Convegno 2025
Progetto DPC-ReLUIS
2024–2026

Hybrid Simulation in support of earthquake engineering

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Contents

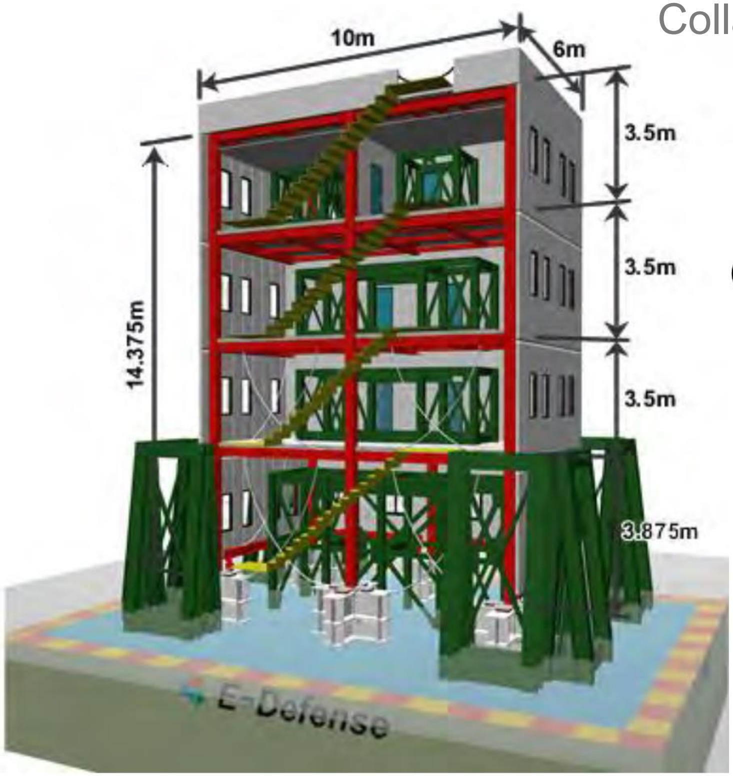
- Brief overview of HS method
- Contribution in earthquake engineering – applications
- Assessment

Needs for testing

- Seismic response of civil eng. materials is inherently non-linear
- Full (large) scale testing necessary for:
  - large size, massive structures (e.g. concrete)
  - verification of Standards for the design of new structures
  - the assessment of existing structures regarding their capacity and the retrofitting techniques
  - new materials introduced in construction
  - the verification of special seismic devices in full scale before application

… **need for experimental testing/verification**

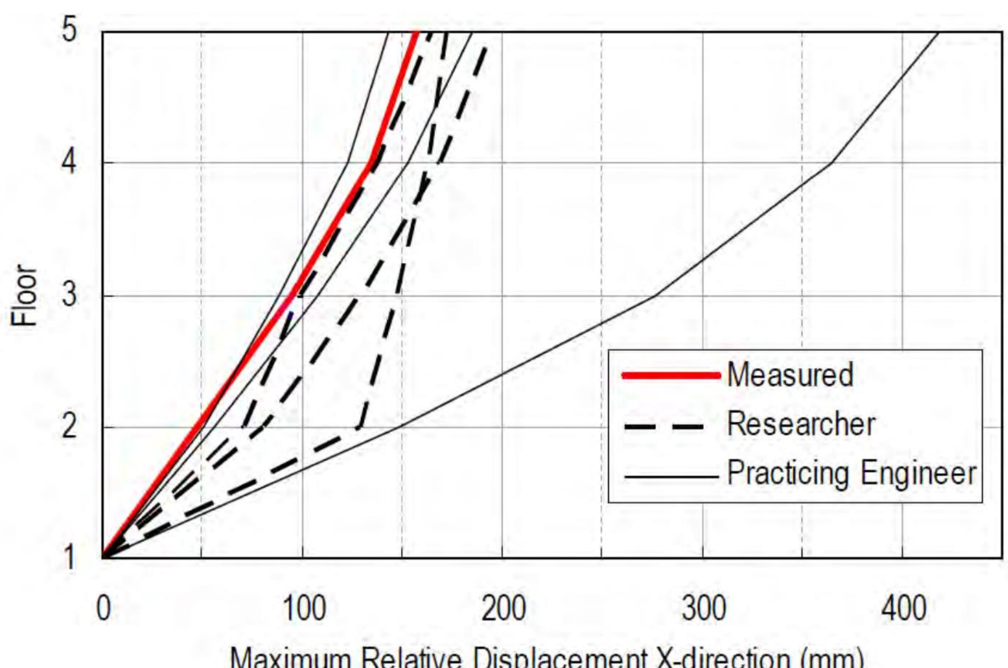
How accurately can we predict structural response?



Collapse test of a full-scale four story steel building , 2007
http://www.blind-analysis.jp/2008/2007/index_e.html

3D Analysis Blind Prediction Results

(measured and best 3 teams of each category. Total 30 participants)

