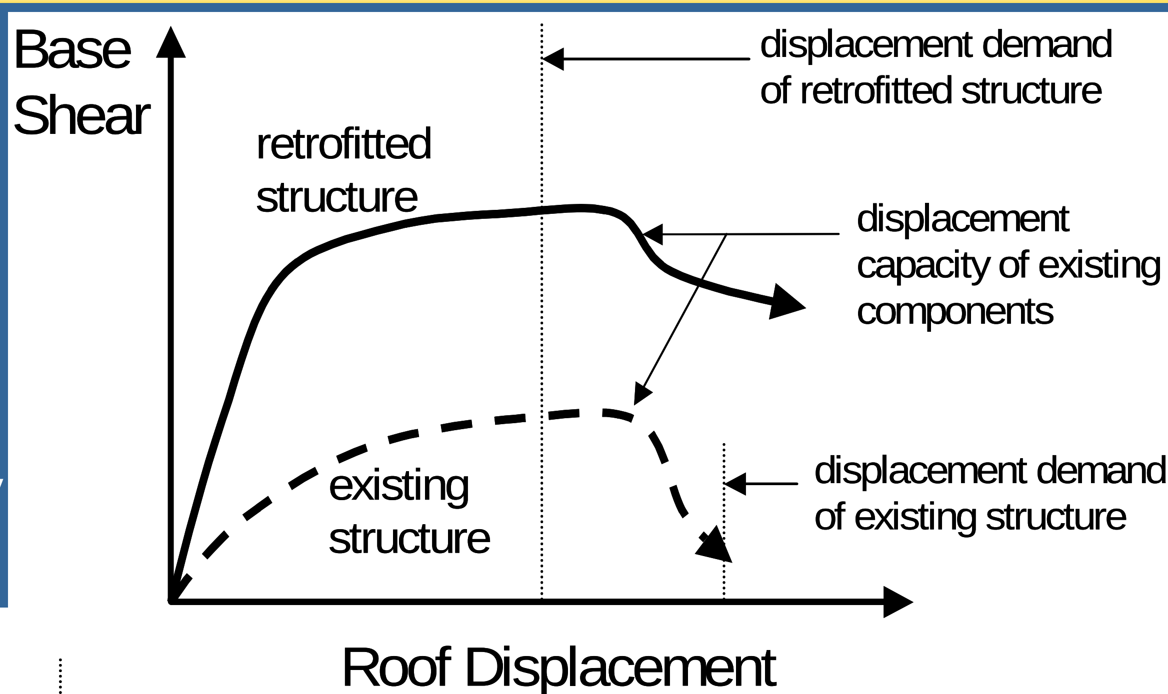
SERIES workshop
Role of research infrastructures in seismic rehabilitation
Istanbul, 8-9 February 2012

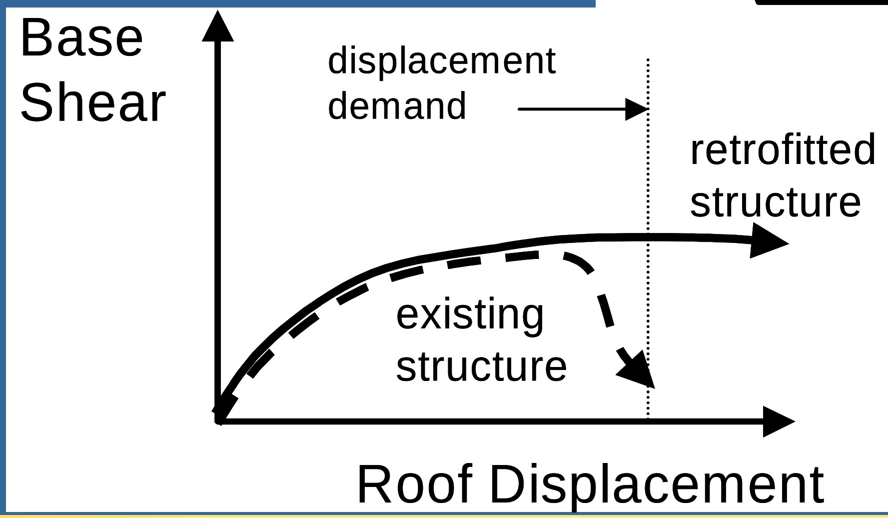
Seismic Rehabilitation of Concrete Buildings by Converting Frame Bays into RC Walls

Michael N. Fardis, Antonis Schetakis, Elias Strepelias
University of Patras, Greece

Strategies for seismic retrofit



Increase member deformation capacity (eg, w/FRPs)



Increase building global stiffness to reduce member deformation demand

Addition of new concrete walls

- Most effective for the reduction of deformation demands in the rest of the structure & avoidance of member strengthening.
- Often by filling bay of existing frame, encapsulating its beams & columns.
- “Collector elements” may need to be provided for the transfer of inertia forces from floors to the new wall.

Added walls

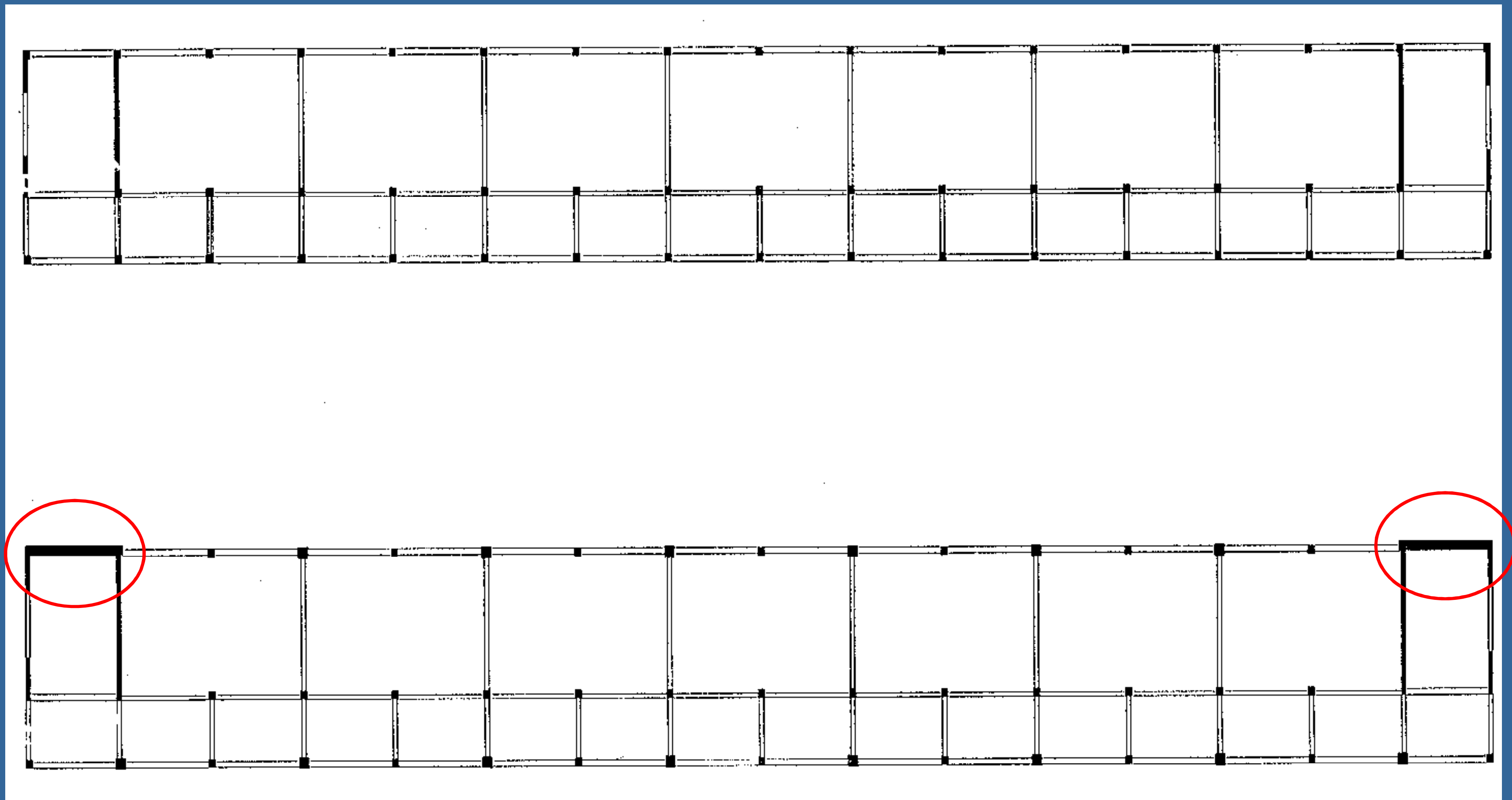
Most serious problem of added walls: Foundation
(transfer of large M with low N, w/o large uplift & base rotation that may weaken the role of the wall)

Possible solutions:

