SAMPLES -** Updated **STANDARD DEVIATION** of basic variables with the **DATA COLLECTION**
Other EPISTEMIC UNCERTAINTIES lack of knowledge on the structural system (as-built), model uncertainties	Reduced with **SENSITIVITY ANALYSIS** to identify **KEY PARAMETERS** and **VULNERABLE ZONES** to be monitored

DATA INFORMED PERFORMANCE ASSESSMENT

Analysis Method Simplification

RISK – INFORMED METHOD	RELIABILITY – BASED METHOD	SEMI-PROBABILISTIC METHOD

Complexity

INSPECTION MONITORING TESTING

$$R_i$$

$$\beta = f(P_f)$$

$$\beta = -\Phi^{-1}(P_f)$$

$$\gamma = f(\beta_{(f(P_f))}; f(\mu,\alpha,\sigma))$$

$$\gamma_m = \frac{X_k}{X^*} = \frac{\mu_X\,(1 - 1{,}645\,\delta_X)}{\mu_X\,(1 - \alpha_R\,\beta\,\delta_X)}$$

UPDATE OF RISK EVALUATION, CONSEQUENCES AND COSTS OF MITIGATION ACTIONS on LEVEL OF KNOWLEDGE

UPDATING ACTUAL RELIABILITY β based on LEVEL OF KNOWLEDGE and DAMAGE MODELING

- **PARTIAL FACTORS** based on **DATA** and **ADJUSTED PROBABILISTIC MODELS** (mean, std) for basic variables and **adjusted MODEL UNCERTAINTIES**
- **GLOBAL RESISTANCE FORMAT** based on **MODEL UPDATING MODELS**

More complex applicability in practice

IM-SAFE

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING OF LONG-SPAN BRIDGES

DATA INFORMED PERFORMANCE ASSESSMENT

SEMI-PROBABISTIC METHOD

LIMIT STATE GENERAL FRAMEWORK (EN 1990/2002)

FORM-based design point

For every limit state (LS):

LS Function ———

$$g(\ F_d,\ X_d,\ a_d,\ \vartheta_d\ ) > 0$$

Actions
design values

Design values of
geometrical quantities

Material properties
design values

Design values of
model uncertaintes

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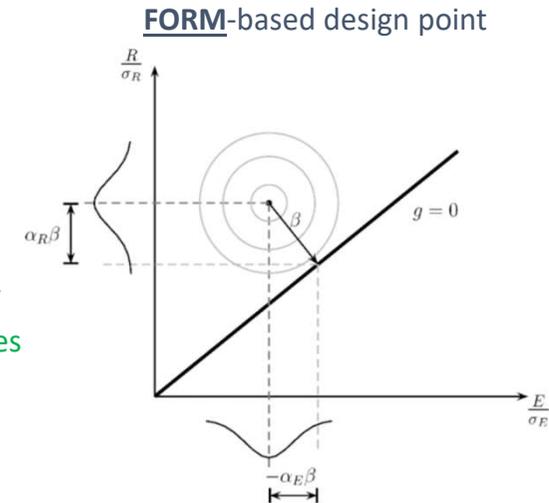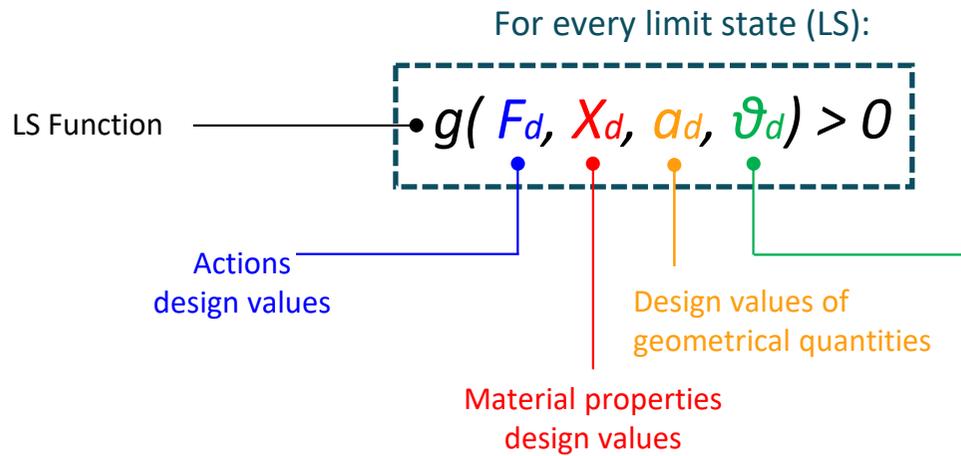
INFORMATION UPDATING

ACTIONS : TRAFFIC LOADS
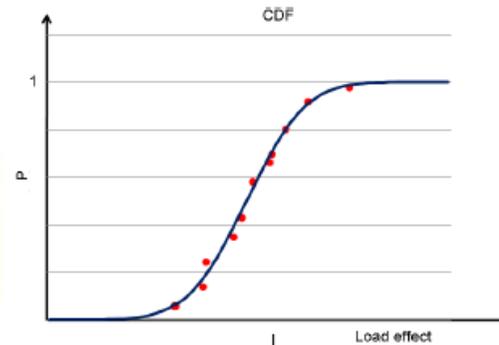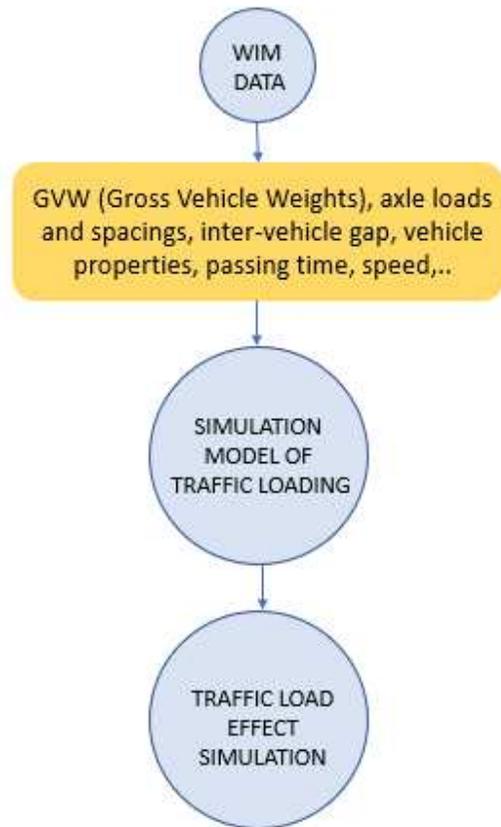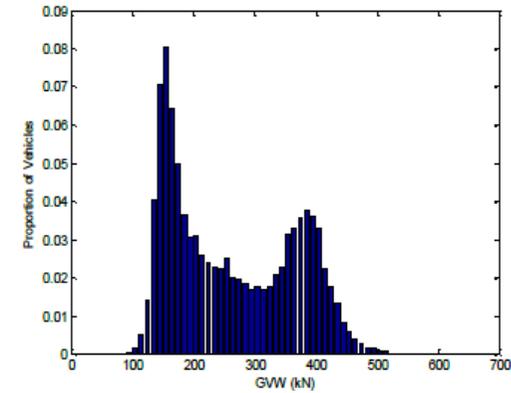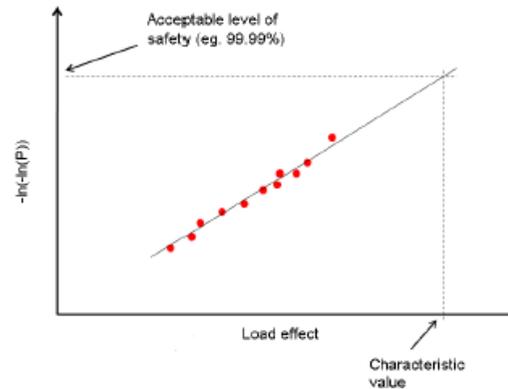
USE DATA TO EVALUATE THE TRAFFIC LOAD:

DETERMINATION OF SUITABLE ADJUSTMENT FACTORS (I.E. α FACTORS) FOR EUROCODE LM1

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING **OF LONG-SPAN BRIDGES**

INFORMATION UPDATING

RESISTANCE :

```
INFORMATION
UPDATING
PROCEDURES
```

UPDATING OF PROBABILITY DISTRIBUTIONS, MEAN VALUES OR ASSESSMENT VALUES OF BASIC VARIABLES

UPDATING OF THE PROBABILITY OF THE STRUCTURAL FAILURE BY USING INFORMATION FROM LOAD TESTING OR ABOUT THE PAST PERFORMANCE