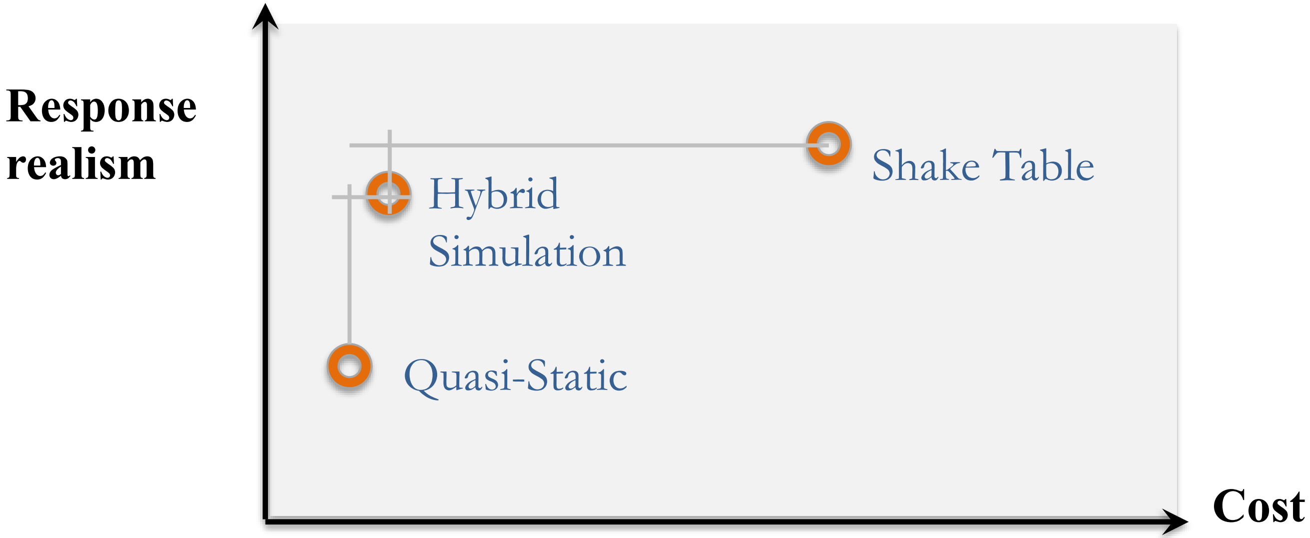


Experimental methods

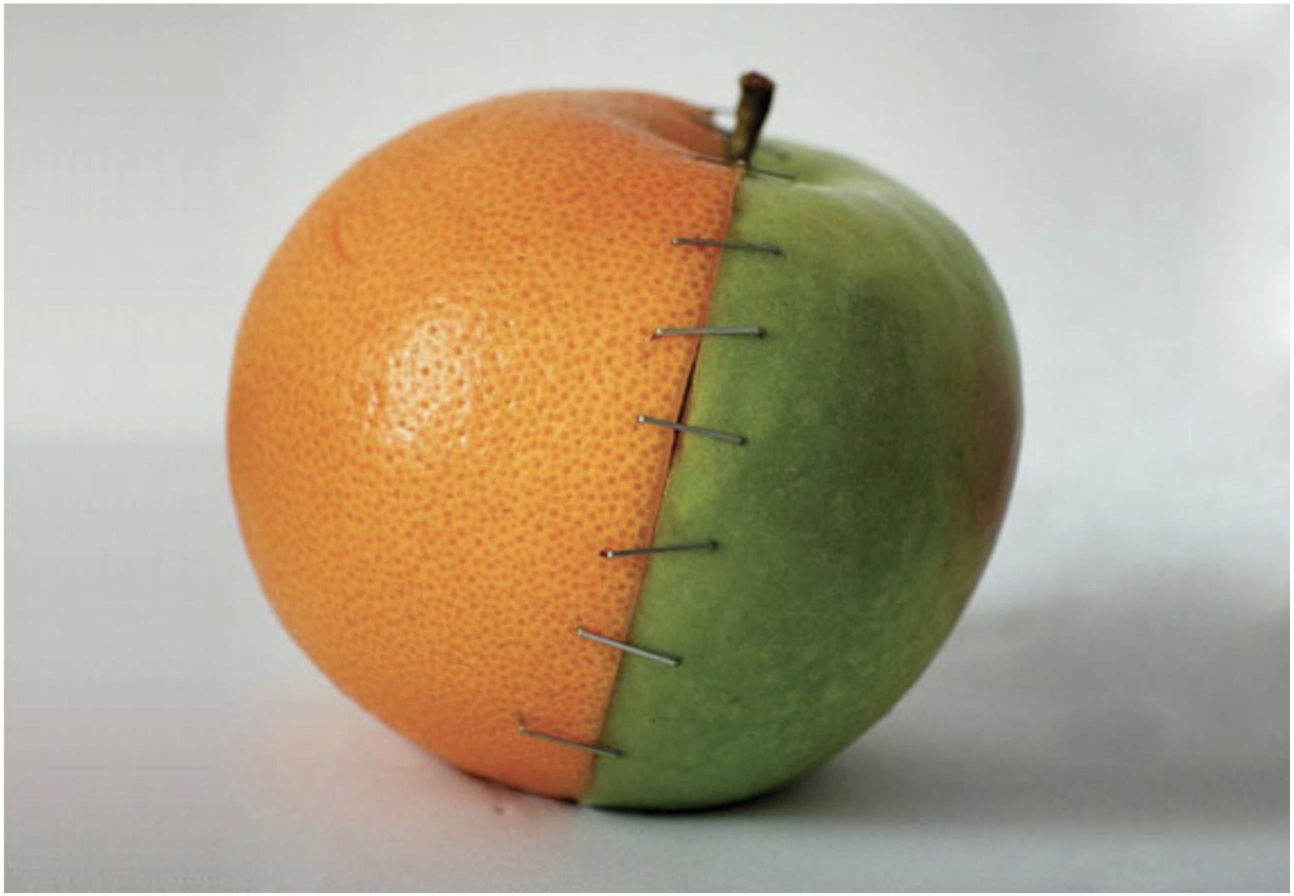
Static testing

Hybrid simulation

Dynamic testing



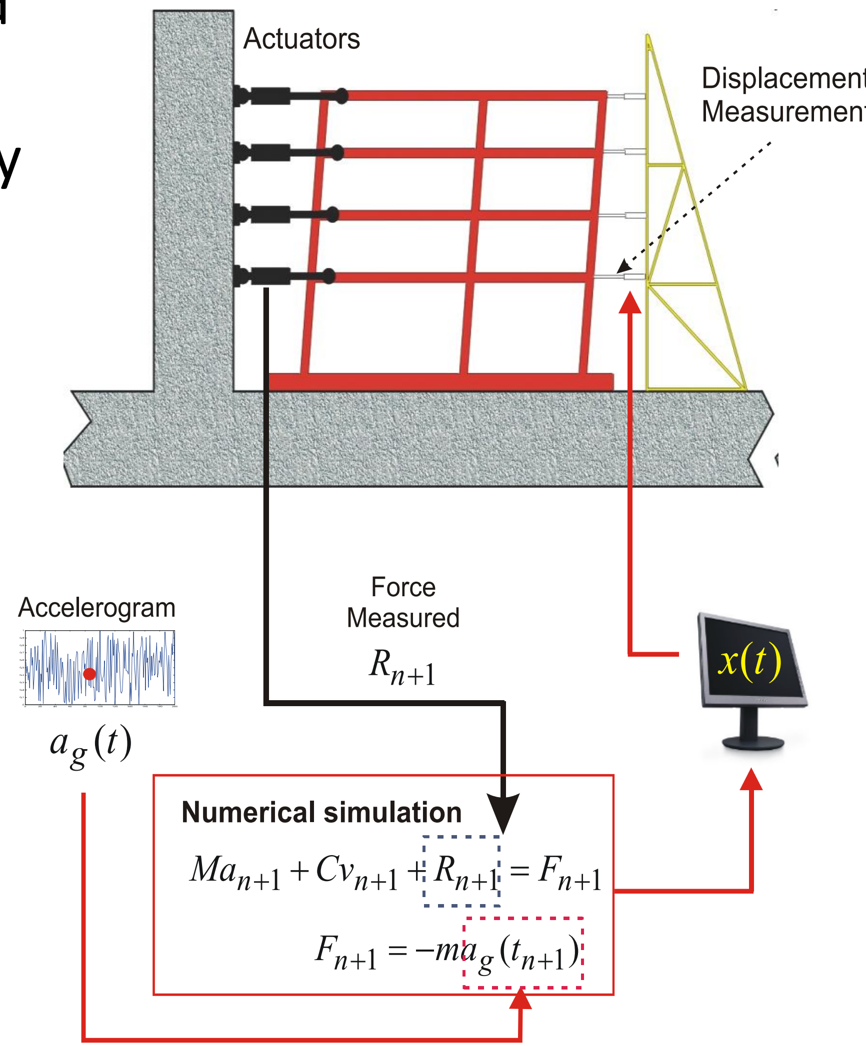
What is Hybrid Simulation ?



idea: Prof. B Stojadinovic, HYBRID_2020, ETH, Zurich
Photo by Horatiu Gheorghe on Flickr

The main idea....

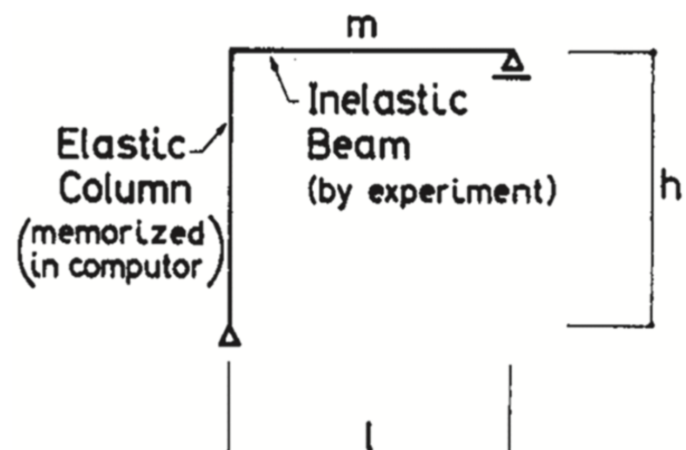
- Inertia/damping accommodated via numerical model while,
- Structural resistance provided by the physical model (specimen)



Brief historical note on HS

- Inititally termed: “online computer-controlled test” or “pseudo-dynamic test”
- Univ. of Tokyo:
  – real-time, small scale & analog computer (Hakuno, 1969)
  – the very first HS system:

    Takanashi et al., 1972-1975
- 1975: the first test with substructuring !



* *Nakashima, M. “Hybrid simulation: An early history”, EESD, 2020, doi:101002/eqe.3274*

** *Udagawa K, Takanashi K, Tanaka H. Non-linear earthquake response analysis of structures by a computer actuator on-line system (Part 2: response analysis of one bay-one story steel frames with inelastic beams). T AIJ. 1978;268:49-59. (in Japanese)*

Timeline

Stage I : 1970 - 1980

Tests at U_Tokyo, on RC structures (Okada et al, 1977), steel frames (Takanashi et al,1980) and 27 tests on Steel–RC–Soil (1978-1985)

Stage II : 1980s - 1990

"US-Japan Joint Research utilizing large scale testing facilities"

Stage : 1990 – today

- new era after1999: NSF-NEES 10-year program
- the term "hybrid simulation" is introduced
- 2000-2018: **215** journal papers

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Implementation

- **Hardware** → low-friction actuators and high-precision control & measurement instruments
- **Software** → special platforms (**UT-Sim, OpenFresco**, ISEEdb, UI-SimCor, Mercury, HyTest, HybridFEM, etc.)
- **Control schemes** → special ones often necessary (mixed control, switched control)
- **Communication** among components
- **Quality** and **reliability**

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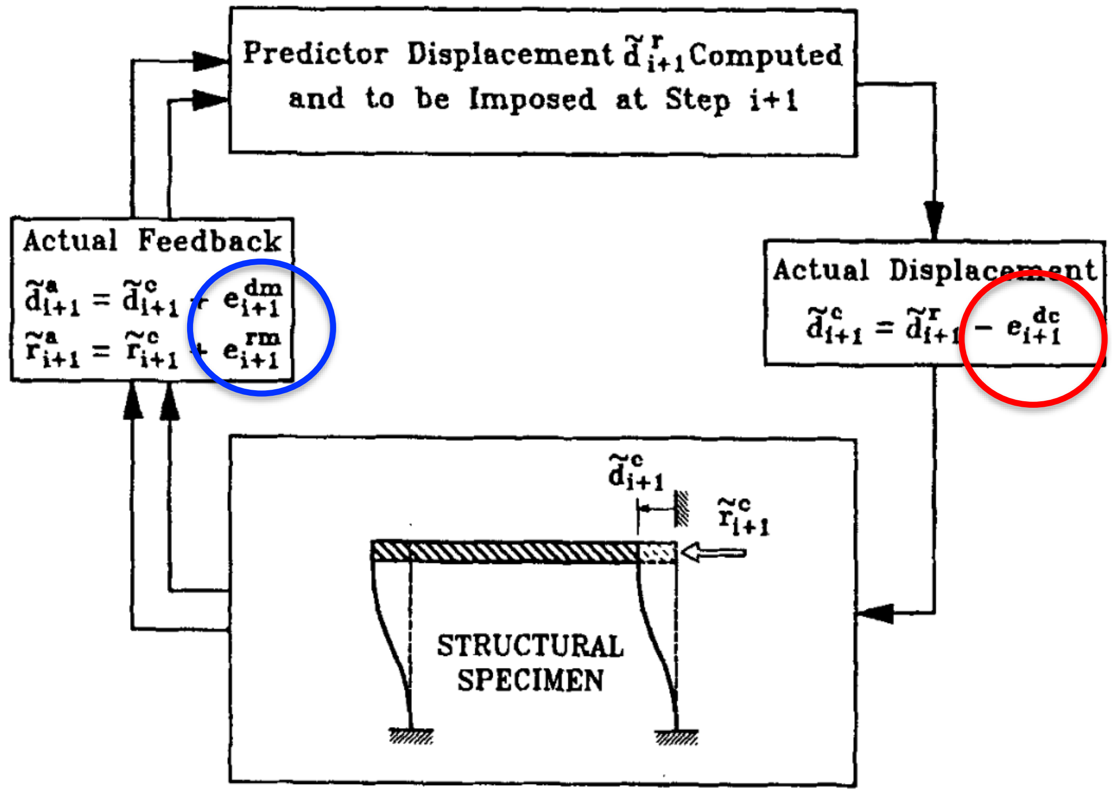
1. Accuracy & stability of HS

Reliability depends on errors:

- Numerical part:
  - simulation (structural idealization, accuracy of num. models)
  - integration algorithm: stability and accuracy
- Experimental part:
  - random (noise)
  - systematic (amplitude-phase over/under-shoooting, D/A conversion, force-relaxation, actuator delay, ...)
  - exp. errors can propagate in the numerical solution and introduce positive or negative damping

