TECHNICAL UNIVERSITY OF CRETE
SCHOOL OF ARCHITECTURAL ENGINEERING
LABORATORY OF APPLIED MECHANICS

Damage detection in concrete structures using "smart" piezoelectric sensors as concrete's aggregates

PhD Dissertation Defense

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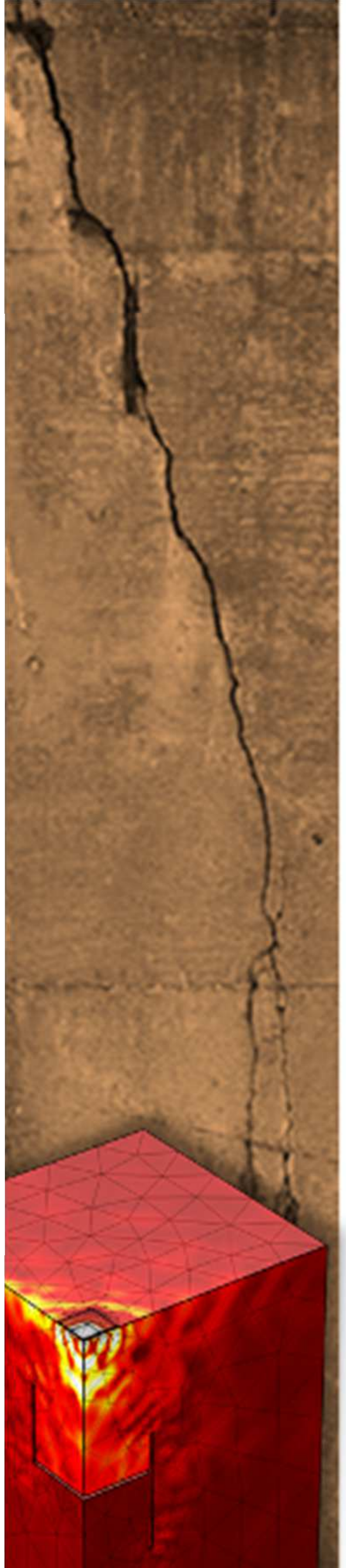

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Papers in Referee Journals

J1. Providakis CP and **Liarakos EV, 2011**. *T-WiEYE: An early-age concrete strength development monitoring and miniaturized wireless impedance sensing system*. Engineering Procedia; **10** 484-89.

J2. Providakis CP, Liarakos EV and **E. Kampianakis, 2013**. *Nondestructive Wireless Monitoring of Early-Age Concrete Strength Gain Using an Innovative Electromechanical Impedance Sensing System*. Smart Materials Research; vol. 2013, doi:10.1155/2013/932568.

J3. Providakis CP and **Liarakos EV, 2014**. *Web-based concrete strengthening monitoring using an innovative electromechanical impedance telemetric system and extreme values statistics*. Struct. Control Health Monit., **vol 21**: 1252–1268. doi: 10.1002/stc.1645.

Papers in Conference Proceedings

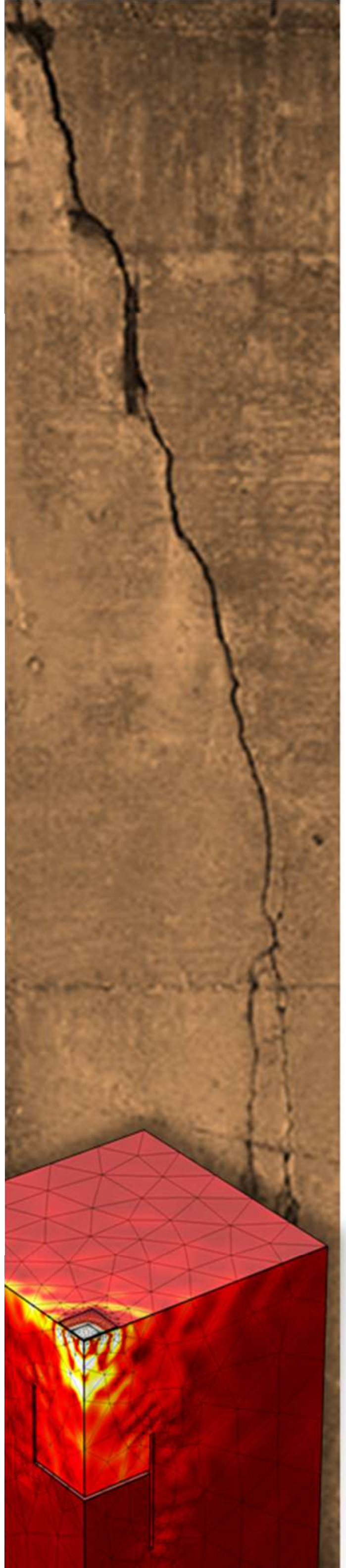
C1. Providakis CP and **Liarakos EV, 2010**. *Early age concrete strength monitoring using embedded smart aggregates as sensors*. Structural Health Monitoring 2010: Proceedings of the Fifth European Workshop; DEStech Publications Inc, July 2010.

C2. Providakis CP, Liarakos EV and **Voutetaki M, 2010**. *Damage detection in concrete components using PZT actuators/sensors and extreme value statistics*.9th HSTAM Congress in Mechanics; Limassol, Cyprus, July 2010.

C3. Providakis CP and **Liarakos EV, 2011**. *T-WiEYE: An early-age concrete strength development monitoring and miniaturized wireless impedance sensing system*. 11th International Conference on the Mechanical Behavior of Materials (ICM2011); Lake Como, Italy, June 2011.

C4. Providakis CP and **Liarakos EV, 2012**. *T-WiEYE early-age concrete monitoring sensor: Computer modeling and simulation*. International Conference on Computational and Experimental Engineering and Science (ICCES' 12); May-June 2012, Crete, Greece.

C5. Liarakos EV and **Providakis CP, 2013**. *A miniaturized early age concrete strengthening and hydration monitoring system based on Piezoelectric transducers*.10th HSTAM Congress on Mechanics. 25-27 May 2013, Crete, Greece.



Presentation Outlines

1. Aims and objectives of dissertation
2. Piezoelectric materials and **E**lectro-**M**echanical **SYS**tems (**EMSYS**)
3. **E**lectro-**M**echanical **I**mpedance method (**EMI**)
4. Structural integrity assessment of concrete structures
5. Integrated wireless system for automatic EMI measurement
6. Applications
7. Conclusions and proposals for future work

1.

Aims and objectives of dissertation

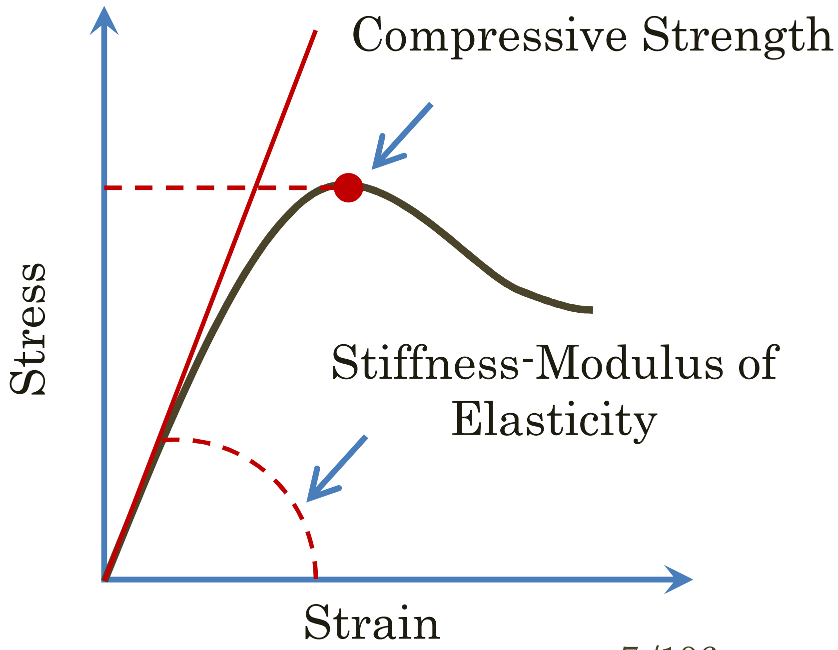
Fundamental definitions

- **Structural Integrity / Structural Health**. The ability of a structure to appear adequate strength to external loading and show compliance with design codes requirements.
- **Structural Properties**.
  - The set of geometric and mechanical properties of a structure (Stiffness, Structural Damping, Mass distribution etc.).
  - The mechanical properties and strength of building materials.
- **Mechanical damage**. Each irregular change of structural properties that affects negatively the global mechanical behavior of the structure and aggravate its structural health.

Structural properties monitoring

- Mechanical properties and strengths of building materials affect crucially both the global mechanical behavior of structures and their response to external loadings.
- Monitoring of mechanical properties is a vital procedure regarding to safety evaluation and total quality control of engineering structures.

Concrete destructive testing (Compression)

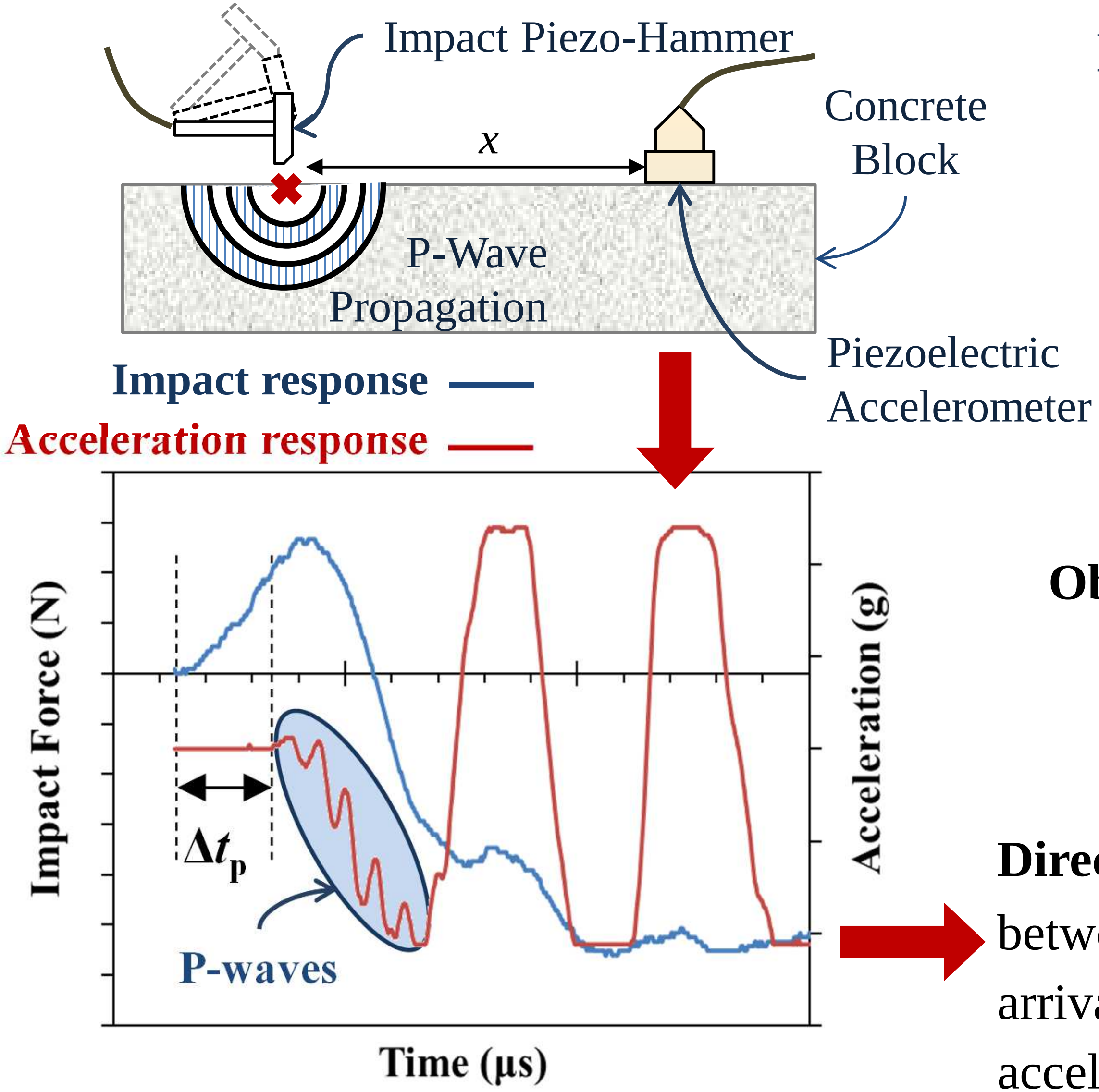


Non Destructive Testing (NDT) of Concrete

- NDT techniques are providing the essential options of:
  - Direct control and evaluation of structures integrity from the early stages of construction and throughout their lifetime.
  - Estimation of concrete's mechanical properties in situ, without need of specimens sampling.
- **NDT fundamental principle: Indirect Determination** (estimation) of mechanical properties (structural properties) based on **Direct Measurement** of a specific physical or mechanical quantity (observation quantity).
  - Structural properties are correlated with observation quantities utilizing either theoretical or statistical/empirical models.

Non Destructive Testing (NDT) of Concrete

➢ Impact-Echo NDT Method



Estimation of concrete's Young Modulus *E* (*f(v)*: Poisson ratio's function and *ρ*: density) .

Theoretical/ Empirical Model: $$E = f(v)\rho V_p^2$$

Observation quantity: P-wave velocity $$V_p = \frac{x}{\Delta t_p}$$

Direct measurement: Time difference Δt_p, between the impact and the first P-wave arrival which is recorded by Piezo-accelerometer.

Non Destructive Testing (NDT) of Early Age and Hardened Concrete

- Monitoring of cement's hydration procedure during the very early stages of concrete curing (age <48 hours).
- Monitoring of early age concrete hardening and strength development, the first 28 days after casting.
- In situ control of hardening level in order to be estimated the suitable time for demolding.
- Detection of changes either in concrete's stiffness or in elastic properties, that could be potentially related with the existence of short or extensive structural damages.

Non Destructive Testing (NDT) of Concrete and Piezoelectric materials

- Piezoelectric materials exhibit the feature of transforming mechanical energy to electrical and vice versa. Implementations in NDT:
  - Dynamic motion sensors, Impact Sensors
  - High frequency vibration actuators (10-400 kHz)
  - Autosensing piezoelectric devices (Both sensing and actuation of mechanical vibrations)
- Monitoring of structural properties changes by observing the alteration of piezoelectric materials electrical response.

Dissertation's Aims

- Development of:
  - Analytical models for the mathematical description of electromechanical **interaction** between PZTs and concrete constructional elements.
  - Analytical methods for the simulation of electrical and mechanical response of **E**lectro-**M**echanical **SYS**tems (**EMSYS**).
  - Reliable set-ups for the safe embedding of PZT based sensors/actuators inside concrete's mass.
  - Statistical control techniques for the evaluation of structure's mechanical integrity.
- Design of an **integrated wireless** system for the NDT of concrete structures, based on **piezoelectric auto-sensing devices**.

Dissertation's Contribution and Novelty

- Regarding to PZT-Concrete electromechanical interaction, in context of present dissertation an innovative analytical model is proposed. This model is based in transmission of **shear (transverse) waves** in concrete mass and is taking into account both the **high stiffness** and the **significant mechanical loss factor** of concrete **[J3]**.
- Simulation of concrete constructional member's mechanical response, by adopting equivalent Multi-Degree Of Freedom (MDOF) dynamic systems **[C2-3,J3]**.
- Development of an **innovative** reusable piezoelectric sensor/actuator, based on a properly designed Teflon (PTFE) casing which combines adequate mechanical strength and high chemical resistance **[J1-2, C3-5].**

Dissertation's Contribution and Novelty

- Development of an integrated system for the measurement of **E**lectro-**M**echanical **I**mpedance (**EMI**), which employs **[J3,C5]**:
  - Piezoelectric Sensors/Actuators (S/A) embedded in concrete mass. After embedding, S/A are mechanically behaving like smart aggregates.
  - Wireless (Wi-Fi) communication among smart aggregates and EMI's measuring equipment.
  - Low cost Printed Circuits Boards (PCB) for the record of smart aggregates electrical response.
  - Permanent in-situ installation.
  - Recording and classification of EMI measurements in a MySQL designed database, for remote access in monitoring data.
  - Post-Processing of EMI data by connecting MySQL workspace with MATLAB environment.

2.

Piezoelectric materials and Electro-Mechanical SYStems (EMSYS)

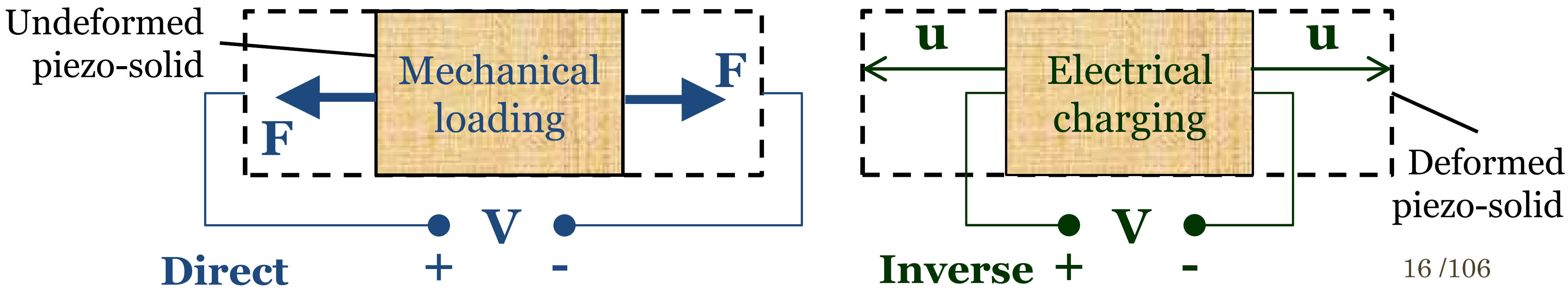
Piezoelectric Materials

- **Direct Piezoelectric Effect.** The application of an external mechanical load on a piezoelectric solid results the generation of an electrical field.

Mechanical energy supplied → Electrical energy stored

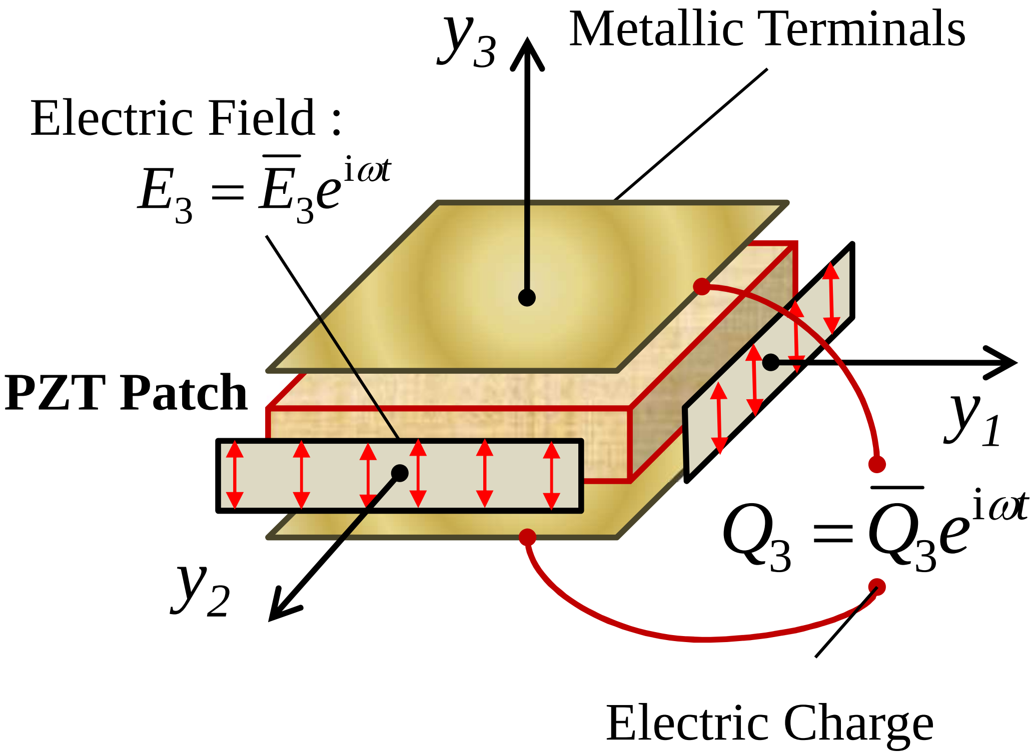
- **Inverse Piezoelectric Effect.** Piezo-materials react to electric voltage stimulation by appearing mechanical deformations.

Mechanical energy stored ← Electrical energy supplied

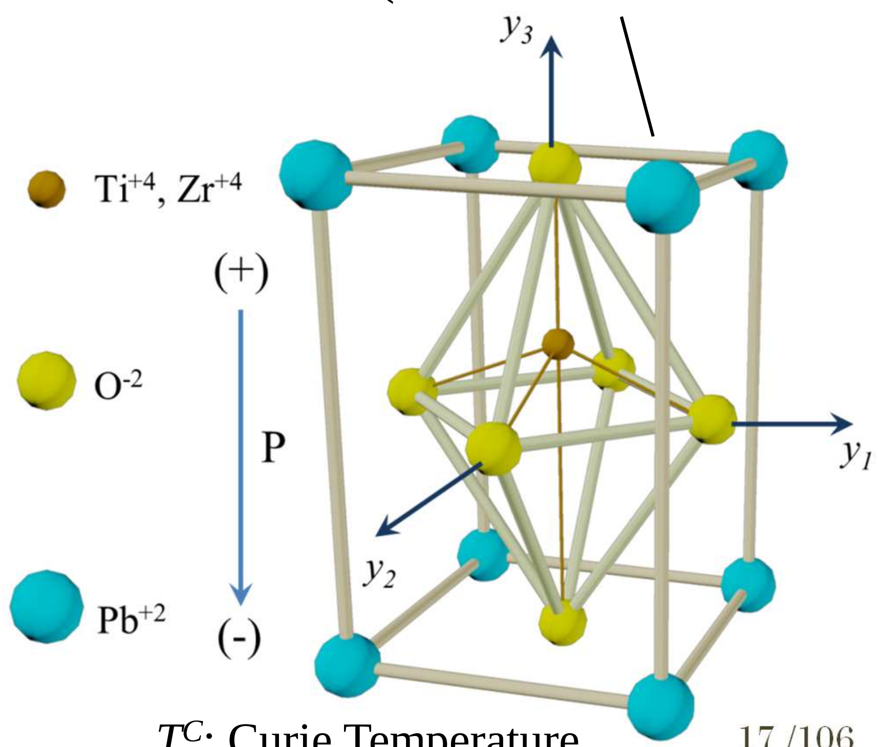


Piezoelectric Materials: Micro-Structure

- Piezoelectric plane patch PZT (Lead Zirconate Titanate)
- Ceramic Core of **Lead and Zirconate/Titanate Oxide crystal Pb(Zr, Ti)O_3**
- Metallic Terminals – Dielectric Element



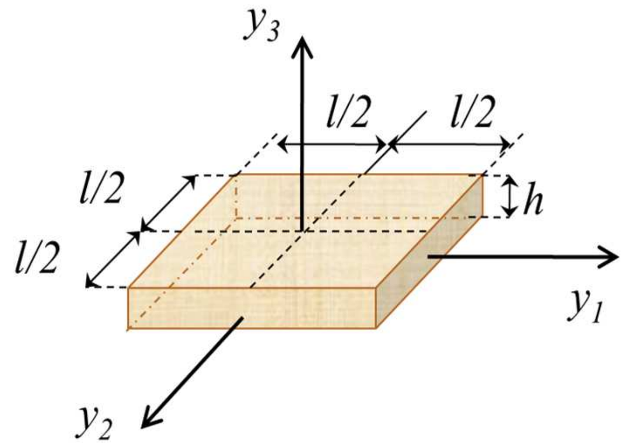
Polarized PZT Crystal (Ferroelectric Phase $T<T^C$)



T^C: Curie Temperature

Piezoelectric Materials: Constitutive equations

- Strain - Charge form equations
- Square PZT patch: **Plane Stress**(1)



$$S_{11} = \frac{1}{\bar{Y}^E}\left(T_{11} - v_{12}T_{22}\right) + d_{31}E_3$$

$$S_{22} = \frac{1}{\bar{Y}^E}\left(T_{22} - v_{12}T_{11}\right) + d_{32}E_3$$

$$D_3 = d_{31}T_{11} + d_{32}T_{22} + \varepsilon_{33}E_3$$

$$\bar{Y}^E = Y^E\left(1 + \mathrm{i}n_{pzt}\right) \quad \bar{\varepsilon}_{33} = \varepsilon_0\varepsilon_{33}\left(1 - \mathrm{i}\delta\right)$$

y_j, j=1:3 : Cartesian Indexes

S_{jj}: Strain Tensor's Component

T_{jj} : Stress Tensor's Component (Pa)

v_{12}: Poisson ratio(1)

Y^E: Young Modulus(1) (Pa)

$d_{31}=d_{32}$: Piezoelectric "*d*" Coefficient(1) (C/N)

D_3: Electrical Displacement (C/m²)

E_3: Electrical Field (V/m)

ε_{33}: Relative Dielectric Permittivity

n_{pzt} : Mechanical Loss Factor

δ: Dielectric Loss Factor

ε_0=8.854e-12 (F/m)

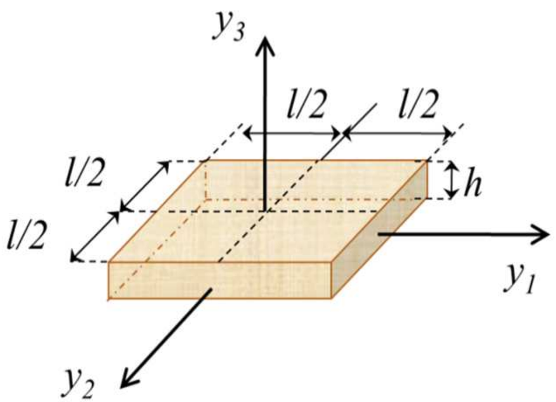
(1) Electric and mechanical transverse isotropy along to y_1-y_2 plane.

