Real-time hybrid simulation in shake table tests – development and application to a soil-structure system

Development and validation of an experimental platform for hybrid simulation and uncertainty quantification

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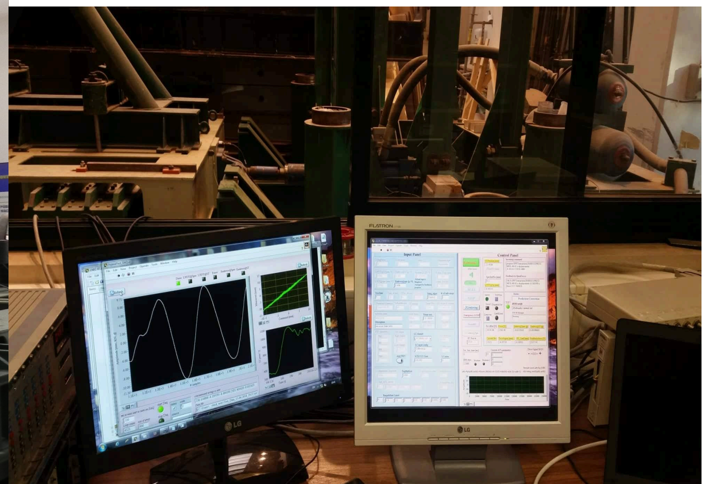
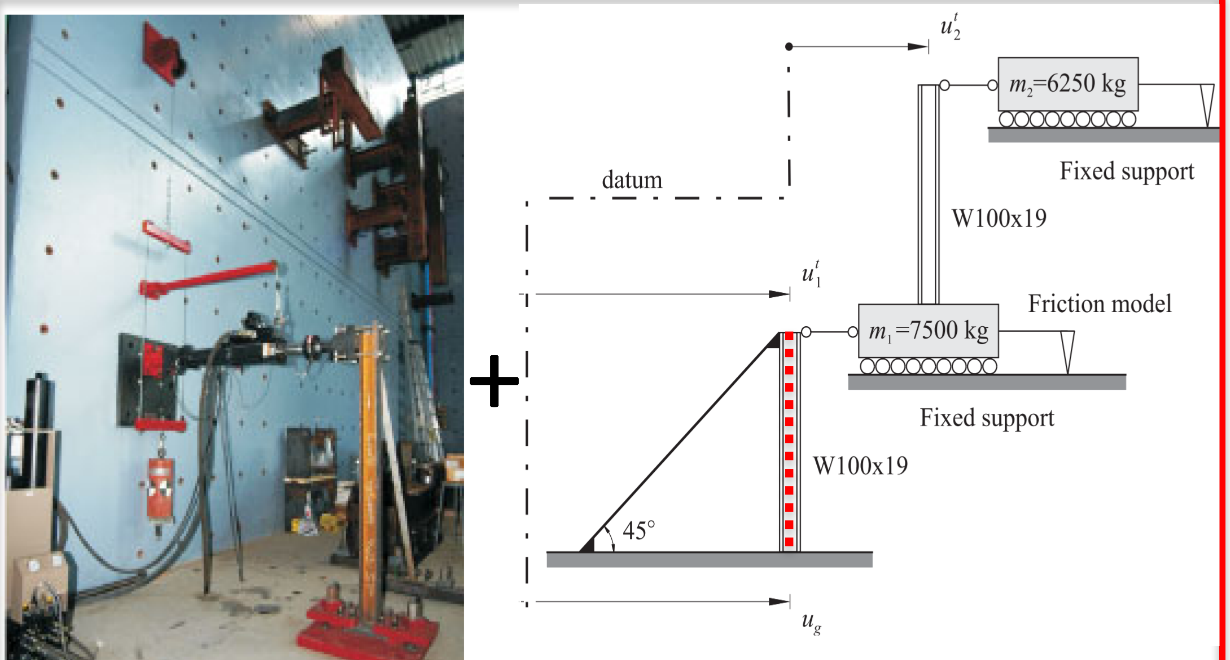


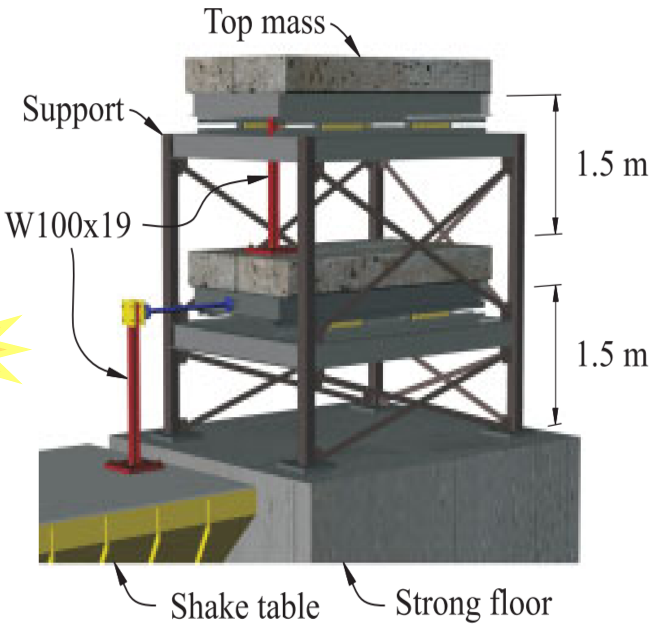
OUTLINE

- A brief recap of Hybrid Simulation (HS)
- State-of-the art on existing experimental platforms for HS
- Development of an experimental platform for HS at LNEC
- Selection of an integration algorithm and a compensation scheme
- Validation of the experimental platform and its performance
- Uncertainty quantification through HS
- Future works

A brief recap of Hybrid Simulation (HS)



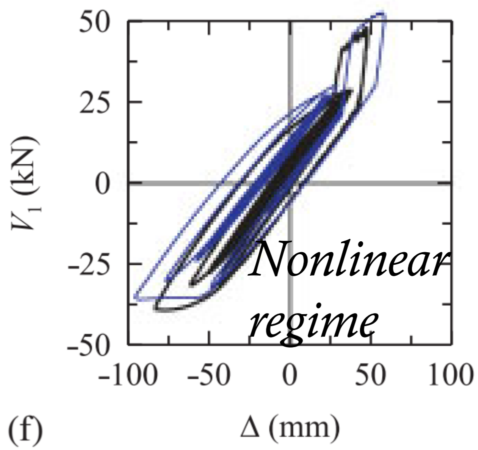
Hybrid simulation

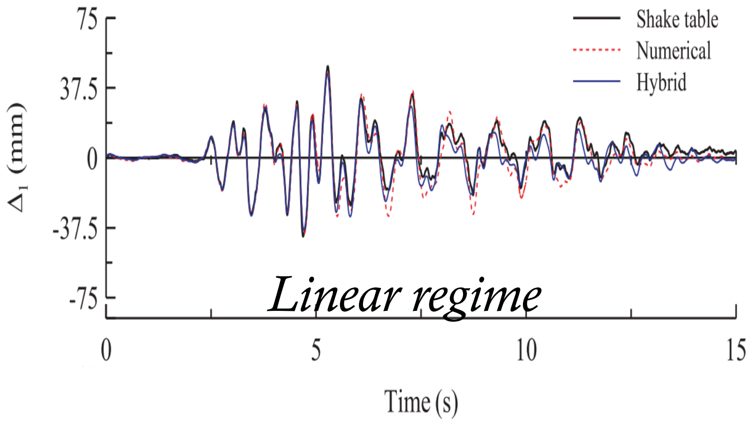


Full shake table test

C.-P. Lamarche et al., (2012)

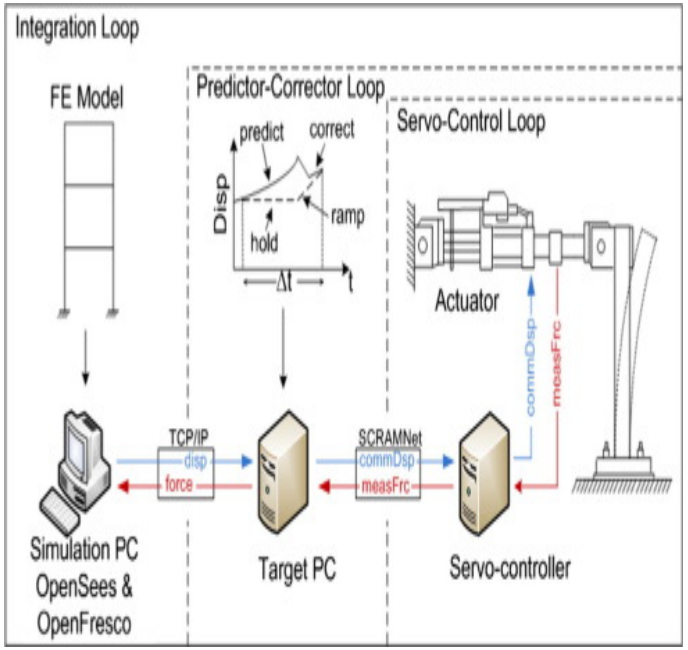
- ❑ Hybrid simulation as a gap-filler to the expensive shake table tests
- ❑ Economical and flexible
- ❑ Demands a skillful operator





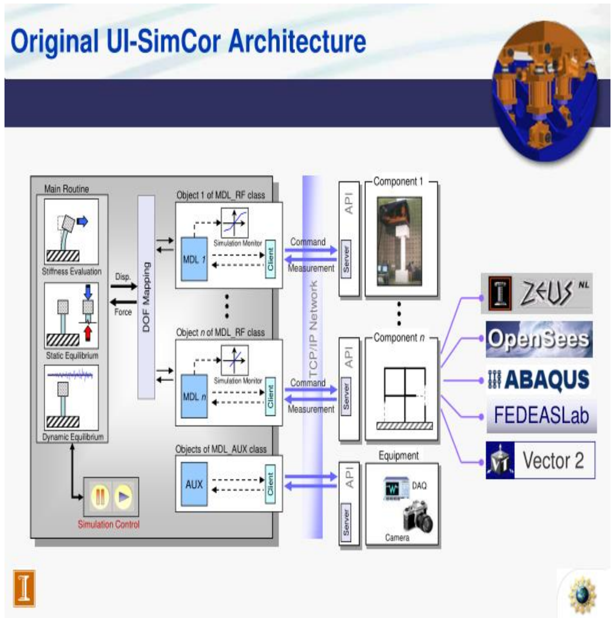
State-of-the art on existing platforms for HS