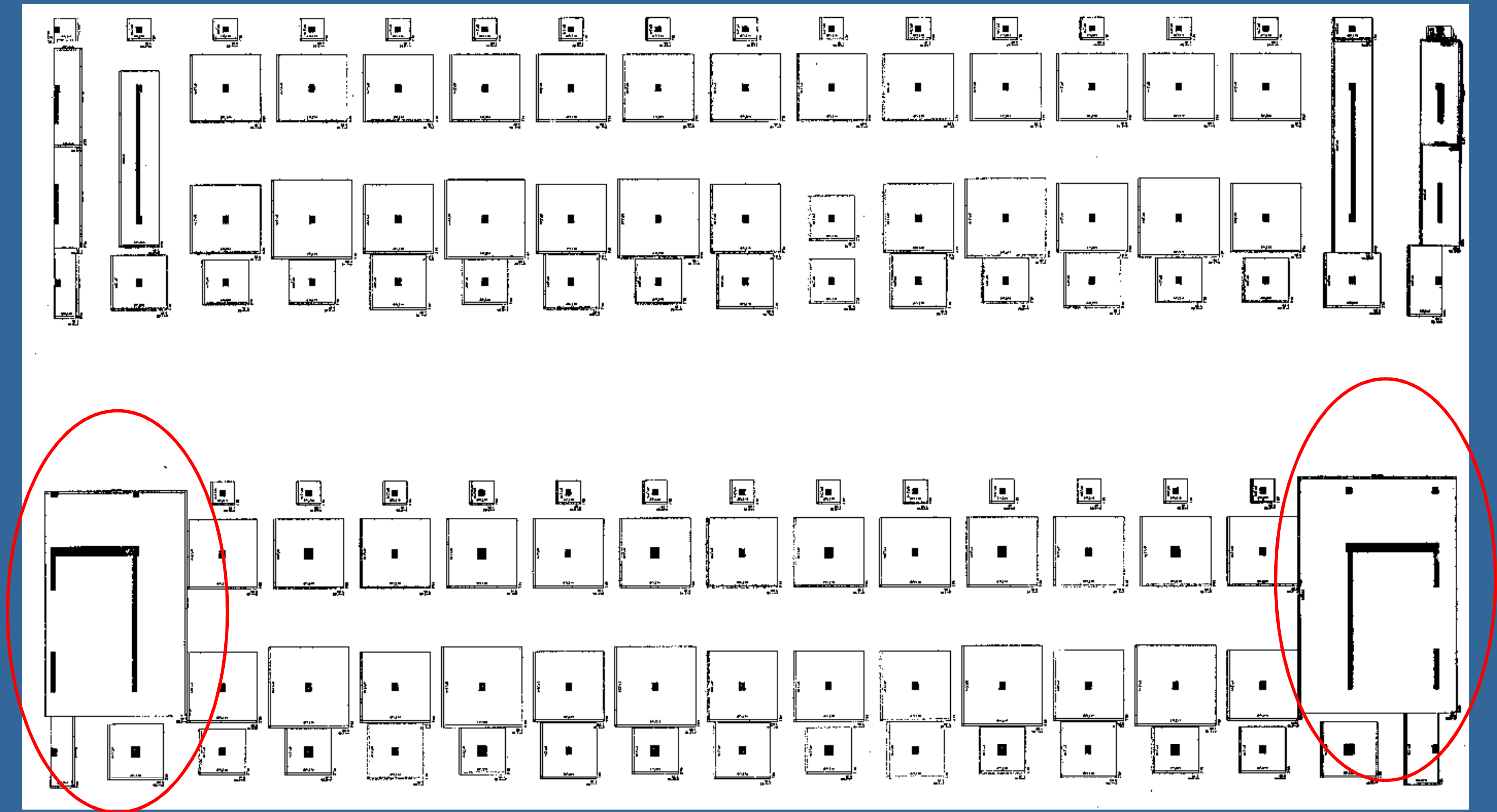
- Large & heavy footing, encapsulating those of neighbouring vertical elements.
- Connection to other footings via strong & stiff tie-beams.
- Micropiles or tie-downs to the soil.

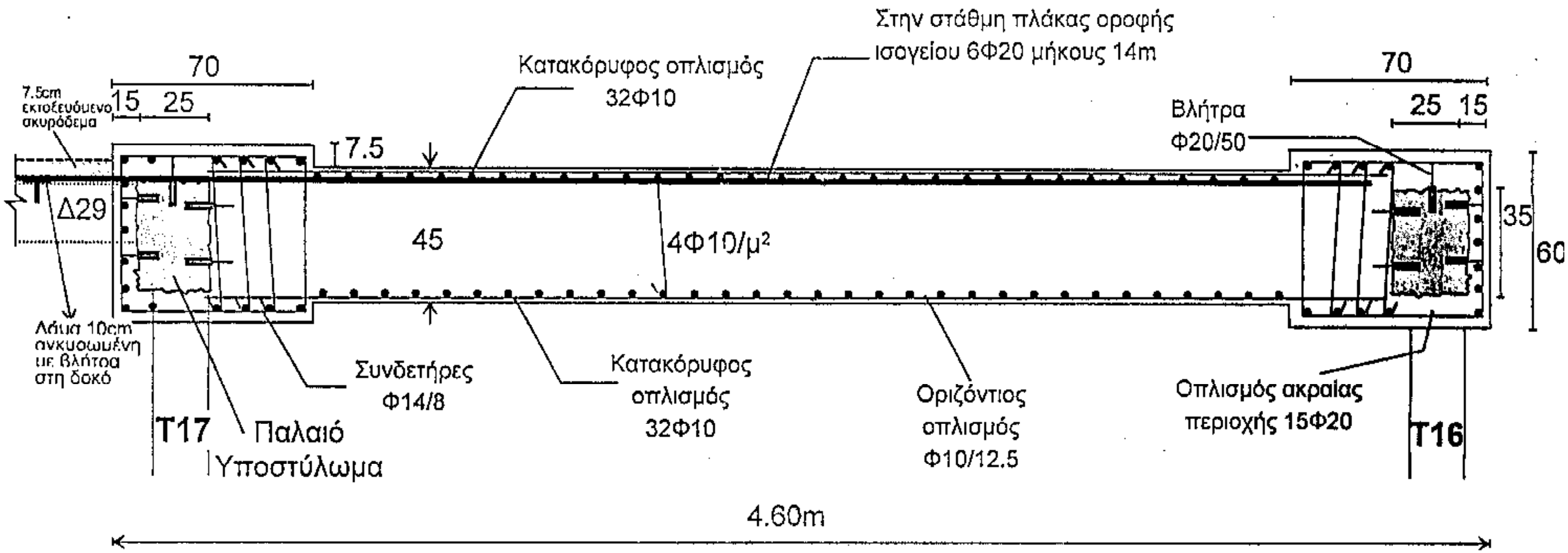
Uplift of footing of new walls should be modelled in nonlinear analysis

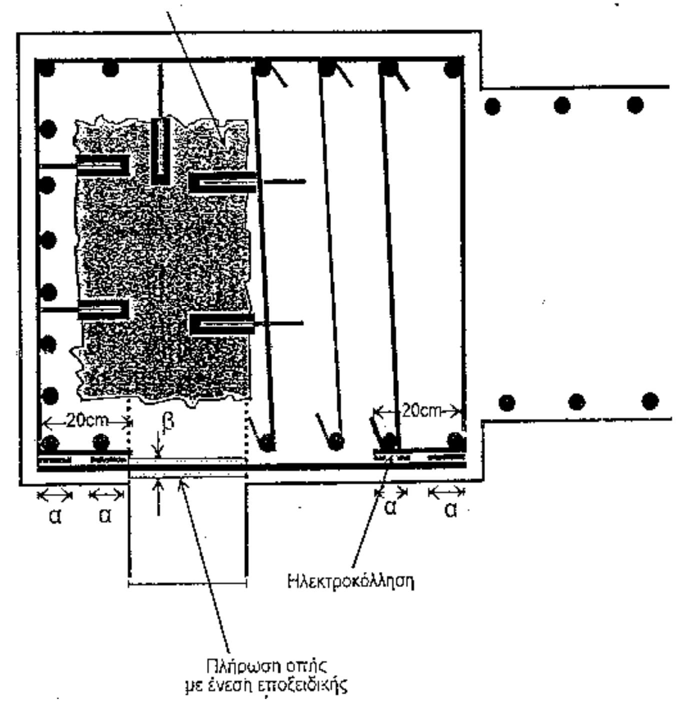
Example of building with 2 strong walls added in the transverse direction



Footings of strong walls to avoid uplift







X-section of new wall w/ detail of boundary element encapsulating the edge of an existing cross-wall.

Note large thickness of new wall

Desirable & most economic solution for the new wall

- The flange width of the new wall is equal to the minimum width of beams or columns in the existing frame

- Objective: fully monolithic behaviour of the new wall with the beams and the columns of the existing frame

Connection of new "web" to existing frame for monolithic behaviour

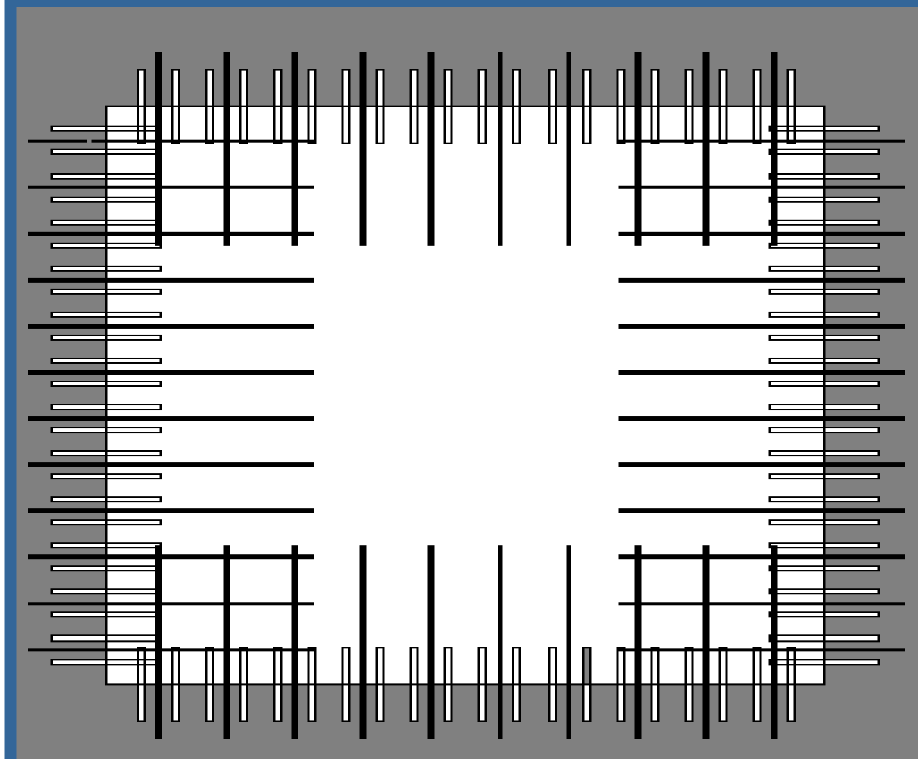
Dowels along the perimeter, at the wall centreline, transfer the web shear