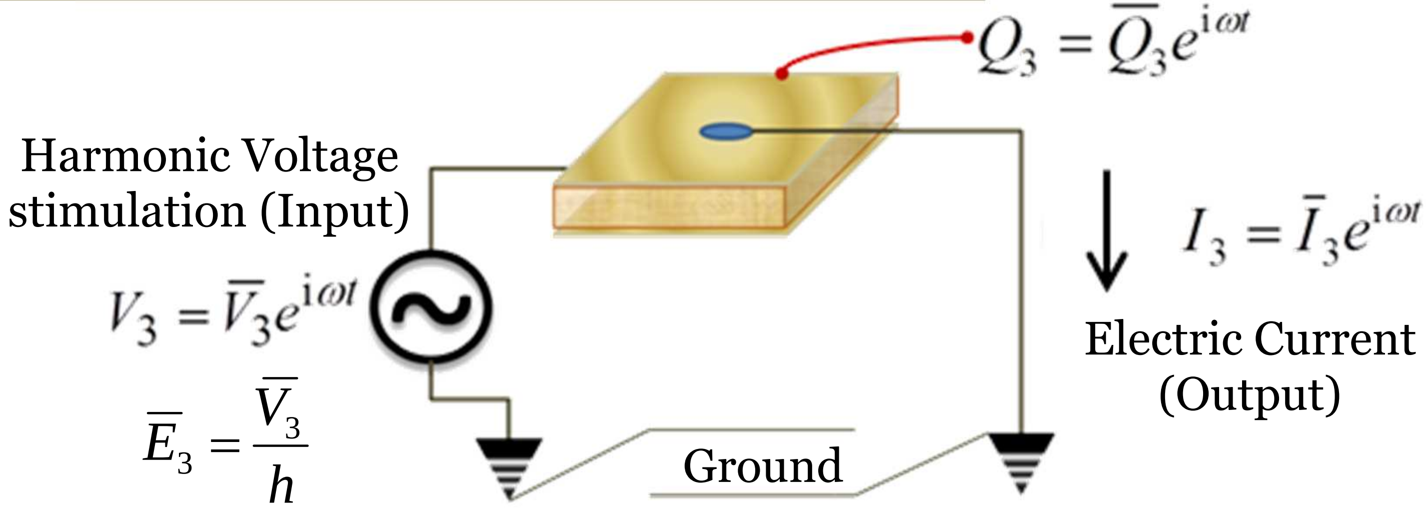
Piezoelectric Materials: Electric Response

- Electric Current, I_3: Harmonic excitation (V_3)

$$I_3 = \frac{dQ_3}{dt} = \mathrm{i}\omega Q_3 \Rightarrow \bar{I}_3 = \mathrm{i}\omega \bar{Q}_3 = \mathrm{i}\omega \int_{A_{pzt}} \bar{D}_3 dA$$

A_{pzt} : Patch plane area





- Electrical Displacement Amplitude:

$$\bar{D}_3 = \frac{d_{31}\bar{Y}^E}{(1-\nu_{12})}\left(\bar{S}_1 + \bar{S}_2\right) + \left[\bar{\varepsilon}_{33} - \frac{2d_{31}^2\bar{Y}^E}{(1-\nu_{12})}\right]\bar{E}_3$$

Electric Impedance / Admittance

- Electric Impedance (Complex quantity):
  - ***R_3*: Resistance** (Real part, Dissipated electric energy)
  - ***X_3*: Reactance** (Imaginary part, Stored electrical energy)

$$Z_3(\omega)=\frac{\overline{V}_3}{\overline{I}_3}=R_3(\omega)+\mathrm{i}X_3(\omega)$$

- Admittance – Inverse quantity of electrical Impedance:
  - ***G_3*: Conductance** (Real part)
  - ***B_3*: Susceptance** (Imaginary Part)

$$Y_3(\omega)=\frac{1}{Z_3}=G_3(\omega)+\mathrm{i}B_3(\omega)$$

Electromechanical response of a PZT patch

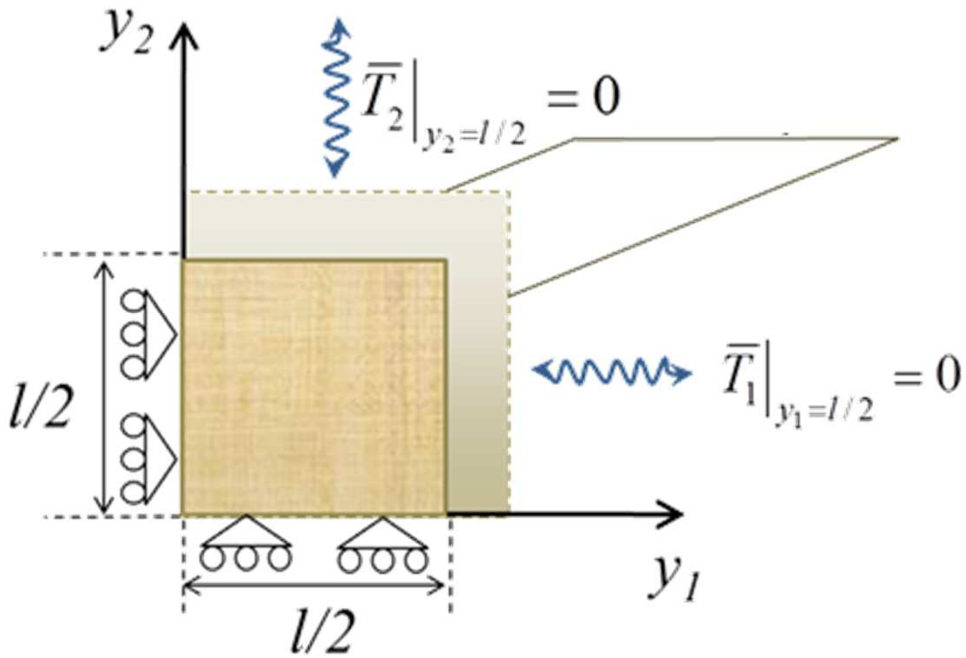
- Admittance, Y_3: Harmonic voltage excitation

$$Y_3^{free} = \mathrm{i}\omega \frac{2l^2 d_{31}^2 \overline{Y}^E}{h(1-\nu_{12})} \frac{\tan(\gamma)}{\gamma} + Y_3^{fix}, \quad Y_3^{fix} = \mathrm{i}\omega \frac{l^2}{h}\left[\overline{\varepsilon}_{33} - \frac{2d_{31}^2 \overline{Y}^E}{(1-\nu_{12})}\right]$$

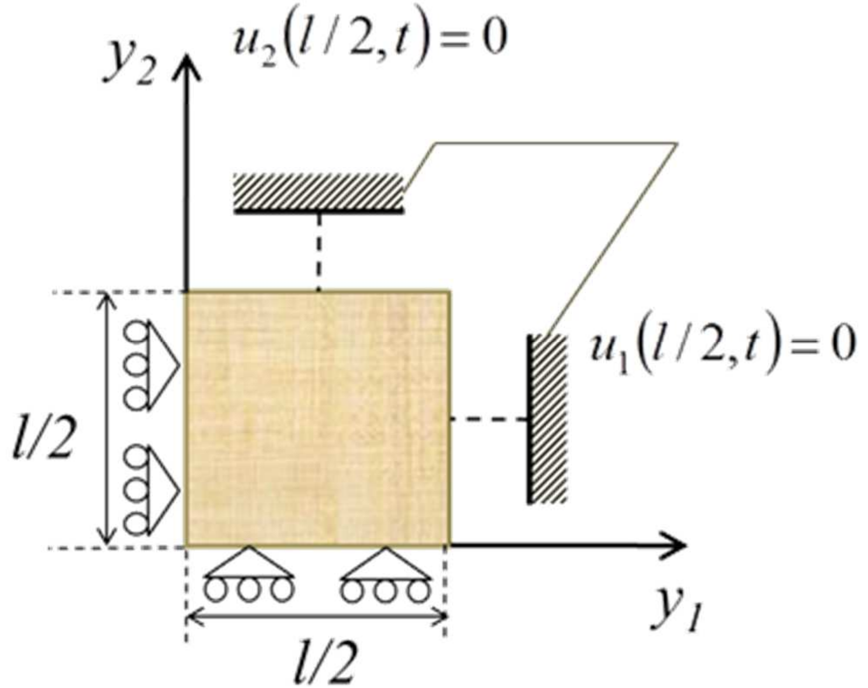
$\gamma = \kappa l/2$

$\kappa = \omega\sqrt{\rho/\overline{Y}^E}$

ρ: Density



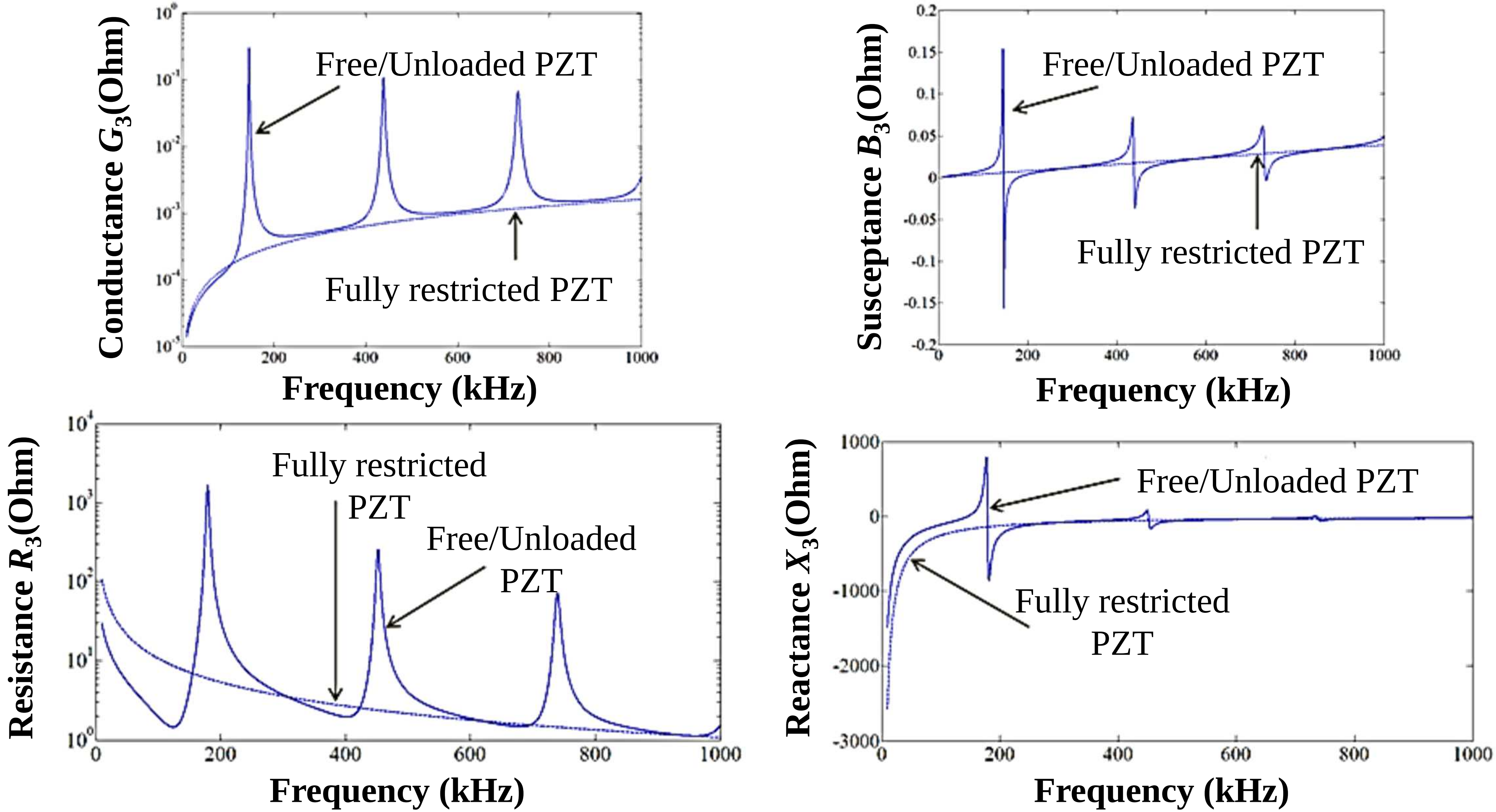
Mechanically free/unloaded PZT (Y_3^{free})



Full restriction of PZT's in-plane displacements (Y_3^{fix})

Electromechanical response of a PZT patch

- PIC 151 [2.1] piezoelectric patch response. Analytical models.



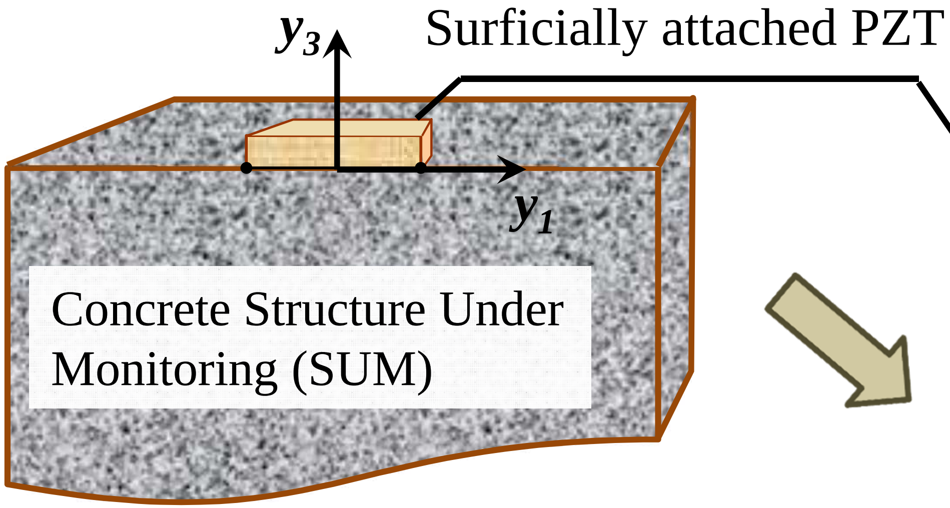
[2.1]. Pi Ceramics, 2014. Piezoelectric Ceramic Products. Fundamentals, Characteristics and Applications.

Piezoelectric Materials and NDT

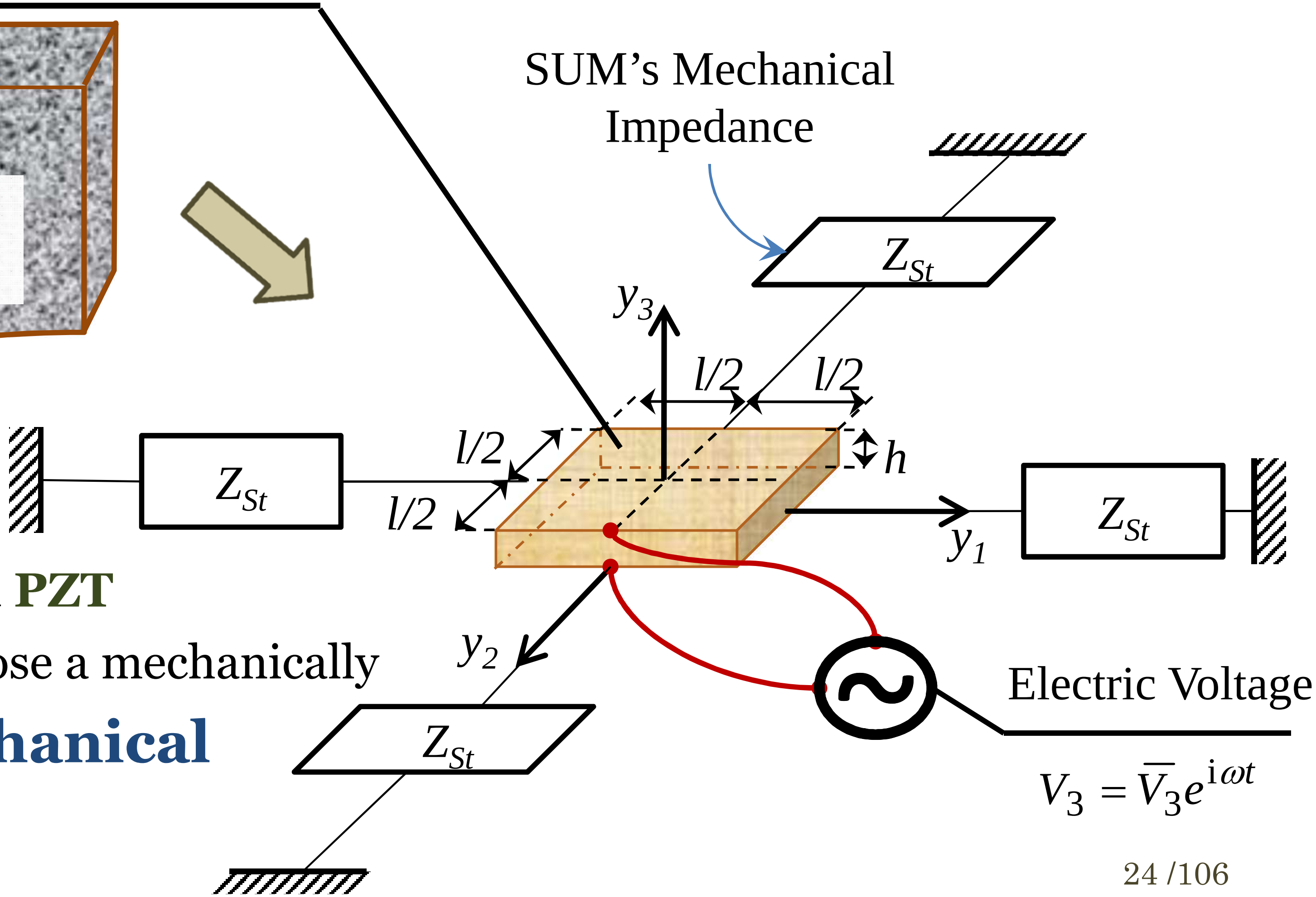
- **Direct Piezoelectric Effect.** Deformation sensors, stress sensors, mechanical vibrations detectors.
  - Observation quantity: **Electric Potential**.
- **Inverse Piezoelectric Effect.** Dynamic motion actuators, harmonic waves generators.
  - Exploited quantity: **Deformation due to electrical stimulation**.
- In PZT based NDT techniques, patches are either surficially attached or embedded in a **Structure Under Monitoring** (**SUM**) and act simultaneously both as **actuators** and **sensors** of dynamic motion (Auto-sensing functionality).

PZT and Concrete structures mechanical coupling

- **From the real structure…**



To equivalent physical model

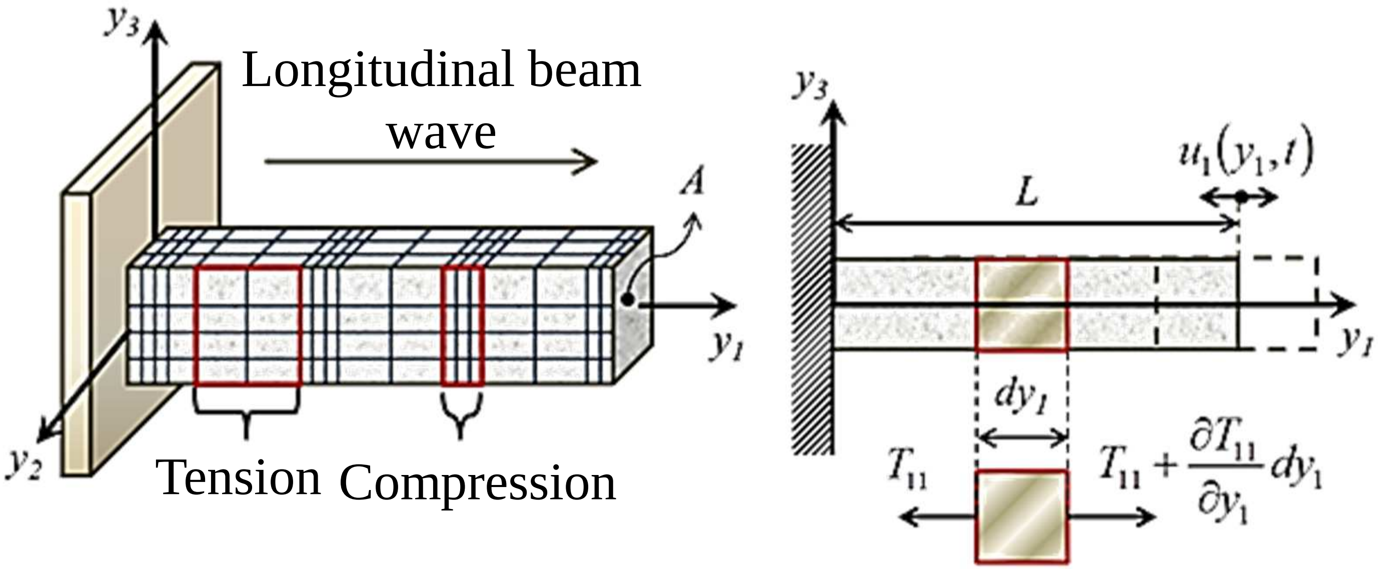


Concrete structure and **PZT sensor/actuator** compose a mechanically coupled **Electro-Mechanical SYStem (EMSYS)**.

PZT and Concrete structures mechanical coupling

- **Dynamic Mechanical Impedance-DMI**

$$Z_{St}(\omega)=\frac{\text{Reaction Force Amplitude}}{\text{Response Velocity Amplitude}}$$



Harmonic Wave:

$$u_1=\underbrace{\overline{U}_1\sin(\kappa_{St}y_1)}_{U_1}e^{i\omega t}$$

$$\kappa_{St}=\omega\sqrt{\rho/\overline{Y}_{St}^{E}}$$

$$T_{11}=\underbrace{\overline{Y}_{St}^{E}\kappa_{St}\overline{U}_1\cos(\kappa_{St}y_1)}_{\overline{T}_{11}}e^{i\omega t}$$

$$Z_{St}(\omega)=\frac{\overline{F}_1\big|_{y_1=L}}{i\omega U_1\big|_{y_1=L}}=\frac{\overline{T}_{11}\big|_{y_1=L}A}{i\omega U_1\big|_{y_1=L}}=\frac{\overline{K}_{St}}{i\omega}\frac{\kappa_{St}L}{\tan(\kappa_{St}L)},\quad \underbrace{\overline{K}_{St}=\overline{Y}_{St}^{E}A/L}_{\text{Static Stiffness}}$$

A: Beam section area

PZT and Concrete structures mechanical coupling

- **Electro-Mechanical Admittance (EMA)**

$$Y_3 = i\omega \frac{l^2}{h} \frac{2d_{31}^2 \overline{Y}^E}{(1-v_{12})} \left(\frac{Z_\alpha}{Z_a + Z_{St}} \right) \frac{\tan(a_l \gamma)}{a_l \gamma} + Y_3^{fix}$$

Z_a: PZT's Mechanical Impedance

$$Z_a = \frac{2\overline{Y}^E h}{i\omega(1-v_{12})} \frac{a_l \gamma}{\tan(a_l \gamma)}$$

- **a_l: Bonding Stiffness Coefficient (BSC).** BSC is a dimensionless quantity which varies between 0 and 1.
  - BSC is introduced in context of present dissertation, to express the direct restriction of any available PZT deformation, resulted from its bonding on a much stiffer SUM.
  - Near-zero values correspond to a structure with very high stiffness. In this case PZT admittance's response peaks is strongly smoothed after the attachment.
  - The case a_l=1 represent the free/unloaded PZT patch.

PZT and Concrete structures mechanical coupling

- **Electro-Mechanical Admittance (EMA) and concrete structures**

Concrete's constructional elements, usually exhibit much higher stiffness than PZT patches.

$\alpha_l \rightarrow 0$

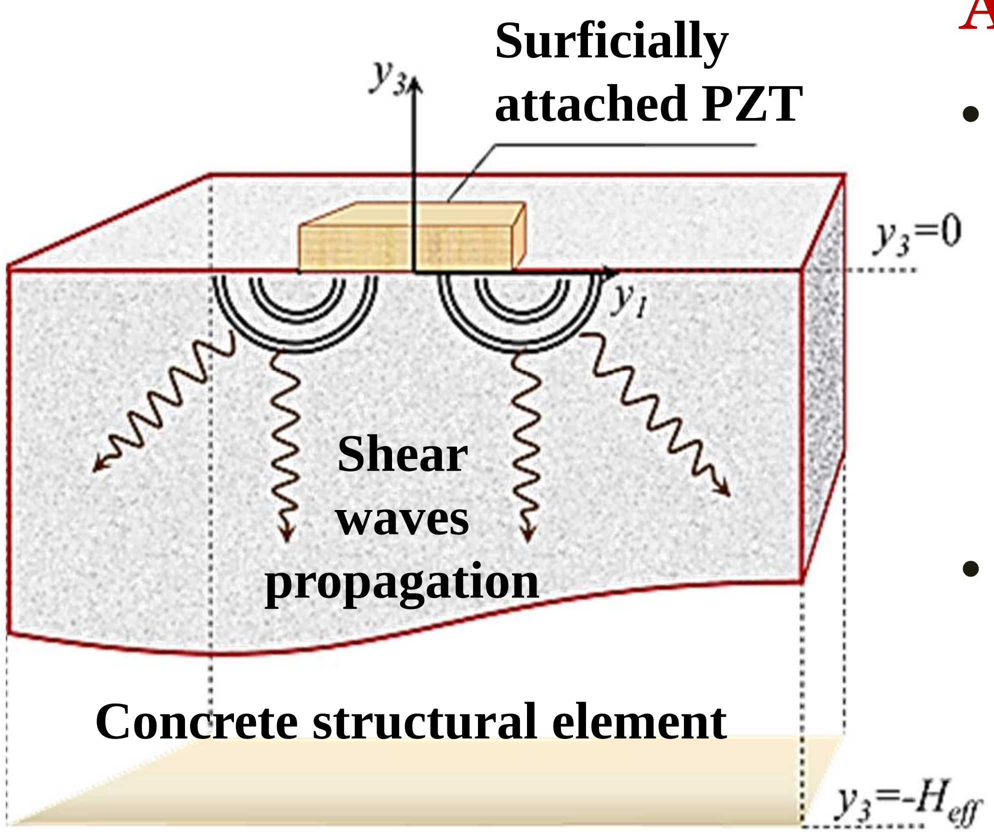
$\tan(\alpha_l \gamma)/\alpha_l \gamma \rightarrow 1$

$$Y_3 = i\omega \frac{l^2}{h} \frac{2 d_{31}^2 \overline{Y}^E}{(1 - \nu_{12})} \left(\frac{Z_\alpha}{Z_a + Z_{St}} \right) + Y_3^{fix}, \quad Z_a = \frac{2 \overline{Y}^E h}{i\omega (1 - \nu_{12})}$$

PZT and Concrete structures mechanical coupling

Concrete's structural elements mechanical impedance

➢ **Shear Mechanical Impedance*** **(SMI)** model **[J3]**:



Assumptions:

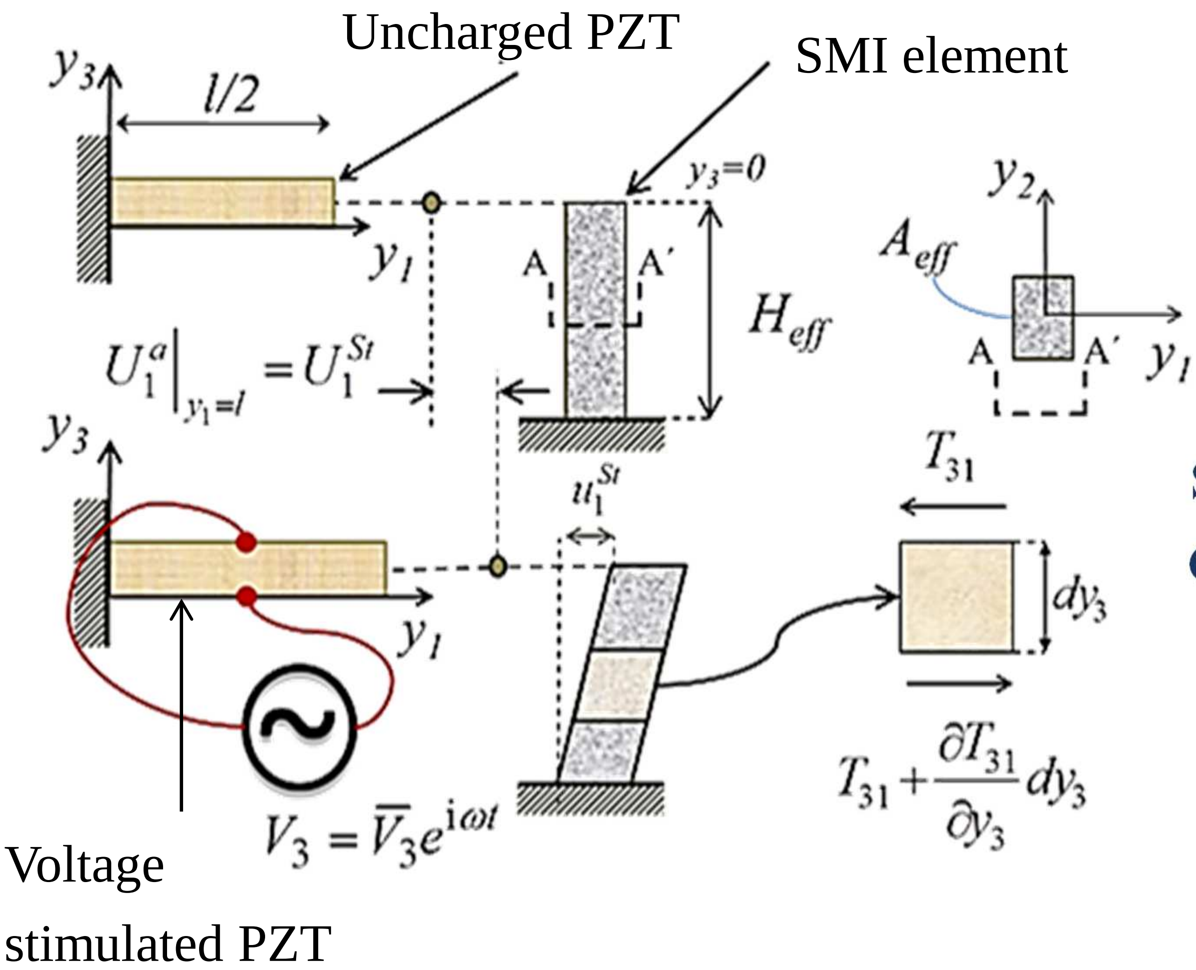
- The mechanical energy which is generated from a voltage excited PZT, is transmitted in concrete element's interior in form of **shear** (**transverse**) **waves**.
- In a **critical depth**, equal to H_{eff}, from PZT-Structure interface, the internal displacement is zeroed, due to **high mechanical loss factor** of concrete (n_{st}).

(*): PhD novelty issue

PZT and Concrete structures mechanical coupling

Concrete's structural elements mechanical impedance

- **Shear Mechanical Impedance [J3]:** **Harmonic excitation**



$$Z_{st} = \frac{\bar{T}_{31}\big|_{y_3=0} A_{eff}}{i\omega U_1^{St}\big|_{y_3=0}} = \frac{\bar{K}_{St}}{i\omega} \frac{\kappa_s H_{eff}}{\tan\left(\kappa_s H_{eff}\right)}$$

Static stiffness: $\bar{K}_{St} = A_{eff} \bar{G}_{St} / H_{eff}$

Complex Shear modulus: $\bar{G}_{St} = G_{St}\left(1 + i n_{St}\right)$

$$\kappa_s = \omega \sqrt{\rho / \bar{G}_{St}}$$

PZT and Concrete structures mechanical coupling

Concrete's structural elements mechanical impedance

➢ Shear Mechanical Impedance (SMI):

- The proposed analytical model is approaching the mechanical response of concrete structural elements by defining an equivalent Single Degree Of Freedom (SDOF) and continuous shear element.
- SMI's mathematical expression is approving the strong physical correlation among the **mechanical response** of a structure, the **geometric features** of constructional elements (H_{eff}) and the **mechanical properties** of building materials (n_{St}, G_{St}).
- Expanding SMI model's philosophy, in context of present dissertation, a **novelty method of structural impedance simulation** is developed based on Multi-Degree Of Freedom (MDOF) dynamic systems which are consisted of a specific number of SMI components in parallel set-up.

3.

Electro-Mechanical Impedance method (EMI)

Fundamental implementation issues

- EMI method is one the most widespread techniques regarding to PZT based non-destructive evaluation of engineering structures **[J1]**.
- PZT patches are surficially bonded **[C2]** or embedded **[J1-3, C1]** to concrete constructional members and via a time-depended voltage excitation force SUMs to vibration mode.
- EMI method's main observation tool is the electrical impedance response spectrum (frequency domain analysis) $\boldsymbol{Z_3(\omega)}$, which is obtained from bonded/embedded PZTs electrical response.
- In cases of engineering structures monitoring, EMI spectra frequency range varies from **10** to **400 kHz** **[J1]**.

Fundamental implementation issues

- EMI method's applications usually are exploiting PZT patches both as mechanical vibration actuators (Inverse Piezo-Effect) and as dynamic motion response sensors (Direct Piezo-effect).
- EMI's spectra of bonded PZTs can be termed as the electromechanical signatures of a SUM.
- EMI signatures are unique for each structure and reflecting their specific dynamic features.