University of California, Berkeley



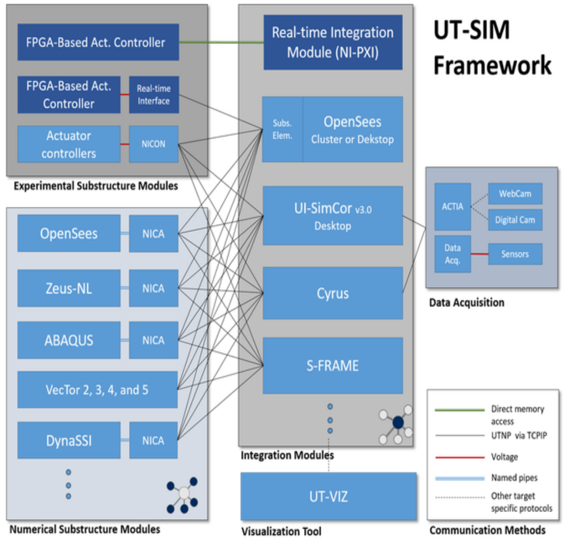
Mosqueda et al., (2007) & Schellenberg et al., (2009)

University of Illinois at Urbana-Champaign



Spencer et al., (2007)

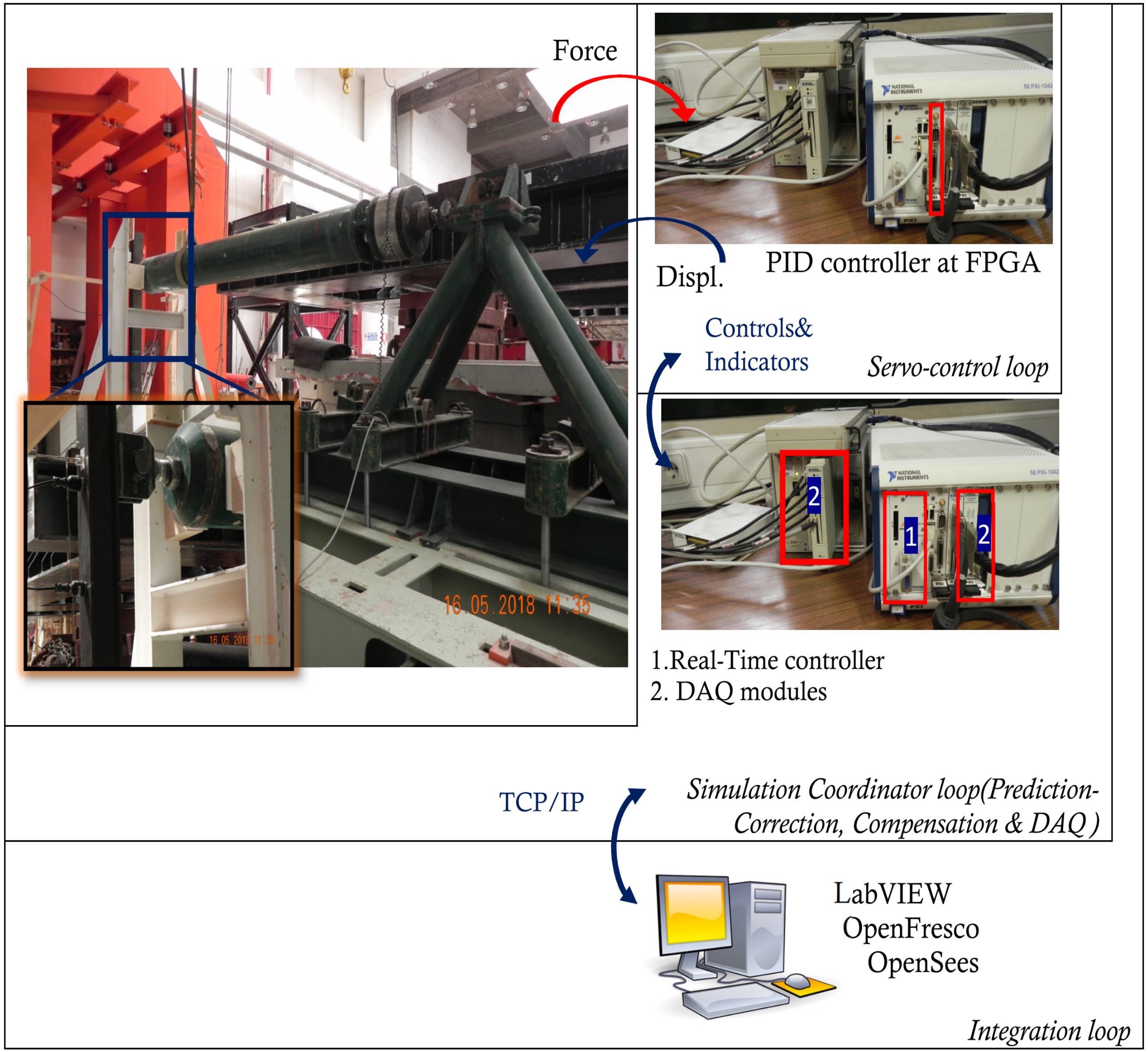
University of Toronto's Simulation (UT-SIM)



Kwon et al., (2017)

Other frameworks include: Internet-based Simulation for Earthquake Engineering (ISEE), Mercury FE software, etc.

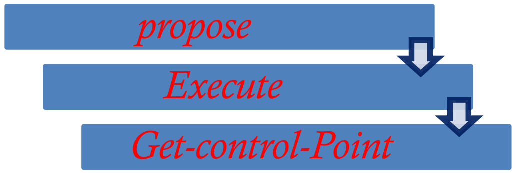
Development of an experimental platform for HS at LNEC



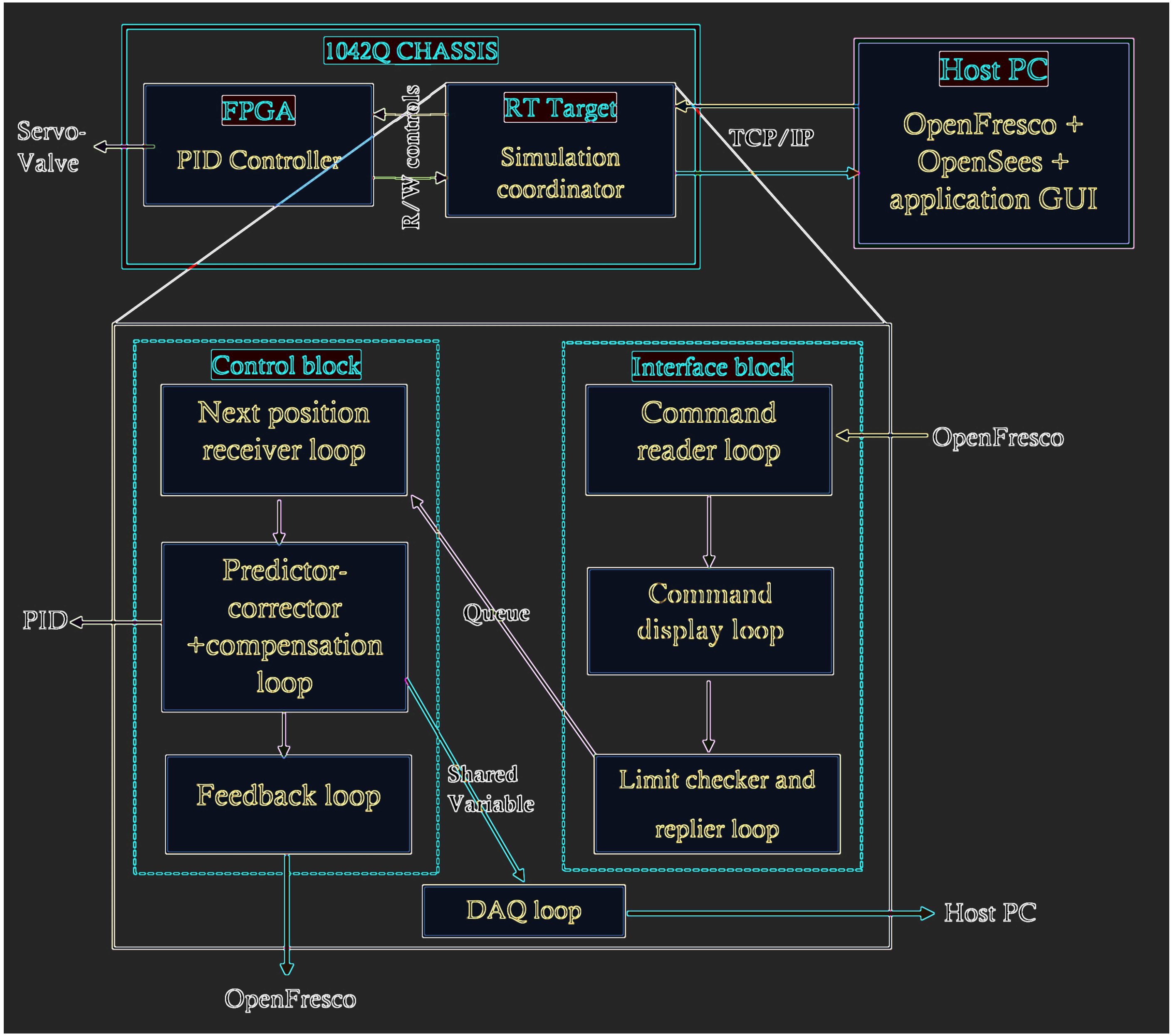
- A three loop platform with a central simulation coordinator capable of executing slow to fast hybrid tests
- TCP/IP protocol bridges the communication between coordinator and ECLabVIEW class of OpenFresco
- Predictor-correction generate commands to servo-valve at 1ms time interval
- Coordinator handles feedback force filtering, limit checks and error reporting

