XXXVIII Cycle PhD in Civil and Envinronmental Engineering

Politecnico di Torino
Dipartimento di Ingegneria Strutturale, Edile e Geotecnica

NONLINEAR MODELLING AND CALIBRATION OF COMPUTATIONAL SIMULATORS

Linda Scussolini

Academic tutors: R. Ceravolo, G.A. Ferro

SCAN ME

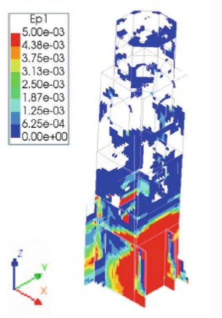
RESEARCH CONTEXT

WHAT IS MODEL CALIBRATION IN STRUCTURAL ENGINEERING?

Model calibration consists in ***estimating the parameters*** of a model by ***minimizing an error function*** measuring the distance between the observed and the simulated data.

The calibration of models, either linear or nonlinear, is fundamental in the field of structural engineering to ***properly simulate*** the real behaviour of a structure, and also to ***support the design*** of proper strengthening interventions.

For these reasons, linear model correlation and validation is a well-estabilished technique in the scientific literature[1]. However, ***the world we live in is nonlinear***.



Simulation of the crack pattern on the calibrated model of the bell tower of the cathedral of Fossano (CN)

LINEAR VS. NONLINEAR: WHICH ONE TO CHOOSE?

Often, if the nonlinearity is negligible for the structural response, the accuracy of the solution is not compromised, and one can rely on these well-known methods.

In the case of extreme events, such as earthquakes, the linearity assumption that generally holds for the dynamic behaviour of relatively simple civil structures under operational conditions should be carefully verified.

If excited by strong excitations, more ***structurally complex systems*** may exhibit non-linear behaviour, which can be difficult to predict, understand and monitor.

Failure at the joints of a bridge

Seismic pounding between adjacent buildings

STILL AN OPEN ISSUE?

Several applications can be found in the case of mechanical systems. In the field of structural engineering the applications are:

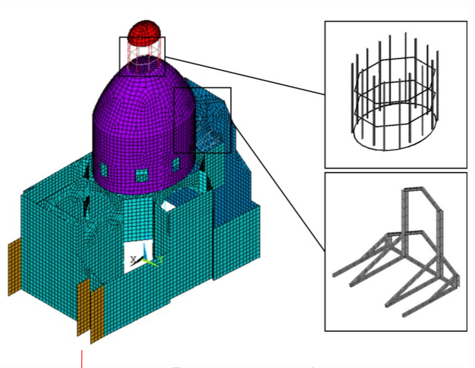
1. mostly **limited to numerical studies**;
2. experiments on **laboratory-controlled systems**;
3. **not** yet related to **real existing structures**;

Moreover, the extension of the already existing methods[2,3], which often are studied for mechanical Single Degree of Freedom (SDoF) systems, to Multi Degree of Freedom (**MDoFs**)systems is **challenging** to realize.

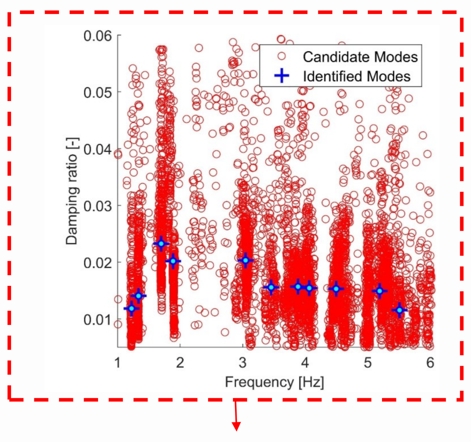
LINEAR CALIBRATION OF REAL COMPLEX STRUCTURES

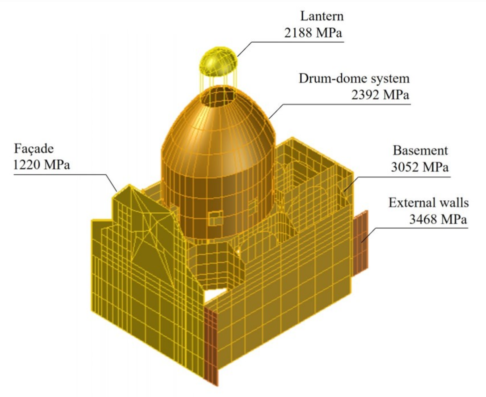
CHURCH OF SANTA CATERINA IN CASALE MONFERRATO (AL)

