Development of a robust and reliable software framework for real-time hybrid simulation (RTHS)

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Co-supervisor

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Outline

- ❑ Introduction
- ❑ Software framework for RTHS
- ❑ Development and validation of a software framework for RTHS
  - ✓ Middleware-based scheme
  - ✓ Middleware-free scheme
- ❑ Conclusion and limitations
- ❑ Future directions in RTHS

Introduction

Kobe earthquake, 1995

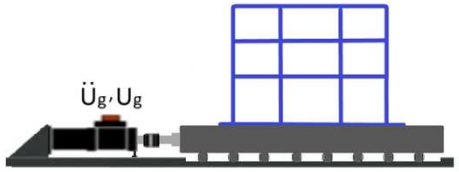
The role of experimental methods?

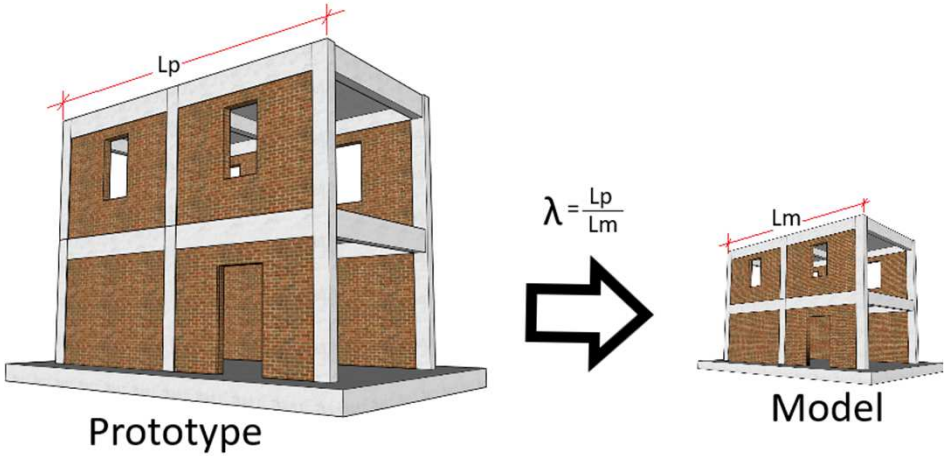
- Calibration of numerical models
- Validation of techniques for mitigating seismic risk
- Developing and revising design code provisions
- Design of important structures
- Seismic risk assessment, etc.

Introduction

Shaking table test:

$$M\ddot{U}_{i+1} + C\dot{U}_{i+1} + P_r = -M\ddot{U}_g$$

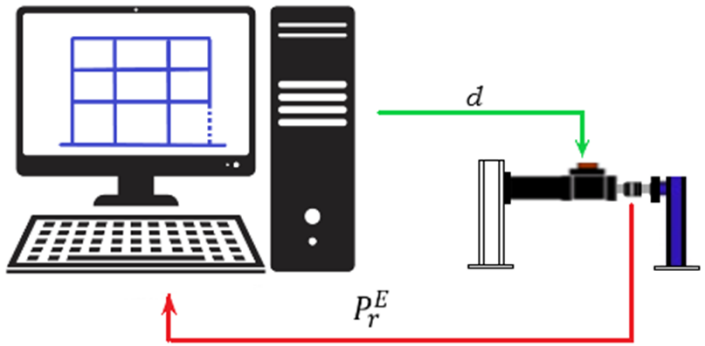




- Limitations of full-scale testing

Hybrid simulation:

$$M\ddot{U}_{i+1} + C\dot{U}_{i+1} + P_r^N + P_r^E = -M\ddot{U}_g$$

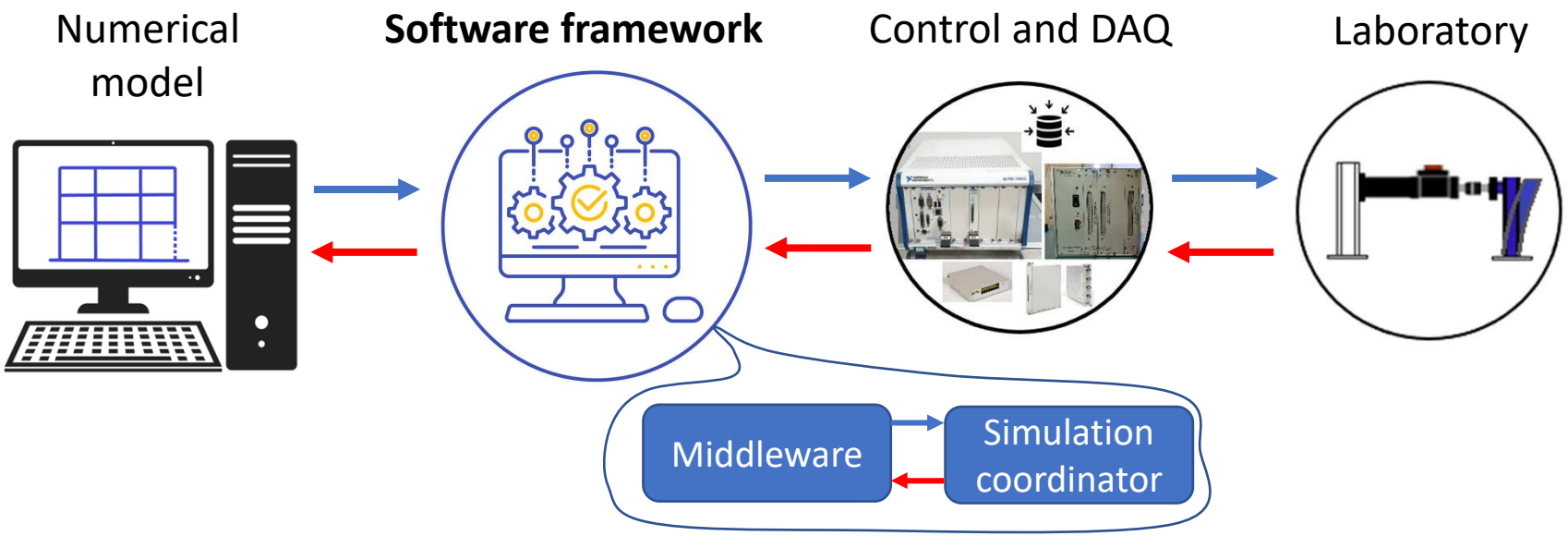


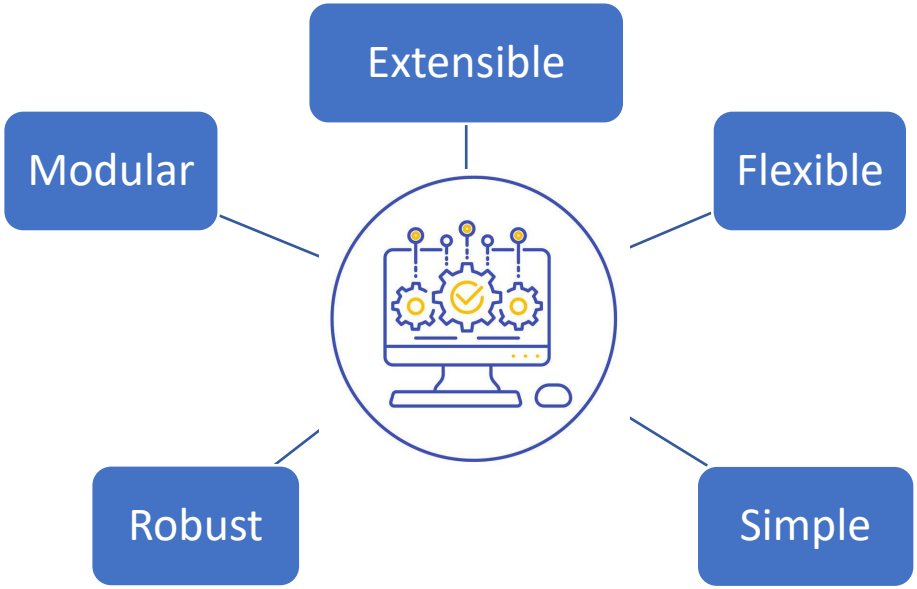
Physical substructure's properties:

- Complex to model
- Absence of a constitutive model
- Relevant in the collapse mechanism of a structure, etc.

Candeias P., Correia, A., **Tekeste, G.** (2021) "Shake table testing techniques: current challenges and new trends", In: *Advances on testing and experimentation in civil engineering*, Springer Tracts in Civil Engineering book series (submitted)