Integrated RLC -Meter

Excitation Electric voltage, V_3 (Input)

Inverse

Direct

Response electrical current, I_3 (Output)

PZT

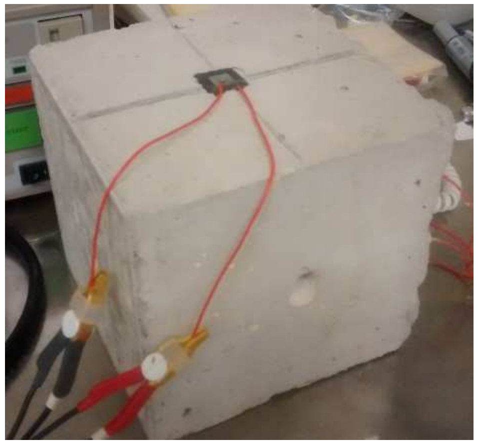
Mechanical strain

Inverse

Direct

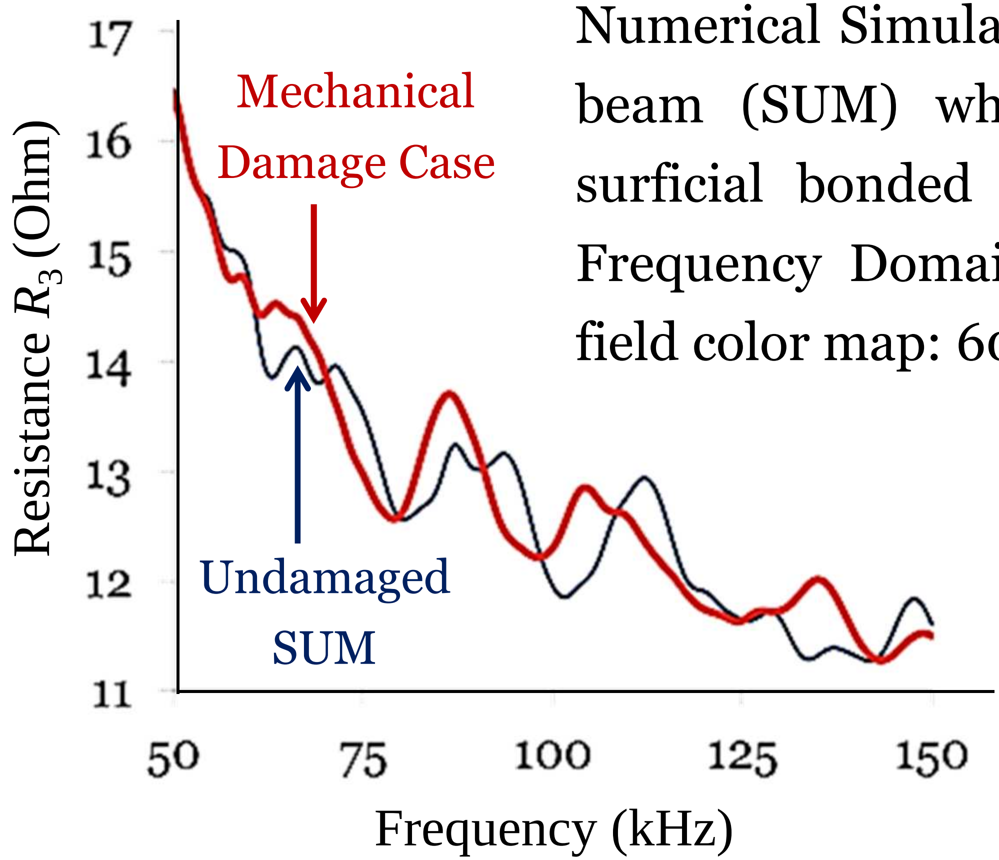
Response mechanical stress

Concrete SUM

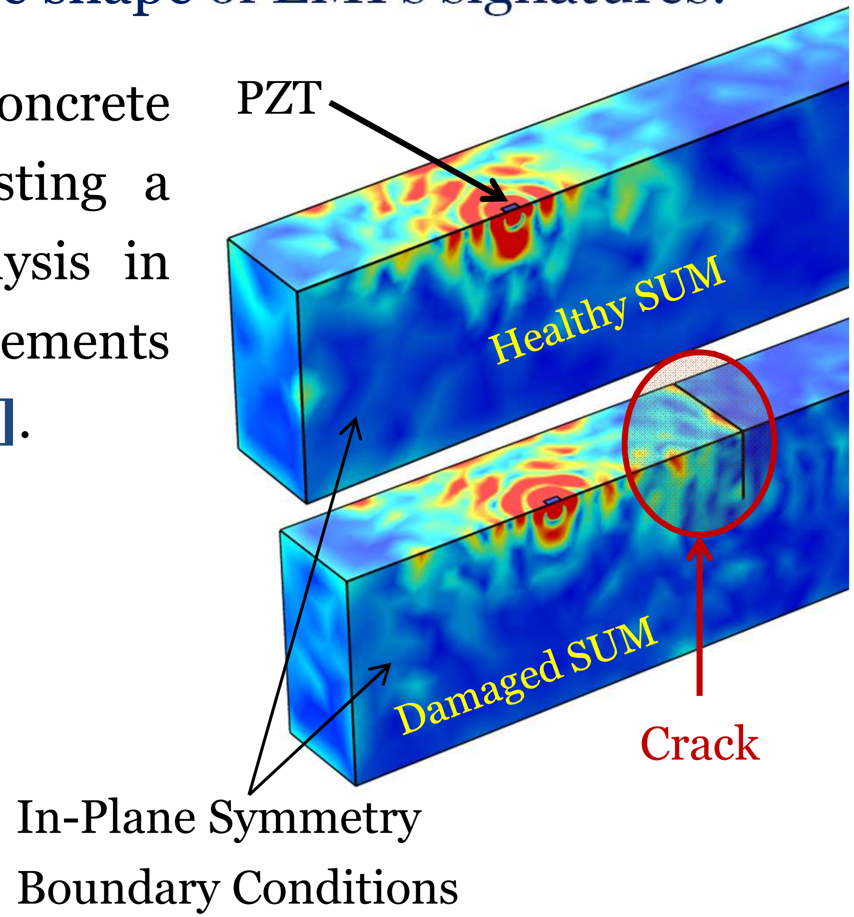


Fundamental implementation issues

Each irregular change in SUM's structural properties that has emerged either from a damage existence or from an alteration in material's mechanical properties, will affect directly the shape of EMI's signatures.



Numerical Simulation of a concrete beam (SUM) which is hosting a surficial bonded PZT. Analysis in Frequency Domain. Displacements field color map: 60 kHz. **[C2]**.



Measuring EMI: Set-ups, Equipment

- Integrated multifunctional RLC-Meters (Impedance Analyzers)
  - High accuracy and broad range of sweeping frequencies (1kHz-5MHz).
  - Significant cost | **Drawback regarding to permanent installation**
  - Restricted portability | **Drawback regarding to structure's in-situ control**
- Simple and custom electronic set-up for EMI measuring
  - Efficient measuring of EMI in narrow frequencies range
  - Low cost measuring circuits based on resistors/capacitors components
  - Low cost Printed Circuits Boards (PCB) which are based on integrated impedance converters

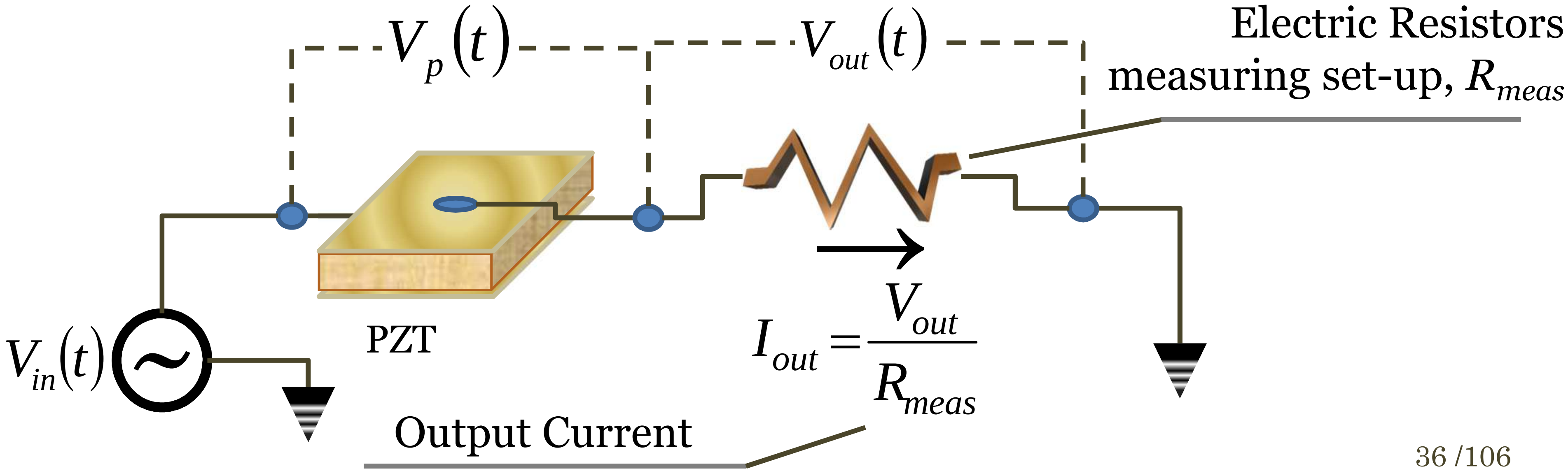
Measuring EMI: Principles

V_{in} and V_{out} data acquisition in time domain applying a sample rate equal to F_s=1/dt.

Discrete Fourier Transform (DFT)

Fourier spectra calculation: FV_{in} and FV_{out}

$$Z_3 = \frac{\bar{V}_p}{\bar{I}_{out}} = R_{meas}\frac{FV_{in} - FV_{out}}{FV_{out}}$$

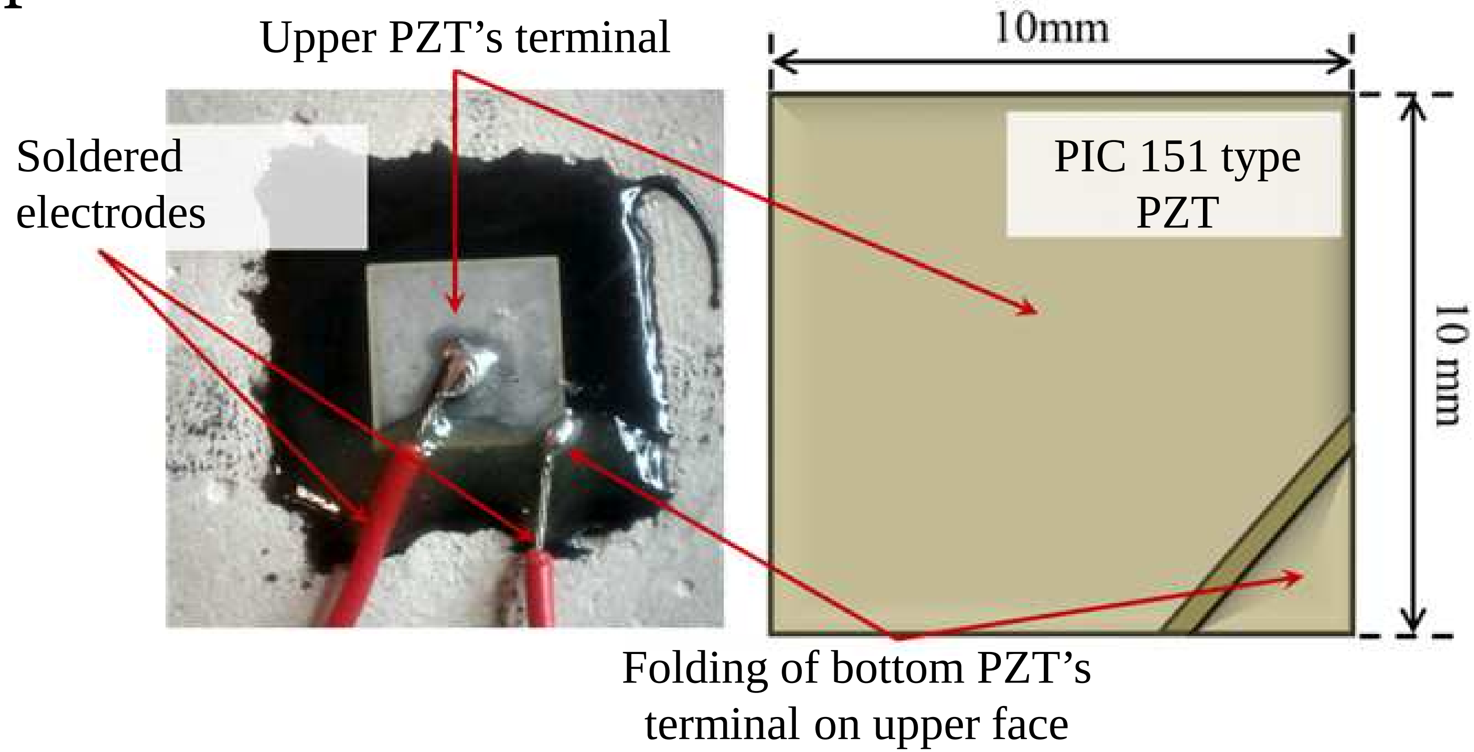


Measuring EMI: Excitation voltage functions V_{in}

- Sweeping frequency range: [$freq_{start}$, $freq_{end}$]
- **Single-Harmonic Functions.** Discrete single-sine signals of determinate excitation frequency and duration.
- **Multi-Harmonic Functions.** Continuous excitation for a specific time window (t_{sweep}).
  - **Multi-Sine Functions**. Sum of single-sine functions of scalar increasing frequencies which are varying between an initial and a final scanning frequency ($\boldsymbol{freq_{start}}$ and $\boldsymbol{freq_{end}}$ respectively).
  - **Chirp Signals.** Trigonometric functions of time-dependent excitation frequency.

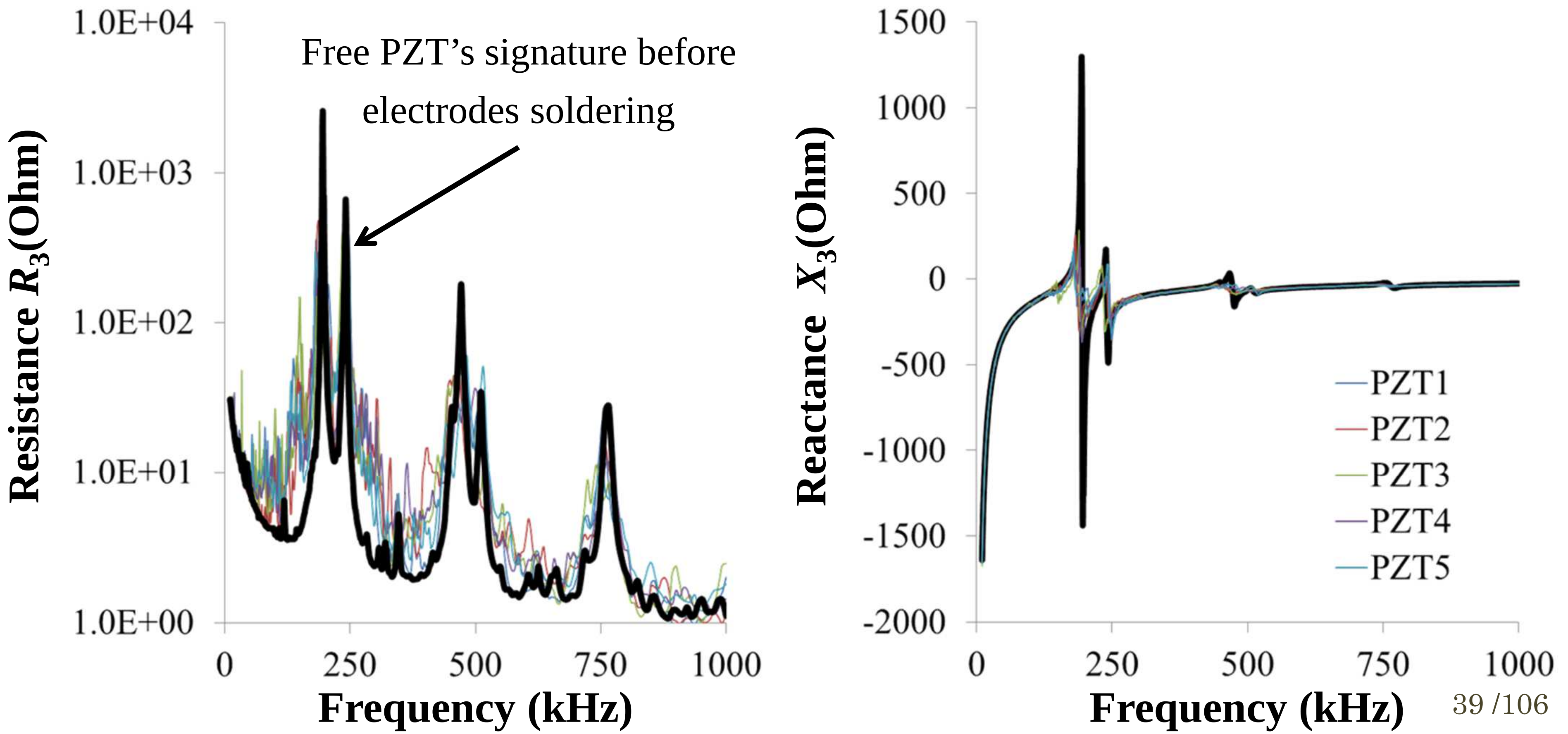
Measuring EMI: Wiring PZT's terminals

- Free/Unloaded PZT patch. Type: **PIC 151**.
- Thermal soldering of electrodes on PZT's terminals using a Tin(Sn)-based alloy.
- Soldering temperature **must not overcomes** the Curie temperature.



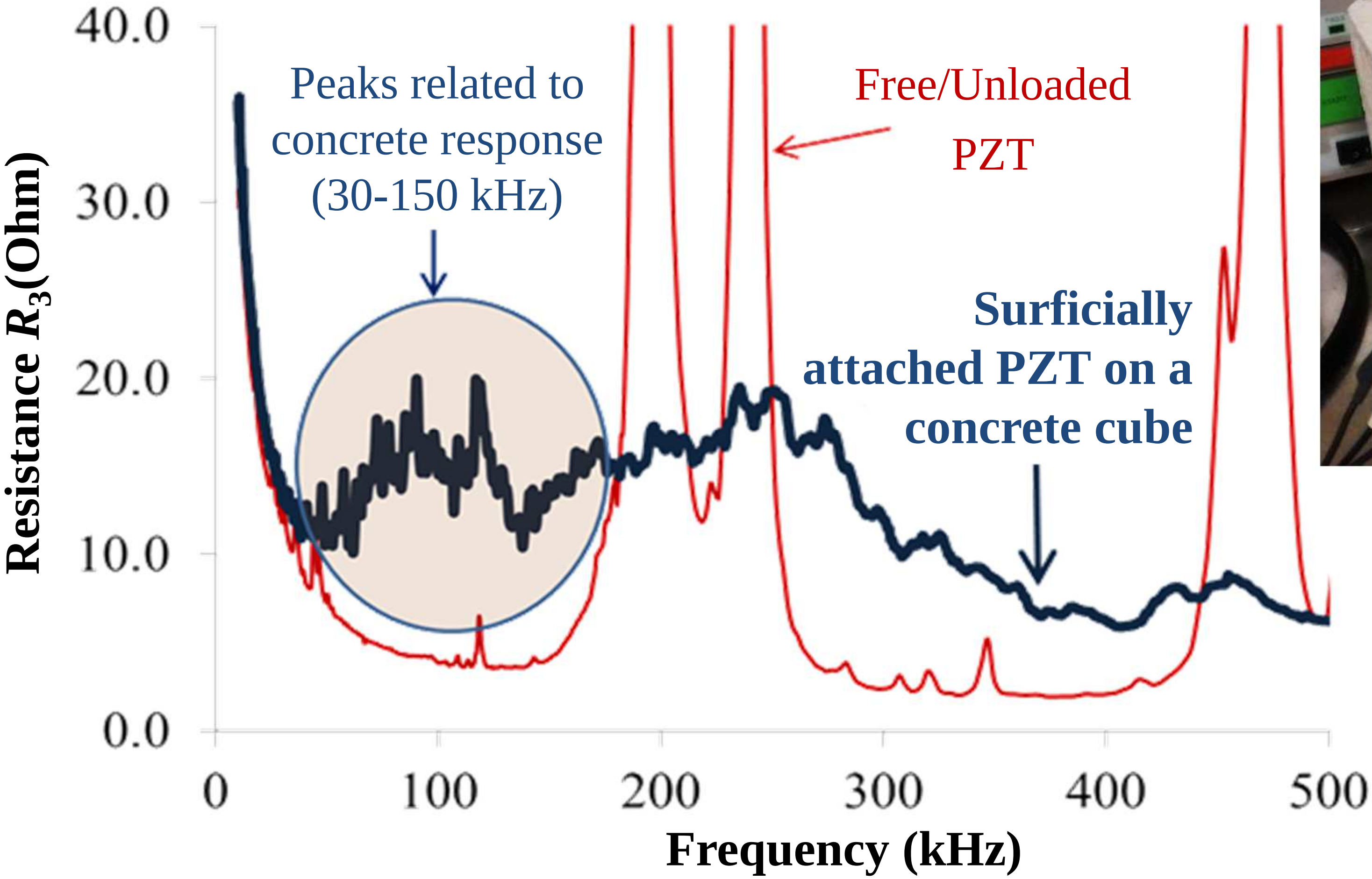
Measuring EMI: Multifunctional integrated RLC-meter

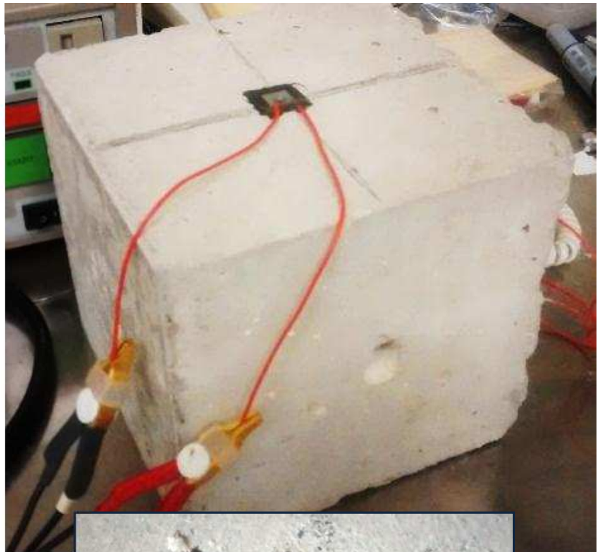
- Free/Unloaded PZT patch. Type: **PIC 151**.
- Sweeping frequencies range 10-1000 kHz, 5 Different PZTs.



Measuring EMI: Multifunctional integrated RLC-meter

- EMI signature of a PZT, bonded on a concrete cubic specimen (Edge length 150 mm).





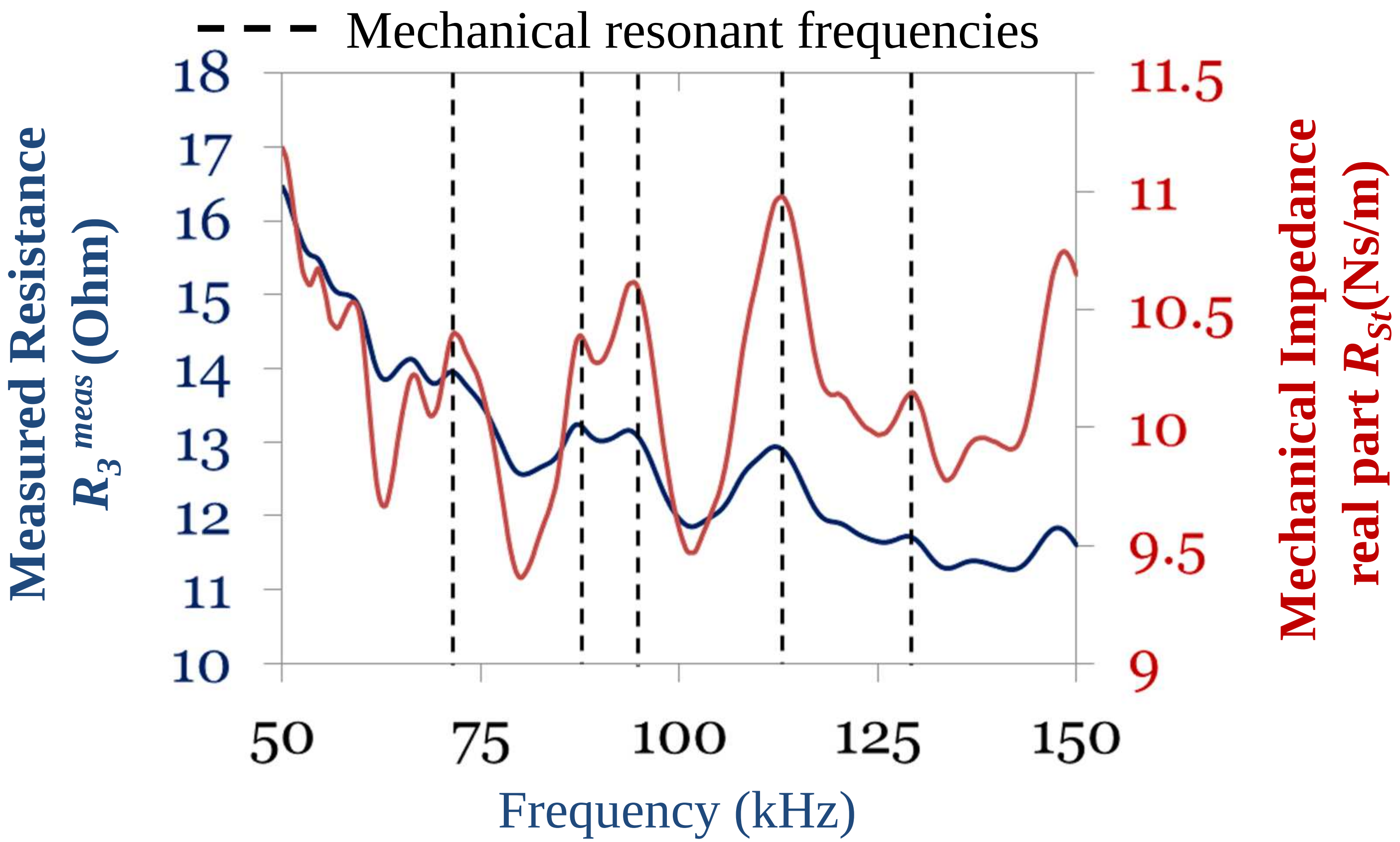
Semi-experimental calculation of mechanical impedance $Z_{St,}$ of a SUM.

- Structure's mechanical impedance signature $Z_{St}(\omega)$, can be calculated from the following equation, taking into consideration:
  - The electromechanical properties of PZT
  - The experimental obtained signature of EMI, Z_3^{meas}.

$$Z_{St} = Z_{\alpha}\left\{ i\omega \frac{l^2}{h} \frac{2d_{31}^2 \overline{Y}^E}{(1-v_{12})\left(\dfrac{1}{Z_3^{meas}} - Y_3^{fix}\right)} - 1 \right\}, \quad Z_a = \frac{2\overline{Y}^E h}{i\omega(1-v_{12})}$$

Semi-experimental calculation of mechanical impedance Z_{St}, of a SUM.

Mechanical impedance signatures $Z_{St}(\omega)$, in several monitoring cases **uncovers** and **amplifies** additional information regarding to SUM's dynamic features.



4.

Structural integrity assessment of concrete structures

Comparative analysis of EMI signatures

Evaluation of structures integrity via **Electro-Mechanical Impedance** (**EMI**) method:

- Based on the acquisition and interpretation of electrical ($\boldsymbol{Z_3}$) or mechanical ($\boldsymbol{Z_{St}}$) impedance signatures (frequency domain), and especially on their real parts $\boldsymbol{R_3}$ and $\boldsymbol{R_{St}}$ **[J2]**.
- It is a procedure of comparative analysis among a **Reference Signature** (***RS***) that represent the response of undamaged (healthy) structure and every other signature which is referred to **current (Current Signature - *CS*)** integrity condition of the structure.

Comparative analysis of EMI signatures

Reference Signatures (*RS*) are expressing:

- In proceedings of structural health monitoring, **the dynamic response of undamaged structures**.
- In proceedings of early age concrete hardening monitoring, **the dynamic response of a structure with specific mechanical characteristics, which is taken arbitrary as reference state.**

RS is determined,

- **Experimentally.** Measuring of electrical response.

Response spectrum RS^{meas}: F measuring points (ω_i, $Z_{3,i}^{meas}$), i=1:F.

- **Approximately.** Simulation of EMSYS electrical response.

$Z_{3,i}^{meas} \approx Z_3^{est}$ (ω_i, $\mathbf{p}$), i=1:F, $\mathbf{p}$: Model's parameters vector.

Statistical Damage indexes

- Statistical quantities based on cumulative variance between the reference signature (**RS**) and every current signature (**CS**).
- **Root Mean Square Deviation** - *RMSD*

$$RMSD(\%) = 100 \times \sqrt{\frac{\sum_{i=1}^{F}(CS_i - RS_i)^2}{\sum_{i=1}^{F} RS_i^2}}$$

Continuous range of angular frequencies.

$$\omega_i = \omega_{\min} + \frac{i-1}{F-1}(\omega_{\max} - \omega_{\min})$$

i*=1:*F, ***F*** : Length of signatures vector.

RS$_i$ and ***CS***$_i$, *i*-th value of each spectrum. Corresponding to angular frequency ω_i.

Statistical Damage indices

Advantages

- Widespread application in EMI based non-destructive evaluation procedures
- Low mathematical complexity
- High level of reliability in cases of early age concrete monitoring procedures **[J2]**

Disadvantages

- Limited detection ability of signatures changes which are located in **short parts** of scanning frequency range and reflect serious damages.
- No confidence limits determination for the **acceptable** changes among consecutive measurements of reference state's signatures.

Statistical Control

Aim: Avoid errors in the evaluation of concrete structural integrity.

- **Type I error:** False detection of a mechanical damage that does not exists (Wrong alarm).
- **Type II error:** Fail of detection of an existing mechanical damage (Damage diagnosis failure).

➢ Definition of a **magnitude** which expresses the range of signatures alteration and it is based on the simulation of undamaged structure's response in frequency domain.

➢ Determination of **confidence limits** regarding to the acceptable changes among EMI's signatures that correspond to undamaged structure.