MODEL UPDATING

PRIOR INFORMATION

MEAN, STANDARD DEVIATION

BAYESIAN APPROACH

DISTRIBUTION OF NEW DATA ONLY

POSTERIOR NORMAL DISTRIBUTION

CHARACTERISTIC VALUES, ASSESSMENT VALUES

INFORMATION UPDATING

RESISTANCE :

INFORMATION UPDATING PROCEDURES

UPDATING OF PROBABILITY DISTRIBUTIONS, MEAN VALUES OR ASSESSMENT VALUES OF BASIC VARIABLES

UPDATING OF THE PROBABILITY OF THE STRUCTURAL FAILURE BY USING INFORMATION FROM LOAD TESTING OR ABOUT THE PAST PERFORMANCE

MODEL UPDATING

DIRECT UPDATING

LOAD TESTING

SATISFACTORY PAST PERFORMANCE

$$P(F|I) = \frac{P(F \cap I)}{P(I)}$$

LOCAL or GLOBAL failure

INSPECTION information

INFORMATION UPDATING

RESISTANCE :

INFORMATION UPDATING PROCEDURES

UPDATING OF PROBABILITY DISTRIBUTIONS, MEAN VALUES OR ASSESSMENT VALUES OF BASIC VARIABLES

UPDATING OF THE PROBABILITY OF THE STRUCTURAL FAILURE BY USING INFORMATION FROM LOAD TESTING OR ABOUT THE PAST PERFORMANCE

MODEL UPDATING

PHENOMENA OBSERVATION

IDENTIFICATION OF VARIABLES

MATHEMATICAL MODEL DESCRIPTION

NUMERICAL SIMULATION

EXPERIMENTAL VALIDATION (STATIC /DYNAMIC LOAD TESTS)

INFORMATION UPDATING

RESISTANCE :

MODEL CALIBRATION

- DETERMINISTIC MODELS
  - DIRECT (one – step)
    - LAGRANGE MULTIPLIERS METHOD
    - MATRIX MIXING APPROACH
    - EIGEN STRUCTURE ASSIGNMENT APPROACH
  - PARAMETRIC (multi-step)
    - METHODS BASED ON PENALTY FUNCTIONS
    - SENSITIVITY ANALYSIS APPROACH
    - MINIMUM VARIANCE METHOD
    - METHODS USING FREQUENCY DOMAIN DATA
- PROBABILISTIC MODELS
  - PROBABILITY ESTIMATORS
  - MONTECARLO METHOD
  - MULTI-MODEL APPROACH

DATA INFORMED PERFORMANCE ASSESSMENT

Example:
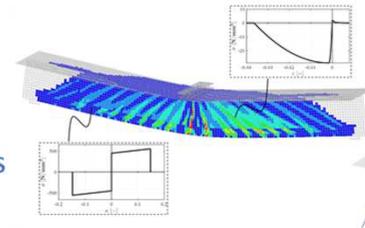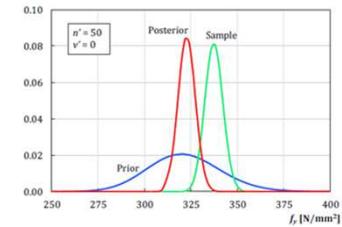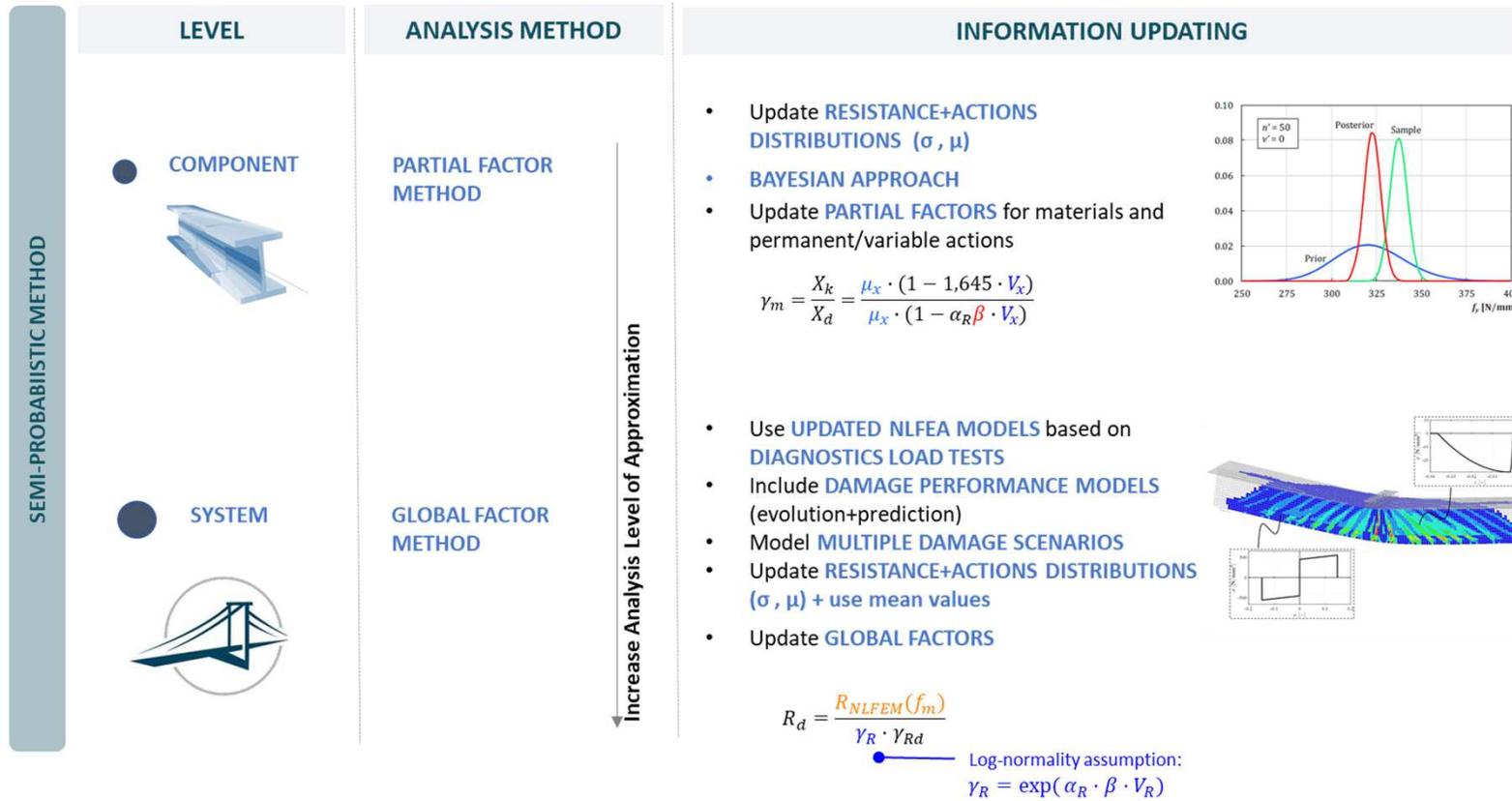
LEVEL	ANALYSIS METHOD	INFORMATION UPDATING
COMPONENT	PARTIAL FACTOR METHOD	• Update **RESISTANCE+ACTIONS DISTRIBUTIONS** (σ, μ) • **BAYESIAN APPROACH** • Update **PARTIAL FACTORS** for materials and permanent/variable actions $$\gamma_m = \frac{X_k}{X_d} = \frac{\mu_x \cdot (1 - 1{,}645 \cdot V_x)}{\mu_x \cdot (1 - \alpha_R \beta \cdot V_x)}$$
SYSTEM	GLOBAL FACTOR METHOD	• Use **UPDATED NLFEA MODELS** based on **DIAGNOSTICS LOAD TESTS** • Include **DAMAGE PERFORMANCE MODELS** (evolution+prediction) • Model **MULTIPLE DAMAGE SCENARIOS** • Update **RESISTANCE+ACTIONS DISTRIBUTIONS** (σ, μ) + use mean values • Update **GLOBAL FACTORS** $$R_d = \frac{R_{NLFEM}(f_m)}{\gamma_R \cdot \gamma_{Rd}}$$ Log-normality assumption: $$\gamma_R = \exp(\alpha_R \cdot \beta \cdot V_R)$$

SEMI-PROBABILISTIC METHOD

Increase Analysis Level of Approximation

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REAL CASE STUDIES – SACERTIS experience

SMART SHM FOR STRUCTURAL DIAGNOSTICS

SACERTIS INGEGNERA

IMPROVE THE QUALITY AND SAFETY OF ANY CONSTRUCTION AND EXTEND ITS USEFUL LIFE

MONITOR IN REAL TIME THE SAFETY OF ANY STRUCTURE, FROM TIME OF CONSTRUCTION TO END-OF-LIFE

SUPPLY A TURN-KEY INFRASTRUCTURE RISK-ASSESSMENT AND DIAGNOSTICS SOLUTION TO OPTIMIZE MAINTENANCE

IMPROVE THE WORLD INFRASTRUCTURE AND HOUSING RESILIENCE

SUPPORT THE CIVIL ENGINEERING COMMUNITY BY SUPPLYING ADVANCED DIAGNOSTICS TOOLS TO INCREASE THEIR PRODUCTIVITY AND THE QUALITY OF THEIR WORK

INTEGRATE DIFFERENT DISCIPLINES, LEVERAGING THE MOST ADVANCED COMPUTING AND SENSING TECHNOLOGIES.

