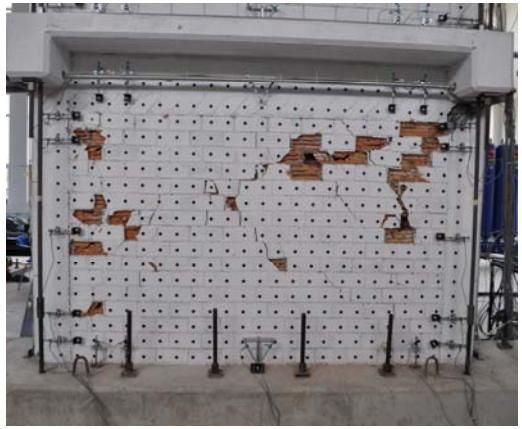
Testing Activities at Structures Laboratory



Prof. Stathis Bousias

[2013]

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Civil Engineering Dept. University of Patras

Activity

- Retrofitting RC columns
- Retrofitting RC & masonry infilled RC structures
- New technologies- New control Algorithms
- Hybrid testing – Isolation devic
- Geographically distributed testing

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Sub-standard structures – the problem

- Greece
  - Codes before 1959: designed for gravity–load
  - Zakynthos earthq. 1953 (6.5/6.8/7.2 R), 1955 (6.2R)
  - New Code: 1985 (after Volvi 6.5R & Alkyonides 6.7R)
  - Athens eq. 1999: 45% of collapses concerned <1959 bldgs.
- Resistance of structures before 1985: ag ≈0,10*g
- Similar in other countries
- Insufficient detailing of reinforcement – deficiencies:
  - Low grade steel (S220), Low quality concrete
  - Small column X–section, much stronger beams
  - Sparse stirrups – not well anchored (closed at 90°)
  - Insufficient lap–splicing length
  - Small cover to the reinforcement
  - Members with low (flexural / shear) strength and low deformation capacity
  - Assymetry in plan and in elevation

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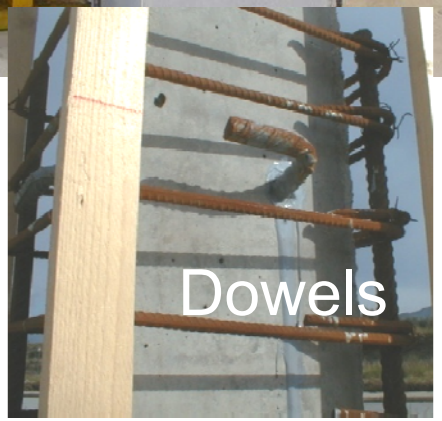

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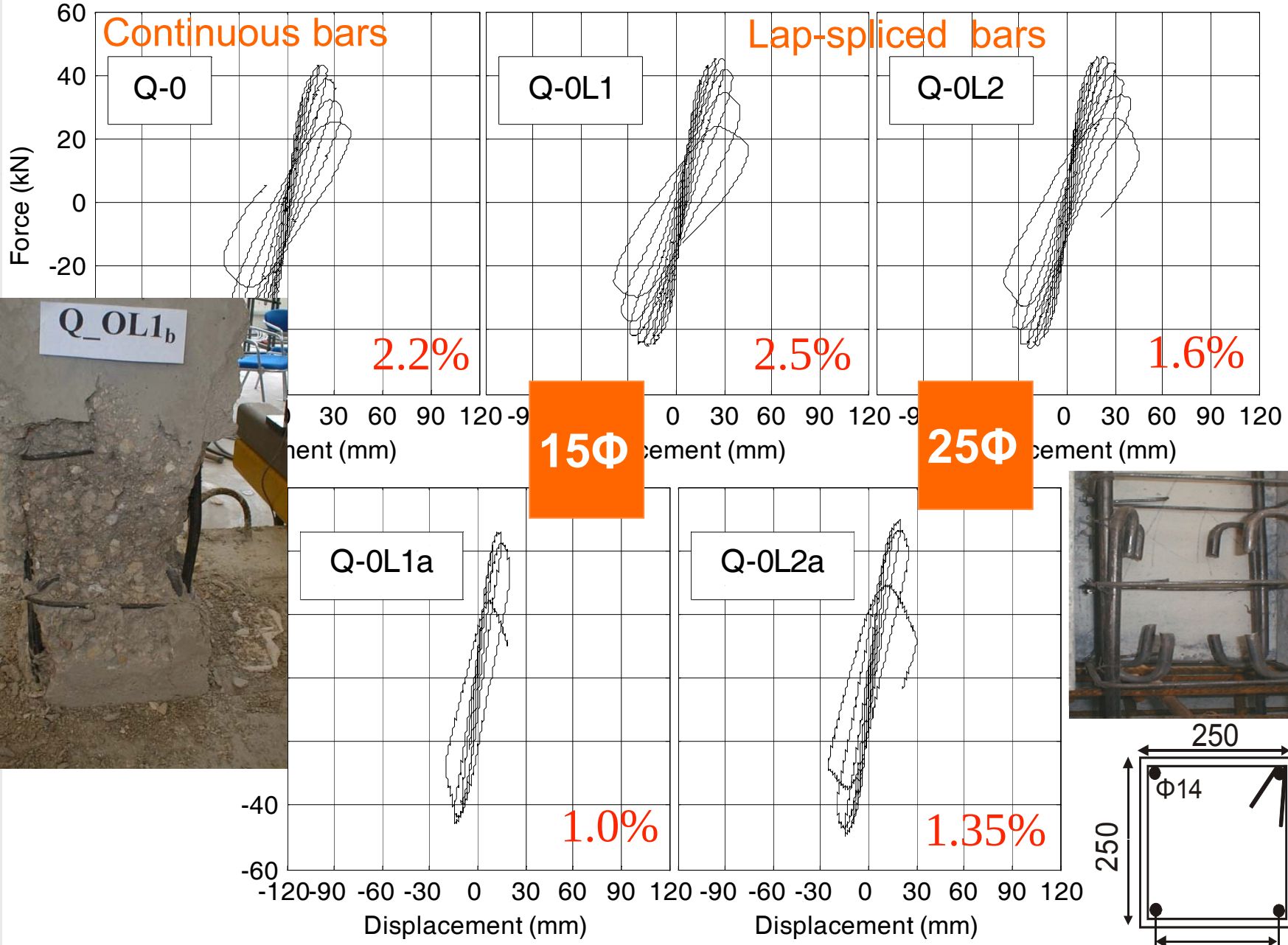
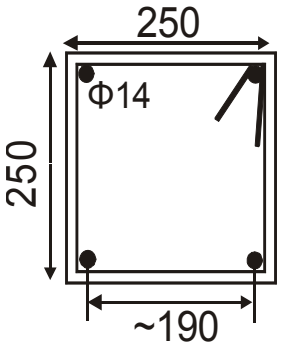
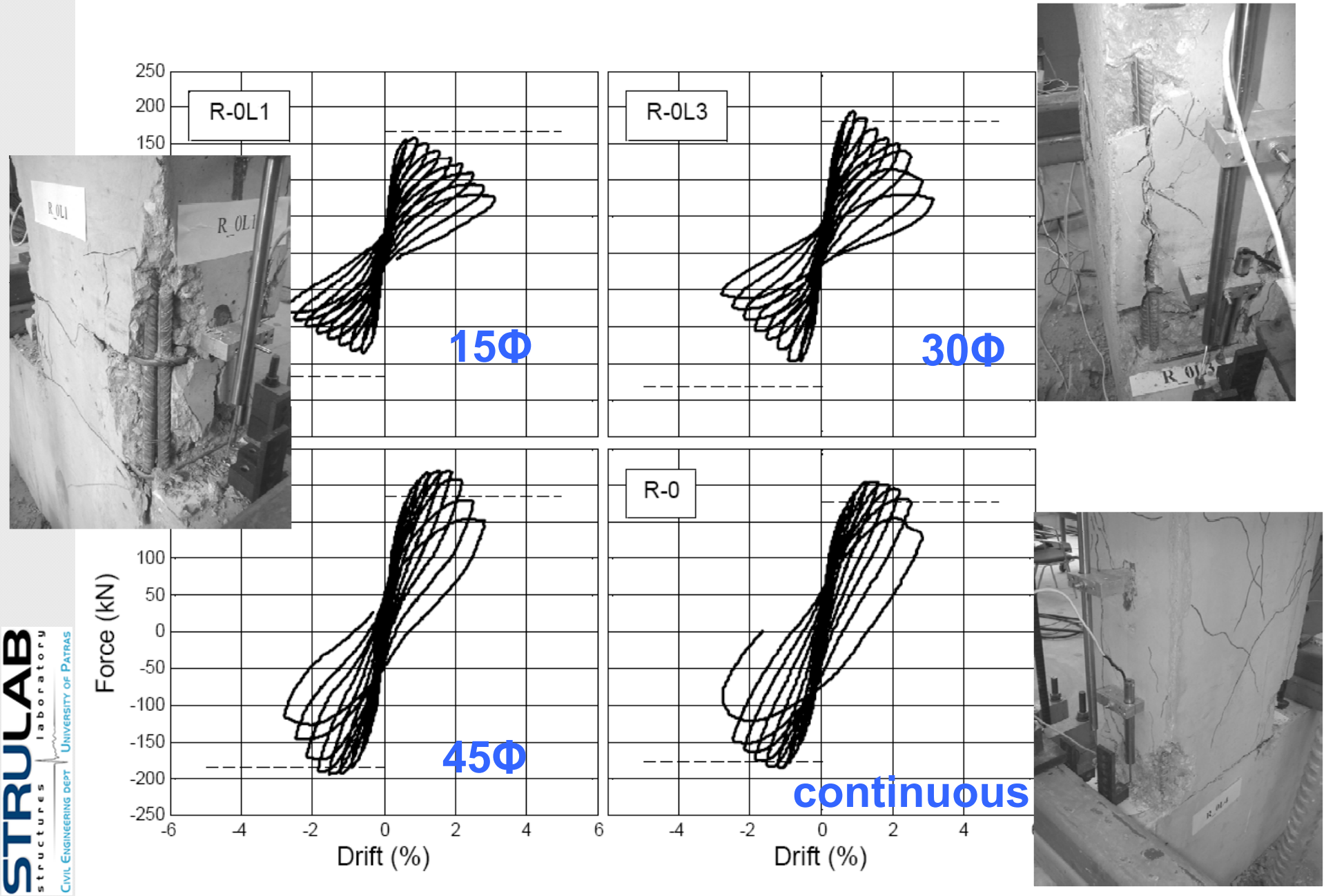
Square columns with smooth bars (S220)





Rectangular columns – deformed bars (S400)



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Conventional retrofitting

- RC Jacketing is widely used & cost-effective for RC buildings:
  - familiar to engineers & construction industry
  - suitable for repair of damage
  - jacket can encapsulate members & joints providing structural continuity
  - multiple effects on stiffness, flexural/shear resistance, deformation capacity, anchorage & continuity of reinforcement
- But, "intrusive" method:
  - Evacuation of building
  - Increased workmanship
  - Environmentally hostile (debris, etc)

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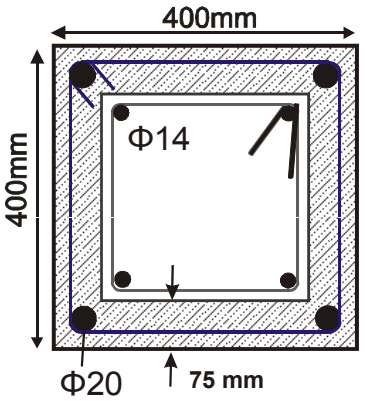
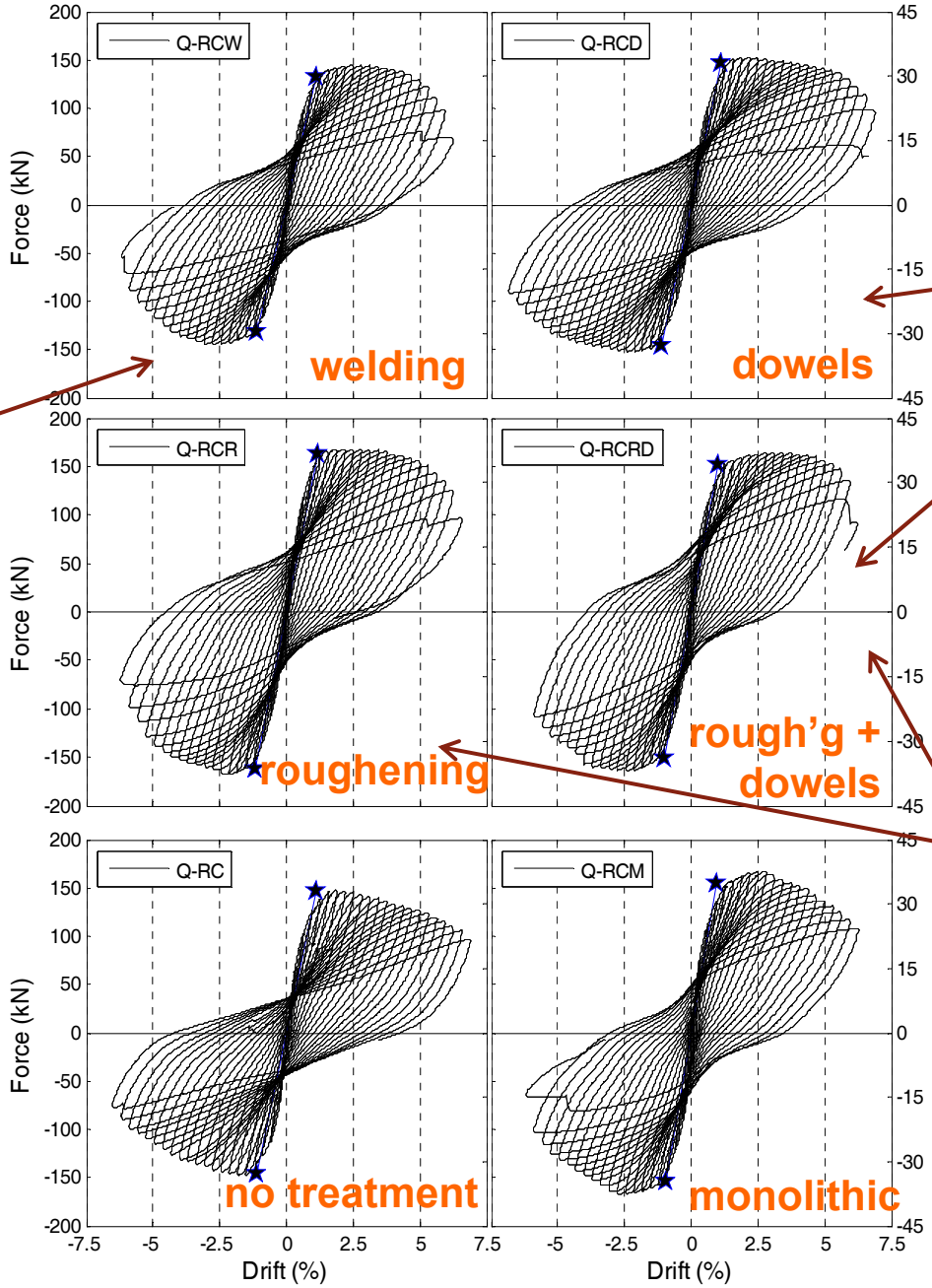
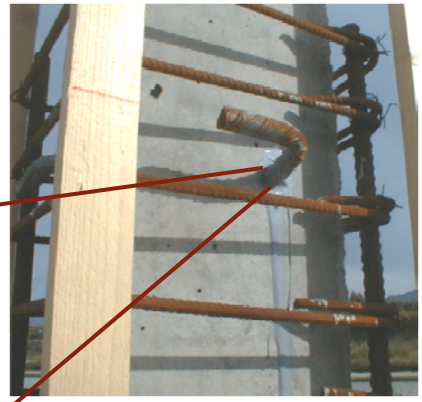
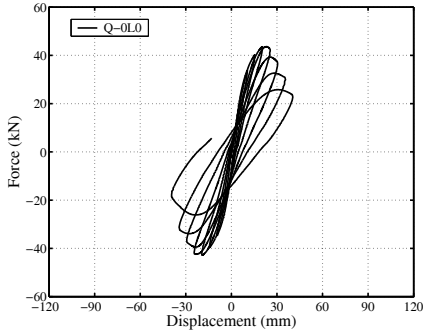
Conventional retrofitting – Smooth bars









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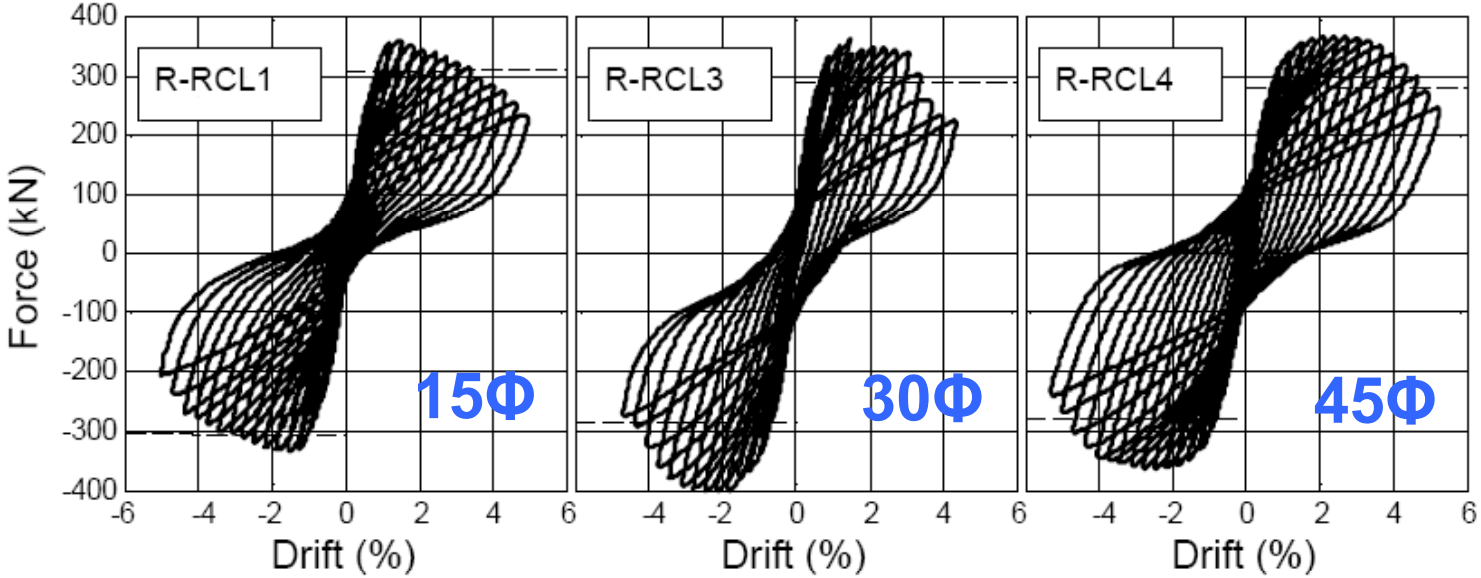
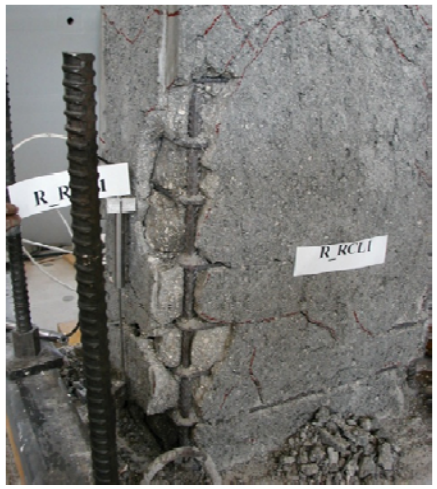
Conventional retrofitting – Deformed bars





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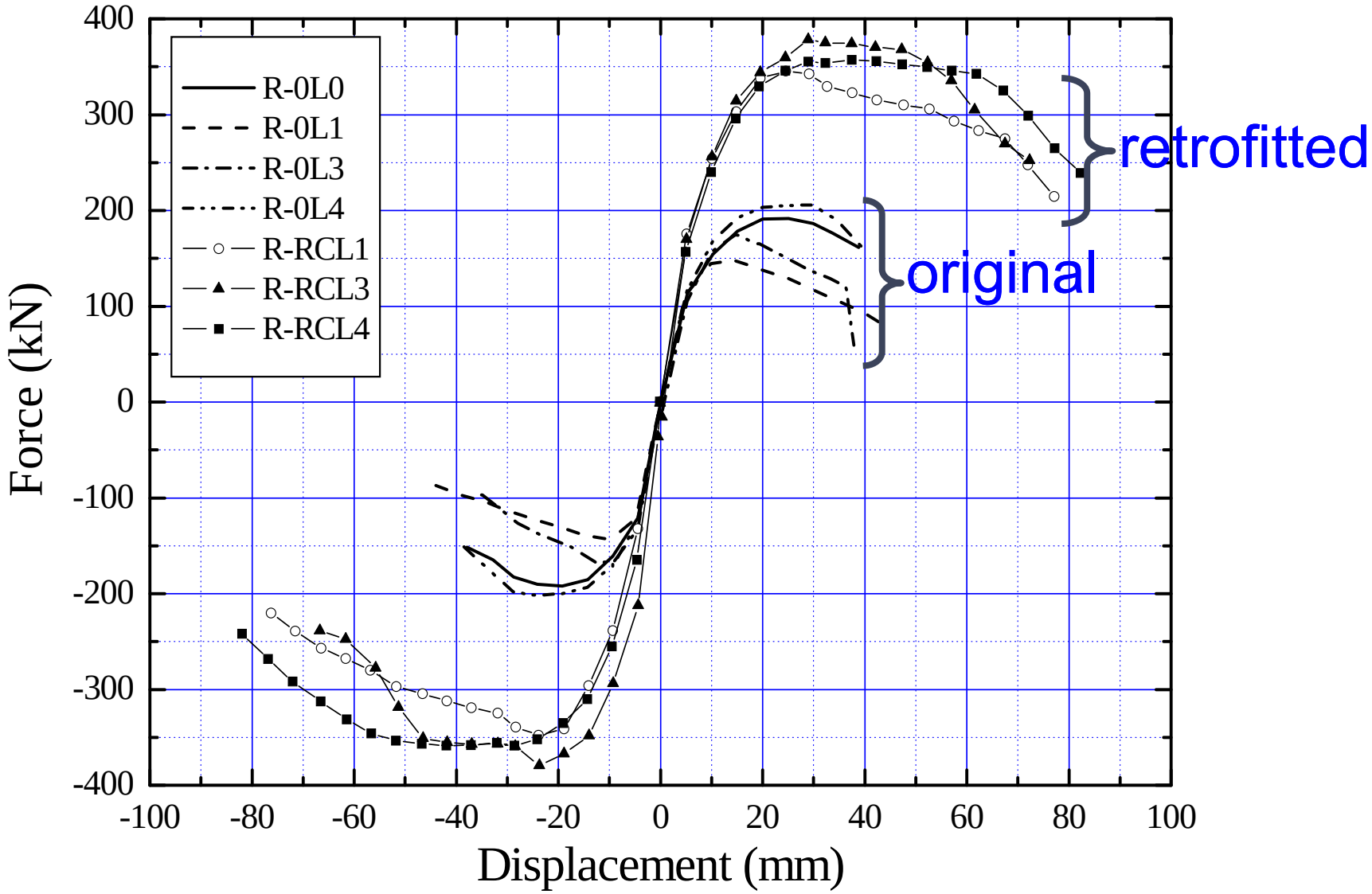

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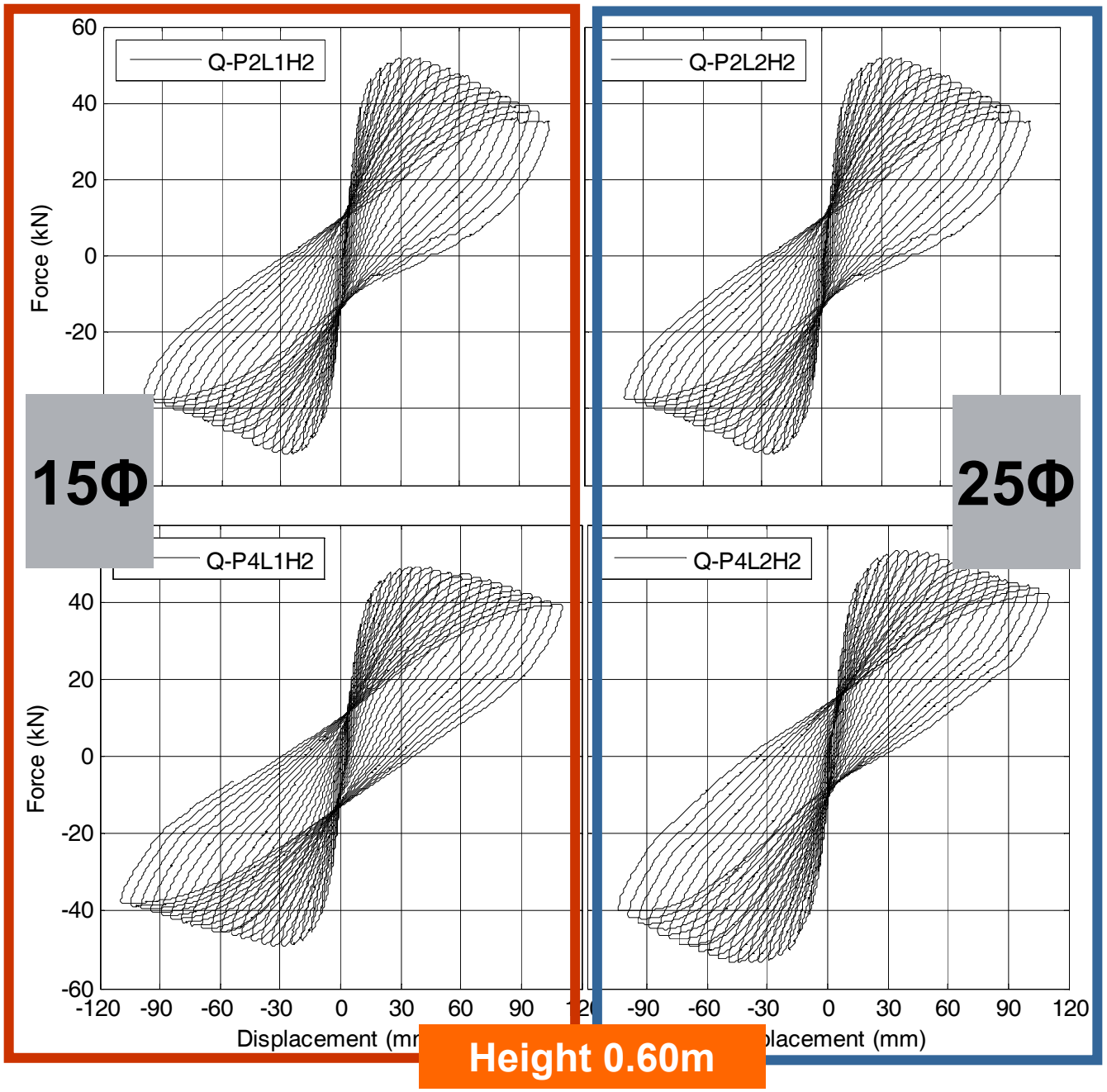

2 layers

4 layers

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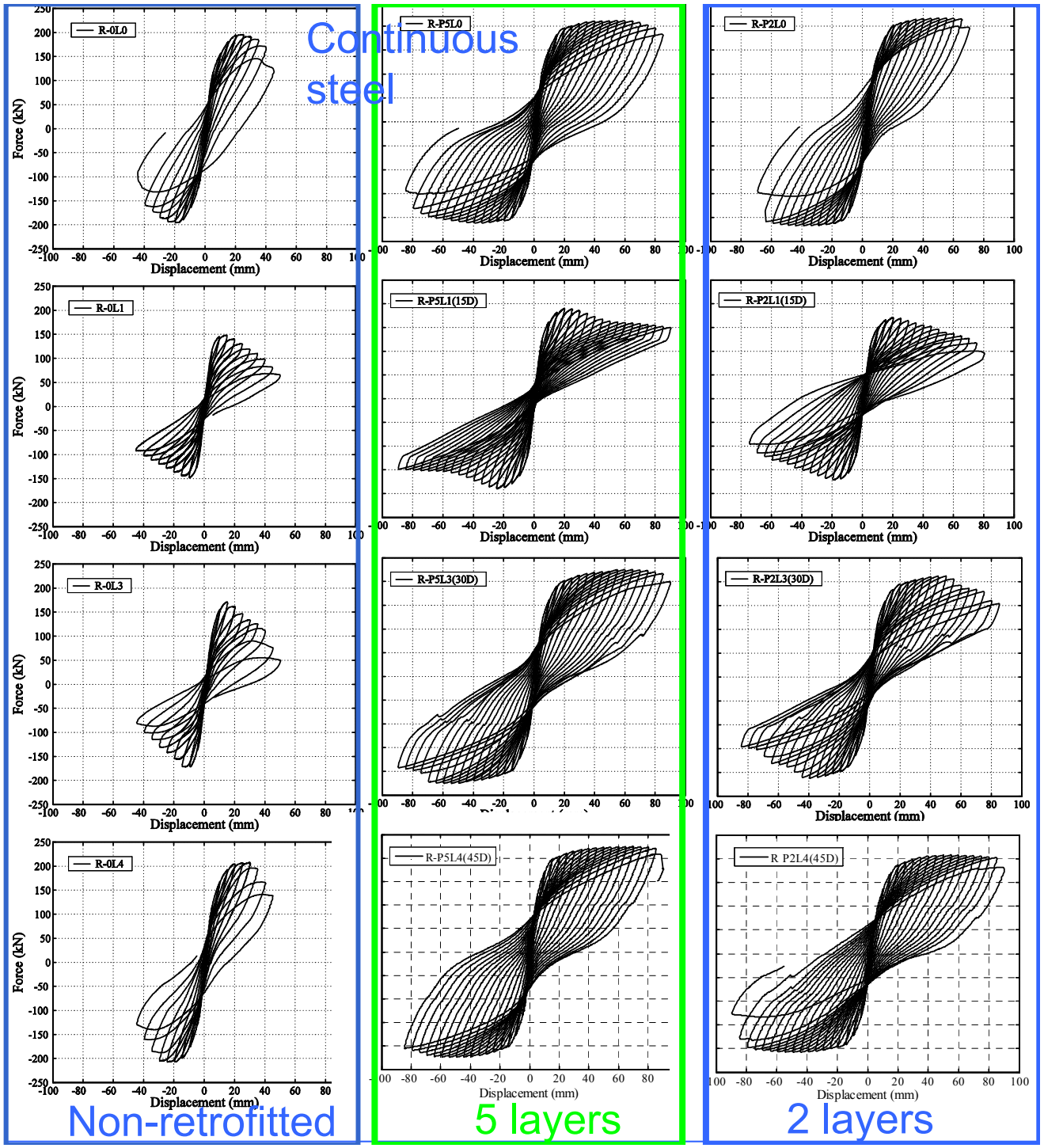
Innovative retrofitting – Deformed bars

Continuous steel

Splicing 15Φ

Splicing 30Φ

Splicing 45Φ



Non-retrofitted

5 layers

2 layers

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Conclusions – Conventional retrofitting

- Columns with smooth bars – hooked ends :
  - no appreciable effect of lapping length on response of jacketed columns
  - deformation capacity enhancement (× 3) – drift levels ~ 5.5% w. or w/o. laps
  - rate of post-peak resistance degradation increases in spliced specimens
  - jacketed pre-damaged cols.: slightly worse behavior
- Columns with ribbed bars – straight ends:
  - inadequate splicing length effects removed, <u>except</u> for very short lapping (15D)
  - original specimens (15D, 30D): low drift (1.9%) vs. 2.5 % for adequate (45D) or no lapping
  - deformation capacity enhanced by jacketing to 3.8 - 4.7%

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Conclusions – Innovative retrofitting

- Columns with smooth bars – **hooked** ends :
  - increases deformation capacity 2.5 times – drift range 4.7-7% at conventional "failure"
  - no systematic effect of # of layers & length of FRP
- Columns with ribbed bars – **straight** ends:
  - splicing : large effect on deformation capacity (for < 45D)
  - original columns : low drift (1.9%) vs. 2.5 % for adequate or no lapping
  - 5 CFRP layers are more effective than 2 – not proportionately
  - lowest limit of lap for improvement of behavior through FRP wrapping: > 30D
  - adverse effects of lap length as short as 15D cannot be fully removed by either 2 or 5 CFRP layers

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Reinforcement Corrosion

Detrimental effects of corrosion:

- Decreases member resistance
- Reduces bond and anchorage
- Favours buckling
- Reduces bar ductility

Examine ductility enhancement issues (confinement of compression zone)

In lab: Accelerated corrosion process

State	Test Direction	Fiber Material	No. of FRP layers	Damage
Non-corroded	Strong	Carbon	**2**	Pre-damaged
Corroded	Weak	Glass	**5**	Non-damaged

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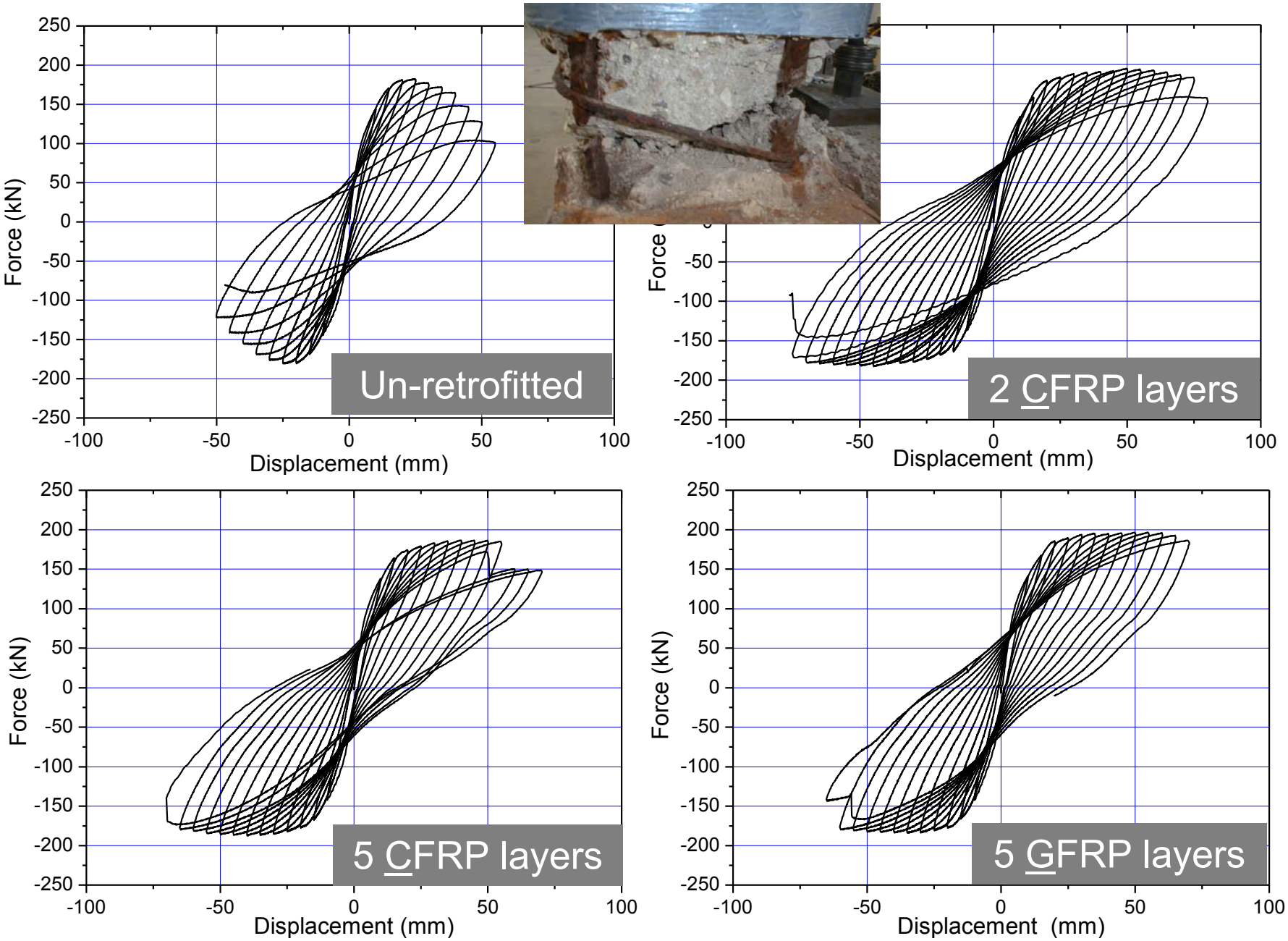
Bending along strong axis