2. Experimental errors

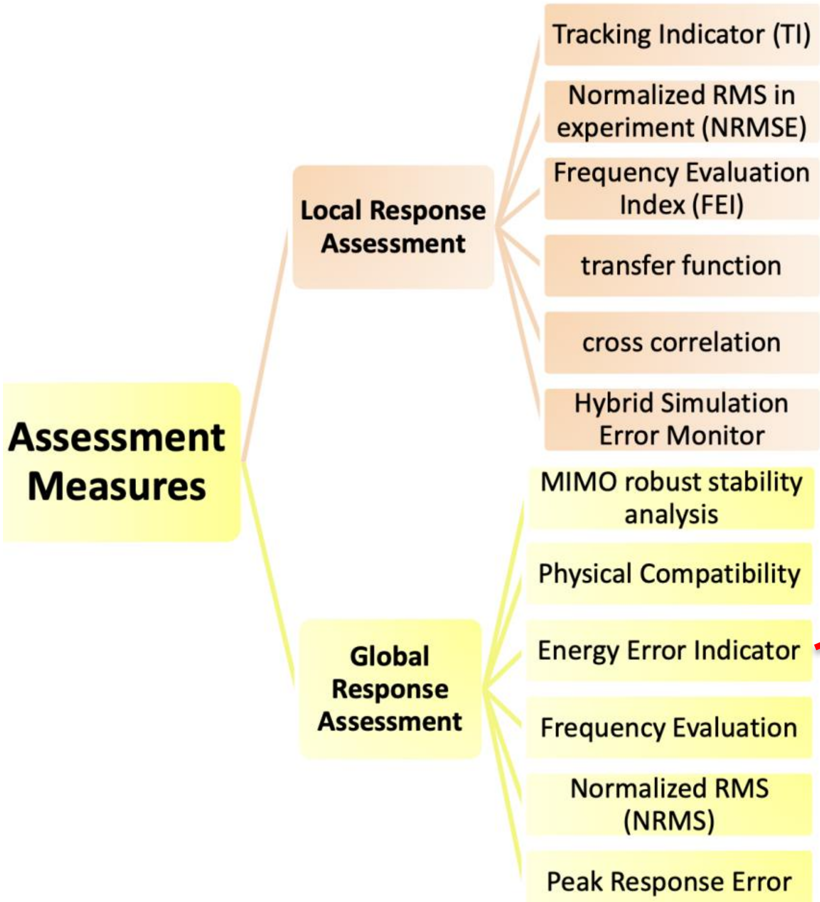
- Random
- Systematic
  - Measurement errors
  - Hybrid simulation technique
  - Control loop
- Reduction through:
  - system tuning
  - advanced control methods
  - integr. methods with numerical damping
  - error compensation methods

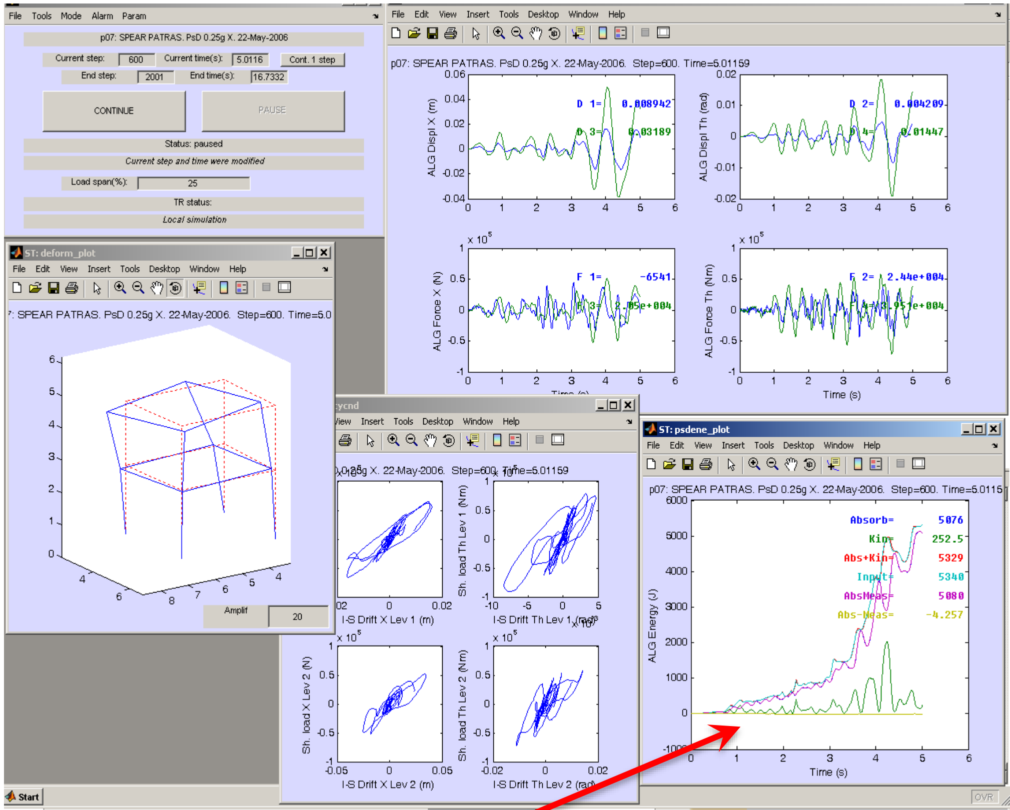


- displacement **control** error
- displ. / force **measurement** error
- $e^{dc} > e^{dm}, e^{rm}$

3. Error tracking indicators

- Local response
- Global response





NEES-MECHS, "Hybrid Simulation: A Discussion of Current Assessment Measures", Hybrid Simulation Task Force meeting, March, 2014

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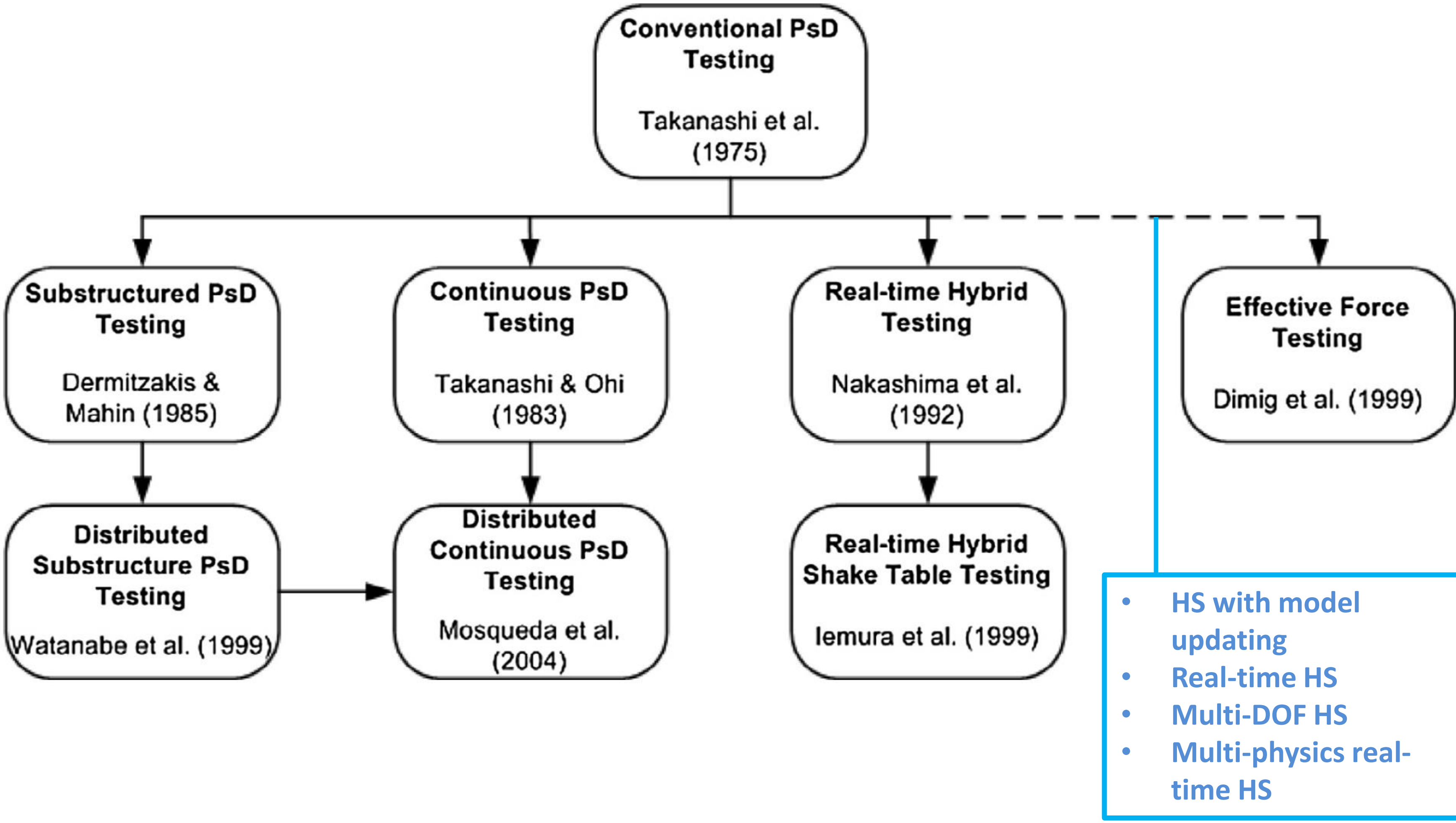
4. HS versions