REAL CASE STUDIES – SACERTIS experience

REAL CASE STUDIES – Sensors selections and optimization
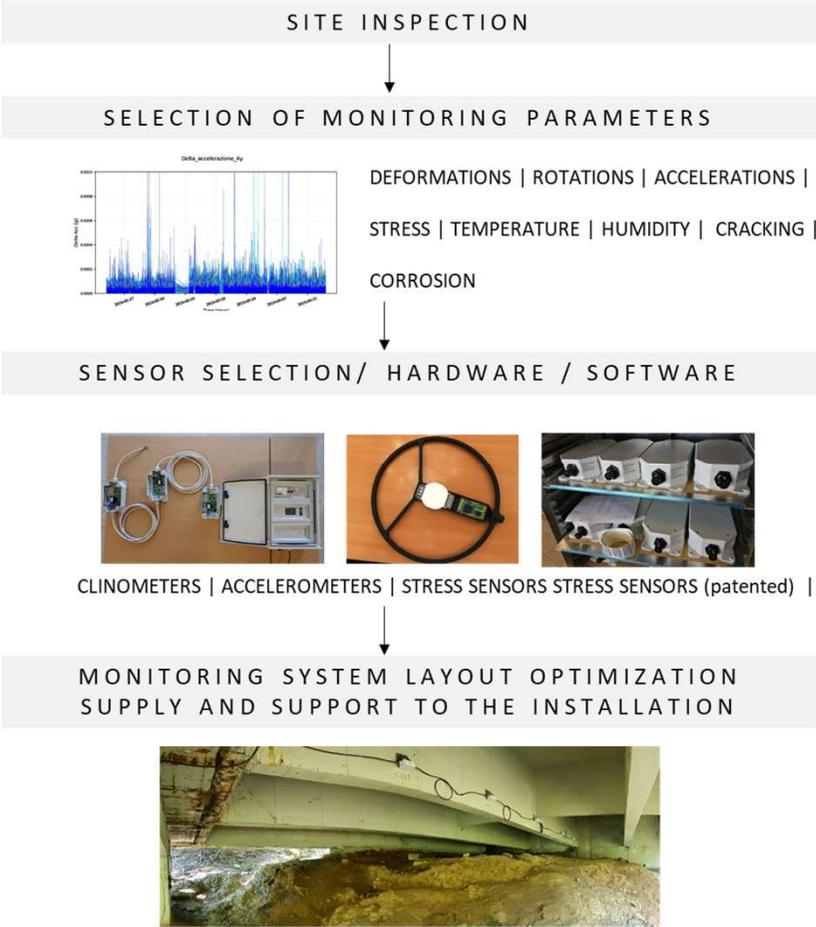
REAL CASE STUDIES – Dense Sensing
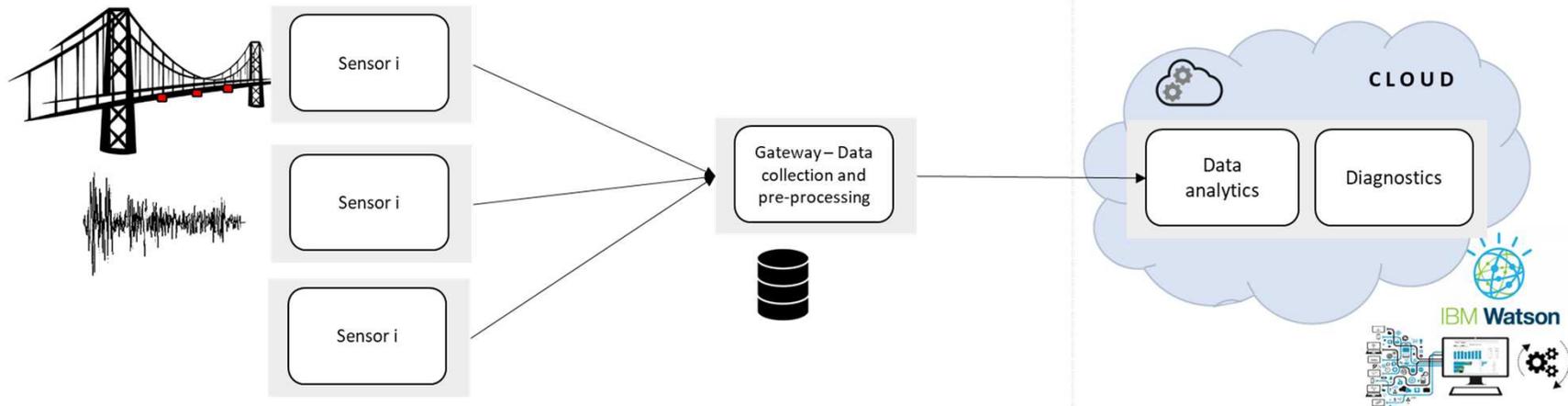
SENSOR-NODE LEVEL

- Variable sampling rate
- Sensor node computational capabilities
- Calculation of synthetic parameters

GATEWAY LEVEL

- Smart data acquisition and data transferring after anomalous events
- Key Data selection / filtering
- Real-time analysis, comparison with thresholds and reports of sudden events

CLOUD LEVEL

- Data collection
- Medium / long-term data analytics
- Comparison with damage thresholds
- Structural diagnostics and proactive maintenance support

REAL CASE STUDIES – Smart Load Test App

REAL CASE STUDIES – Load Test and Model Updating
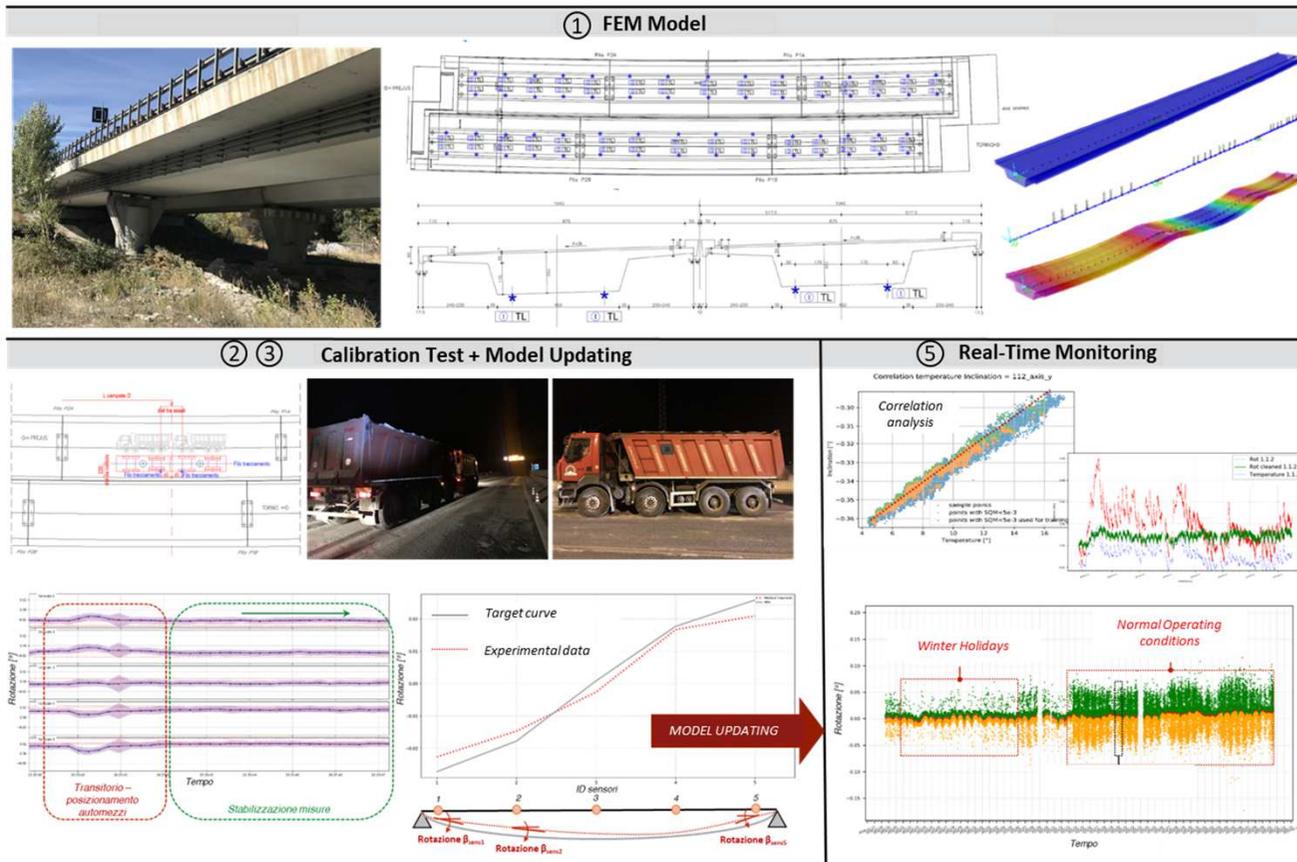
1. Numerical Model
2. On-site Calibration Test
3. Model Updating
4. Thresholds definition and Real-Time Monitoring