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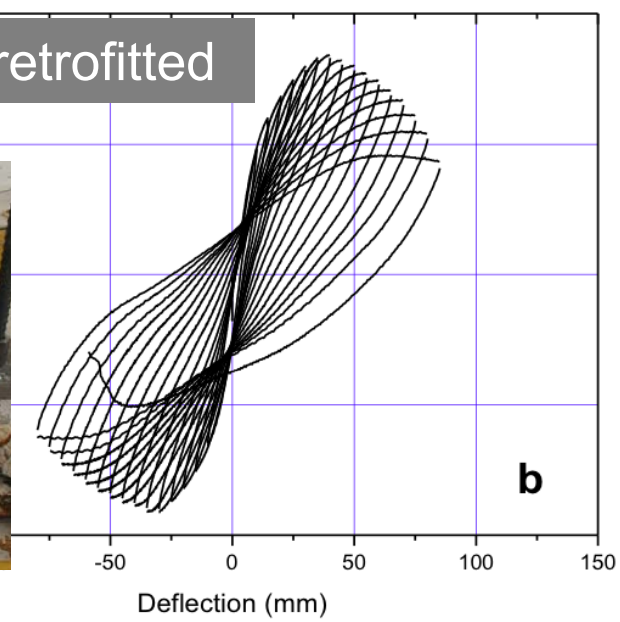
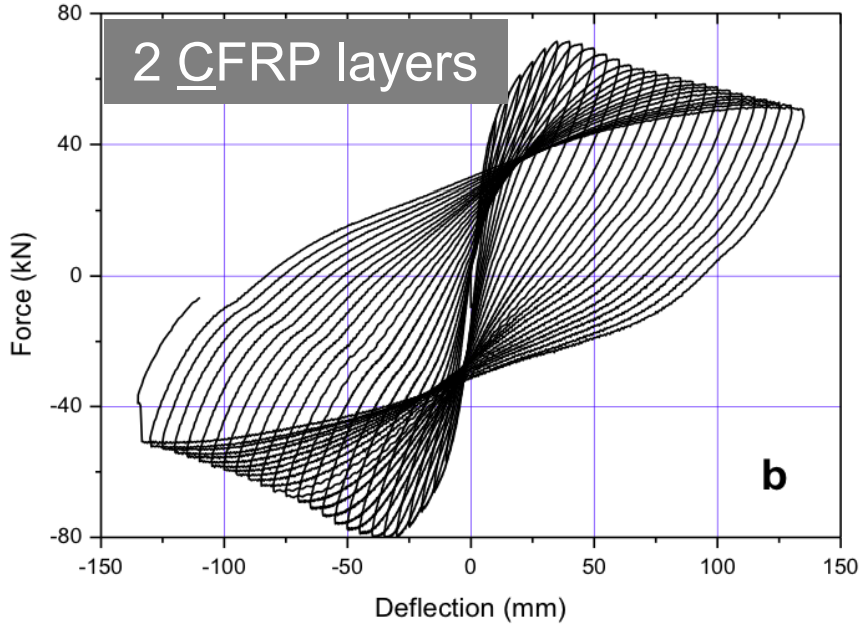
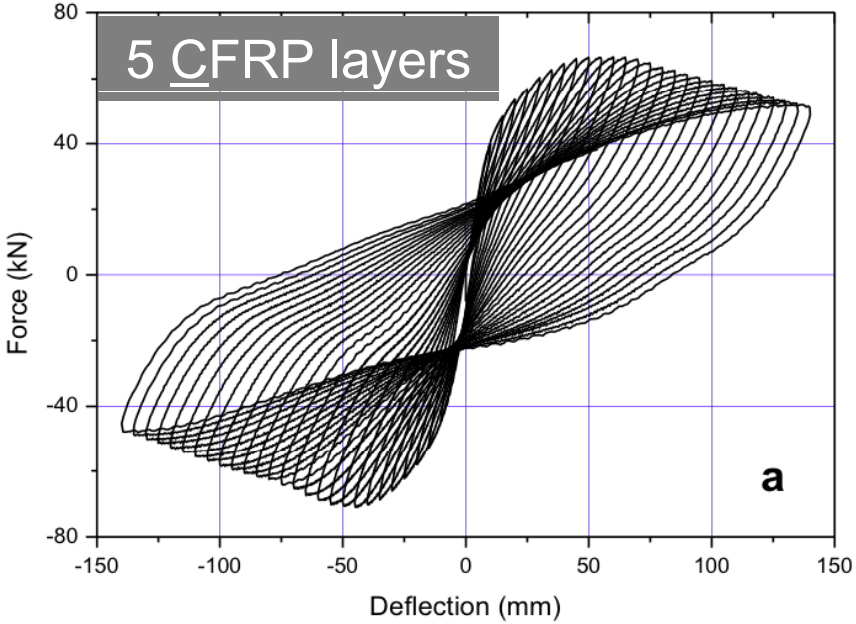
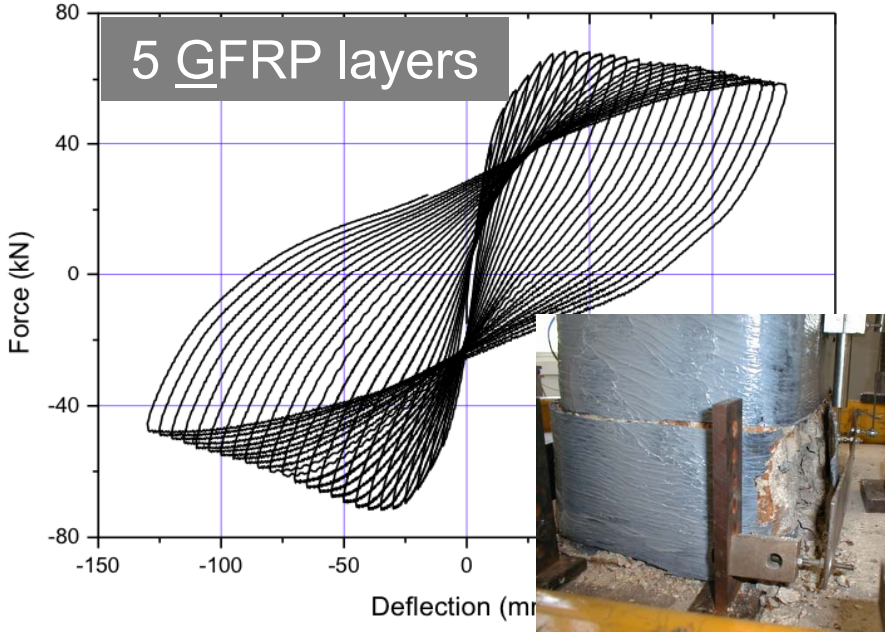
Bending along weak axis









Conclusions

- Bending along Strong Axis : bar fracture
  - increase in deformation capacity:
    - Corroded + FRP → 50%
    - Non-corroded + FRP → 130%.
- Bending along Weak Axis – no bar fracture
  - increase in deformation capacity:
    - Corroded + FRP → 35%
    - Non-corroded + FRP → 80%
- A gross ratio in terms of effectiveness :

  2CFRP layers → 5GFRP layers

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Activity

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- New technologies- New control Algorithms
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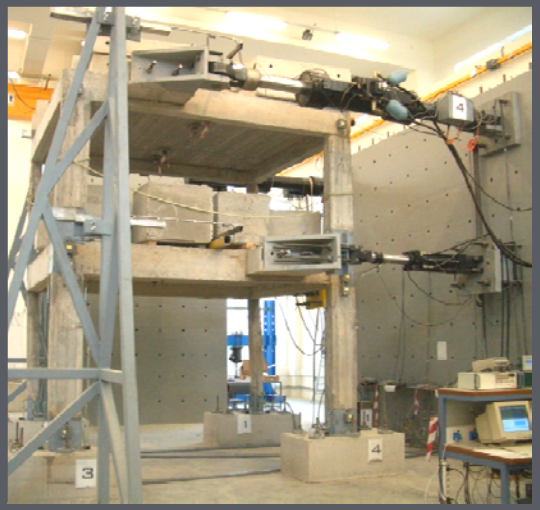
- Geographically distributed testing



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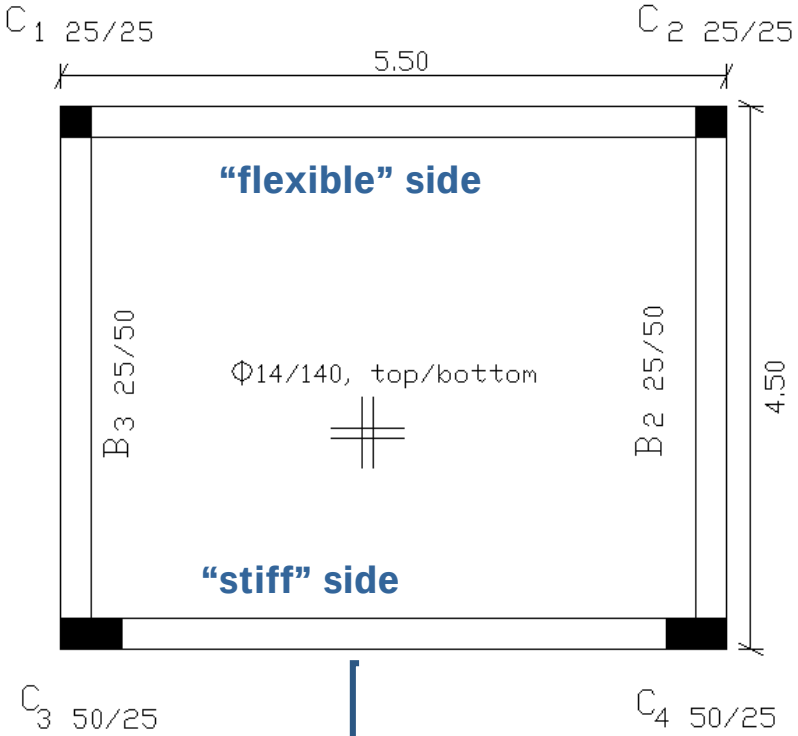
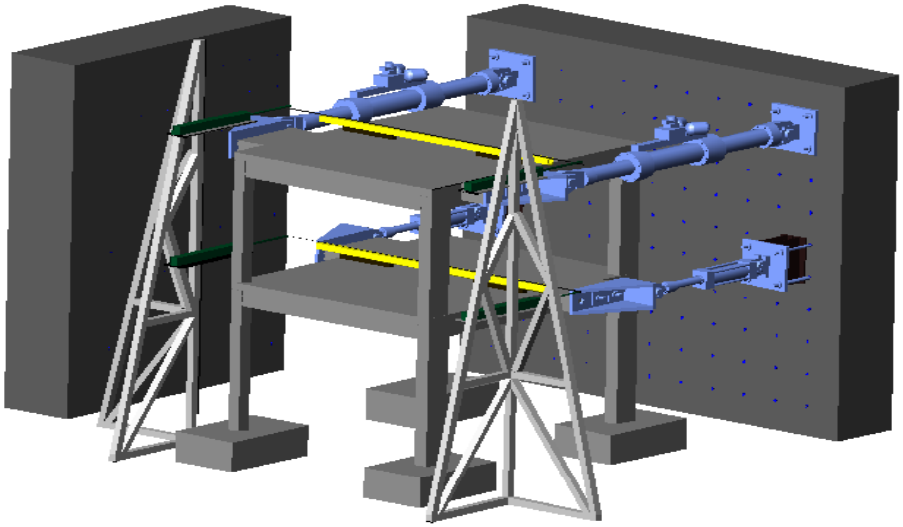
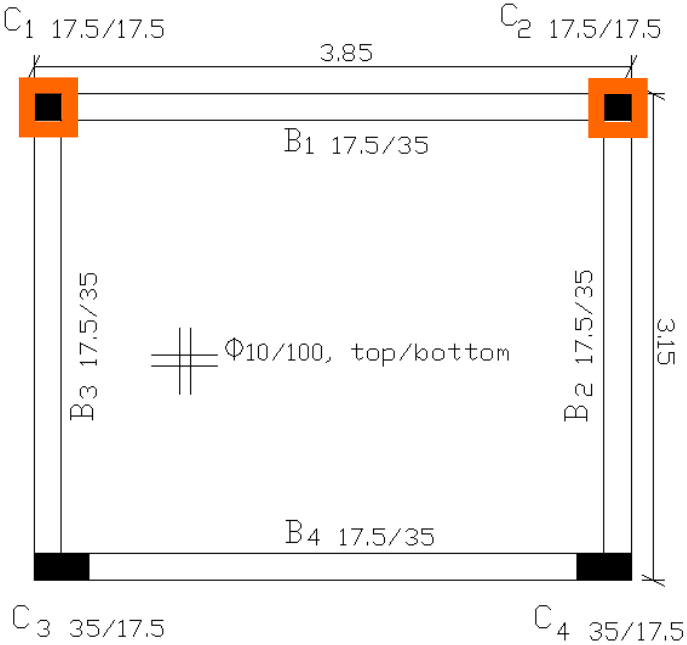
Structural asymmetry in plan







Scale 0.7:1

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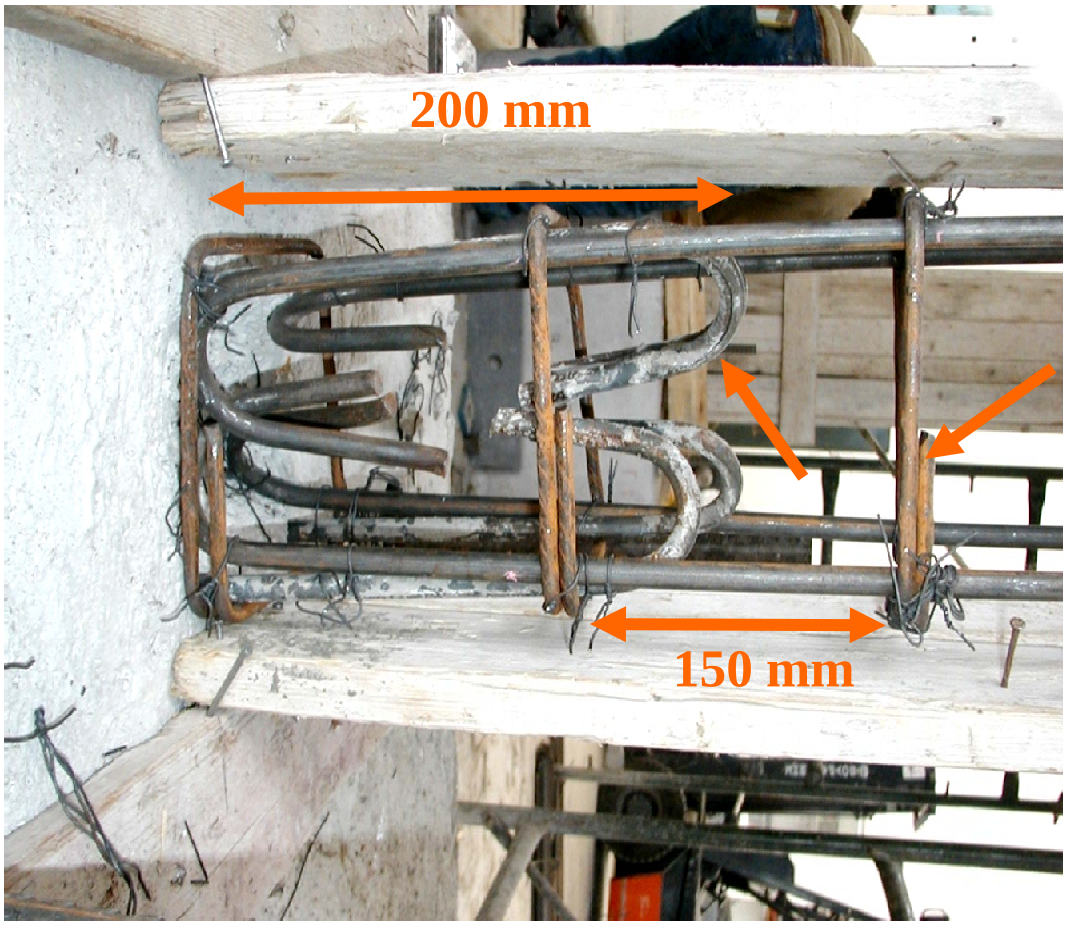
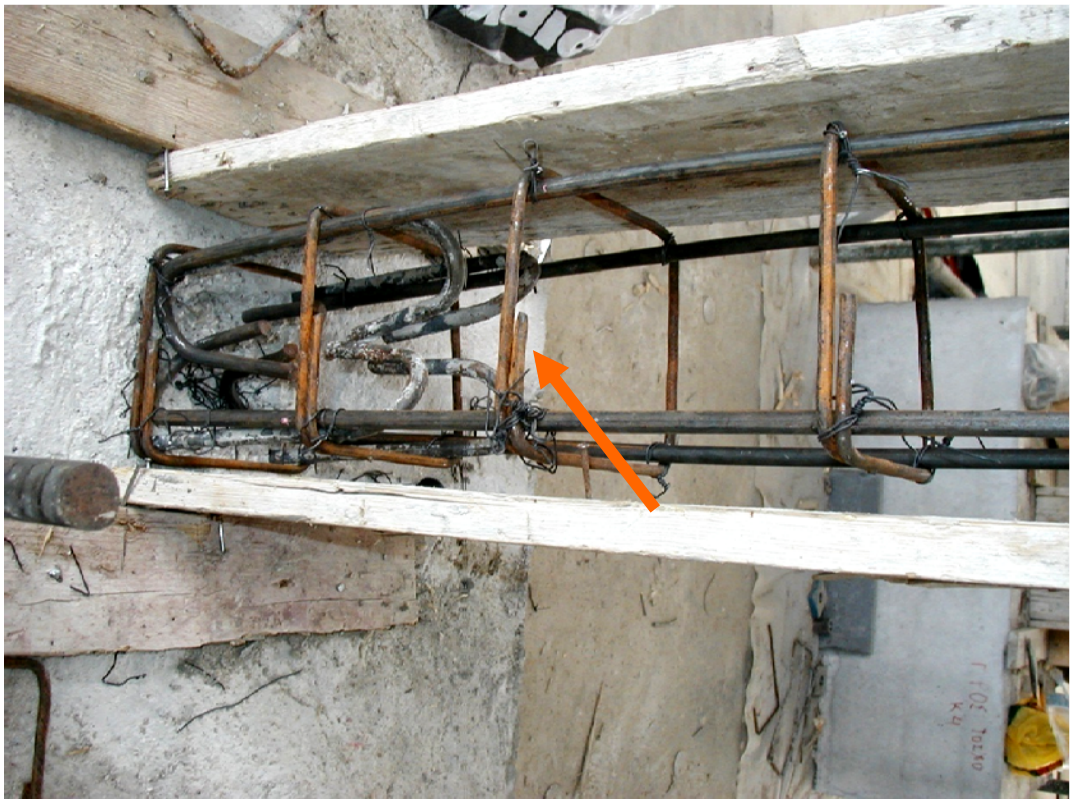
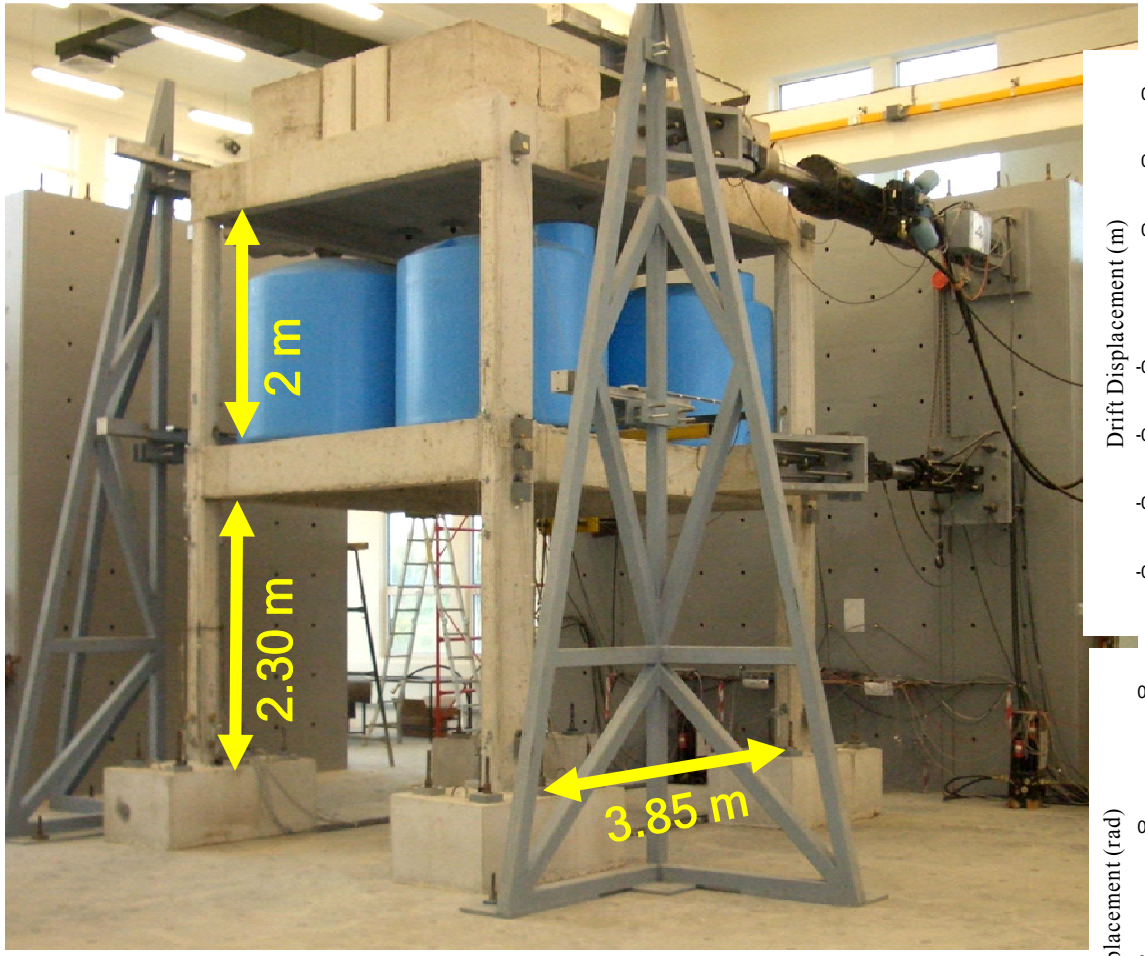
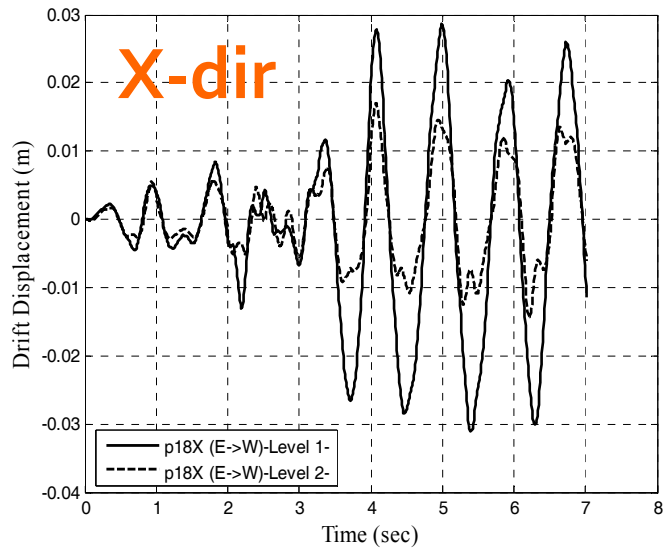
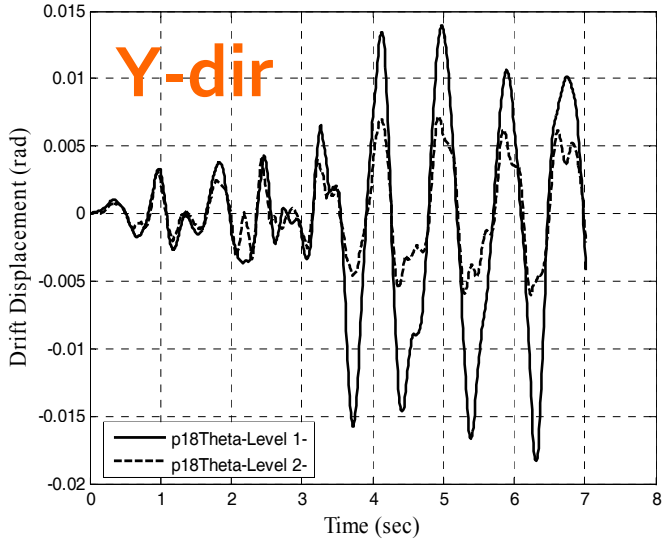

200 mm
150 mm



Original structure







Original structure

- Ground : 2.9% & 1.5% drift
- Top : 2.6% & 1.1% drift

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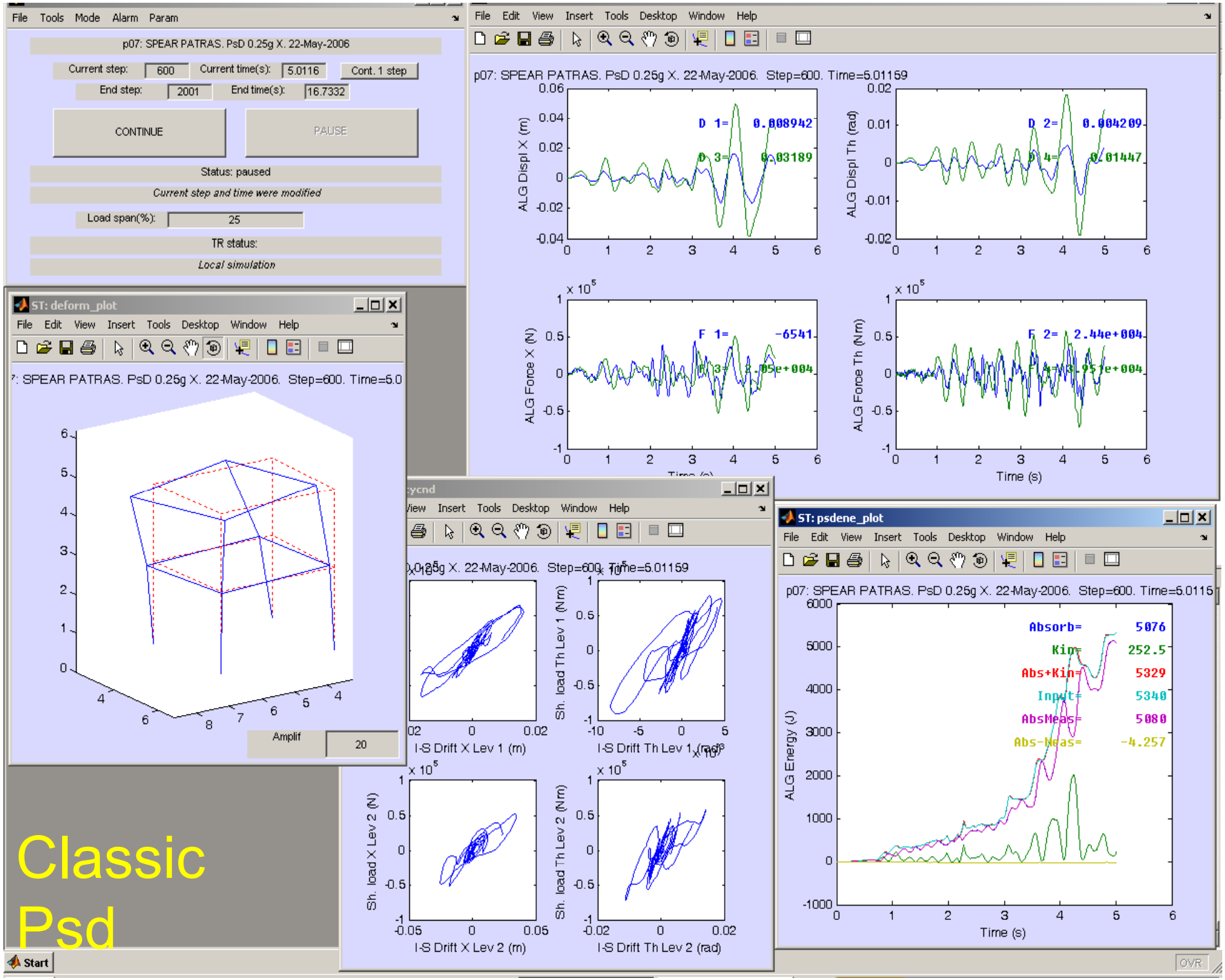

Classic Psd

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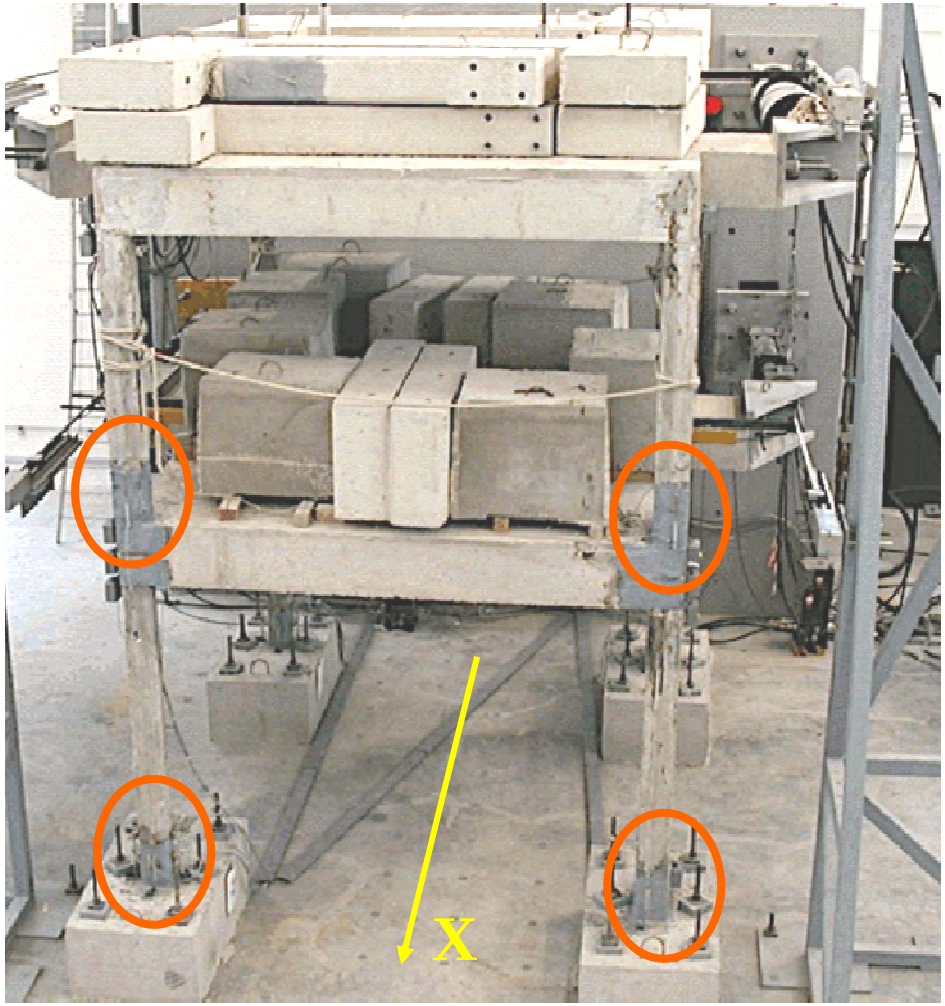
Conventional retrofitting

Innovative retrofitting

Carbon Fiber Reinforced Polymers – CFRP



- Excitation level 0.3g
- Ground story: 3.6% &1.8% drift
- Top story: 3.9% &1.9% drift

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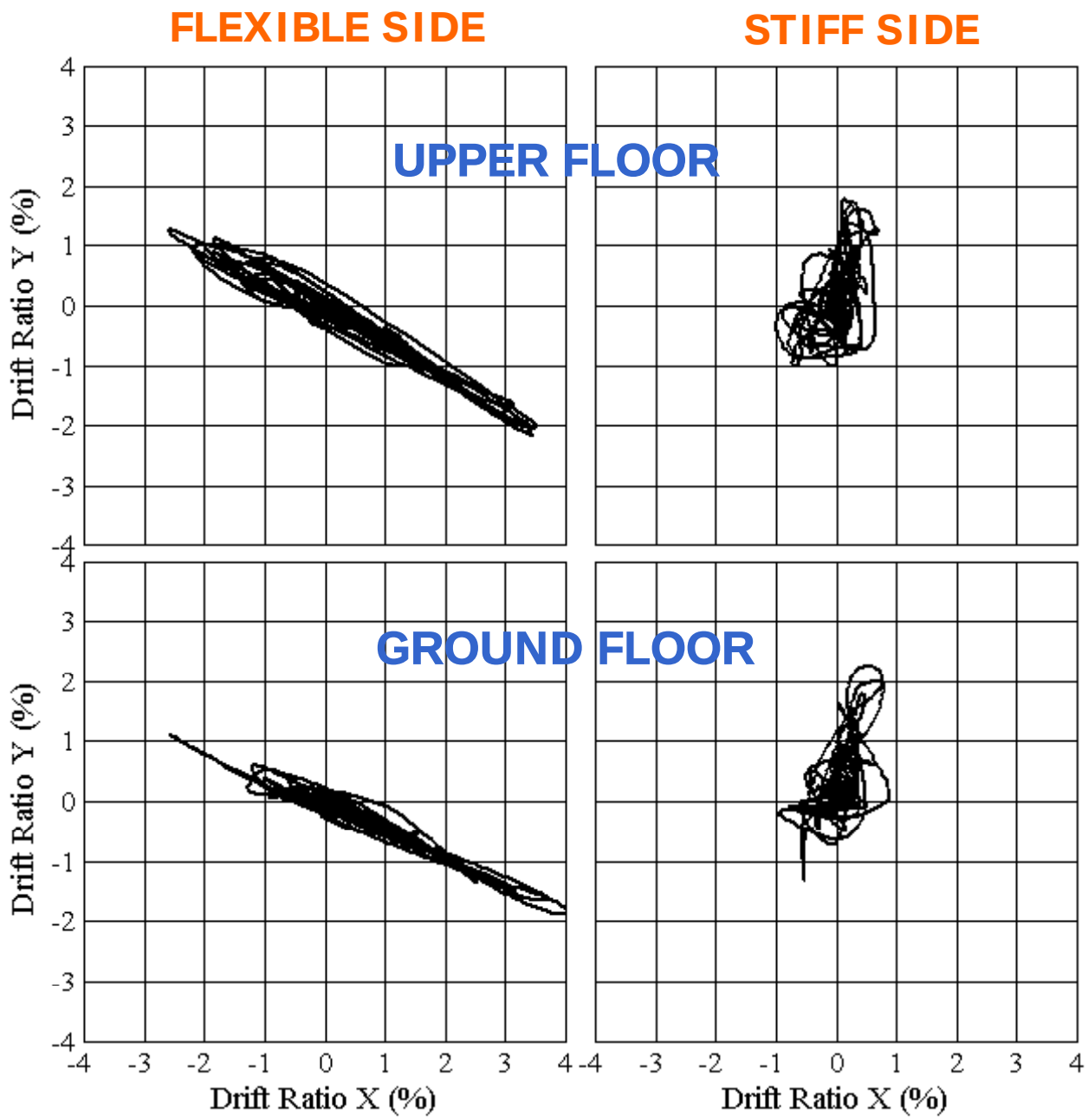
Drift ~4% in X,

&

simultaneous drift ~2% in Y



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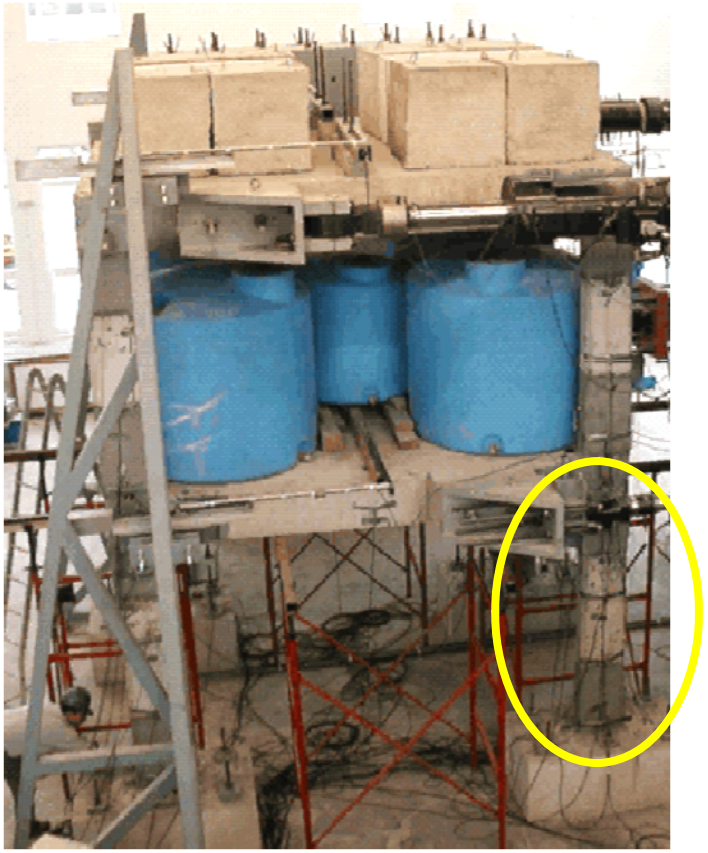
Textile Reinforced Mortar