Software framework for RTHS





UI-SIMCOR

OpenFresco

Development of a software framework

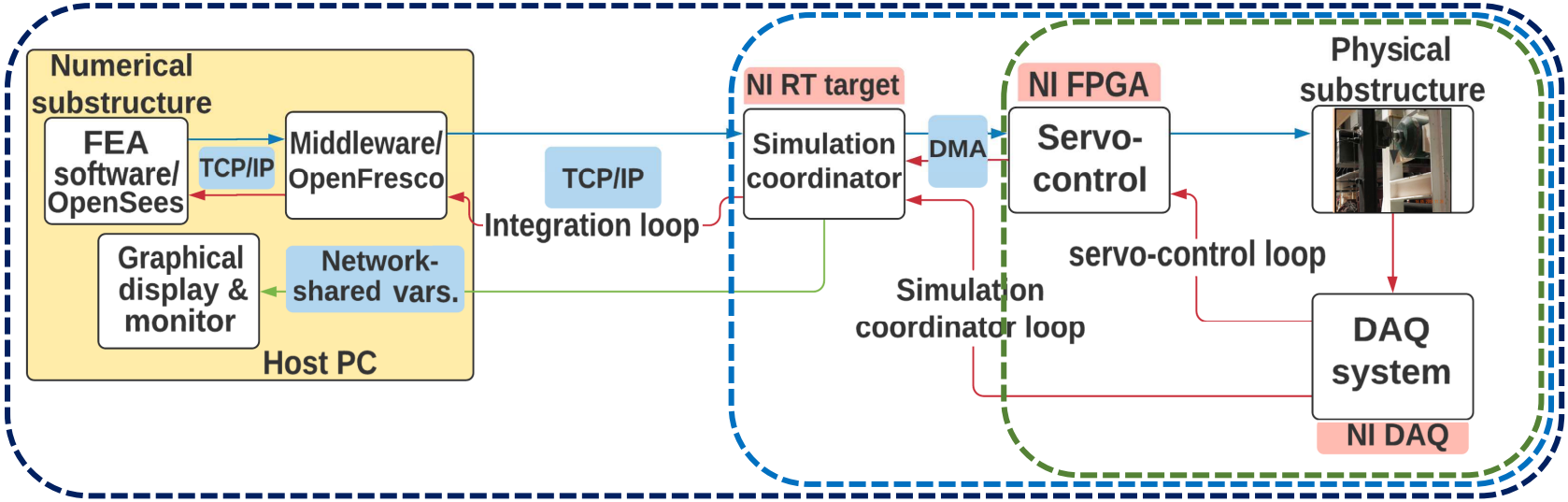
LNEC-HS software framework includes two schemes, namely:

i. Middleware-based scheme (using OpenFresco)

ii. Middleware-free scheme

Main features:

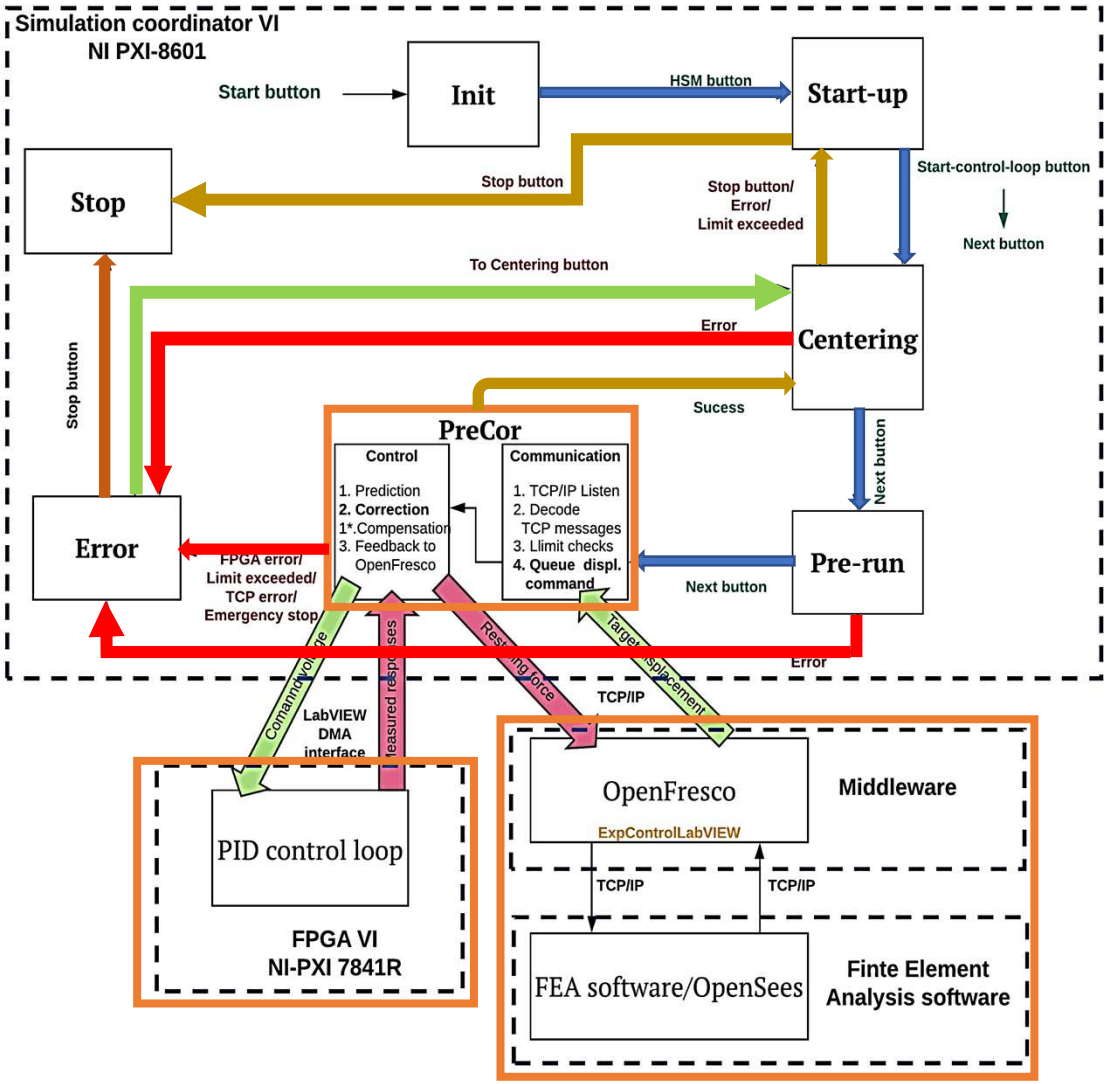
- Three-loop architecture including a FE software
- Simulation coordinator programmed in LabVIEW
- NI hardware for control and DAQ system



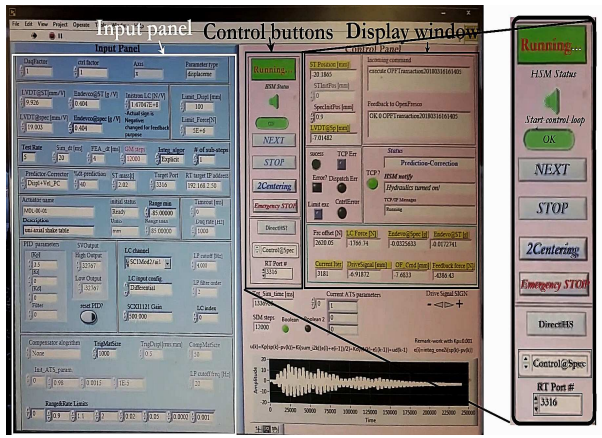
Tekeste, G.G., Correia, A.A., Costa, A. G. (2021) "Development and validation of a robust and flexible software framework for hybrid simulation" *Experimental techniques* (submitted)

Development of a software framework

Middleware-based scheme of LNEC-HS:



User interface

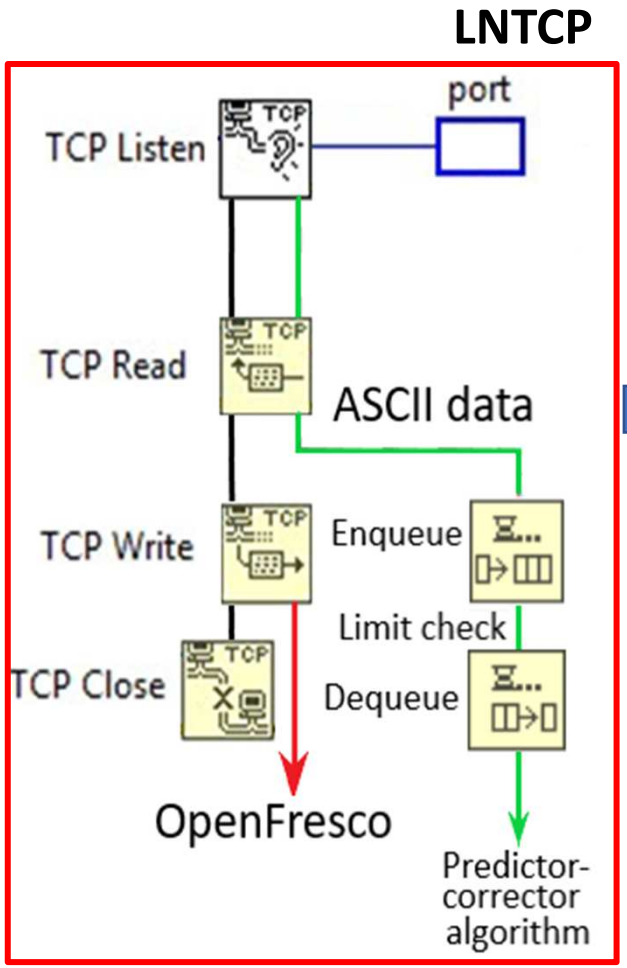


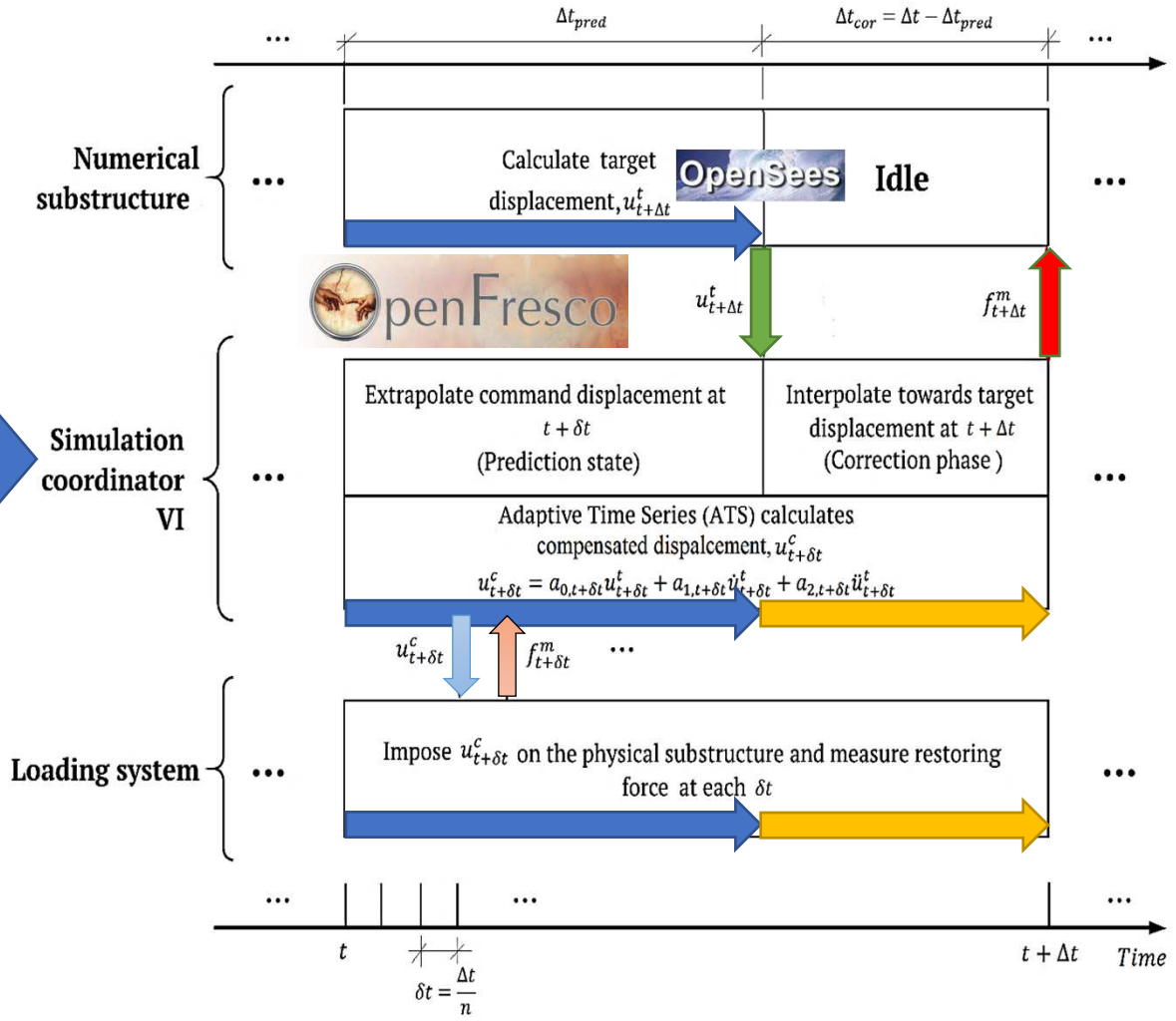
Characteristics:

- Robust
- Flexible
- Modular
- Extensible

Development of a software framework

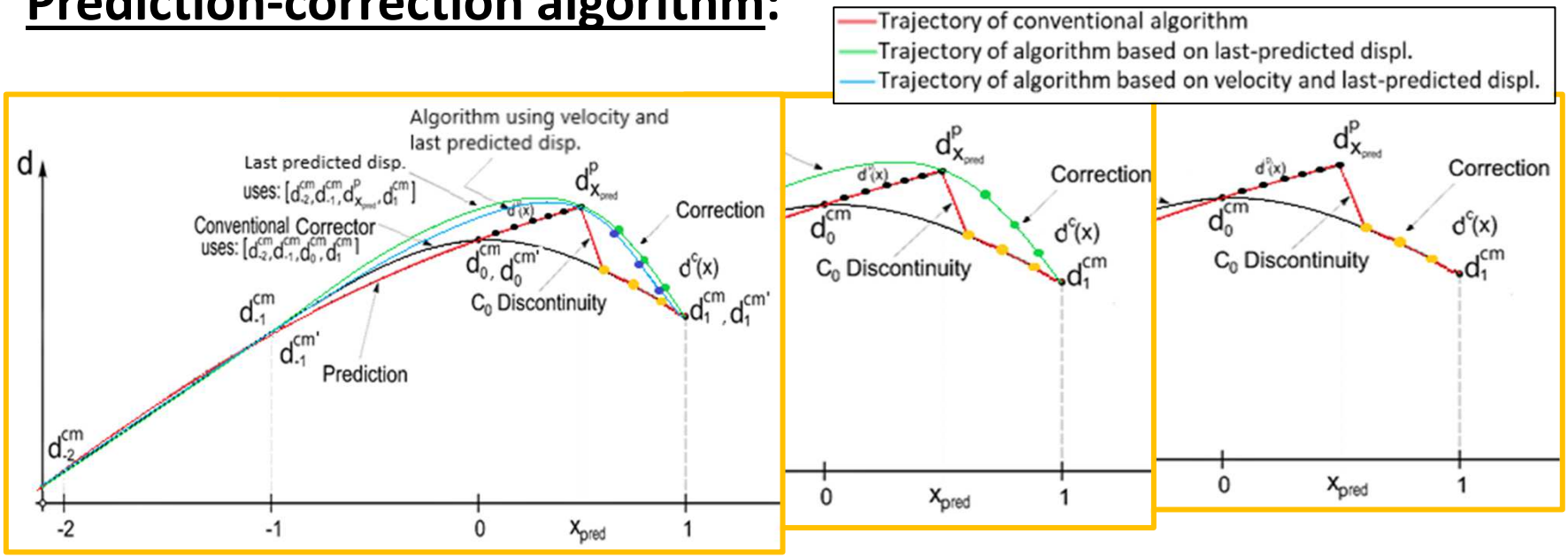
Order of operations in LNEC-HS:



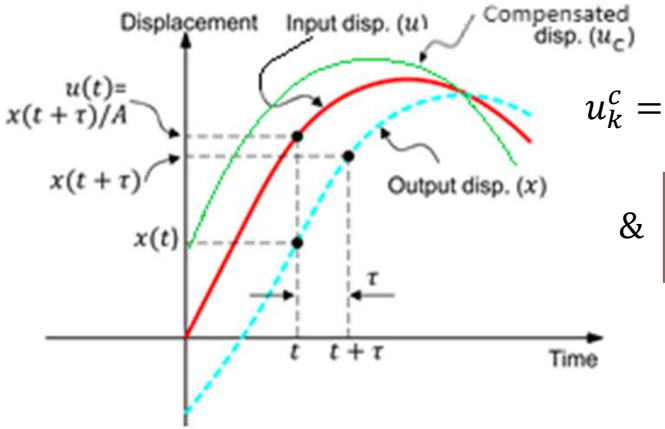


Command generation and compensation

Prediction-correction algorithm:

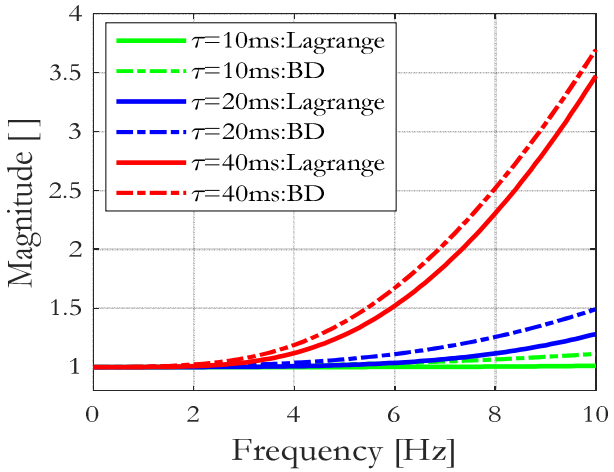


Adaptive Time Series (ATS) compensator:



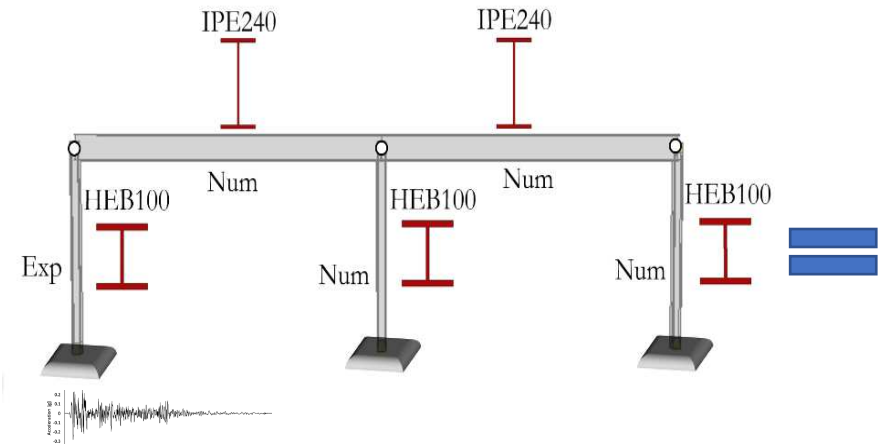
$$u_k^c = [u_k \quad \dot{u}_k \quad \ddot{u}_k] \begin{bmatrix} a_{0k} \\ a_{1k} \\ a_{2k} \end{bmatrix}$$

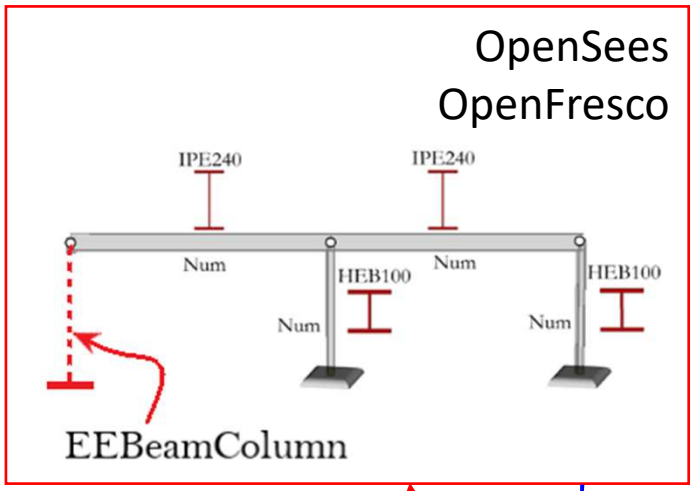
$$\& \quad \begin{bmatrix} a_{0k} \\ a_{1k} \\ a_{2k} \end{bmatrix} = (X_m^T X_m)^{-1} X_m^T U_C$$