REAL CASE STUDIES – Model Updating examples
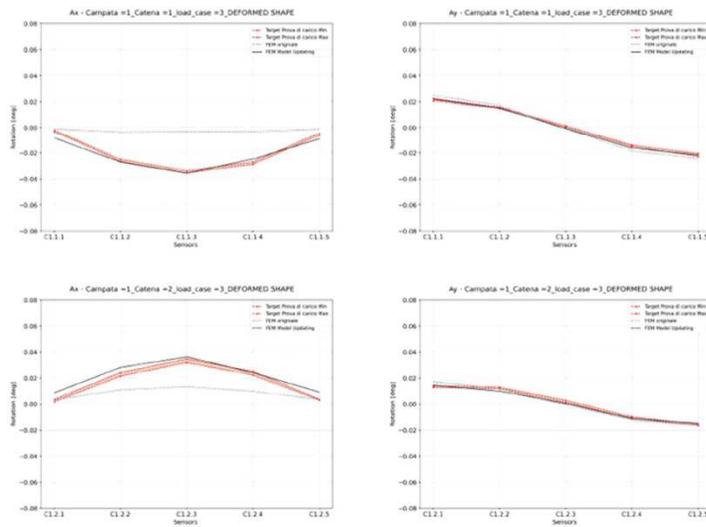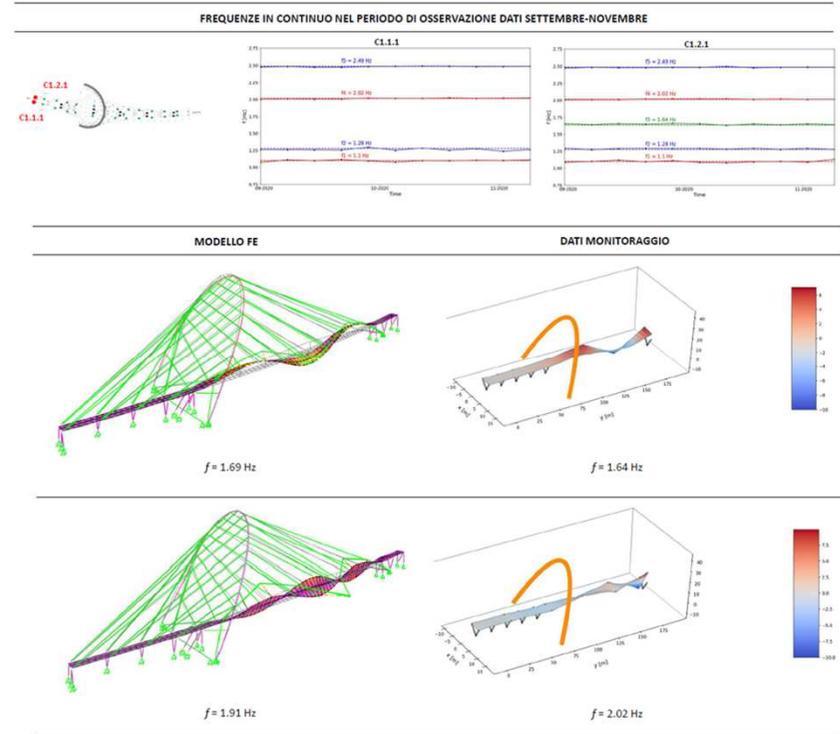
REAL CASE STUDIES – Near Real Time vs Long term Monitoring

STATIC AND DYNAMIC RESPONSE ANALYSIS **IN NEAR-REAL TIME**

GATEWAY LEVEL
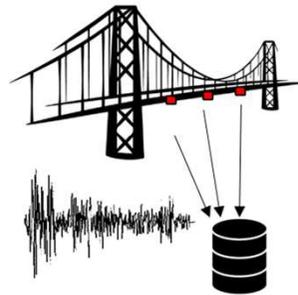
- Rotation / differential settlements analysis
- Time-domain and Frequency-domain analysis of vibration signals
- Key Performance Indicators analysis
- Correlation between logical groups of sensors for robust anomaly detection
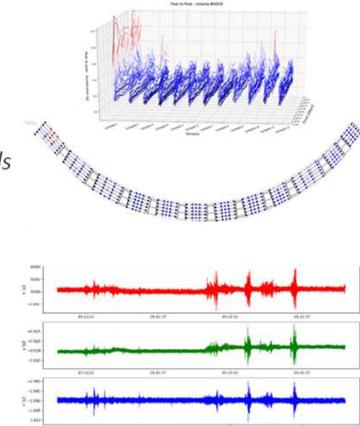
STATIC AND DYNAMIC RESPONSE ANALYSIS **– LONG TERM**

CLOUD LEVEL

- Residual plastic rotations / foundation settlements
- Frequency domain analysis of the modal response, evaluation of frequency shift
- Long-term trend analysis of Key Performance Indicators
- Correlation between parameters for efficient diagnostics
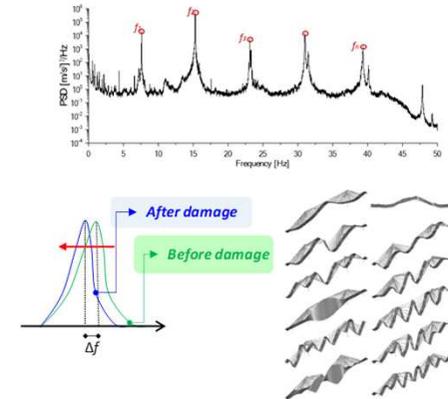
REAL CASE STUDIES – CONCRETE BRIDGES & TUNNELS

1) **CASE STUDY 1: MONITORING OF PRE-STRESSED EXTERNAL TENDONS OF A CONCRETE BRIDGE**
   - Identification of earthquake effect
   - Changes in dynamic properties have been observed after a strand FAILURE

2) **CASE STUDY 2: HIGHWAY PRESTRESSED BRIDGE MONITORING**
   - Observed anomalies in dynamic and static properties have triggered an
   - on-site inspection verifying prestressing strands corrosion.
   - Measured the recovery after structural repair.