- Grid: openining 7mm, roving 3mm (f_t=3800 Mpa,)
- 5 layers with 2mm mortar in-between
- Structure sustained drifts of 3% no loss of lateral load capacity

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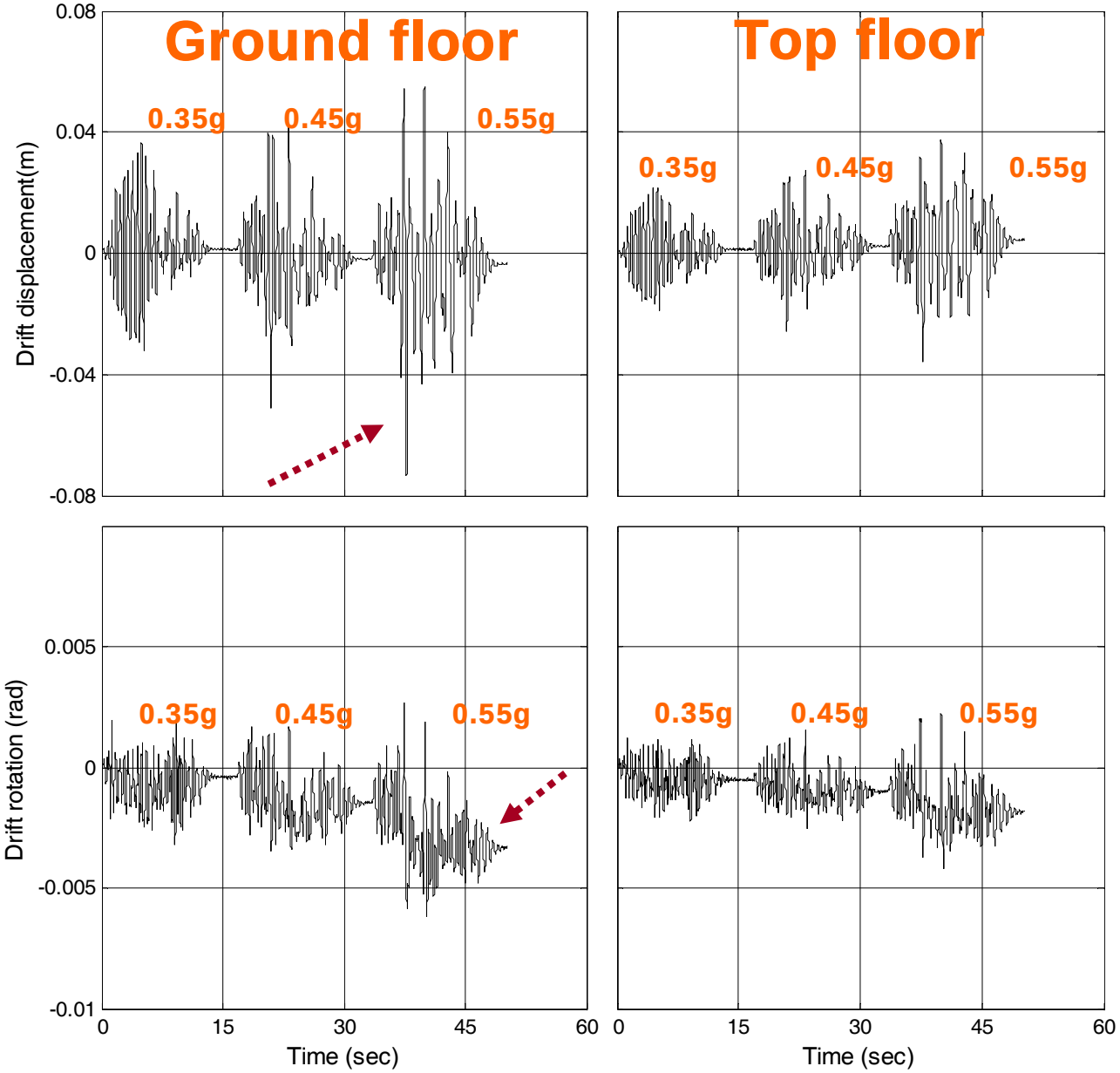

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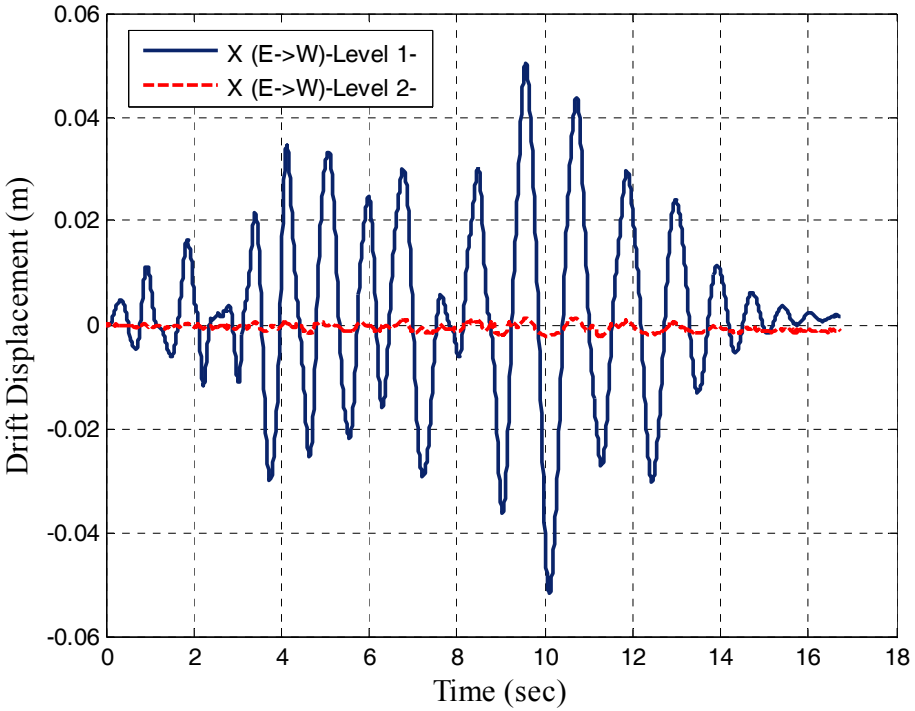
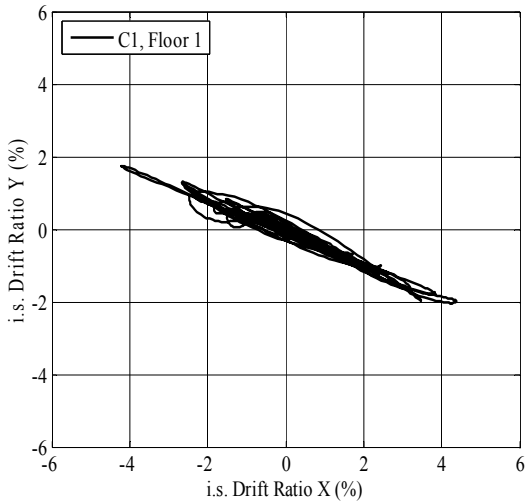
Structural asymmetry in elevation



Peak drifts, soft-side columns, ground storey: 4.2% and 2% in orthogonal direction



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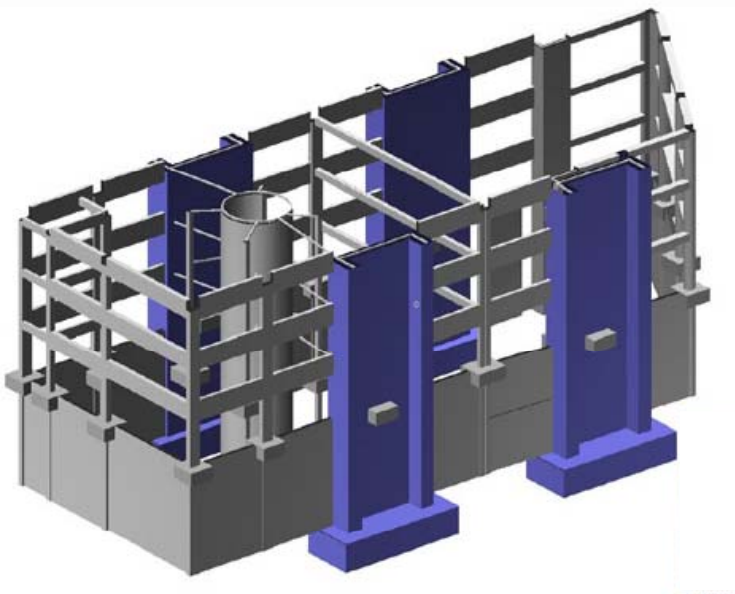
Retrofitting via bay RC-infilling

- RC infilling
- Include boundary columns - beams



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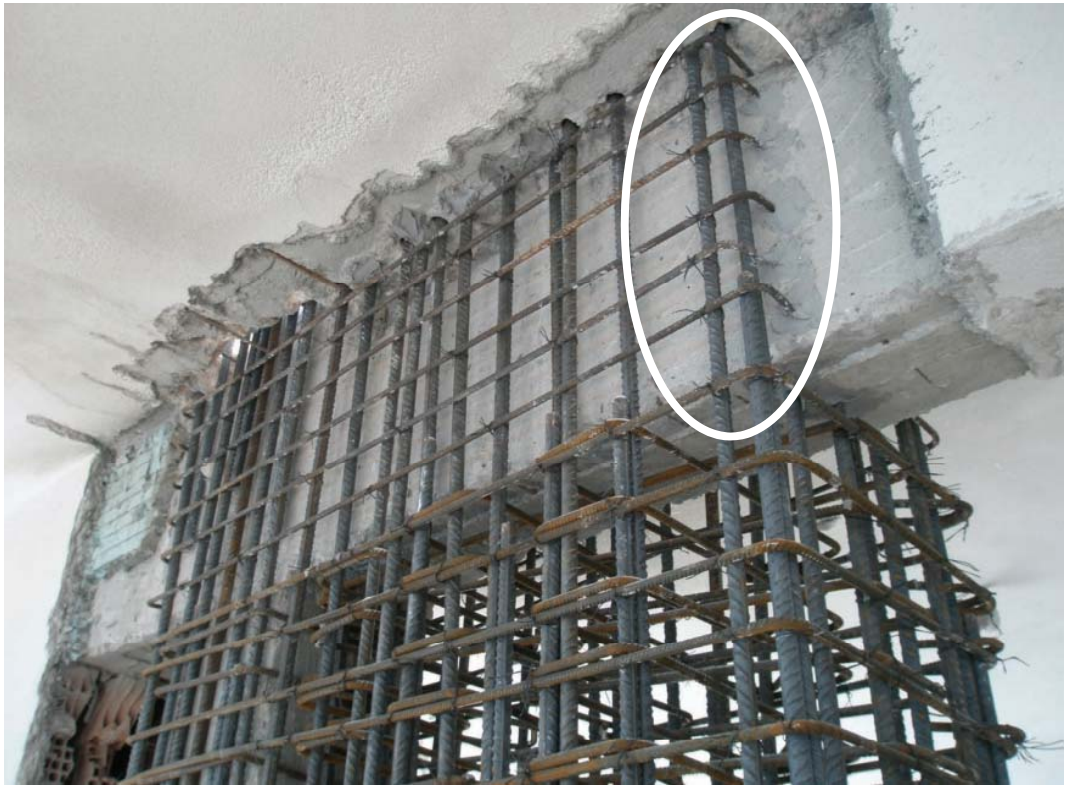
Construction issues

- Extensive drilling
- Foundation issues
- Concreting
- Anchoring horizontal bars



Past research results - Open issues

- Structures tested with one/two storeys, with low shear span ratio → shear dominated response
- Small thickness of web infill → prone in diagonal compression failure
- No consideration of the interaction with the rest structure
- Can monolithicity be achieved in a more practical & economical way ?

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Connection to frame

- Design satisfying EC8 – *fib* Model Code 2010
- Design shear forces : $V_{sd} = \varepsilon \cdot V_{elast}$

$$\varepsilon = q \cdot \sqrt{\left(\frac{\gamma_{Rd}}{q} \cdot \frac{M_{Rd}}{M_{Ed}}\right)^2 + 0{,}1\left(\frac{S_e(T_C)}{S_e(T_1)}\right)^2} \leq q$$

$$F_s = F_{0,max}\sqrt{\frac{s}{s_{max}}} = kA_s\sqrt{f_c f_y}\sqrt{\frac{s}{s_{max}}} \qquad l_{em} = 7.4d_{bw}^2/\sqrt{d_b + 5}$$

$$F_{max} = F_{0,max}\sqrt{1 - \left(\frac{\sigma_s}{f_y}\right)^2} = F_{0,max}\sqrt{1 - \left(\frac{d_{bw}}{d_d}\right)^4}$$

- Two approaches for the connection:
  - A : Wall reinforcement spliced with equal diameter anchors. Additionally, one row of dowels is placed to resist shear
  - B : One row of bars (dowels + anchors) along mid-width at centers of ¼ of the wall reinforcement spacing

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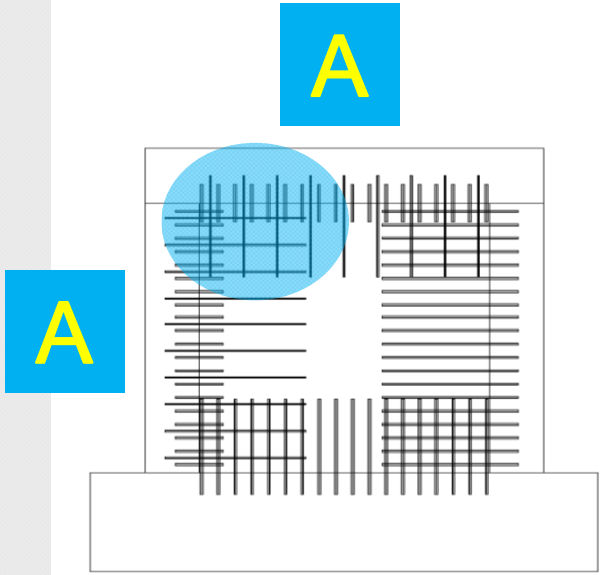
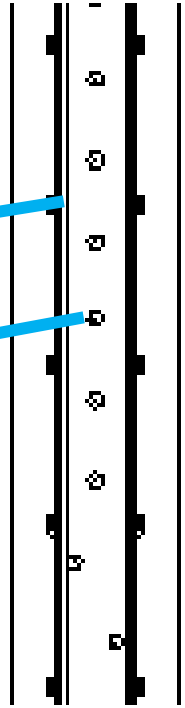
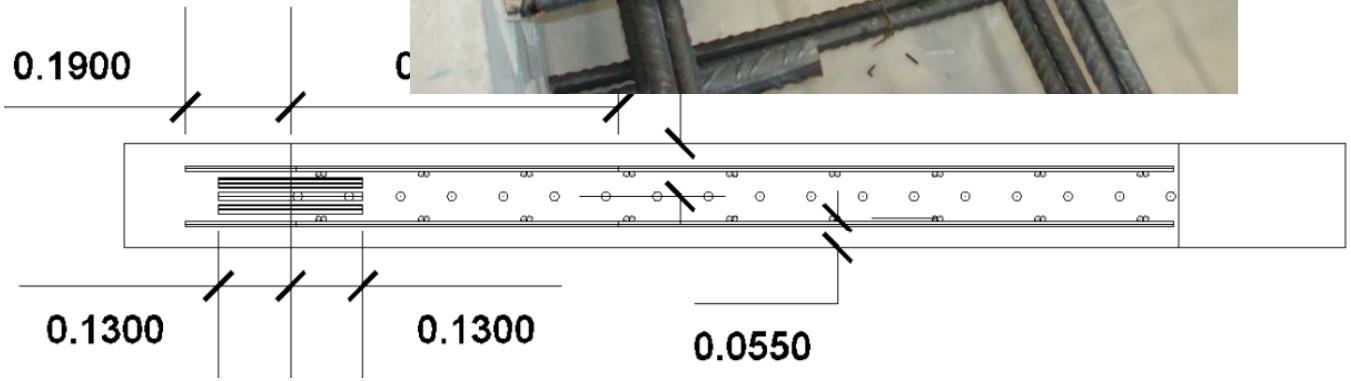
Scheme A

- Dowels (16mm,130+130mm)
- Anchors (10/8 mm, 130+590mm)







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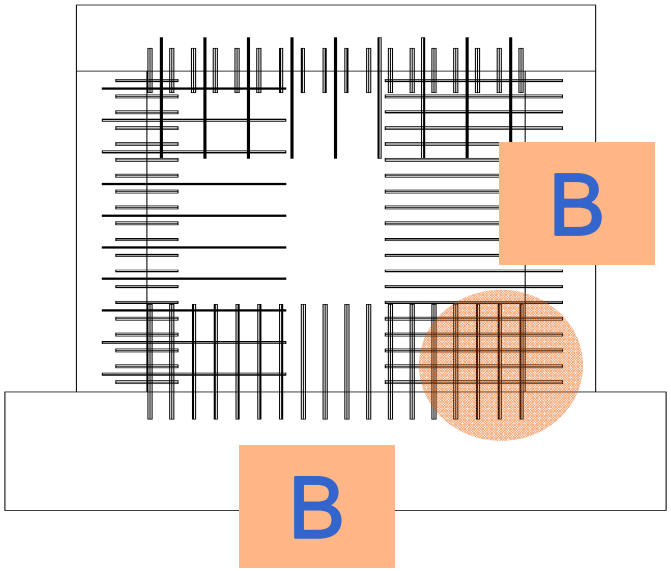
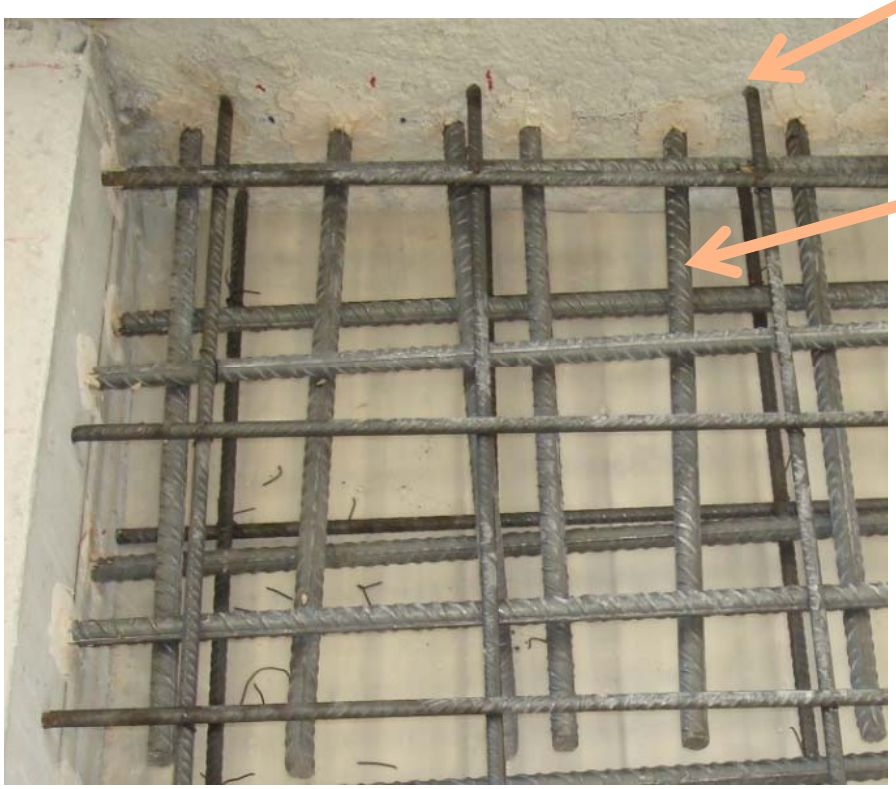
Scheme B

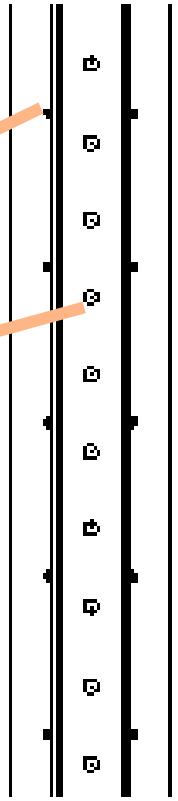
16mm bars acting both as dowels & anchors

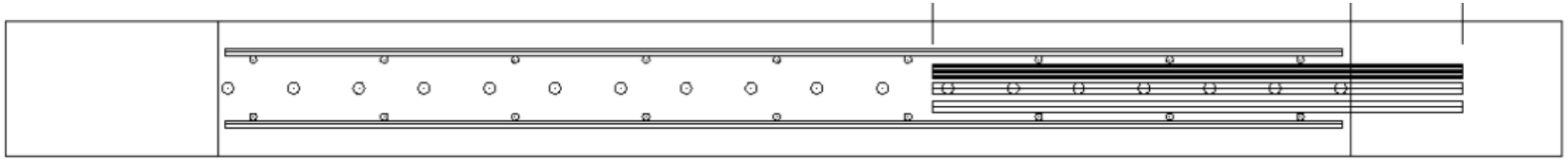
Embedment length

130+590mm









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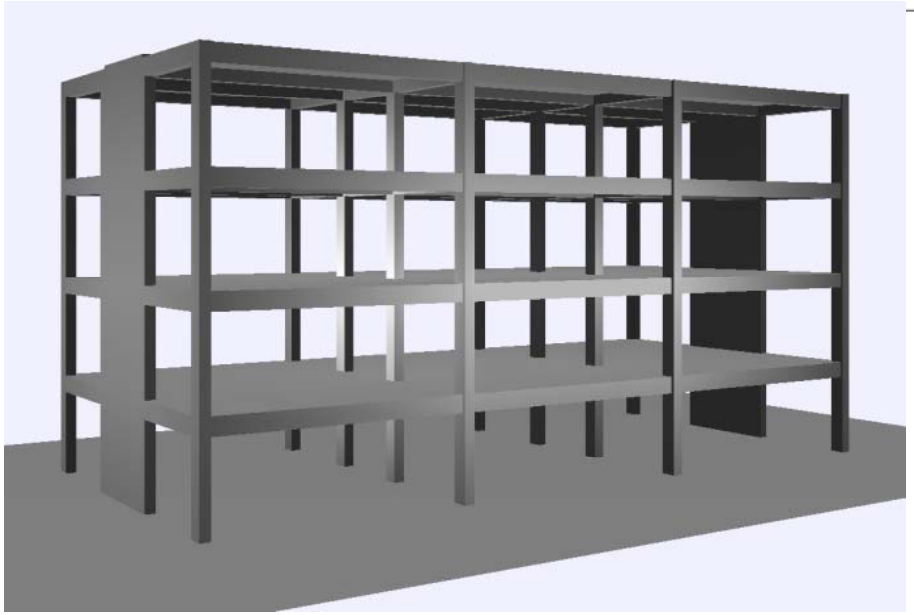
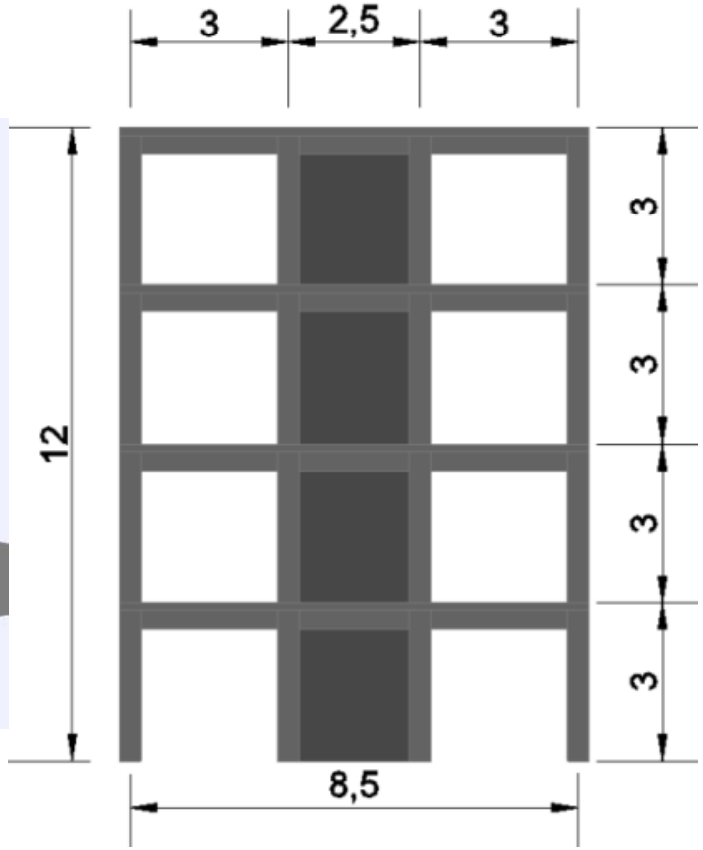
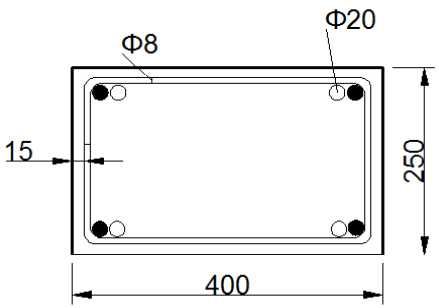
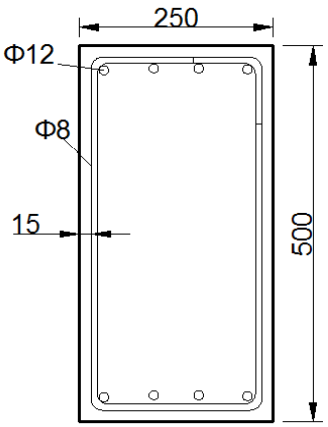
Test structure – Prototype









- Non-ductile frame
- Concrete: C16/20
- Reinforcing Steel: S400, S220

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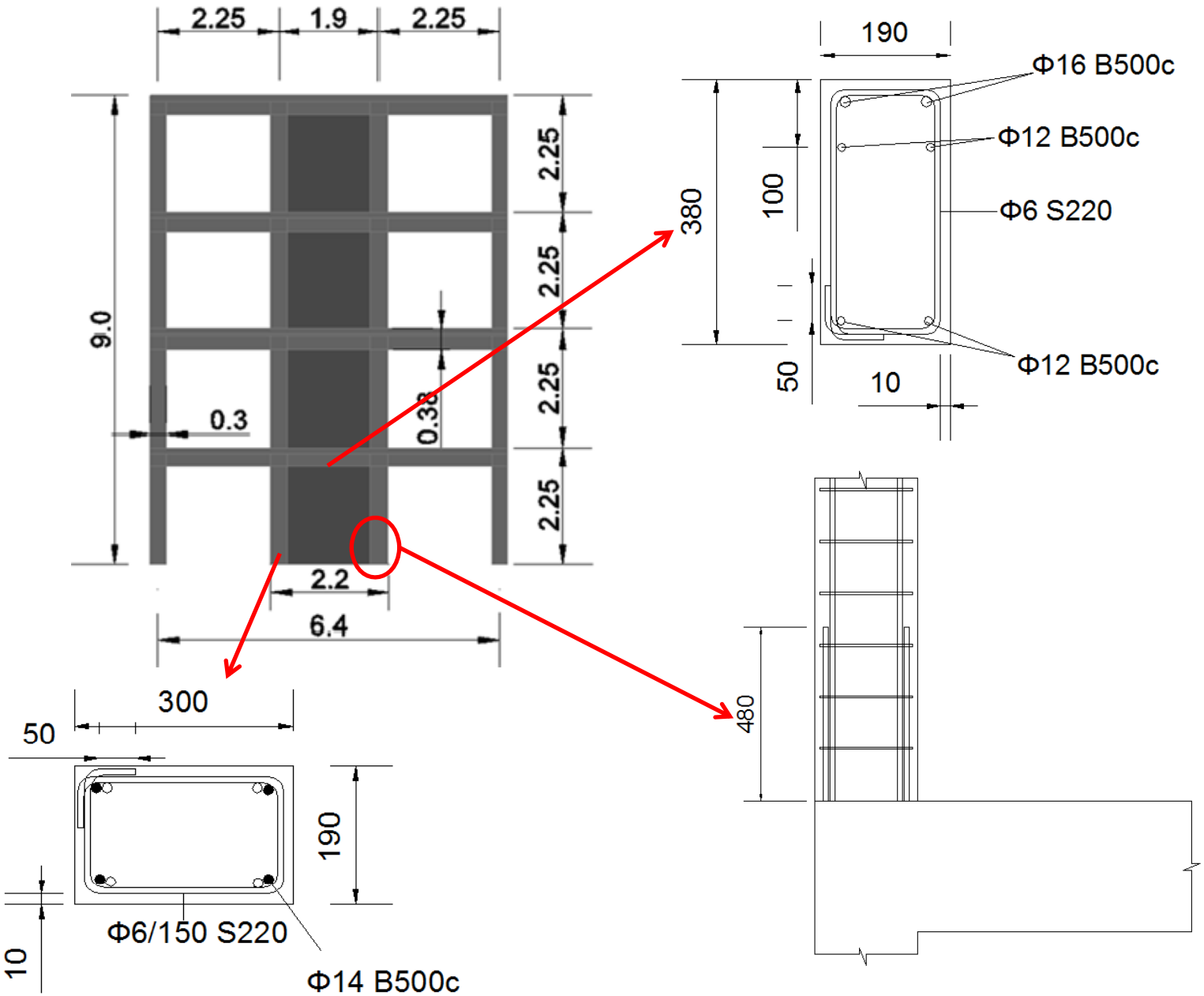
3:4 scaled structure



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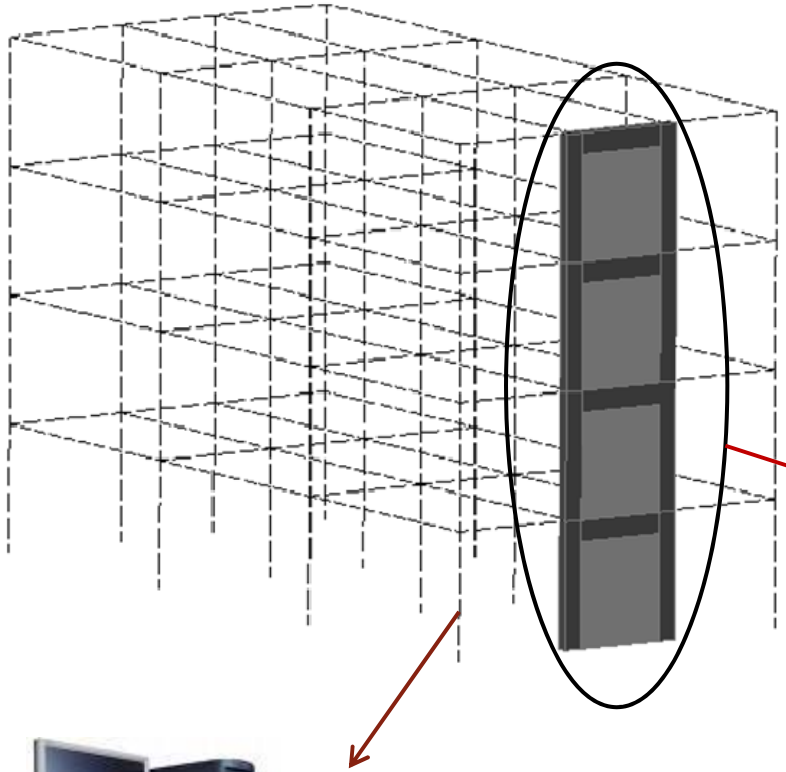
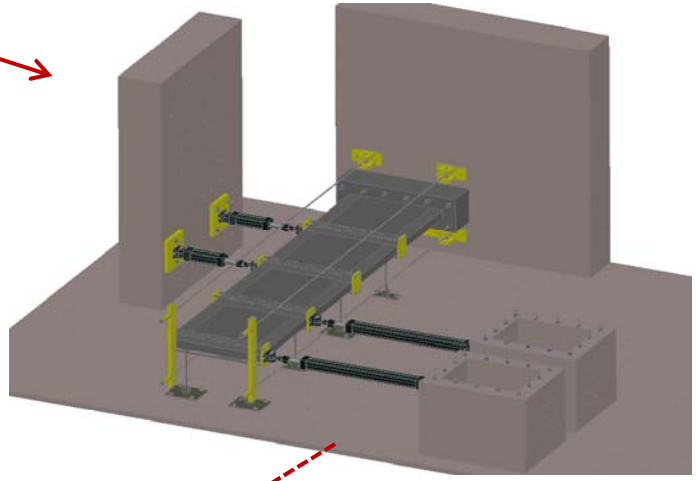
Hybrid testing method