1) Orthodox solution: Direct connection of web bars to frame via overlapping with starter bars anchored in the frame **+** dowels

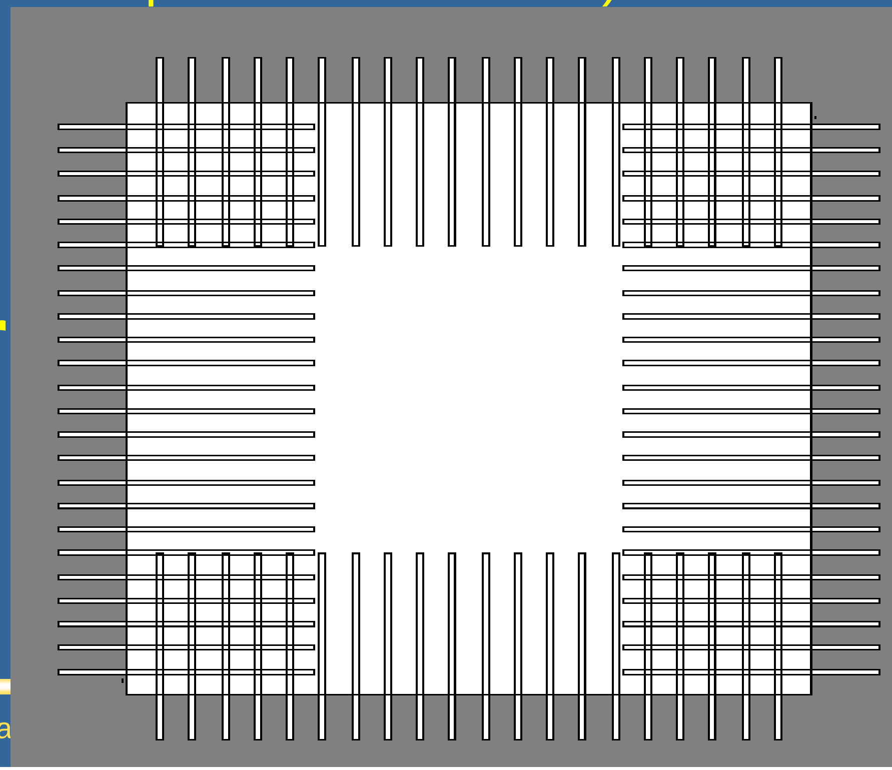
Dowel depth: 8Φ in frame or wall

2) Indirect connection of web bars to the frame – dowels double as anchorage

Dowel depth: 8Φ in frame, length in wall = lapping of web bars (but max distance between spliced bars violated)



or



habilita

Design shear for dimensioning the dowels

- Calculate max moment of wall at the base, $maxM_w$

1. either from the "overturning" moment of its footing, $M_0=0.5BN$, the footing height and the wall "shear span" $L_s=M/V \sim H_w/2$:

$$M_{wo}= M_0/(1+h/L_s)$$

2. or from the moment capacity at the base, M_{Rwd}, for the new web reinforcement and the reinforcement of the 2 existing columns.

- If $M_{wo}< M_{Rwd} \rightarrow maxM_w=M_{wo}$, no plastic hinge develops at the base. Design shear at the wall base: $V_d=maxM_w/L_s$.
- If $M_{wo}> M_{Rwd} \rightarrow maxM_w=M_{Rwd}$, a plastic hinge forms at the base. The design shear at the base includes the shear magnification factor for higher modes (Keinzel): $V_d=\sqrt{[1+0.1(qS_e(T_c)/S_e(T_1))2]}\ maxM_w/L_s$
  - $S_e(T)$: elastic spectral value, T_1: building fundamental period,
  - T_c: T at upper limit of the spectrum constant-acceleration range,
  - q: calculated from yield & ultimate wall chord rotations: $q \sim \theta_u/\theta_y$.

Dimensioning of dowels in shear

- Shear resistance of **one** dowel (design value)

1. working as dowel only (solution 1)

$$F(s) \approx F_{0,\max}\sqrt{1-\frac{s}{s_{\max}}} = 1.6A_s\sqrt{f_{cd}f_{yd}}\sqrt{1-\frac{s}{s_{\max}}}$$

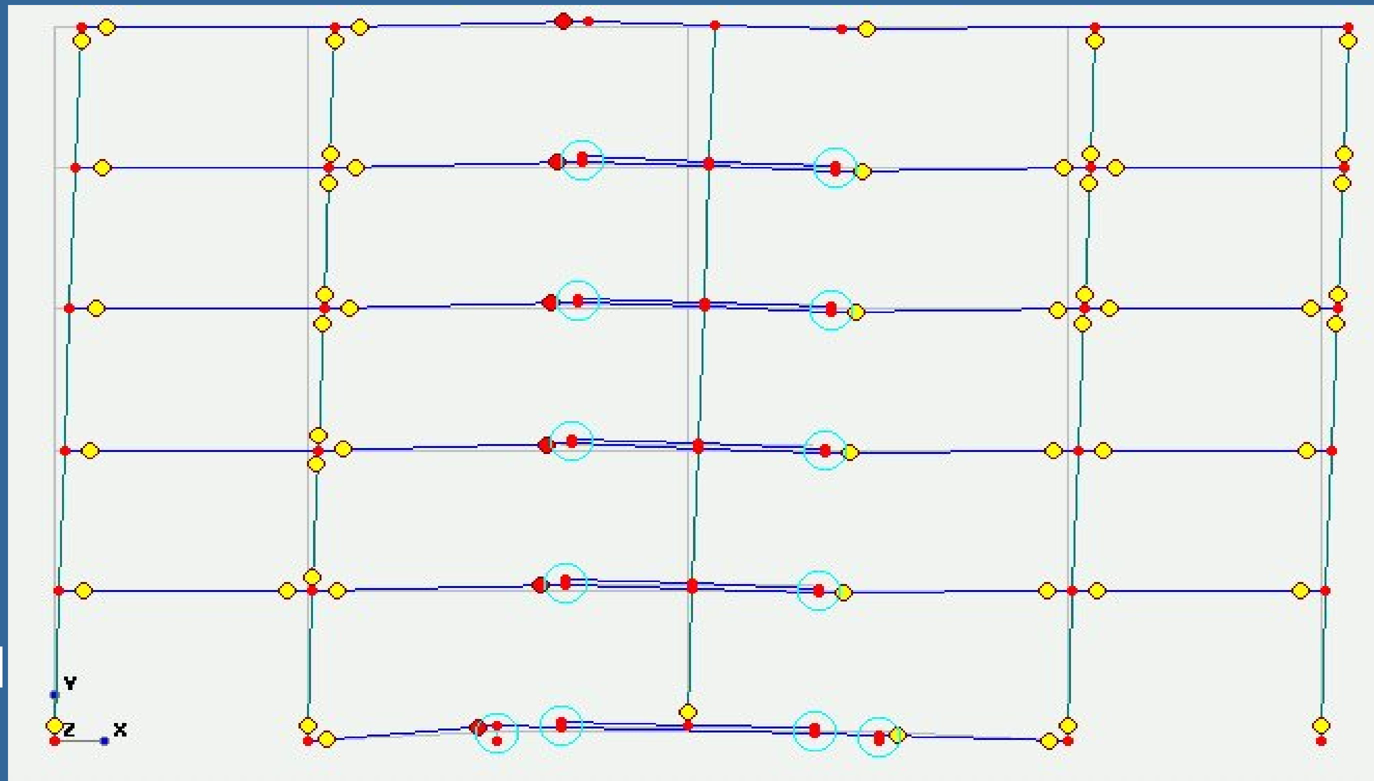
s: slippage, $s_{max} \sim 0.1d_b$

2. transferring the tension resistance of web bars (diameter d_{bw}) to the existing frame (solution 2) through tensile stress $\sigma_s=f_{yd}(d_{bw}/d_b)^2$

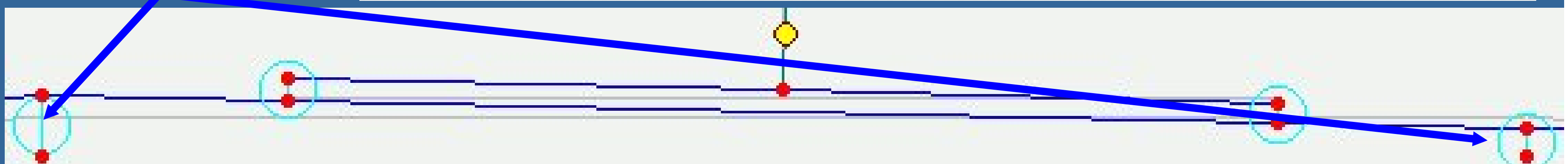
$$F_{\max} = F_{0,\max}\sqrt{1-\left(\frac{\sigma_s}{f_{yd}}\right)^2} = F_{0,\max}\sqrt{1-\left(\frac{d_{bw}}{d_d}\right)^4}$$