3) **CASE STUDY 3: CONCRETE TUNNEL MONITORING UNDER LANDSLIDE EFFECT**
   - Monitoring of the deformed shape and lining stress of the lining of concrete tunnels under the effect of an instable landslide

REAL CASE STUDIES – Case 1 | Prestressed external cables

INSTRUMENTED BRIDGE SECTIONS

Output signal

Tri-axial accelerometers

Sensor positioning on the external pre-stressed tendons

TRI-AXIAL ACCELEROMETER

For each monitored tendon, 2 sensors have been installed near the tendon ends
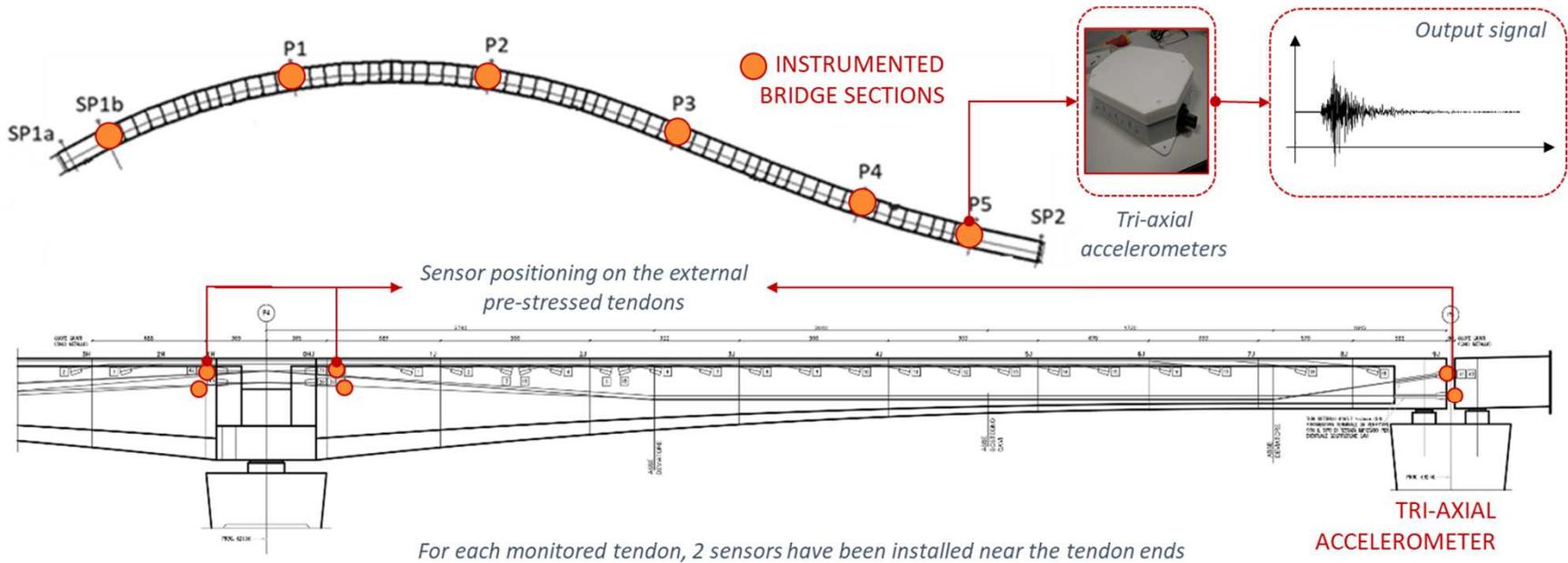
REAL CASE STUDIES – Case 1 | Prestressed external cables

EARTHQUAKE ON NOVEMBER 2017
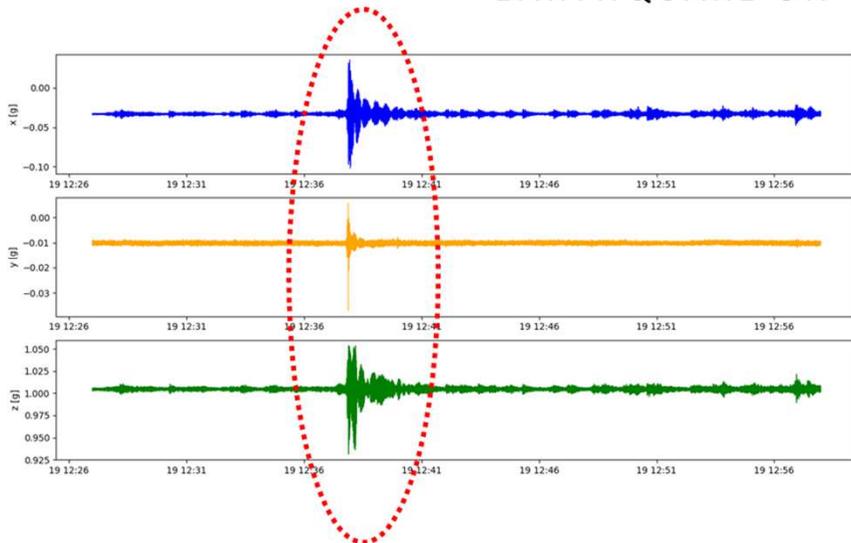
1 ALL SENSORS EXCEEDED THE FIRST LEVEL THRESHOLDS!! ✗
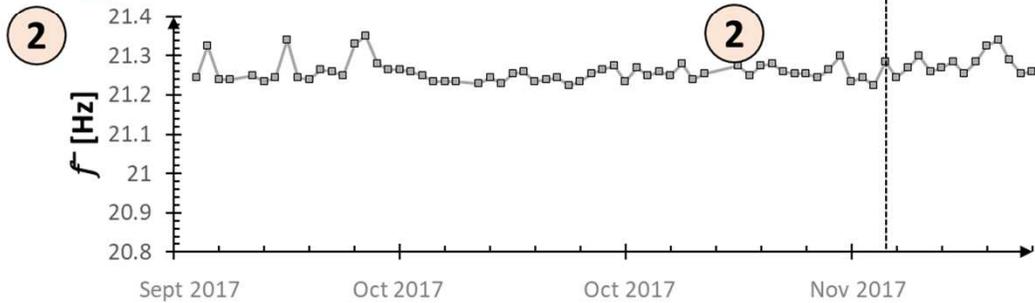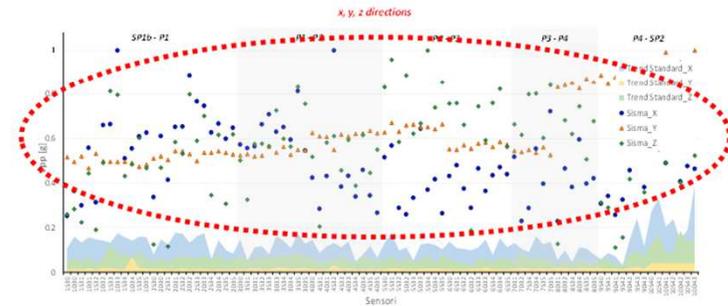
NO FREQUENCY SHIFT!! ✓