1. Preliminary mechanical model
2. Identification of modal parameters
3. Updating of mechanical parameters



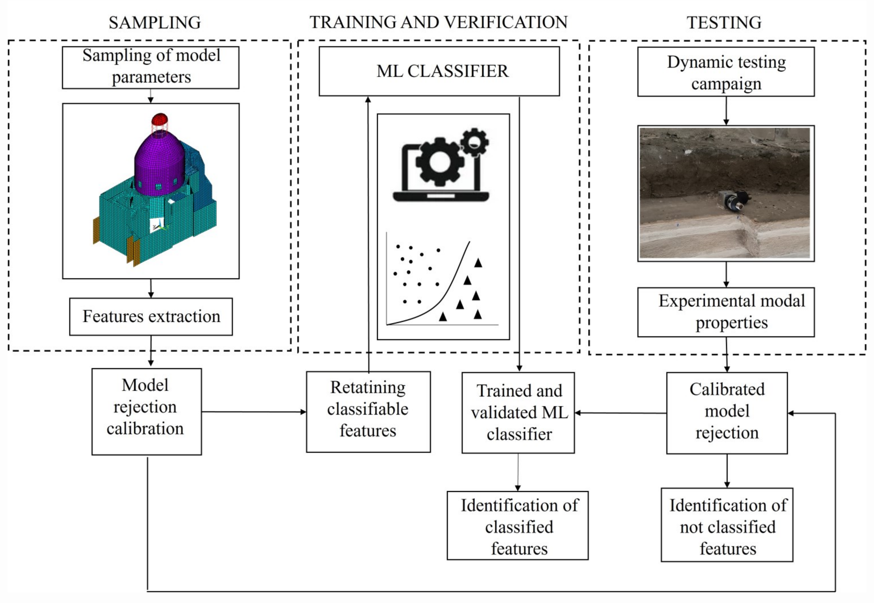
Presence of temporary installations due to restoration works



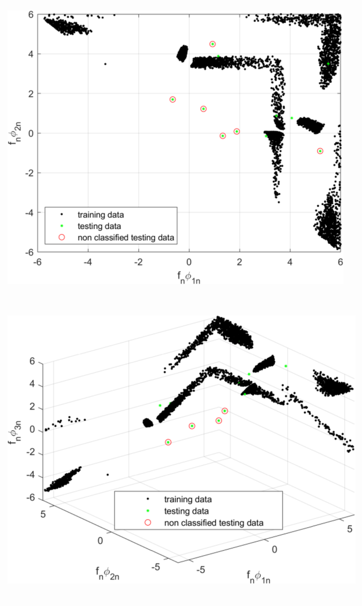


WHICH MODES SHOULD BE USED FOR UPDATING AMONG THE IDENTIFIED ONES?

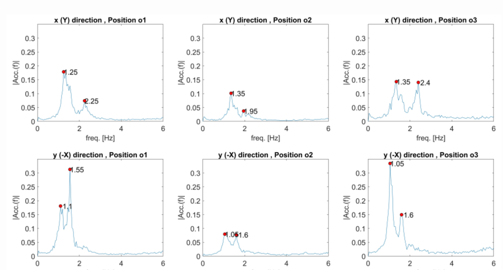
DEVELOPMENT OF TECHNIQUES TO ***SEPARATE*** THE STRUCTURAL ***MODES*** FROM THE NON-STRUCTURAL ONES



Workflow of the proposed procedure based on a model-driven approach using a SoftMax classifier



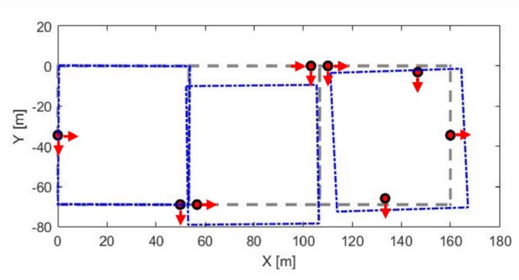
Results

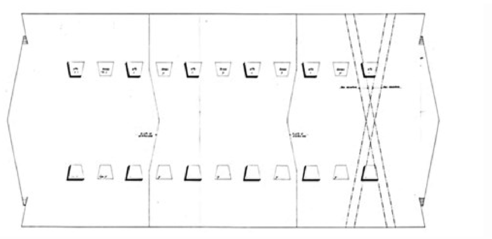


Experimental validation through a MEMS accelerometer placed on non-structural parts (in this case, a scaffolding)