- If slippage is large, the design shear resistance of the two existing columns is activated (and added to the total capacity of the dowels)

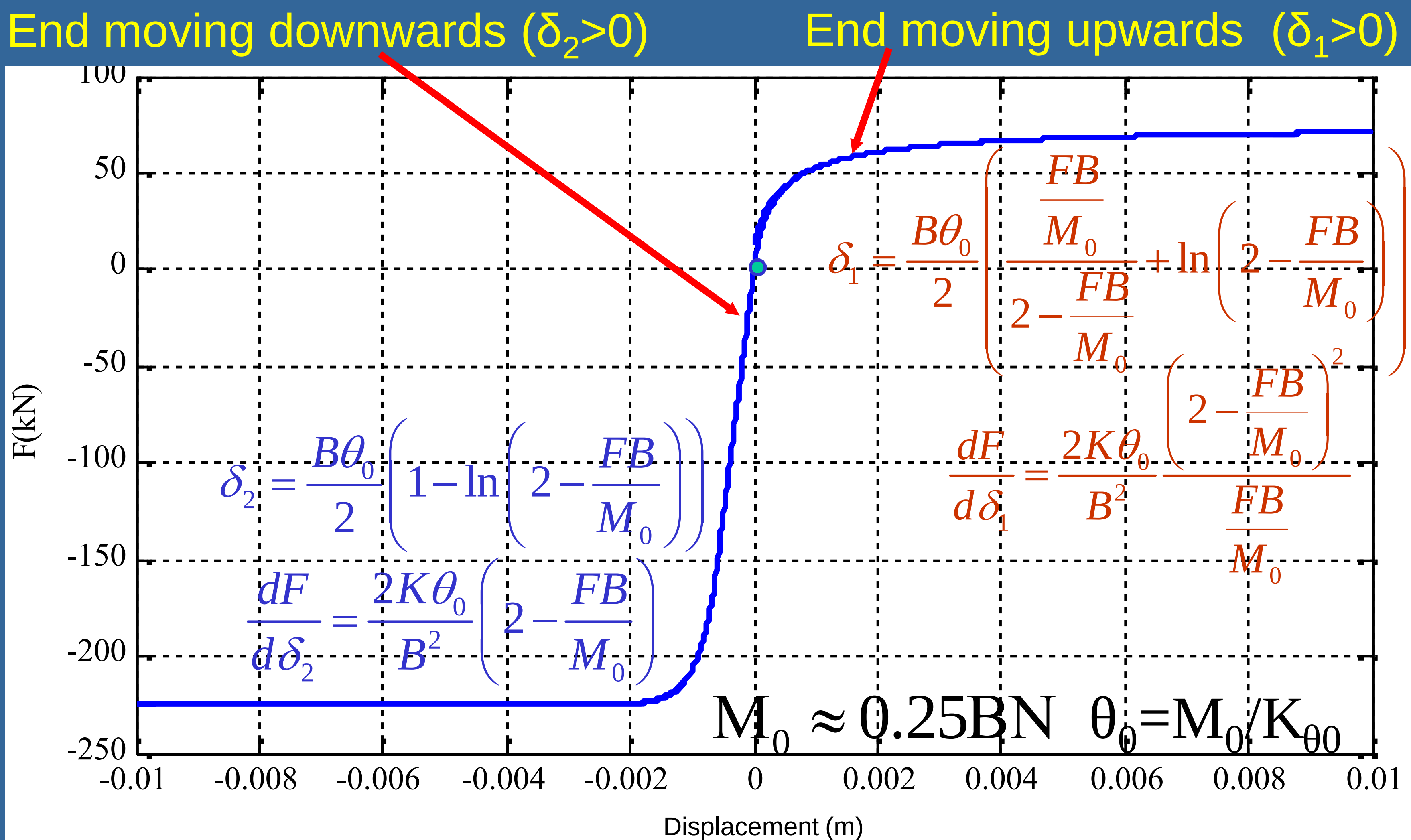
Nonlinear modelling of footing uplift



nonlinear springs
connecting the soil
to the foundation



Nonlinear spring constitutive law



$$\delta_1 = \frac{B\theta_0}{2}\left(\frac{\frac{FB}{M_0}}{2-\frac{FB}{M_0}} + \ln\left(2-\frac{FB}{M_0}\right)\right)$$

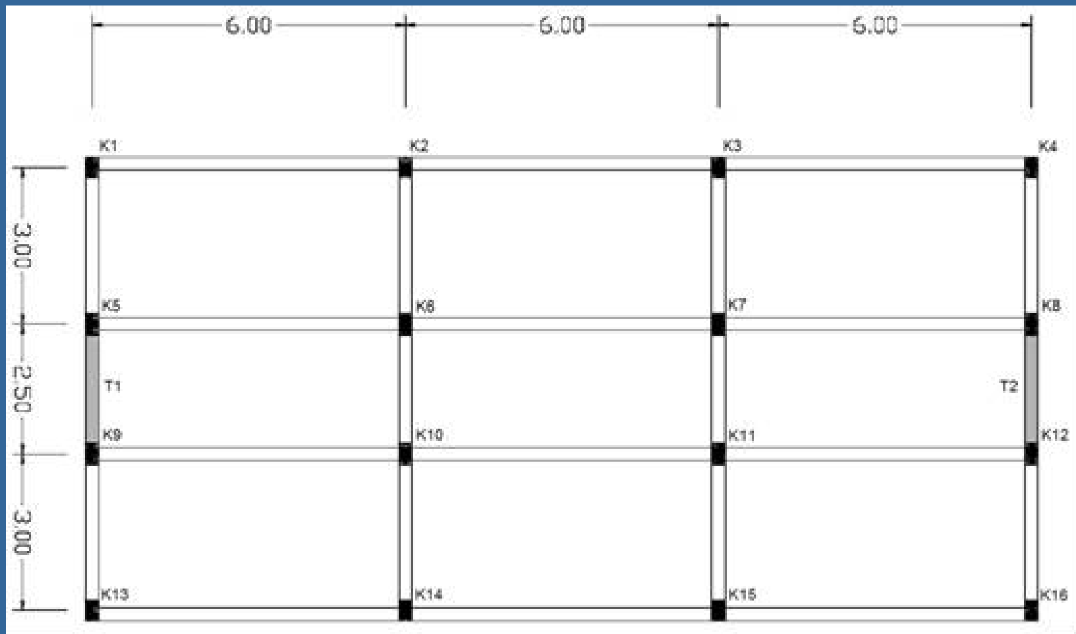
$$\frac{dF}{d\delta_1} = \frac{2K\theta_0}{B^2}\frac{\left(2-\frac{FB}{M_0}\right)^2}{\frac{FB}{M_0}}$$

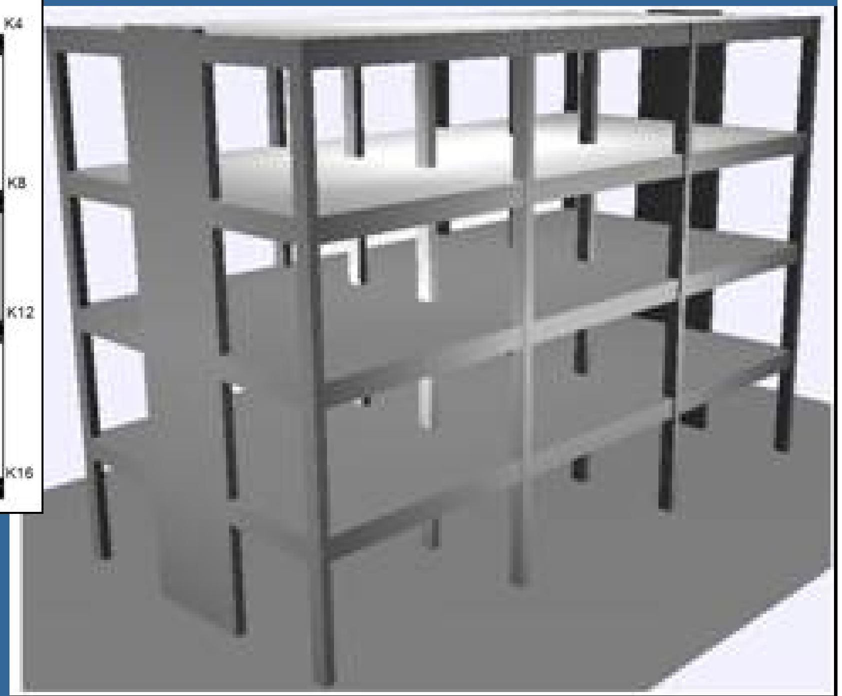
$$\delta_2 = \frac{B\theta_0}{2}\left(1-\ln\left(2-\frac{FB}{M_0}\right)\right)$$

$$\frac{dF}{d\delta_2} = \frac{2K\theta_0}{B^2}\left(2-\frac{FB}{M_0}\right)$$

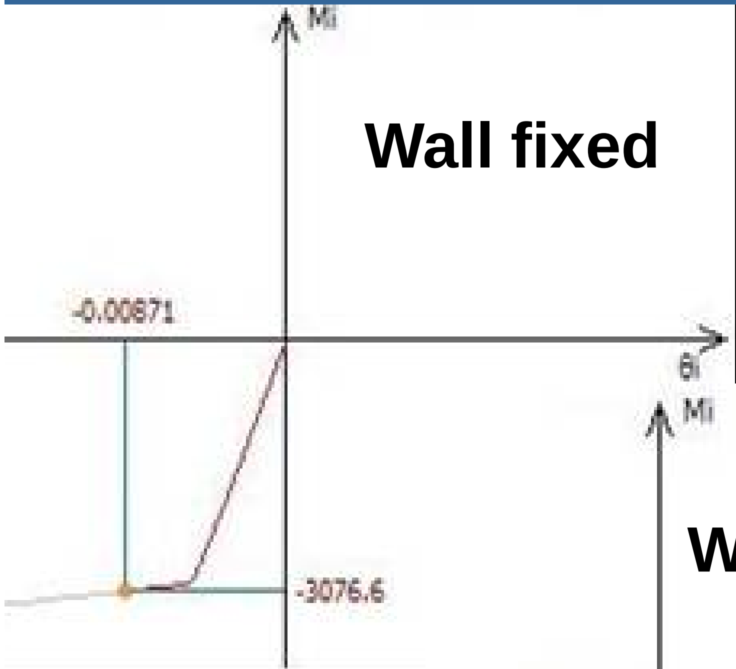
$$M_0 \approx 0.25BN \quad \theta_0 = M_0/K_{\theta 0}$$