Components of the experimental platform and their interaction

- Limit checker and replier loop follows a sequence:

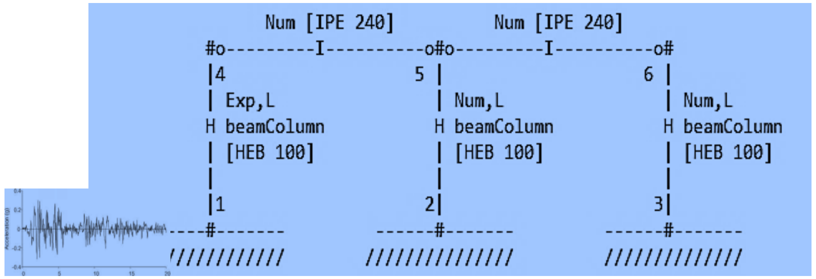


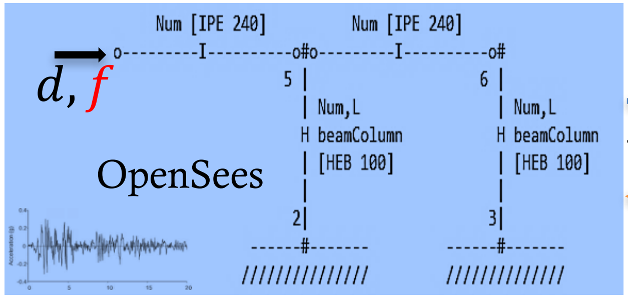
- Arrival of next command triggers correction phase & completion of correction phase triggers feedback
- Adaptive Time Series compensates commands received from predictor-generator algorithm
- Feedback loop sends measured and processed feedback force and measured displacement back to OpenFresco

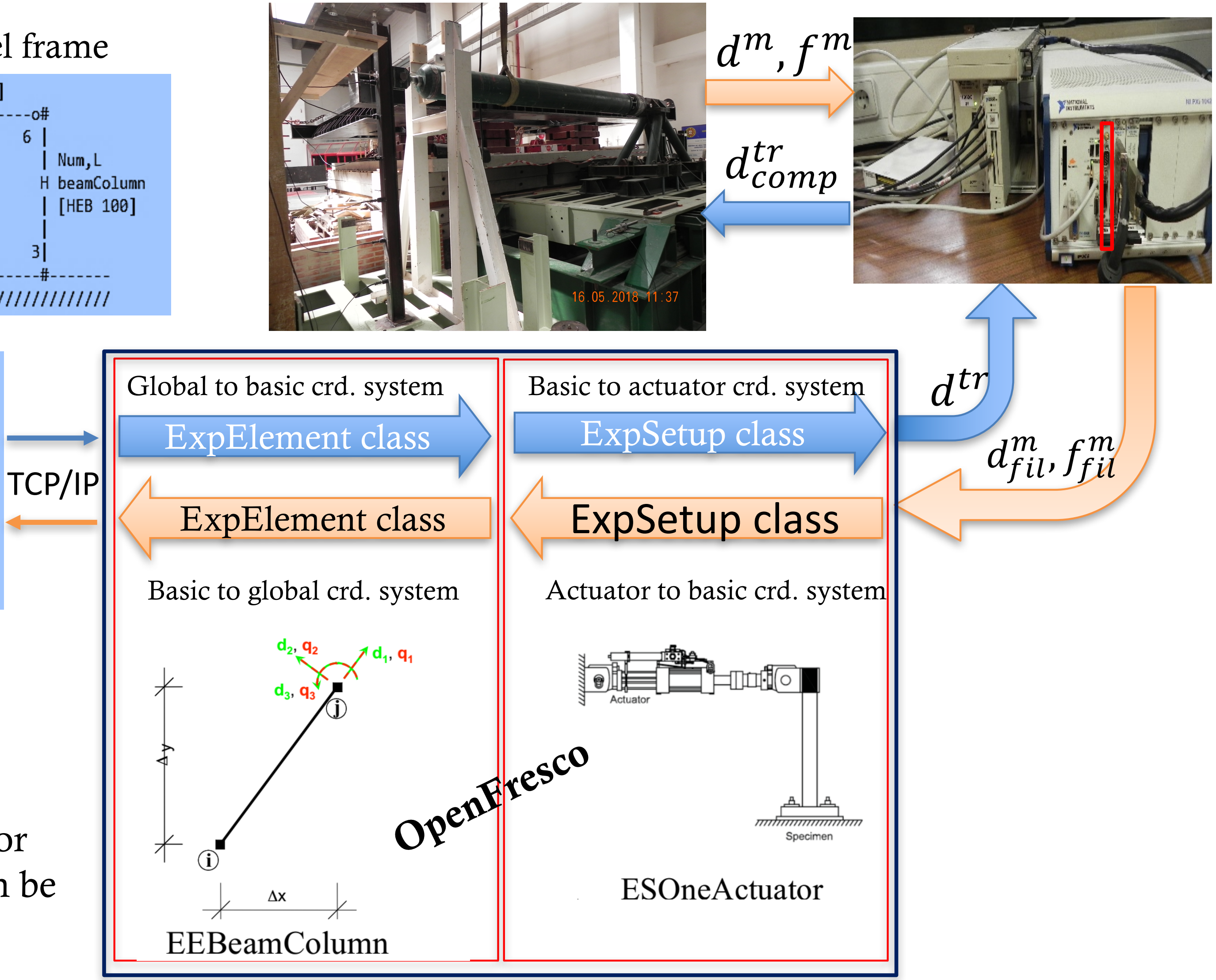


Data flow

Reference structure: 2bay-1story steel frame

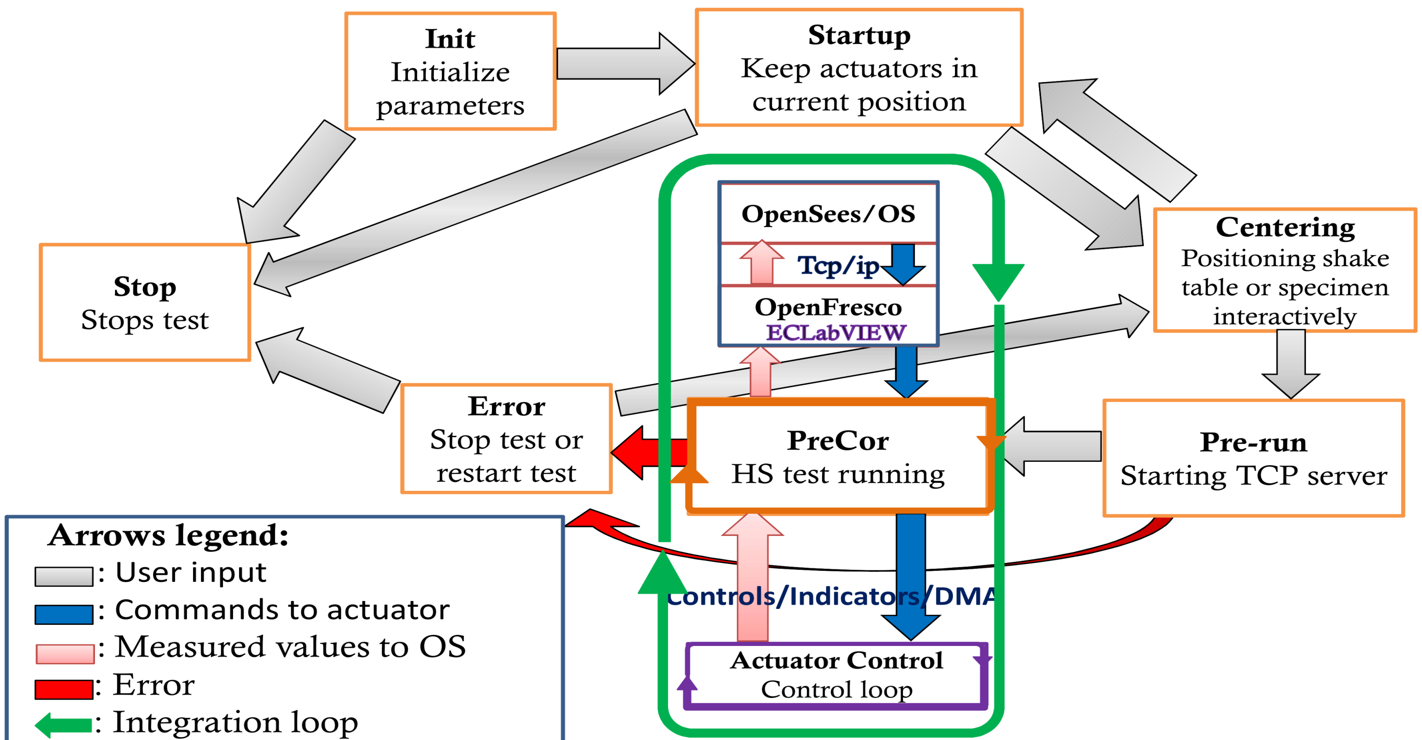


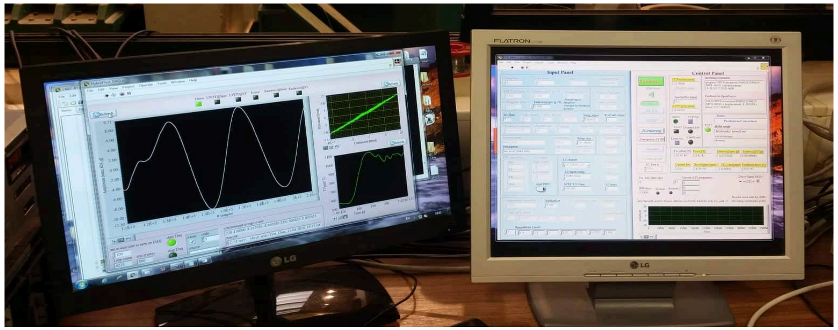




- A two point control is only developed to date (allow one control parameter)
- OneActuator transformation or NoTransformation classes can be adopted in this platform

Simulation coordinator and the GUI at host PC





- Versatile and easily extensible due a state-machine architecture
- GUI offers real-time response visualization, Sub-space synchronization plot (SSP) and a plot of Tracking Indicator (TI)