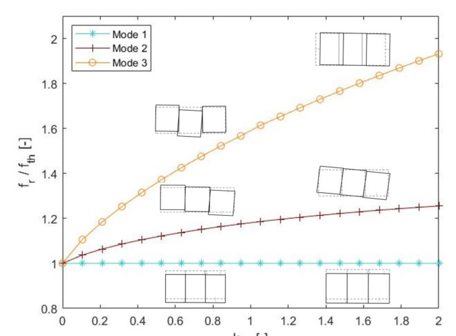
PAVILLION V OF TORINO ESPOSIZIONI (RICCARDO MORANDI)

1. Identification of the modal parameters (here represented the mode shape at 2.57 Hz)
2. Parametric study on the behaviour of collaborating diaphragmatic blocks
3. Single block calibration

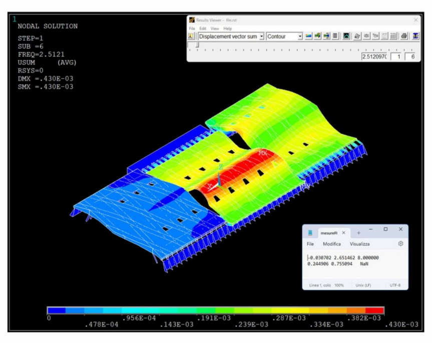




Plan of the structure

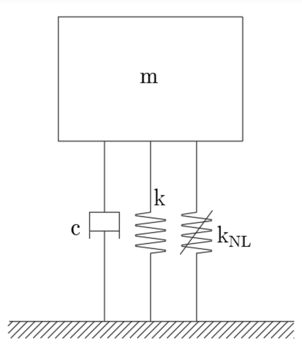


Variation of the ratio between the natural frequency and the theoretical fundamental frequency for different values of the spring stiffness of the interacting joints



The mechanical parameters of the blocks are calibrated singularly, and then unified in the preliminary model, showing a good agreement with the experimental results

THEORETICAL KNOWLEDGE OF NONLINEAR SYSTEMS



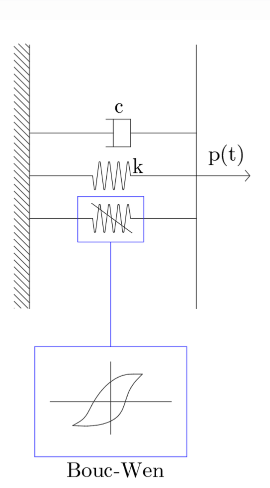
SDOF mass-lumped system with mass m, damping c, linear stiffness k and nonlinear stiffness k_{NL}

The easiest way to simulate a nonlinearity is to vary the stiffness of the dynamic system.

HOW TO ***MODEL*** THE ***NONLINEAR STIFFNESS*** k_{NL}?

Several models exist, among others:

- Duffing oscillator: **HYSTERETIC BEHAVIOUR WITHOUT MEMORY**
- Bouc-Wen-Baber-Noori (BWBN) model of hysteresis: **HYSTERETIC BEHAVIOUR WITH MEMORY**



WHICH MODEL?

The Duffing oscillator is one of the simplest models, but sometimes, it not sufficient to describe a hysteretic behaviour with memory (i.e., the derivative of the restoring force does not depend on the velocity).

In the case of civil structures, plastic hysteresis is a common behaviour model, especially in the case of strong excitations.