Physical
sub-structure



Analytical
sub-structure

$$M \cdot a + C \cdot v + r_s^a + r_s^e = f$$

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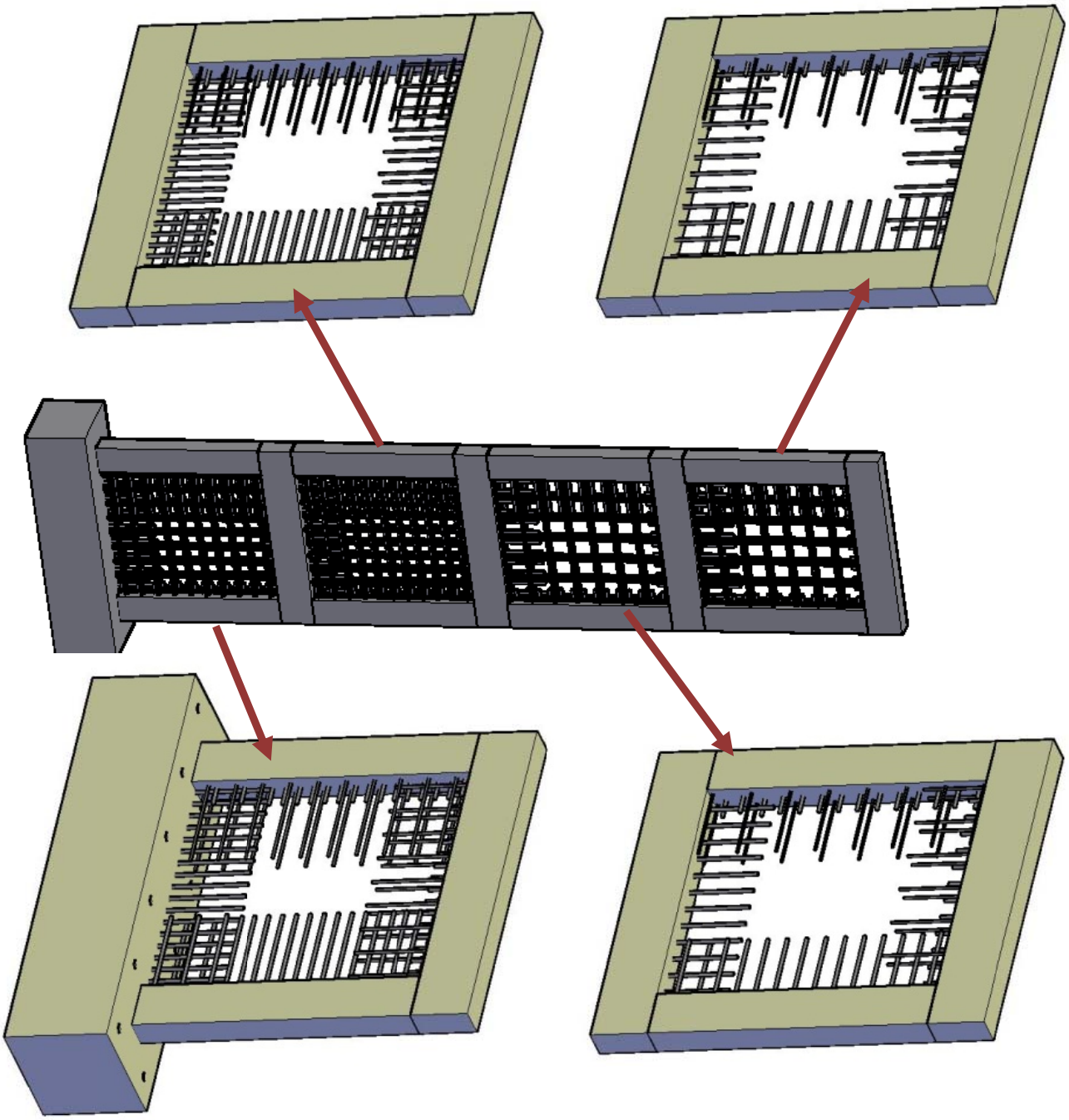
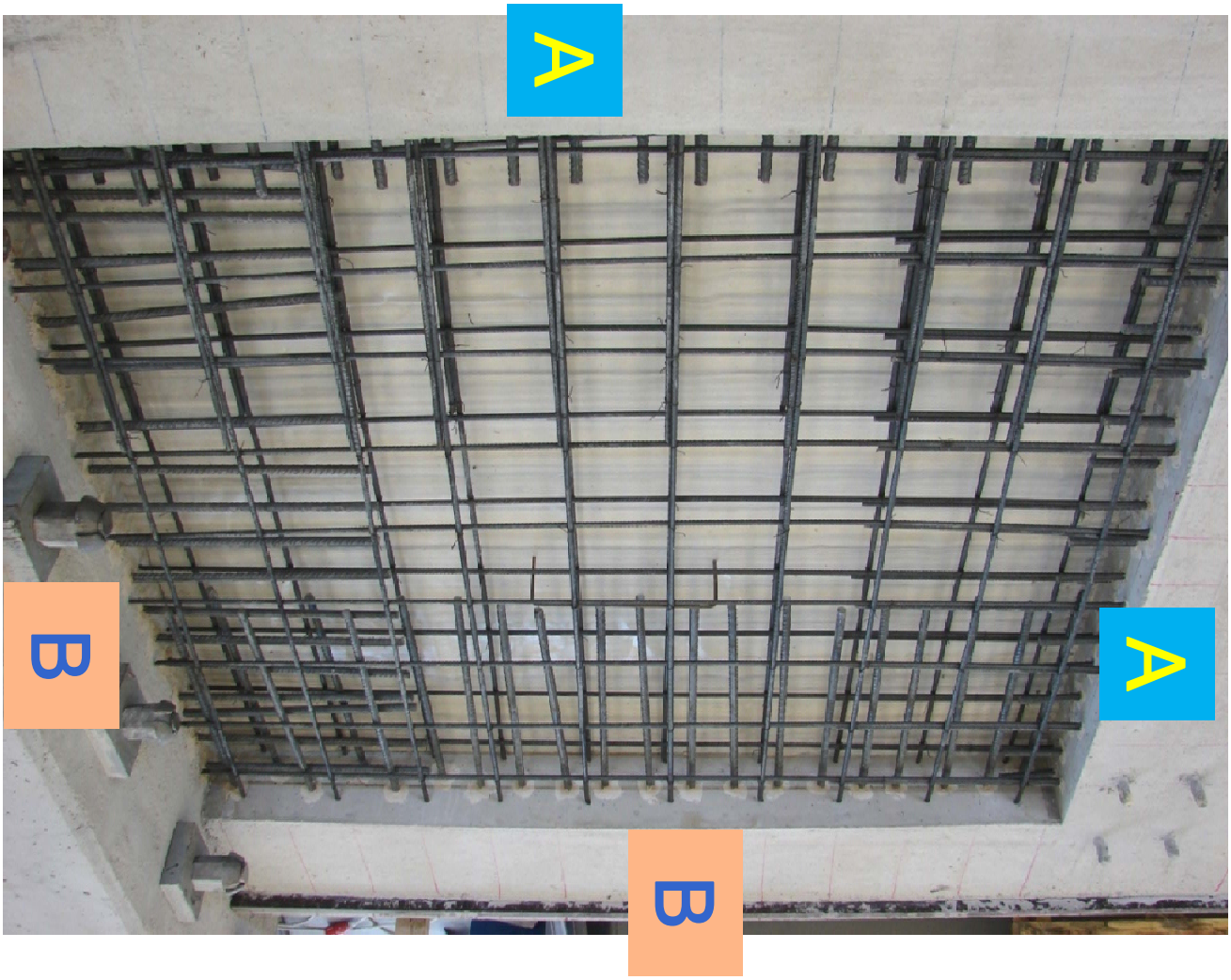
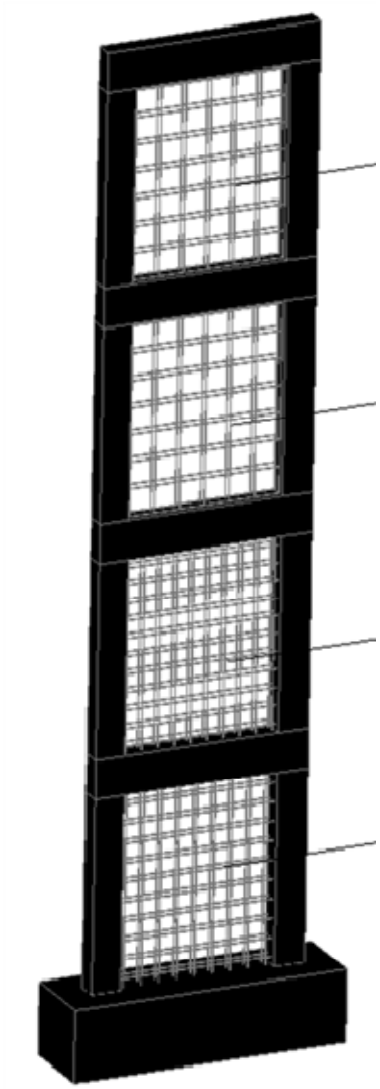



A
A
B
B

Specimens



SW1	SW2	SW3
∅8 / 260	∅8 / 260	∅8 / 260
∅8 / 260	∅8 / 260	∅8 / 260
∅8 / 170	∅ 8 / 260	∅8 / 260
∅10 / 185	∅ 8 / 170	∅8 / 260

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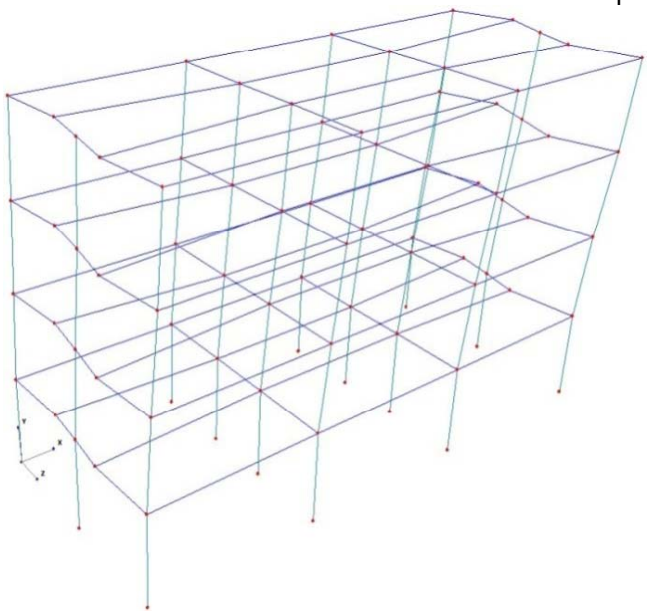
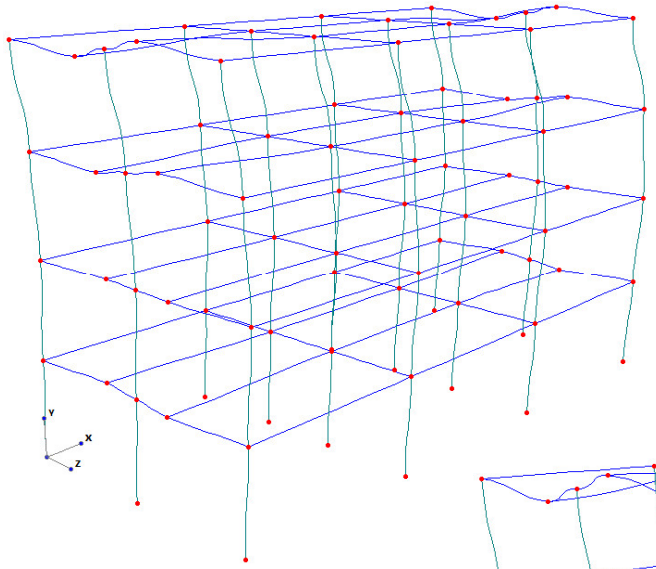
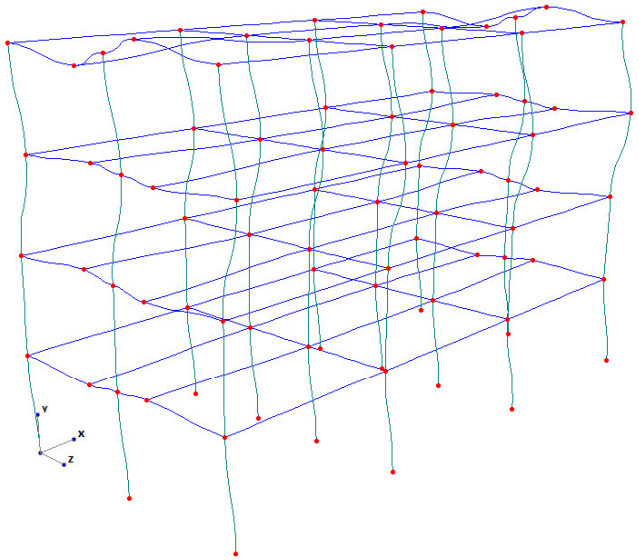
mode	Period (sec)	Part. Factor	Model mass (%)
2η	0.6114	16.08	74.53
6η	0.1783	6.85	13.54
7η	0.0865	4.73	6.45







Analysis via ANSRUOP

www.ansruop.net

(group of Prof. M. Fardis)

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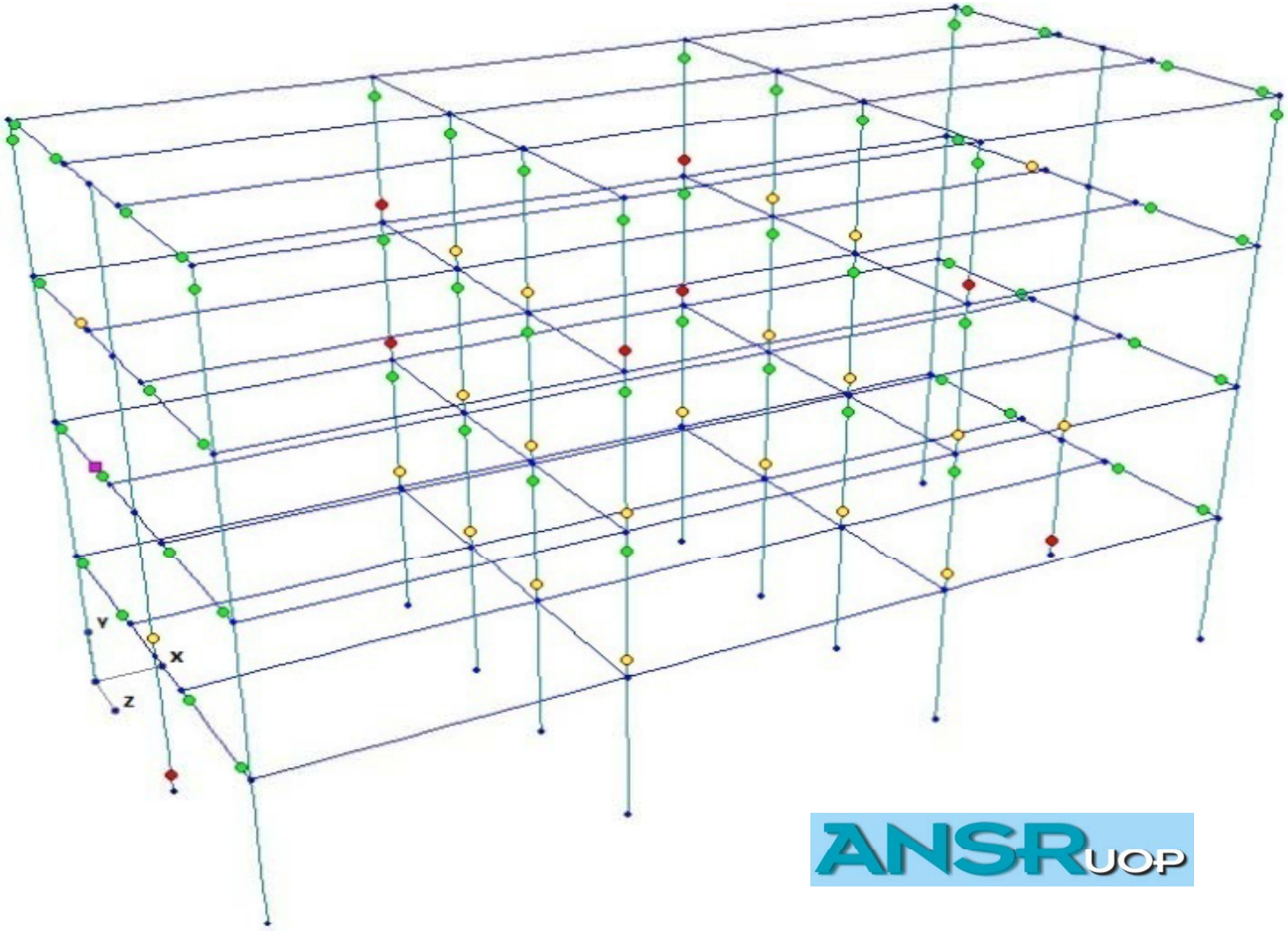
Nonlinear time history analysis§



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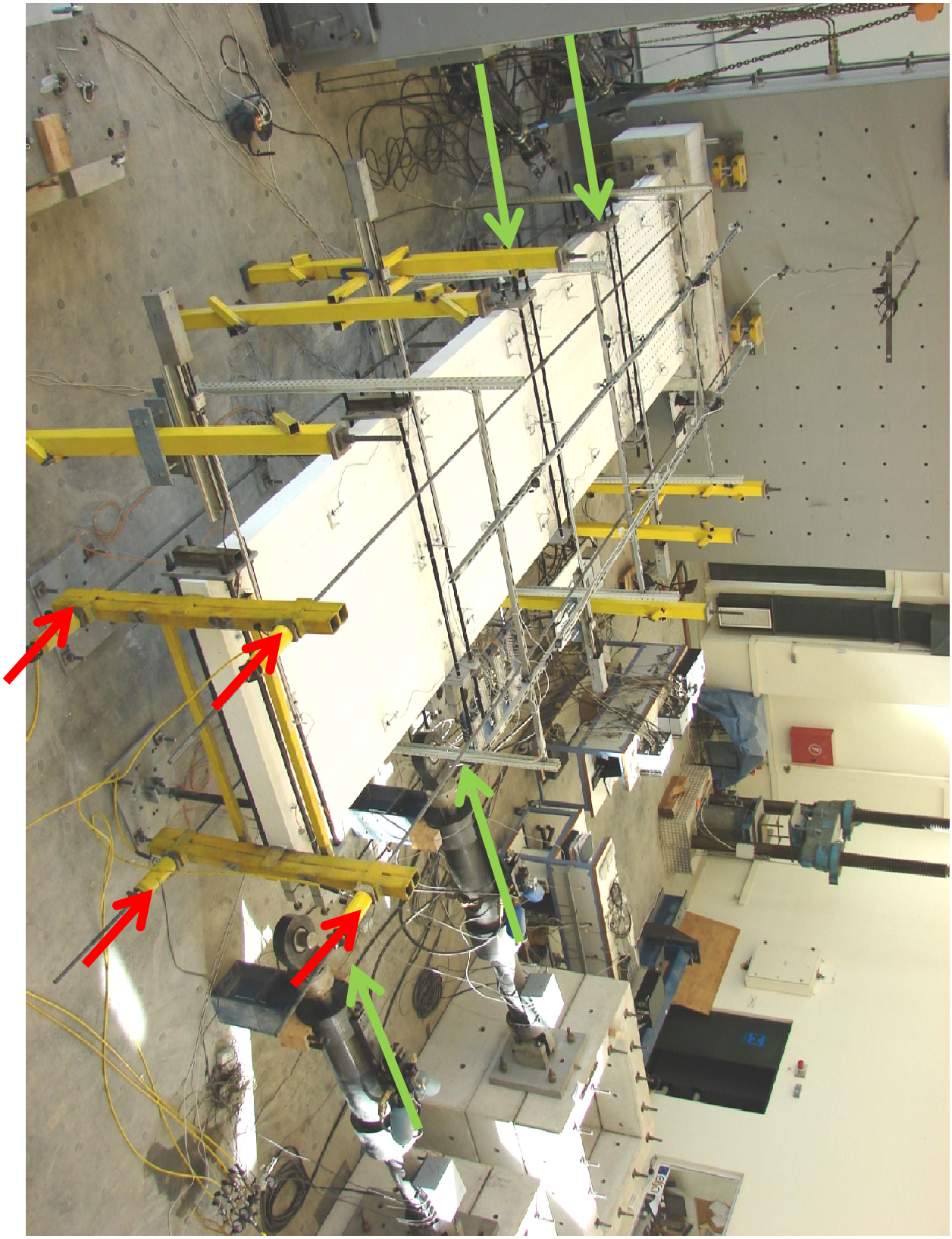
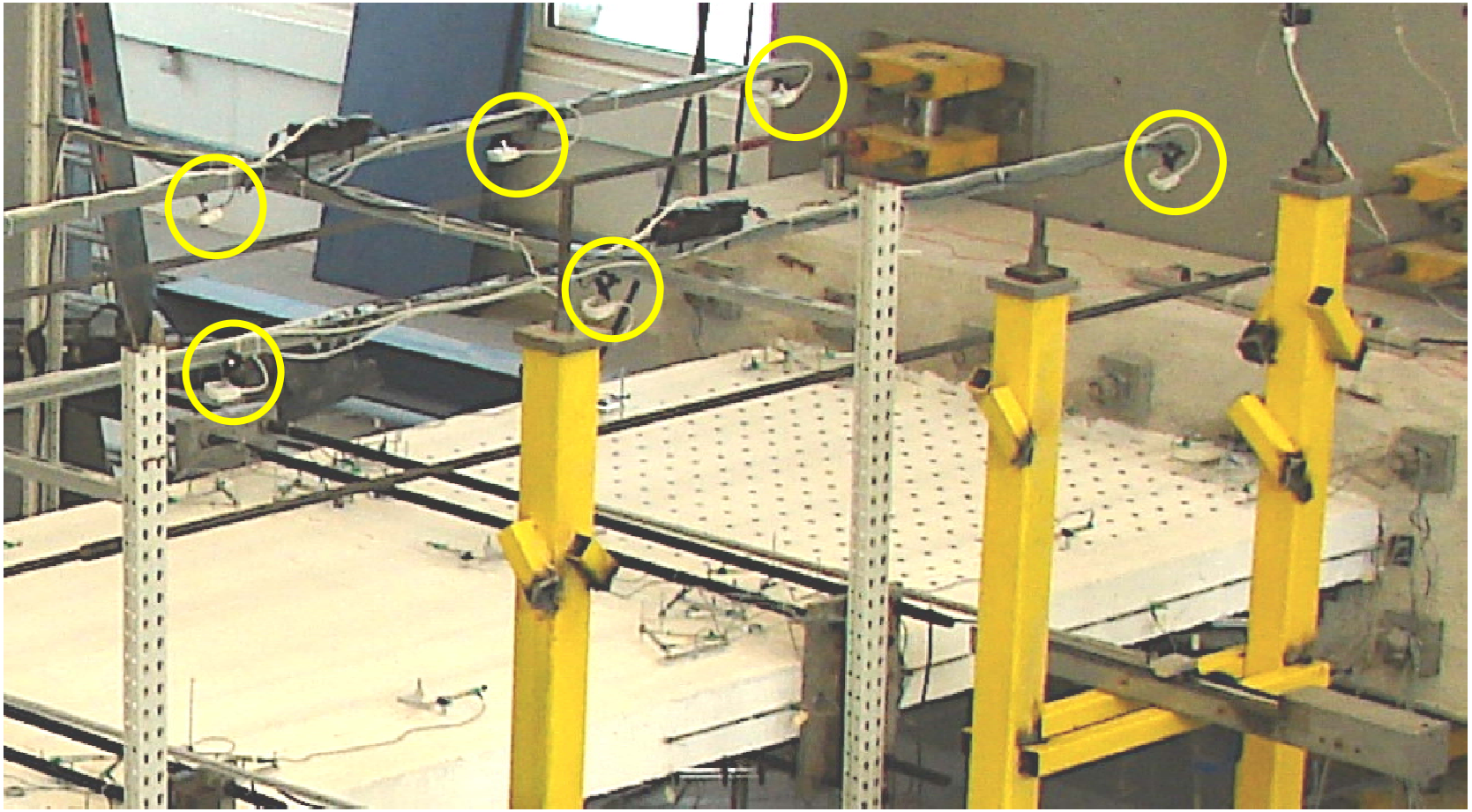
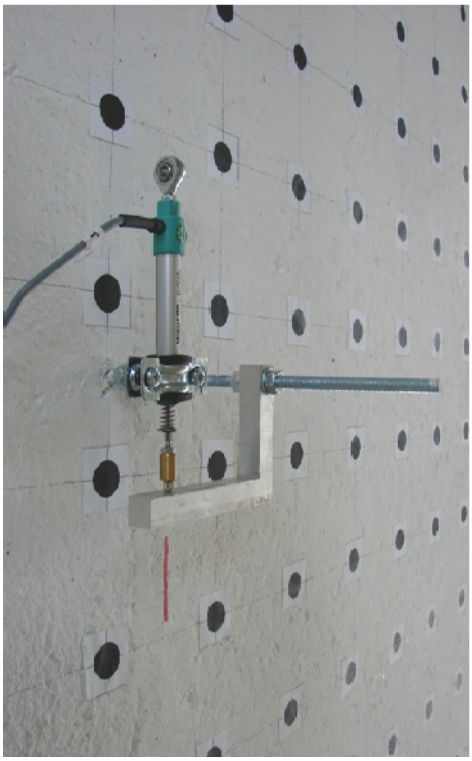
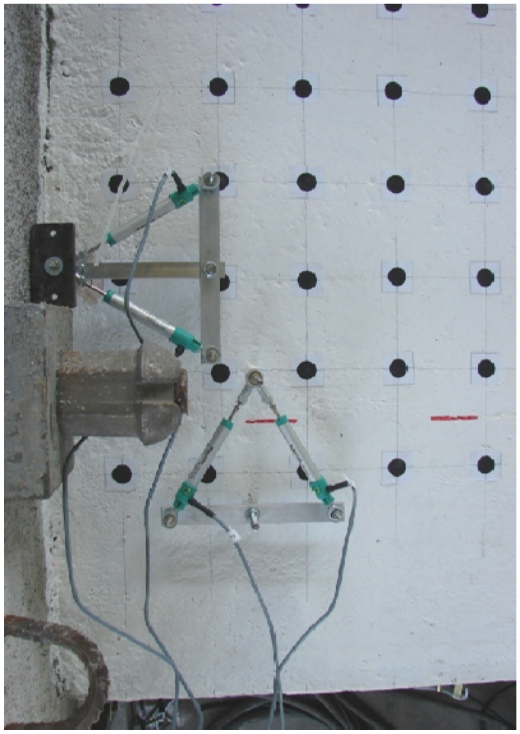


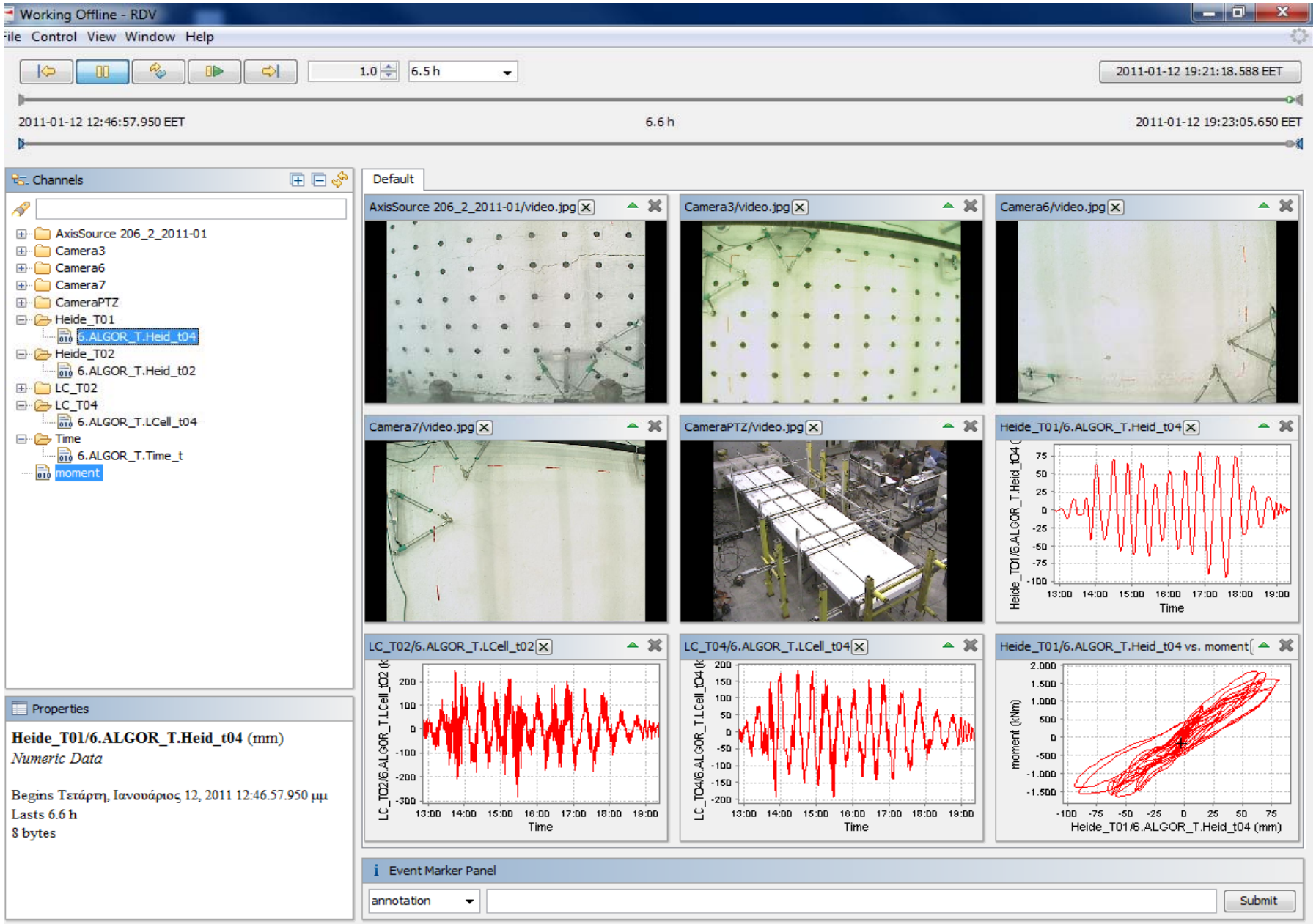
- 96 acquisition channels
- 13 network cameras
- Photogrammetry at ground floor







Tele-presence



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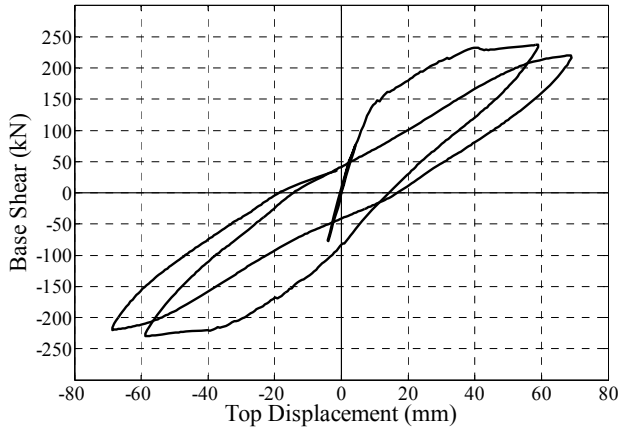
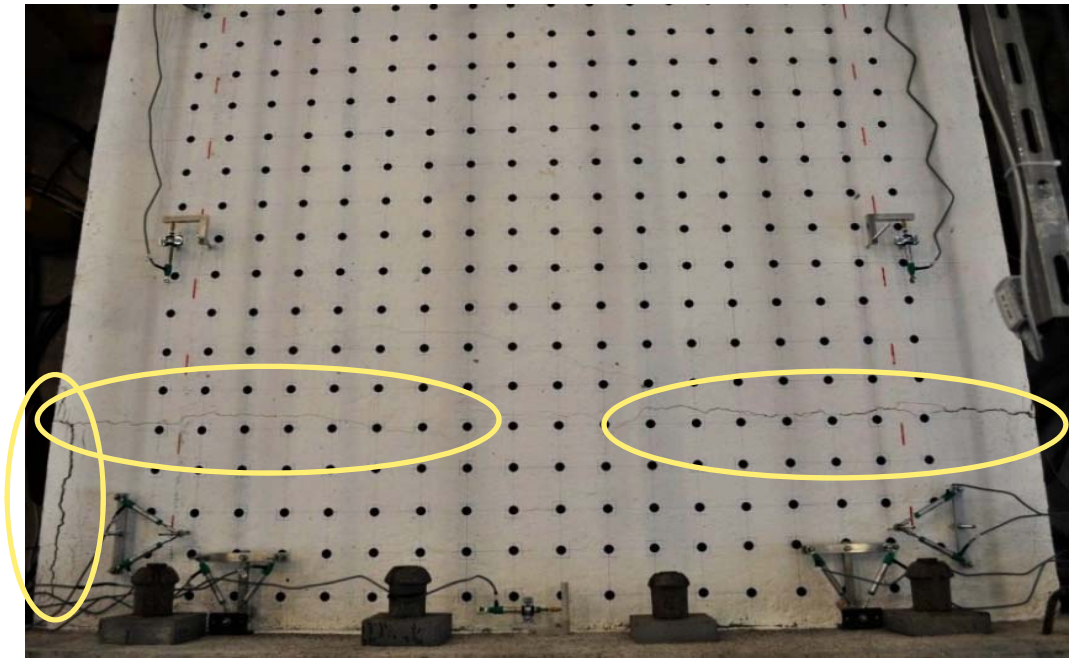
Specimen SW1: Cyclic test

- Yielding at the base – concrete spalling on the exterior side of lap-splices
- Cracking along tip of dowels at the base





lap-splice failure

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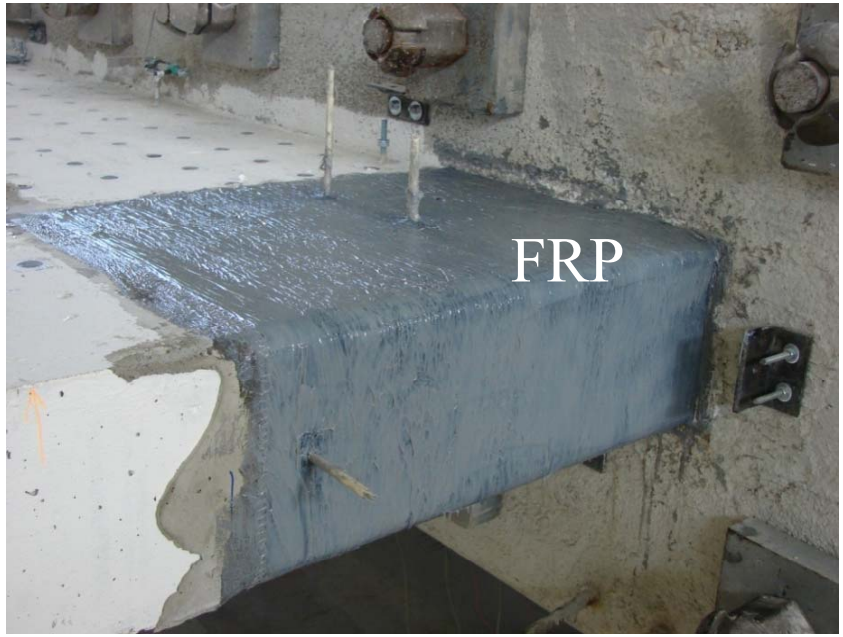
Specimen SW1: repair



Specimen SW1: hybrid test, 0.25g

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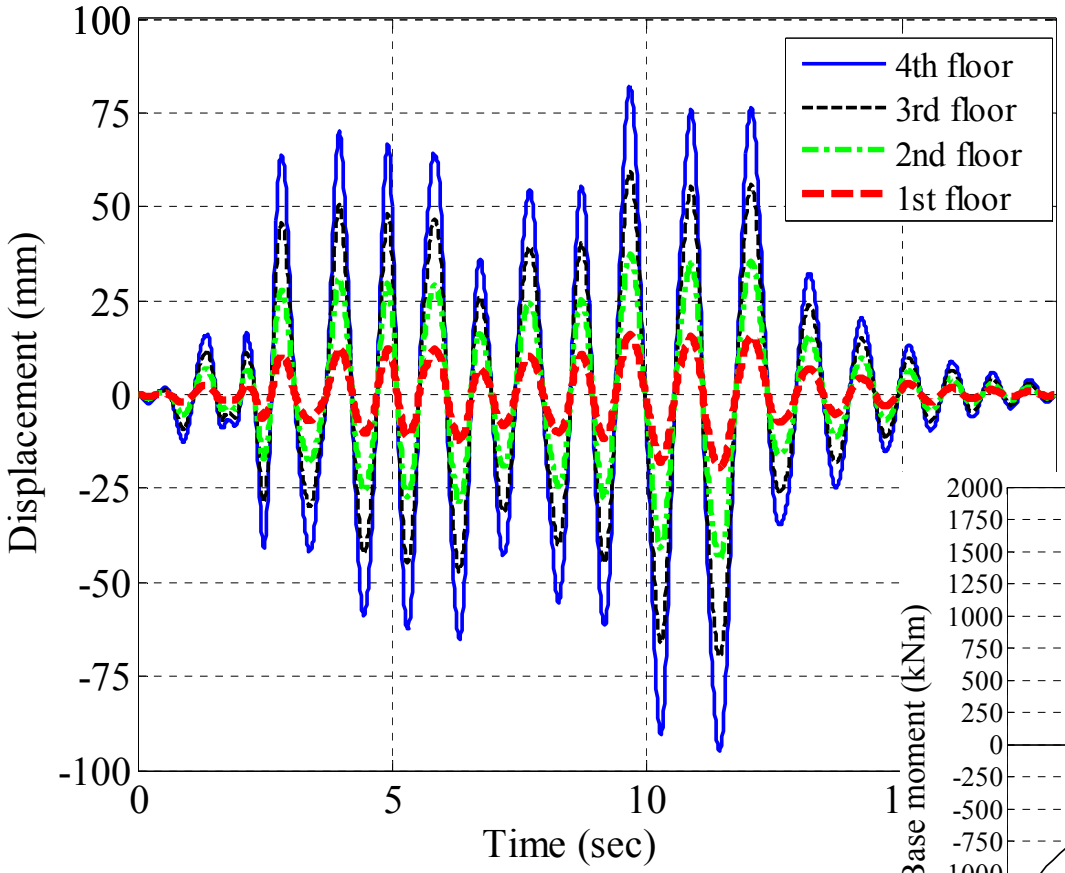
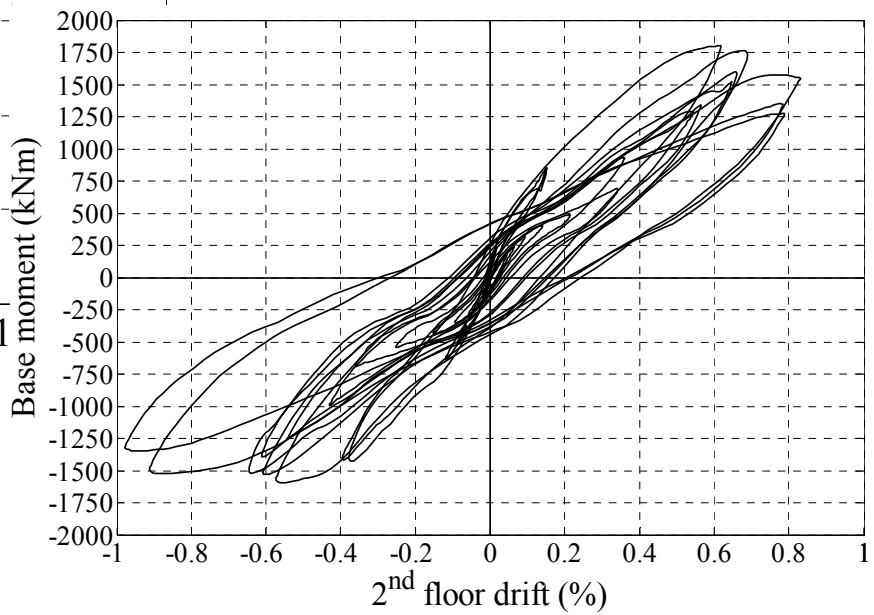
Specimen SW1: hybrid test