Selection of integration algorithm and its parameters

A study based on a simulated hybrid test

Methods studied:

- Alpha Operator separator (α-OS)
- Newmark fixed number of iterations (NMHS)
- Hilber-Hughes-Taylor hybrid simulation (HHTHS)

Criteria for comparison:

1. Maximum of the relative energy error indicator in %:

$$EEI_k = \left\{ \frac{E_{err,k}}{I_{r,k} + 0.5 \times K \times u_y} \times 100\% \right\}$$

$$\boldsymbol{EEI_{max}} = \underbrace{\boldsymbol{max}}_{\boldsymbol{k}} \{|\boldsymbol{EEI_k}|\}$$

$$E_{err,k} = D_k + H_k + T_k - I_{r,k}$$

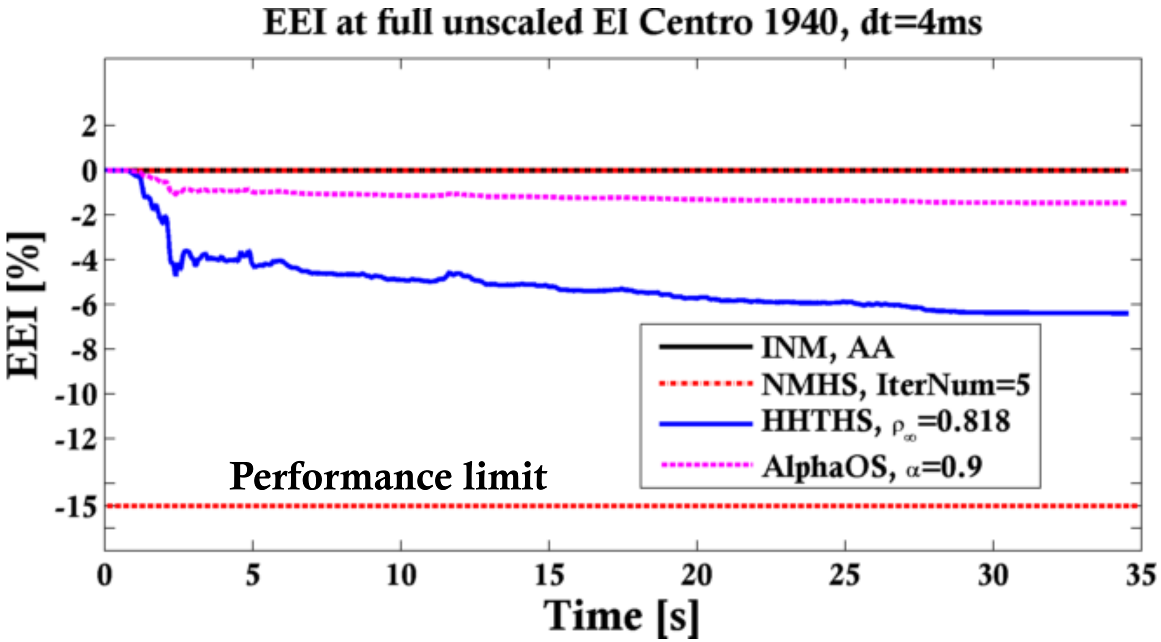
Where: D_k=Viscous damping energy

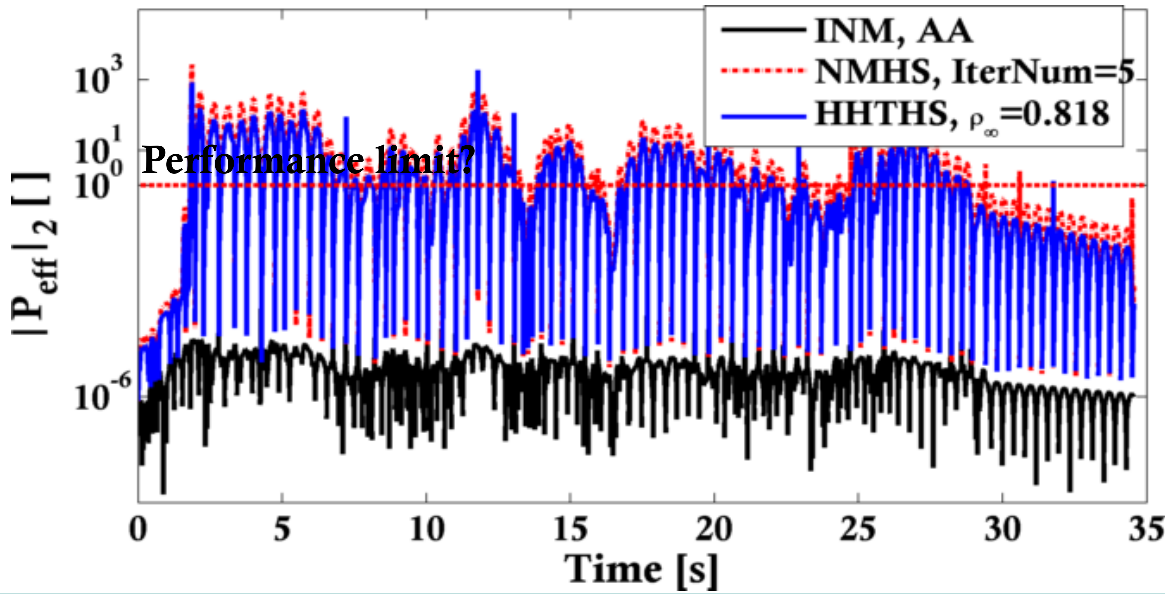
H_k=Kinetic energy; T_k=Dissipative energy

$I_{r,k}$=Input/Inertial energy

2. Norm of residual force:

$$\left|P_{eff}^{(k)}\right|_2 = \left|-M\ddot{u}_{i+1}^{(k)} - C\dot{u}_{i+1}^{(k)} - \mathrm{r}\left(u_{i+1}^{(k)}\right) + P_{i+1}\right|_2$$





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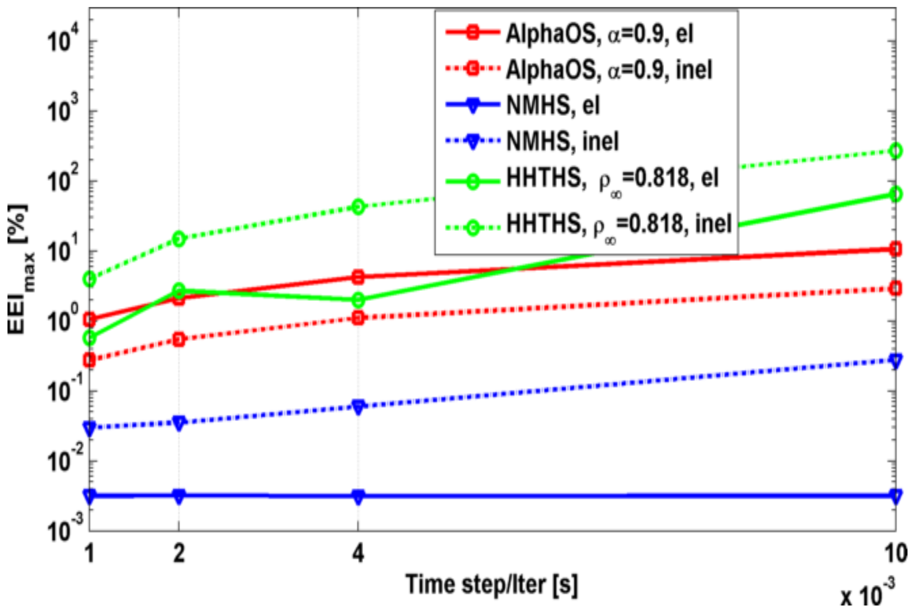
Case study: 2bay-1story steel frame

Parameters of study:

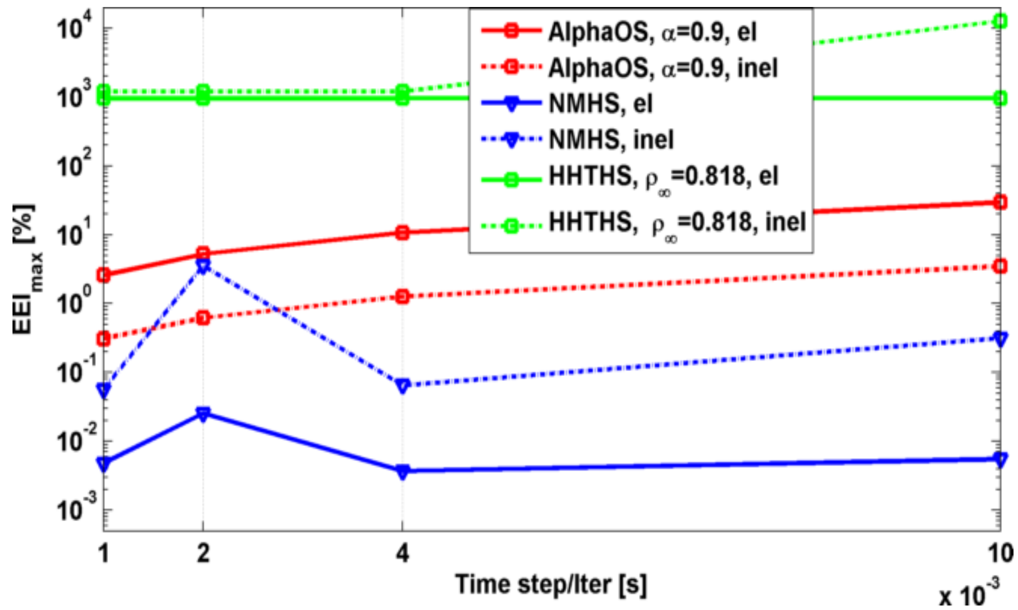
1. Input motion type
2. Degree of inelasticity
3. Simulated experimental error $[\pm 5\% \; of \; max. displ]$
4. Algorithm parameters (α value, Number of iterations)
5. Time-step of analysis

Conclusion:

- Norm of residual force in many cases is a stringent and unreliable criteria for selection, but it can indicate possible instability in a hybrid test
- AlphaOS was found to be robust under an experimental error