NONLINEAR CALIBRATION OF STRUCTURAL SIMPLIFIED MODELS

IDENTIFICATION PROCEDURE

In general, the **characterization** of a vector of parameters $\{p\} = \{p_1, p_2, \dots, p_k, \dots, p_{m-1}, p_m\}$ can be performed in the time-domain by **minimizing** an **error function** $\boldsymbol{J}$. Defining n as the total number of iterations, the residual error function J can be defined for each j-th iteration as follows:

$$J(j,\{p\}) = \sum_{j=1}^{n-1} \left| \left(\ddot{u}_{sim}(j,\{p\}) - \ddot{u}_{meas}(j) \right) \right|$$

This error function provides a **measure of the distance between the simulated response** $\boldsymbol{\ddot{u}_{sim}}$ for a given configuration of the set of parameters $\{p\}$ **and the measured response** $\boldsymbol{\ddot{u}_{meas}}$ at the iteration j. The **identified set of parameters** $\boldsymbol{\{p_{id}\}}$ is given by:

$$\{p_{id}\} = \arg(\min(J(j,\{p\})))$$

CHARACTERIZATION OF A SDoF SYSTEM UNDER EARTHQUAKE EXCITATION WITH BWBN TYPE NONLINEARITY

Equation of motion

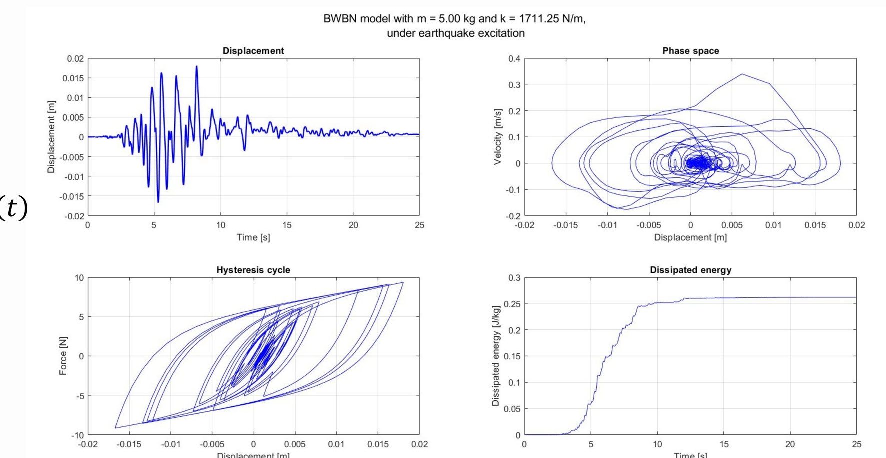
$$m\ddot{u} + c\dot{u} + f_r(u(t), z(t)) = -m\ddot{u}_g$$

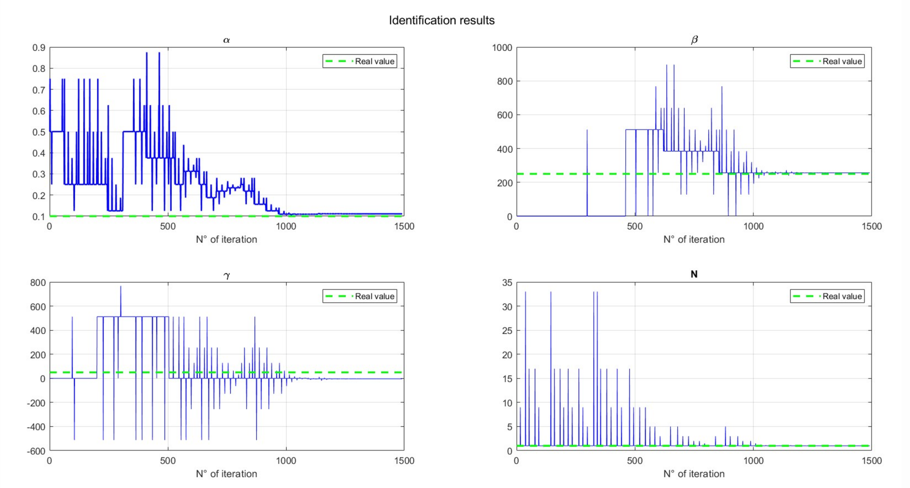
Restoring force

$$f_r(u(t), z(t)) = f_r^{el}(u(t), z(t)) + f_r^{h}(u(t), z(t)) = \alpha k u(t) + (1-\alpha) k z(t)$$