- Flexure-dominated failure
- Monolithic response – minor slippage at interfaces





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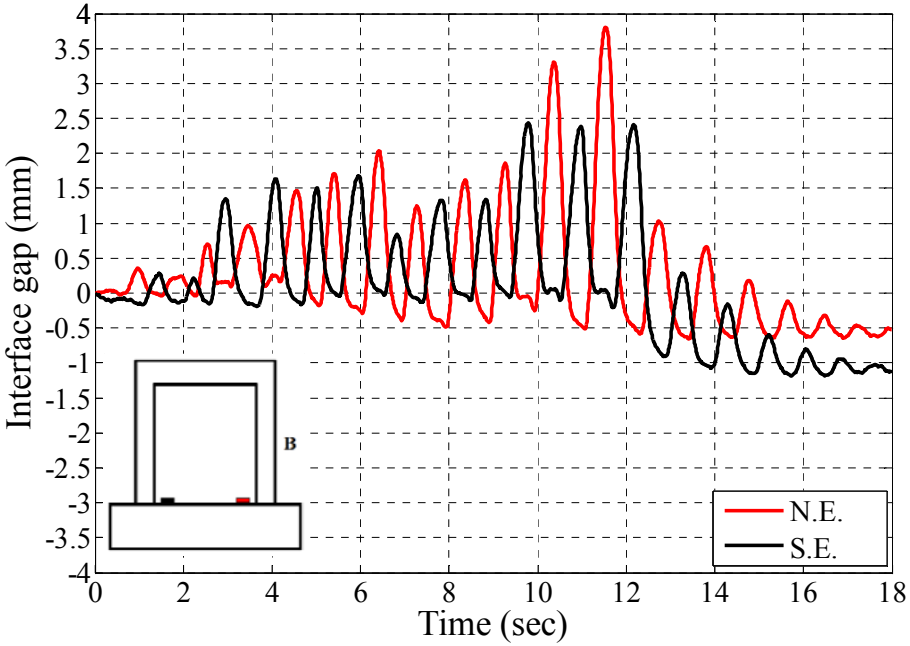

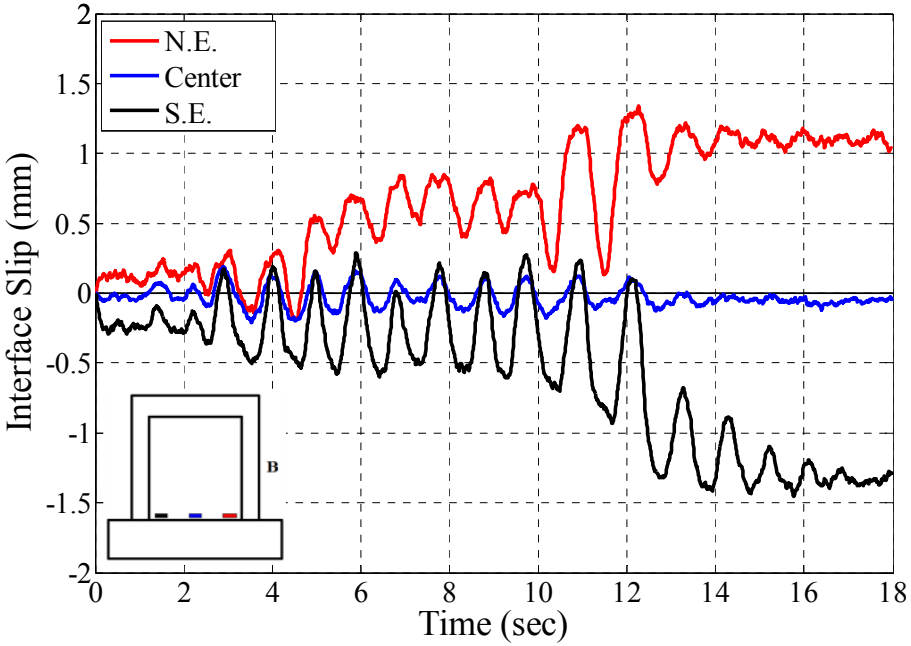

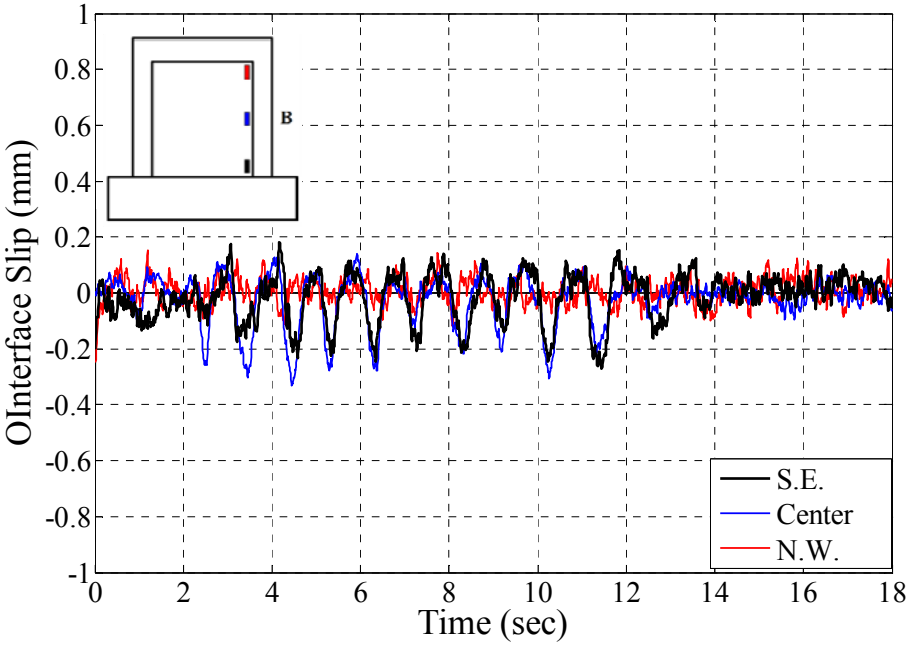

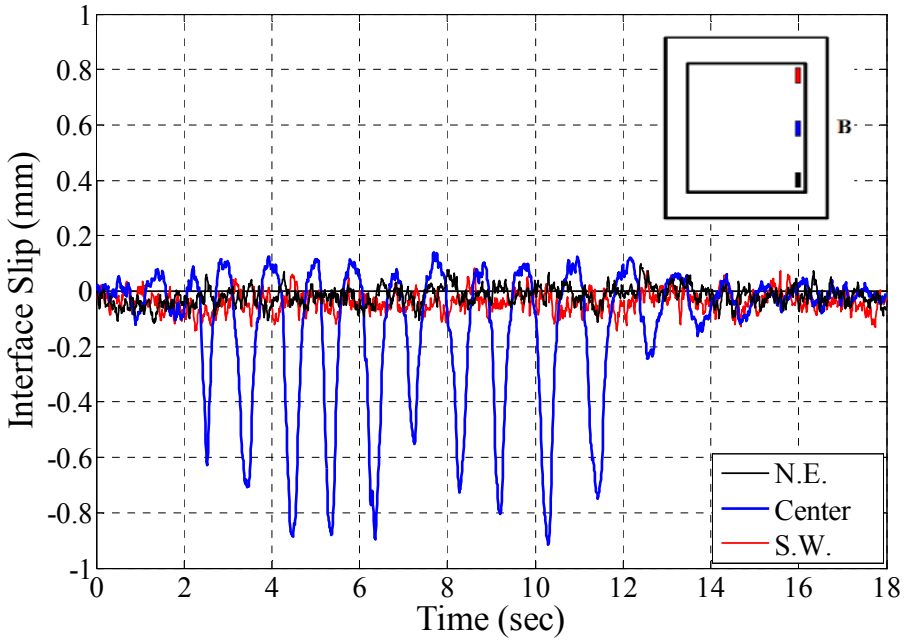

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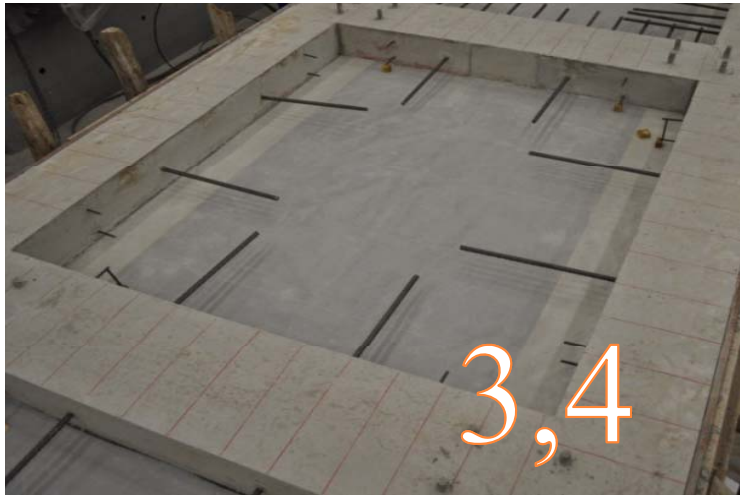
Specimen SW2

- Results of SW1: symmetric response, with sliding being higher at sides with scheme-B
- SW2: only scheme-B
- 1st :∅16/85, 2nd :∅16/130
- 3rd, 4th floor: no connection
- CFRP jacket applied before test



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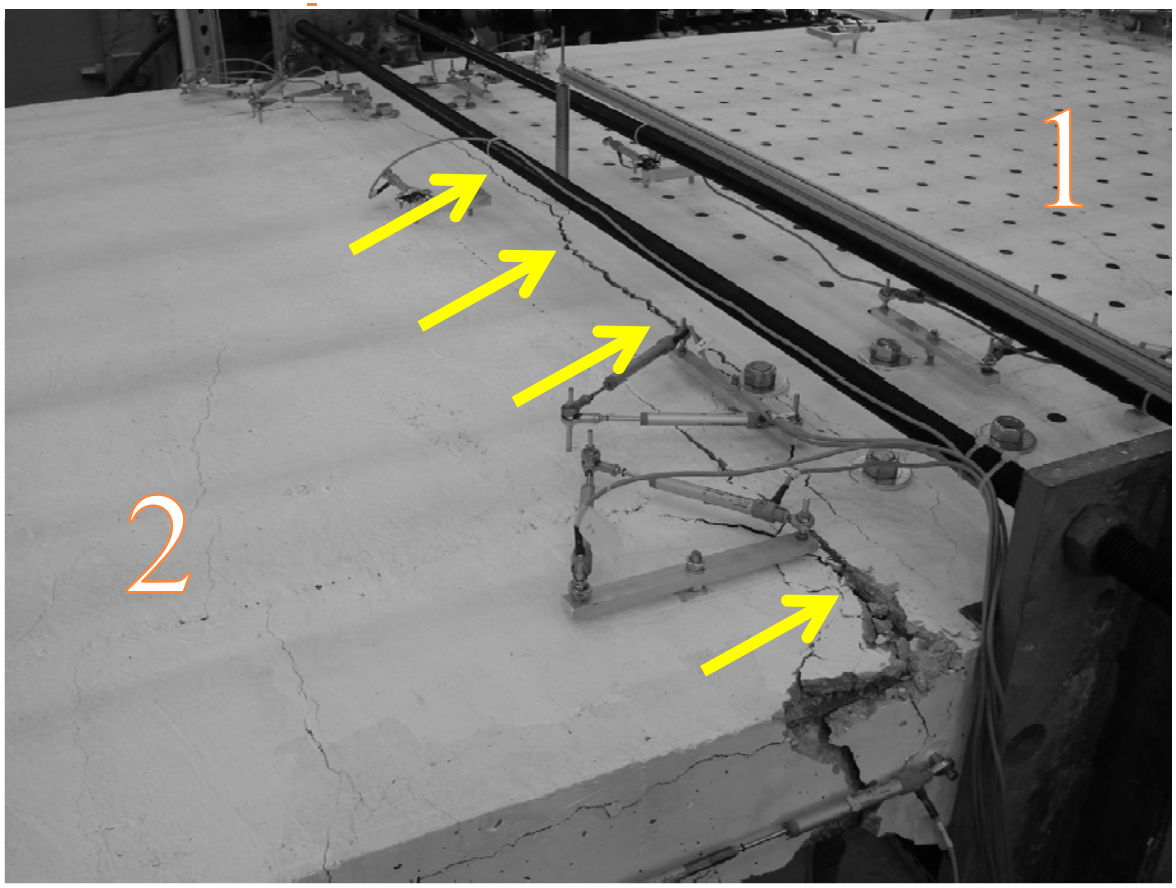
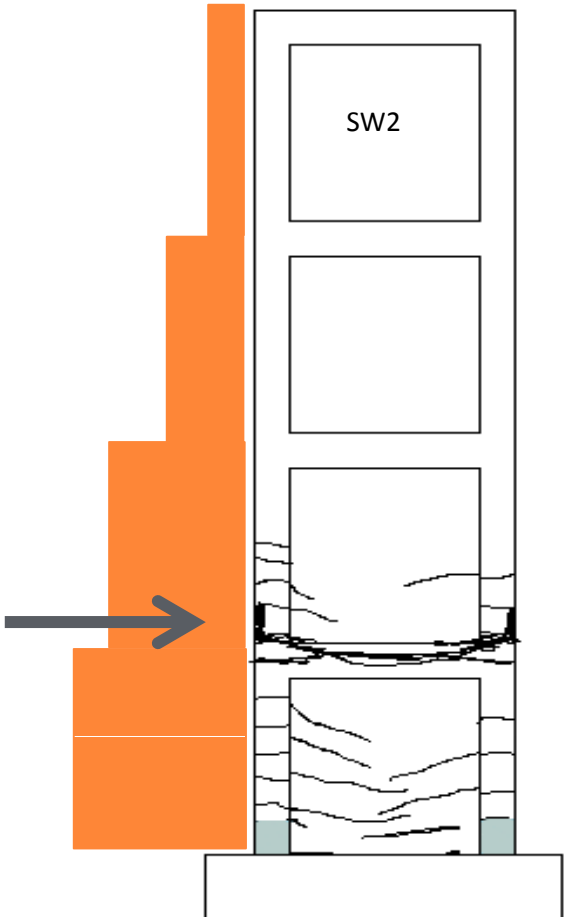
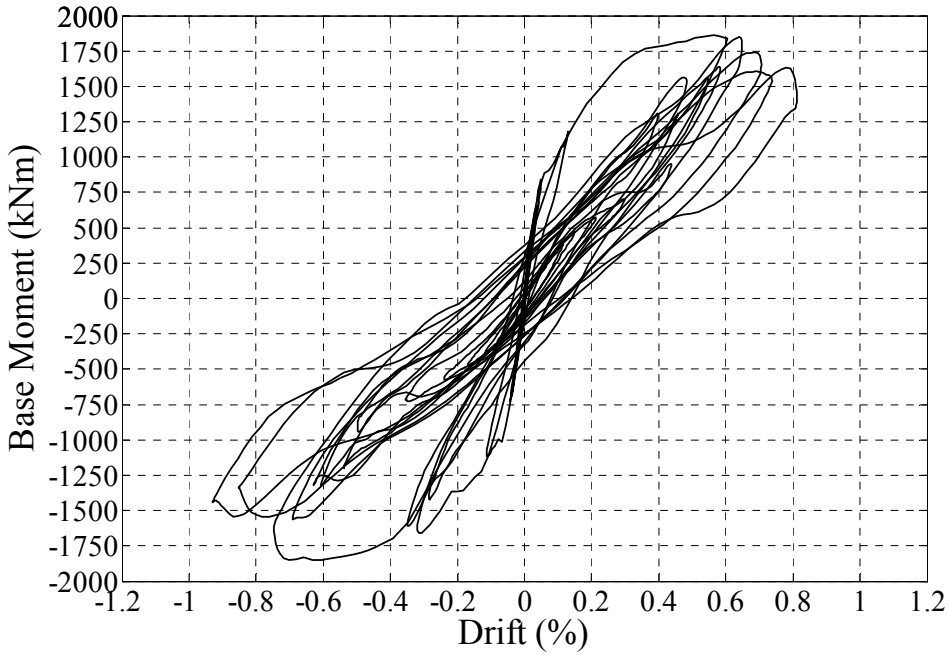
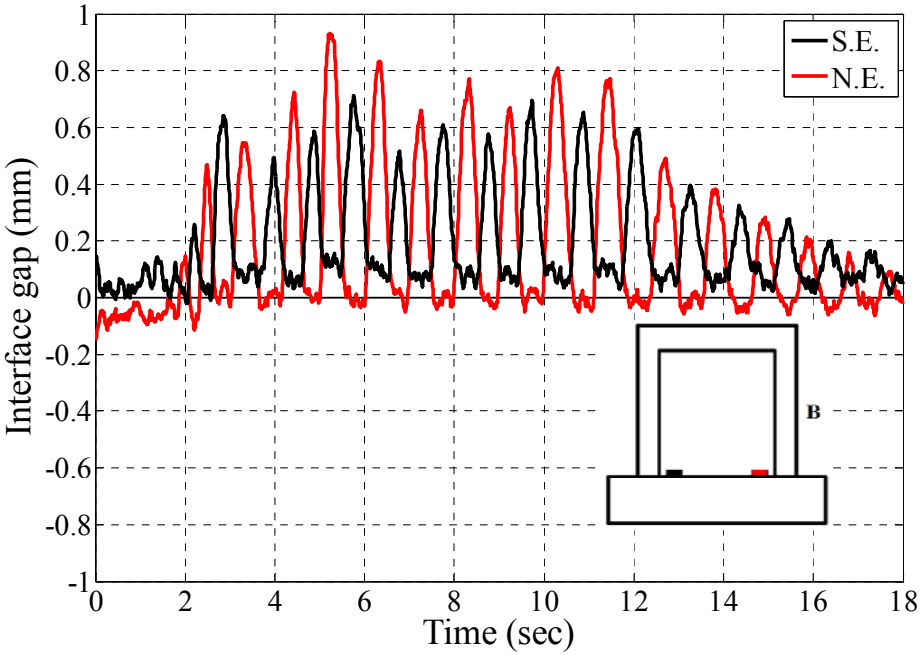
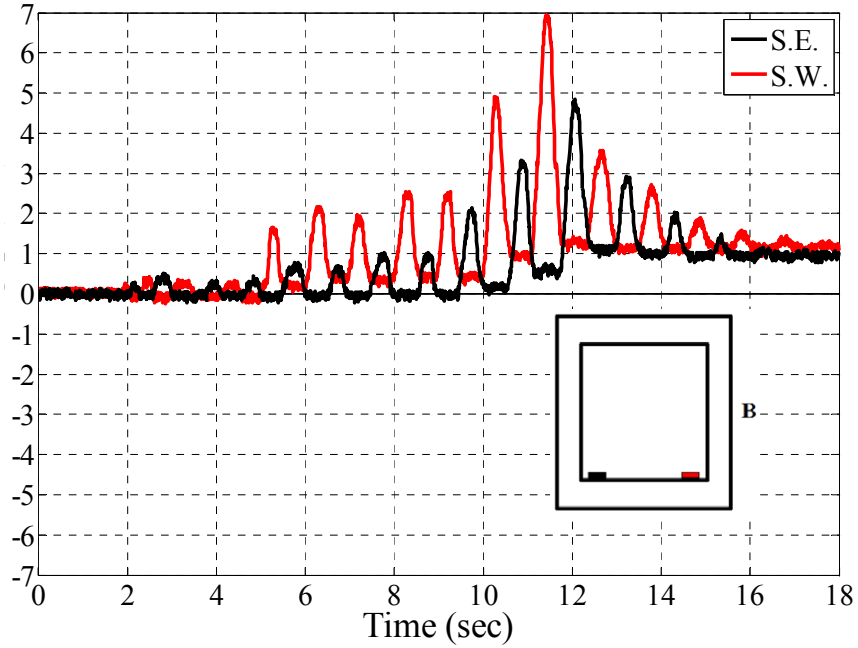
- Lap-splice failure at base of 2nd floor columns
- Longitudinal crack at mid-height of 2nd floor base beam











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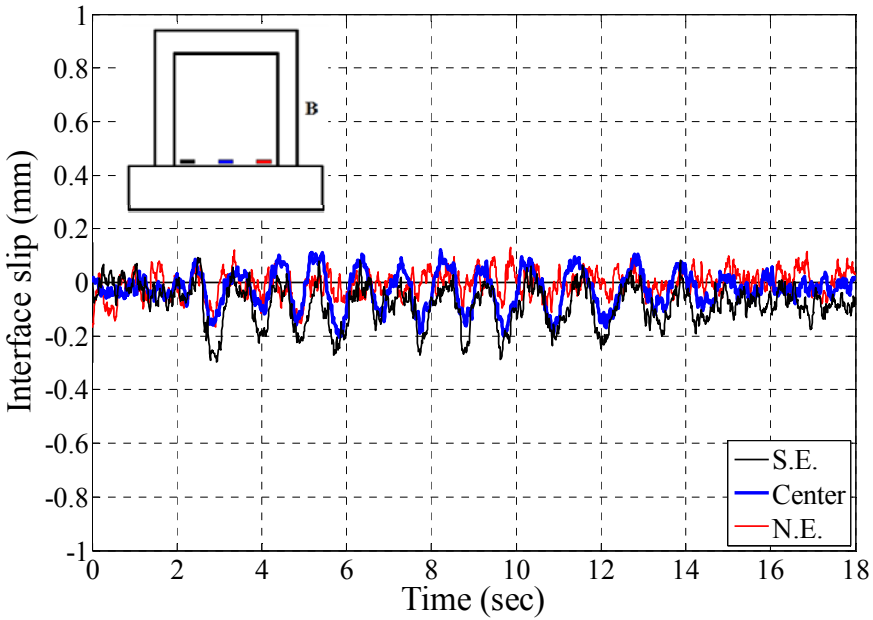

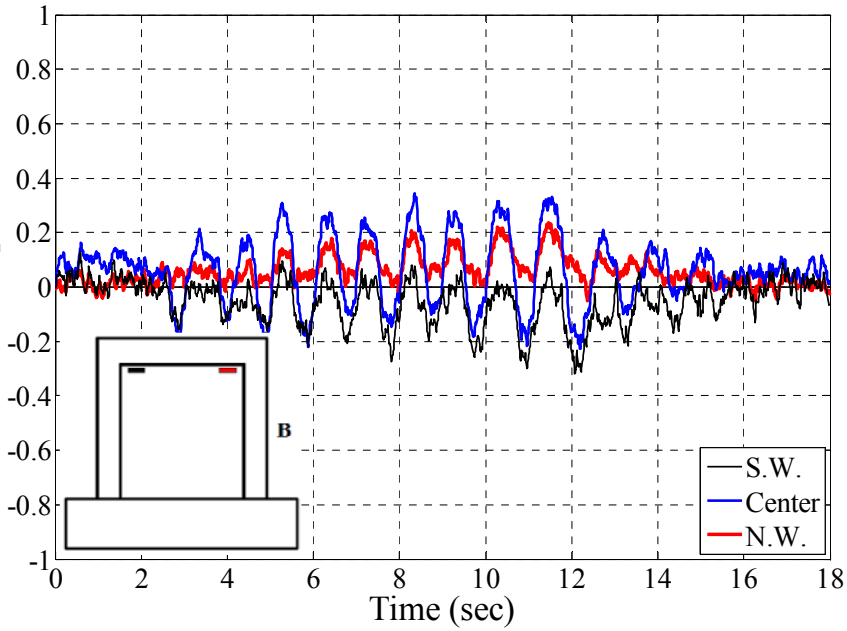

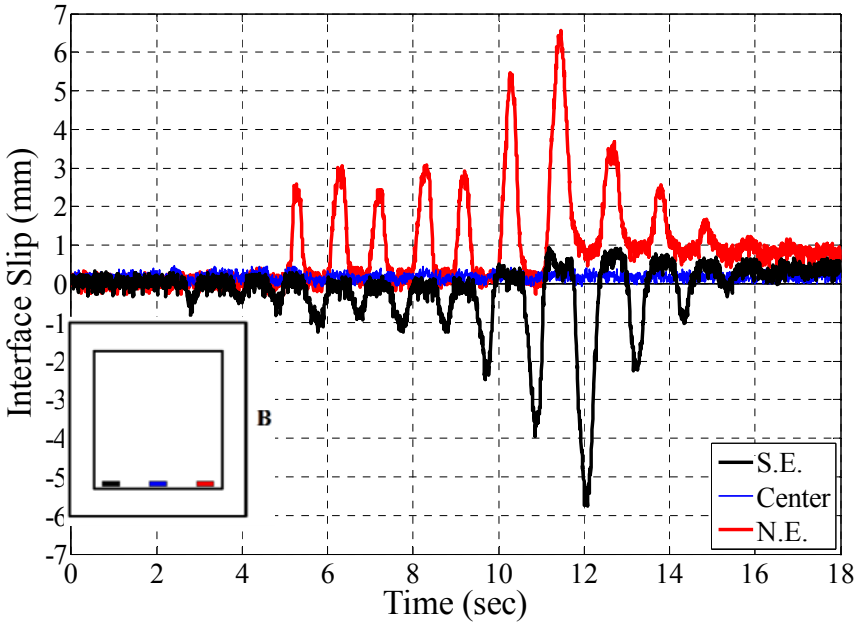

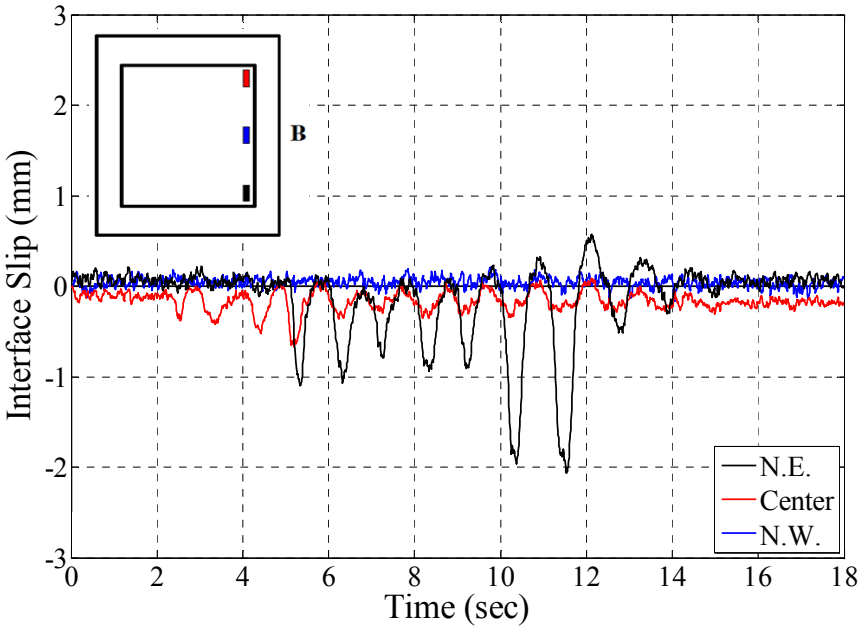

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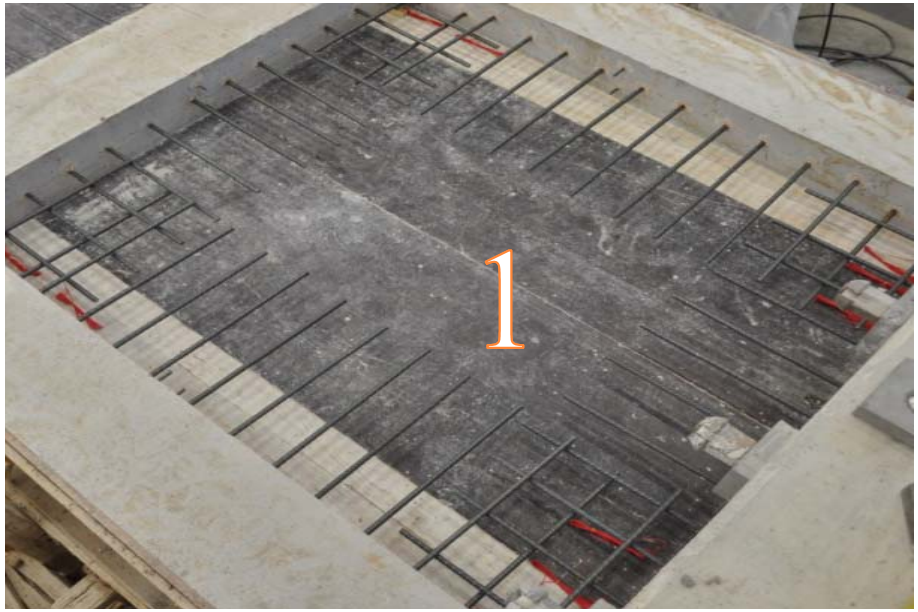
Specimen SW3

- Only Σcheme B applied
- Further reduction in dowels:
  - 1st : ∅14/130,
  - 2nd : ∅12/130
  - 3rd, 4th floor: no connection
- FRP jacket at base test



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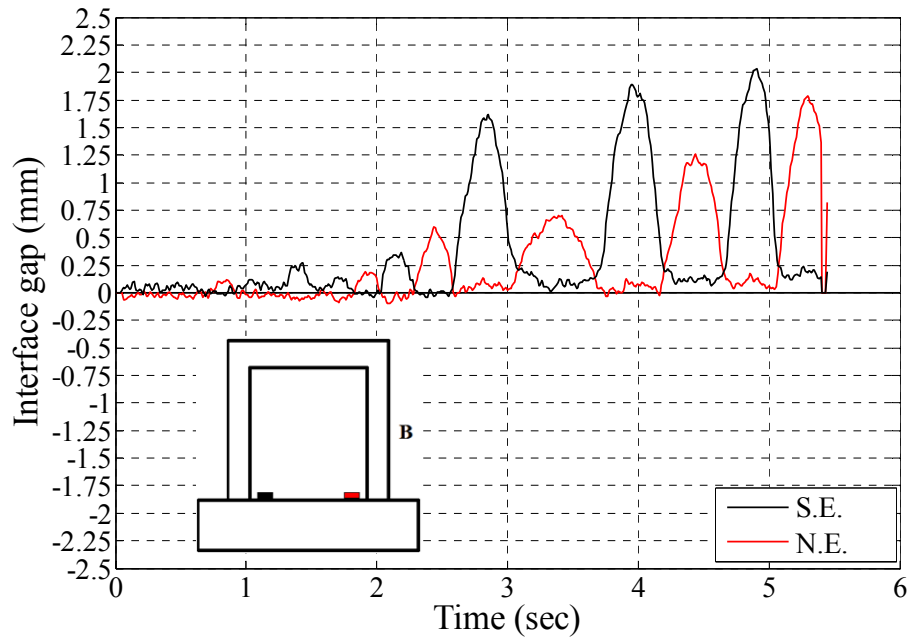
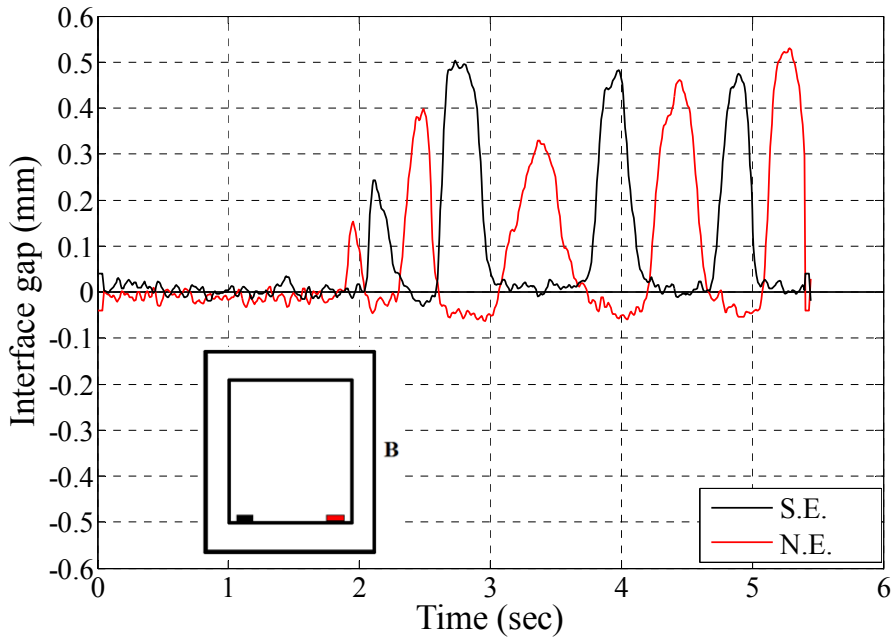
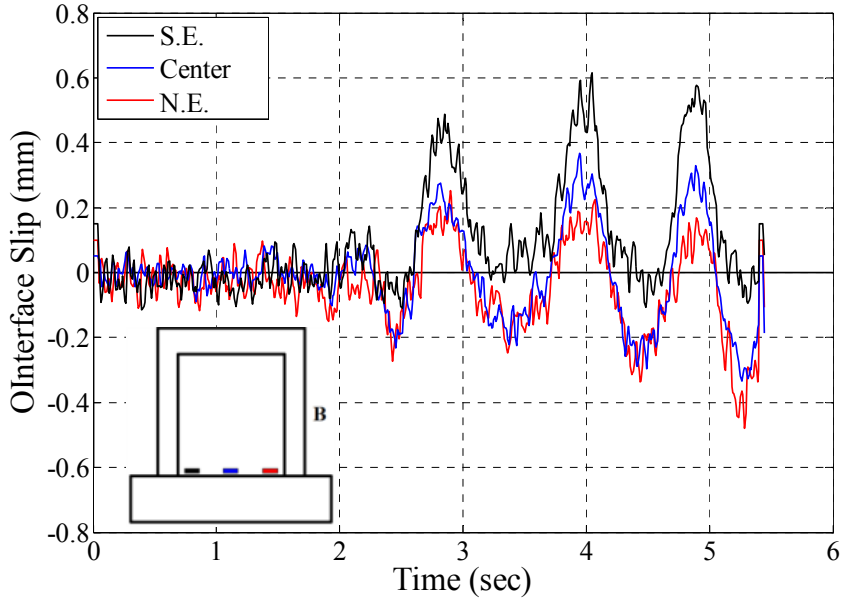
SW3 – hybrid test (run 1)