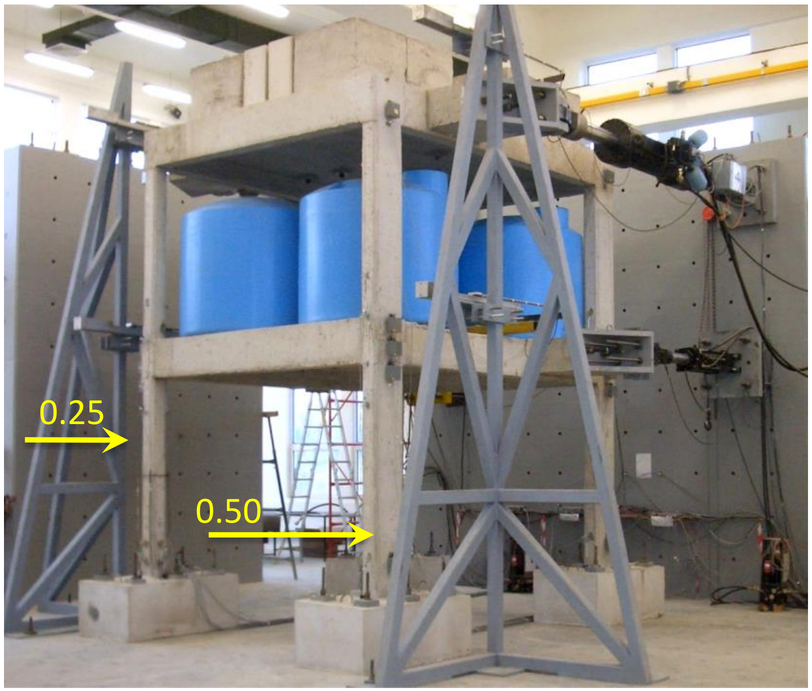
Carrion and Spencer (2007)

Applications in earthquake engineering

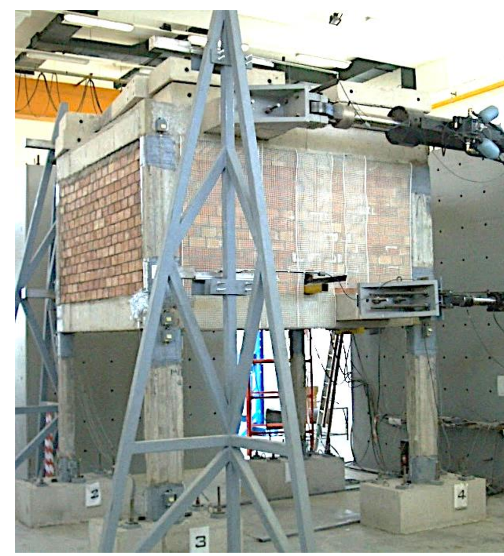
1. Pseudodynamic testing (full structures)
2. HS with substructuring
3. Continuous HS with substructuring
4. Substructuring on non-structural components
5. Soil-structure interaction
6. Distributed hybrid simulation

HS on full structure (Pseudodynamic method)

Seismic response of seismically deficient RC structures (SPEAR)

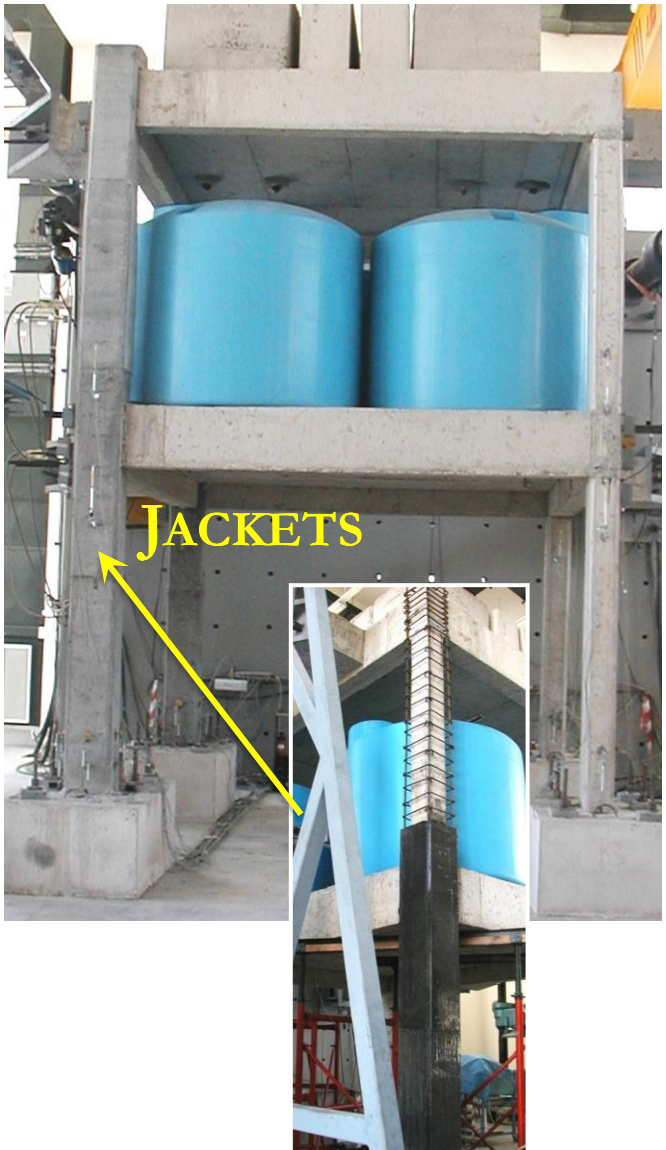


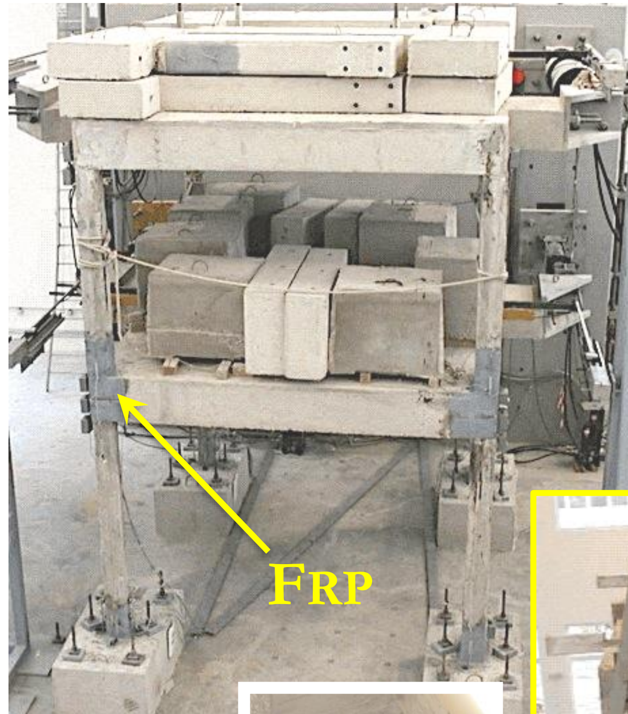
- structural deficiencies
- torsionally unbalanced
- torsional effects, response of splicing region
- regular & open story configuration

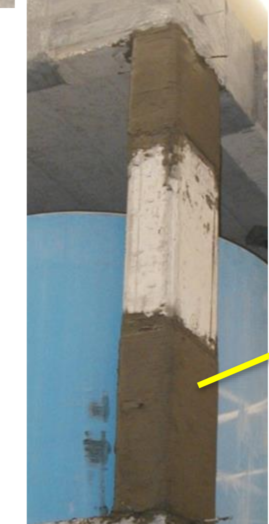


Retrofitting methods: RC/FRP/TRM jackets (ARISTION)

- reinstall stifness balance



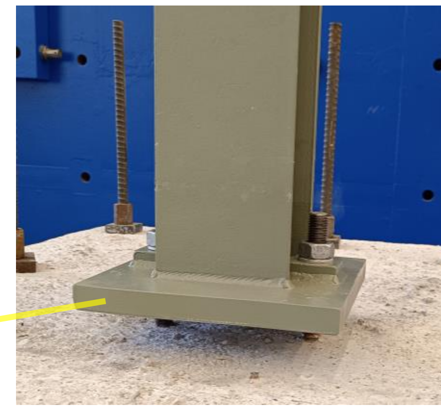


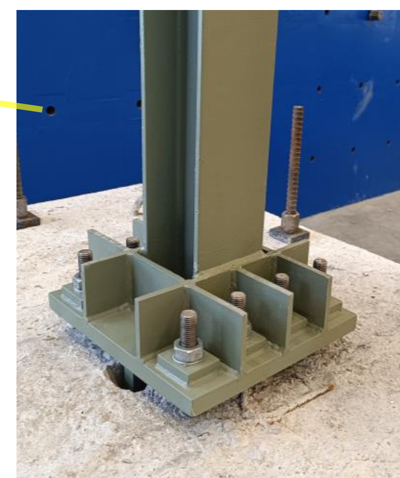


- provide sufficient ductility
- supress brittle modes of failure

Existing steel structures under 2D seismic excitation (ERIES-HITBASE)

non-stiffened
(pinned base)