Energy error indicator under no experimental error

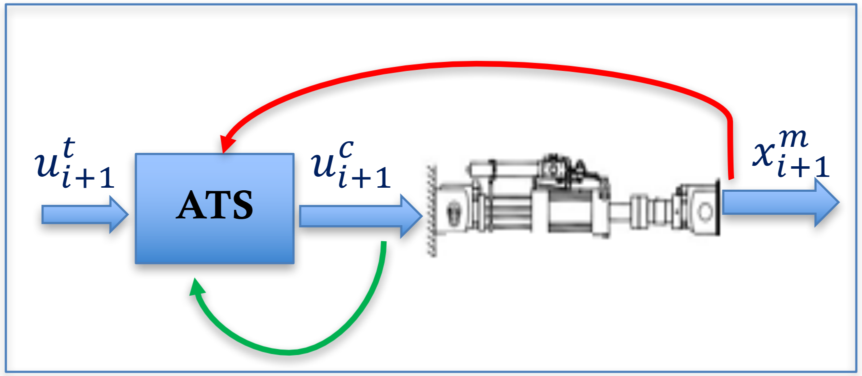


Energy error indicator with undershoot error

Compensation algorithm

Adaptive Time Series (ATS) based on third order polynomials:

- Corrects commands generated by the predictor-corrector using the last 3 commands
- Measured velocity and acceleration are computed using Lagrange polynomials (original formulation was based on back difference(BD))
- RMS value of the last 1sec data should above 0.5mm for an update to occur

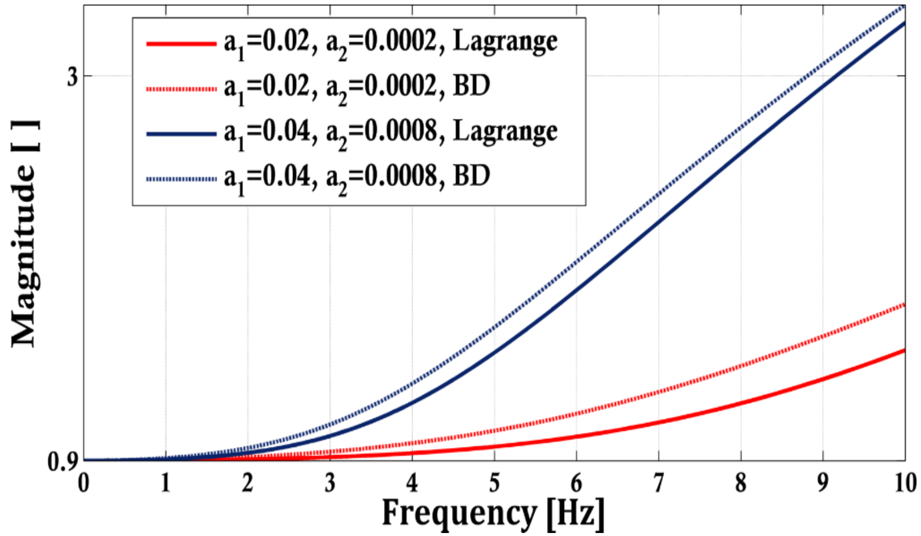


ATS algorithm (with $\boldsymbol{a_0}$, $\boldsymbol{a_1}$ and $\boldsymbol{a_2}$ parameters) can be written as a discrete transfer function as:

$$G_{ATS}(z) = \frac{x_c(z)}{x_t(z)} = \frac{1}{(\Delta t)^2 z^{3N}}\{q_3 z^{3N} + q_2 z^{2N} + q_1 z^N + q_0\}$$

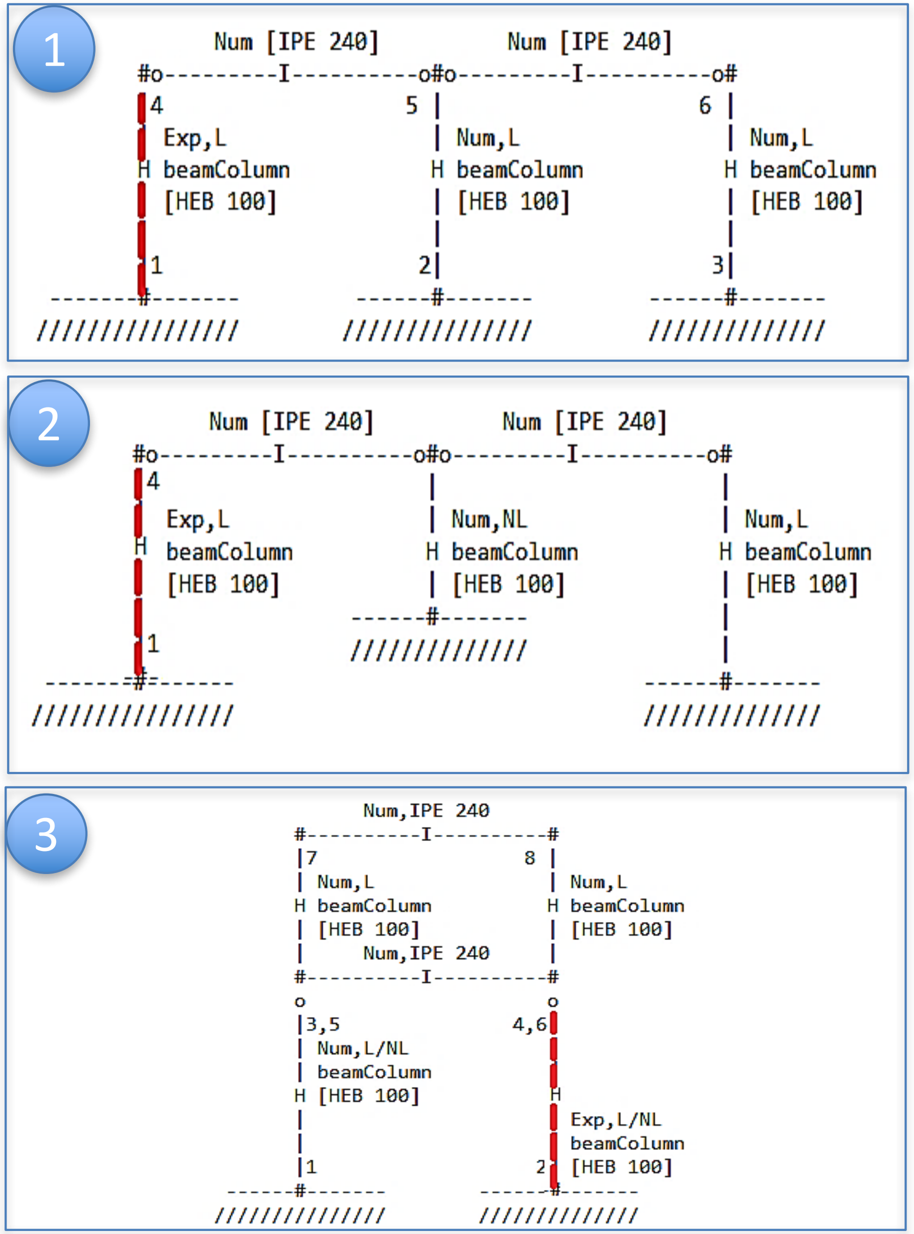
$$q_3 = a_0(\Delta t)^2 + \frac{11}{6}a_1(\Delta t) + 2a_2\,;\; q_2 = -\frac{18}{6}a_1(\Delta t) - 5a_2\,;$$

$$q_1 = -\frac{9}{6}a_1(\Delta t) + 4a_2; \qquad q_0 = -\frac{2}{6}a_1(\Delta t) - a_2$$



Lagrange based ATS exhibits smaller overshoot at higher frequencies compared to BD method

Validation of the platform-plan



--- **Test specimen**

Scheme for validation

Pre-test:

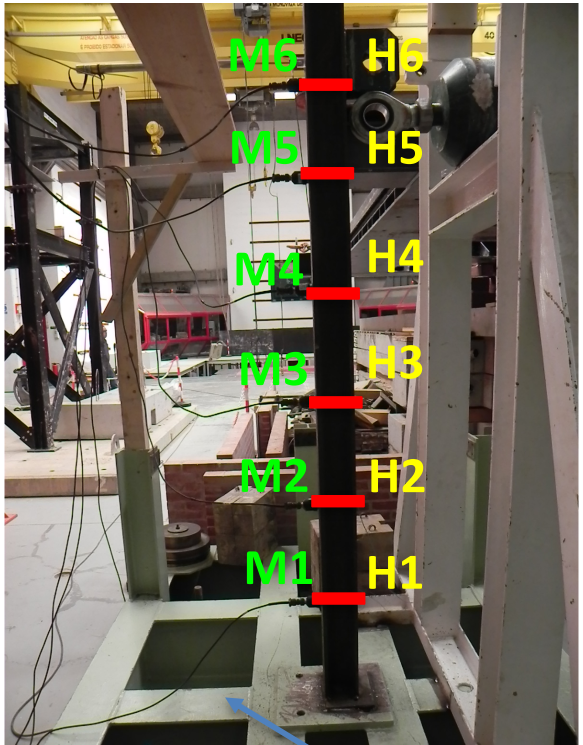
- Experimental element identification through hammer test and updating of the initial stiffness matrix in the hybrid test model & updating the purely numerical models for the purpose of comparison
- Identification of system response function and delay compensation parameters via a white noise signal

Test sequence for hybrid tests:

1) Frame 1 at elastic regime
2) Frame 2 at inelastic regime(source of inelasticity is from numerical side)
3) Frame 3 at elastic regime
4) Frame 1 at increasing inelasticity