Statistical Control: Methodology

- Simulation of **measured** reference signatures RS^{meas}, via an **estimation mathematical model, RS^{est}**.
  - Non linear regression of RS^{meas}. Rational polynomials of angular frequency ω, with complex parameters.
  - Mathematical models that derived from the approximation of real structure with equivalent semi-discrete dynamic systems.
- Calculation of **residuals r (signatures changes magnitude)**, between estimated reference signature RS^{est} and each measured current state signature CS^{meas}.

$$r = CS^{meas} - RS^{est}$$

Statistical Control: Methodology

- **Evaluation of signatures changes:** Number of outliers N_{out}, regarding to the confidence limits of **residuals, *r***.
- **Residuals** confidence limits are approximated from the statistical analysis of **reference residuals r_o**, taking into consideration a specific level of **certainty**.
  - Normal distribution
  - Generalized Extreme Values distribution – GEV

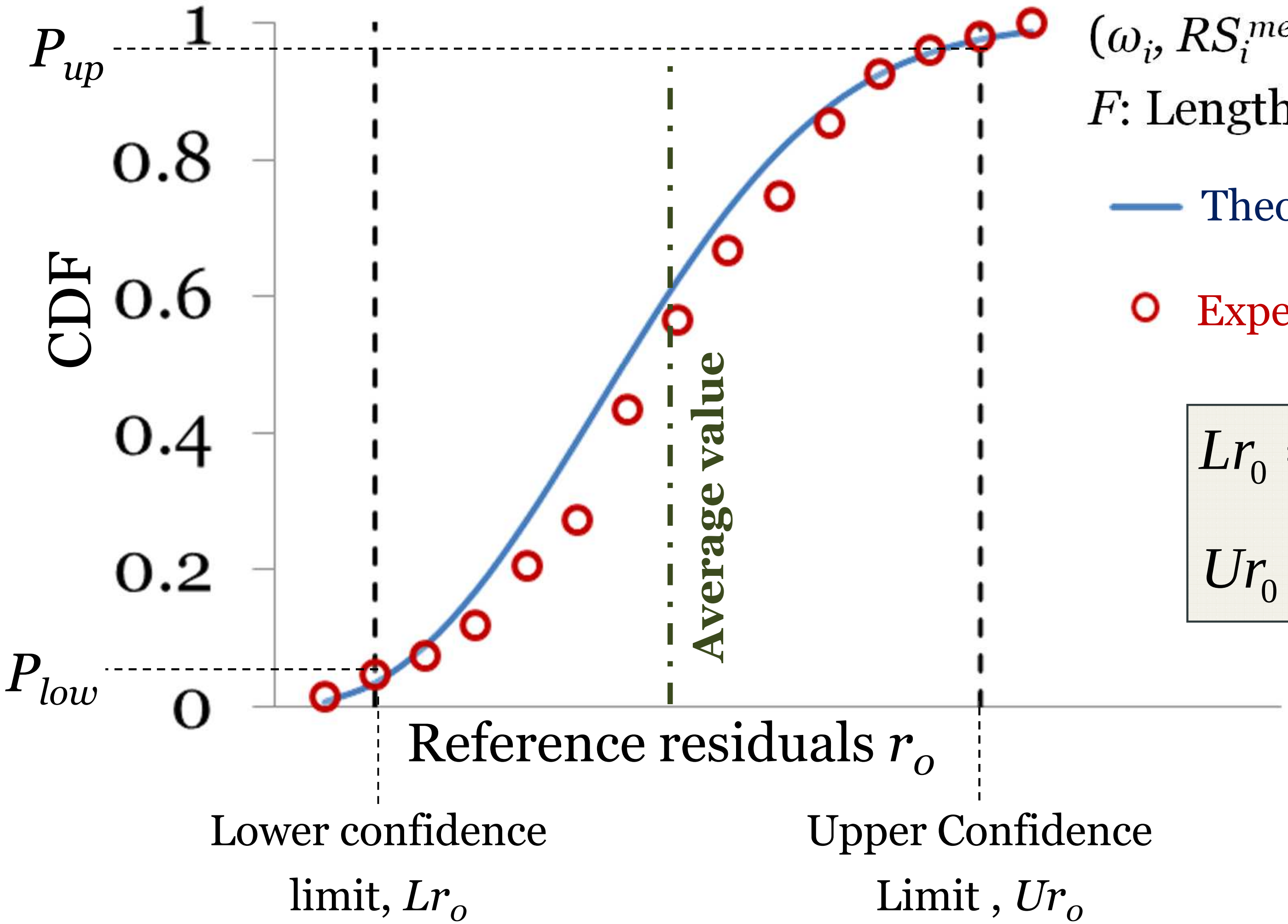
$$r_0 = RS^{meas} - RS^{est}$$

- **Confidence limits**: Fixing a theoretical **Cumulative** probability **Density Function - CDF** (depending from the chosen analysis distribution) on experimental cumulative probability data.

Statistical Control: Confidence limits

Acceptable number of outliers: $$N^0_{out} = F \times \left\{ 1 - \left(P_{up} - P_{low}\right) \right\} \times 100$$

Certainty level (%) = $(P_{up}$-$P_{low})$ x 100



$(\omega_i, RS_i^{meas}), i=1:F$

F: Length of RS vector

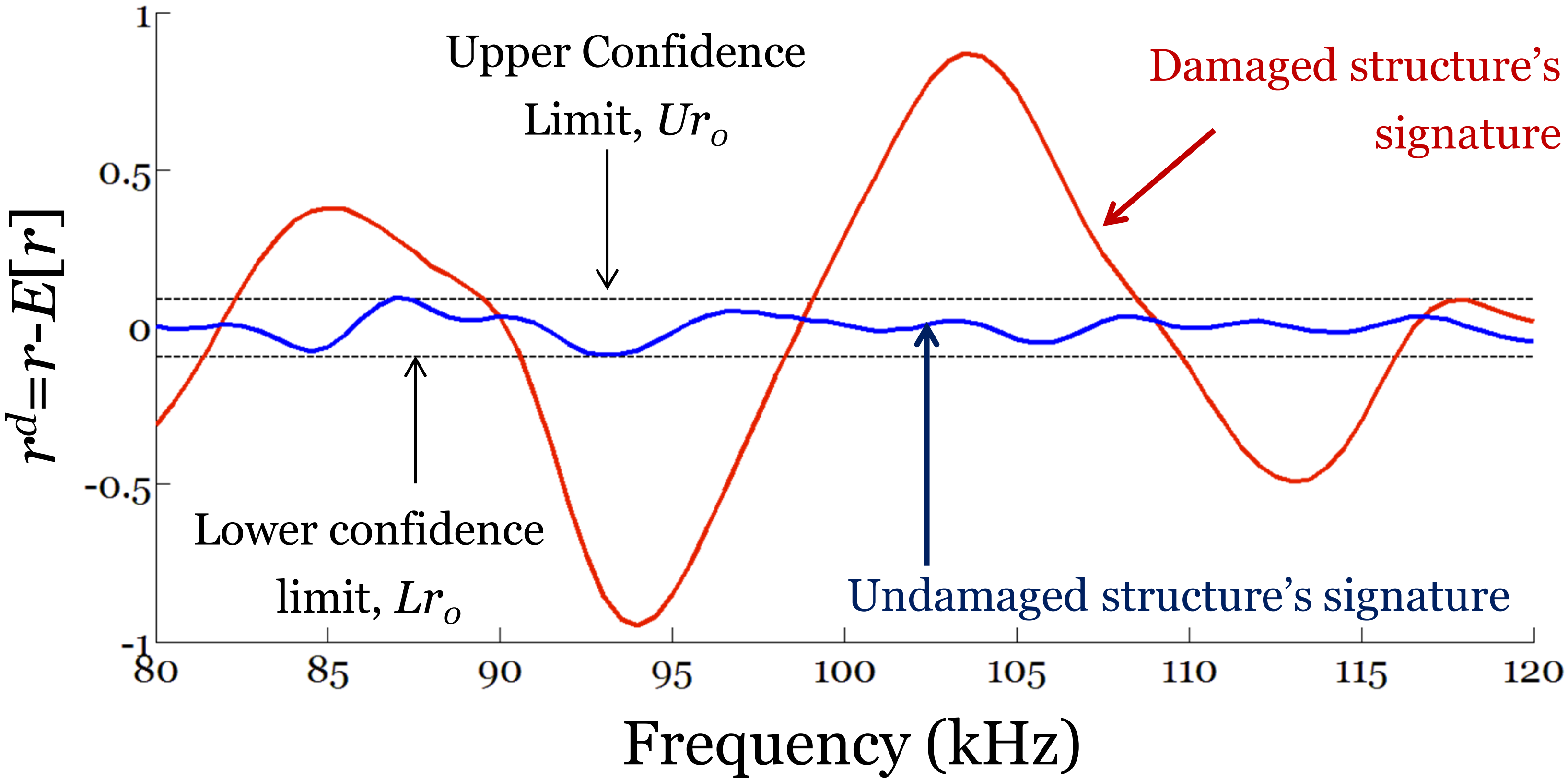
$$Lr_0 = CDF^{-1}\left(P_{low}\right)$$

$$Ur_0 = CDF^{-1}\left(P_{up}\right)$$

Statistical control of outliers: Signatures evaluation

Changes in structural integrity or in mechanical properties of concrete.

$$N_{out} > N_{out}^{0}$$



Certainty: 99%

P_{low}=0.005 ή 0.5 %

P_{up}=0.995 ή 99.5 %

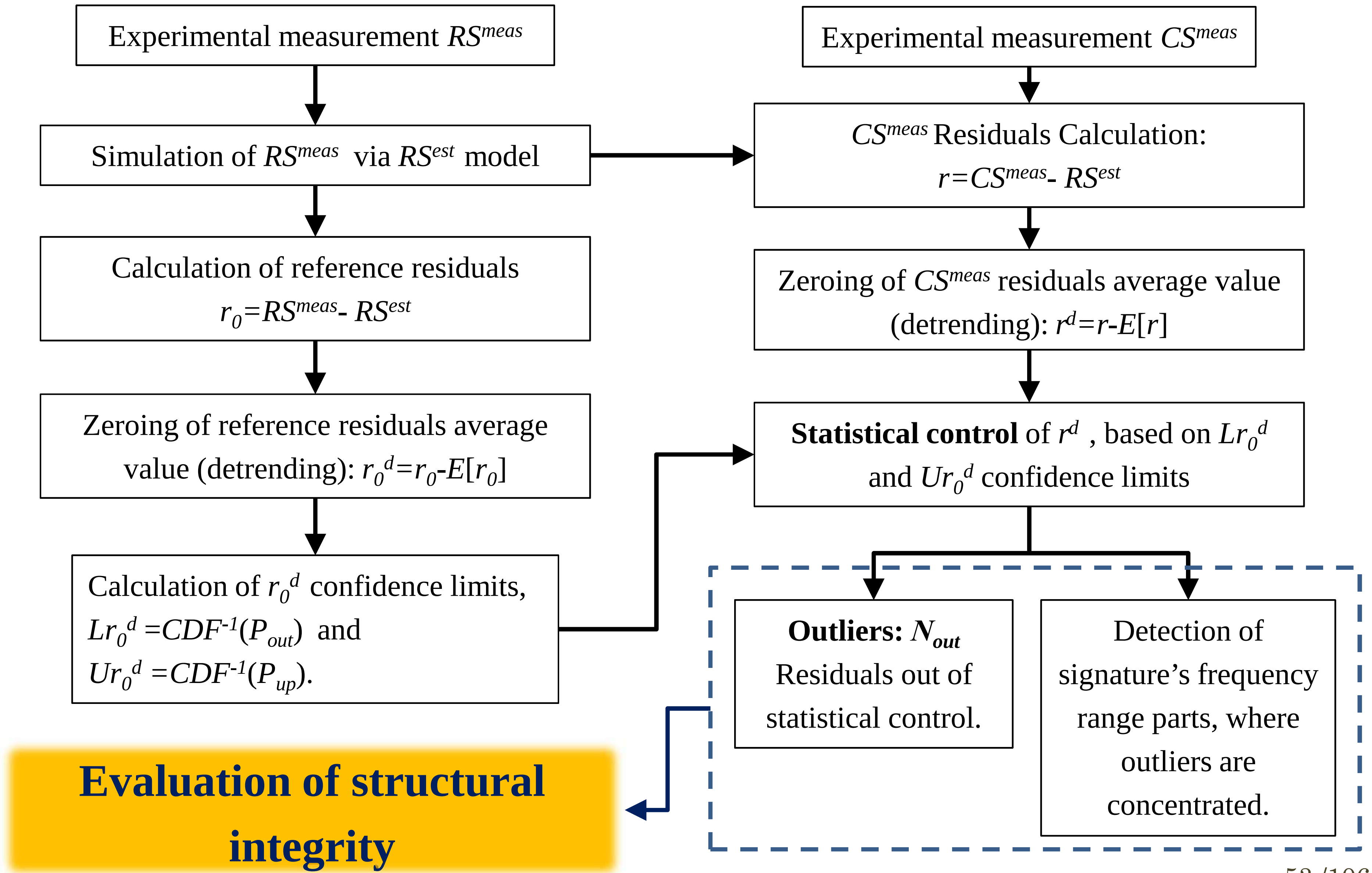
N_{out}^{o}= 1

N_{out}=68

F=105

$E[r]$: Residuals Average

Statistical control of outliers: Functional Diagram



Simulation of undamaged structure reference signature: Electro-Mechanical Impedance (EMI), Z_3.

Measured EMI signature Z_3^{meas}, can be simulated from a **rational polynomial function** of angular frequency, $Z_3^{est}(\omega,\mathbf{p})$ **[J3]**.

$$Z_{3,i}^{meas} = R_{3,i}^{meas} + \mathrm{i}X_{3,i}^{meas} = Z_3^{est}\left(\omega_i,\mathbf{p}\right) + r_i \qquad i = 1:F$$

$$Z_3^{est}\left(\omega_i,\mathbf{p}\right) = \frac{N\left(\omega_i,\mathbf{b}\right)}{D\left(\omega_i,\mathbf{a}\right)} = \frac{\sum_{p=1}^{no+1} b_{p-1}\omega_i^{p-1}}{\sum_{q=1}^{do+1} a_{q-1}\omega_i^{q-1}}$$

$$\underset{(no+do+2\times 1)}{\mathbf{p}} = \begin{bmatrix} a_0 & a_1 & \cdots & a_{do} & b_0 & b_1 & \cdots & b_{no} \end{bmatrix}^T$$

Simulation of undamaged structure reference signature: Electro-Mechanical Impedance (EMI), Z_3.

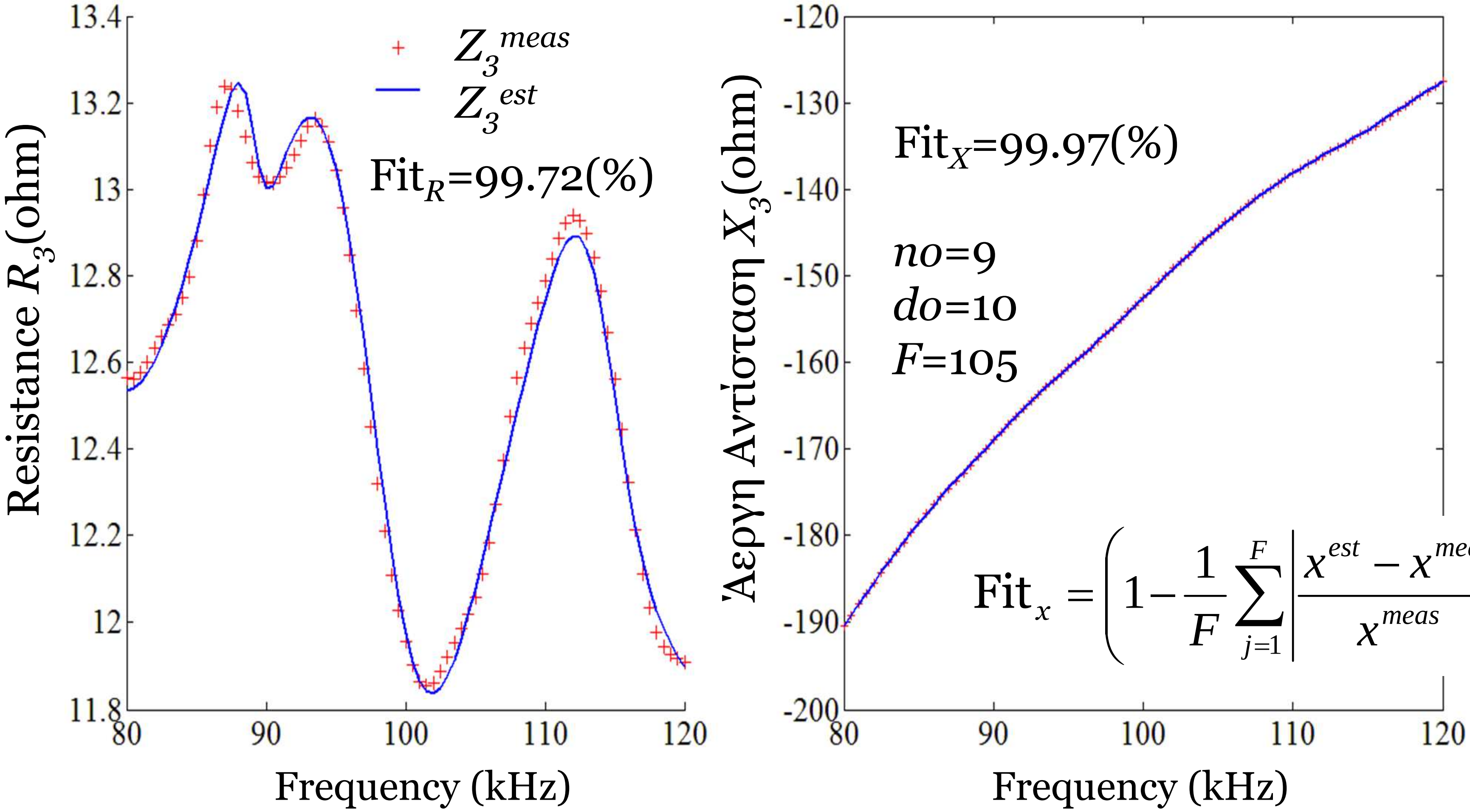
p-vector's optimum values are identified via minimization of sum of squared differences (residuals) between experimentally measured and model-calculated signatures (Least Squares Method - LSM).

$$\min_{\mathbf{p}} \sum_{i=1}^{F} \left\{ Z_{3,i}^{meas} - Z_3^{est}\left(\omega_i, \mathbf{p}\right) \right\}^2 = \min_{\mathbf{p}} \sum_{i=1}^{F} r_i^{\;2}$$

Present problem is classified in family of non-linear least squares problems and could be resolved via **lsqnonlin** MATLAB function (MATLAB | Optimization toolbox).

Simulation of undamaged structure reference signature: Electro-Mechanical Impedance (EMI), Z_3.

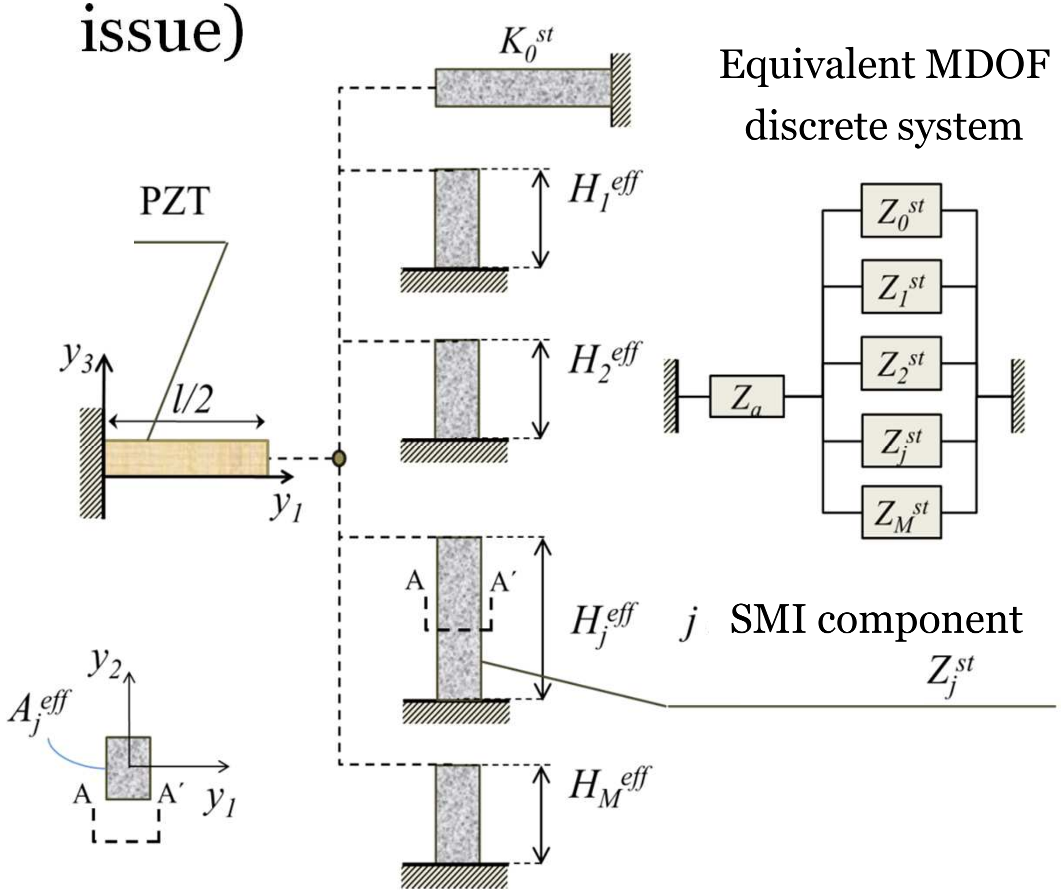
Number of model's parameters: *no*+*do*+2=21 | Complex numbers



$$\mathrm{Fit}_x = \left(1 - \frac{1}{F} \sum_{j=1}^{F} \left| \frac{x^{est} - x^{meas}}{x^{meas}} \right| \right) \times 100$$

Simulation of undamaged structure reference signature: Mechanical Impedance, Z_{St}.

multi Mechanical Impedance System–mMIS (PhD Novelty issue)



Dynamic response of concrete structure could be simulated via an equivalent Multi-Degree Of Freedom (MDOF) discrete system of Shear Mechanical Impedance (SMI) components, connected in parallel set-up.

$$Z_{St} = \sum_{j=0}^{M} Z_j^{st}$$

Simulation of undamaged structure reference signature: Mechanical Impedance, Z_{St}.

Frequency response function of equivalent system.

$$Z_{St}(\omega,\mathbf{p}) = Z_0^{st} + \sum_{j=1}^{M} Z_j^{st} = \frac{K_0^{st}}{\mathrm{i}\omega} + \frac{1}{\mathrm{i}\omega}\sum_{j=1}^{M}\frac{A_j^{eff}\kappa_{s,j}\overline{G}_{St,j}}{\tan\left(\kappa_{s,j}H_j^{eff}\right)}$$

$$\overline{G}_{St,j} = G_{St}\left(1+\mathrm{i}n_j^{st}\right)$$

$$\kappa_{s,j} = \omega\sqrt{\rho_{St}/\overline{G}_{St,j}}$$

$$freq_{0j} = \frac{1}{2H_j^{eff}}\sqrt{\frac{G_{St}}{\rho_{St}}}$$

$$\mathbf{p} = \left[K_0^{st} \quad A_1^{eff} \quad \cdots \quad A_M^{eff} \quad H_1^{eff} \quad \cdots \quad H_M^{eff} \quad n_1^{st} \quad \cdots \quad n_M^{st}\right]$$

Experimental signatures of mechanical impedance Z_{St}^{meas}, are calculated from the measured electrical impedance signature Z_3^{meas}.

$$Z_{St,i}^{meas} = Z_{\alpha,i}\left\{\mathrm{i}\omega_i\frac{l^2}{h}\frac{2d_{31}^2\overline{Y}^E}{\left(1-\nu_{12}\right)\left(\frac{1}{Z_{3,i}^{meas}}-Y_3^{fix}\right)}-1\right\}, \quad j=1:F$$

Simulation of undamaged structure reference signature: Mechanical Impedance, Z_{St}.

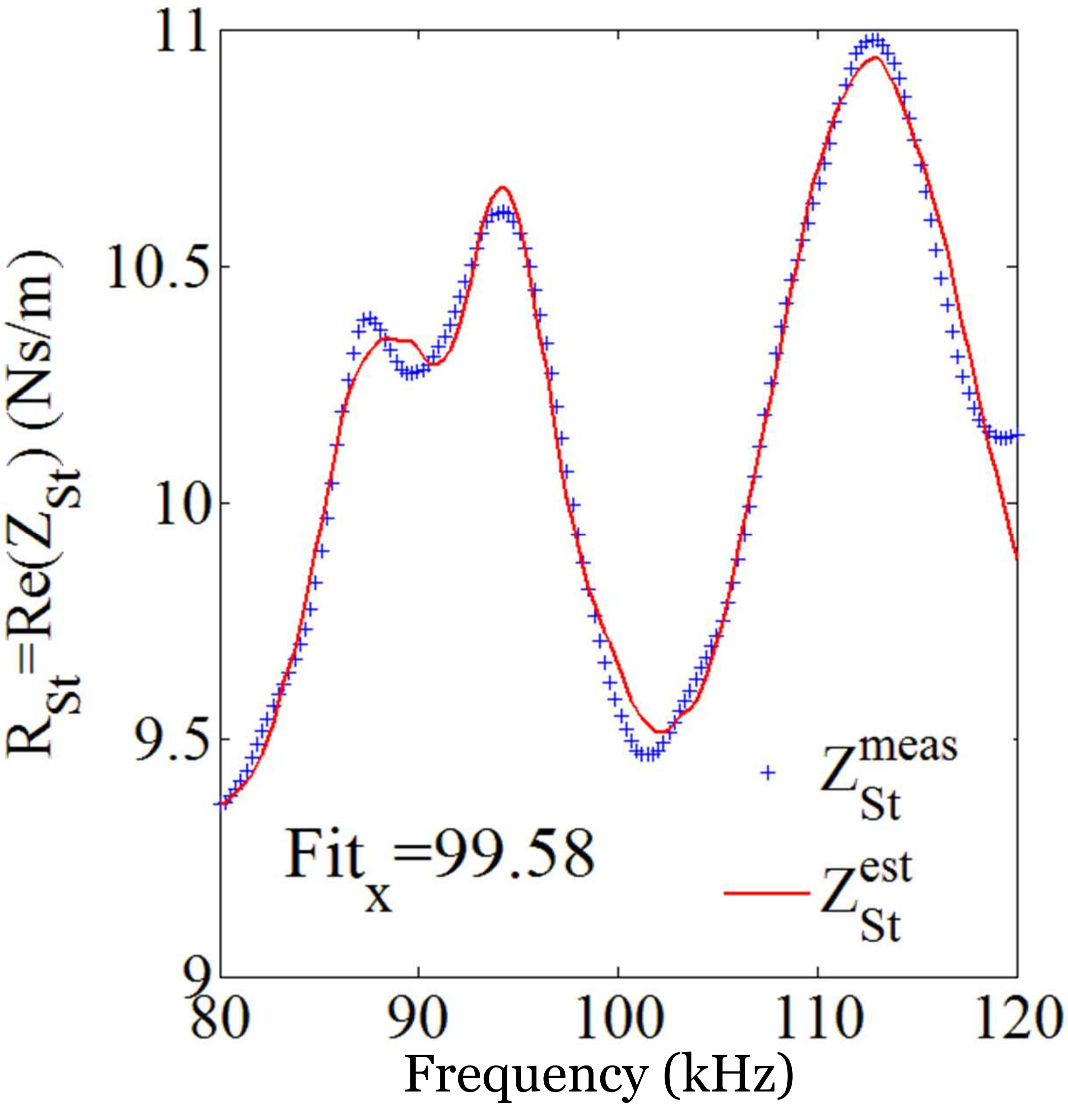
p-vector's optimum values are approximated via minimization of sum of squared differences between experimentally measured and model-calculated, signatures. (Non-linear least squares with **constraints**, **lsqnonlin** | MATLAB – Optimization Toolbox)

$$\min_{\mathbf{p}} \sum_{i=1}^{F} \left[\operatorname{Re}\left\{ Z_{St,i}^{meas} \right\} - \operatorname{Re}\left\{ Z_{St}^{est}(\omega_i, \mathbf{p}) \right\} \right]^2$$

$$\text{subject to} \quad \begin{array}{l} \mathbf{p} > 0 \\ n_j^{st} < 1 \end{array}$$

$$\mathbf{p} = \left[K_0^{st} \quad A_1^{eff} \quad \cdots \quad A_M^{eff} \quad H_1^{eff} \quad \cdots \quad H_M^{eff} \quad n_1^{st} \quad \cdots \quad n_M^{st} \right]$$

Simulation of undamaged structure reference signature: Mechanical Impedance, Z_{St}.



mMIS model's parameters: 15

$freq_{o,j}$ (kHz)	$H_{eff,j}$ (mm)	$A_{eff,j}$ (mm²)	$n_{st,j}$
3.32	343.24	2.20E-03	0.01
9.78	116.65	1.49E+00	0.17
85.67	13.32	6.73E-02	0.14
94.23	12.11	3.03E-02	0.07
112.22	10.17	9.55E-02	0.14

$$\overline{G}_{St,j} = G_{St}\left(1 + i n_j^{st}\right)$$

$$\kappa_{s,j} = \omega\sqrt{\rho_{St} / \overline{G}_{St,j}}$$

$$freq_{0j} = \frac{1}{2H_j^{eff}}\sqrt{\frac{G_{St}}{\rho_{St}}}$$

Simulation of undamaged structure reference signature: Mechanical Impedance, Z_{St}.

Advantages of mMIS model in comparison to non-linear polynomial regression

- Significantly fewer modelling parameters.
- Modelling parameters are representing mechanical quantities which are strongly correlated with the dynamic features of the structure.
- Calculation of structure's resonant frequencies.
- Estimation of structure's dynamic response and resonant frequencies at frequency points **out** of experimentally swept range.

Restrictions regarding to concrete structures monitoring

mMIS parameters have physical interpretation only if concrete constructional elements have adequate stiffness (at least 24 hours after concrete fabrication).

5.

Integrated wireless system for automatic EMI measurement

In context of present dissertation (PhD Novelty issue) is developed an integrated monitoring system termed as **T-WiEYE (Teflon-based Wireless intergratEd monitoring SYstEm),** combining **[J3]:**

- Piezoelectric patches as sensors/actuators.
  - PZT – PIC 151 (PI Ceramics Inc.)
  - **SMart Agreggates-SMA.** Embedding of PZT patches in concrete mass simultaneously with the casting of constructional elements.
  - **Teflon casing of PZT patches**. PZT protection from early age concrete moisture, concrete condensation vibration and concrete shrinkage deformation.
- Wi-Fi contact between SMAs and data acquisition/storage system.

In context of present dissertation (PhD Novelty issue) is developed an integrated monitoring system termed as **T-WiEYE (Teflon-based Wireless intergratEd monitoring SYstEm),** combining **[J3]:**

- **AD5933 (Analog Devices).** Low cost integrated circuit for the measurement of EMI in frequency domain.
- Ability of permanent installation in structure's space, for continuous evaluation of structural integrity.
- Integrated access and overview of measured EMI data.
  - EMI data registration in a MySQL developed database.
  - Access to MySQL database through MATLAB workspace.
  - Remote mining and overview of EMI data for post-processing and signature's evaluation (Statistical control of signatures).