Hysteretic displacement

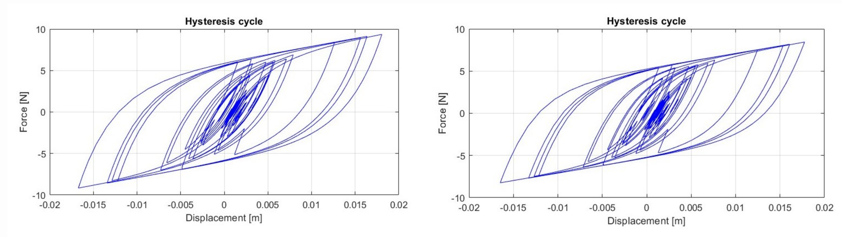
$$\dot{z}(t) = \frac{A(\varepsilon)\dot{u}(t) - \nu(\varepsilon)[\beta|\dot{u}(t)||z(t)|z(t) + \gamma \dot{u}(t) z(t)]}{\eta(\varepsilon)}$$



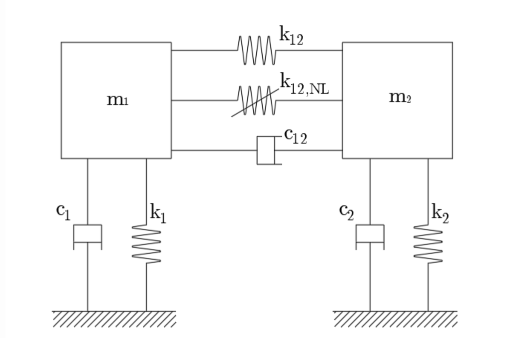


The hysteresis cycle shows a good fit between the exact and the simulated response, confirming the goodness of the restoring force function used. However, in the simulated response, for equal values of the displacement, the system showed slightly higher values of the restoring force.

Simulated vs. exact hysteresis cycle

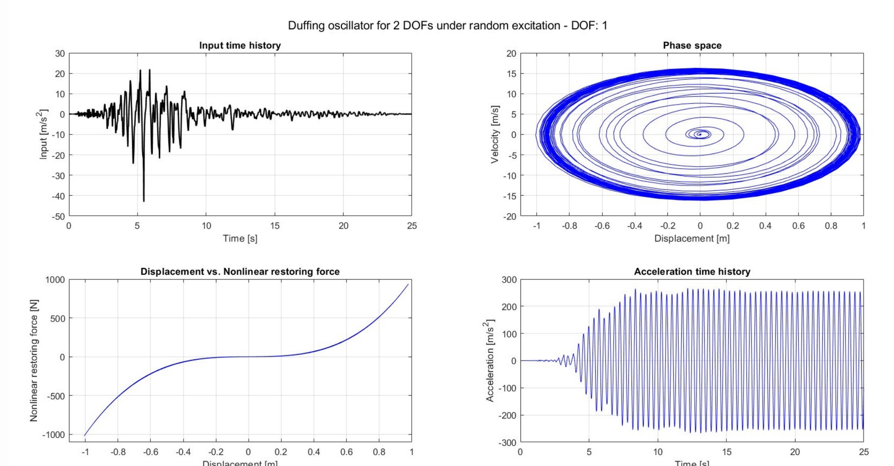


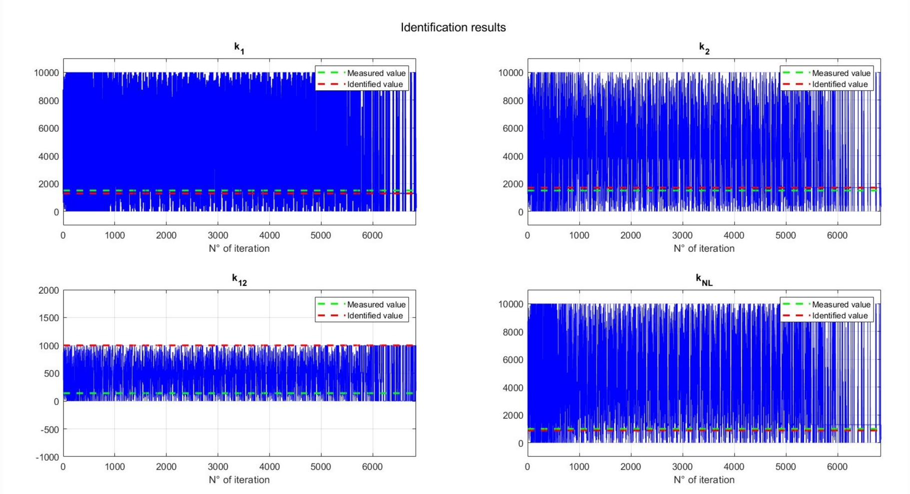
CHARACTERIZATION OF A 2 IN PARALLEL-DoFs SYSTEM UNDER EARTHQUAKE EXCITATION WITH DUFFING TYPE NONLINEARITY AT THE INTERACTION