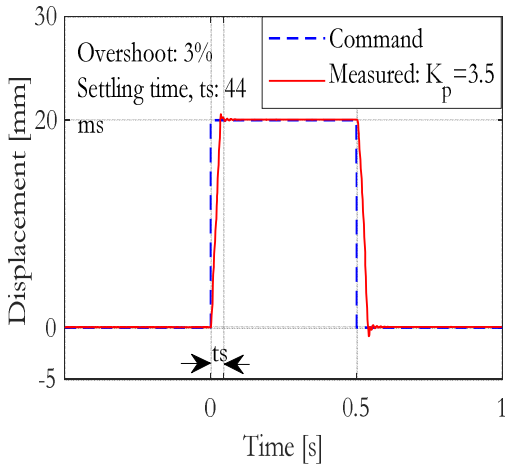
Validation of LNEC-HS: model and test rig

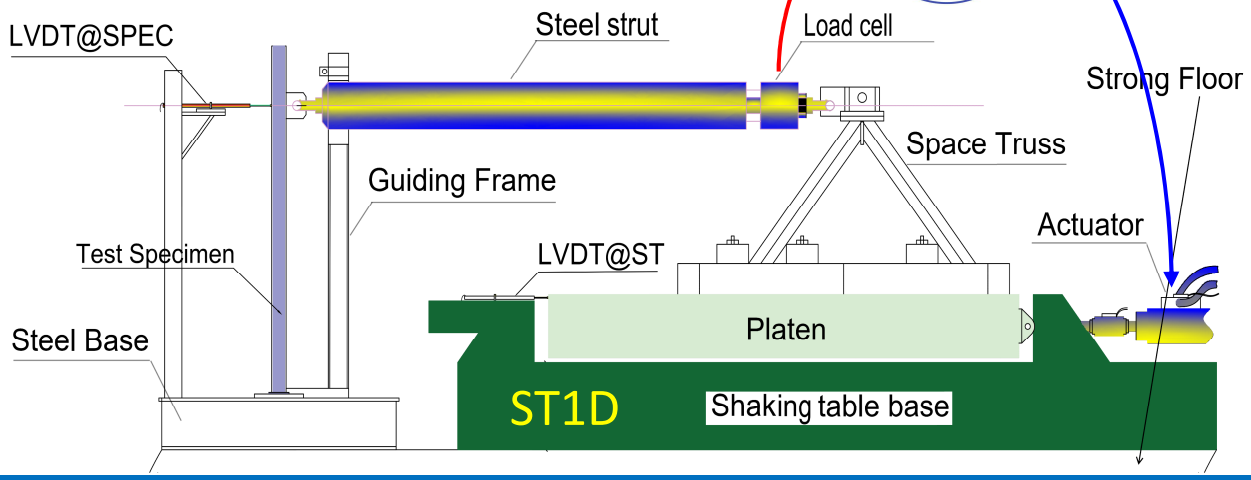
Modelling and test-setup:



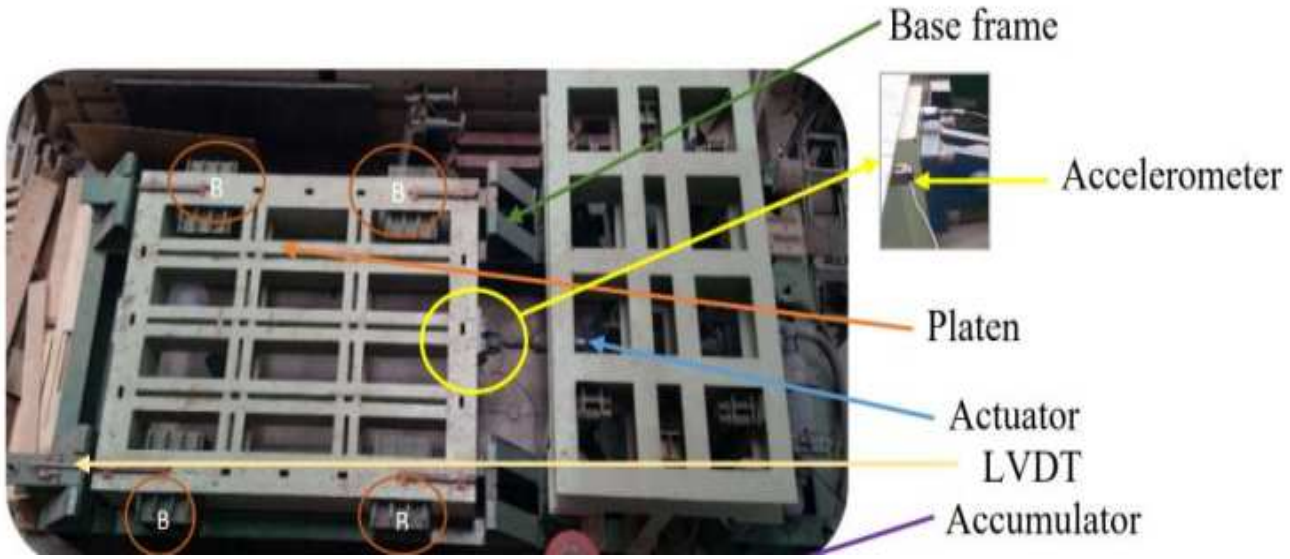


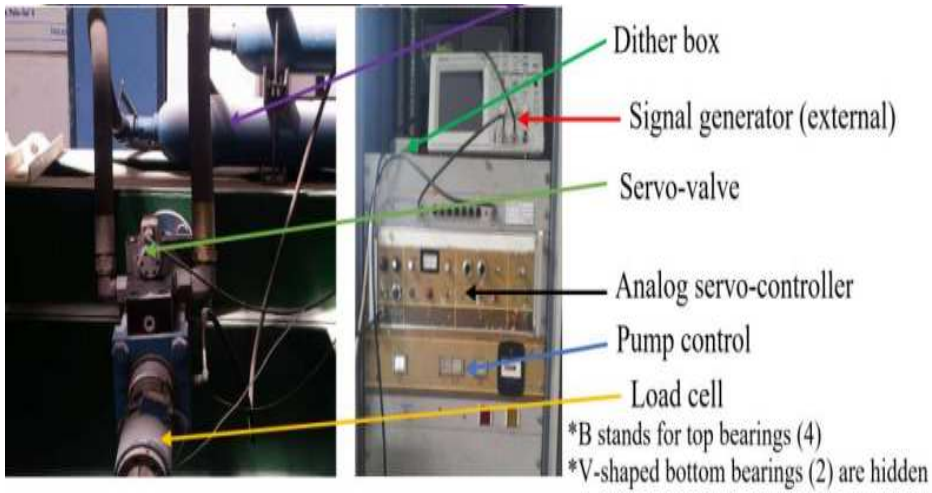
Control performance





System identification of ST1D



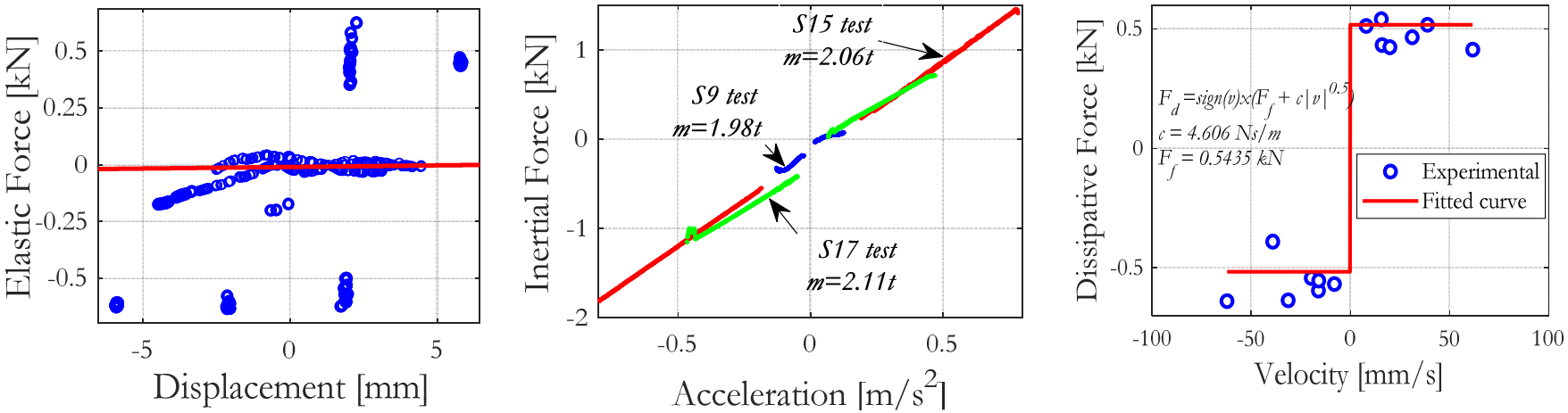


Step 1	Step 2	Step 3	Step 4
Identify 1. Inertial 2. Elastic 3. Damping forces	FRF estimate	Work out empirical equation of load transfer system	Parametric Identification via constrained nonlinear LS; and validation