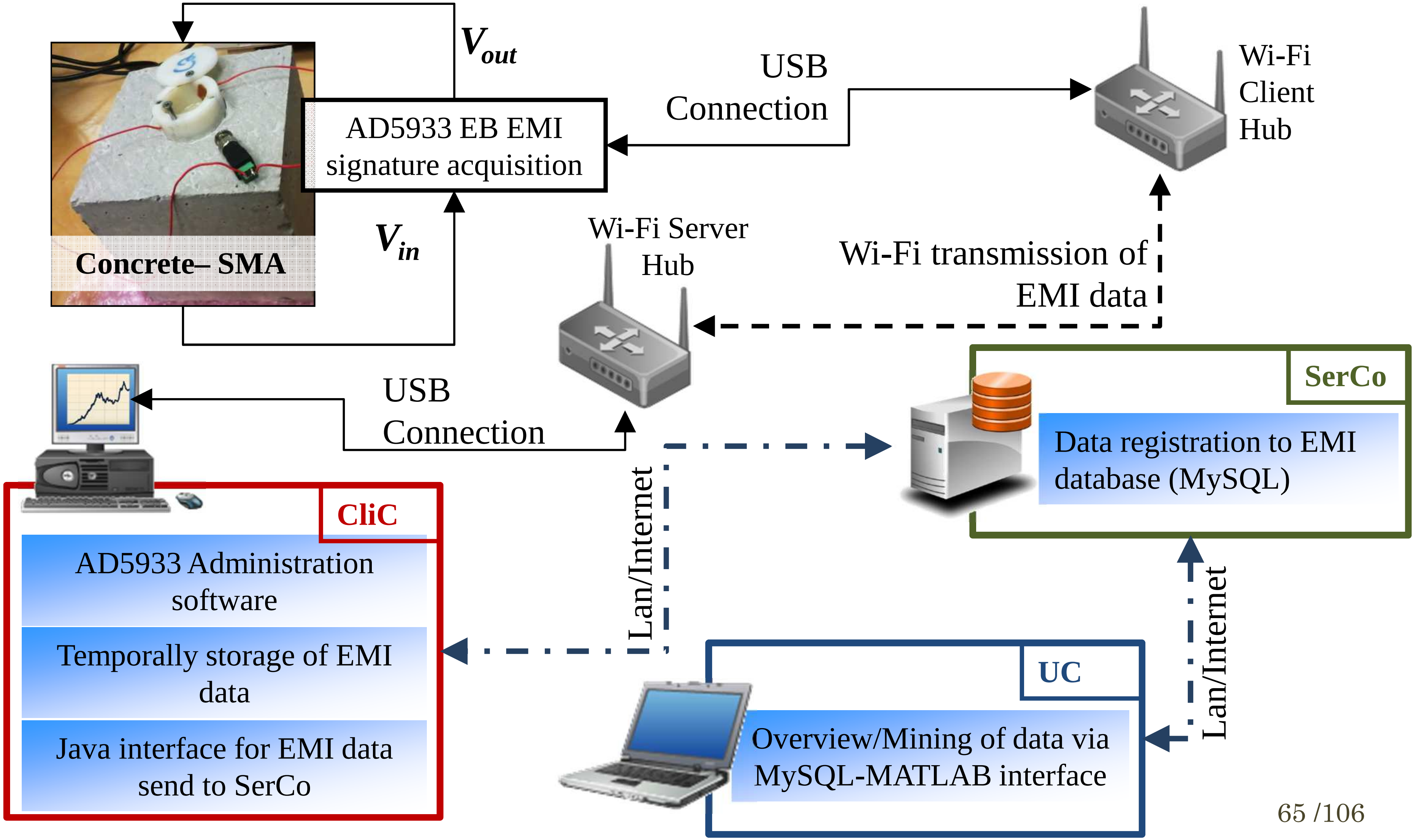
T-WiEYE System

Functionality diagram [J3]

CliC: Client Computer

SerCo: Server Computer

UC: User Computer

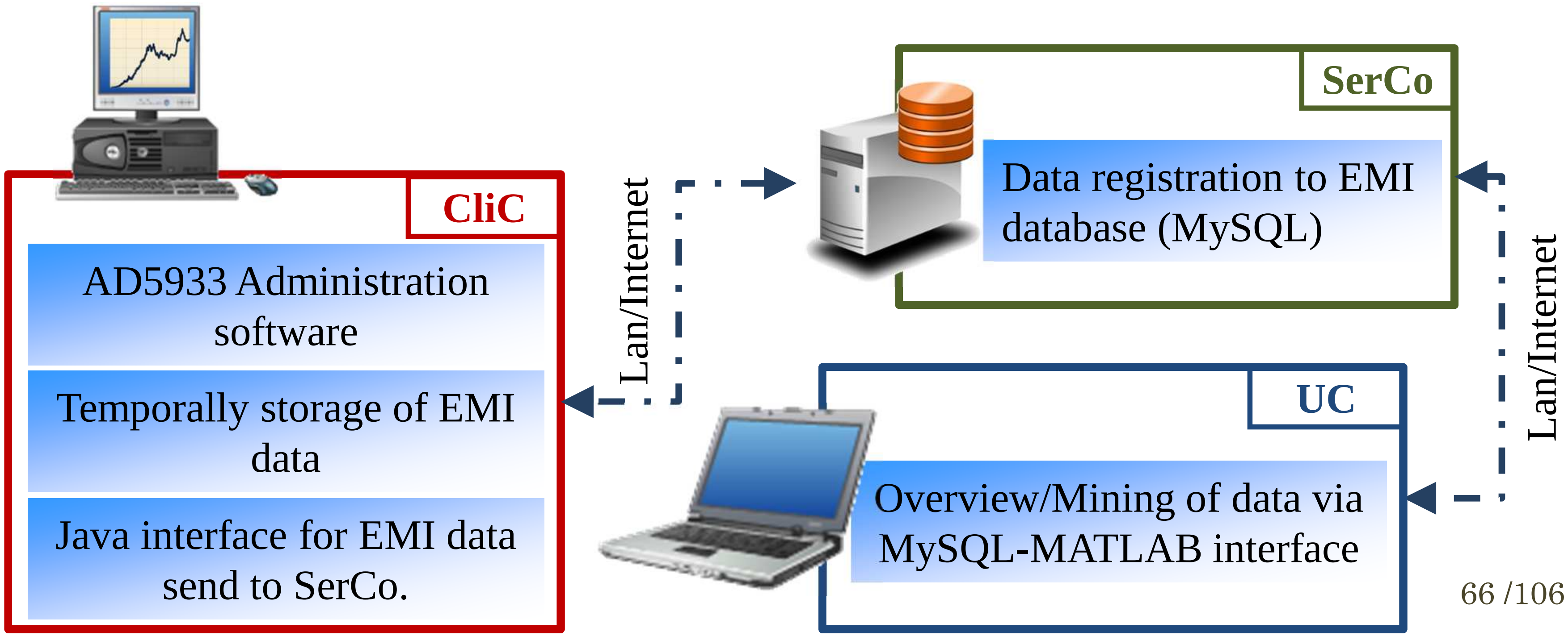


T-WiEYE System

CliC: Client Computer
SerCo: Server Computer
UC: User Computer

Functionality diagram

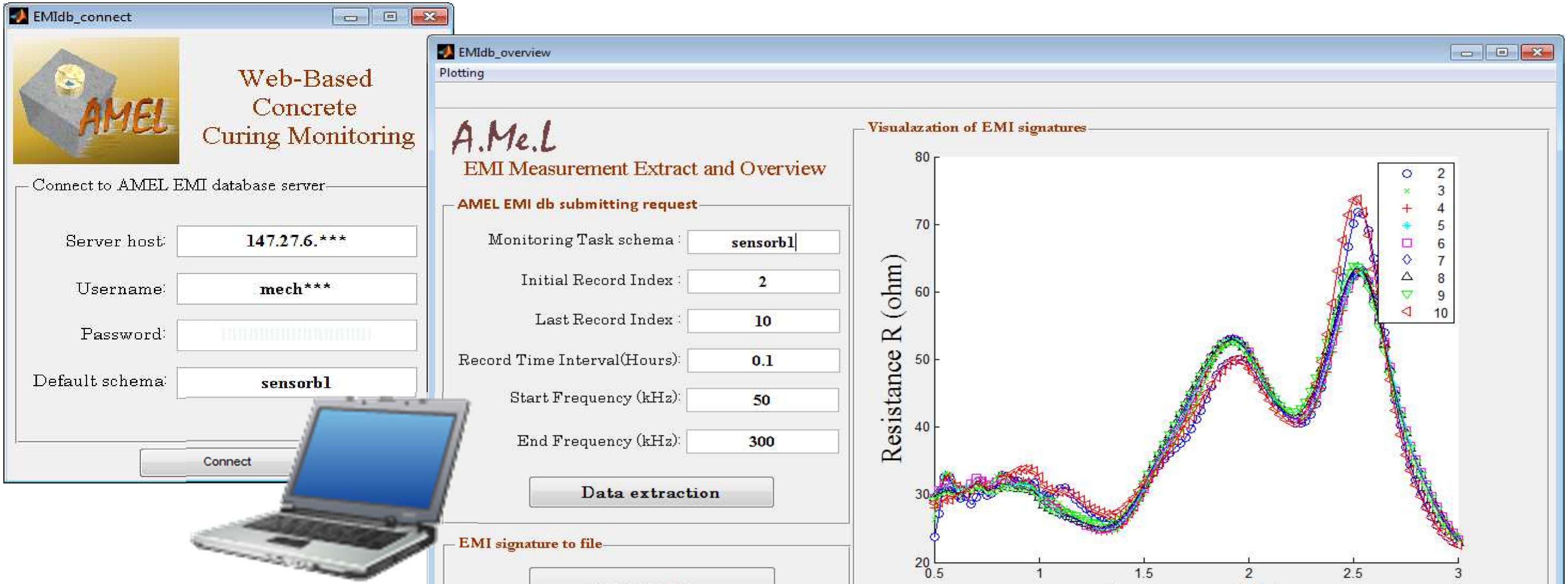
- CliC: Client Computer.
  - Control and administration EMI measurement system (AD5933).
  - Set-up in structure's space, inside to Wi-Fi covering area.
  - Connection with **SerCo** via internet or LAN.



T-WiEYE System

Functionality diagram

- Remote MySQL workspace administration via MATLAB environment
- Development of a MATLAB scripted, GUI application

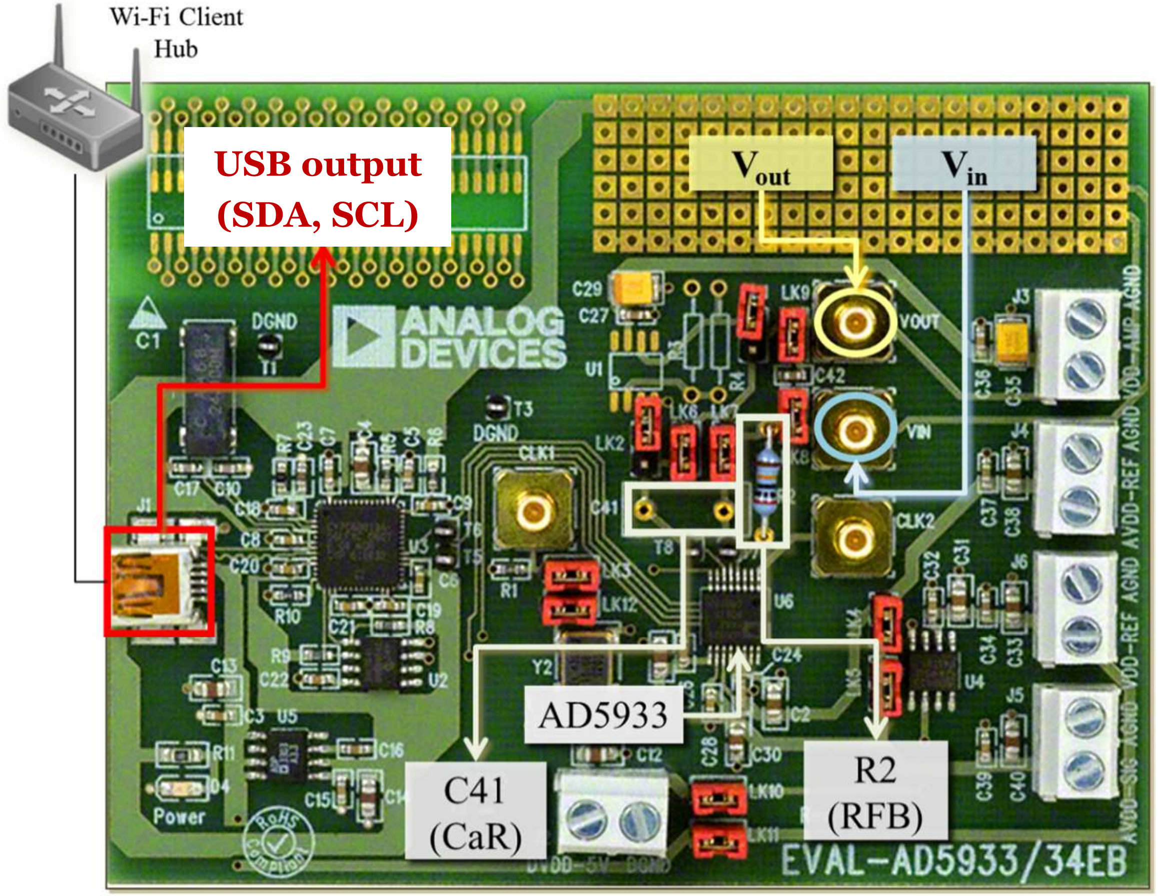


UC|Remote user

T-WiEYE System

Functionality diagram

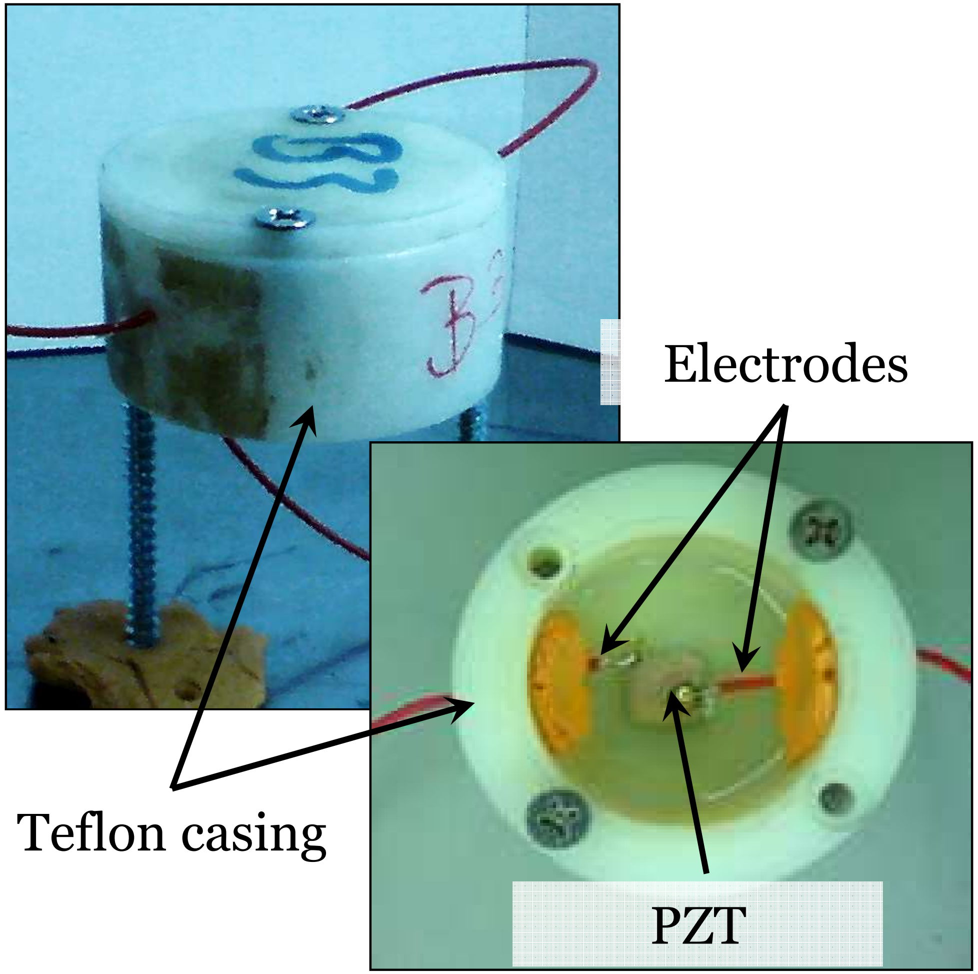
➢ PCB: AD5933 Evaluation Board (Analog Devices). Electrical impedance measurement integrated circuit.



- C41: Calibration Resistor.
- R2: Feedback Resistor.
- EMI measurements accuracy 99.5 %. Frequency range:
  - 10-100 kHz: No correction.
  - 100-150 kHz: Simple linear correction.

T-WiEYE System

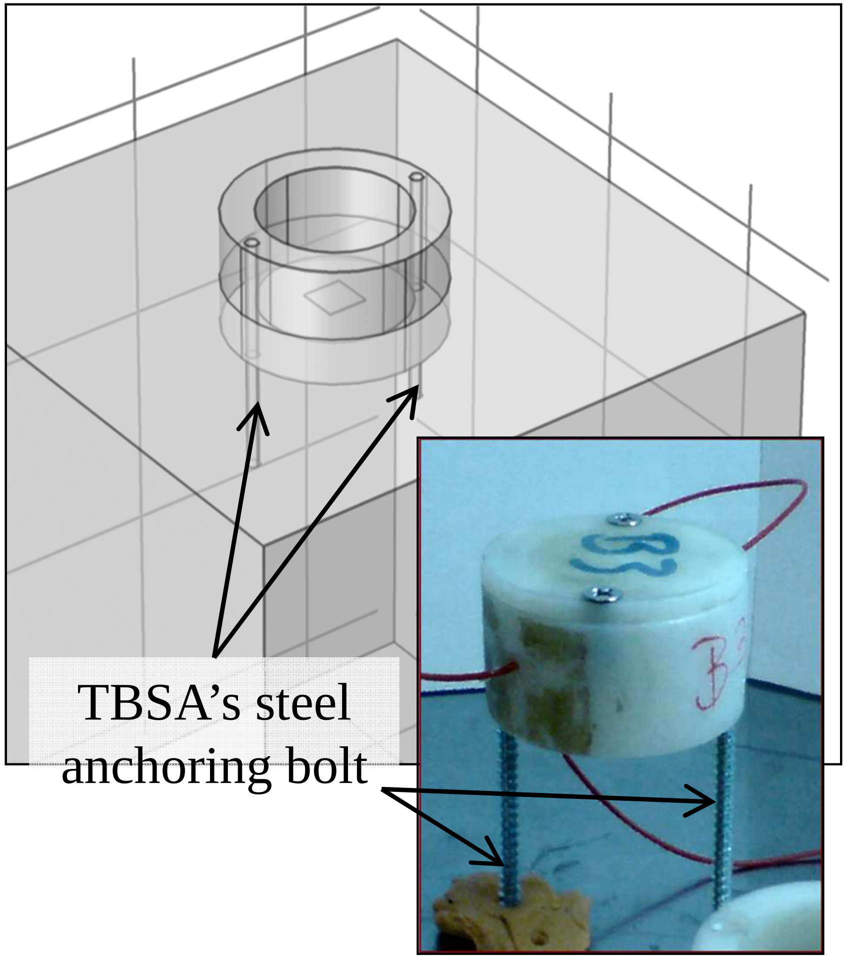
Teflon Based Smart Aggregate–TBSA [J2-J3] (PhD Novelty issue)



- Fabrication of a properly designed Teflon (PTFE) casing for the protection of PZT patch.
- Adaption of PIC 151 type PZT, with dimensions 10x10x0.2 mm, inside Teflon casing.
- Electrodes soldering on PZT's terminals for the connection of TBSA on AD5933 EB's V_{in}-V_{out} pins.

T-WiEYE System

Teflon Based Smart Aggregate –TBSA [J2-J3] (PhD Novelty issue)



- Fixing of steel bolt on Teflon casing for robust anchoring of TBSA in concrete mass.
- Anchoring is improving the mechanical conductivity between TBSA and concrete's mass.
- **Mechanical conductivity.** The ability of an interface between different materials to allow the transmission of mechanical energy, via waves, with the fewer possible losses.

T-WiEYE System

Teflon Based Smart Aggregate –TBSA

Resume of innovative elements:

- Teflon casing. Adequate mechanical strength and chemical resistance regarding to chemically active components of concrete (cement and water).
- Anchoring in concrete mass
- Accessibility to sensing/actuating core of TBSA for possible repairing of PZT's electrodes.
- Ability of TBSA recovering after the ending of a monitoring session and reusability option.

6.

Applications

Laboratory scale concrete structural elements

- Monitoring of physical processes.
  - Hydration of very early age concrete. Until 48 hours after fabrication.
  - Development of stiffness and hardening evolution of early age concrete. Until 28 days after fabrication.
- Monitoring of damages (cracks) start and propagation, in concrete elements.
  - Cubic specimens under compression loading
  - Beam specimens under bending

Mechanical properties of concrete

- Laboratorial concrete (No chemical admixtures)
- C20/25. Composition (kg/m³):
  - Gravel | Coarse aggregates (d_g>25mm): **850**
  - Middle size aggregates (2.5 mm< d_g < 9.5mm): **450**
  - Sand | Fine aggregates (d_g <2.5mm): **550**
  - Cement, CEM II/A-M 42.5 N: **310**
  - W/C = **0.65** (Water to Cement ratio)

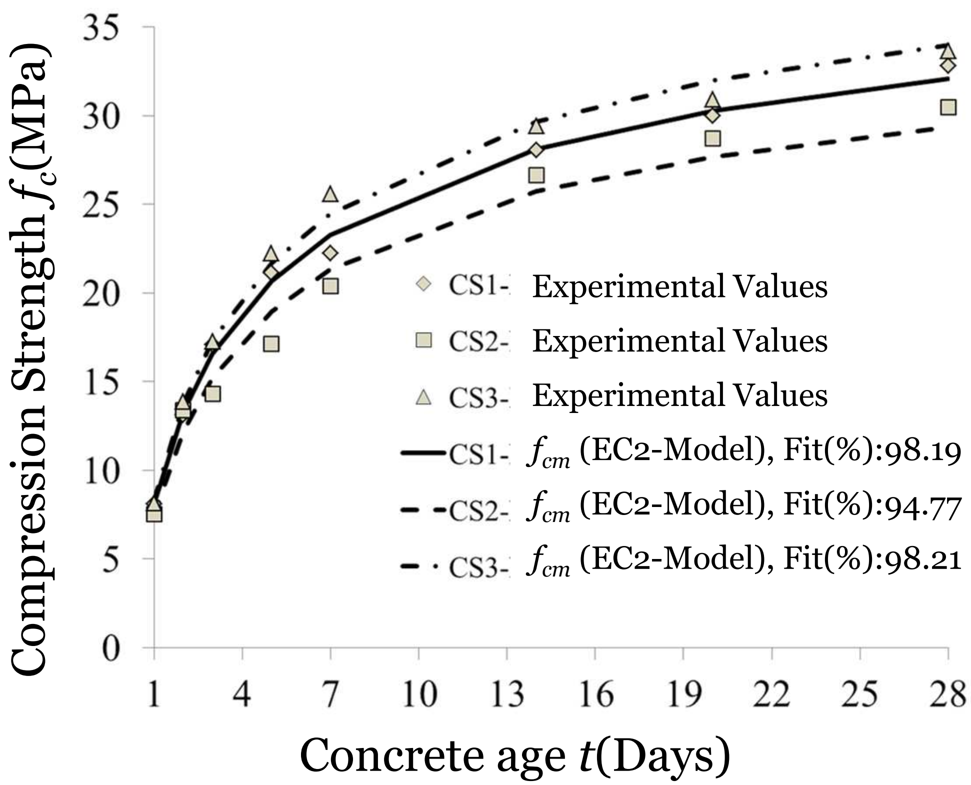
d_g: Grind size/ Sieve mesh opening
Cubic specimen's edge length: 150mm

- Theoretical density : 2360 kg/m³
- Theoretical weight of cubic specimen : 7.95 kg

Mechanical properties of concrete

Destructive evaluation of concrete's compression strength development.

Compression test for specimen's ages: 1, 2, 3, 5, 7, 14, 20, 28 days.



Set of specimens (3 sets) →	CS1	CS2	CS3
f_{cm}^{28}(MPa)	32.09	29.35	33.97
cem	0.321	0.320	0.328
E_{cm}^{28}(GPa)	28.54	27.71	29.09

EC2 Model [5.1]:

$$f_{cm}(t) = f_{cm}^{28} \exp\left\{cem\left(1-\sqrt{\frac{28}{t}}\right)\right\}$$

CEB-FIP Model:

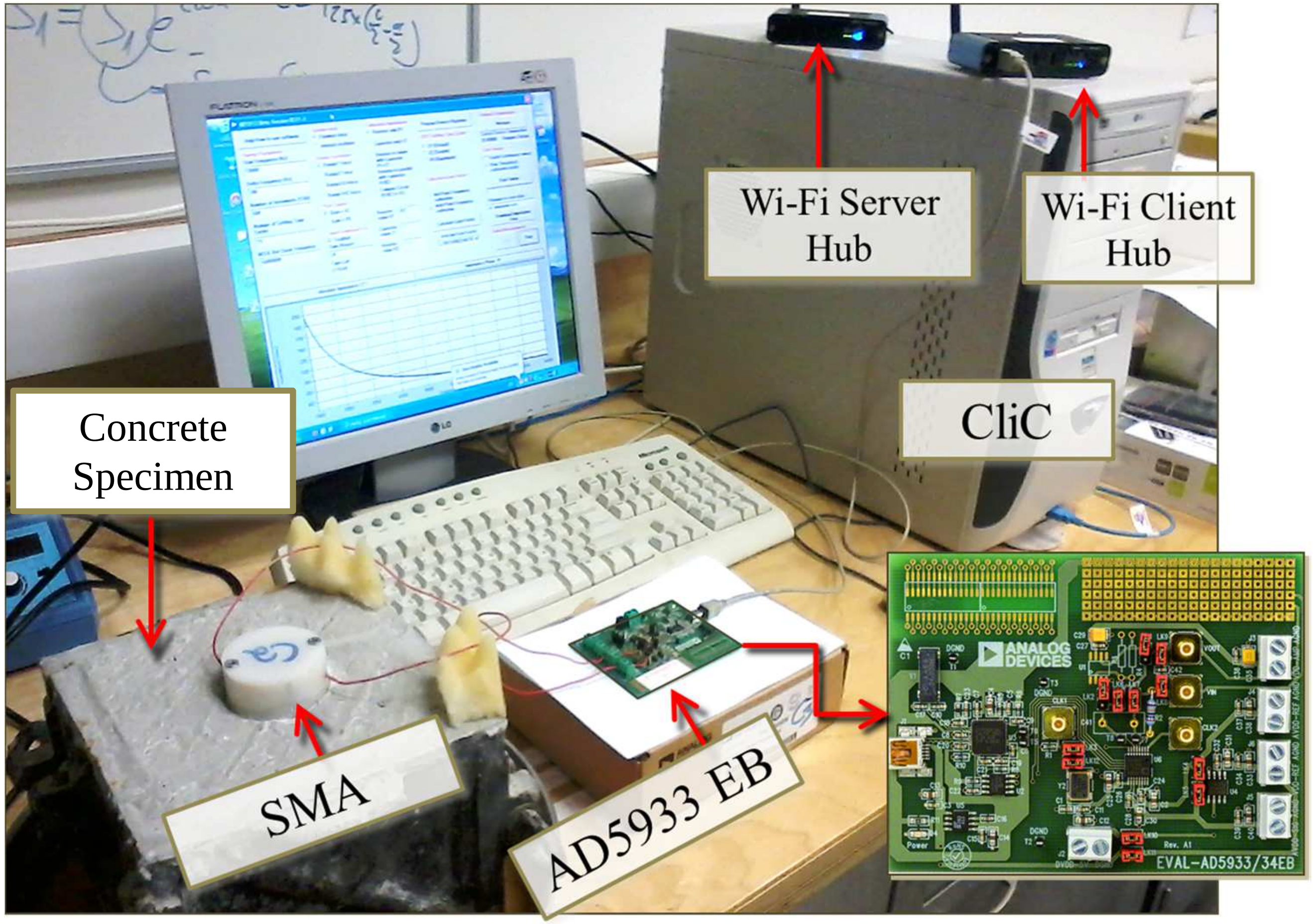
$$E_{cm}^{28} = a_e 21.5\left(\frac{f_{cm}^{28}}{10}\right)^{\frac{1}{3}}$$

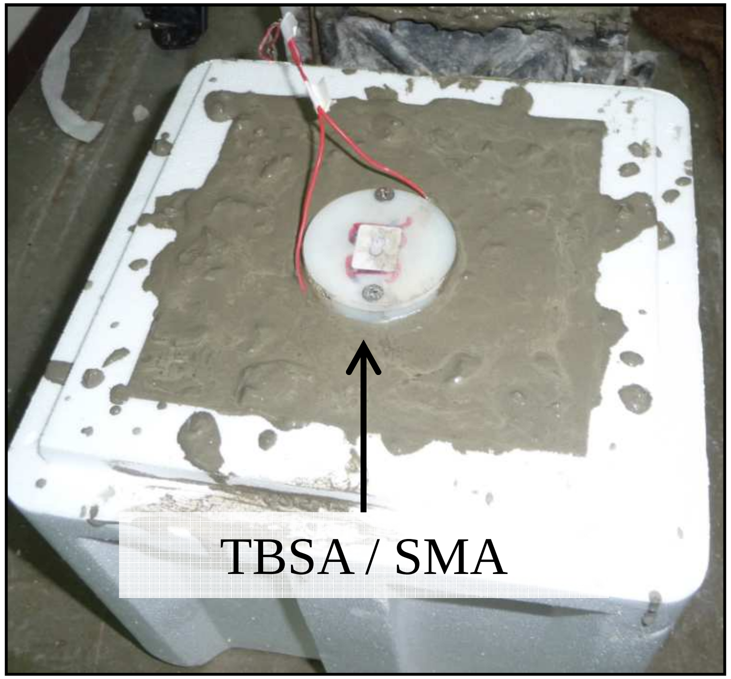
α_e=0.9 (Limestone)

[5.1] **Bamforth P., Chisholm D., Gibbs J.** and **Harisson T., 2008.** Properties of concrete for use in EuroCode 2.

EMI based monitoring of early age concrete

- 5 concrete cubic specimens. 3 of them are fabricated from the same casting portion (C1-3) and the other 2 from different casting portions (C4, C5).