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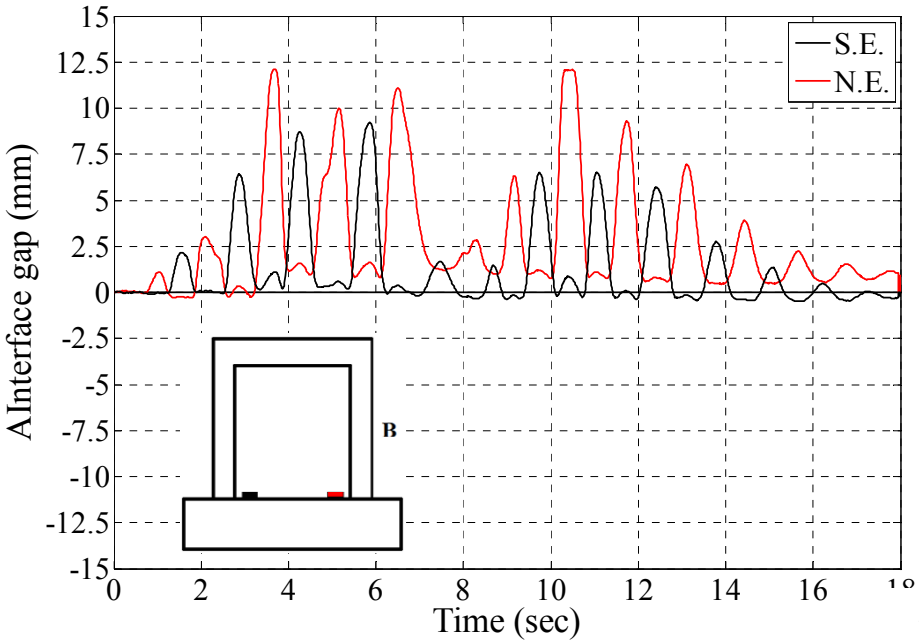
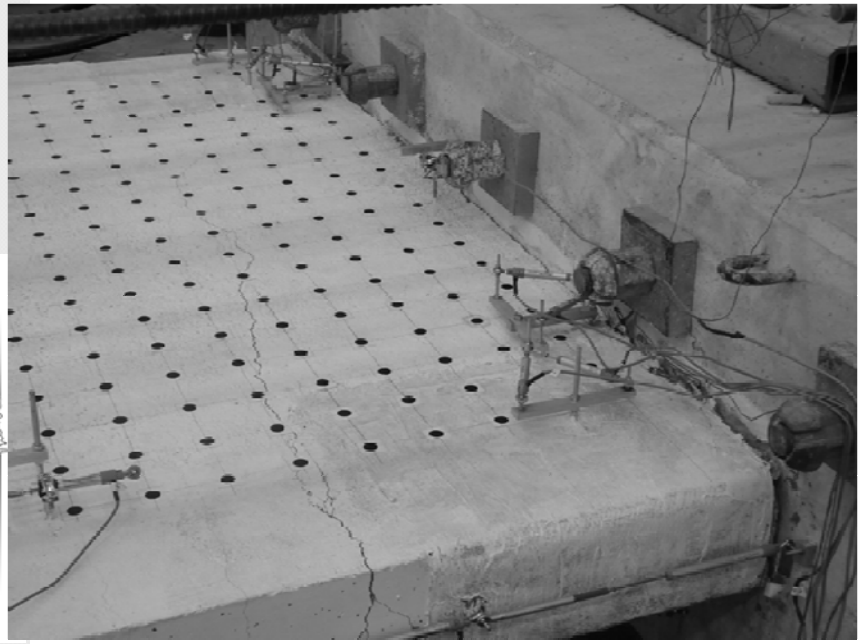
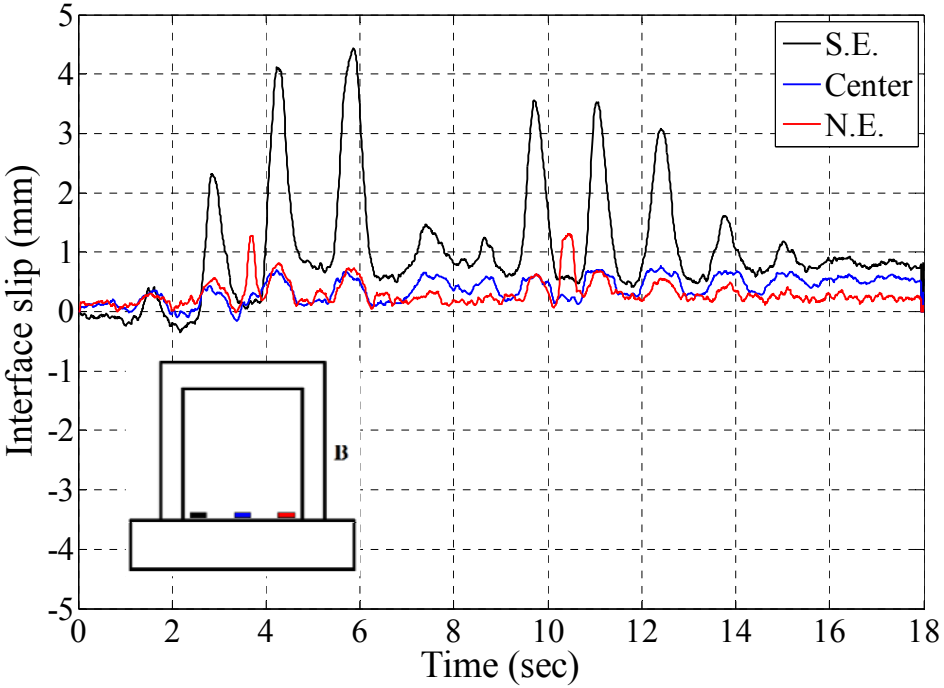
SW3 – hybrid test (run 3)







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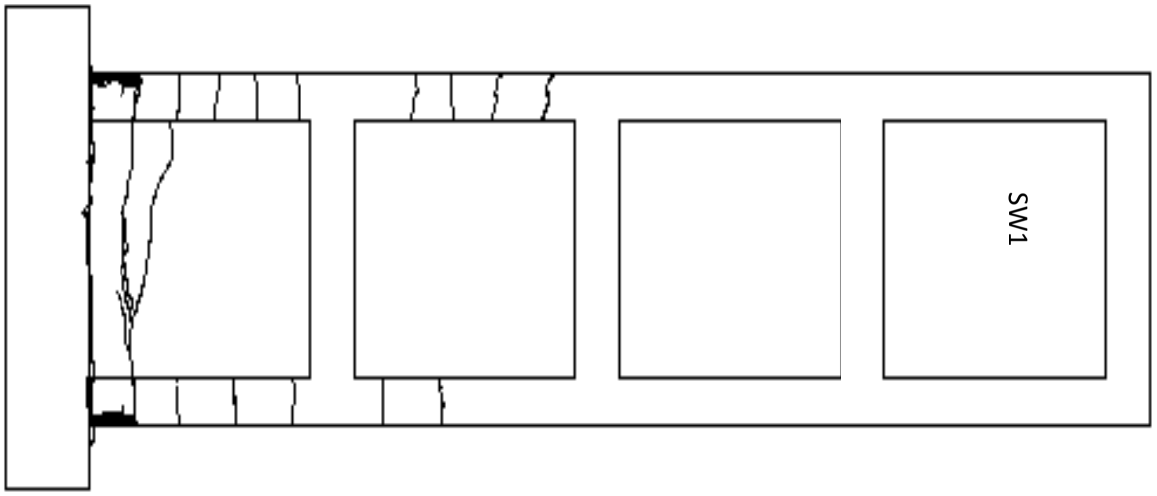
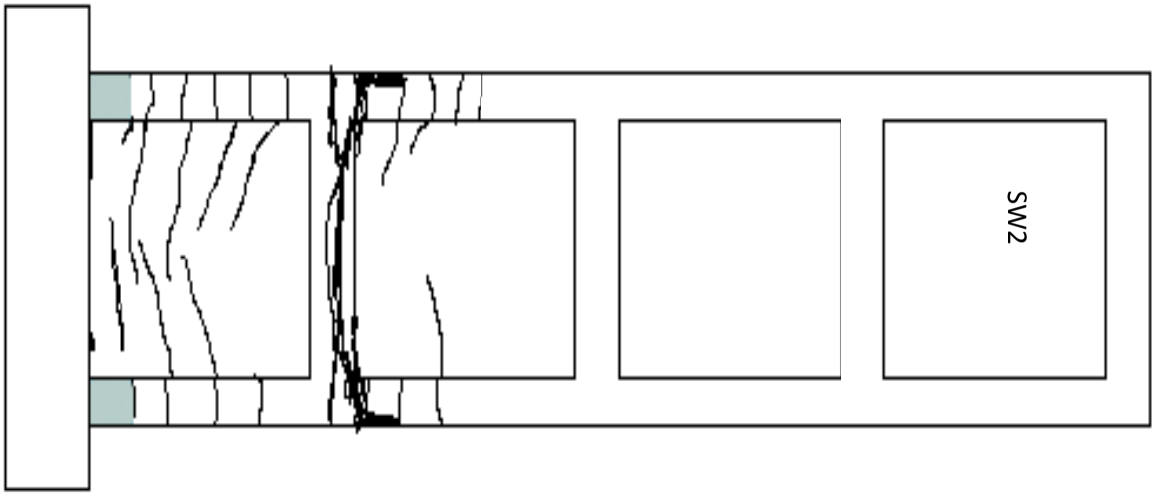
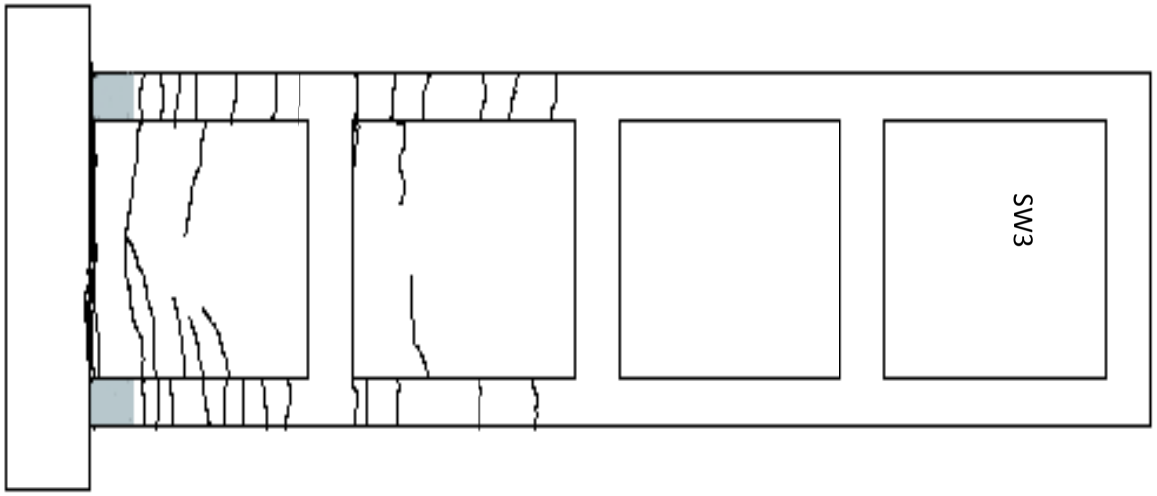
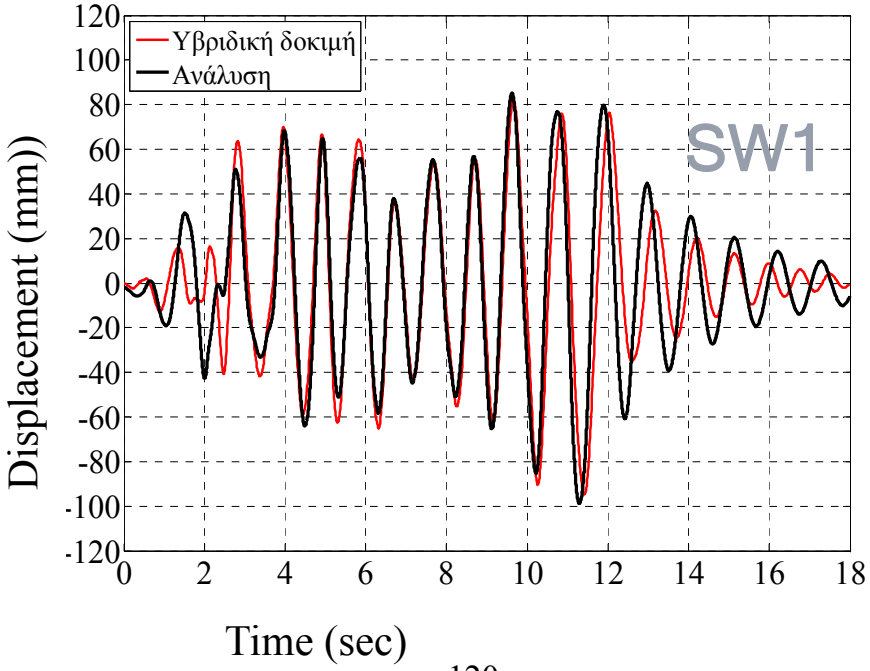
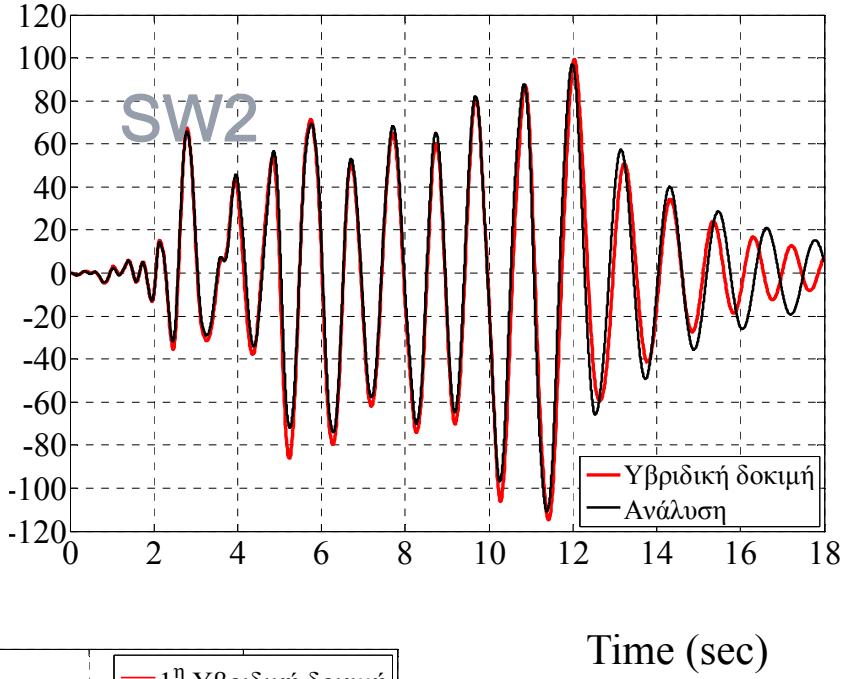

SW1

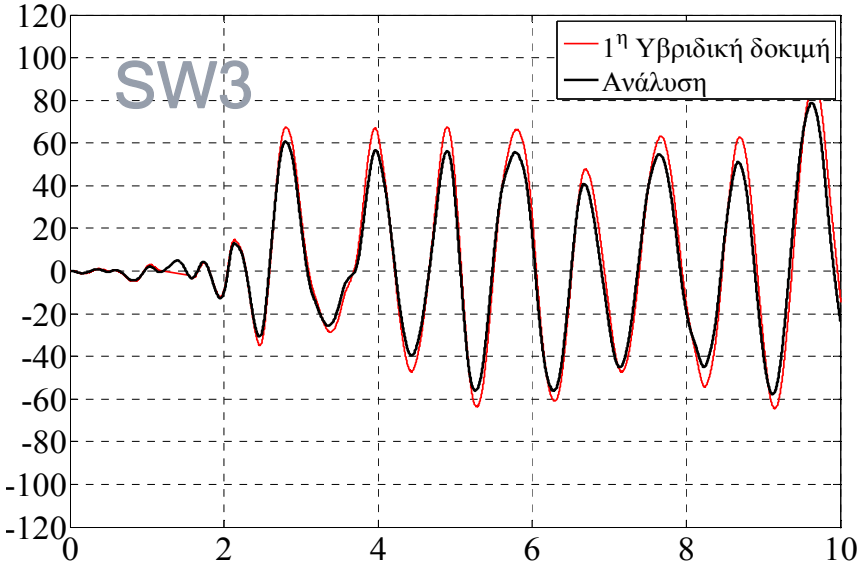

SW2


SW3

Nonlinear dynamic analyses via OpenSees







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Conclusions

- The presence of lap at the base is decisive
- Retrofitting lap-splicing → 2 layers of CFRP suffices
- Minor slippage at interface observed (higher for scheme B) → monolithic behavior under both schemes
- Dowels for web-frame connection in shear can successfully play also the role of starter bars for the web reinforcement, yielding a construction–wise feasible and economic solution
- EN1998–Part 3 provisions may be, judiciously, applied

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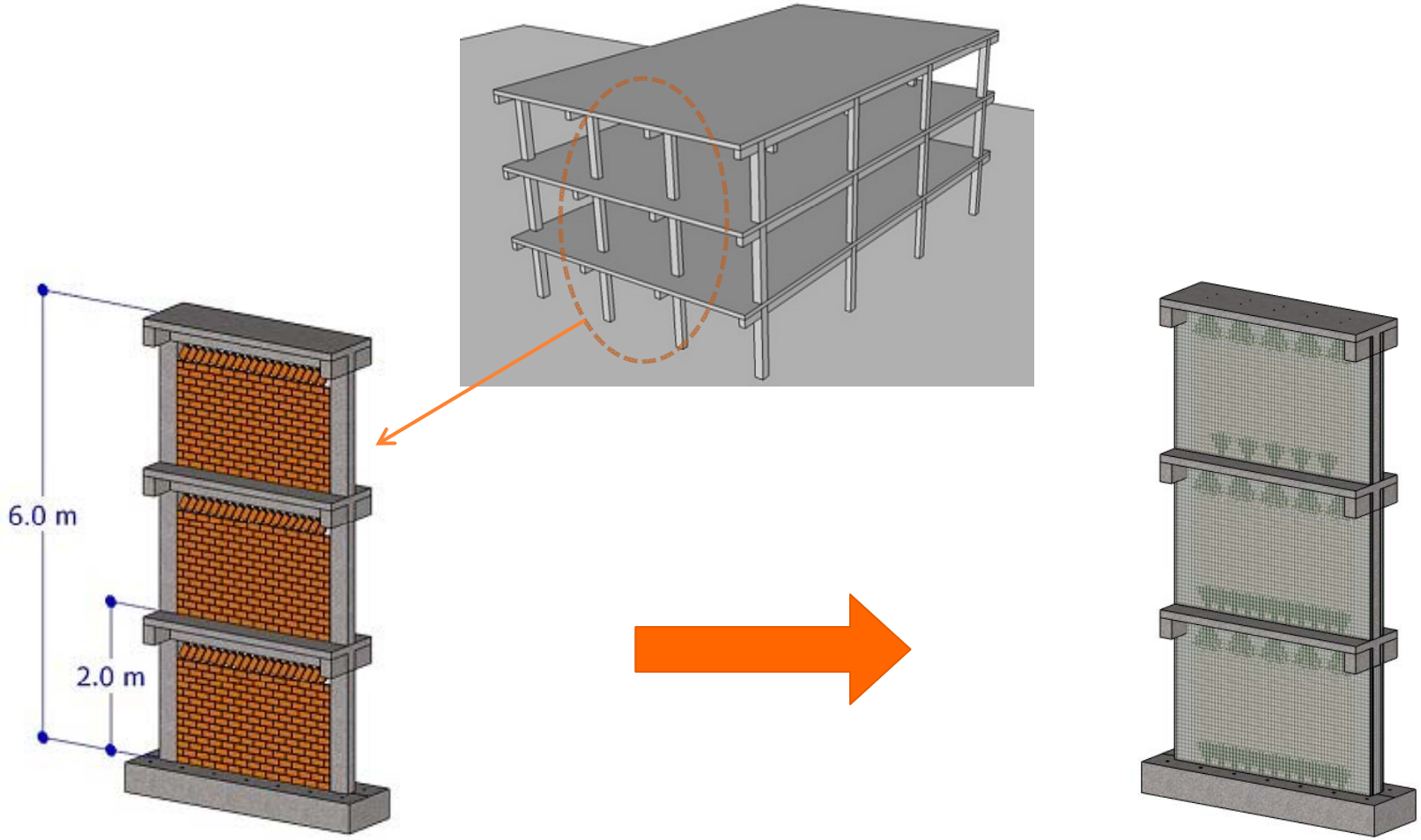
Retrofitting masonry-infilled RC structures



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Cyclic test

Excitation:

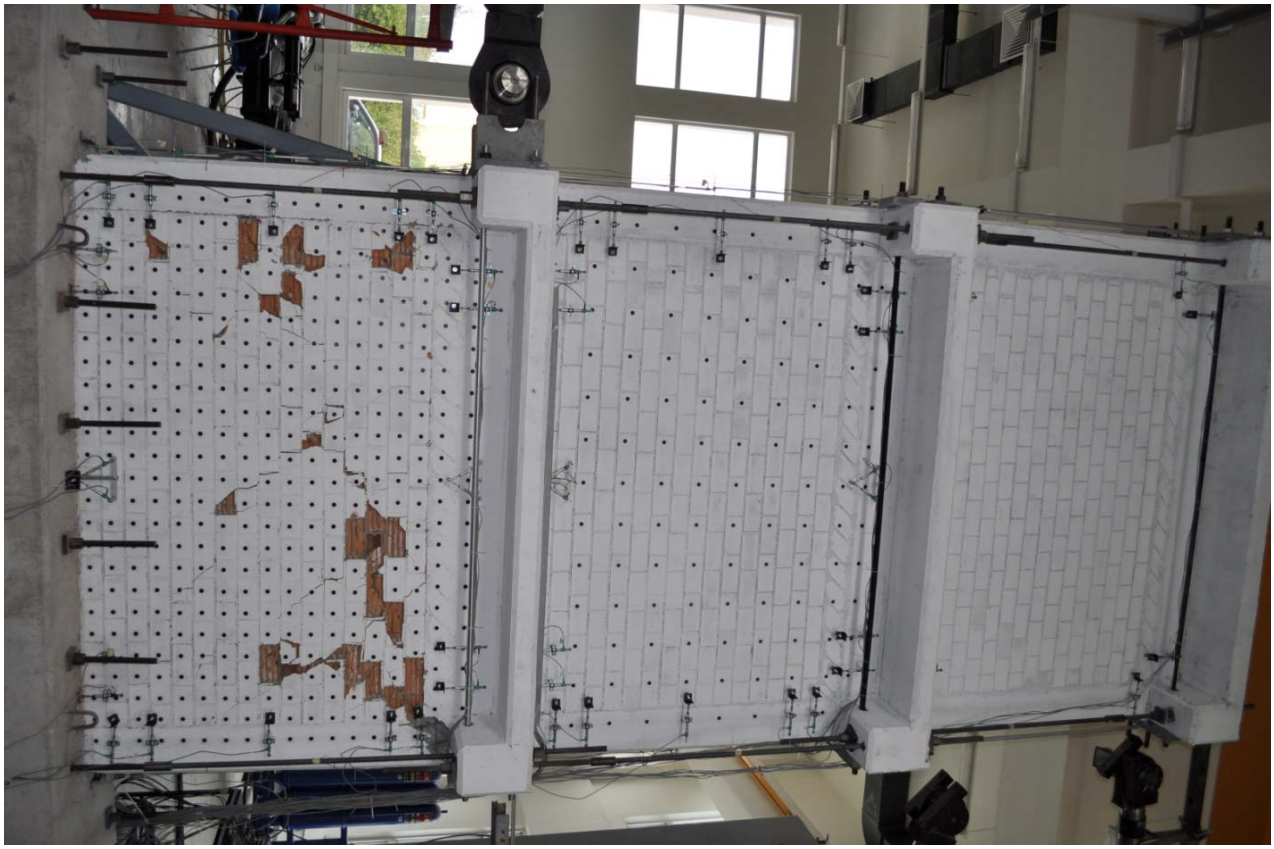
Triangular force distribution

Instrumentation:

72 Potensiometers
24 Strain gages
3 Heidenhain sensors

Telepresence:

11 net cameras
Synchronous data measurements

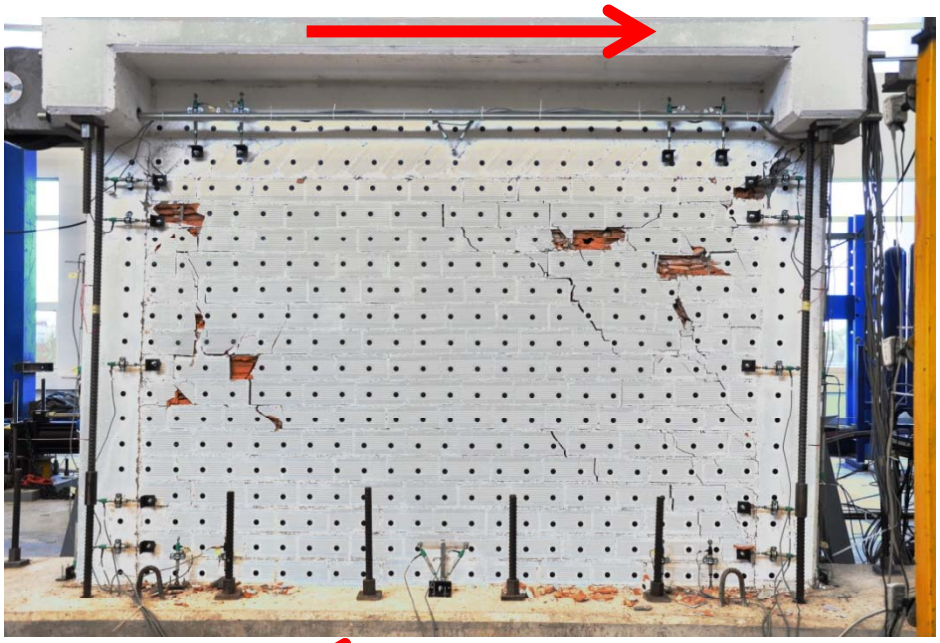


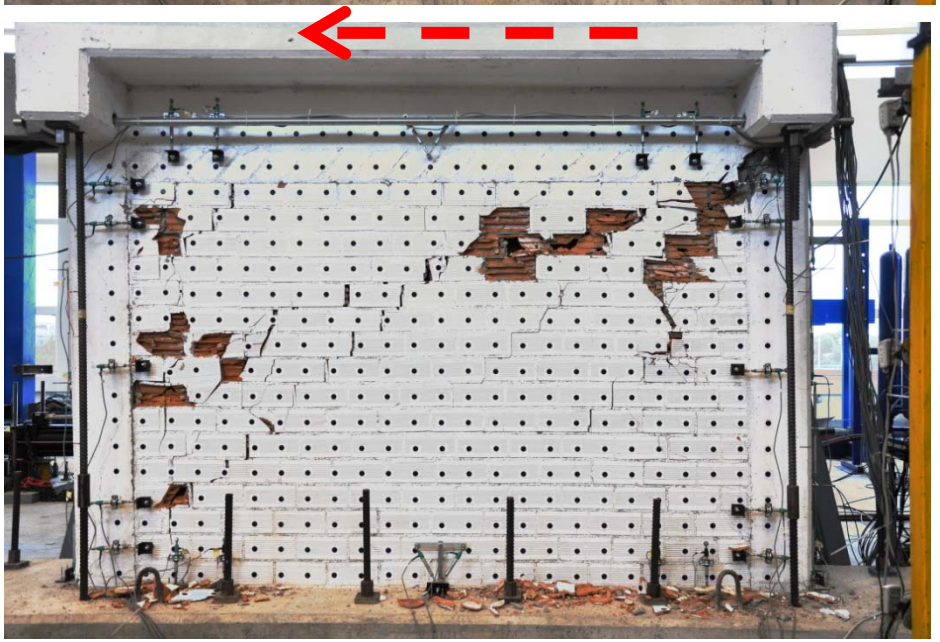
1st floor:

- Formation of diagonal struts in both directions
- Crushing of bricks
- Shear failure of the east column on the top (below the joint)

2nd floor – minor diagonal cracks

3rd floor – no damage





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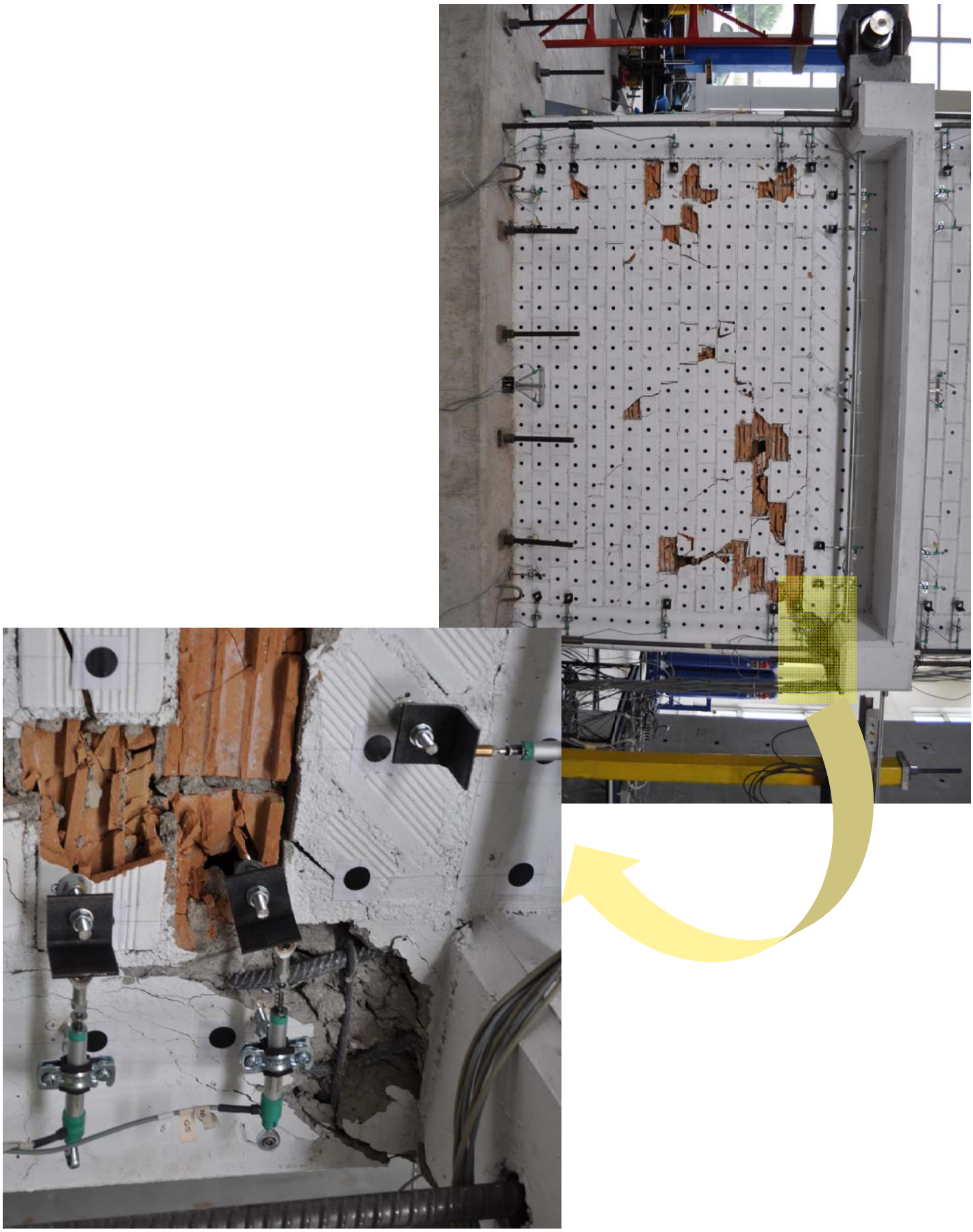
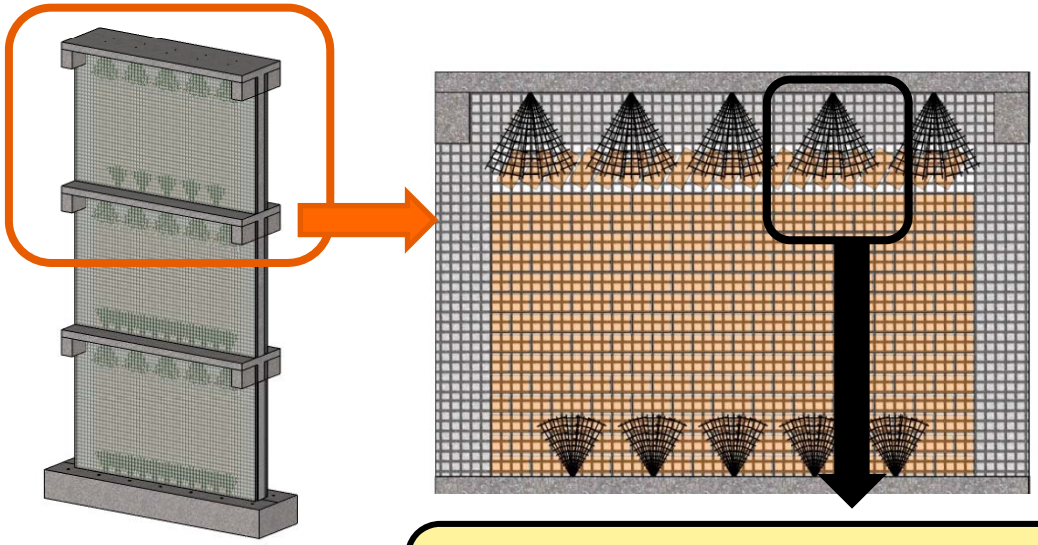
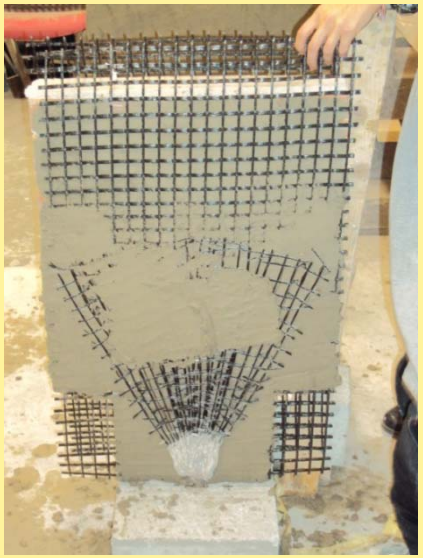


TRM-connection to frame



Glass or Carbon Fiber Textile in combination with Cementitious Mortar



Investigation of the effectiveness of the technique

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Activity

- Retrofitting RC columns
- Retrofitting RC & masonry infilled RC structures
- New technologies- New control Algorithms
- Hybrid testing – Isolation
- Geographically distributed testing

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New Control Algorithms

Issues to be resolved when testing very stiff structures:

- high level of forces for minimal displacement increments
- Ideally : tests under force control – problems with control (low P values)
- Problem : algorithms for hybrid simulation yield displacements
- First approach : ad–hoc system
  - External loop on displacements by MATLAB and with a sampling that is much slower (1 or 2 s),
  - The actuators use the force as feedback at the usual 2ms of the controller (continuous PsD)

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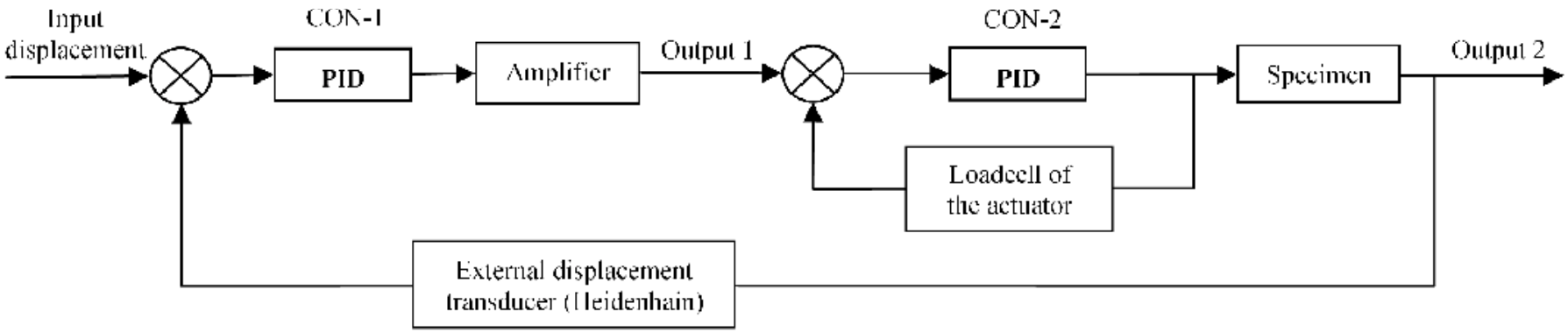
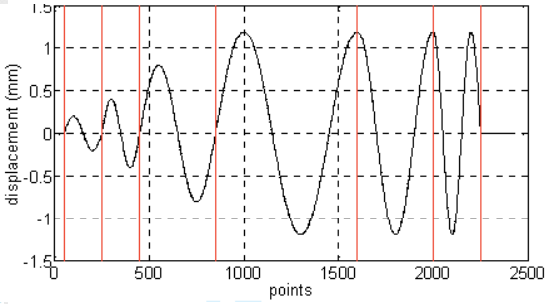
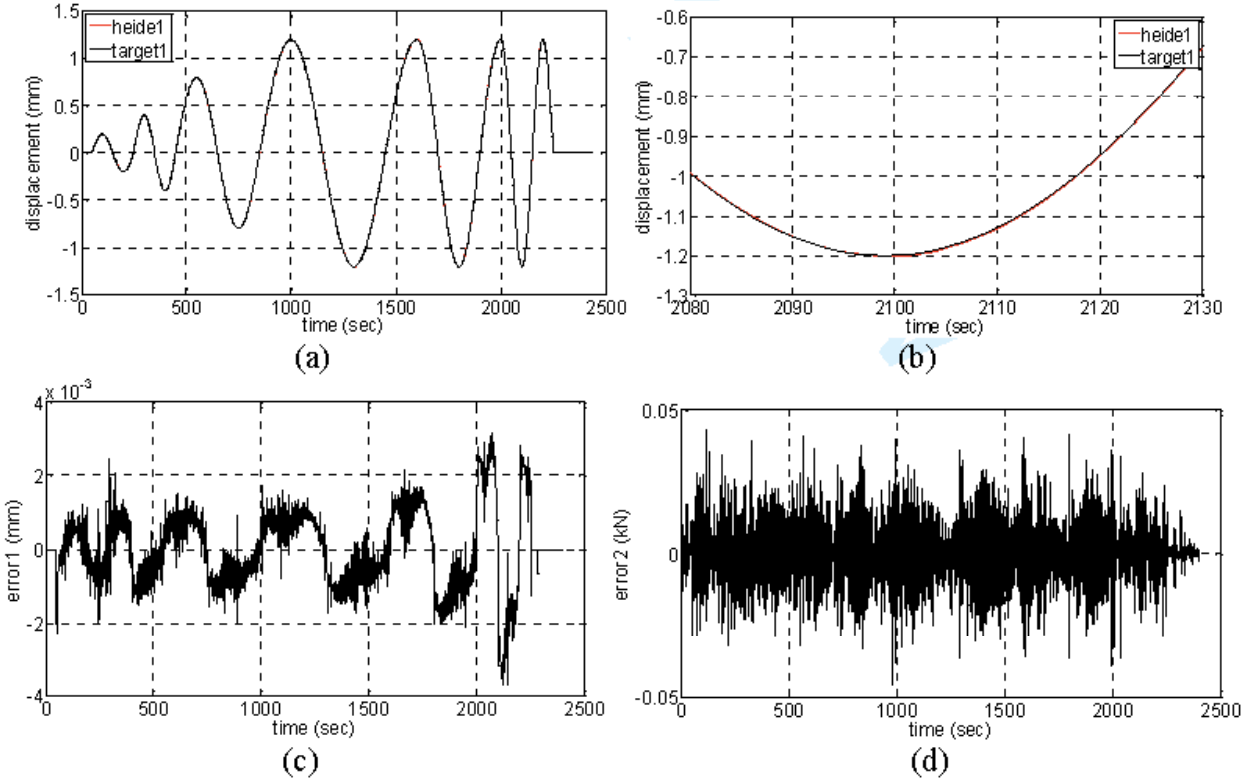
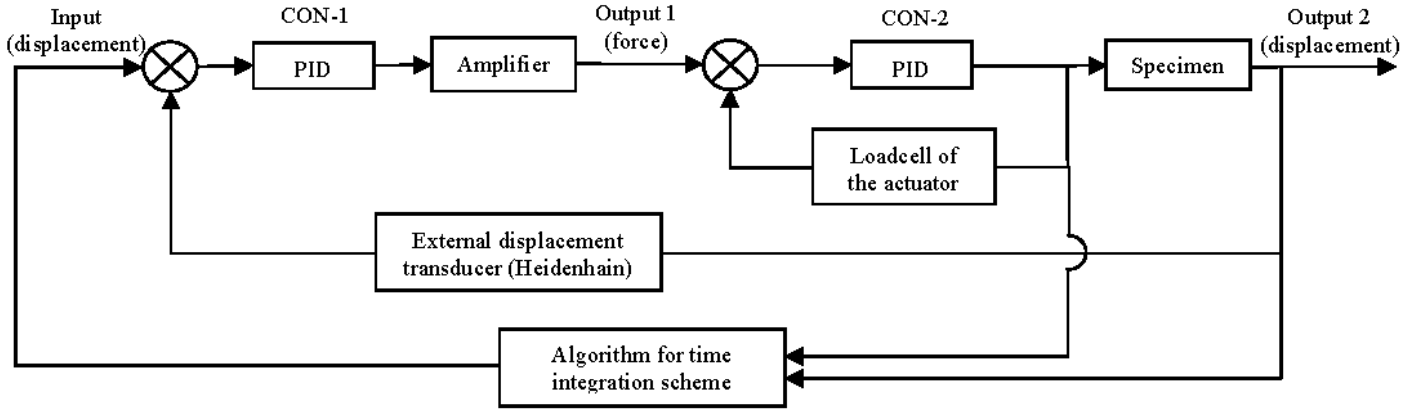
Dual Control Mode strategy