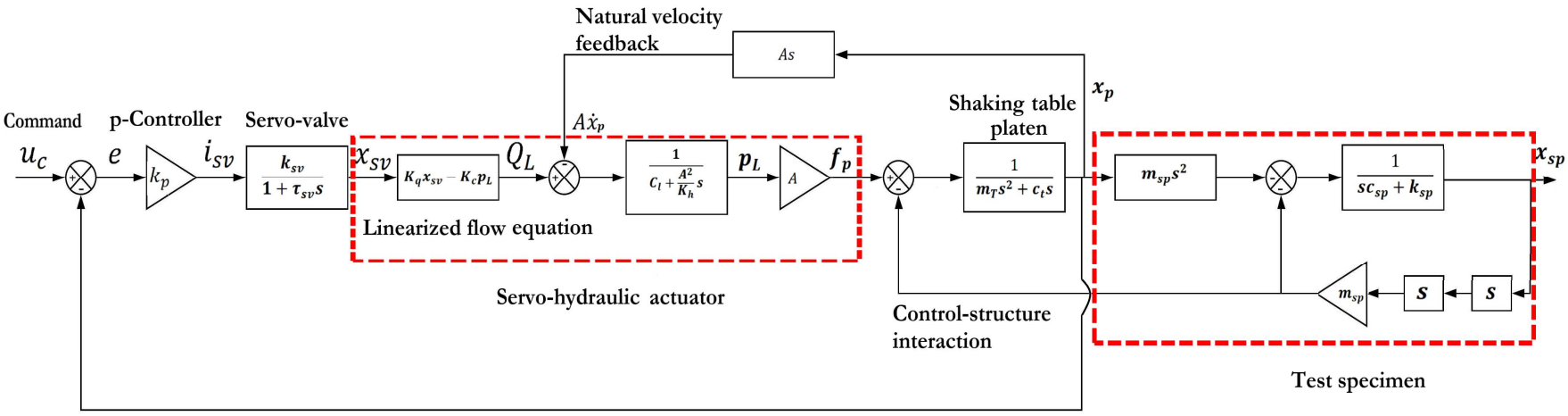
System identification of ST1D

Identification of shaking table forces (step-1):

Method: Periodicity of input signals (triangular and sinusoidal)

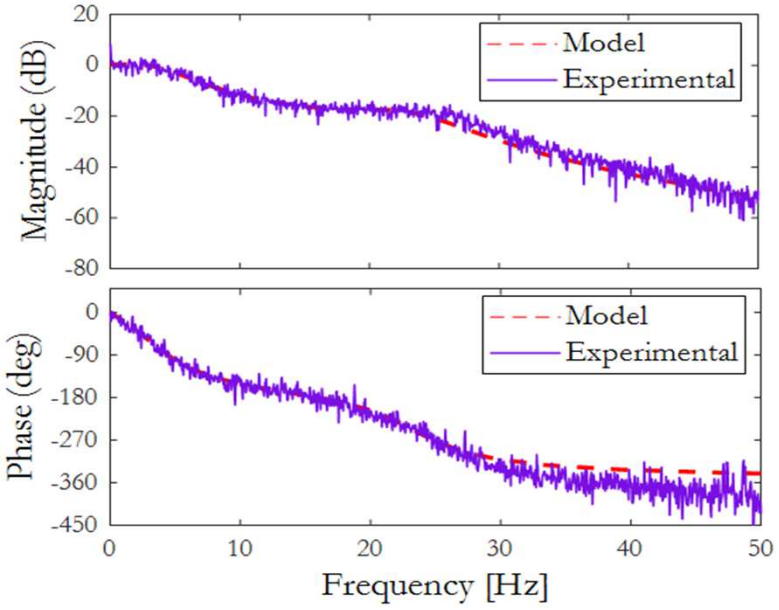


Block diagram of a shaking table system (step-3):

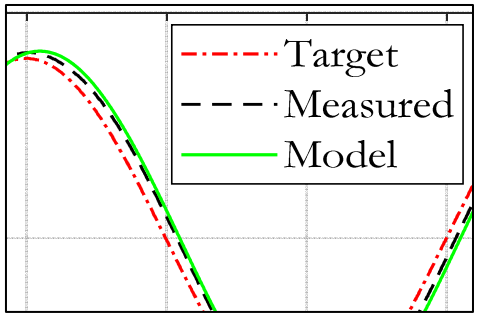


System identification of ST1D

Parametric system identification and model validation (step-4):



Validation

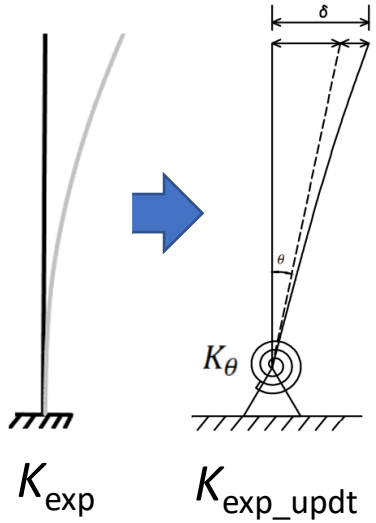


Component	Description	Parameter	Estimated values	unit
Servo-controller	P-gain	K_P	1.2993	V/cm
Servo-valve	Valve time constant	τ_{sv}	0.0246	s
	Valve flow gain	$k_{sv}K_q$	1934.50	$cm^3/s/V$
	Valve pressure gain & leakage factor	k_{pl}	1.67401e-7	$m^3/s/kPa$
Actuator	Oil bulk modulus	β_e	193716.28	kPa
	Volume of oil in actuator's chamber	V_t	0.002659	m^3
	Area of piston	A	0.012456	m^2
Platen	Platen mass	m_p	1.9751	ton
	Total damping (actuator & platen)	c_t	5.7800	kNs/m

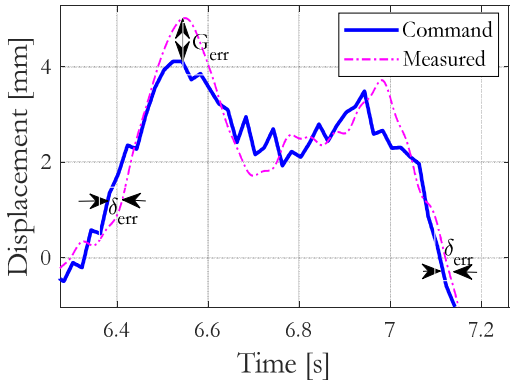
Validation of LNEC-HS: Pre-test works

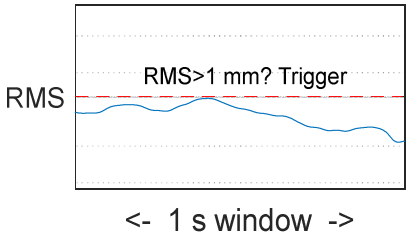
Pre-test identification:

- Model updating

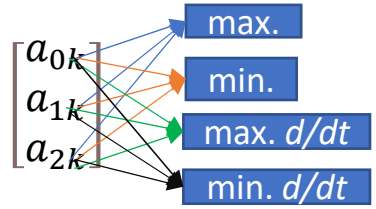


- Setting parameters for ATS compensator

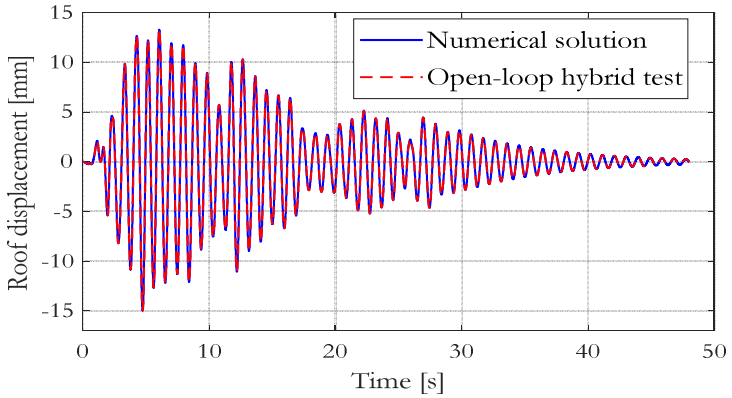


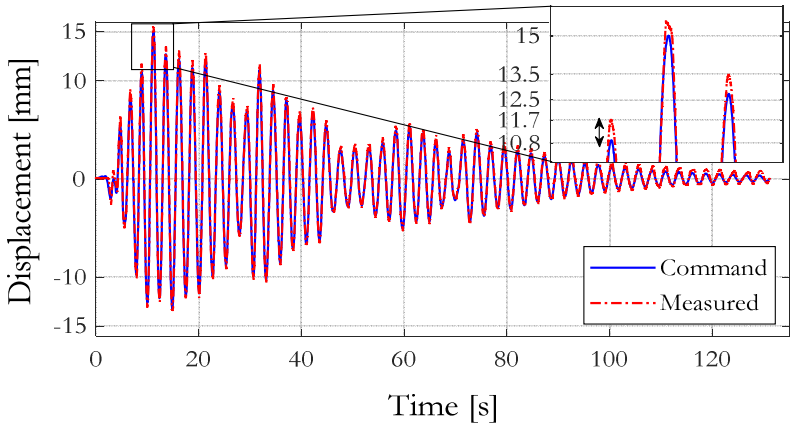


$$u_k^c = [u_k \quad \dot{u}_k \quad \ddot{u}_k] \begin{bmatrix} a_{0k} \\ a_{1k} \\ a_{2k} \end{bmatrix}$$