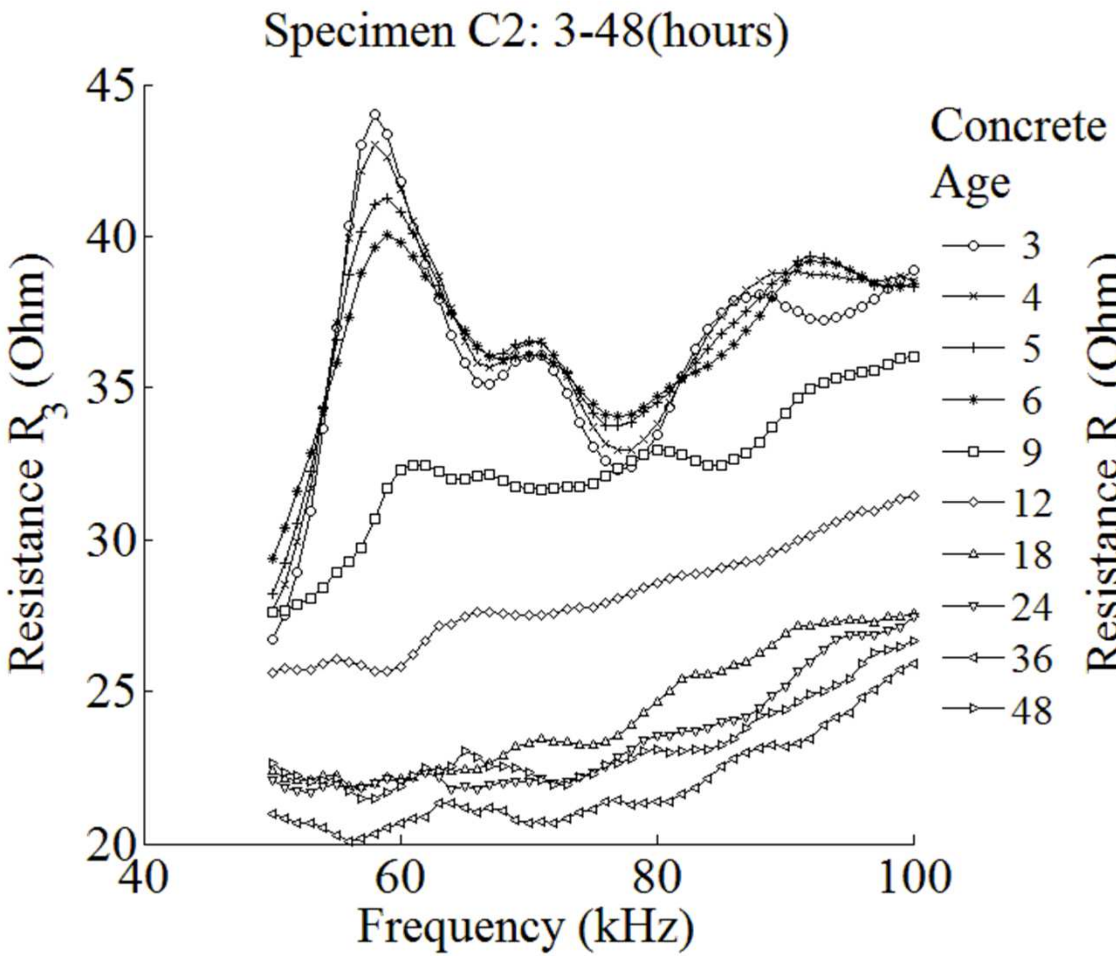


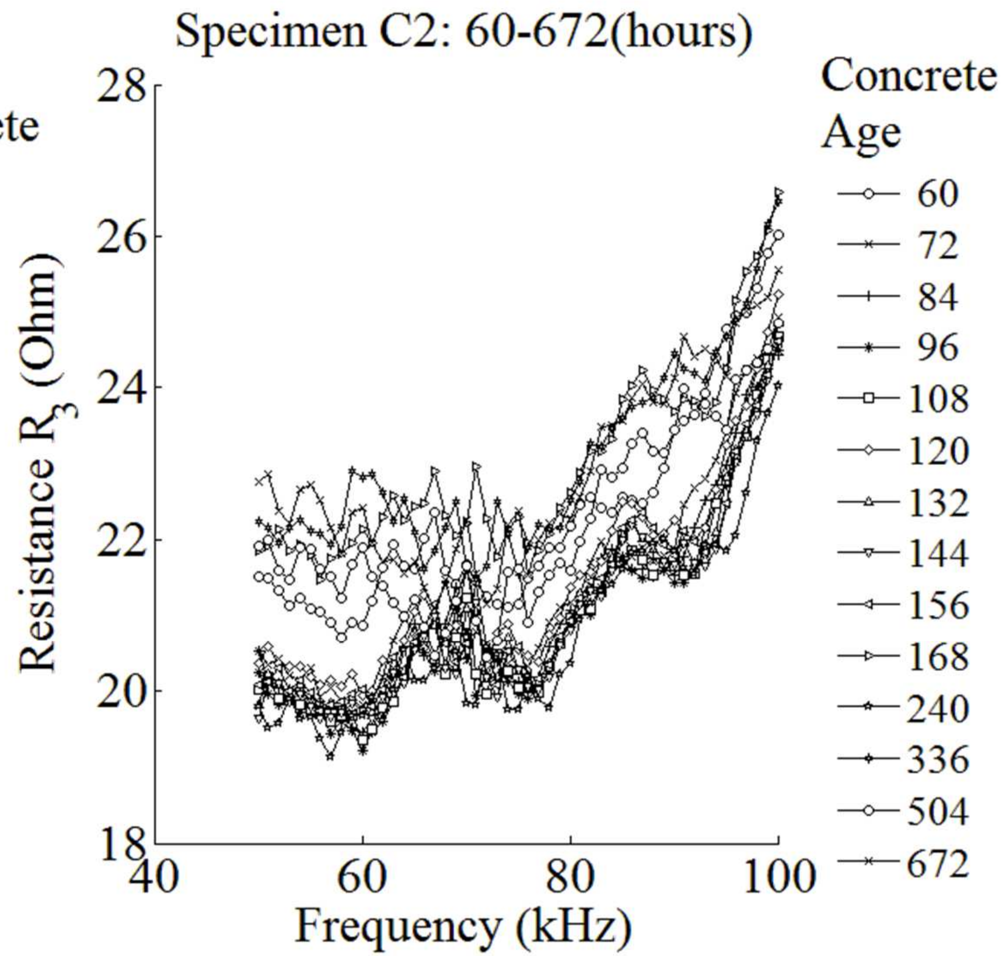
EMI based monitoring of early age concrete

- T-WiEYE System.
  - Recording signature: EMI real part, R_3 (Resistance).
  - Frequency range: **50-100 kHz**
  - Continuous recording of R_3 signatures, starting 3 after concrete casting.
  - **Signatures recording rate:** 1 signature per hour for the first 192 hours (8 days) and 1 signature per day from 9 to 28 days.
- Evaluation of R_3 signatures changes
  - **Reference signature:** The R_3,signature which is corresponding to **3 hour age** concrete (semi-liquid phase)
  - Evaluation of signatures changes via RMSD
  - Investigation of RMSD changes relatively to concrete age

EMI based monitoring of early age concrete

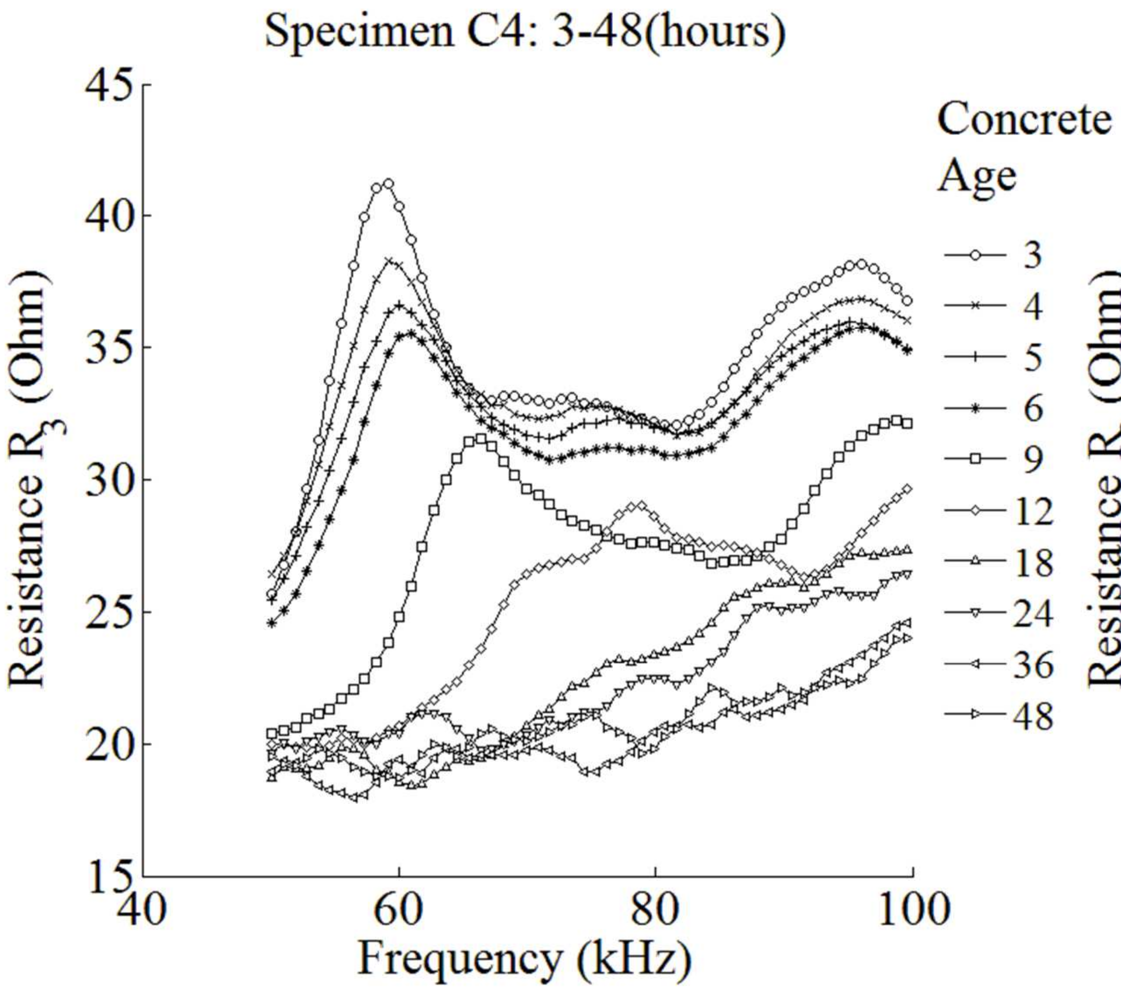
Specimen C2: EMI real part (Resistance), R_3=Re{Z_3}.

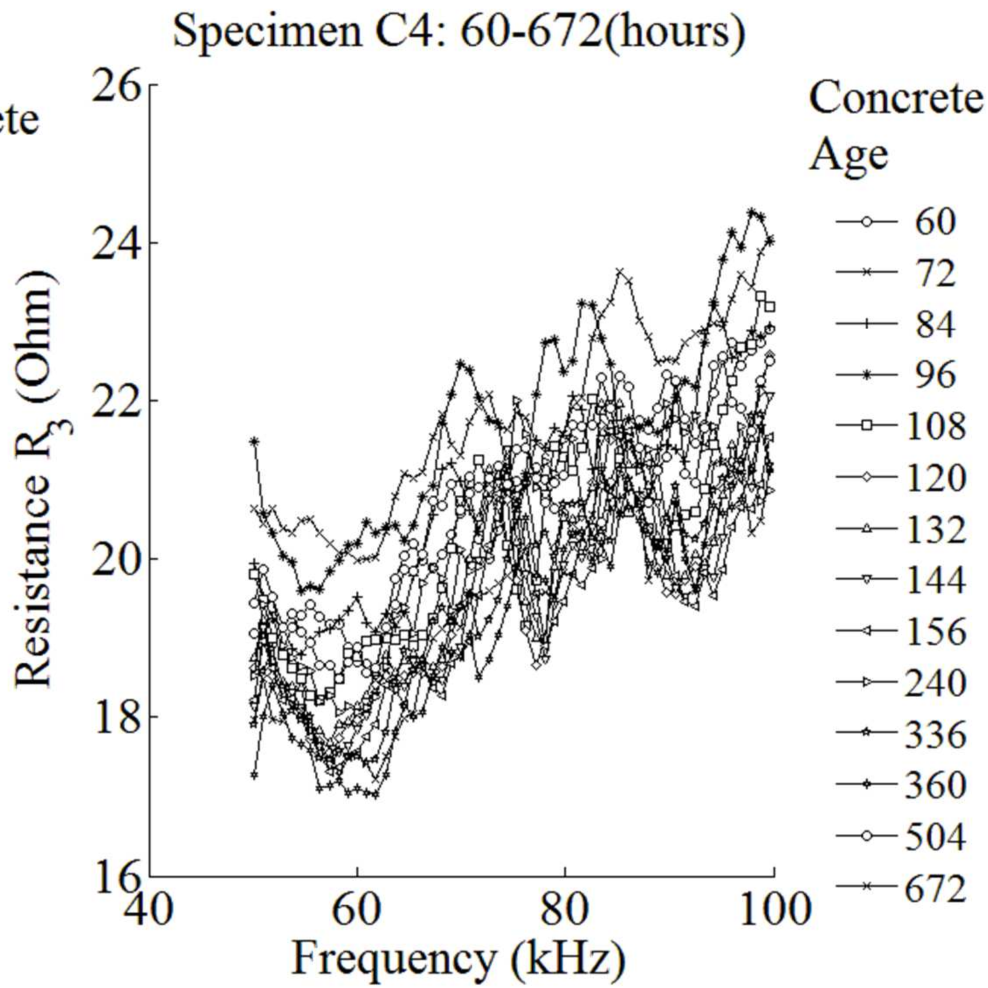




EMI based monitoring of early age concrete

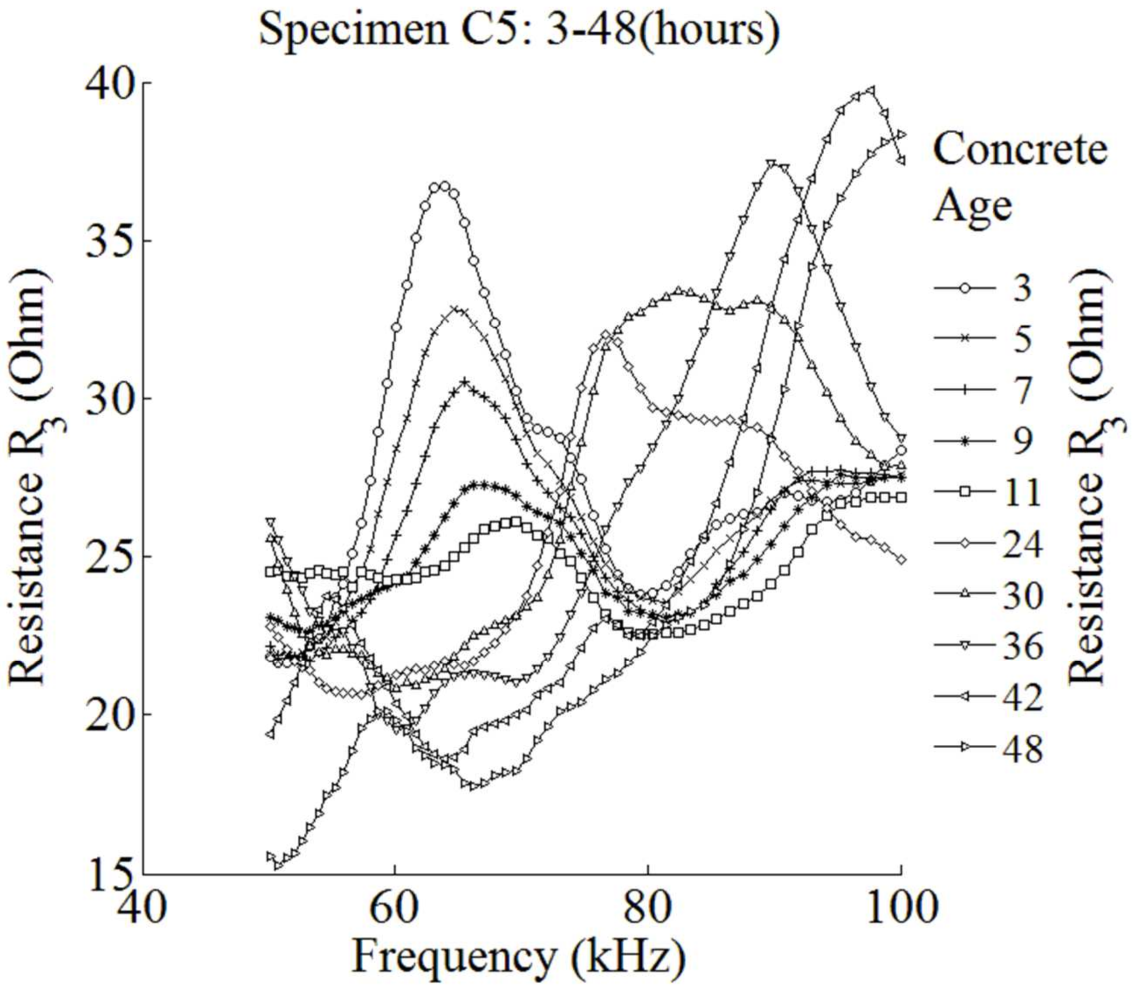
Specimen C4: EMI real part (Resistance), R_3=Re{Z_3}.

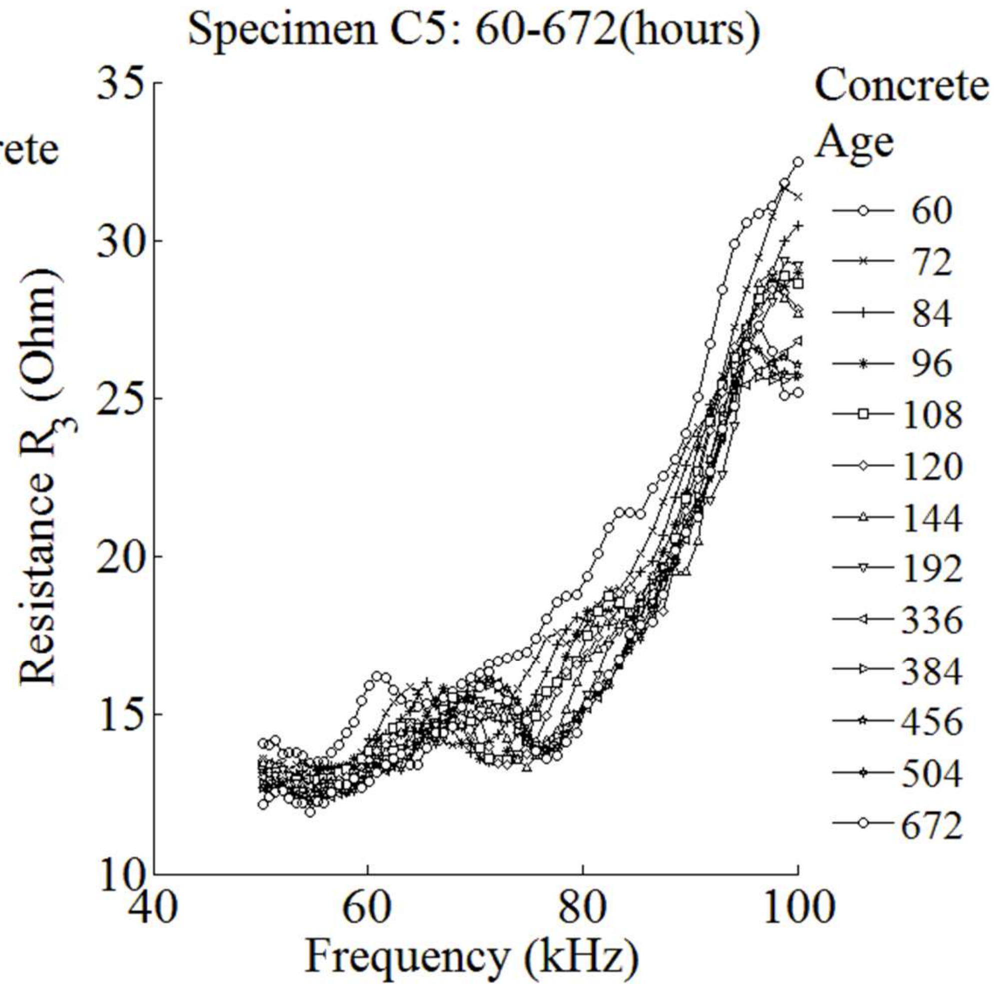




EMI based monitoring of early age concrete

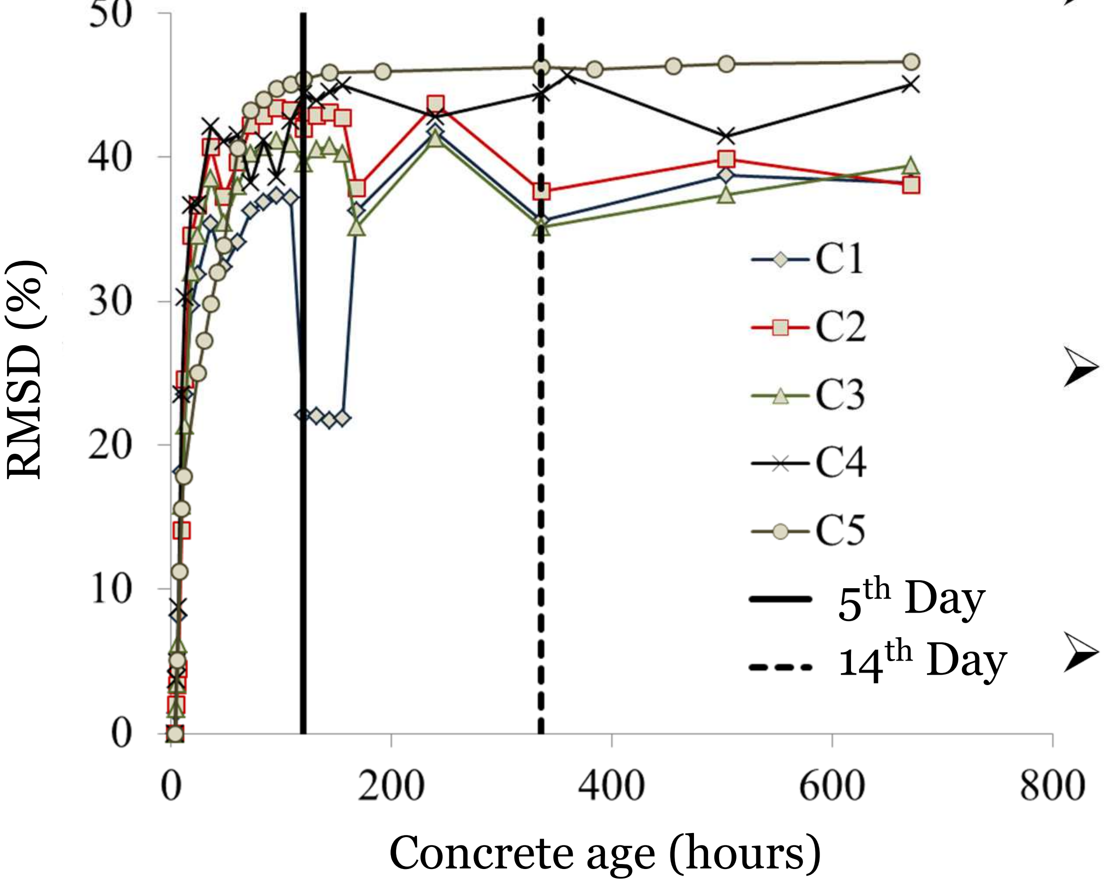
Specimen C5: EMI real part (Resistance), R_3=Re{Z_3}.





EMI based monitoring of early age concrete

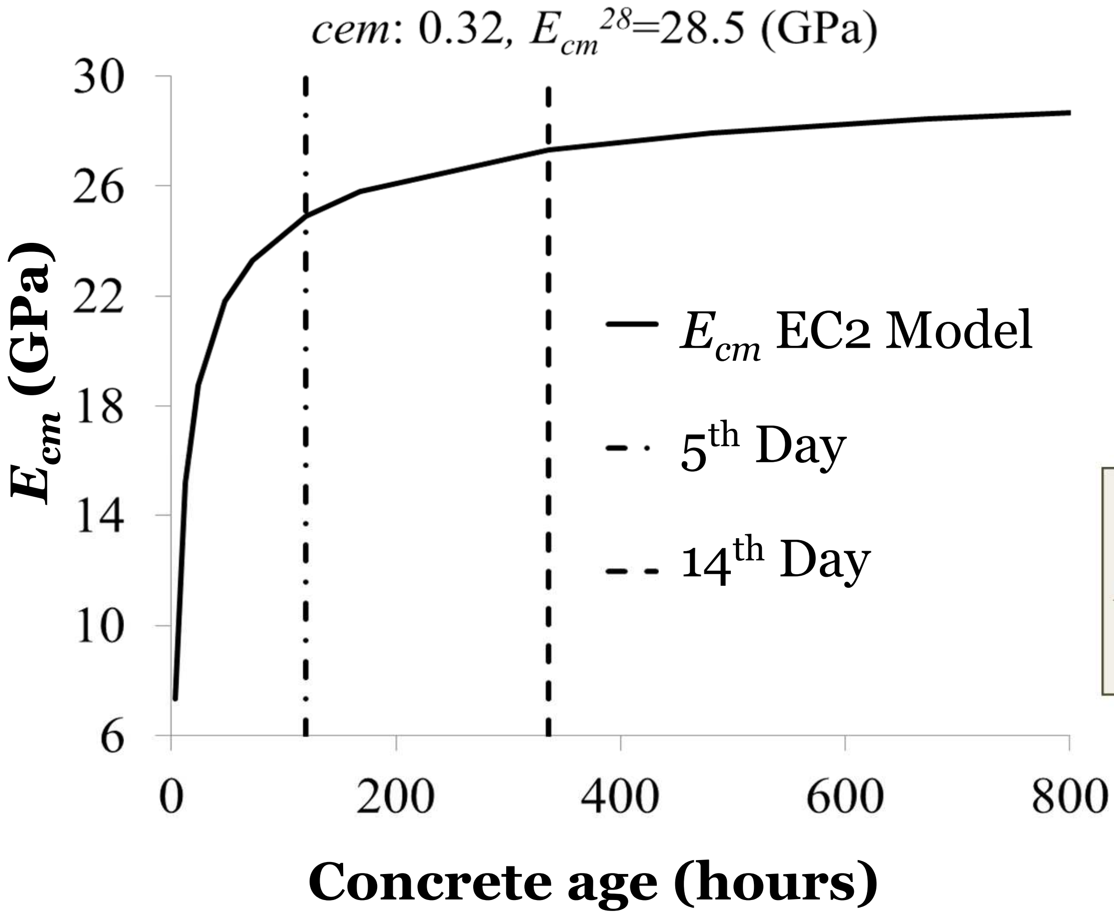
Signatures evaluation: Statistical index RMSD



- RMSD values are increasing continuously until **120 hours** after concrete casting (Age: **5 Days**).
- From **5** to **14** days, RMSD values are varying between 35-45%, depending from the specimen.
- **After 14 days**, RMSD values are stabilized around a specific mean value.

EMI based monitoring of early age concrete

Comparison between RMSD and concrete Young Modulus, time-dependent evolution.



- E_{cm} Model, Eurocode 2 [5.1].
- **5th Day**: 87% of E_{cm}^{28}
- **14th Day**: 96% of E_{cm}^{28}

$$E_{cm}(t) = E_{cm}^{28}\left(\exp\left\{cem\left(1-\sqrt{\frac{672}{t}}\right)\right\}\right)^{0.33}$$

[5.1] **Bamforth P., Chisholm D., Gibbs J.** and **Harisson T., 2008.** Properties of concrete for use in EuroCode 2.