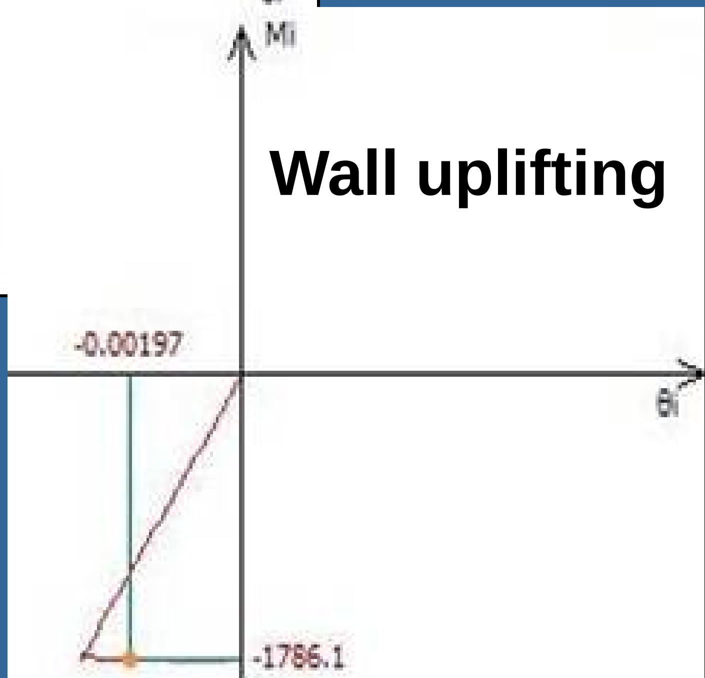
Application to prototype building of 4 frames, converting the central bay of exterior frames into walls (~SERFIN)





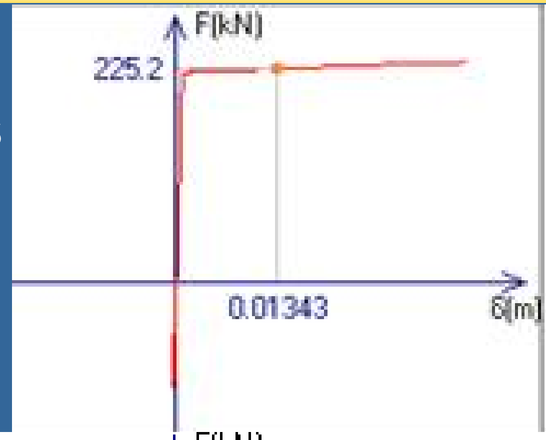
Nonlinear static analysis with fixed or uplifting footings