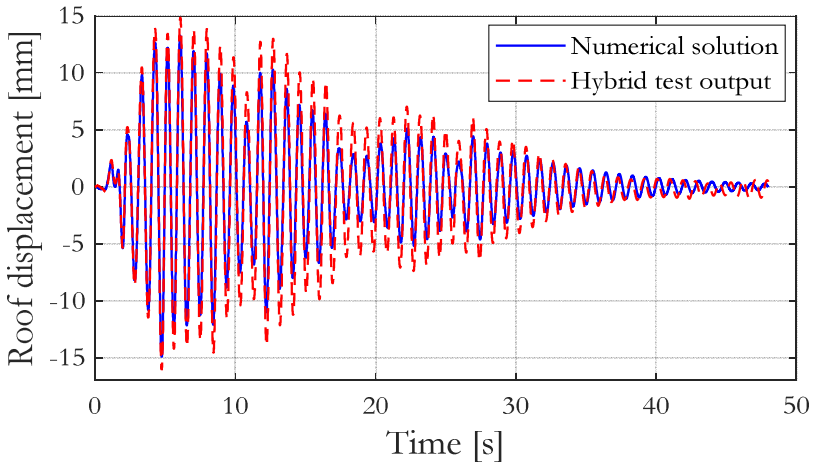
Open-loop/virtual hybrid test:

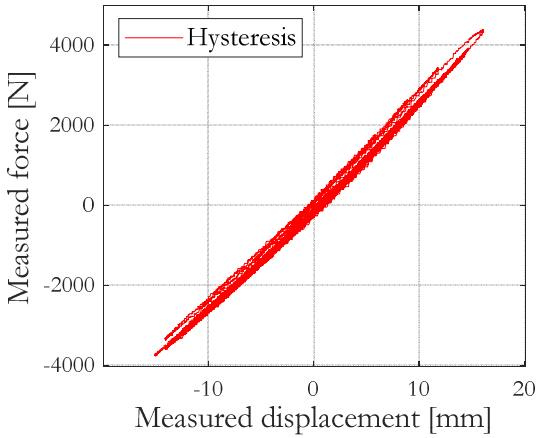


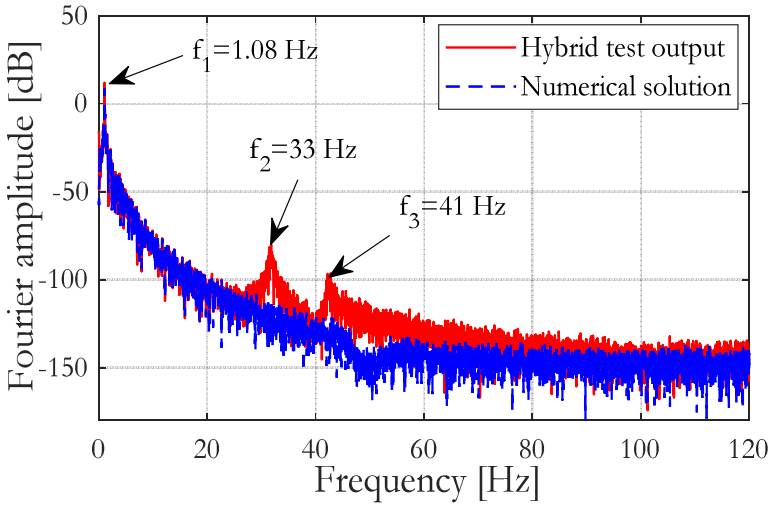


Validation of LNEC-HS: Results

Hybrid test results:



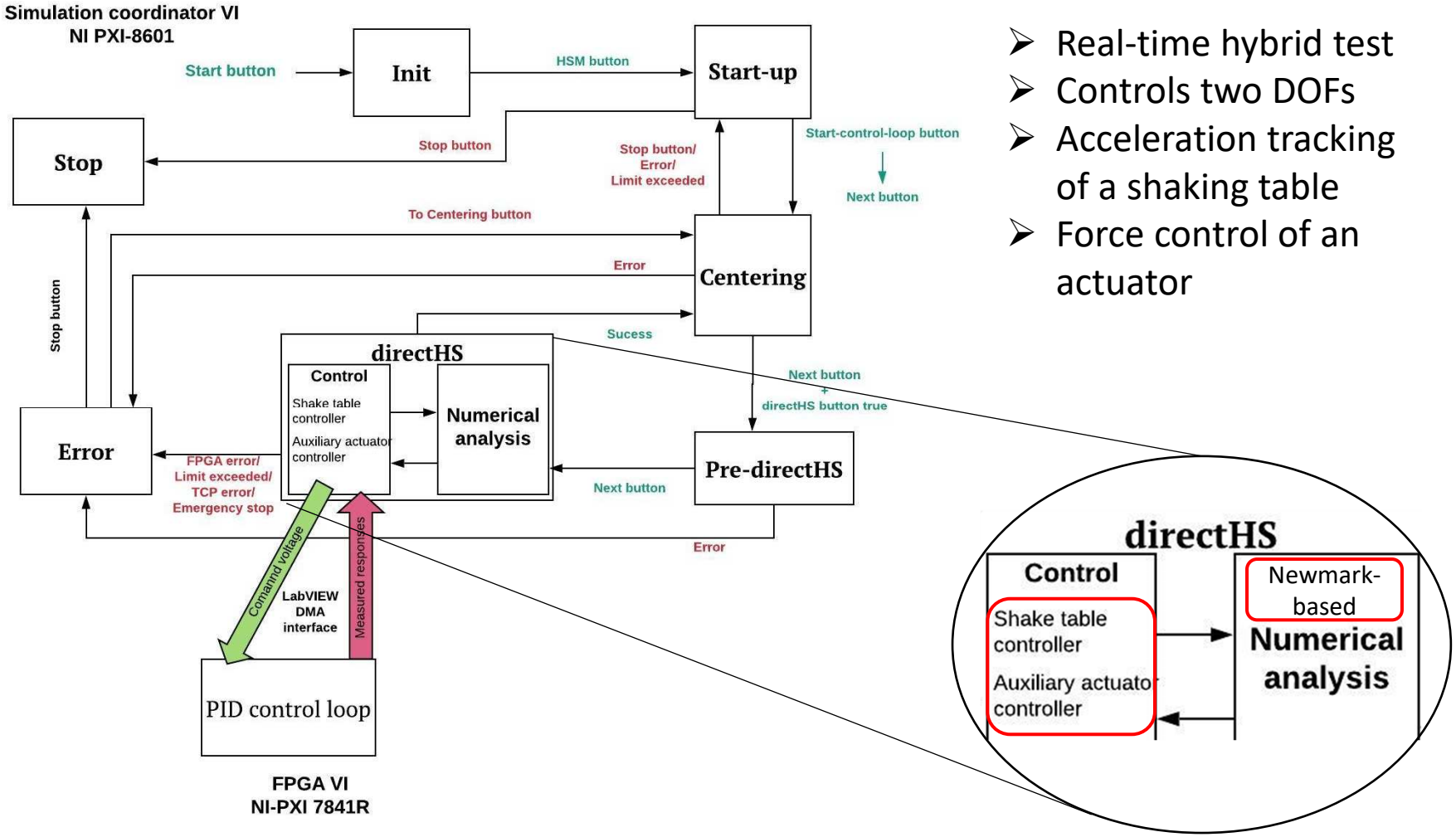




Correia, A.A., Benavent, A., Bousias, S., **Tekeste, G.G.,** Abbiati, G., Stojadinovic, B. (2020) "Use of improved hybrid dynamic simulation for novel isolators/dissipators, for thermomechanical applications, and for soil-structure interaction studies", *Deliverable 27.3 (WP27-JRA5)*, SERA – EU H2020 Project

Development of a software framework

Middleware-free scheme of LNEC-HS:

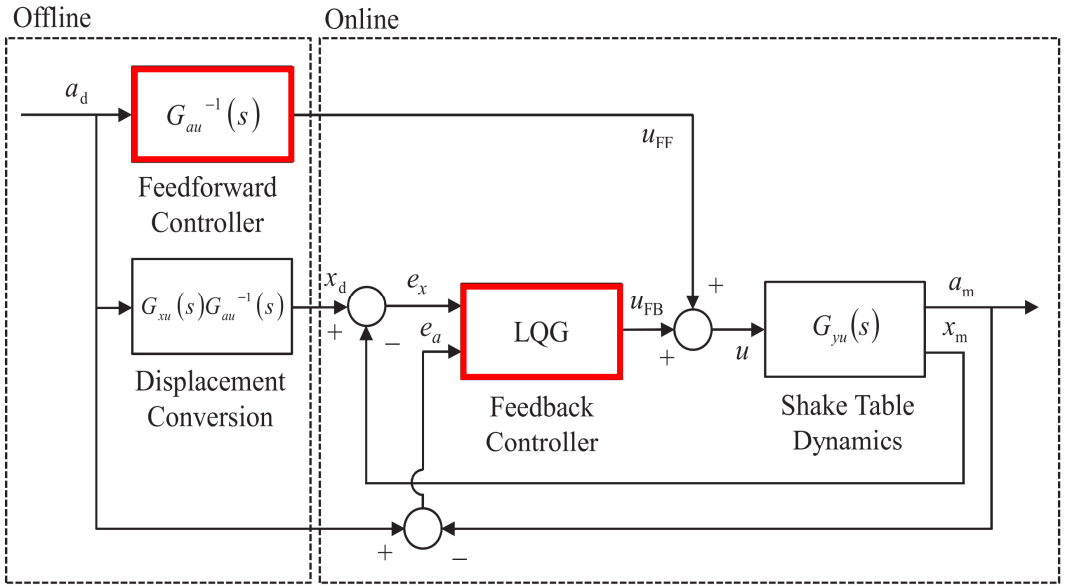


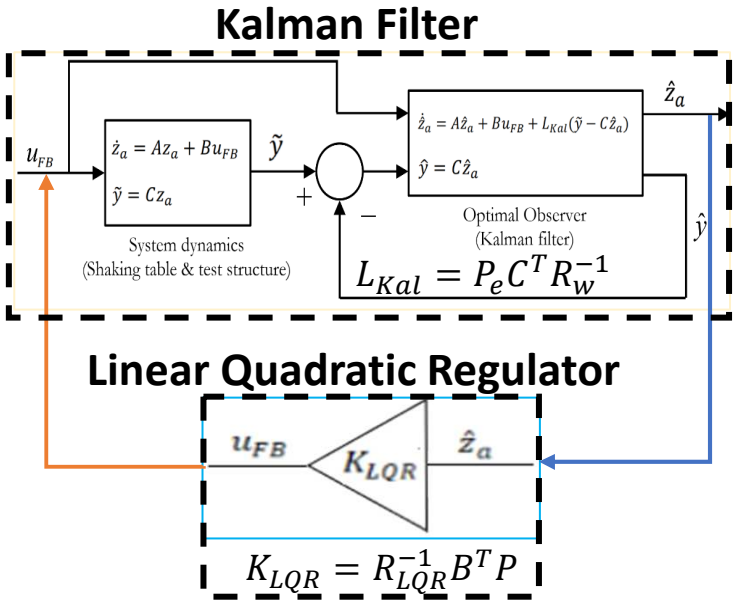
- Real-time hybrid test
- Controls two DOFs
- Acceleration tracking of a shaking table
- Force control of an actuator