EMI based monitoring of early age concrete

Monitoring of hydration process: 3-48 hours

- RMSD time rate is possible to be correlated with concrete's hydration rate and stiffness development rate (hardening) of very early age concrete (<24hr).
- RMSD time rate indexes

$$DRMSD(t_n)=\begin{cases}\left|\dfrac{\Delta RMSD_n}{\Delta t_n}\right|=\left|\dfrac{RMSD_n-RMSD_{n-1}}{t_n-t_{n-1}}\right| & ,n>1\\ 0 & ,n=1\end{cases}$$

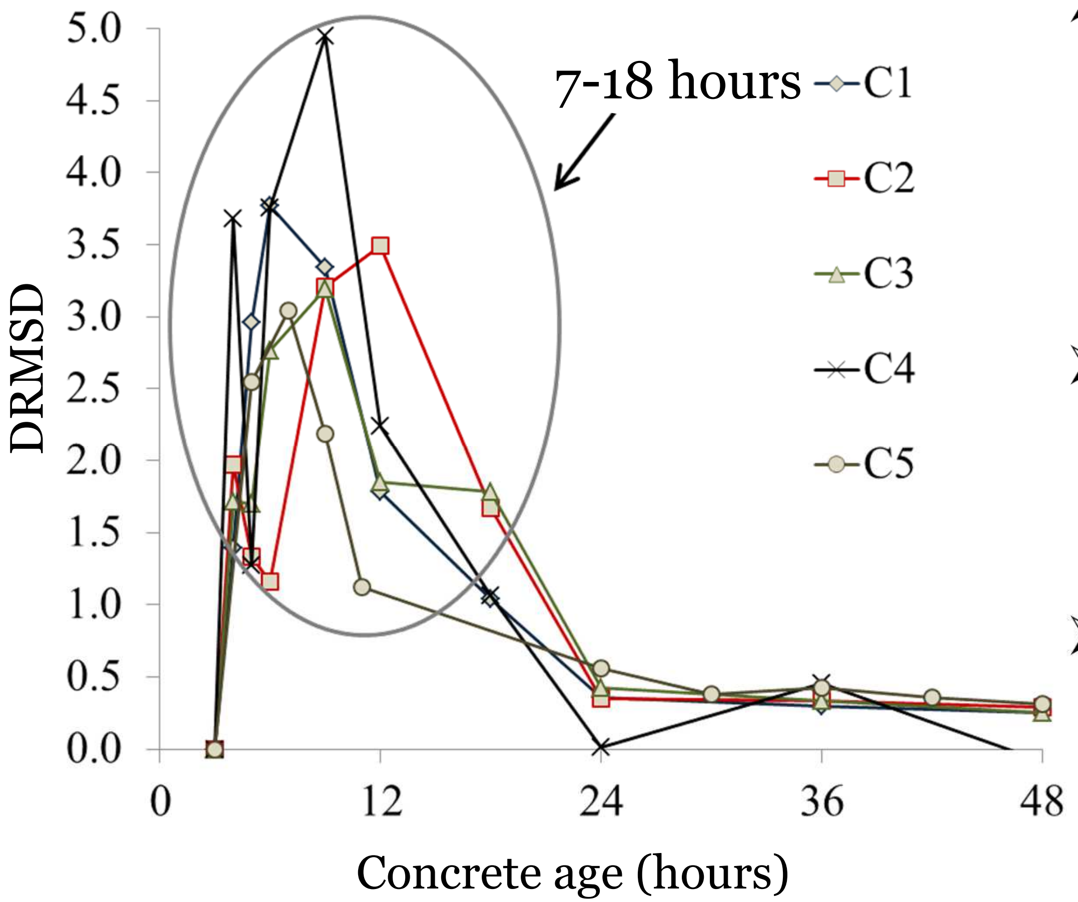
$$RMSD\_R(t_n)=\begin{cases}\dfrac{\sum_{m=1}^{n}\Delta RMSD_m}{\sum_{m=1}^{n}\Delta t_m}=\dfrac{\sum_{m=1}^{n}(RMSD_m-RMSD_{m-1})}{\sum_{m=1}^{n}(t_m-t_{m-1})} & ,n>1\\ 0 & ,n=1\end{cases}$$

t_n: Concrete age corresponding to n-th recorded signature.

t_1: 3 hours (Reference signature recording time)

EMI based monitoring of early age concrete

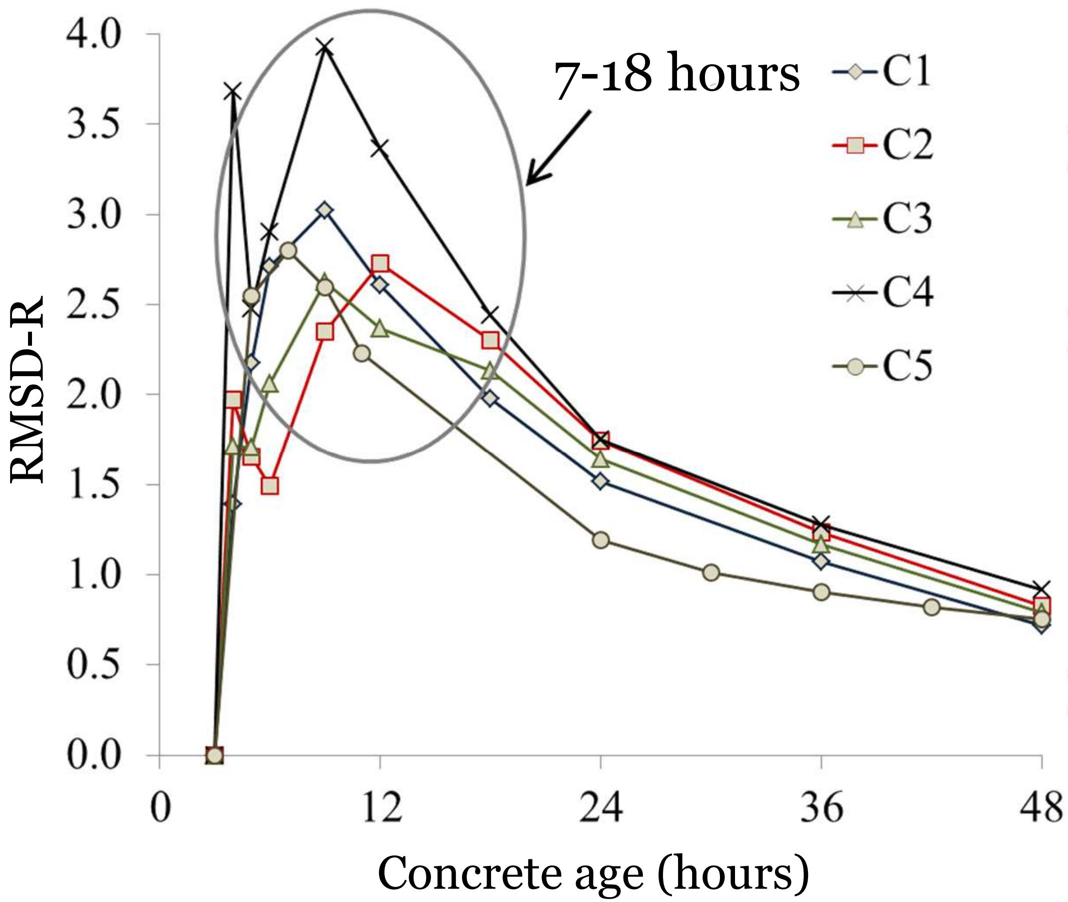
Monitoring of hydration process : *DRMSD*



- Approximately from **3** to **7** hours after cement and water mixing, it is confirmed a rapid growth of *DRMSD*.
- From **7** hours and until **24** there is a normal decreasing of DRMSD values.
- In period between **7 and 18 hours**, depending from specimen, DRMSD index is receiving the maximum value (peak).

EMI based monitoring of early age concrete

Monitoring of hydration process : *RMSD-R*

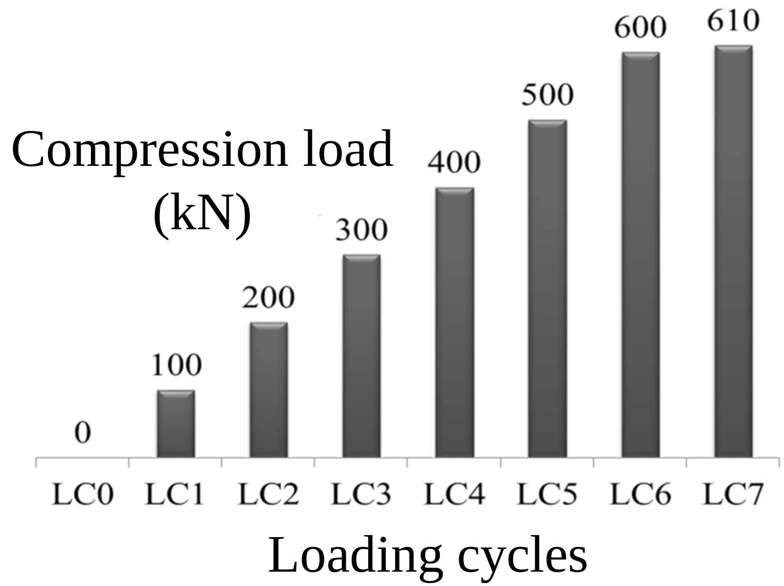


- Proportional behavior with DRMSD index.
- RMSD-R curves are smoother than DRMSD ones.
- Both DRMSD and RMSD-R concrete age dependent evolution, reflects the evolution of cement's hydration rate.
- Hydration rate is strongly related with the rate of water-cement crystals formation, as fresh concrete is being hardened.

Monitoring of damage evolution in a concrete cubic specimen under compression

Concrete specimen compression

- C20/25 concrete cubic concrete specimen
- Edge length: 150mm
- Concrete age: **2 months**
- Final strength after 7 **compressive loading-unloading cycles** with scalar increasing amplitude**: 27.2 MPa**

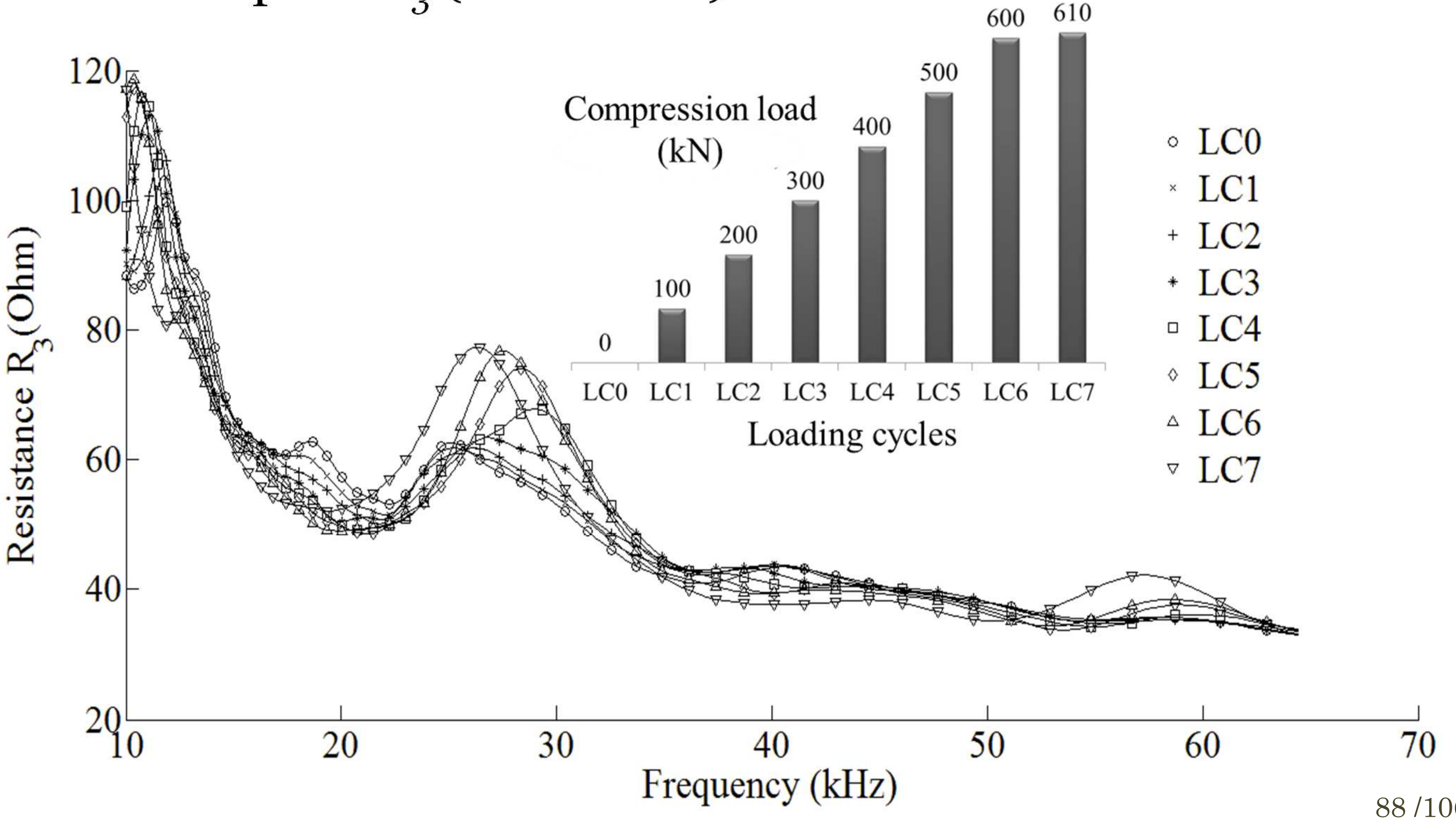


Monitoring of damage evolution in a concrete cubic specimen under compression

- T-WiEYE System.
  - Recording signature: EMI Z_3.
  - Calculation of mechanical impedance: Z_{St}.
  - Frequency range: **10-65 kHz**
- Evaluation of mechanical impedance signatures changes
  - **Reference signature**: Real part of Z_{St} signature which corresponds to undamaged specimen (LC0).
  - Residuals Statistical Control. Normal and GEV distributions.
  - Simulation of **reference signature** utilizing **mMIS** method.

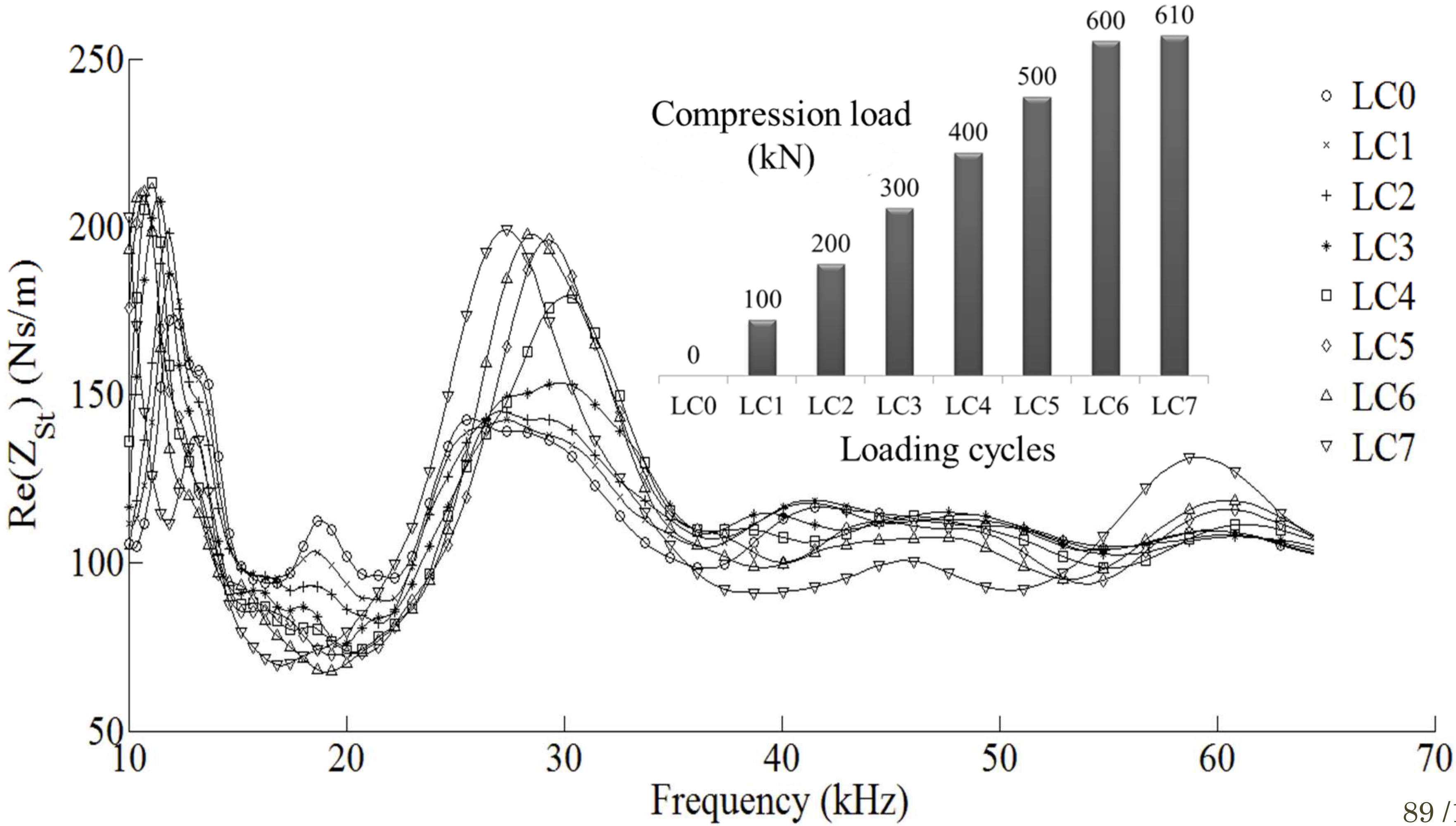
Monitoring of damage evolution in a concrete cubic specimen under compression

- EMI real part: R_3 (Resistance).



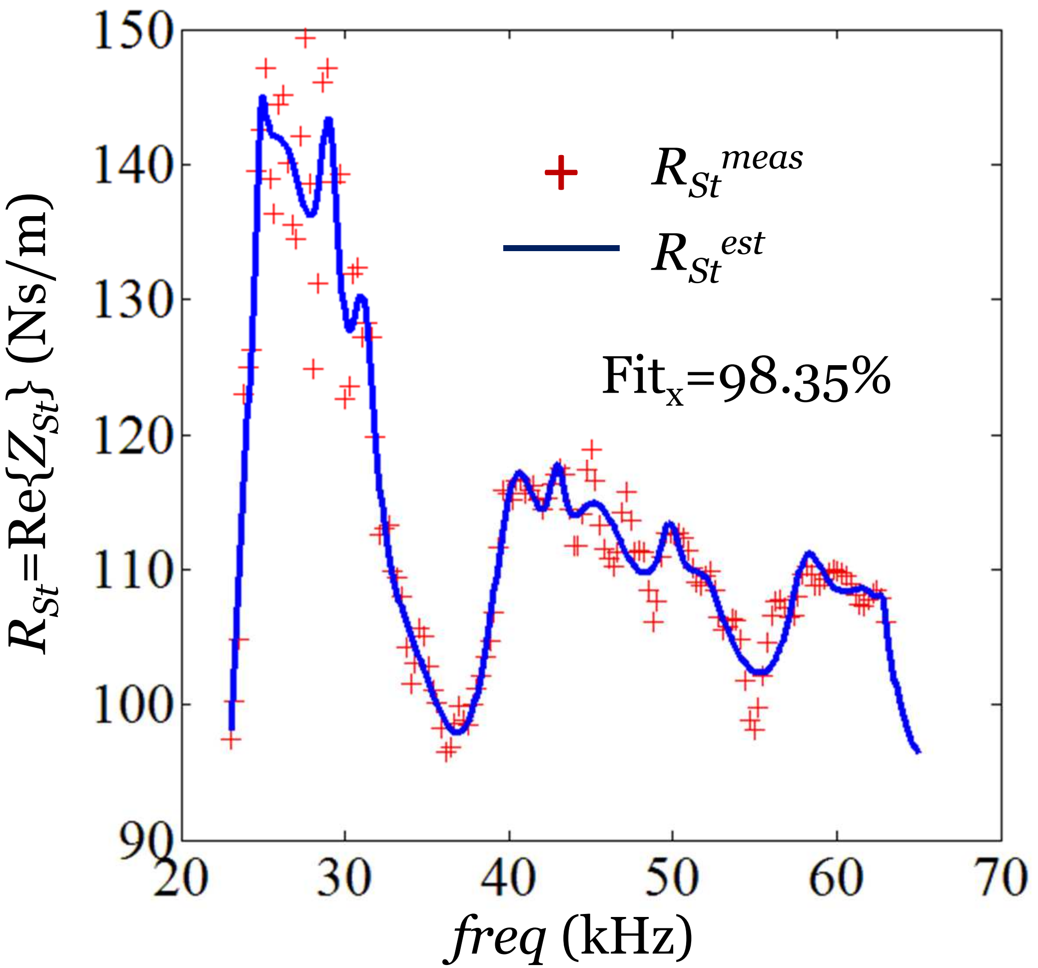
Monitoring of damage evolution in a concrete cubic specimen under compression

- Mechanical impedance real part: R_{St}=Re{Z_{St}}.



Monitoring of damage evolution in a concrete cubic specimen under compression

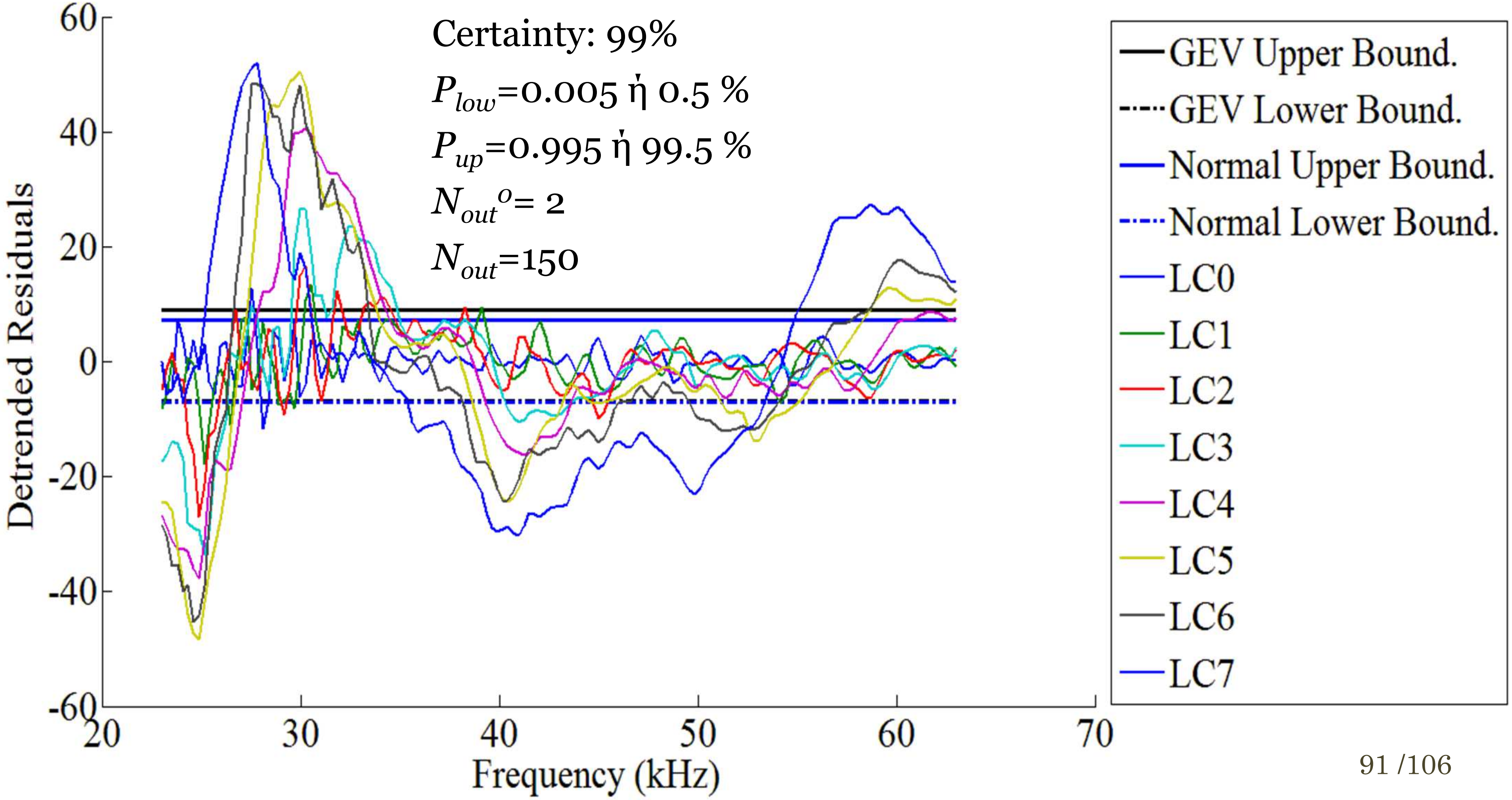
➢ Reference signature simulation (mMIS model) RS^{meas}: Z_{St}^{meas} |LCo



j	$freq_{o,j}$ (kHz)	A_j^{eff} (mm²)	H_j^{eff} (mm)	n_j^{st}
1	24.91	0.10	45.82	0.03
2	31.09	0.40	36.71	0.06
3	29.02	0.37	39.32	0.06
4	24.64	11.89	46.31	0.38
5	40.21	1.50	28.38	0.13
6	42.94	0.07	26.57	0.03
7	33.32	3.05	34.24	0.30
8	44.90	1.12	25.41	0.14
9	51.99	0.05	21.95	0.05
10	59.96	0.52	19.03	0.12
11	62.78	0.01	18.17	0.01

Monitoring of damage evolution in a concrete cubic specimen under compression

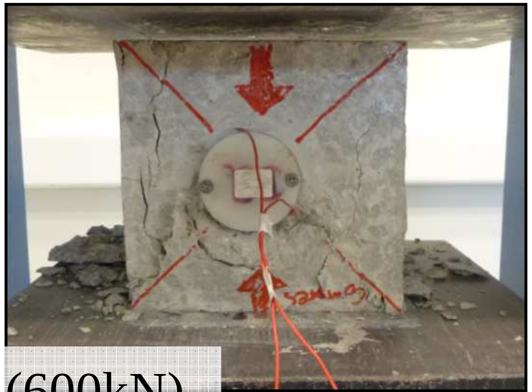
- Statistical control of residuals: $r_{LC0\text{-}7} = (R_{st}^{meas})_{LC0\text{-}7} - R_{St}^{est}$



Monitoring of damage evolution in a concrete cubic specimen under compression

Evaluation of damages evolution

LC7 (610 kN)



LC6 (600kN)

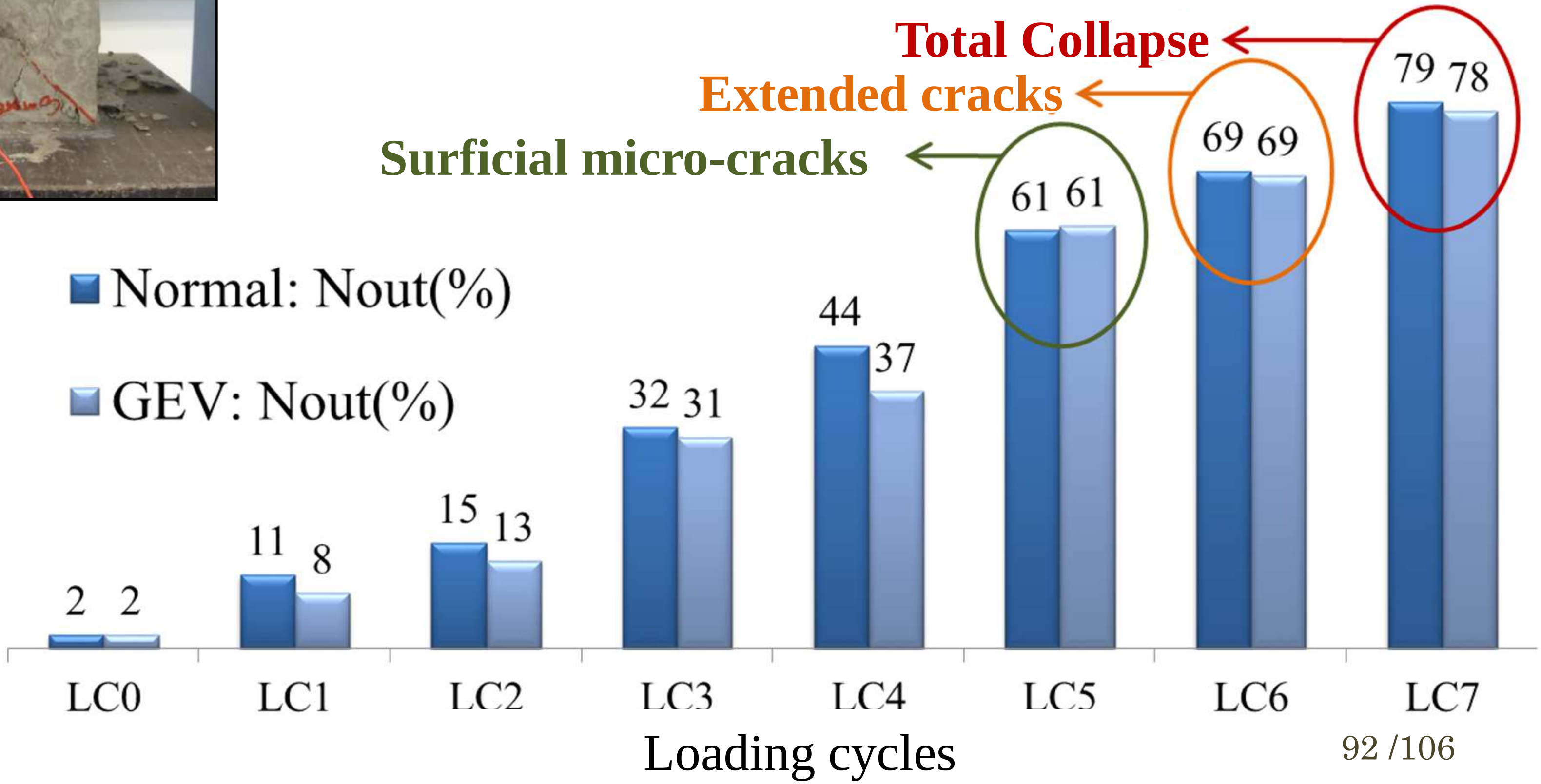
Certainty: 99%

P_{low}=0.005 ή 0.5 %

P_{up}=0.995 ή 99.5 %

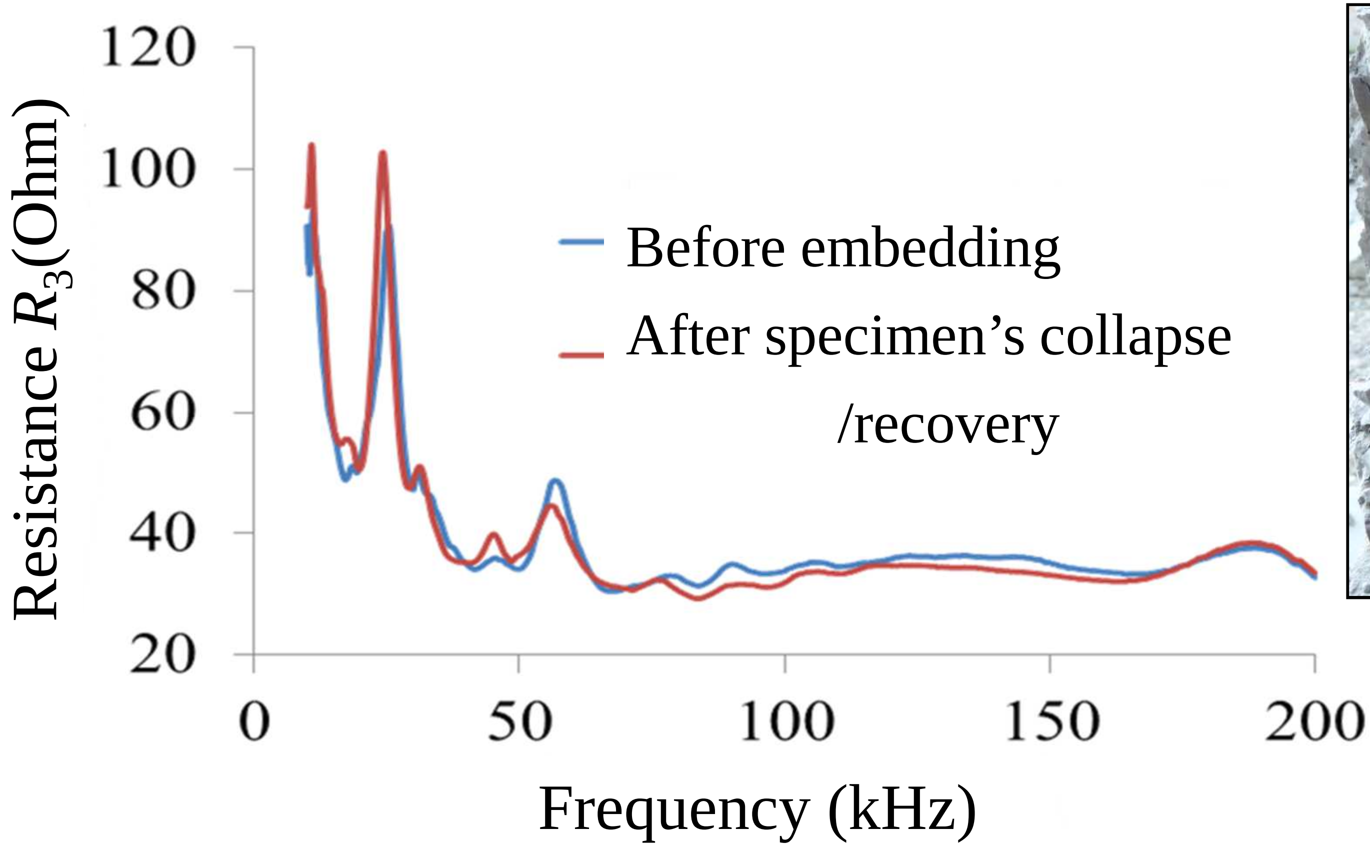
N_{out}^{o}= 2

N_{out}=150



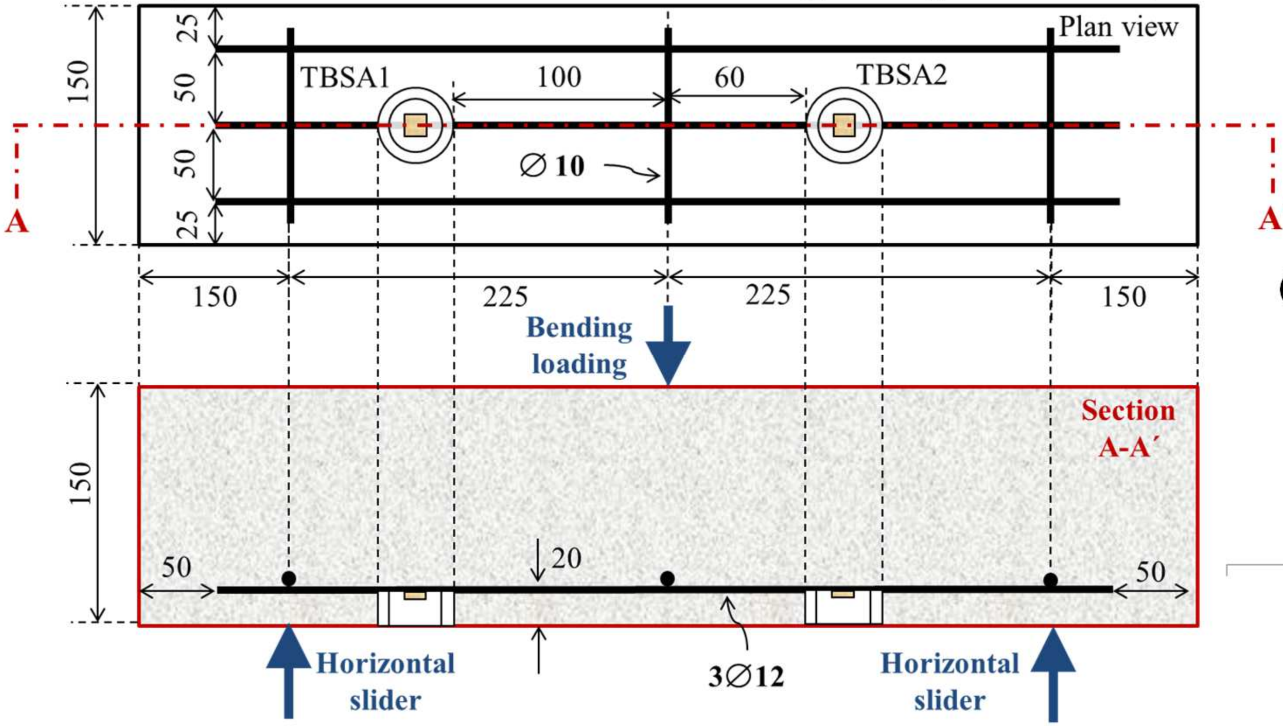
Monitoring of damage evolution in a concrete cubic specimen under compression