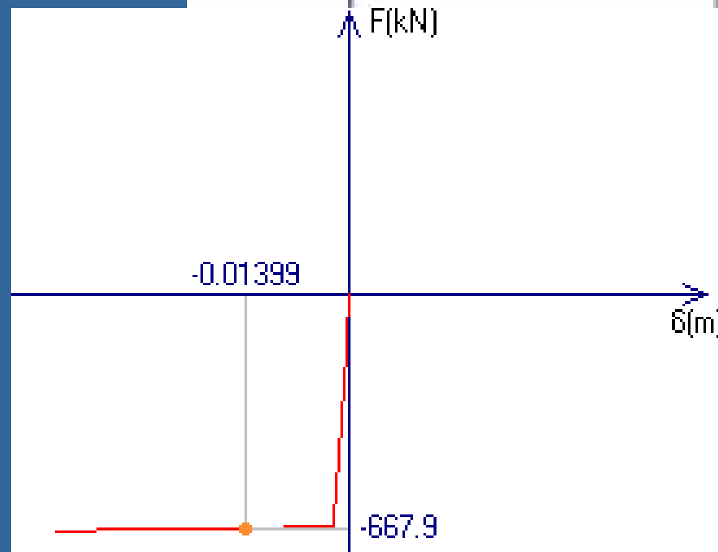




M-θ diagram of wall at the base

End moving upwards

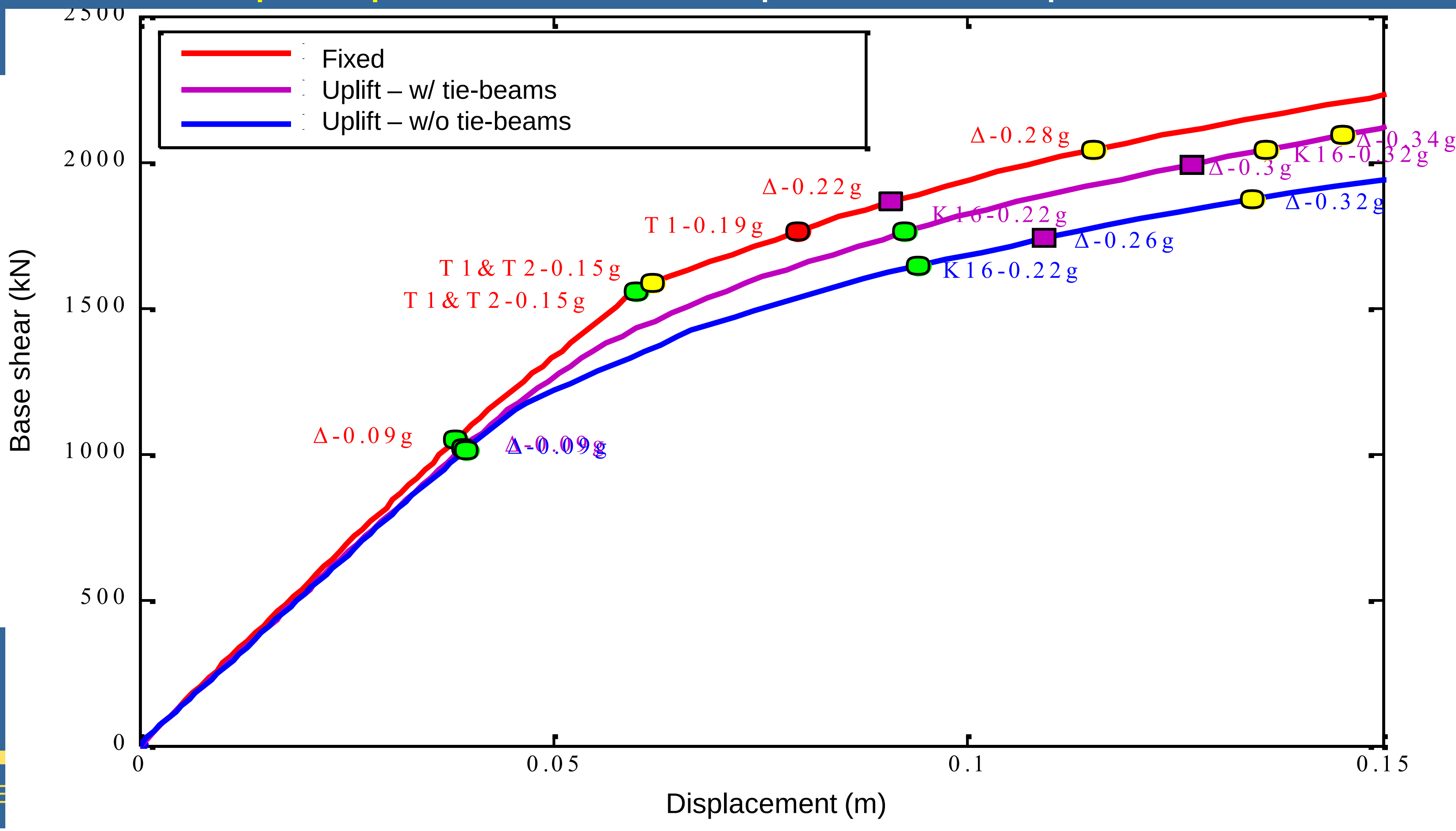




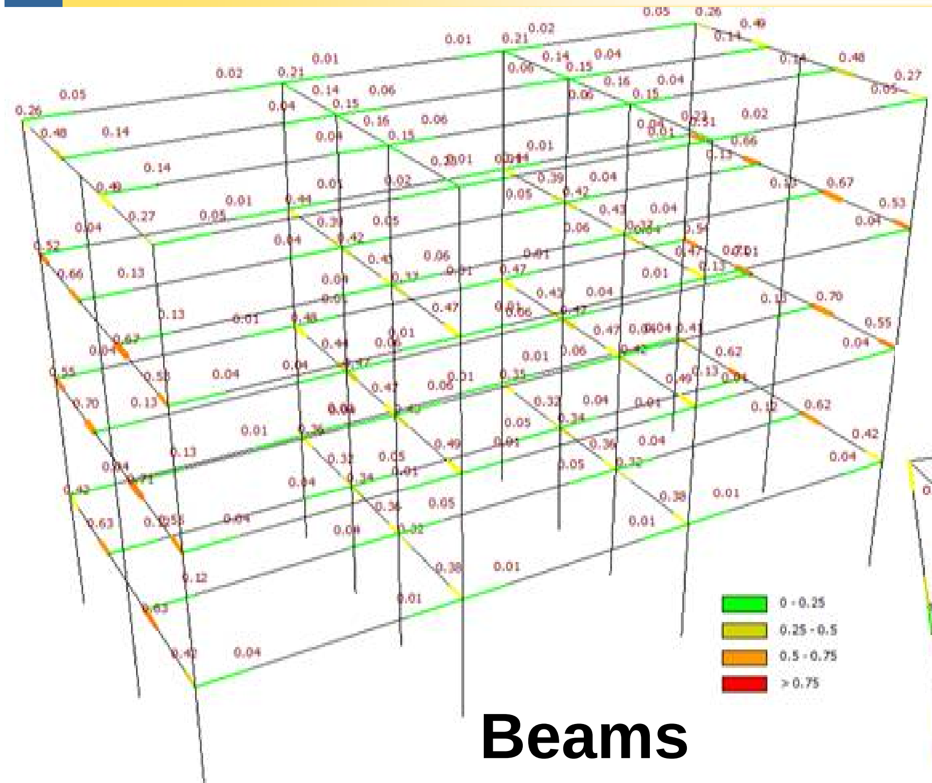
End moving downwards

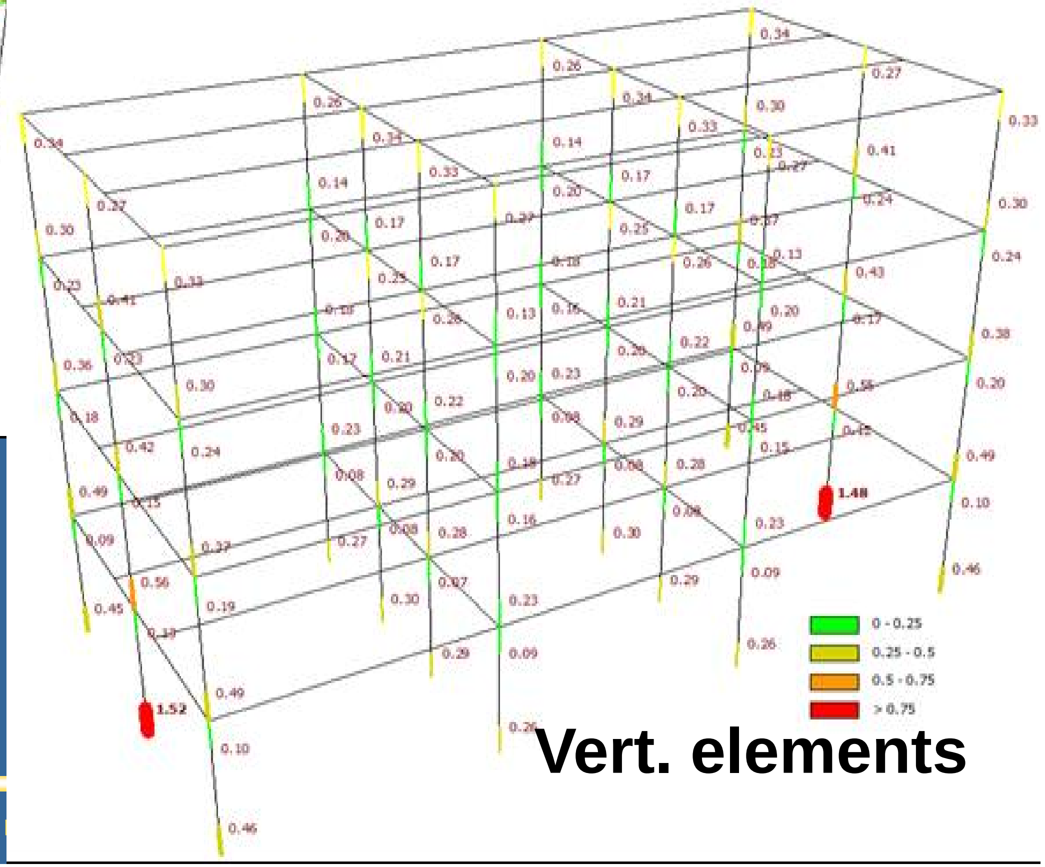
Nonlinear static analysis with fixed or uplifting footings (1.5x1.5x0.8m under columns, 1.5x4.0x0.8m under walls, w/ or w/o 0.25x0.6m tie-beam)

Green circle: “Damage :imitation” per EC8-3
Yellow circle: “Significant damage” per EC8-3
Red circle: “Near Collapse” in bending per EC8-3
Purple square: “Near Collapse” in shear per EC8-3

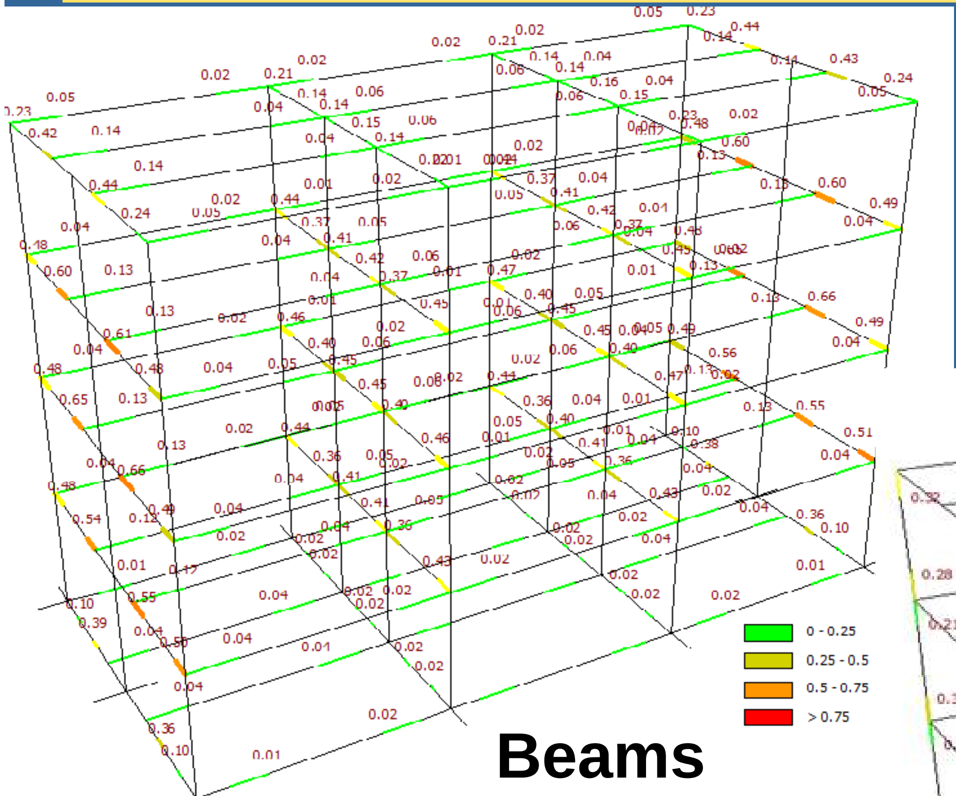


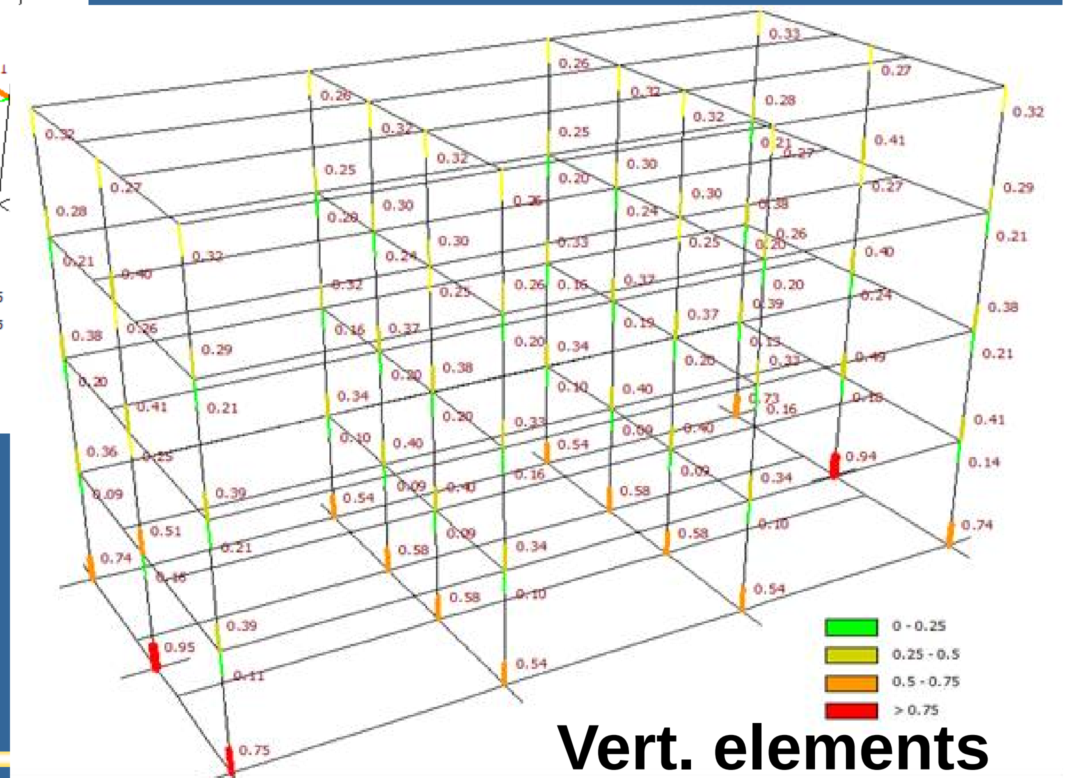
***Flexural** damage index for Significant Damage - Nonlinear dynamic analysis, 0.25g - **fixed** footings (average over 14 records)*