Correia, A.A., Benavent, A., Bousias, S., **Tekeste, G.G**. (2019) "Experimental tests by HDS and shaking tables", *Milestone 27.2 (WP27-JRA5)*, SERA – EU H2020 Project

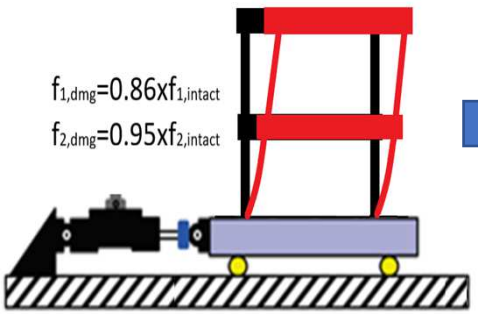
Acceleration tracking of a shaking table

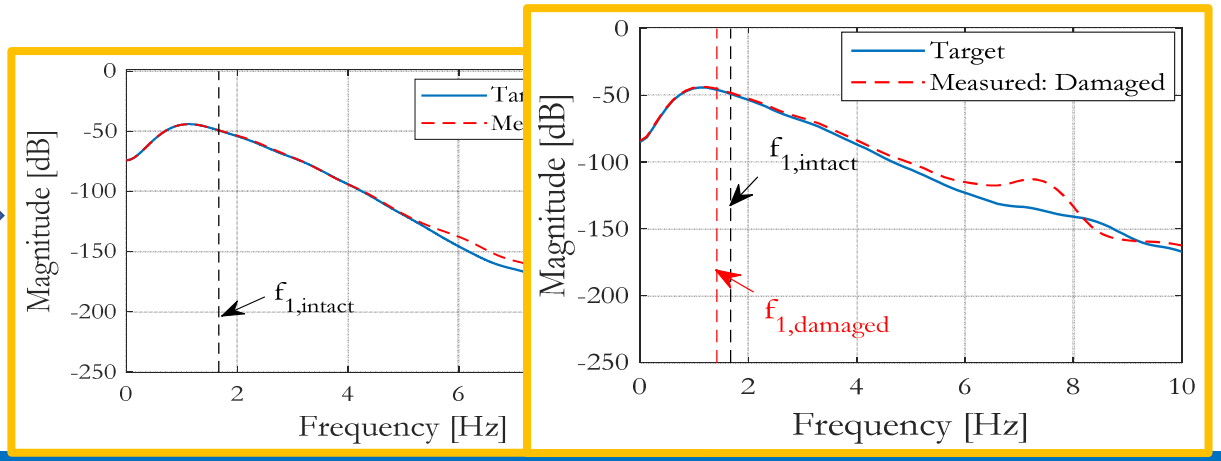
Feedforward-feedback controller:





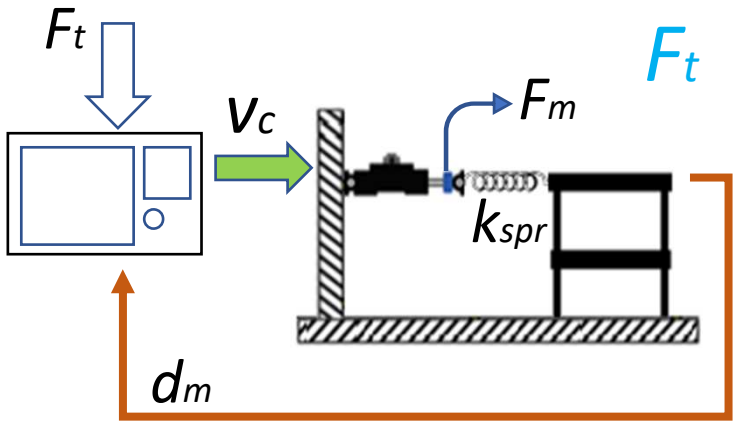
Simulated study: Two story shear building



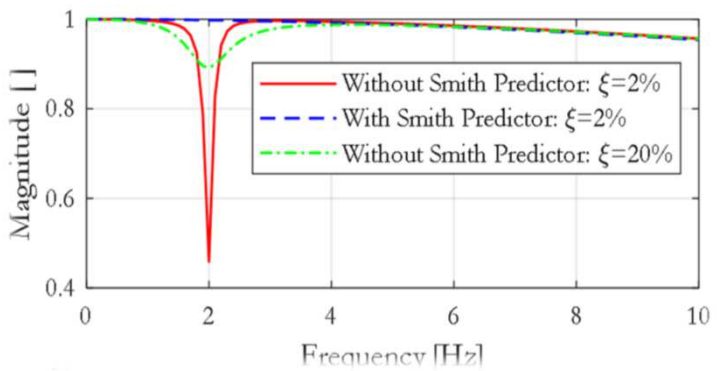


Equivalent force control of an actuator

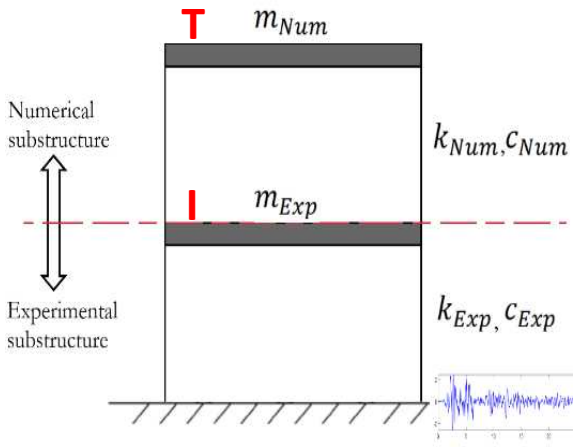
Force control through compliance spring and Smith Predictor:

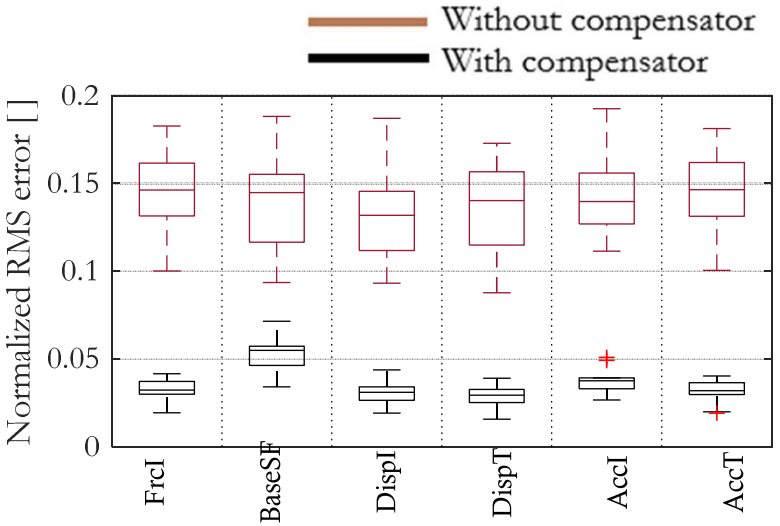


F_t vs F_m



Parametric study:

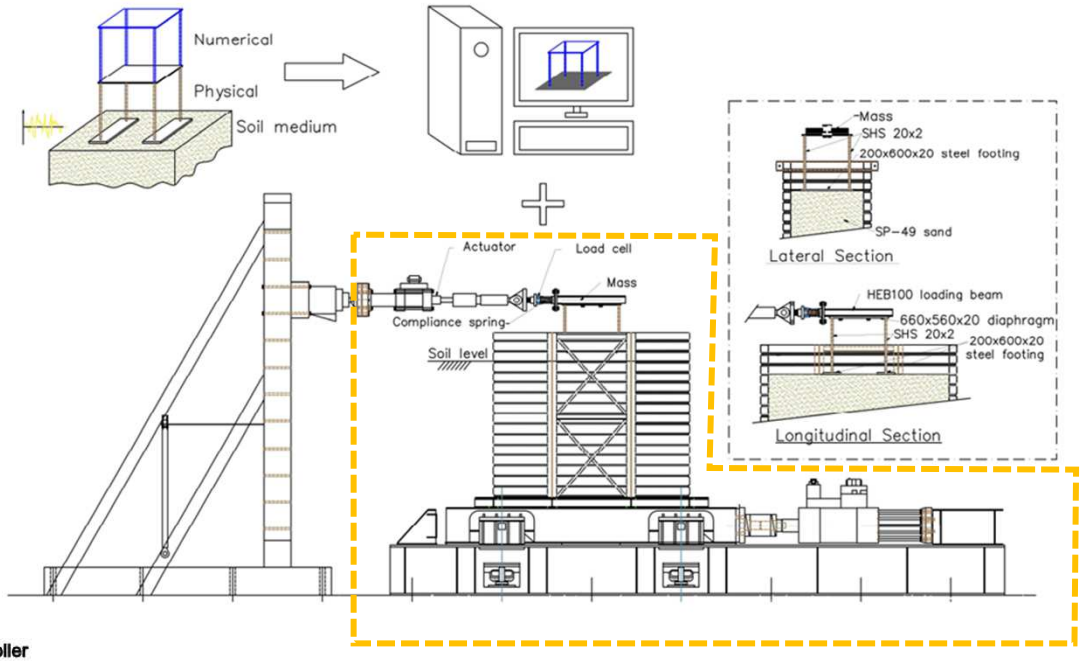


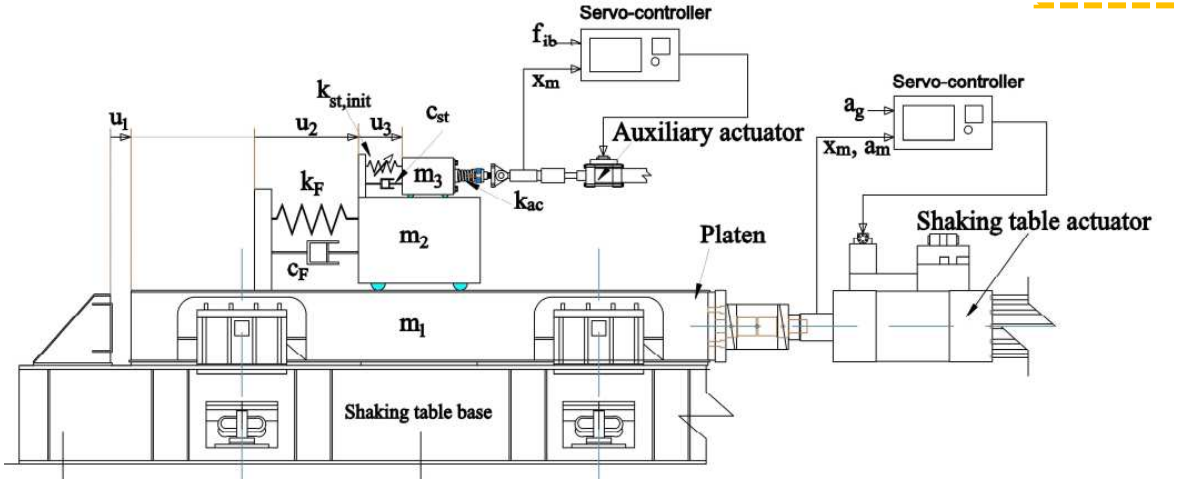


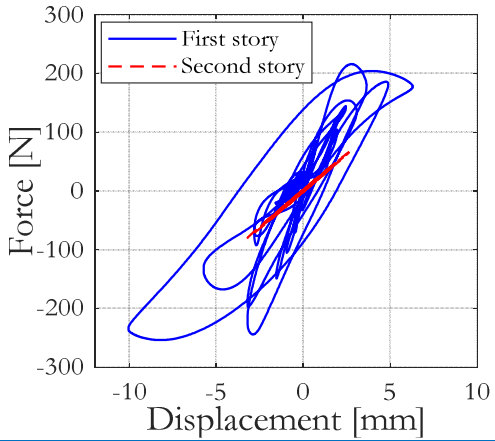
Soil-structure interaction (SSI) test in HS

Validation of middleware-free scheme of LNEC-HS:

- Shear building with a soft-story mechanism
- SDOF model for equivalent shear beam (ESB)
- Bouc-wen hysteretic model of the first story
- Newmark based solver for the linear-elastic second story







Conclusions and limitations

Conclusions:

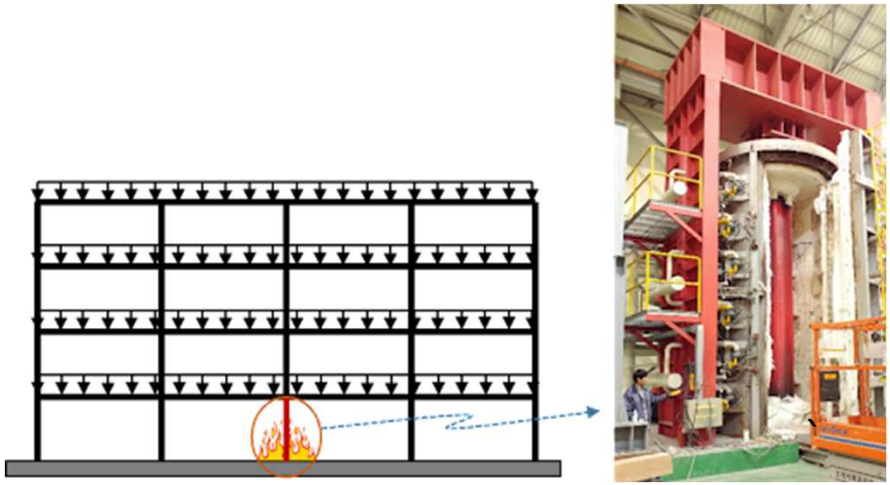
- ✓ The **middleware-based scheme for *LNEC-HS software framework*,** developed and validated in the scope of this thesis, is a robust and reliable software framework for conducting slow and fast hybrid tests.
- ✓ The current implementation of the **middleware-free scheme of *LNEC-HS*,** capable of controlling two DOFs of the physical substructure, can support SSI hybrid tests of shear buildings with dominant soft-story mechanism.

Limitations:

- ✓ Custom control of actuators in **middleware-based scheme for LNEC-HS software framework** is not currently available
- ✓ Structures other than shear buildings are not possible for SSI hybrid testing with the current implementation of **middleware-free scheme of *LNEC-HS***

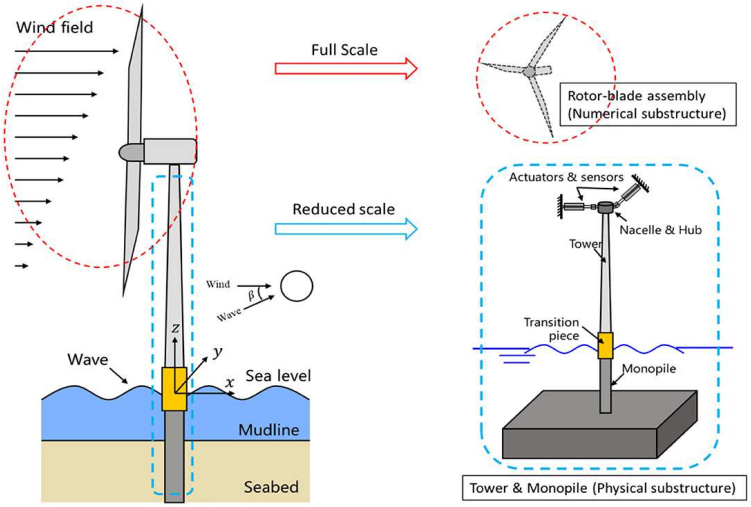
Future directions in RTHS

✓ Structures subjected to Fire



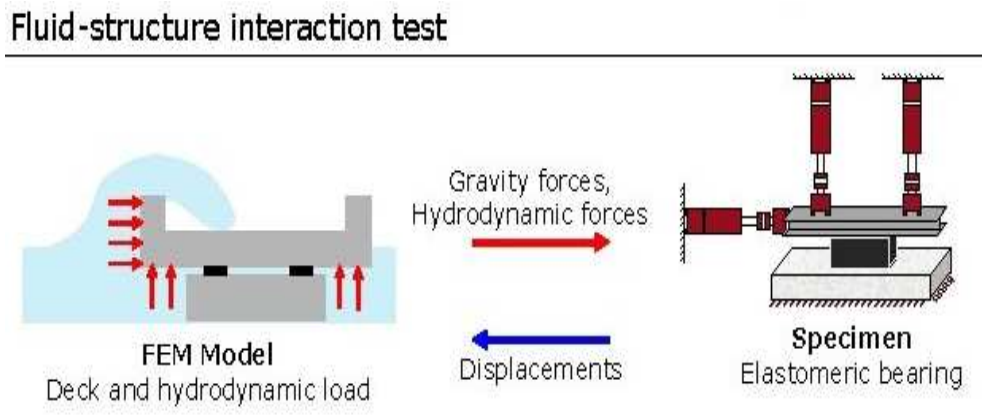
Xuguang Wang et al., 2018

✓ Structures under wind loading



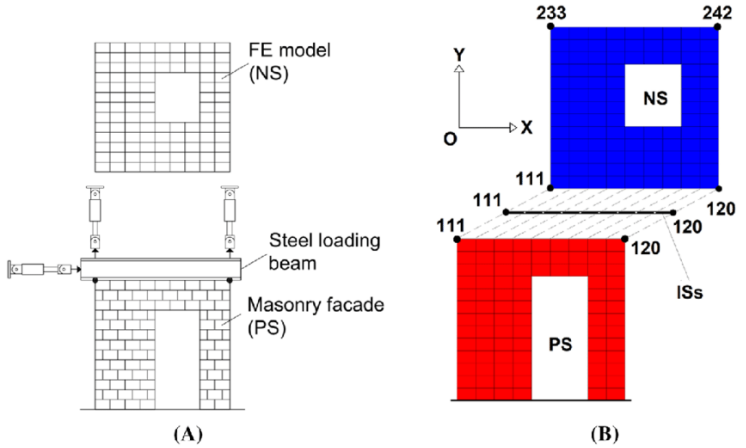
Wei Song et al., 2020

✓ Structures under hydrodynamic loading (Tsunami)



Phillips Brian et al., 2014

✓ Masonry structures



Abbaiti Giuseppe et al., 2017

Thank you for your attention!

gidewon.tekeste@ua.pt