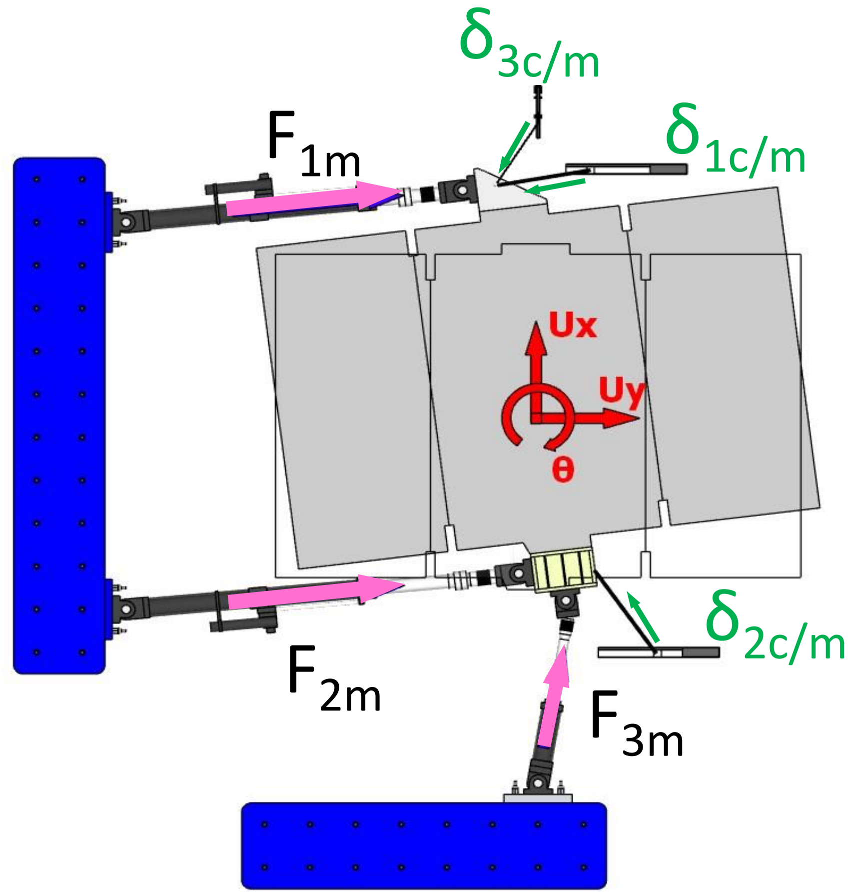


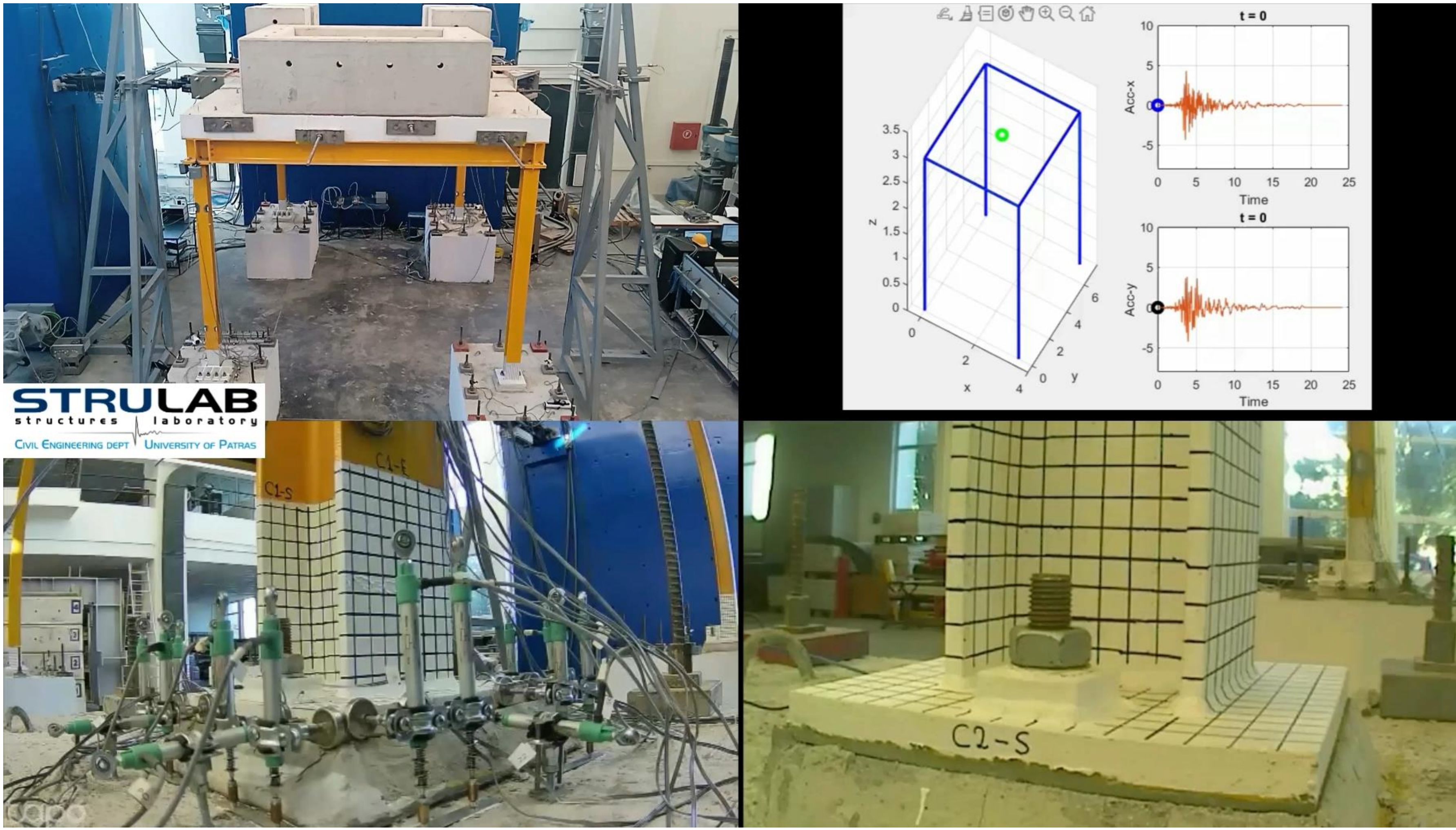


5.80x3.80mx3.0m

stiffened
(fixed base)

- influence of biaxial response of base plates to actual seismic motions
- effect of successive seismic motions
- adjustments to the testing strategy

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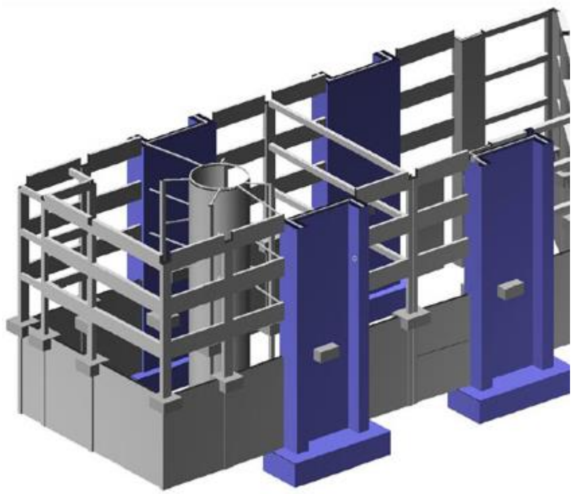
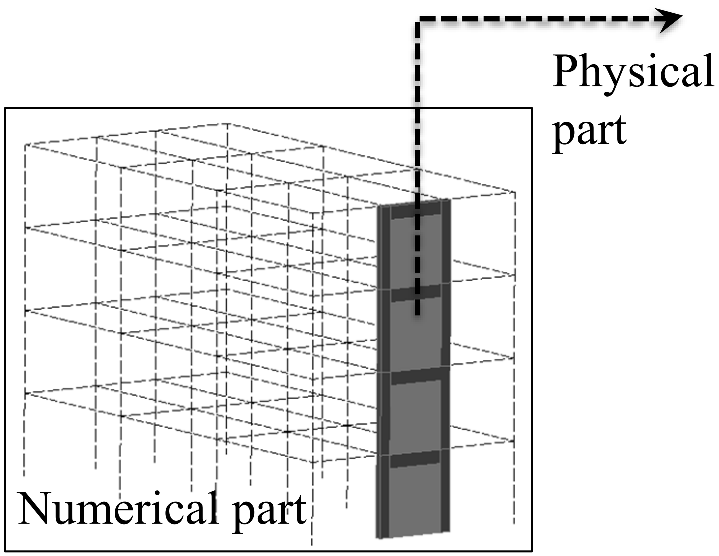
t = 0
Acc-x
Time
t = 0
Acc-y
Time
x
y
z
C1-S
C1-E
C2-S

HS with substructuring

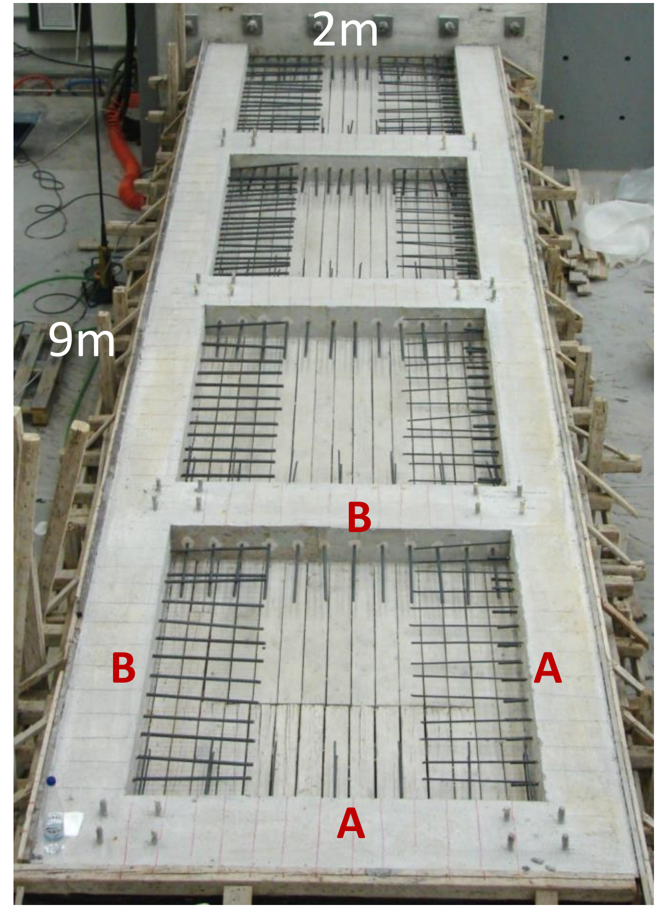
Retrofitting via RC infilling of bays (OASP)