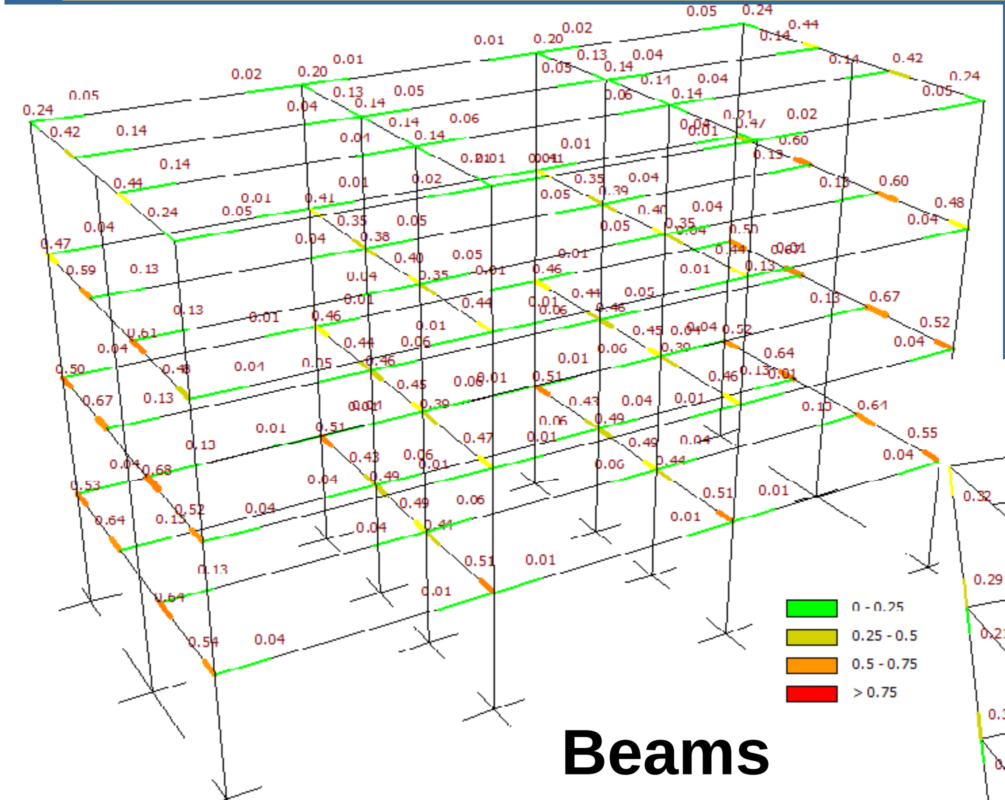


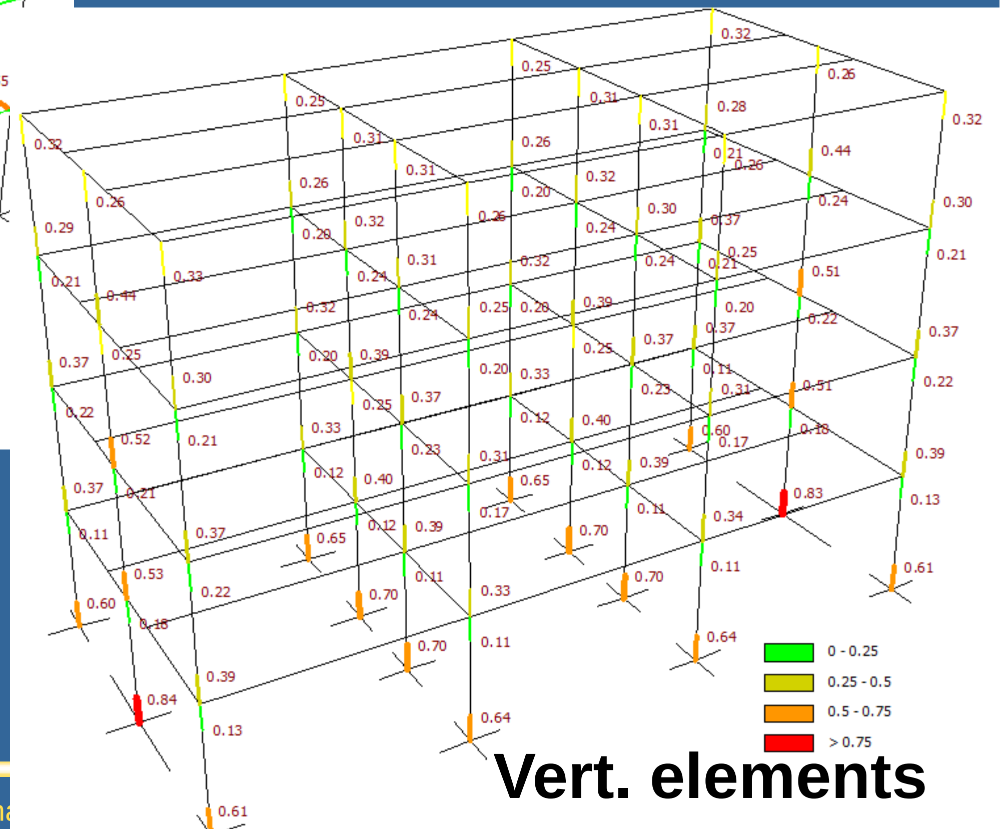
Flexural *damage index for Significant Damage - Nonlinear dynamic analysis,* ***uplifting*** *footings* ***w/ tie-beams*** *(av/ge over 14 records, 0.25g)*



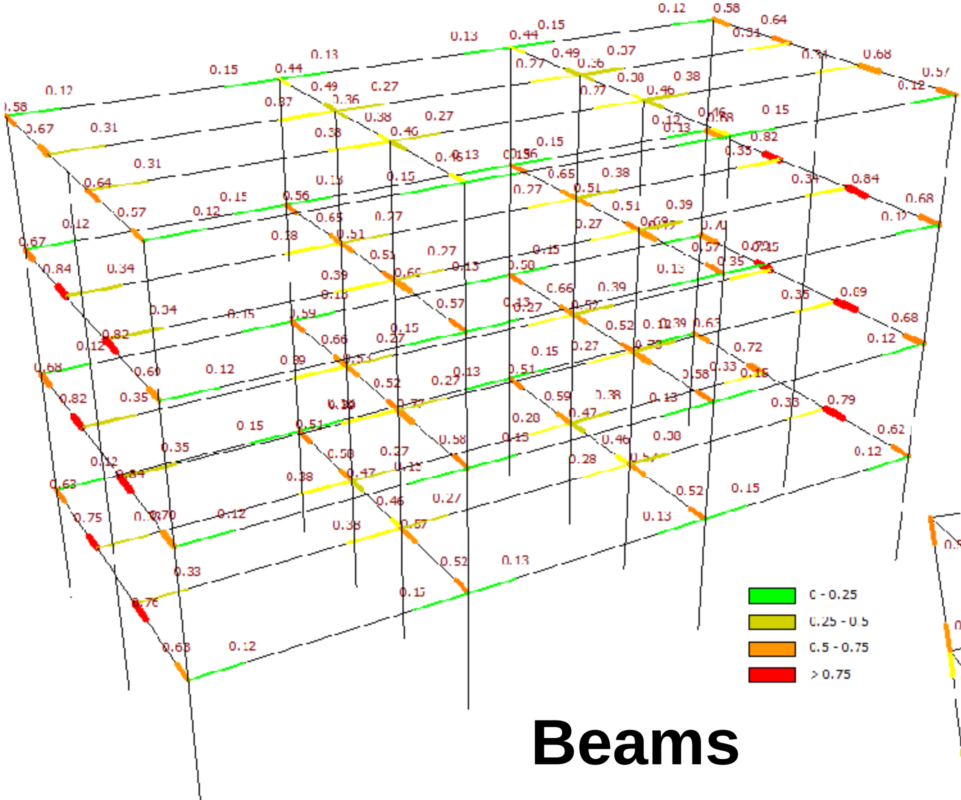


***Flexural** damage index for Significant Damage - Nonlinear dynamic analysis, **uplifting** footings, **no tie-beams** (av/ge over 14 records, 0.25g)*