RESULT: NO STRUCTURAL MODIFICATION

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING OF LONG-SPAN BRIDGES

REAL CASE STUDIES – Case 1 | Prestressed external cables

① On December 10th 2017 a threshold was exceeded ✗

Potential STRAND breakage ⚠

PHYSICAL EVENT

② FREQUENCY SHIFT DUE TO STIFFNESS REDUCTION ✗

After damage
Before damage
Δf

A reduction in stiffness leads to a reduction in the natural frequencies

09/12/2017
10/12/2017

⚠ *Strand breakage* — 1S33

DETECTION OF THE EVENT IN REAL-TIME

DAMAGE IDENTIFICATION
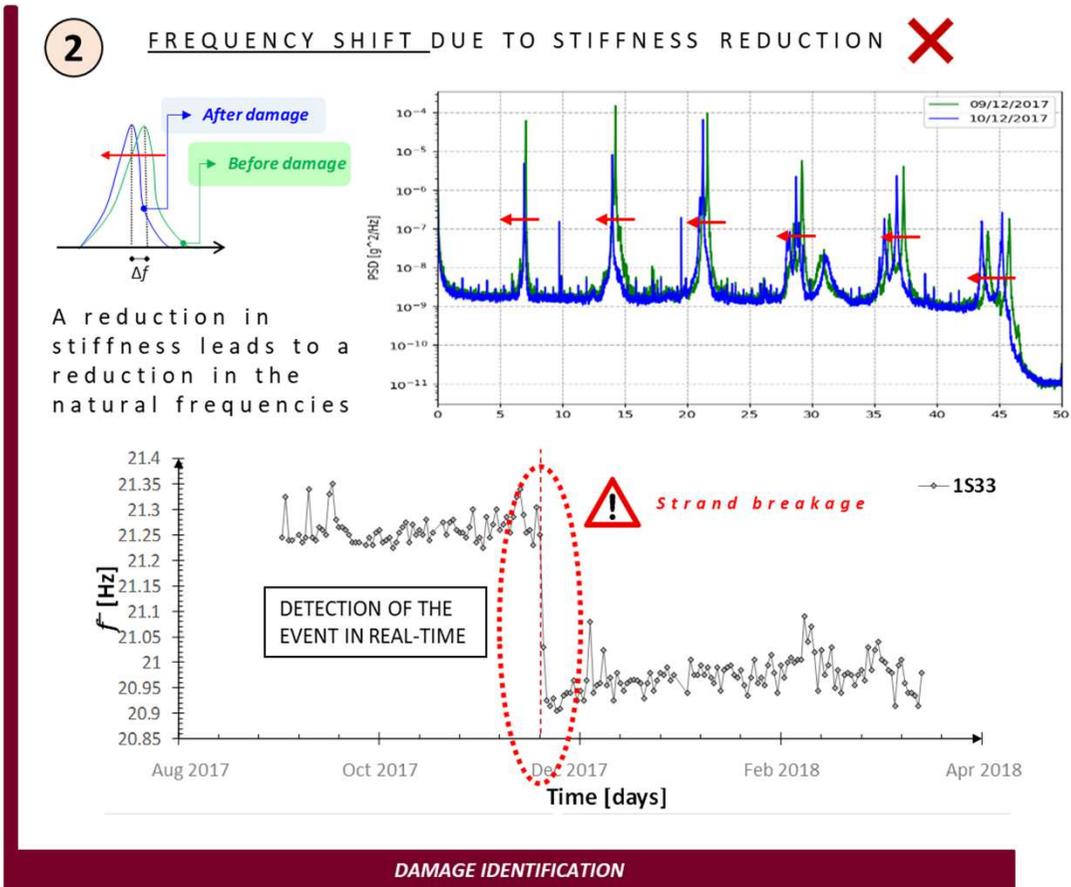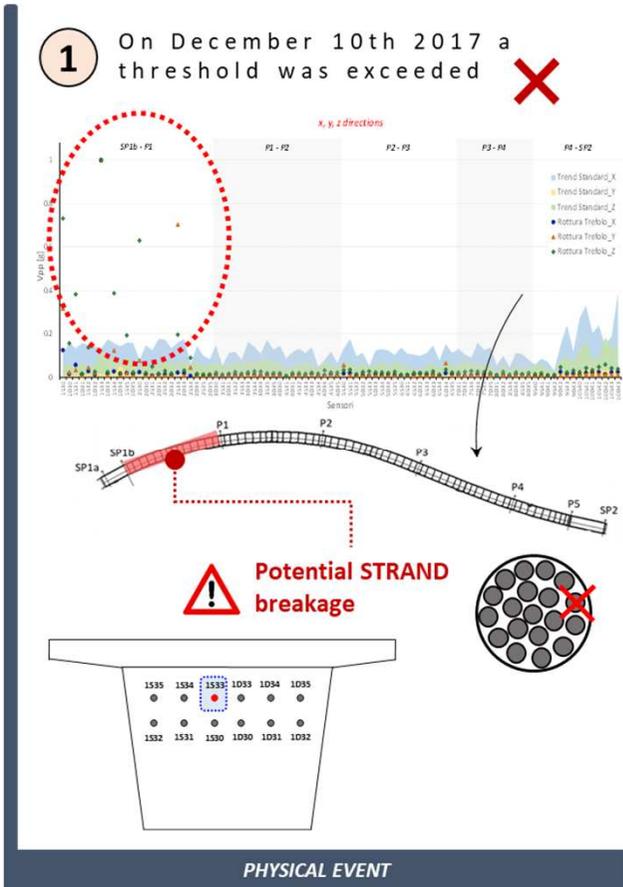
REAL CASE STUDIES – Case 2 | Prestressed concrete deck

③ DESIGN AND INSTALLATION OF MONITORING SYSTEM

SEZ. LONGITUDINALE CAMPATA TIPO

SEZIONE TRASVERSALE A-A CAMPATA TIPO
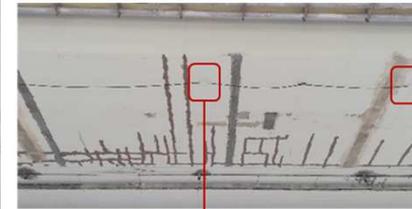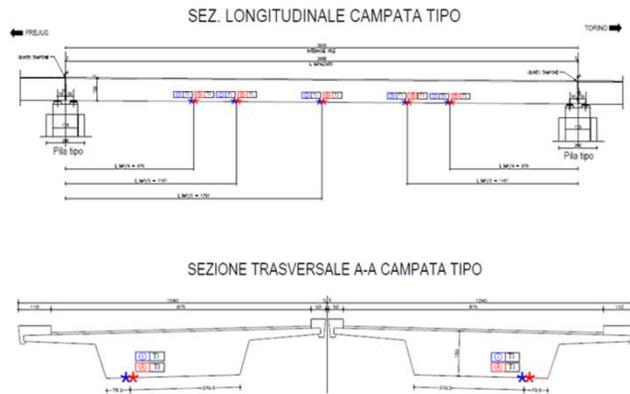
N.5 accelerometers + clinometers per span

④ LOAD TEST ON DAMAGED SPAN
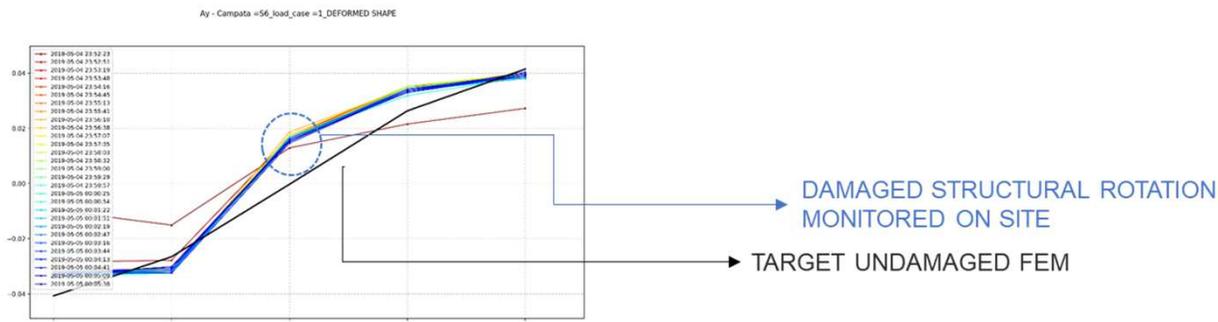
Ay - Campata =S6_load_case =1_DEFORMED SHAPE

DAMAGED STRUCTURAL ROTATION MONITORED ON SITE

TARGET UNDAMAGED FEM

SYNERGY BETWEEN STRUCTURAL ASSESSMENT AND MONITORING

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING **OF LONG-SPAN BRIDGES**

REAL CASE STUDIES – Case 2 | Prestressed concrete deck

③ DAMAGE INSPECTION

Tendons status

Prestressed simply supported slab bridge
Tendons failure
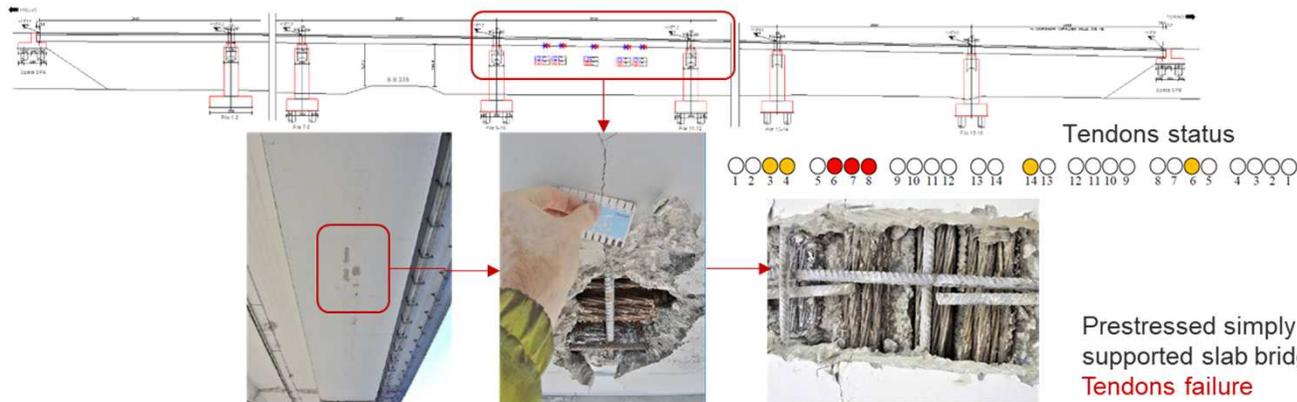
④ STRENGHTENING WORKS DESIGN