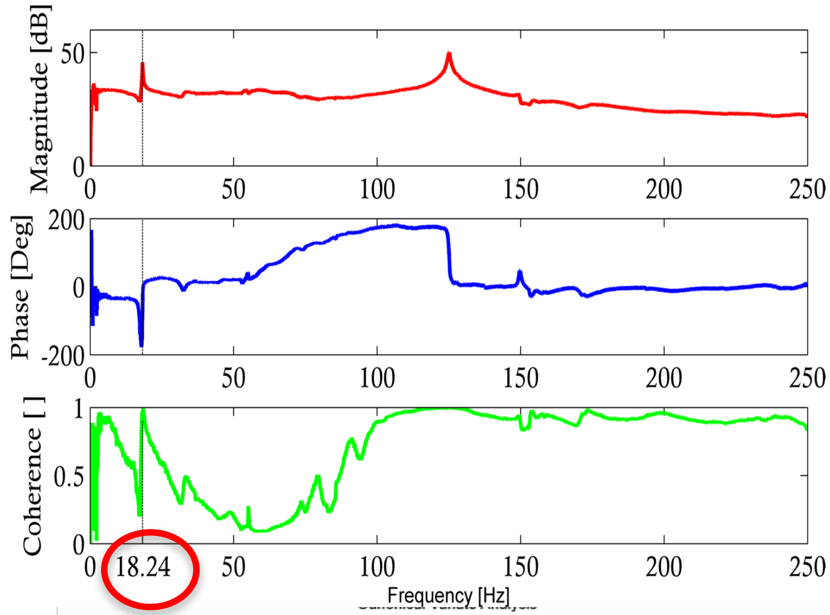
Validation of the platform-specimen identification

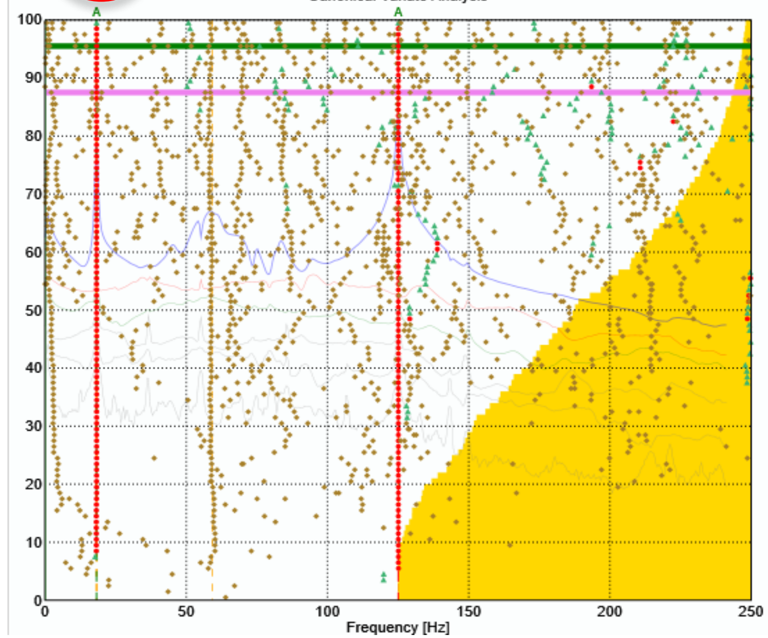
Hammer test setup



Steel base

M-measurement pt. [fixed]
H-hammer pt. [roving]

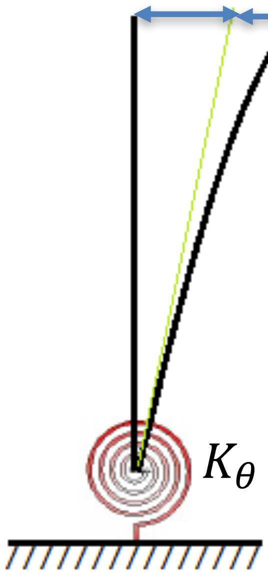




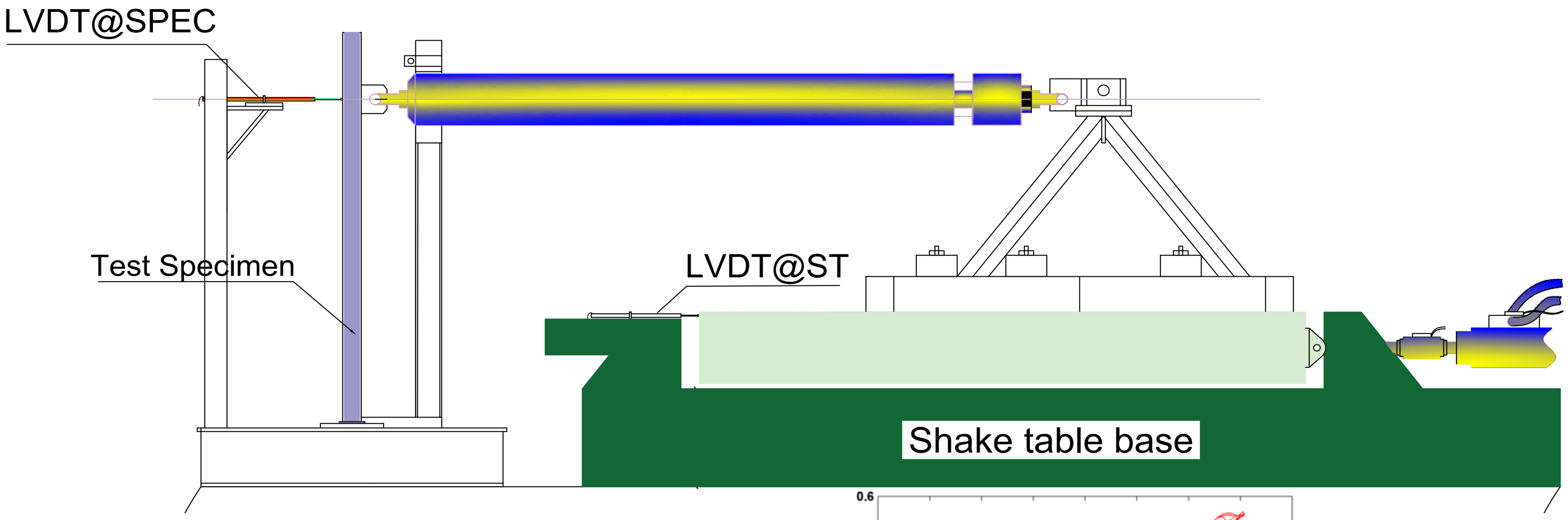
Theoretical frequency (1st):
25.32Hz
Experimental estimation:
18.24Hz

Possible reasons:
Non-rigid connection of the steel base to strong floor

Model update:
Defining a rotational spring, k_θ, at the base that models the non-rigid connection

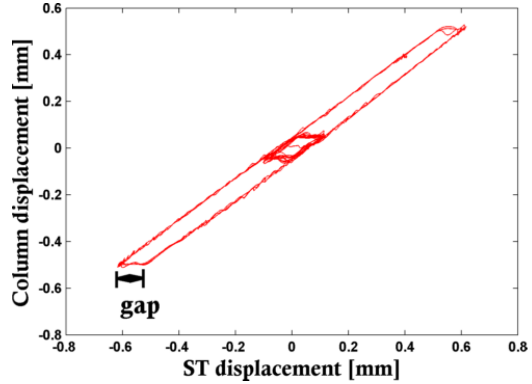


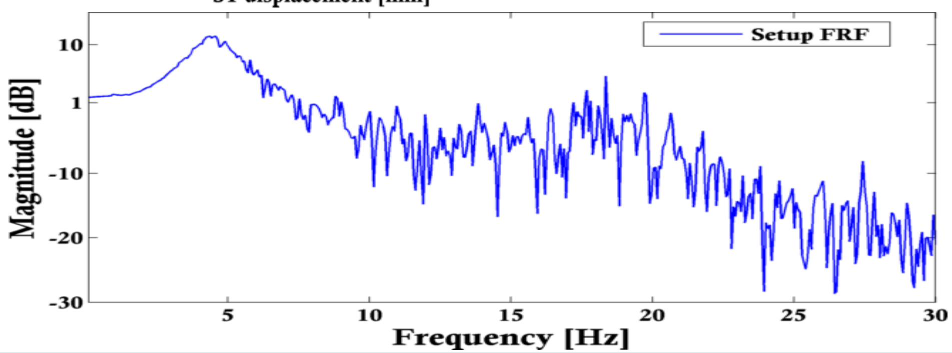
Test setup preparation and system identification



Characteristics:

- ❖ Uniaxial shake table (ST), space truss and steel strut assembly as a loading system
- ❖ Steel base fixed to a strong floor
- ❖ Load cell connected to strut end
- ❖ Experimental steel column (*HEB100* & fy=355Mpa) welded to a steel base
- ❖ ST actuator feedback control is done from LVDT@ST or LVDT@SPEC





Simulated hybrid test –what for?