Equation of motion

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + c_{12} & -c_{12} \\ -c_{12} & c_2 + c_{12} \end{bmatrix} \begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_{12} & -k_{12} \\ -k_{12} & k_2 + k_{12} \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} + \begin{bmatrix} k_{NL,12} & -k_{NL,12} \\ -k_{NL,12} & k_{NL,12} \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix}^3 = -\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \{\ddot{u}_g\}$$





To consider the error related to the two masses separately, the identification was carried out through a multi-objective optimization algorithm.

The procedure provided overall good results, except for the stiffness describing the linear interaction.

Criticalities

- > number of DoFs, > complexity of system
- Four is the limit number of parameters to obtain an acceptable result
- High computational effort

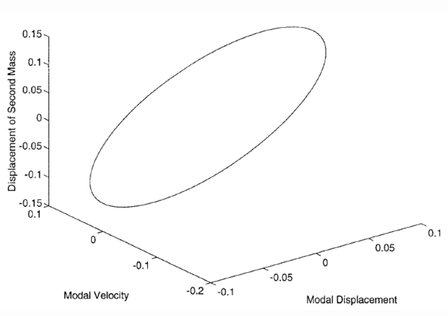
CONCLUSIONS

- Even in the range of small linear deformation (such as in the case of ambient vibrations) analysing and understanding the behaviour of civil structures may be challenging, such as the case of structures undergoing variations of configurations (due for instance to temporary installations) or structures composed by several interacting bodies.
- When dealing with nonlinearities, the situation is even more complicated. Although simple identification procedures could lead to acceptable results, even increasing of just one DoF could be a major issue.
- If the nonlinearities are localised, such as in the case of nonlinearity at the interaction spring, specific analytical models should be formulated, and costumized accordingly to the type of simulated nonlinearity.
- Moreover, the number of parameters of nonlinear systems to be calibrated is often high (see for instance a BWBN model), but it is known that the number of parameters to be calibrated should not be too high (this is true also for linear procedures),

FUTURE WORKS

FURTHER NUMERICAL INVESTIGATIONS

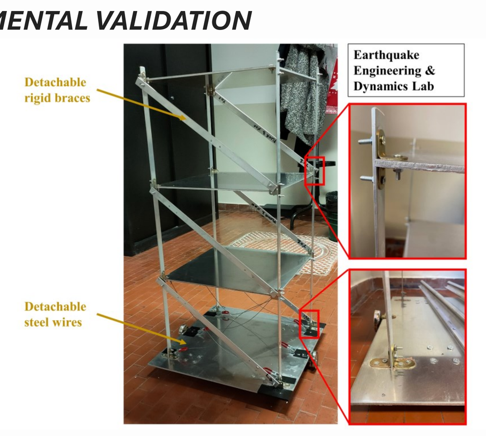
Investigating other metrics to correlate the simulated and the measured response of more complex systems (e.g., a Finite Element Model). This can be done for instance using the Nonlinear Normal Modes (NNM), which are the nonlinear alterego of the vibrational modes.



Representation of a NNM (Slater, 1993)

EXPERIMENTAL VALIDATION

Validating identification procedures on laboratory-controlled structures and then calibrating the parameters of simple real structures, such as bell towers, approximated to well-known structural models (e.g., cantilever beams)



DISSEMINATION ACTIVITIES

Scientific journals

Ceravolo, R., Lenticchia, E., Miraglia, G., Oliva, V., & **Scussolini, L.** (2022). Modal Identification of Structures with Interacting Diaphragms. *Applied Sciences*, *12*(8), 4030.

Ceravolo, R., Lenticchia, E., Miraglia G., **Scussolini, L.** (2023). Open-world classification problem to solve vibration modes separation in structural systems using model-based approaches . *Measurements* (under submission).

Conferences

Scussolini, L., Coletta, G., Oliva, V., Miraglia, G., Lenticchia, E., & Ceravolo, R. (2022, June). Sensitivity Analysis of the Environmental Effect on the Dynamics of Concrete Historical Architectures with Structural Joints. In European Workshop on Structural Health Monitoring (pp. 81-88). Cham: Springer International Publishing.