Additional external tendons
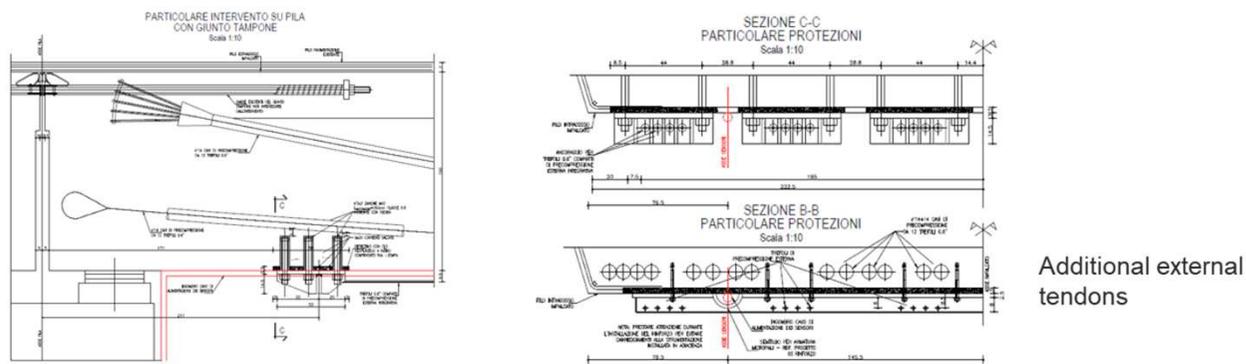
SYNERGY BETWEEN STRUCTURAL ASSESSMENT AND MONITORING

REAL CASE STUDIES – Case 2 | Prestressed concrete deck

REAL CASE STUDIES – Case 3 | Tunnel monitoring

MONITORED CROSS SECTIONS WITH POST-INSTALLED MEMS SENSORS

MONITORED RING: N. 9 MEMS CLINOMETERS
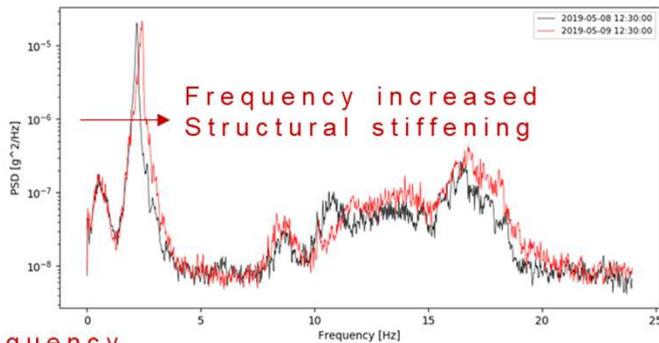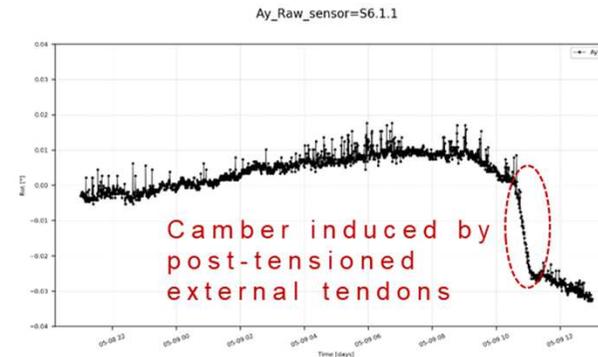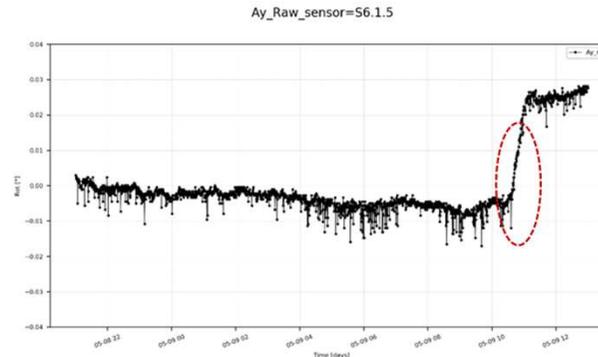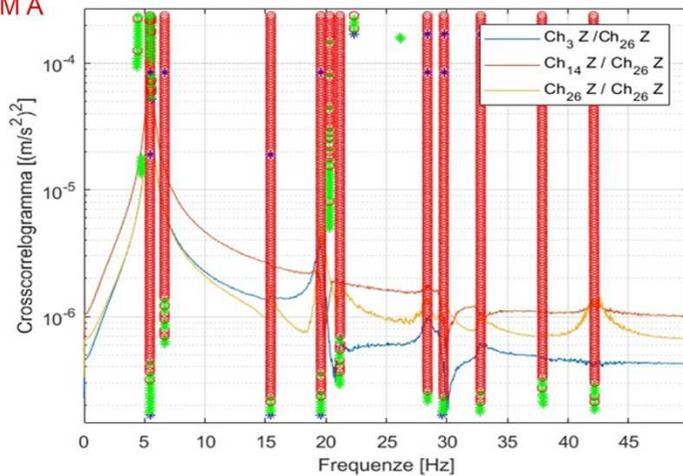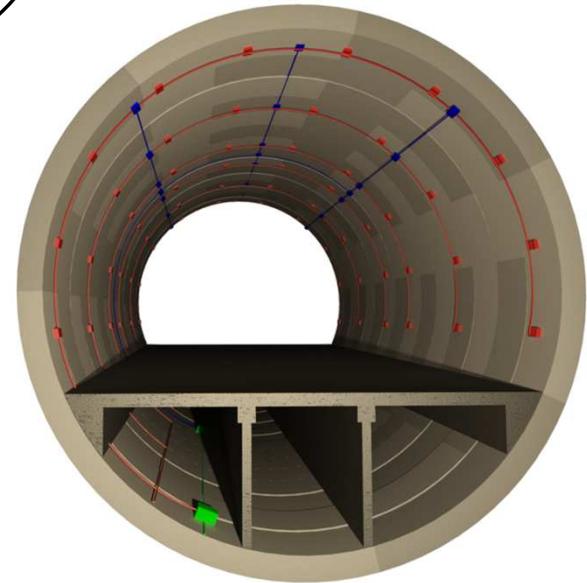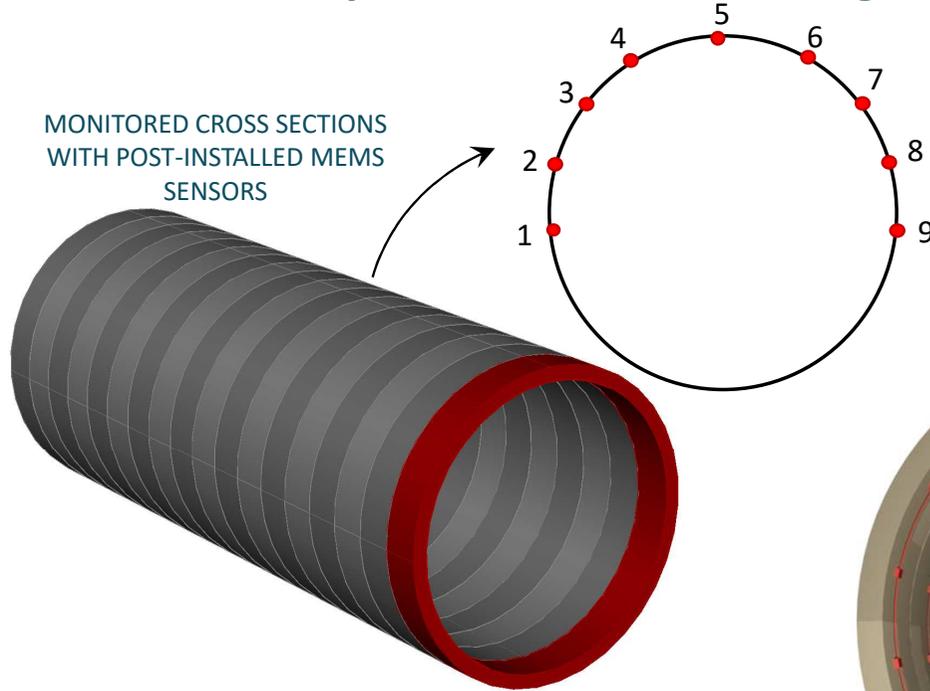
NETWORK OF DENSE SENSING:
- **1500 SENSORS UNDER CONTINUOUS**
- **MONITORING SINCE 2016**
- **160 MONITORED CROSS SECTION**