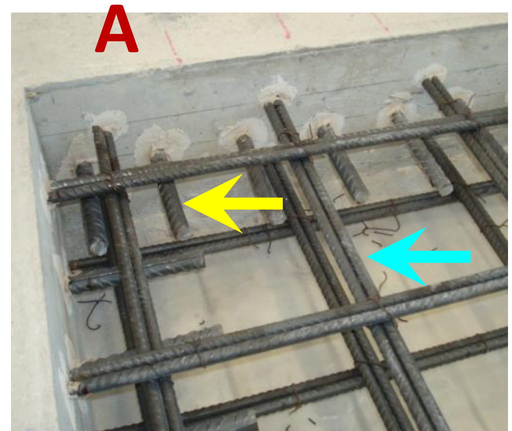


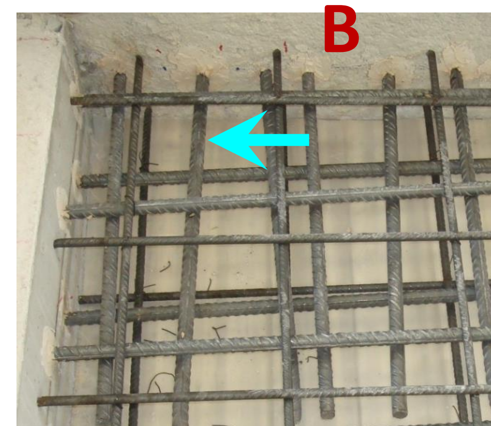
Problems studied:

- Structural response:
  - target: frame-infilling monolithicity
  - two schemes of different level of applicability



- Testing issues:
  - **stiff** structurs → tiny target displacements → control issues
  - tight cross-coupling of the DOFs → instability





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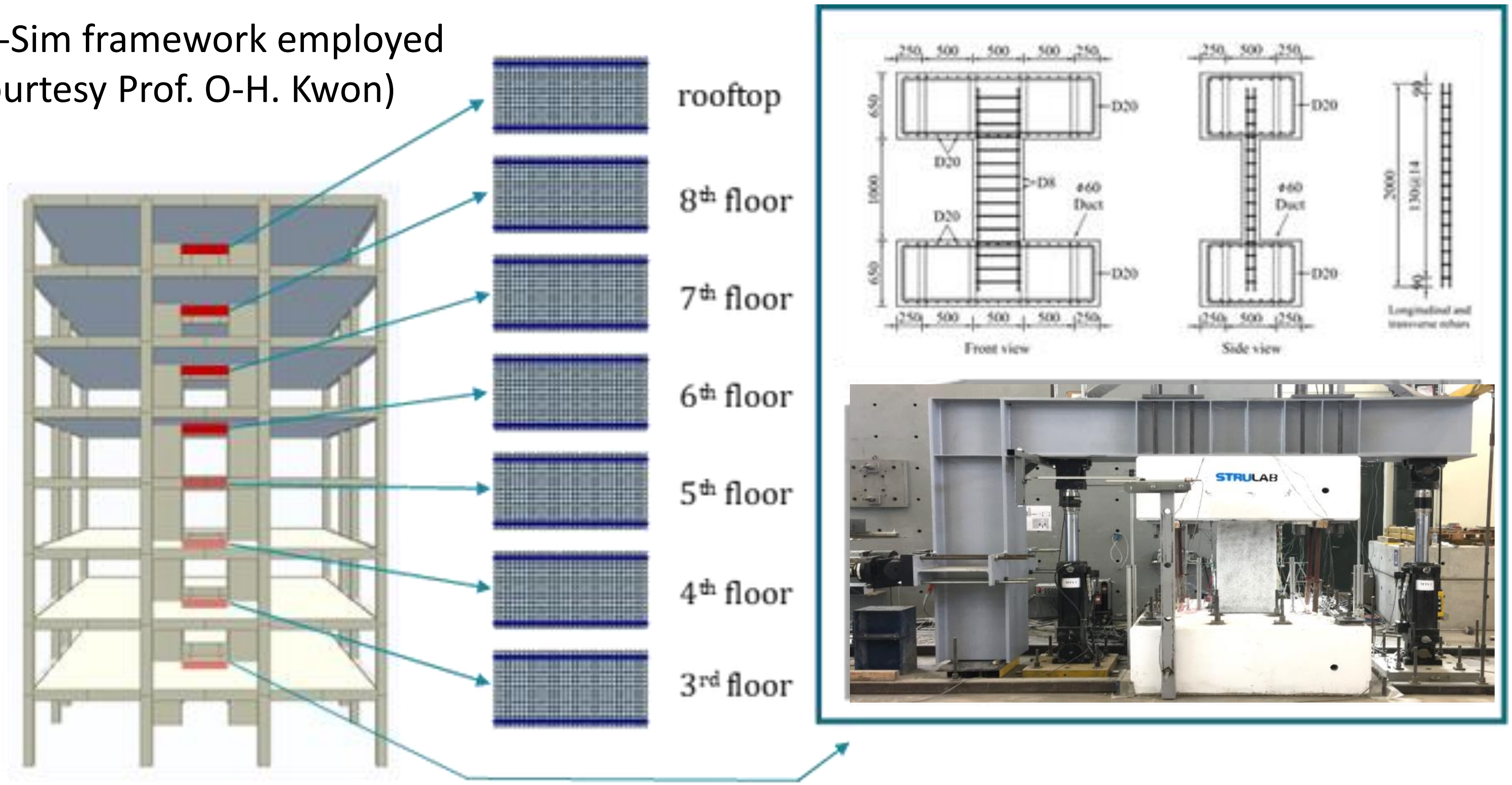
Effect of the real axial restraining on (inelastic) link beams in coupled–wall structures

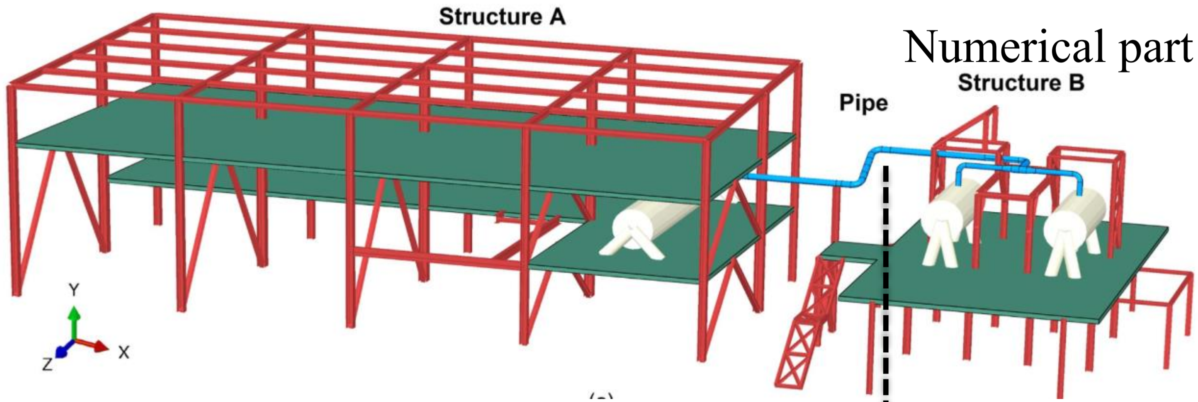
UT-Sim framework employed
(courtesy Prof. O-H. Kwon)



S-Frame linear elastic model VecTor2 model Laboratory specimen

Seismic response of piping in industrial buildings (Exchange-RISK)

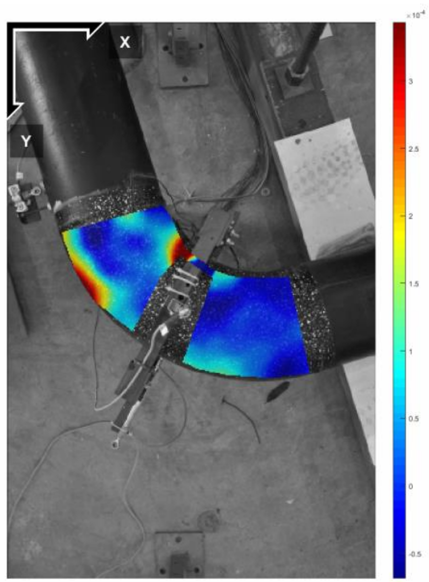
Numerical part



Numerical part

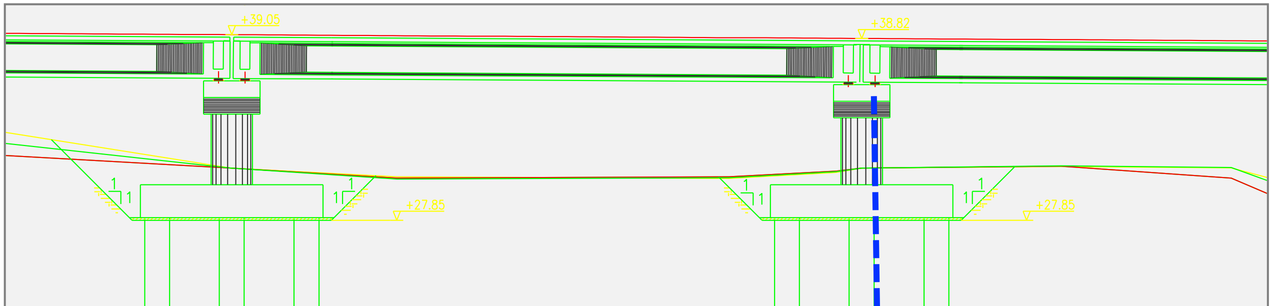
Physical part

Advanced measuring systems (DIC)