Miraglia, G., Cavanni, V., Crocetti, A., Lenticchia, E., Oliva, V., **Scussolini, L.**, and Ceravolo, R., (2023, June). Digital twinning for the prognosis of spatial architectures: Morandi's underground pavilion in Turin. In Proceeding of Italian Workshop on Shell and Spatial Structures 2023 (IWSS2023), Lecture Notes in Civil Engineering book.

Scussolini, L., Foti, V., Civera, M., Ceravolo, R., & Pistone, G. (2023, August). Redesign of Strengthening Interventions on Historical Buildings. The Case Study of an Earthquake-Damaged Bell Tower. In International Conference on Experimental Vibration Analysis for Civil Engineering Structures (pp. 708-717). Cham: Springer Nature Switzerland.

Scussolini, L., and Ceravolo, R. (2024, June). Model selection for nonlinear interacting in-parallel masses under seismic excitation. In World Conference of Earthquake Engineering (submitted).

REFERENCES

1. Mottershead, J. E., & Friswell, M. I. (1993). Model updating in structural dynamics: a survey. Journal of sound and vibration, 167(2), 347-375.
2. Kerschen, G., Worden, K., Vakakis, A. F., & Golinval, J. C. (2006). Past, present and future of nonlinear system identification in structural dynamics. Mechanical systems and signal processing, 20(3), 505-592.
3. Noël, J. P., & Kerschen, G. (2017). Nonlinear system identification in structural dynamics: 10 more years of progress. Mechanical Systems and Signal Processing, 83, 2-35.

ATTENDED CLASSES

Hard skills (124 hours)

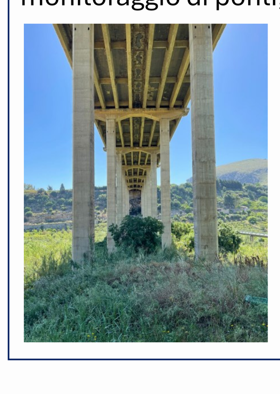
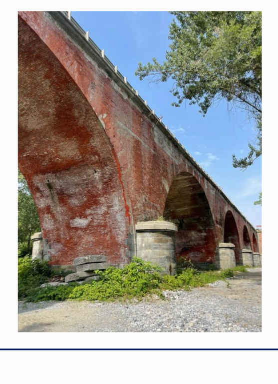
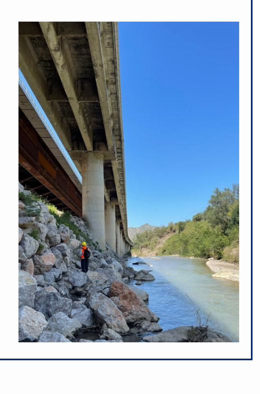
- Experimental modeling: costruzione di modelli da dati sperimentali
- Dinamica e identificazione di sistemi non lineari
- Programmazione scientifica avanzata in Matlab
- Tecniche innovative per l'ottimizzazione
- Rischio sismico dei beni culturali

Soft skills (32 hours)

- Writing scientific papers in english
- Facing the scientific publishing world
- Research integrity
- Time management

INVOLVEMENT IN PROJECTS

Fabre - Consorzio nazionale di ricerca per la valutazione e il monitoraggio di ponti, viadotti e altre strutture

TEACHING ACTIVITIES

Course tutor:

Earthquake engineering, A.Y. 2022/2023 – A.Y. 2023/2024

MSc thesis co-supervisor:

Marta Di Carlo, "Analisi e progetto del miglioramento sismico della facciata della chiesa barocca di Santa Caterina a Casale Monferrato".

Valerio Foti, "Identificazione di meccanismi di collasso e valutazione di interventi di miglioramento sismico su torri campanarie: il caso del Campanile di Fossano"

Daniele Leoni, "Calibrazione dinamica di modelli per architetture storiche a blocchi collaboranti: il caso studio del padiglione Morandi"

Alessio Crocetti, "Machine Learning approaches for damage detection strategy in Structural Health Monitoring: application to experimental data"

Valeria Cavanni, "Transfer Learning between full-scale Structure Health Monitoring systems: application to oval masonry domes"