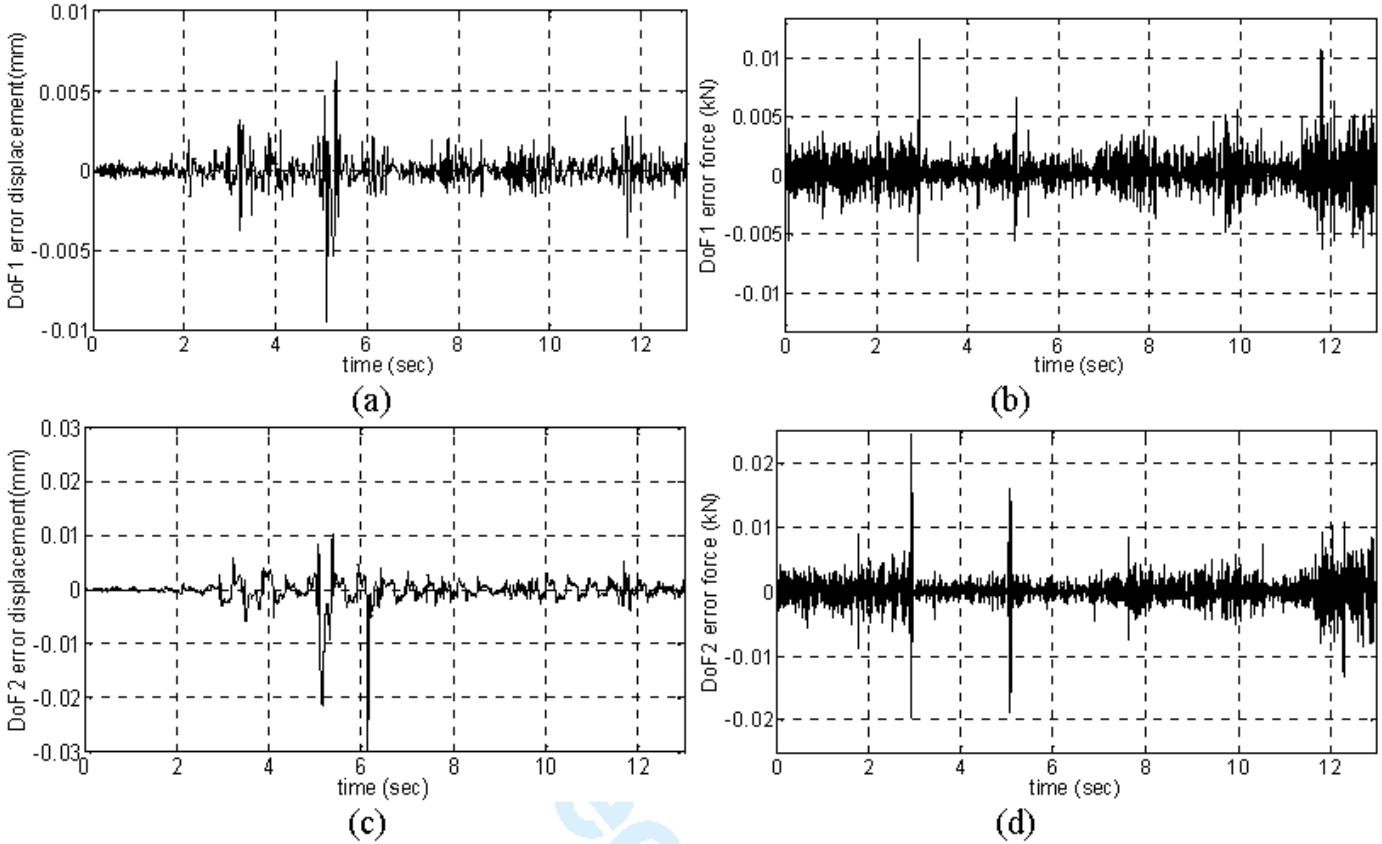






DCM applied for hybrid simulation





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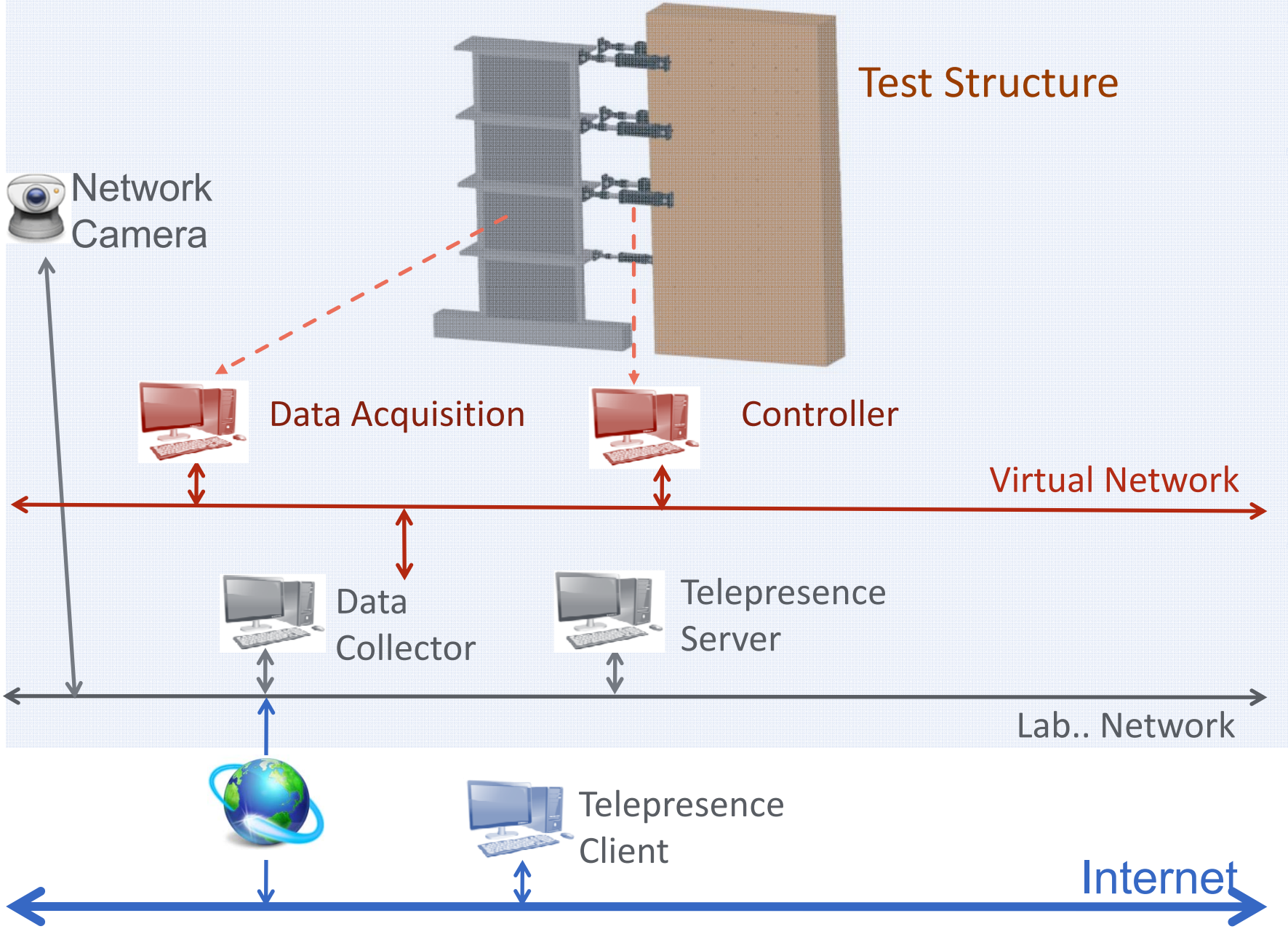
Tele-presence



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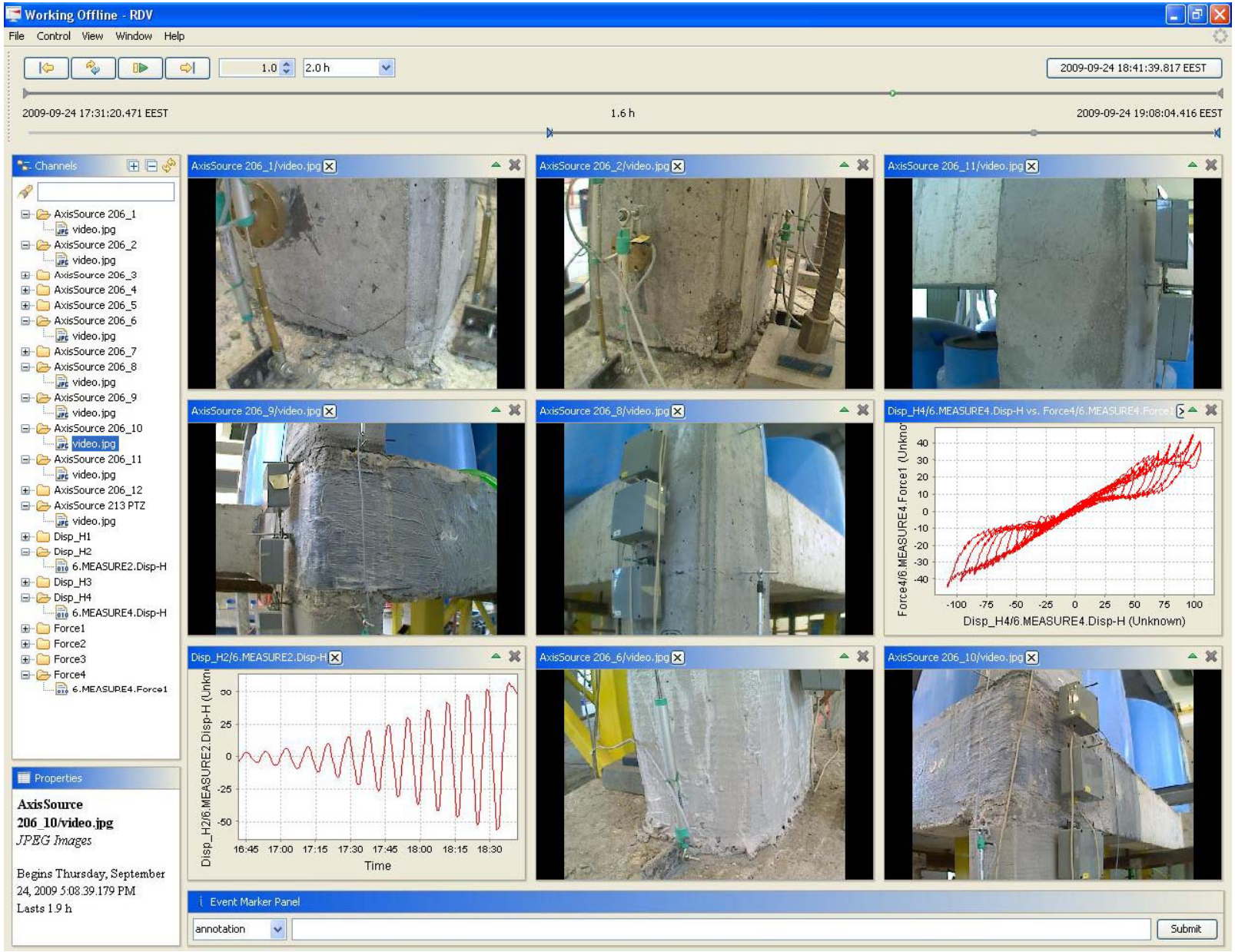
telepresenceserver.civil.upatras.gr:3333



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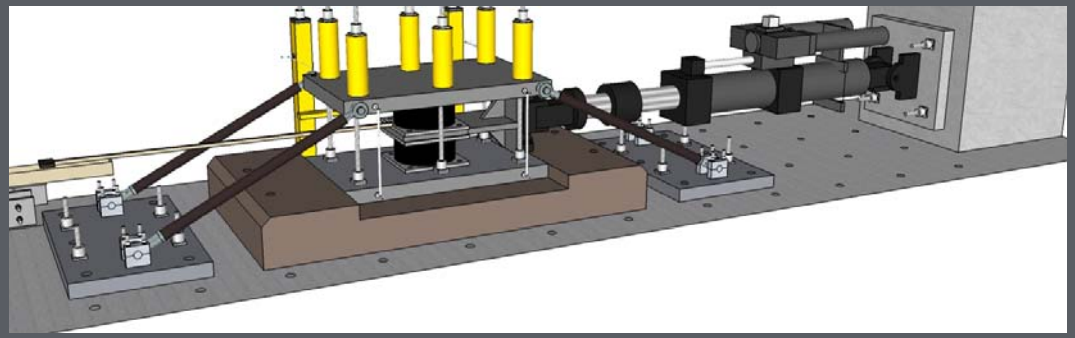
CIVIL ENGINEERING DEPT UNIVERSITY OF PATRAS

Activity

- Retrofitting RC columns
- Retrofitting RC & masonry infilled RC structures
- New control Algorithms
- Hybrid testing – Isolation devices
- Geographically distributed testing



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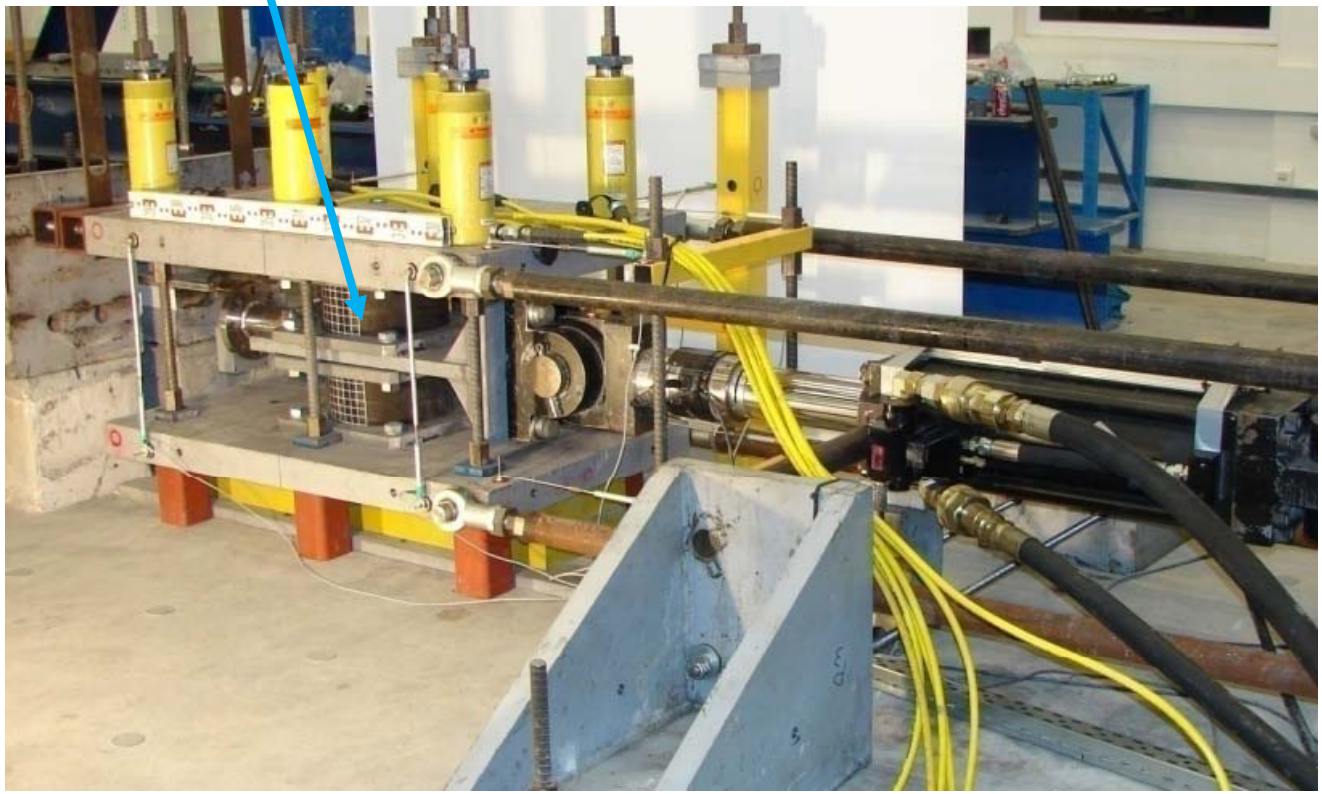
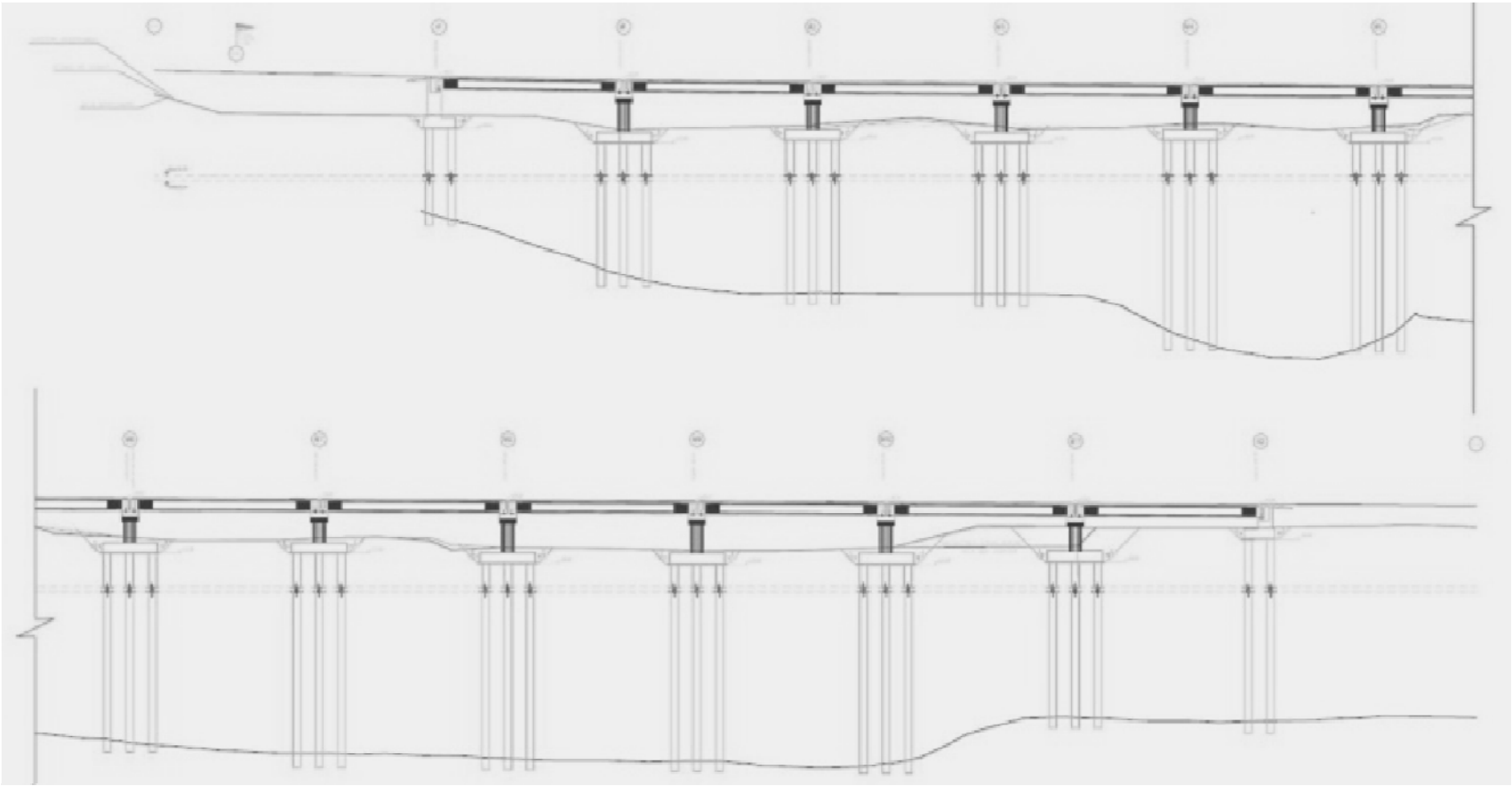


- Rubber Bearings
- Lead Rubber Bearings
- RB + Damper

Bridge structure

- 12-span highway bridge, 38m spans
- 5 PC – PS girders per span, supported on ERBs



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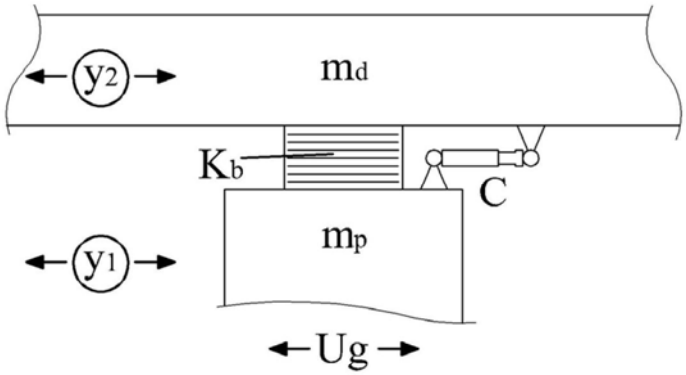
Simplified model



Plain EBRs: D=350mm,
77mm (rubber), 36mm (steel)

Model Parameter	Per 10 bearings (prototype)	Per pair of bearings (numerical model)
Pier stiffness (longitudinal) K_{xx}	2200 MN/m	440 MN/m
Pier stiffness (transverse) K_{yy}	13600 MN/m	2720 MN/m
Deck mass	917000 kg	183400 kg
Pier mass	430300 kg	58200 kg (effective)

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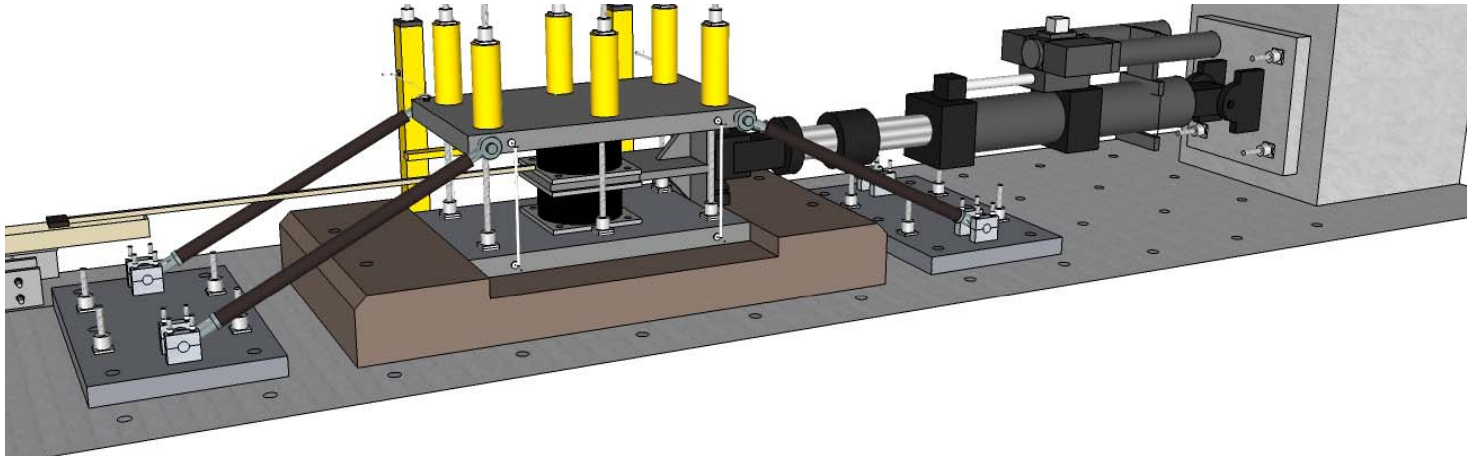
Test setup



Testing procedure

- Continuous PsD approach: time scale factor

$$\lambda = \frac{laboratory\ time}{prototype\ time} = \frac{N \cdot \Delta t}{\Delta T}$$

- Smooth command & filtering
- Tests run at different λ factors ("speeds")
- Strain rate compensation (correction) force

$$F_{SRAdd} = F_0 \cdot F_{meas} + D_0 \cdot u_{meas} + F_1 \cdot \dot{F}_{meas} + D_1 \cdot u_{meas}$$

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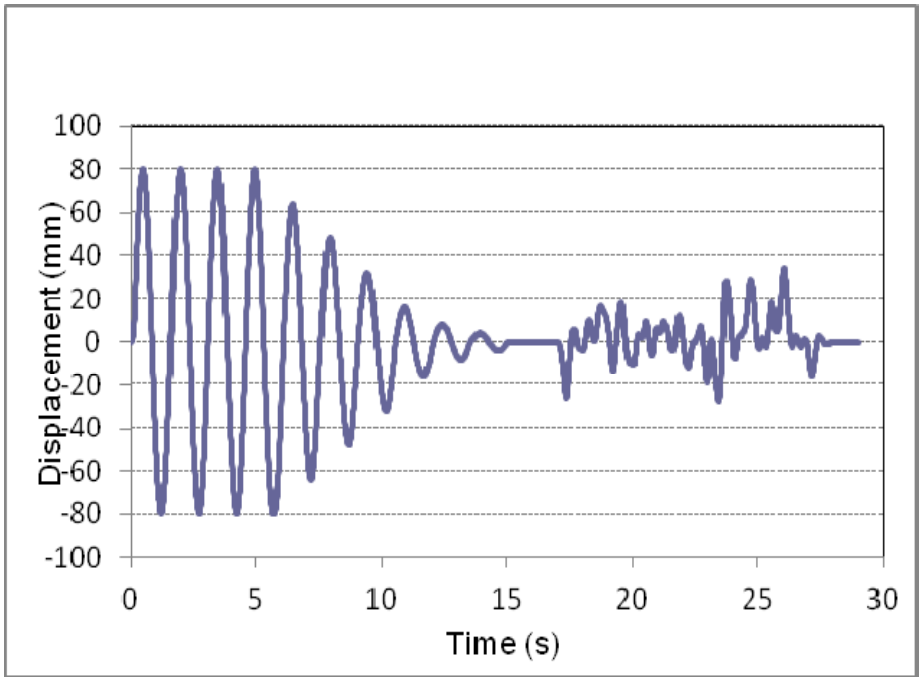
Characterization testing



Characterization test series				
Correction Parameter	**λ = 10 (4 param.)**	**λ = 10 (2 param.)**	**λ = 10 (1 param.)**	**λ = 100 (4 param.)**
F_0	0.2003	0.1368	0.0852	0.2757
F_1	-0.0022	N/A	N/A	-0.0019
D_0	-0.3483	-0.1573	N/A	-0.3692
D_1	-0.0023	N/A	N/A	-0.0013

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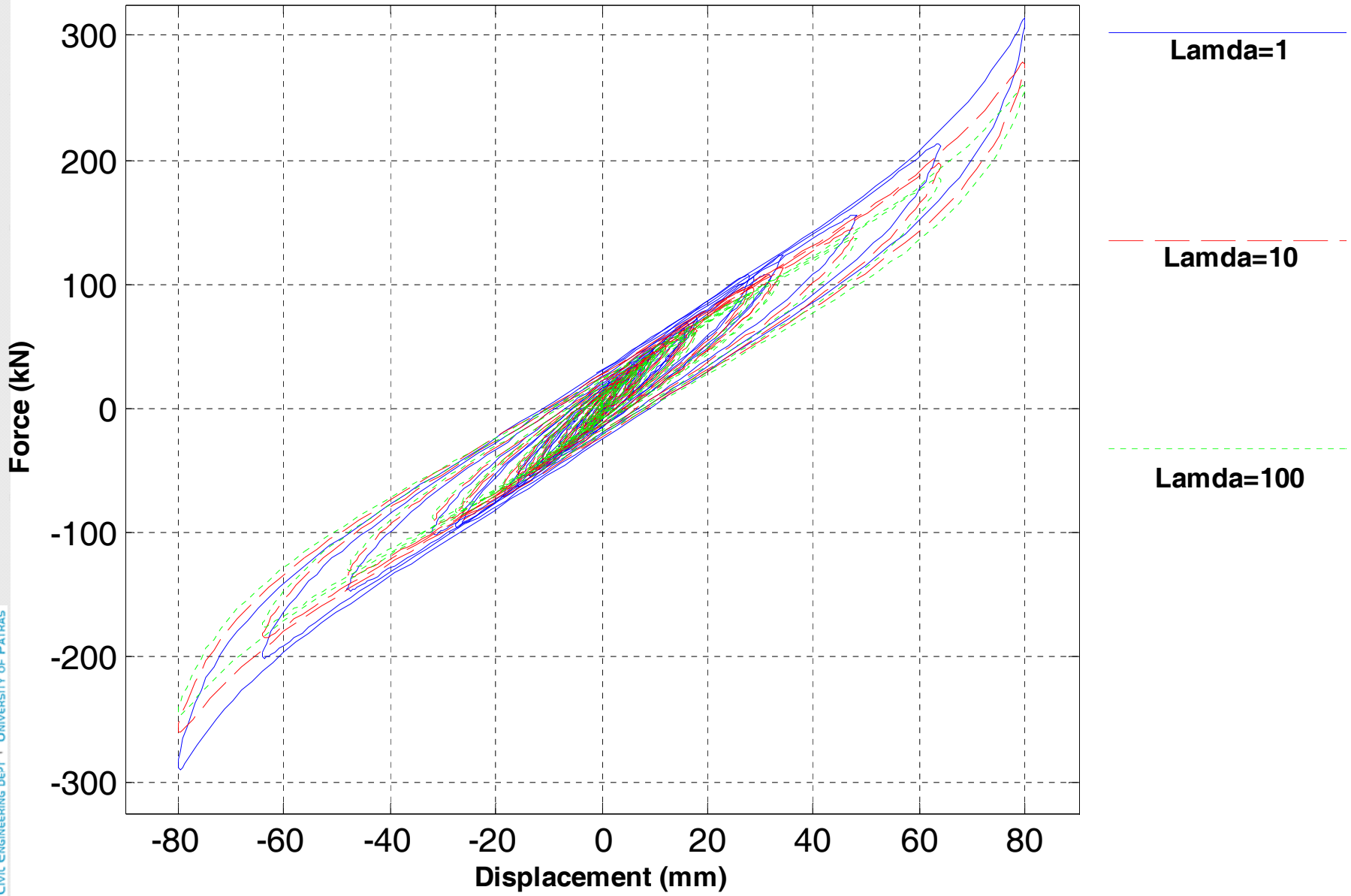

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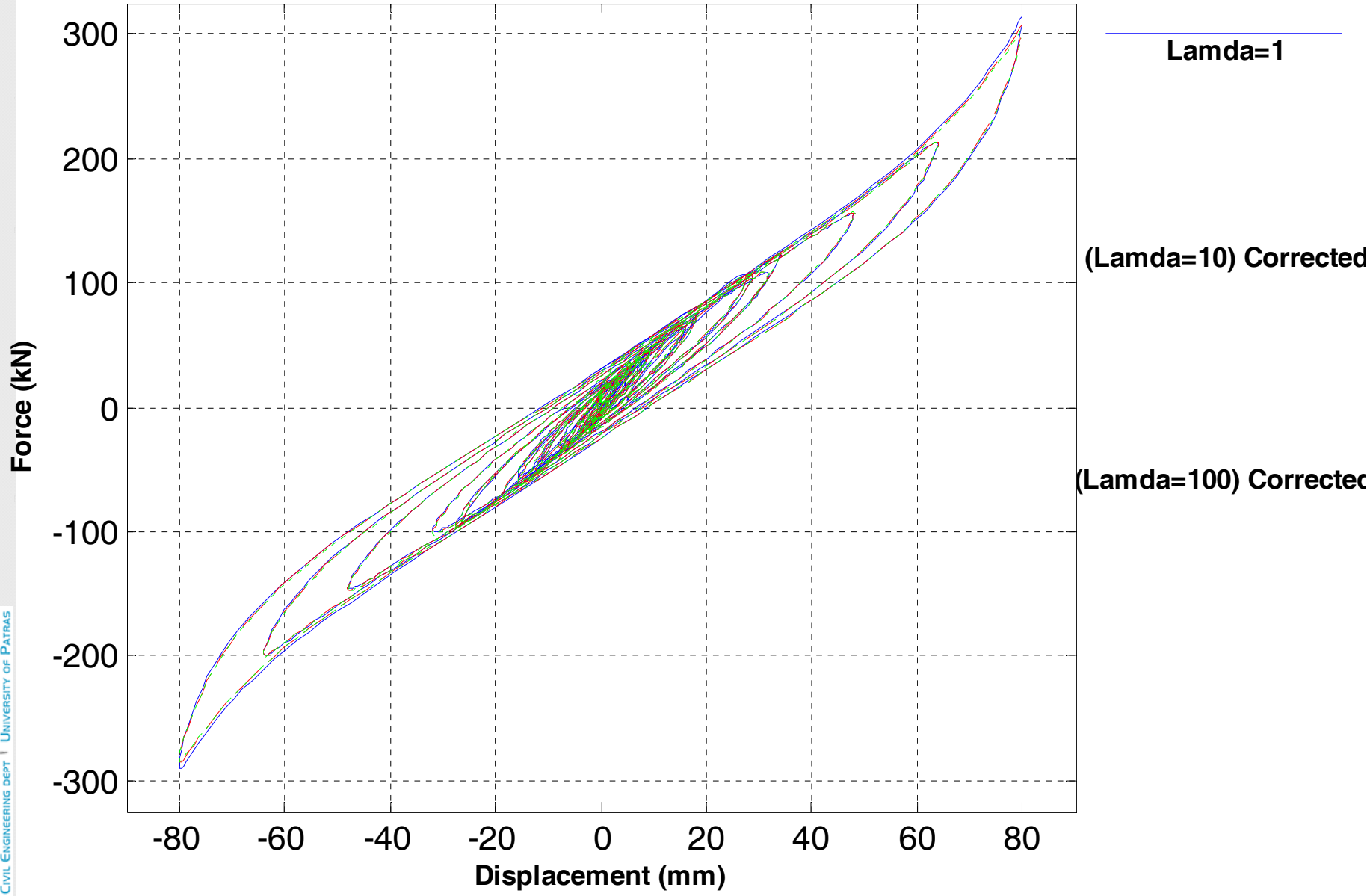