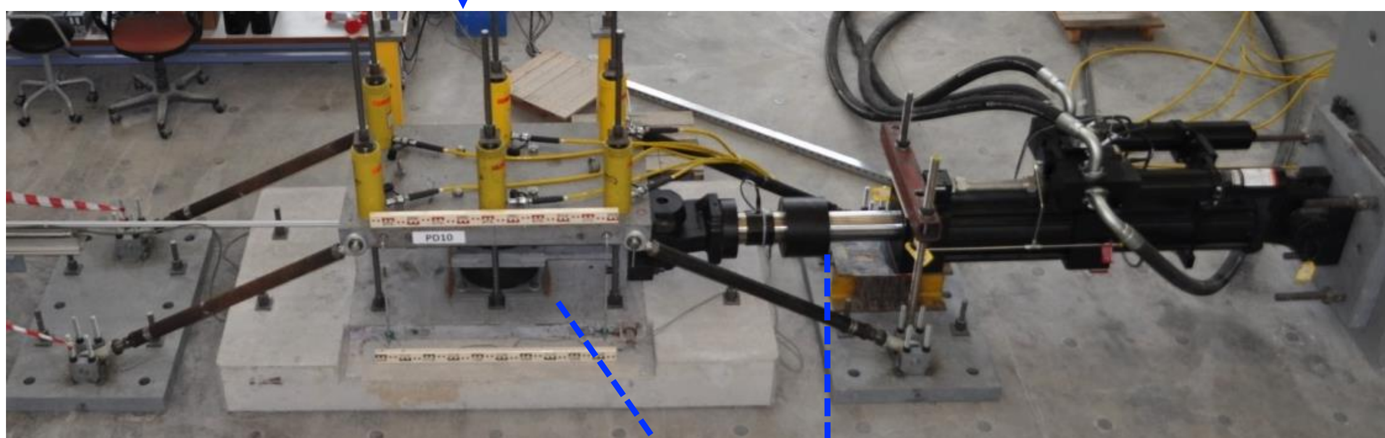
Substructured continuous HS

Tests on elastomeric bearings (ASPROGE)



- test only the nonlinear part of large structures
- increased testing speed

Physical DOFs



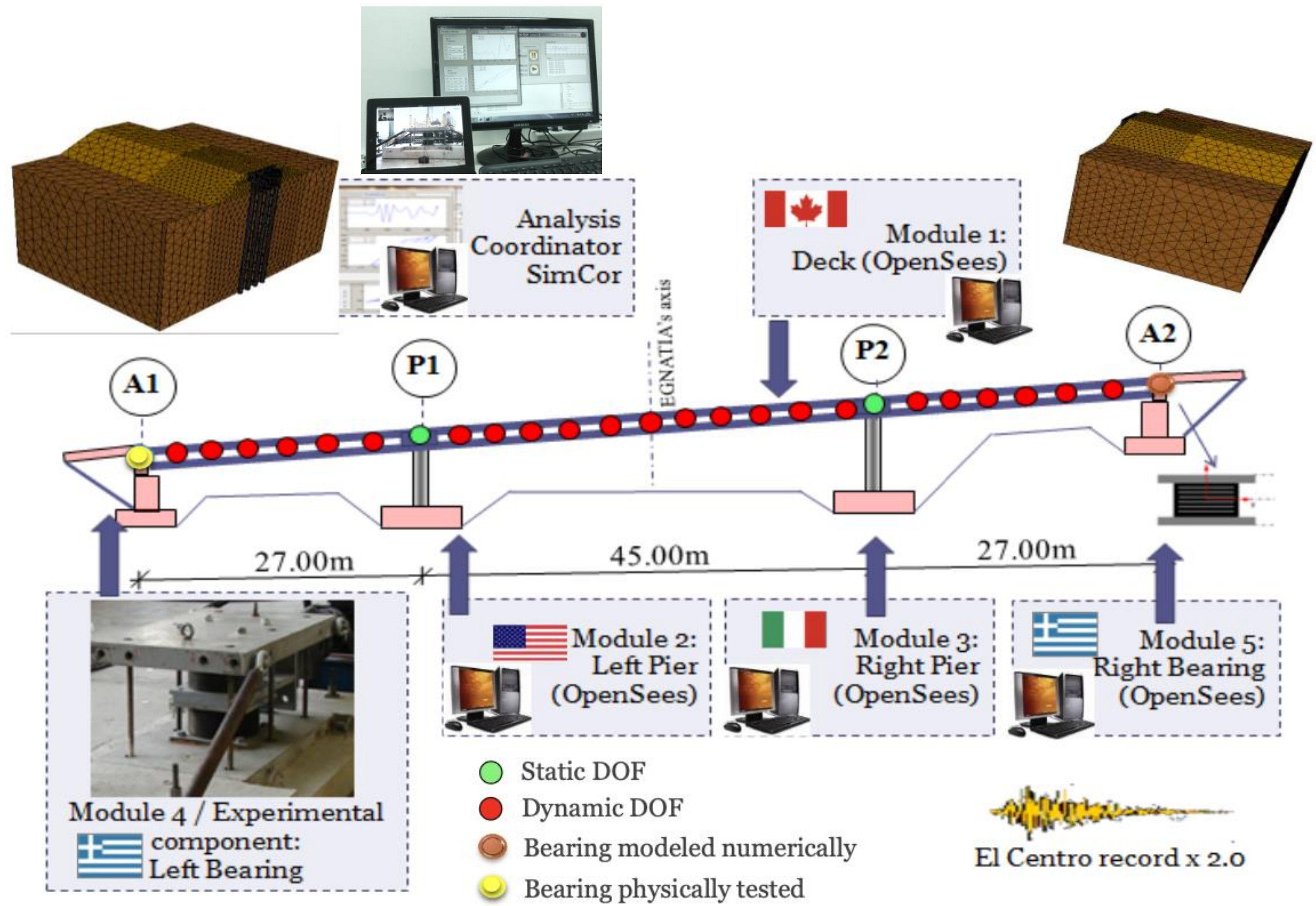
Numerical DOFs

$$\begin{bmatrix} M_{LL} & M_{LC} & 0 \\ M_{CL} & M_{CL}+M_{CN} & M_{CN} \\ 0 & M_{NC} & M_{NN} \end{bmatrix} \begin{bmatrix} \ddot{u}_L \\ \ddot{u}_C \\ \ddot{u}_N \end{bmatrix} + \begin{bmatrix} C_{LL} & C_{LC} & 0 \\ C_{CL} & C_{CL}+C_{CN} & C_{CN} \\ 0 & C_{NC} & C_{NN} \end{bmatrix} \begin{bmatrix} \dot{u}_L \\ \dot{u}_C \\ \dot{u}_N \end{bmatrix} + \begin{bmatrix} R_L \\ R_C \\ R_N \end{bmatrix} = \begin{bmatrix} f^{ex}_{L(t)} \\ f^{ex}_{C(t)} \\ f^{ex}_{N(t)} \end{bmatrix}$$

Interface DOFS

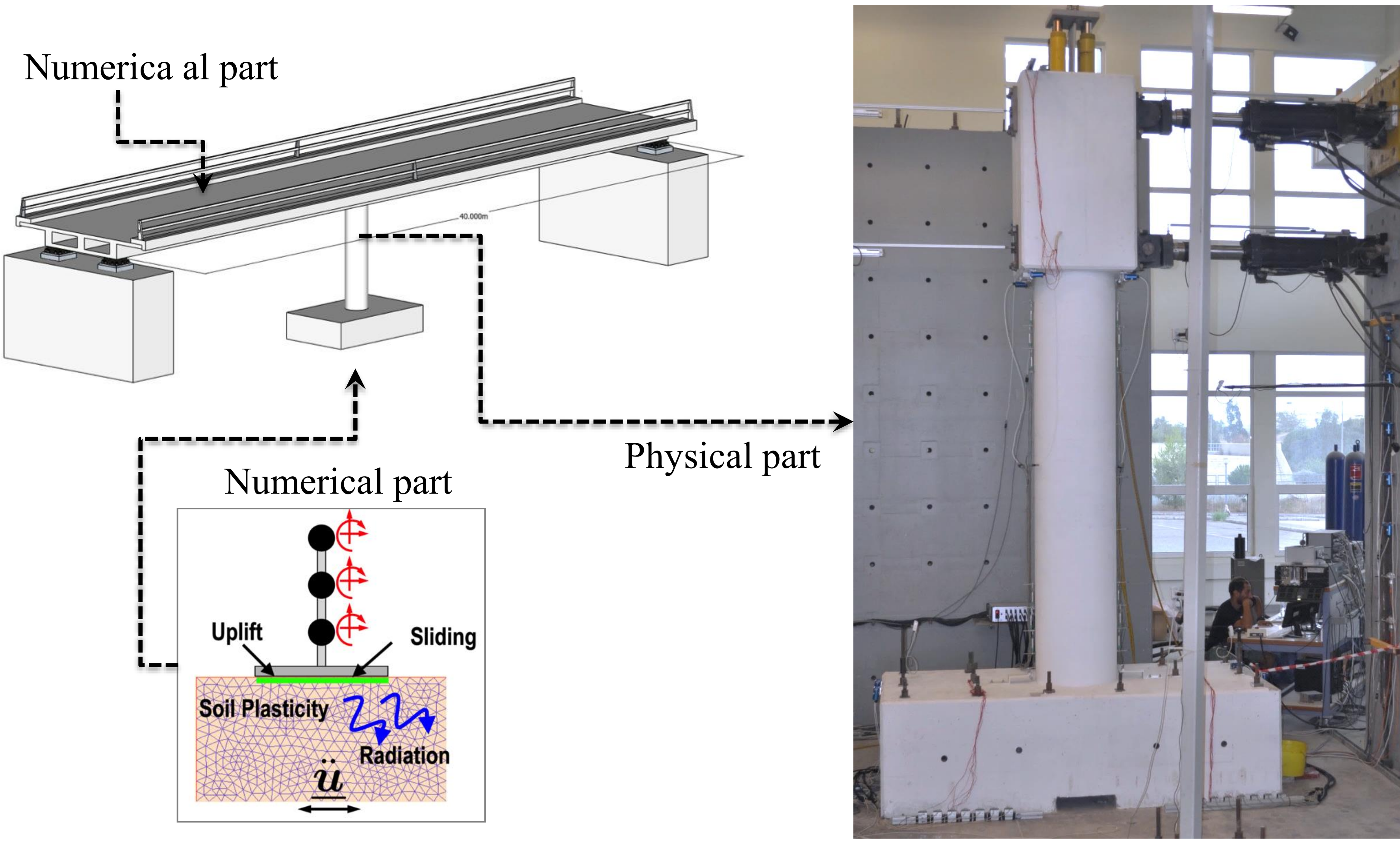
HS with geographically distributed substructuring