Step 1
- Open loop test w/o specimen

Ascertain proper functioning of all components of the platform

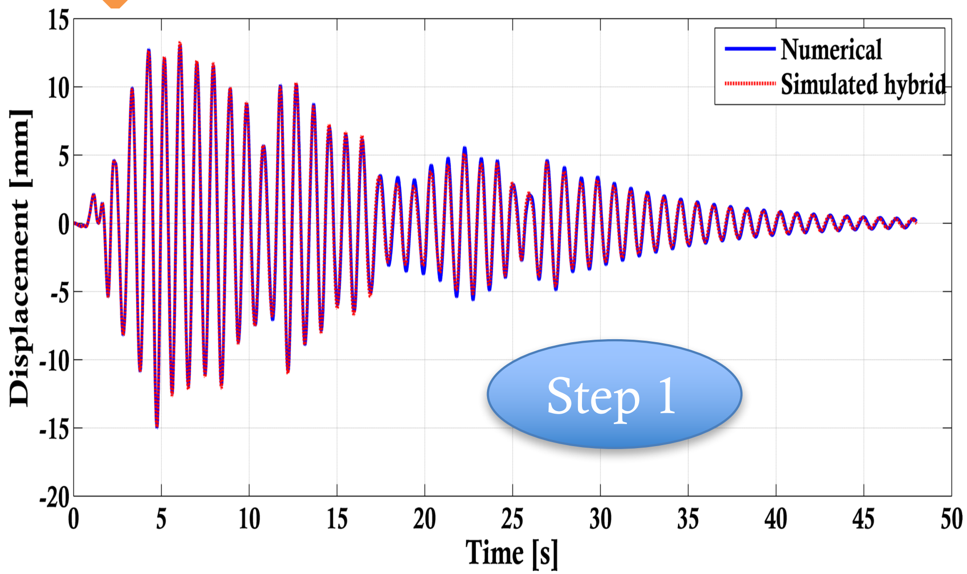
Step 2
- Open loop test w/ specimen

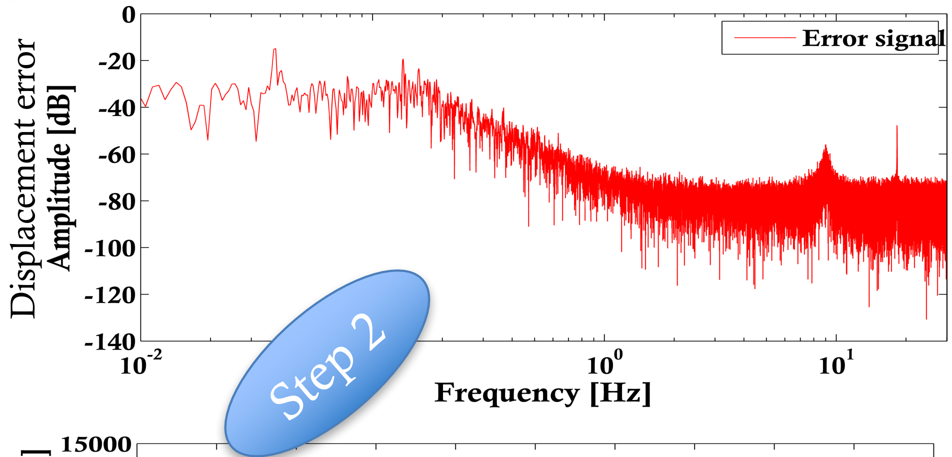
Assess adequacy of actuation system and control

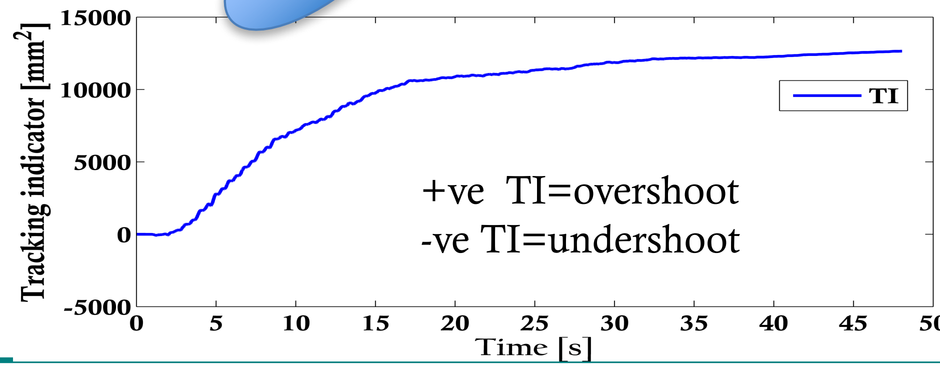
Step 3
- Closed loop test at low-level excitation

Step 4
- Closed loop test at desired excitation level

Stability and performance of tests and comparison with numerical solutions





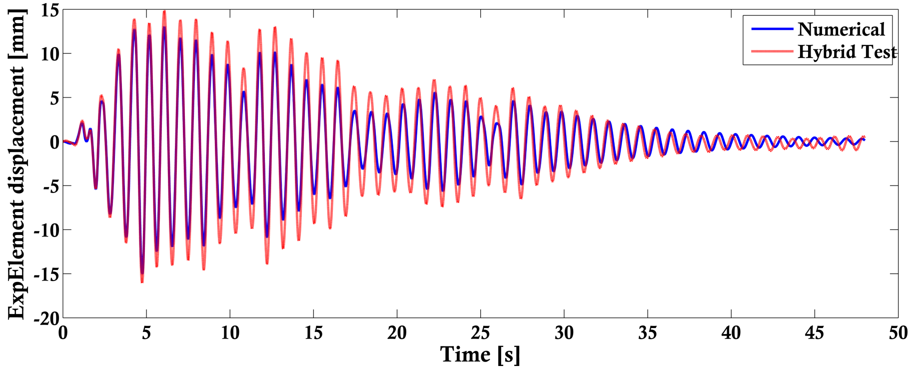


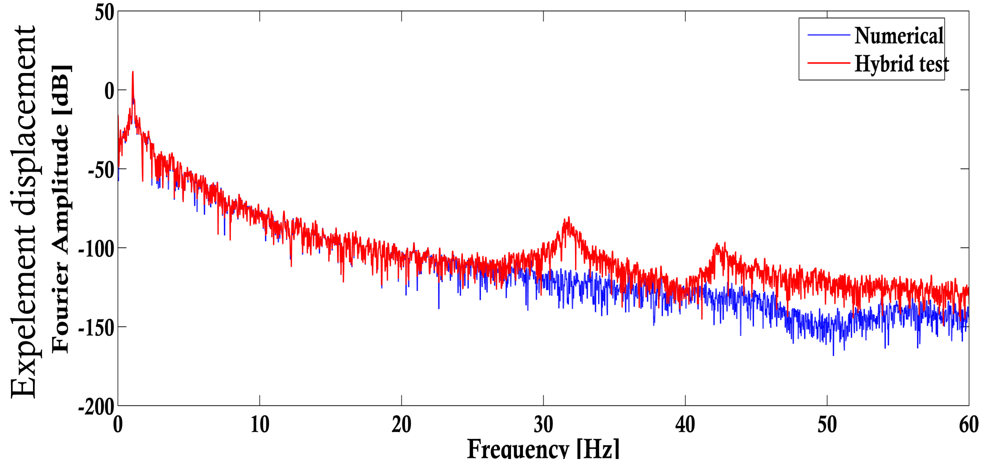
Actual hybrid tests and system performance

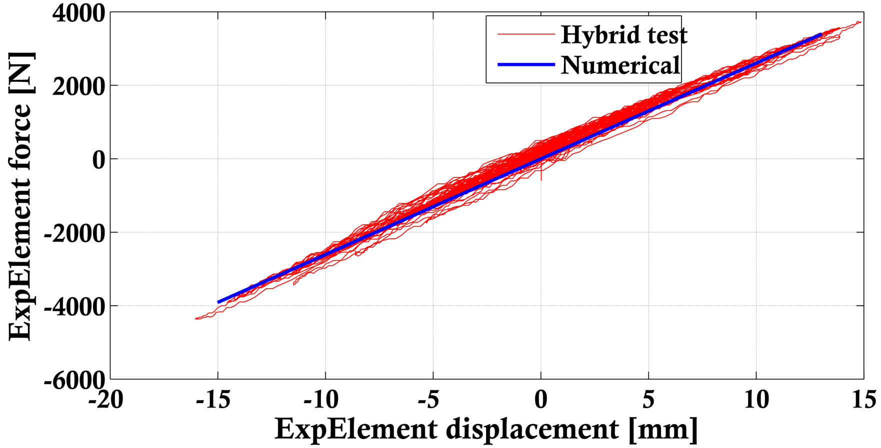
- Test structure: Frame 1, 1st mode=1.08Hz
- Load cell force: Low pass filtered at 4Hz
- Test rate($\frac{\delta t_{sim}}{\delta t_{act}}$)=27.8
- Integration method: AlphaOS at $\alpha = 0.9$
- Extrapolation time=40% δt_{sim}
- Input motion: El Centro at 0.03g PGA
- Initial stiffness matrix of experimental element initialized from the hammer test

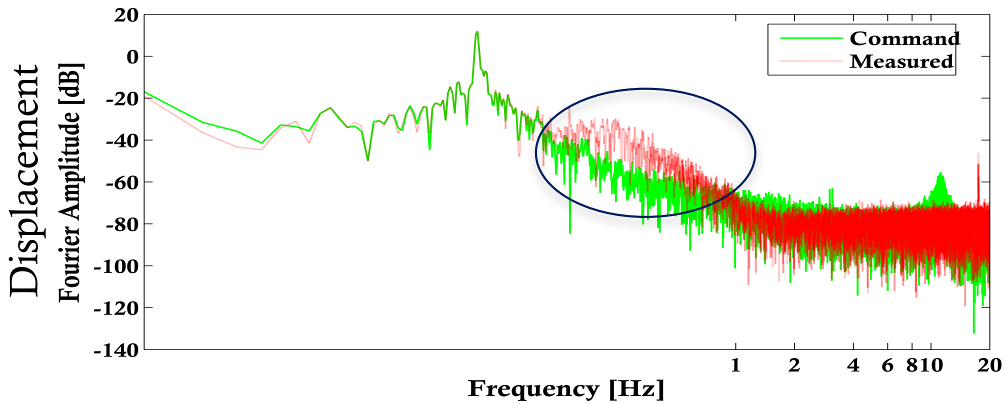
Observations:

- An overshoot in the hybrid test response
- Higher mode effect prevails in the response









Uncertainty quantification using hybrid test

Objectives: The need to substitute uncertainty and sensitivity analysis of structures or structural members solely based on a purely numerical simulation by a hybrid simulation

Reason: Trusting pure numerical methods up to collapse level can be questioned

Requirement: The need to reduce the number of response evaluations since each evaluation is equivalent to a new experimental element

How it is done: Using meta modelling

Previous research: Application using polynomial chaos expansion (PCE) as a surrogate model (Abbiati et al., 2015)

Method selected: Multiplicative dimensional reduction method (M-DRM)

Basic concept of the method: Response surface function, y, can be approximated as:

$$y = h(x) \approx \sum_{i=1}^{n} h_i\,(x_i) - (n-1)\, h_0$$

$$\approx {h_0}^{(1-n)} \times \prod_{i=1}^{n} h_i(x_i)$$

Where $h_i(x_i) = h(c_1, \dots c_{i-1}, x_i, c_{i+1}, .. c_n)$ and c_i is the mean value of a variable i; and

$$h_0 = h(c_1, \dots c_n) = a\ \ constant$$

Moments are then computed by:

$$\mu_y = {h_0}^{(1-n)} \times \prod_{i=1}^{n} E[h_i(x_i)] = {h_0}^{(1-n)} \times \prod_{i=1}^{n} \rho_i$$

$$V_y = (\mu_y)^2 \times {h_0}^{(1-n)} \prod_{i=1}^{n} E[(h_i(x_i))^2] = \prod_{i=1}^{n} \theta_i$$