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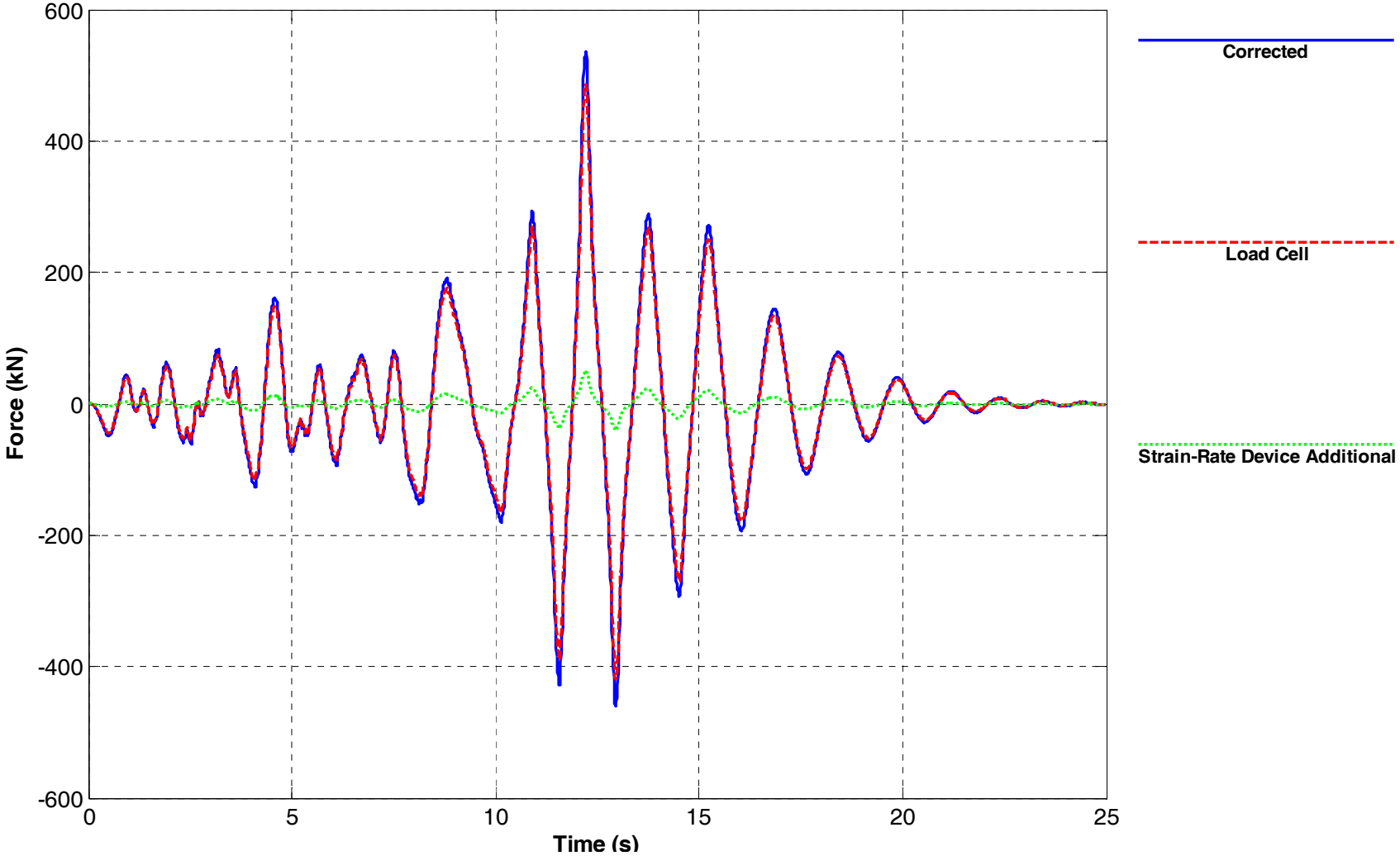
Test PD10 (λ=10)



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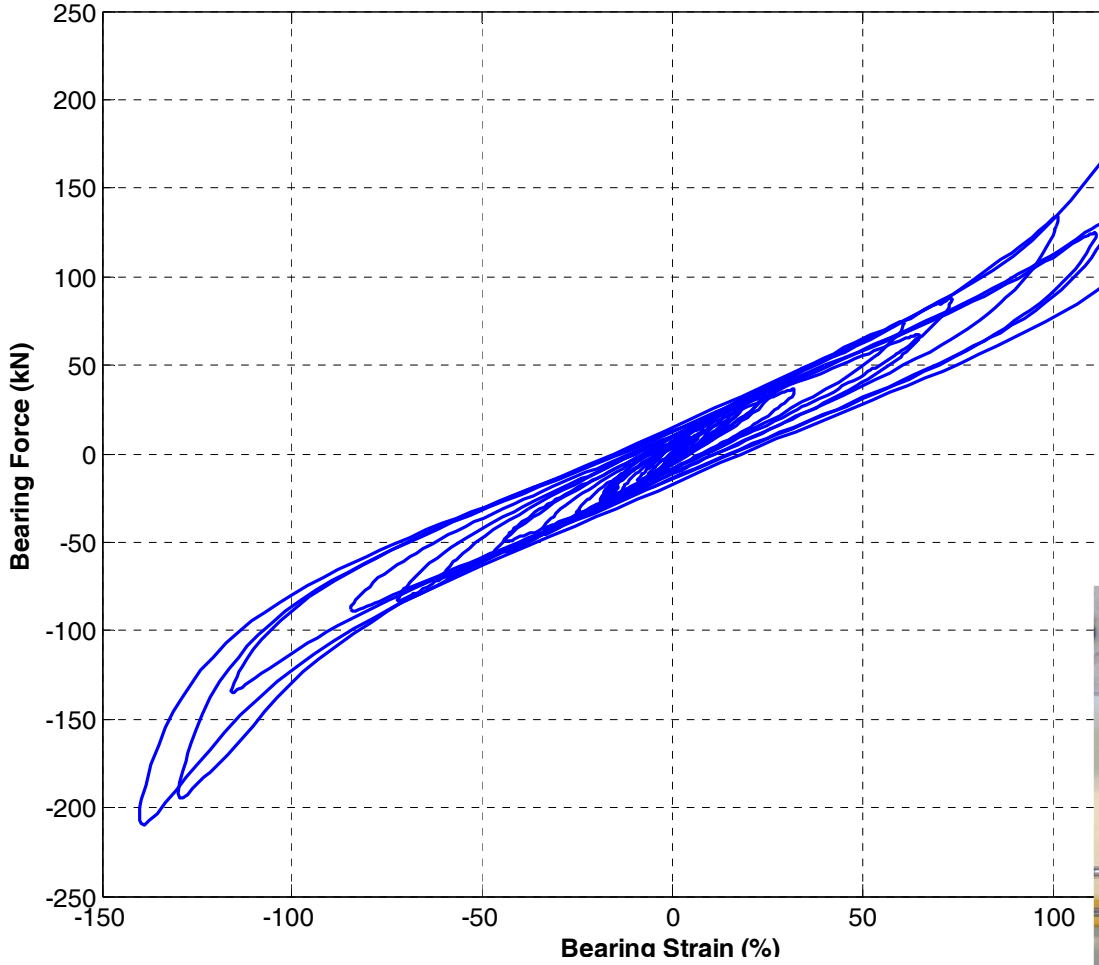

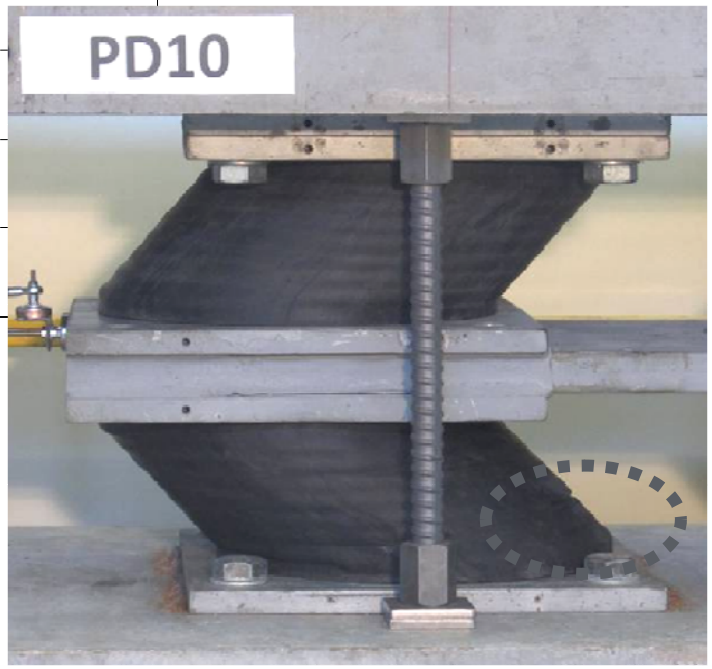

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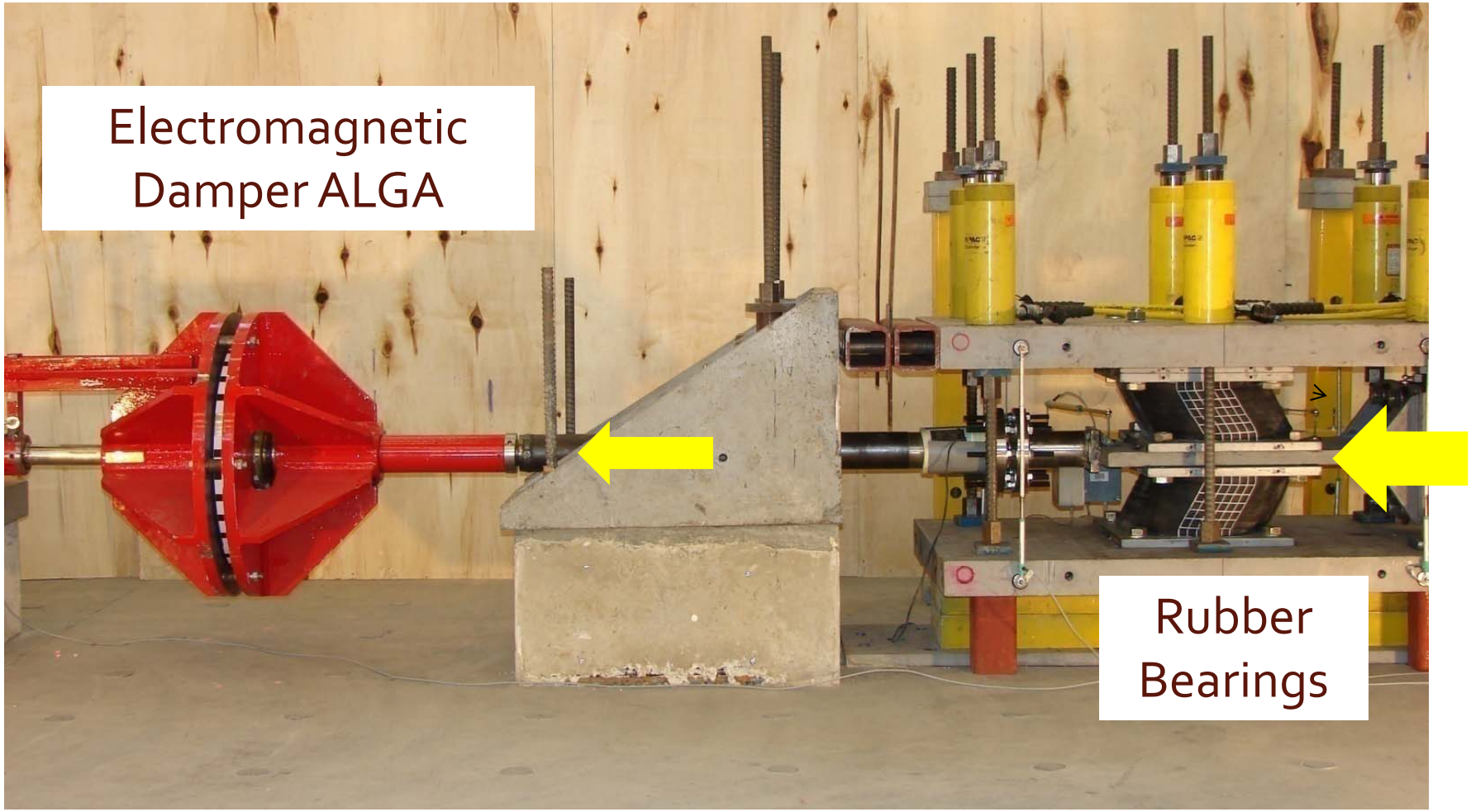
Isolator & Additional Damping

- Different compensation to the force on rubber bearing and to that of the damper



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Activity

- Retrofitting RC columns
- Retrofitting RC & masonry infilled RC structures
- New control Algorithms
- Hybrid testing – Isolation devices
- Geographically distributed testing

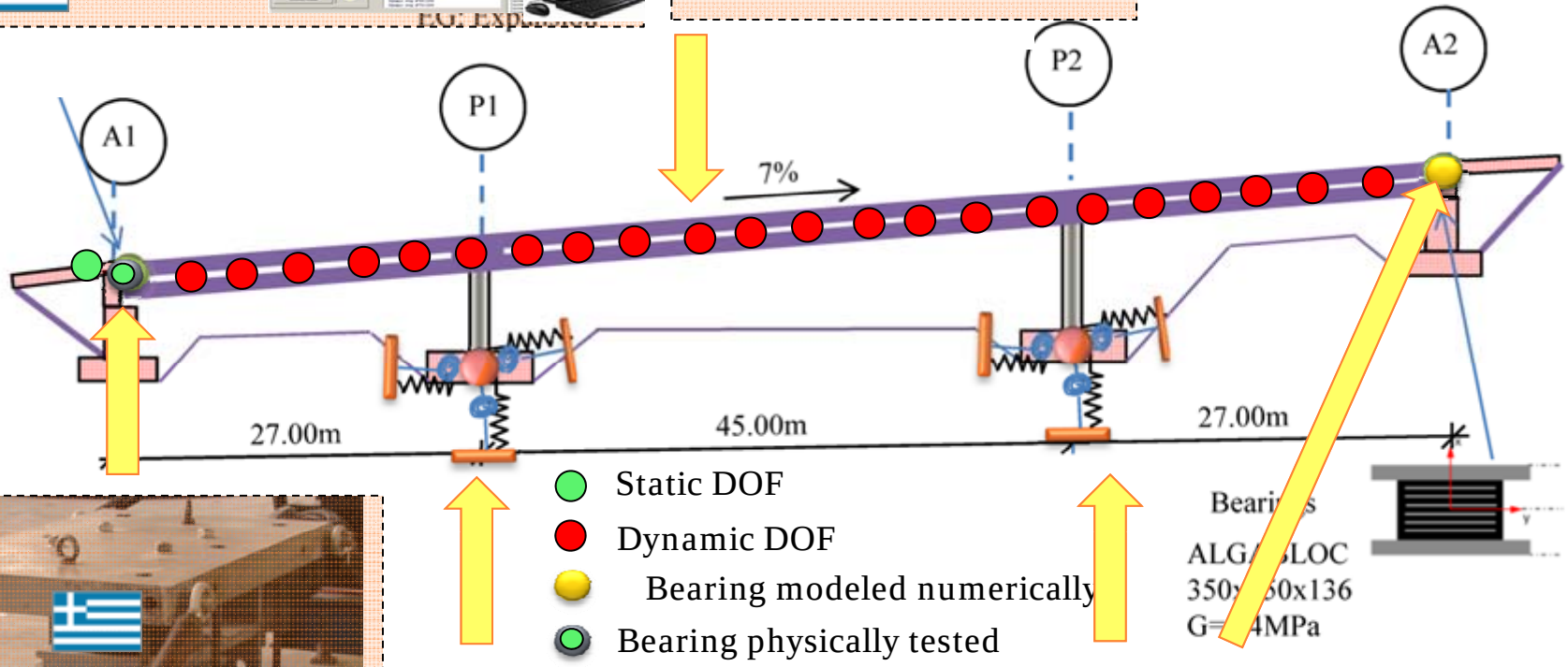
Distributed Testing

- Exchange–SSI (Marie–Curie) project
- U.Illinois, U.Toronto, U.Thessaloniki, U.Naples
- SSI problems
- Sub-structuring via UI-SIMCOR (on TCP-IP protocol)

Analysis Coordination. UI-SimCor (AUTH)

Modu

Deck Opensees (AUTH)



Module 2 / Experimental Component: Left Bearing (University Patras)

Modu

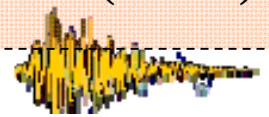
Left Pier Opensees (AUTH)

Modu

Right Pier Opensees (AUTH)

Modu

Right Bearing Opensees (AUTH)



EL CENTRO RECORD x 2.0

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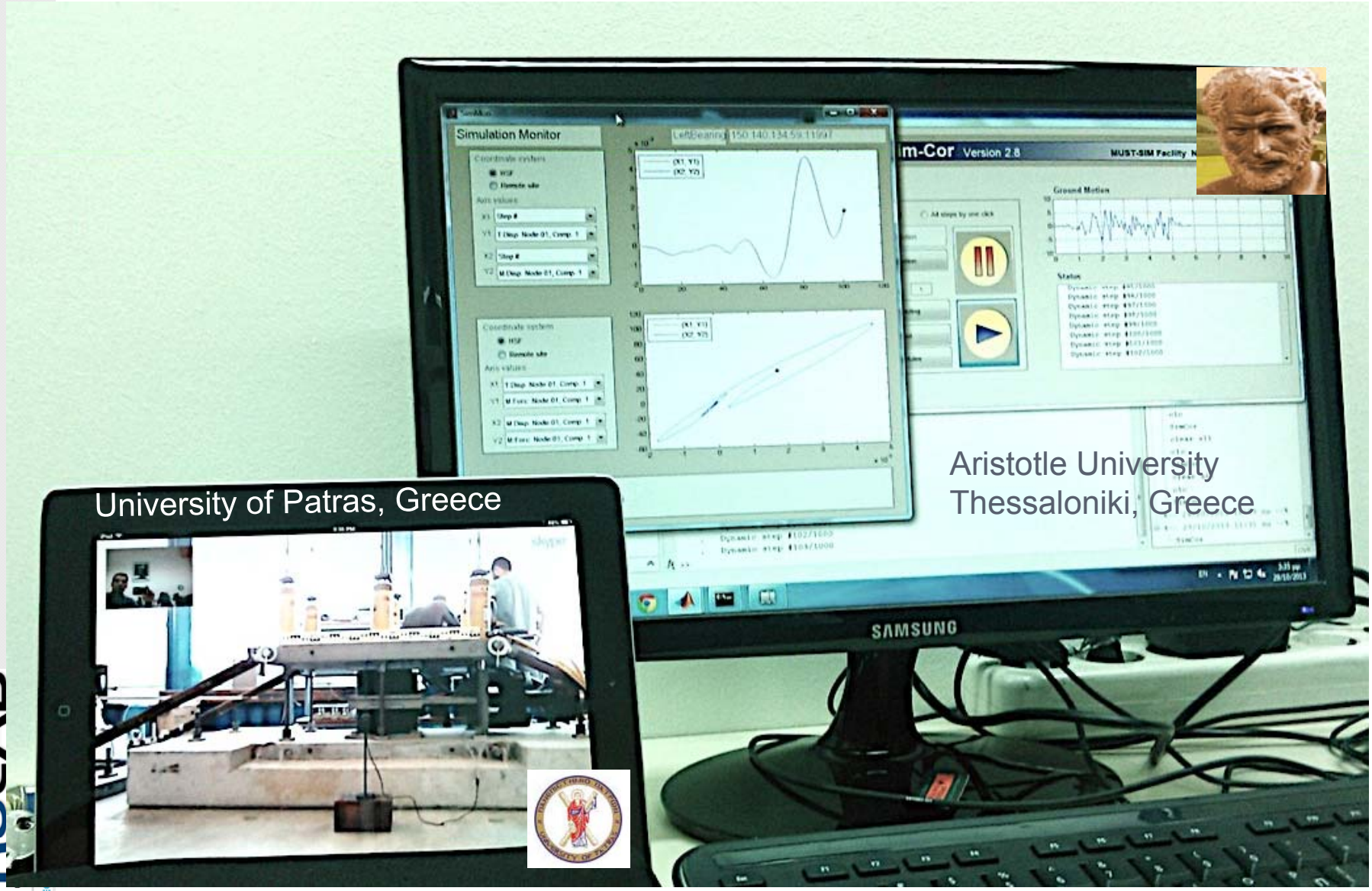

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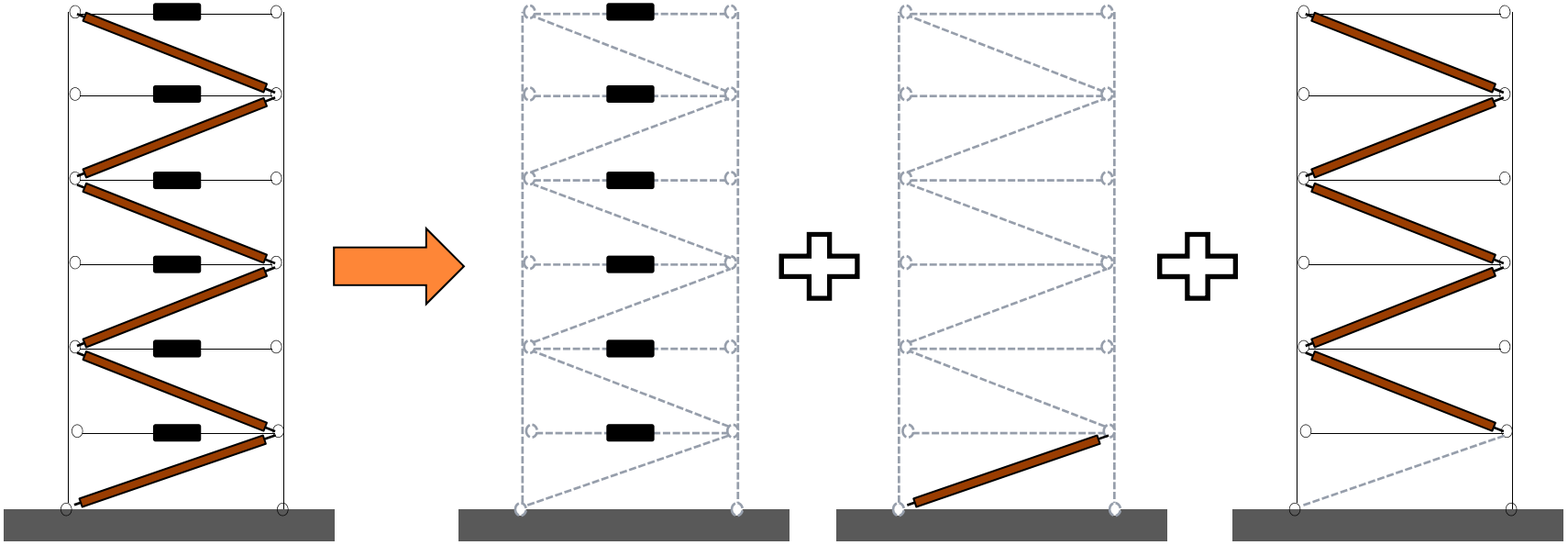
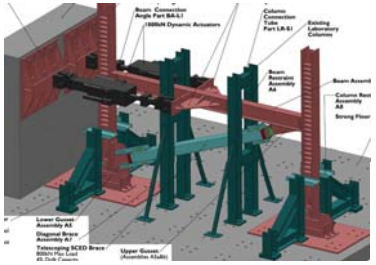
structures
Civil Engineering

Hybrid Simulation Configuration





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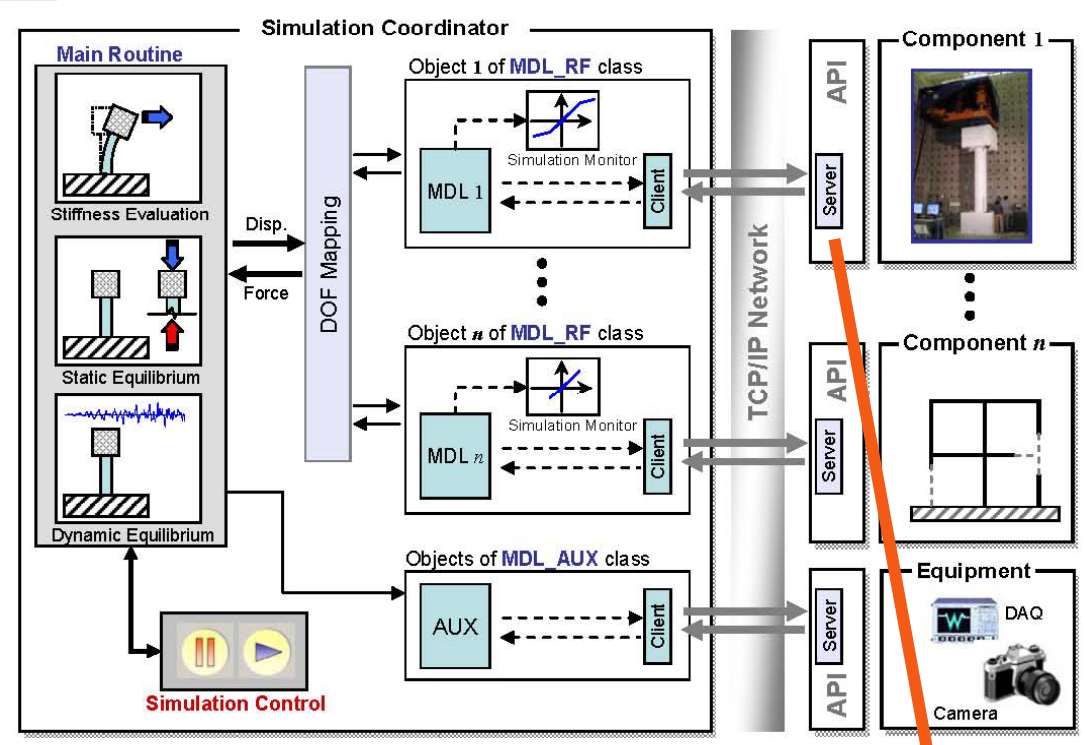
Scheme A for distributed testing



- Local
- Remote

SimCor

MatlabAPI

- Receive/send displ

- RemoteControl
- .NET Framework
- Controller

Lab

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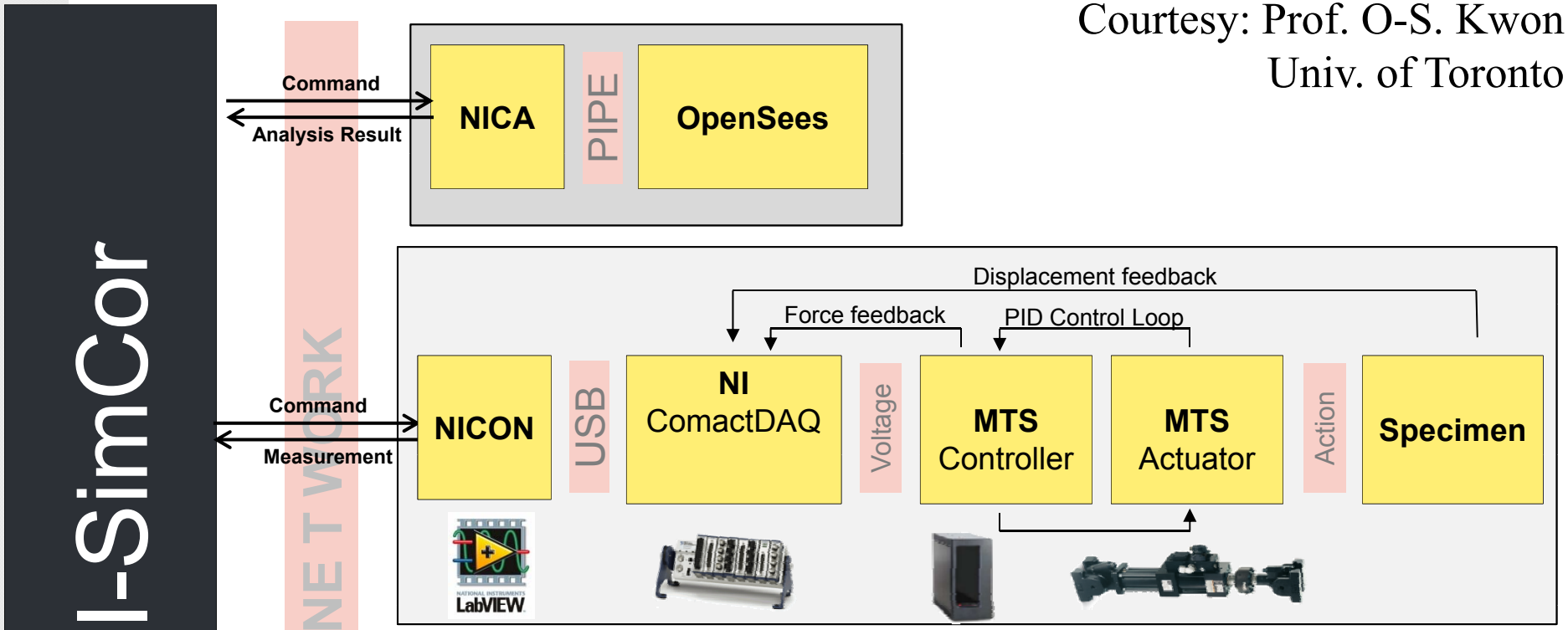
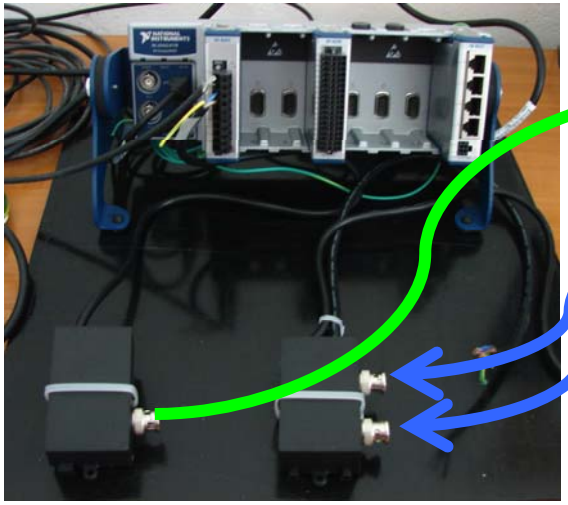
Scheme B for distributed testing

Courtesy: Prof. O-S. Kwon
Univ. of Toronto

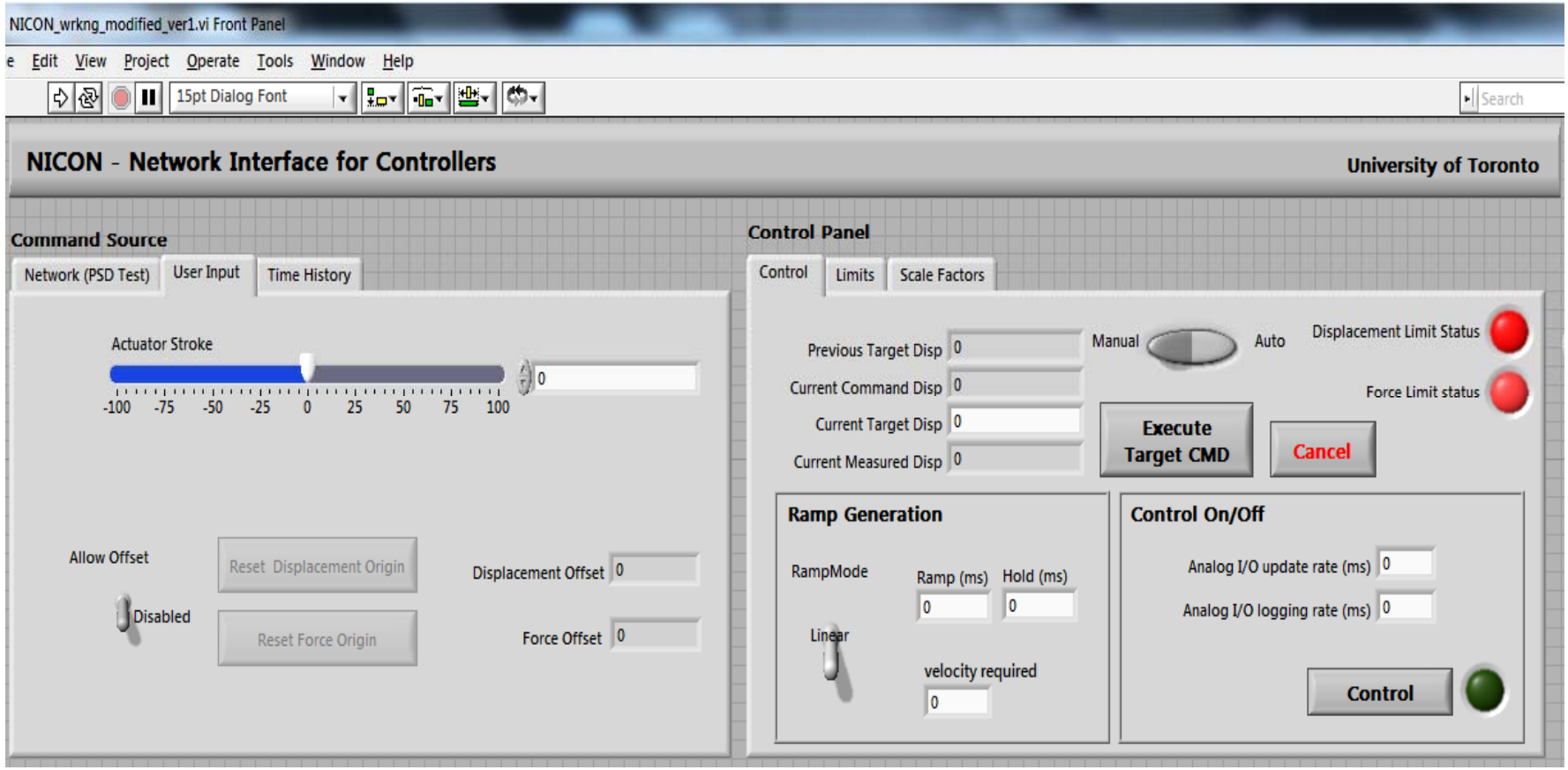




Analog target disp to actuator

Analog measured force – disp from actuator

- NICON: Network Interface for Controllers
  - Network interface application for generic controllers
  - Communication through voltage command signal



Courtesy: Prof. O-S. Kwon

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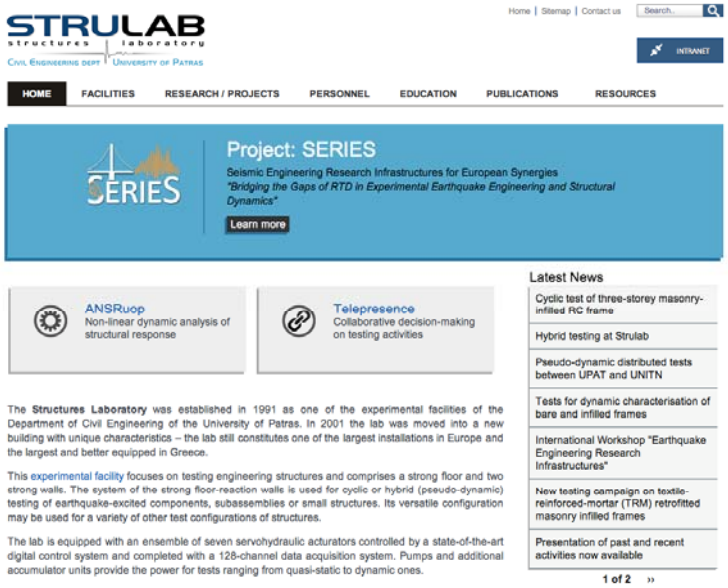

More on Structures Lab:

strulab.civil.upatras.gr

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