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING *OF LONG-SPAN BRIDGES*
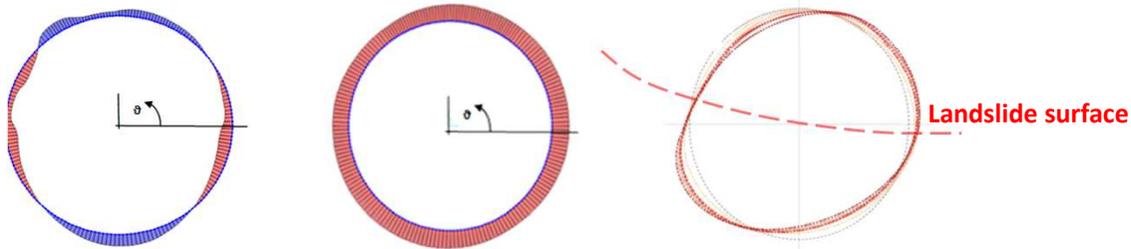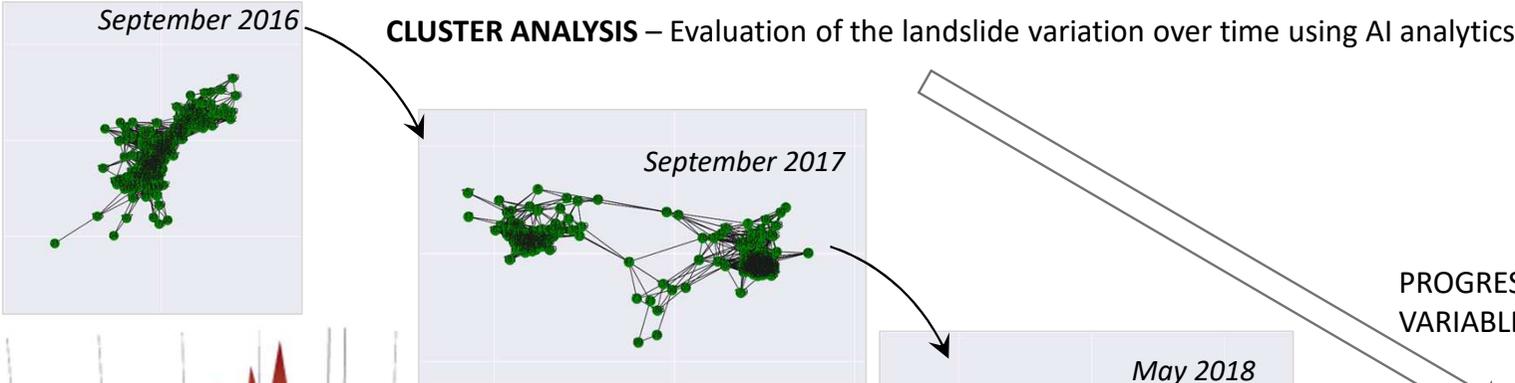
REAL CASE STUDIES – Case 3 | Tunnel monitoring

DATA ACQUISITION
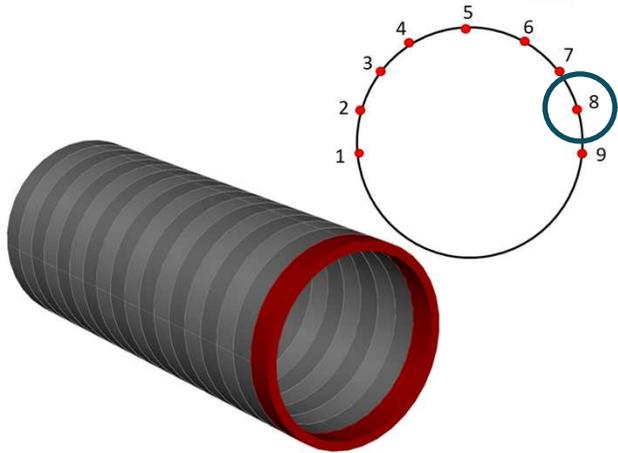
DATA PROCESSING
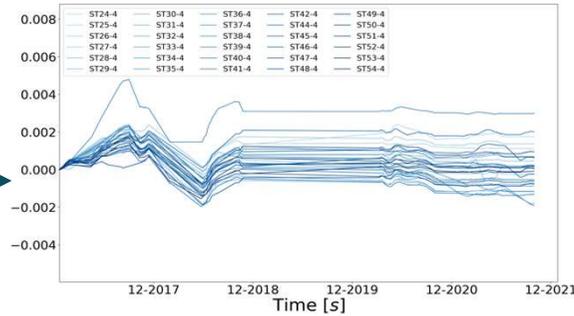
STRUCTURAL ANALYSIS
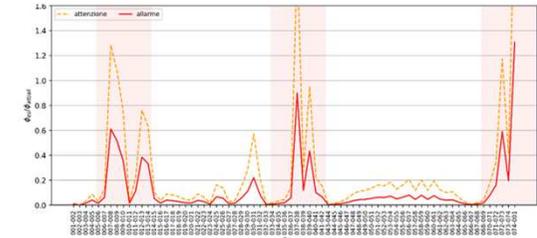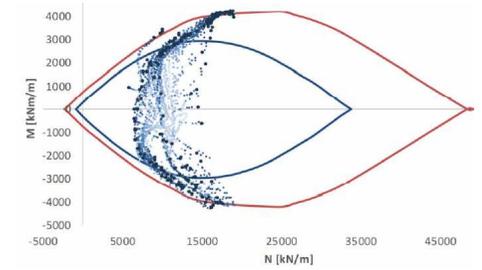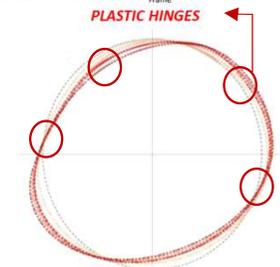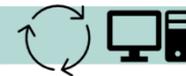
Landslide surface

FEM MODELING

PLASTIC HINGES
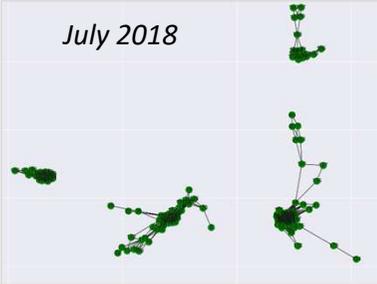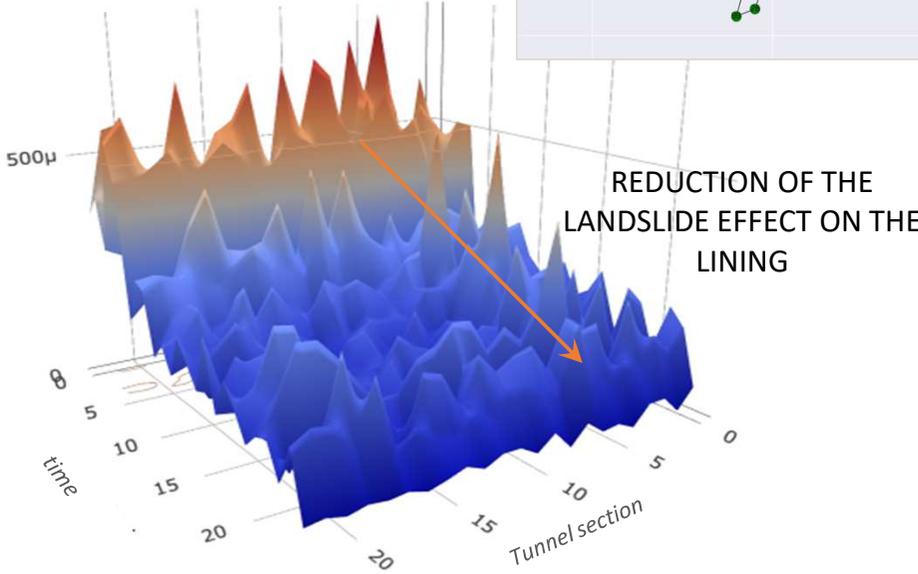
DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING **OF LONG-SPAN BRIDGES**

REAL CASE STUDIES – Case 3 | Tunnel monitoring

September 2016

CLUSTER ANALYSIS – Evaluation of the landslide variation over time using AI analytics

September 2017

PROGRESSIVE CLUSTERING – TIME VARIABLE PHENOMENON

May 2018

REDUCTION OF THE LANDSLIDE EFFECT ON THE LINING

July 2018

Friday 3 December 2021 | Prof. Giuseppe Mancini

DESIGN, CONSTRUCTION, AND STRUCTURAL HEALTH MONITORING OF LONG-SPAN BRIDGES

Q&A session

THANK YOU FOR THE ATTENTION