The kth moment of the *ith* cut-off function ($h_i(x_i)$) can be approximated as a weighted sum using Gauss- quadrature points:

$$E[h_i(x_i)^k] = \int h_i(x_i)^k f(x_i) dx_i \approx \sum_{j=1}^{L} w_j\, (h_i(x_j))^k$$

x_j and w_j are the coordinates and weights of the quadrature rule and L is the number of integration points

Total # of model runs= # of random var.*L+1

Case study for M-DRM and comparison

Case study: Frame 1

Node 4 is tip of experimental element

Input motion: El Centro, 1940, PGA=0.3g

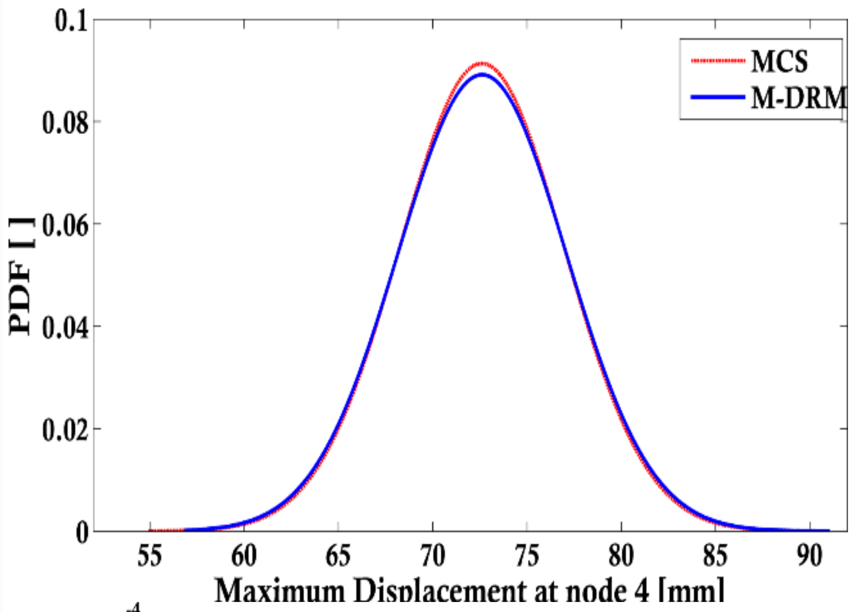
Random variables: stiffness and damping of numerical elements with lognormal distributions

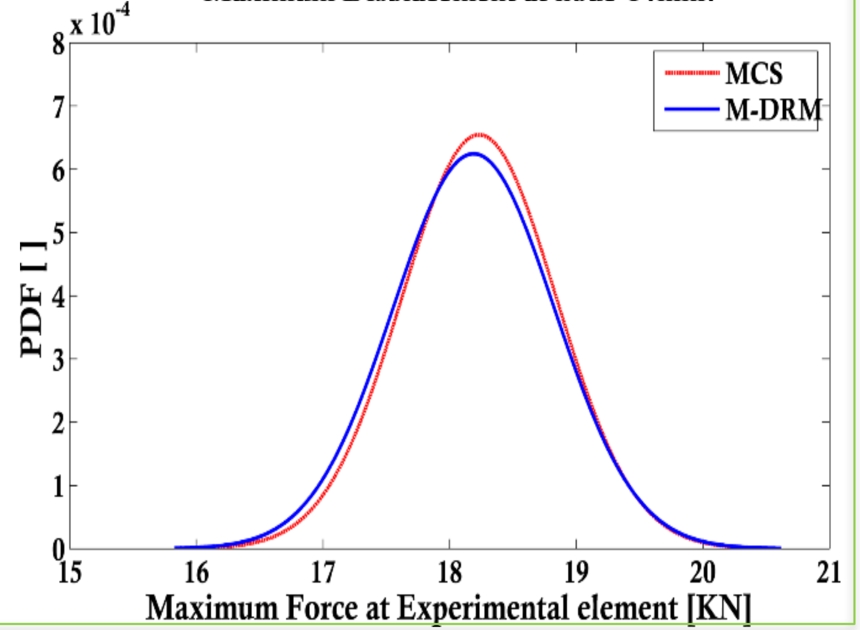
Gauss-quadrature points: 7

	$k_{num}[\frac{KN}{m}]$	ξ_{num}[%]	Analysis
mean	323.47	0.02	
Cov1	5.0%	30.0%	M-DRM
Cov2	5.0%	15.0%	M-DRM
Cov3	1.0%	2.0%	M-DRM
Cov4	6.5%	10.0%	M-DRM & MCS

	Scale
PGA1	0.3
PGA2	0.6
PGA3	1.5

PGA	Maximum displacement	M-DRM	MCS	$e_r = \|MCS - MDRM\|/MCS * 100$ [%]
PGA1	Mean	45.5143	45.3429	0.3780
	Standard deviation	1.3039	1.2674	2.8836
	Cov4	0.02865	0.02795	2.4961
PGA2	Mean	72.6213	72.6087	0.01728
	Standard deviation	4.4761	4.3684	2.4652
	Cov4	0.06164	0.06016	2.4475





Sensitivity analysis using M-DRM method

Following the M-DRM formulation, the 1st order and total Sobol indices can be shown to be:

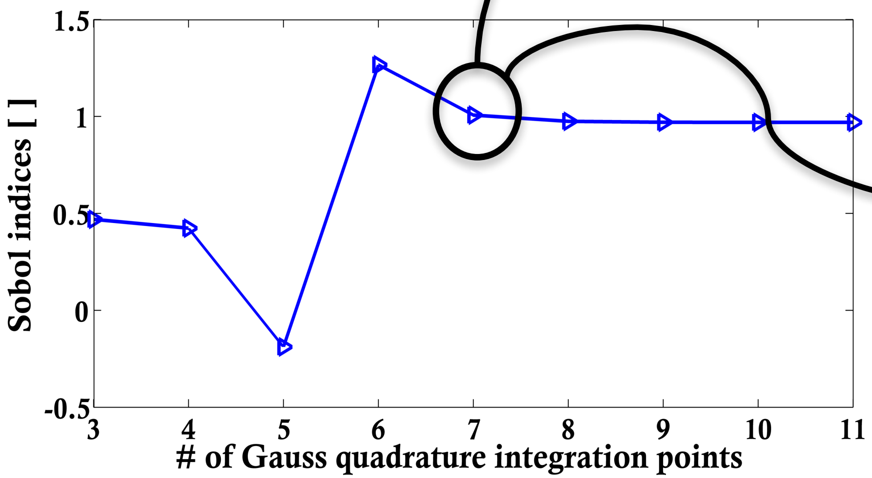
$$S_i = \frac{V_i\{(y|x_i)\}}{V_Y} \approx \frac{\theta_i/\rho_i^2 - 1}{\left\{\prod_{k=1}^{n} \theta_k/\rho_k^2\right\} - 1}$$

$$ST_i \approx \frac{1 - \rho_i^2/\theta_i}{1 - \left\{\prod_{k=1}^{n} \rho_k^2/\theta_k\right\}}$$

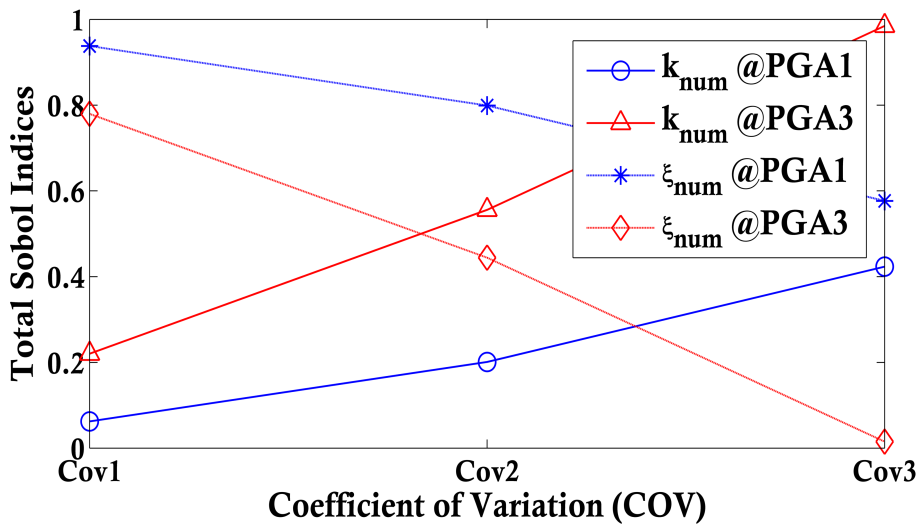
$$ST_{iinteaction} = ST_i - S_i$$

1st order, total and interaction Sobol indices for max. displacement

u_{max}		S_i		ST_i		ST_i-S_i	
		k_{num}	ξ_{num}	k_{num}	ξ_{num}	k_{num}	ξ_{num}
PGA1	Cov1	0.06229	0.93749	0.06251	0.93771	0.00022	0.00022
	Cov2	0.20141	0.79840	0.20160	0.79859	0.00019	0.00019
	Cov3	0.42343	0.57656	0.42344	0.57657	0.00001	0.00001
PGA3	Cov1	0.27787	0.72188	0.27812	0.72213	0.00025	0.00025
	Cov2	0.59802	0.40184	0.59816	0.40198	0.00014	0.00014
	Cov3	0.87132	0.12867	0.87133	0.12868	0.00000	0.00000



Maximum shear force at experimental column



Total # of *hybrid tests*=2*7+1=15

Future works

- Completion of planned hybrid tests on the steel frames
- Preparation of the platform to support a hybrid test that involves a shake table and an auxiliary actuator
- Conducting an equivalent force control in the auxiliary actuator
- Implementation acceleration tracking controller in the shake table
- Preparation & testing of a hybrid simulation that involves soil-structure interaction

THANK YOU FOR YOUR ATTENTION!