Three-span continuous RC bridge (EXCHANGE-SSI)



HS to soil-structure interaction applications

Bridge pier foundation uplifting (PRESCIENT)



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Geographically distributed HS of multi-storey timber structure

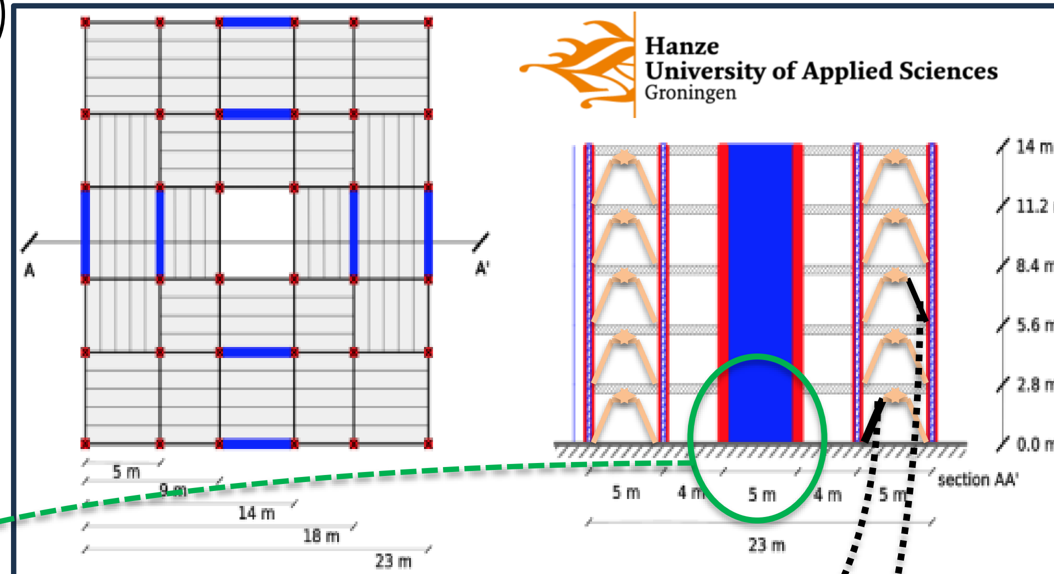
(ERIES-HYSTERESIS)

Two physical sites:

- SSI physical substr.
- 2 physical sand dampers

2

Numerically simulated substructure



1

UNIVERSITY OF TORONTO

Analysis coordination

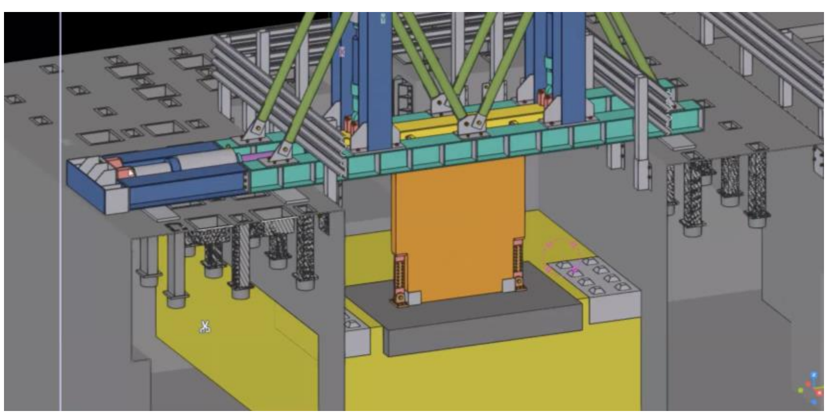
3

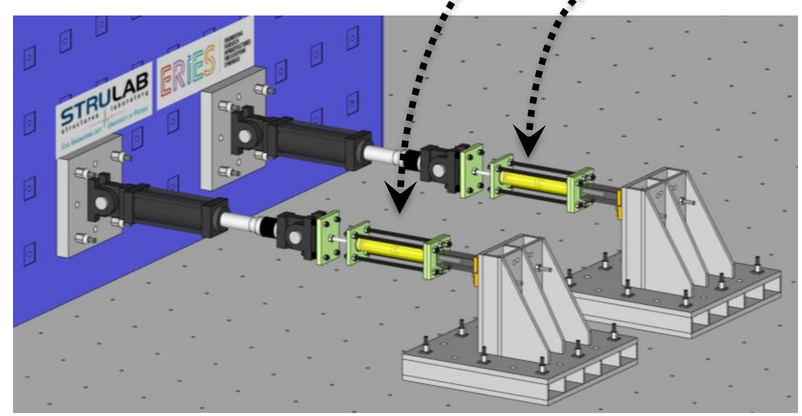
University of BRISTOL

4

UNIVERSITY OF PATRAS

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ





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Contribution to Open Science

- Voluminous data of large scale, expensive experiments
- The value of such data:
  - data does not deplete with time (unlike to other assets)
  - increases with demand
  - the more it is shared, the higher its value becomes
- Data should be FAIR:

  Findable – **A**ccessible – **I**nteroperable – **R**eusable
- The highest level of **FAIR maturity** observed for data → machine agents can not only **locate** and **access** the data, but also **reuse** them while **maintaining** the intended semantics of the original datasets.

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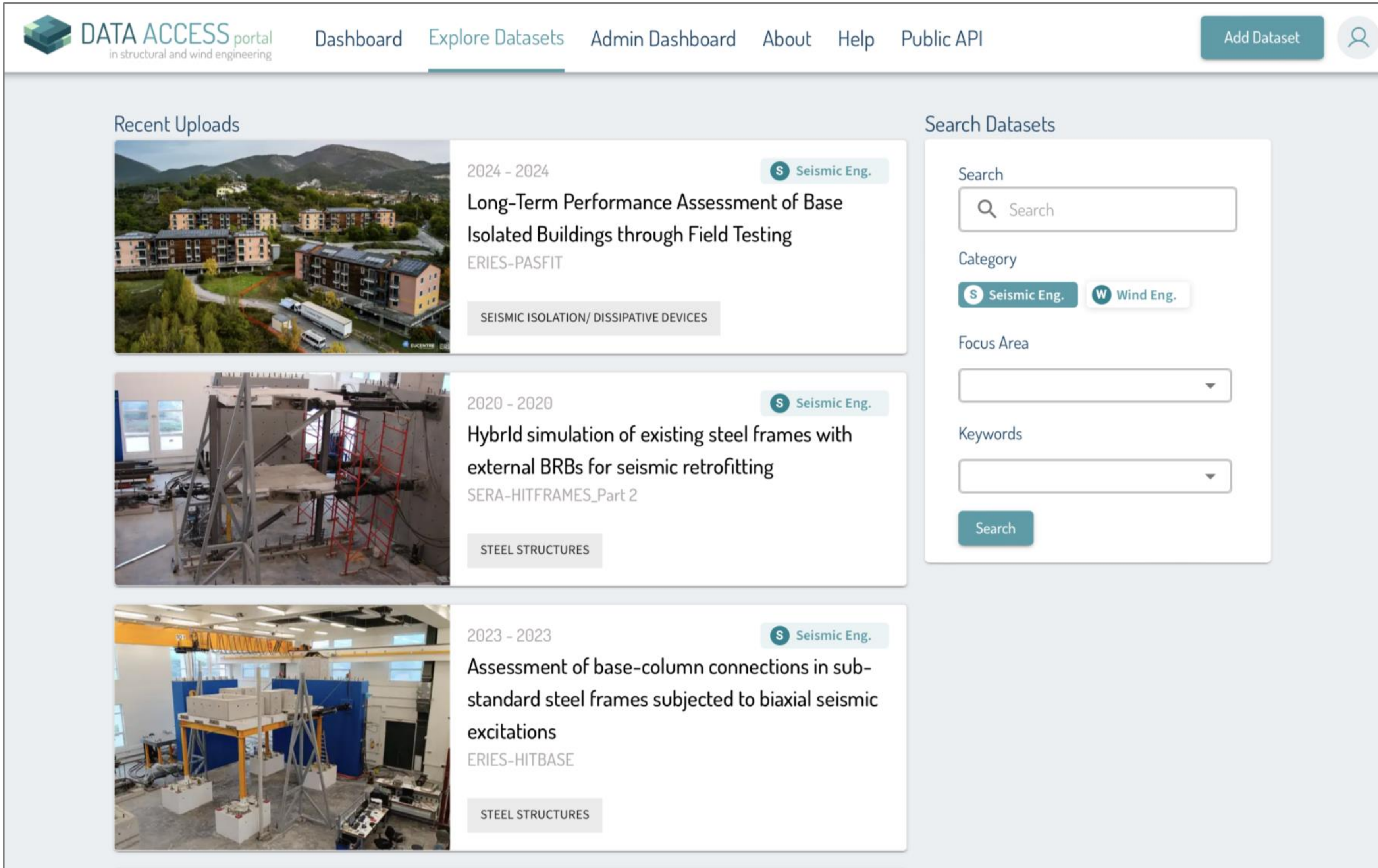
ERIES Data Access Portal - www.dataaccessportal.eu



The big picture for HS

Where are we today ?

- Some research using/advancing HS
- Few industry-supported products
- No Standards on the use of the method

Observation:

Experimental research still resorts basically to quasi-static cyclic testing

CEN/TS250
FprCEN/TS 1998-1-101Q2025

Eurocode 8 — Design of structures for earthquake resistance — Part 1-101: Characterisation and qualification of structural components for seismic applications by means of cyclic tests

Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components

FEMA 461 / June 2007

FEMA MCEER nehrp

Hybrid Simulation

- is **a way of solving problems** rather than "a method"
- has (and will continue doing so) considerable potential for earthquake engineering research and beyond

Acknowledgements

The research effort presented received funding from the European Commission (SPEAR, SERIES, PRESCIENT, SERA, ERIES projects) and national resources.

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