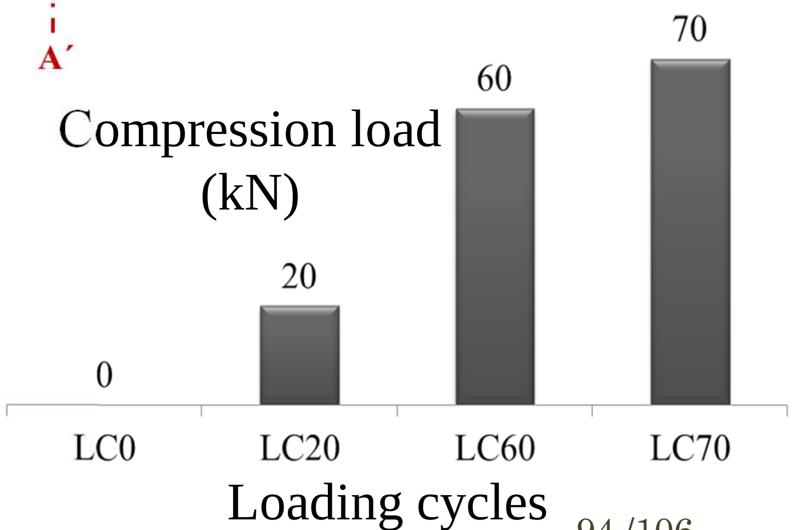
Recover of TBSA after specimen's failure



Monitoring of damage evolution in a concrete beam under bending

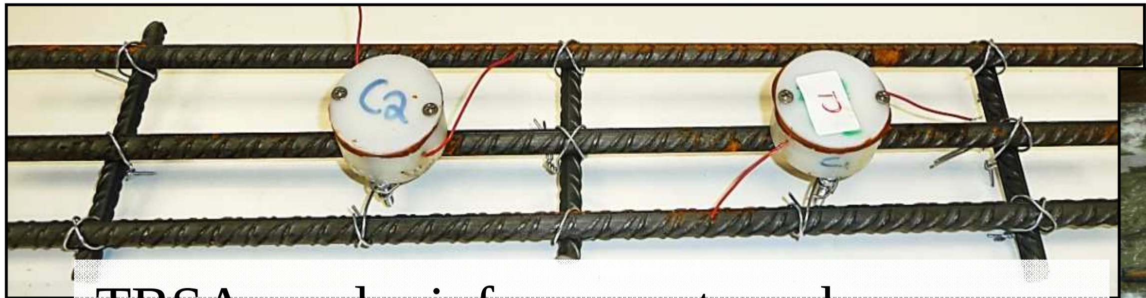
- Concrete beam, **150** x **150** x **750** mm, C20/25.
- Concrete age: **4 months**.
- 3-points bending. Final (collapse) load after **4 loading-unloading cycles** of scalar increasing amplitude: **70 kN**.



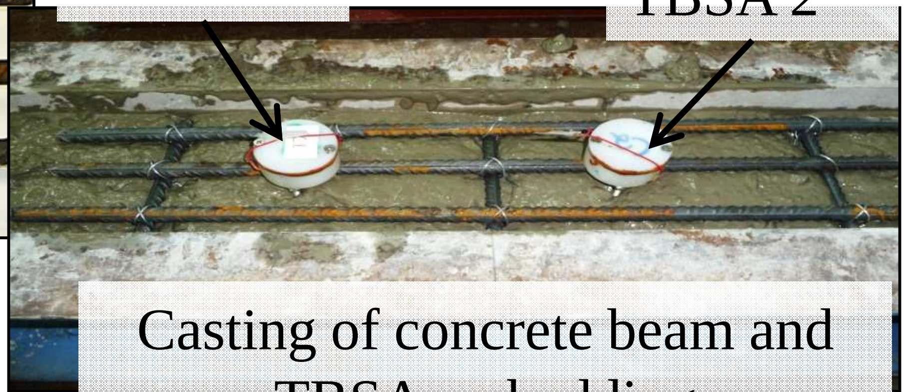


Monitoring of damage evolution in a concrete beam under bending

- Steel bar reinforcement only in tension zone
- TBSA bonding on reinforcement mesh

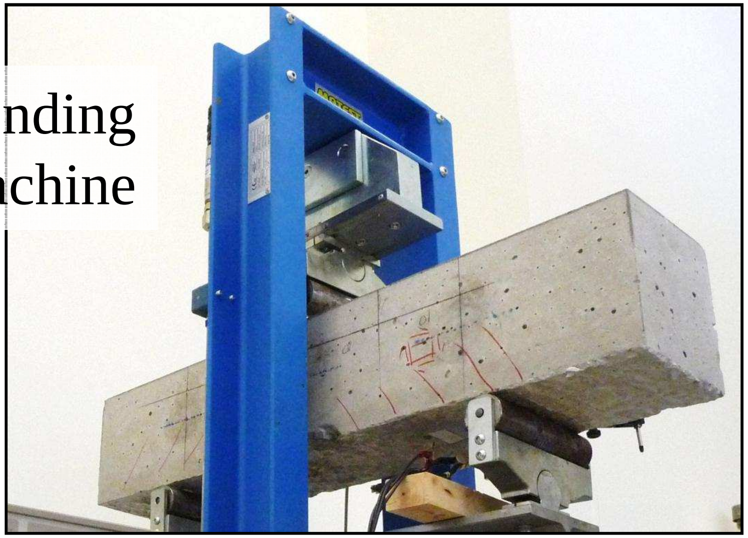


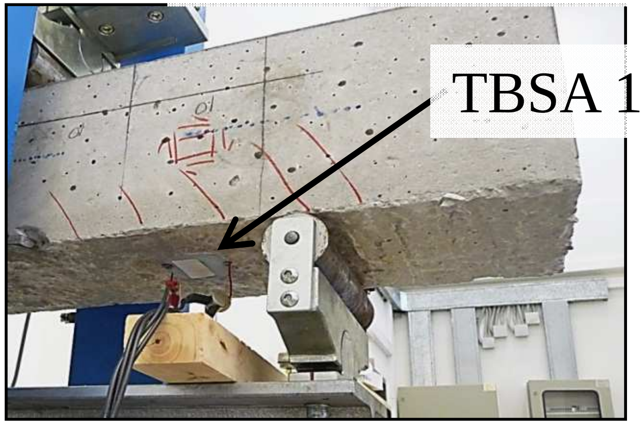
TBSAs and reinforcement mesh



Casting of concrete beam and TBSA embedding

3 point bending machine



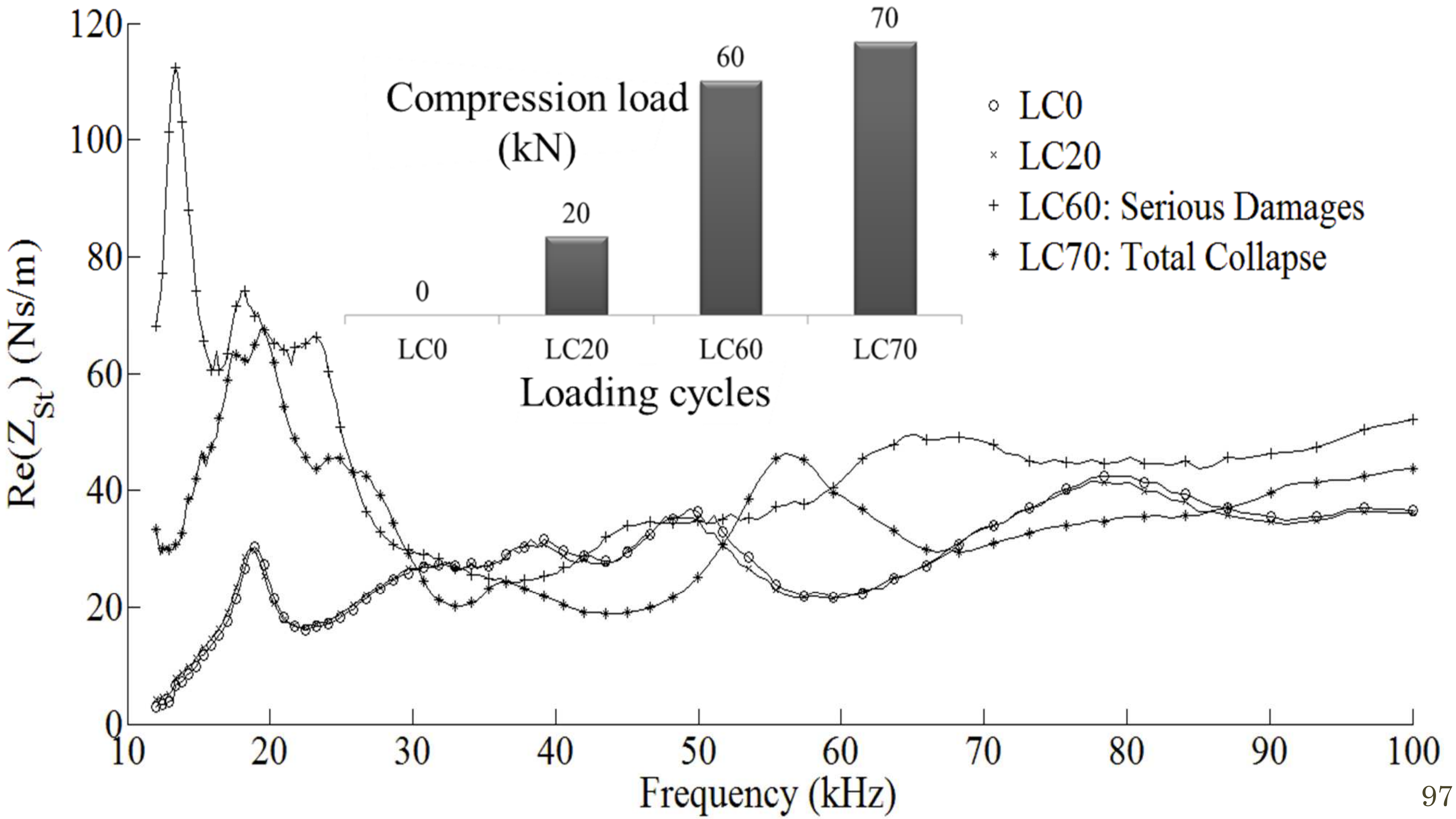


Monitoring of damage evolution in a concrete beam under bending

- T-WiEYE system.
  - Recording signature: EMI Z_3.
  - Calculation of mechanical impedance: Z_{St}.
  - Frequency range: **10-100 kHz**
- Evaluation of mechanical impedance signatures changes
  - Monitoring based only on TBSA 1
  - **Reference signature**: Real part of Z_{St} signature which corresponds to undamaged specimen (LC0).
  - Residuals Statistical Control. Normal and GEV distributions.
  - Simulation of **reference signature** utilizing **mMIS** method.

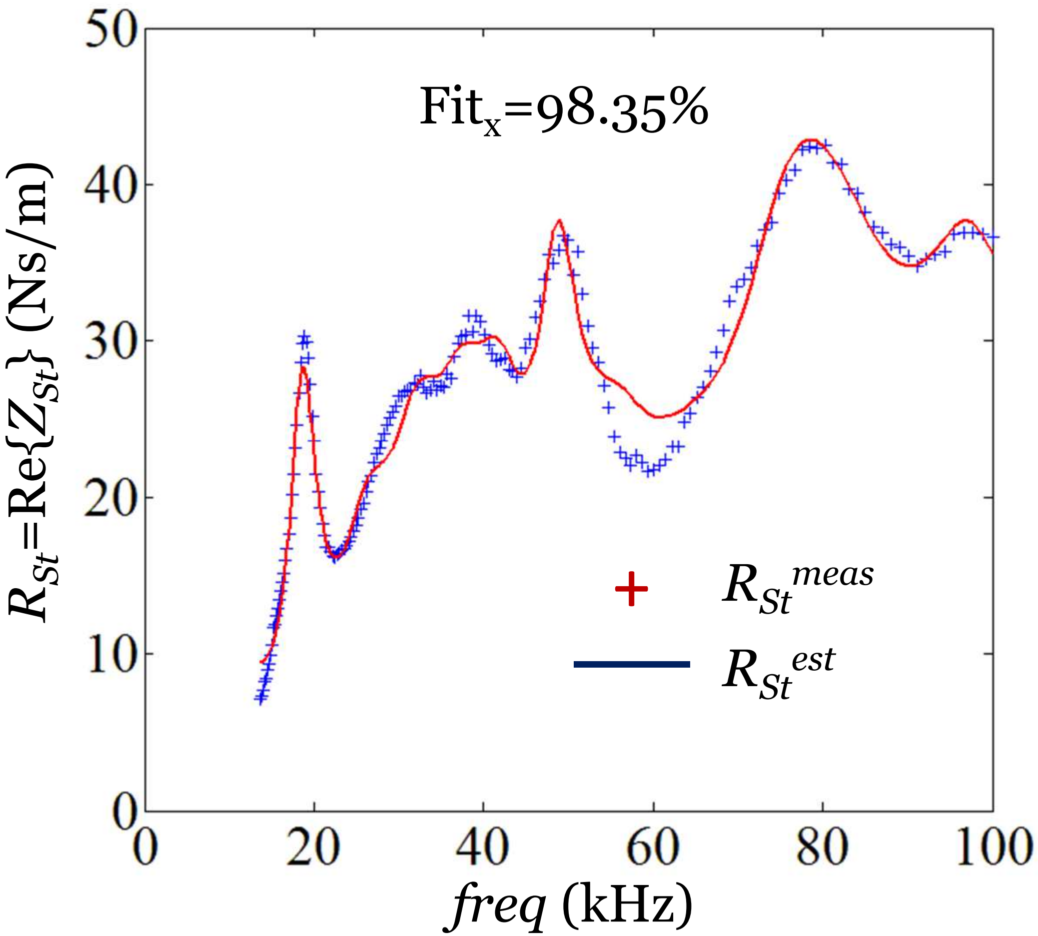
Monitoring of damage evolution in a concrete beam under bending

➢ Mechanical impedance real part: R_{St}=Re{Z_{St}}.



Monitoring of damage evolution in a concrete beam under bending

- Reference signature simulation (mMIS model) RS^{meas}: Z_{St}^{meas} |LCo



j	$freq_{o,j}$ (kHz)	A_j^{eff} (mm²)	H_j^{eff} (mm)	n_j^{st}
1	18.43	1.21	61.91	0.21
2	25.73	0.91	44.36	0.31
3	31.65	0.96	36.05	0.26
4	41.30	0.70	27.63	0.20
5	48.55	0.60	23.50	0.12
6	76.36	1.26	14.94	0.24
7	116.92	2.86	9.76	0.02

Monitoring of damage evolution in a concrete beam under bending

➢ Statistical control of residuals: $r_{LC0\text{-}70} = (R_{st}^{meas})_{LC0\text{-}70} - R_{St}^{est}$

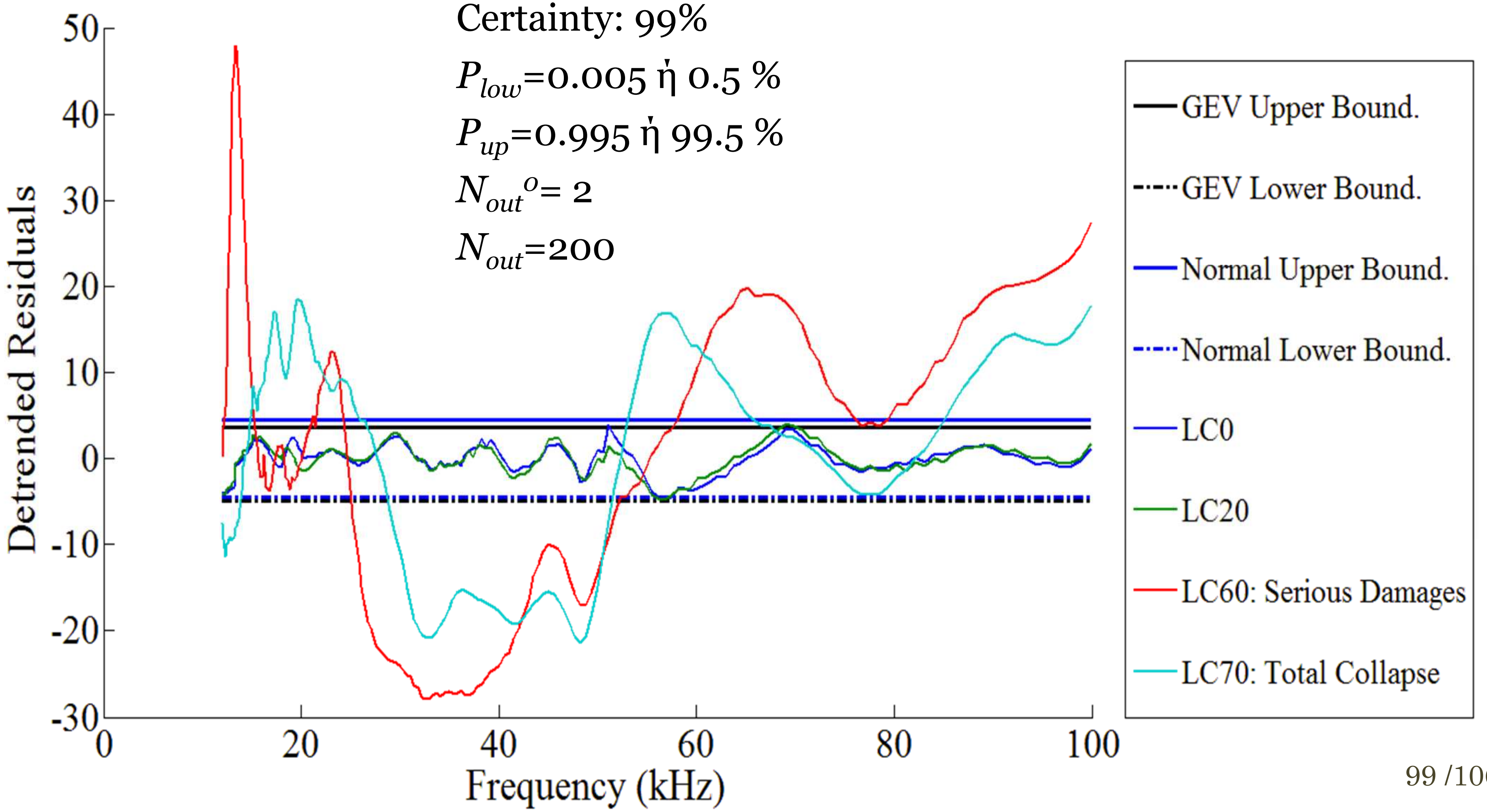
Certainty: 99%

P_{low}=0.005 ή 0.5 %

P_{up}=0.995 ή 99.5 %

N_{out}^{o}= 2

N_{out}=200



Monitoring of damage evolution in a concrete beam under bending

Evaluation of damage evolution: Shear failure

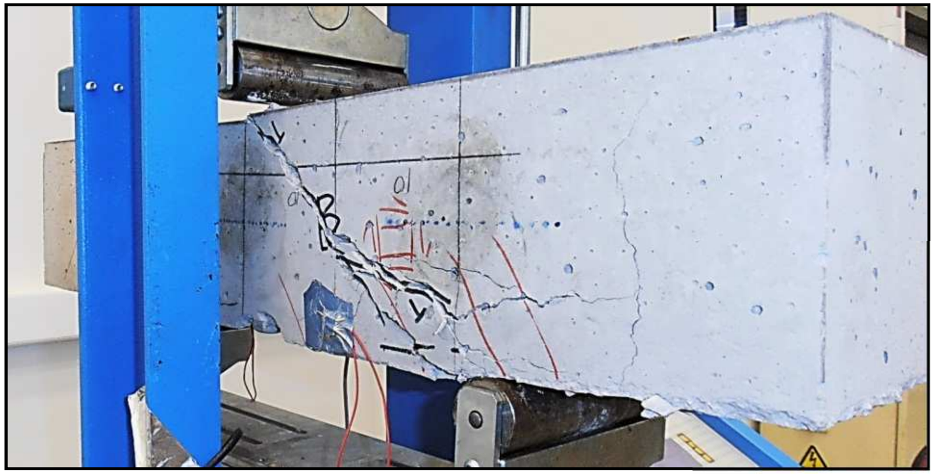
Certainty: 99%

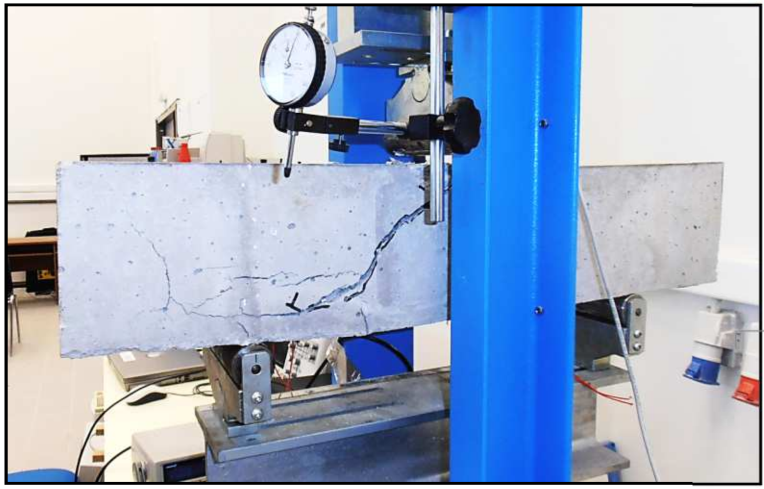
P_{low}=0.005 ή 0.5 %

P_{up}=0.995 ή 99.5 %

N_{out}^{o}= 2

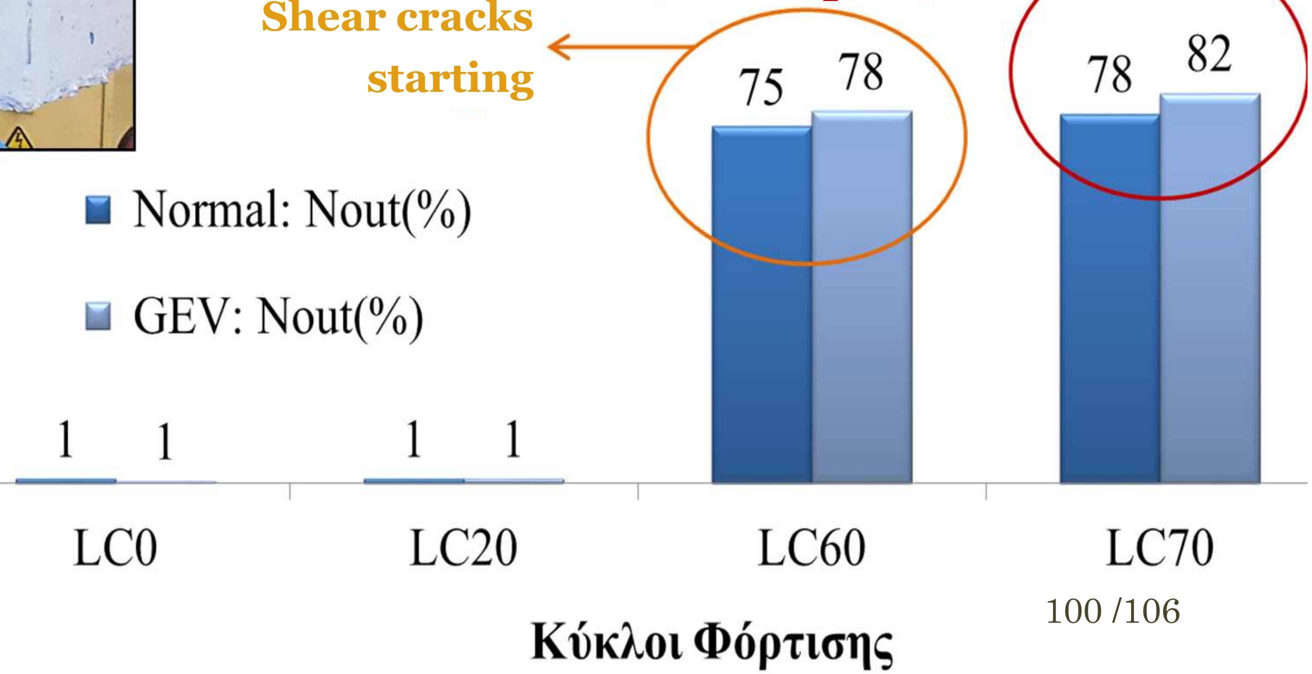
N_{out}=200





Shear crack extending – Total collapse

Shear cracks starting



7.

Conclusions and Proposals for future work

Conclusions

- Ceramic piezoelectric materials and especially PZT (Lead Zirconate Titanate) have successfully adopted in non destructive evaluation methods of concrete constructional elements.
- Based on theoretical analysis of mechanical interaction between PZTs and **Structures Under Monitoring** (**SUM**), it could be stated that the electrical response of a PZT is strongly related with SUM's dynamic response.
- Experimentally acquired **Electro-Mechanical Impedance** (**EMI**) signatures in frequency domain, could be termed as the dominant tool for the monitoring and evaluation of structures dynamic response.

Conclusions

- The dynamic response of a structure which is hosting one or more PZTs, could be approximated semi-experimentally from PZTs measured electrical response (EMI), based on theoretical models that have been developed in context of present dissertation.
- Both the statistical indexes (RMSD, DRMSD, RMSD-R) and residuals statistical control are contributing vitally in comparative analysis of EMI signatures.
- Embedded piezoelectric **SMart Aggregates** (**SMA**) behave as part of concrete's micro-structure, enabling the monitoring of constructional members from the very early stages of hydration and throughout their lifetime.

Conclusions

- An integrated monitoring system which combines the automatic EMI data acquisition and storage, with wireless technology, contributes crucially in the following points :
  - Remote control and continuous inspection of structural integrity.
  - Effective acquisition and classification of large amount of data.
  - Enables the development of an extended multi-SMA grid for the holistic approach of large scale structures monitoring.
- Connection of MySQL's workspace with MATLAB's environment, provides the possibility of immediate post-processing of recording EMI data and time-effective evaluation of structural integrity.

Proposals for future work

- Improvement of Electro-Mechanical Systems response simulation algorithms, by decreasing their complexity.
- Optimization of Teflon Based Smart Aggregate's design, regarding to its shape, PZT gluing adhesive and anchoring bolts set-up.
- Further development EMI data, post-processing MATLAB GUI, and re-scripting of an executable MATLAB-independent application.
- Application of T-WiEYE system in monitoring of large scale concrete structures.
- Investigation of the case where SMAs are applied in structures passive control, acting exclusively as sensors (structure's natural vibration recording, without electrical voltage stimulation).

Thank you for your attention