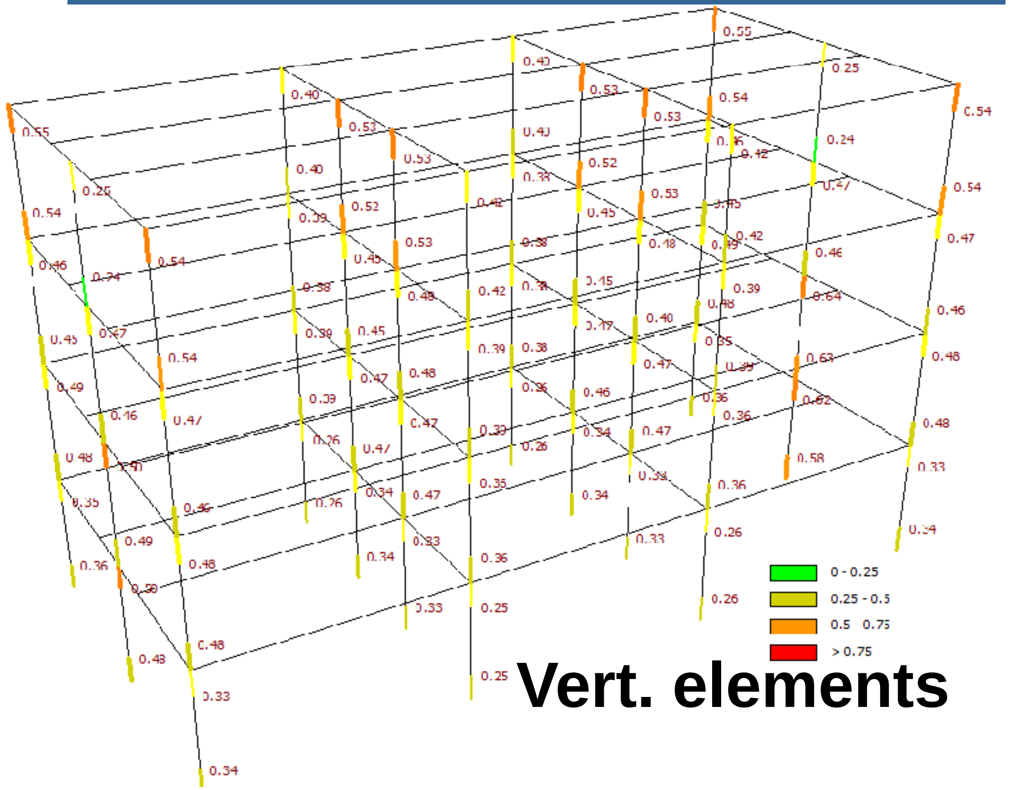




Shear *damage index for Significant Damage - Nonlinear dynamic analysis, **fixed** footings (av/ge over 14 records, 0.25g)*

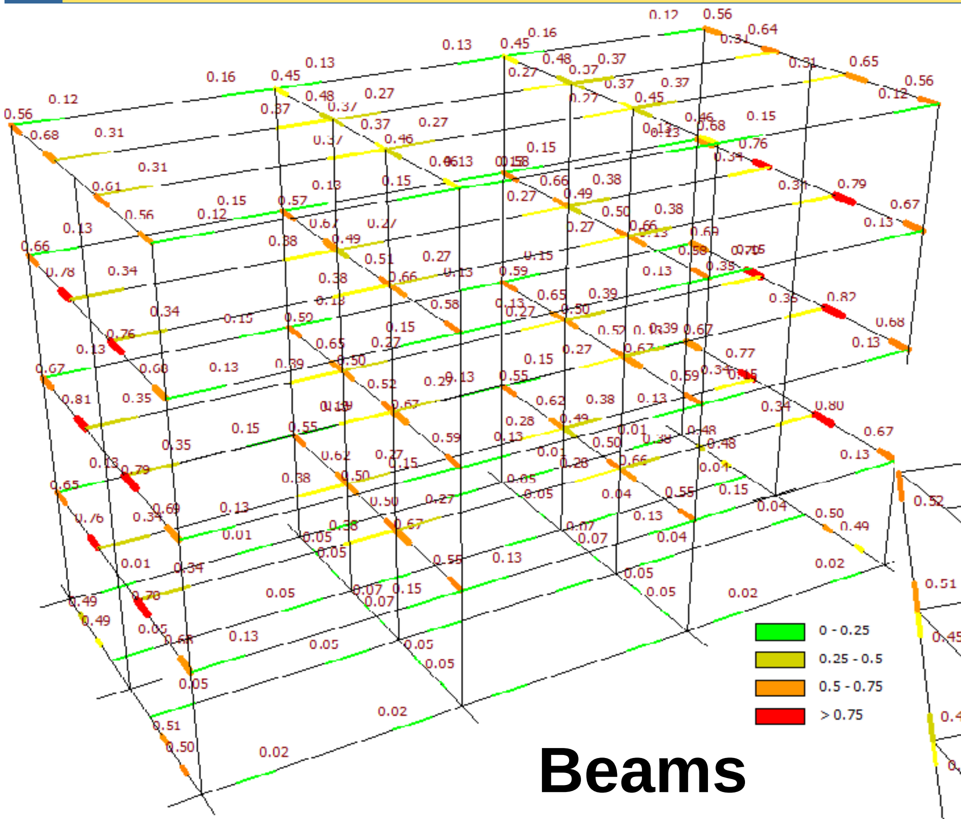


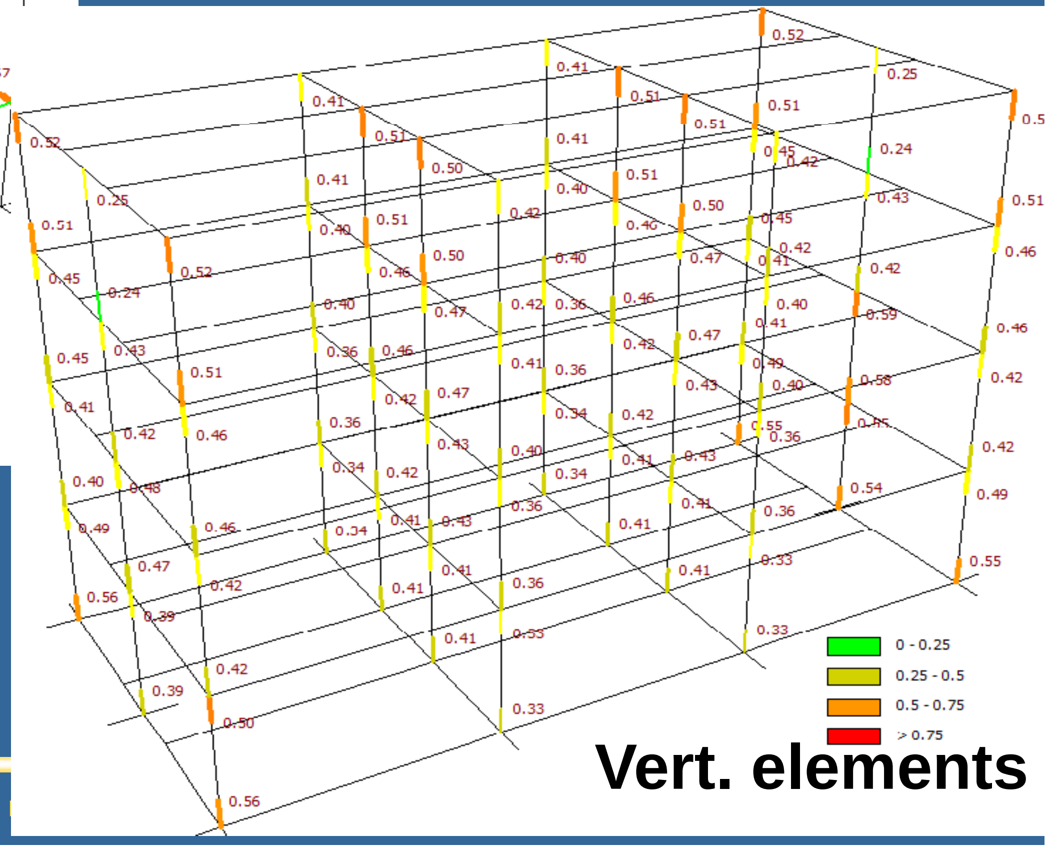
Beams



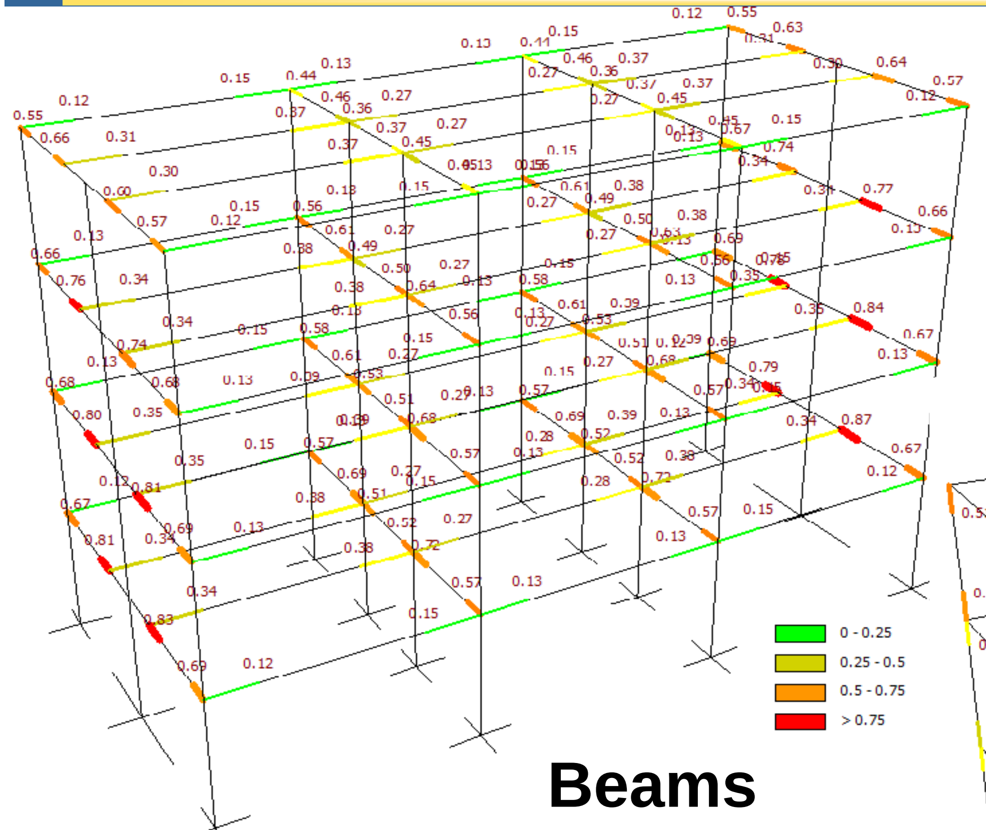
Vert. elements

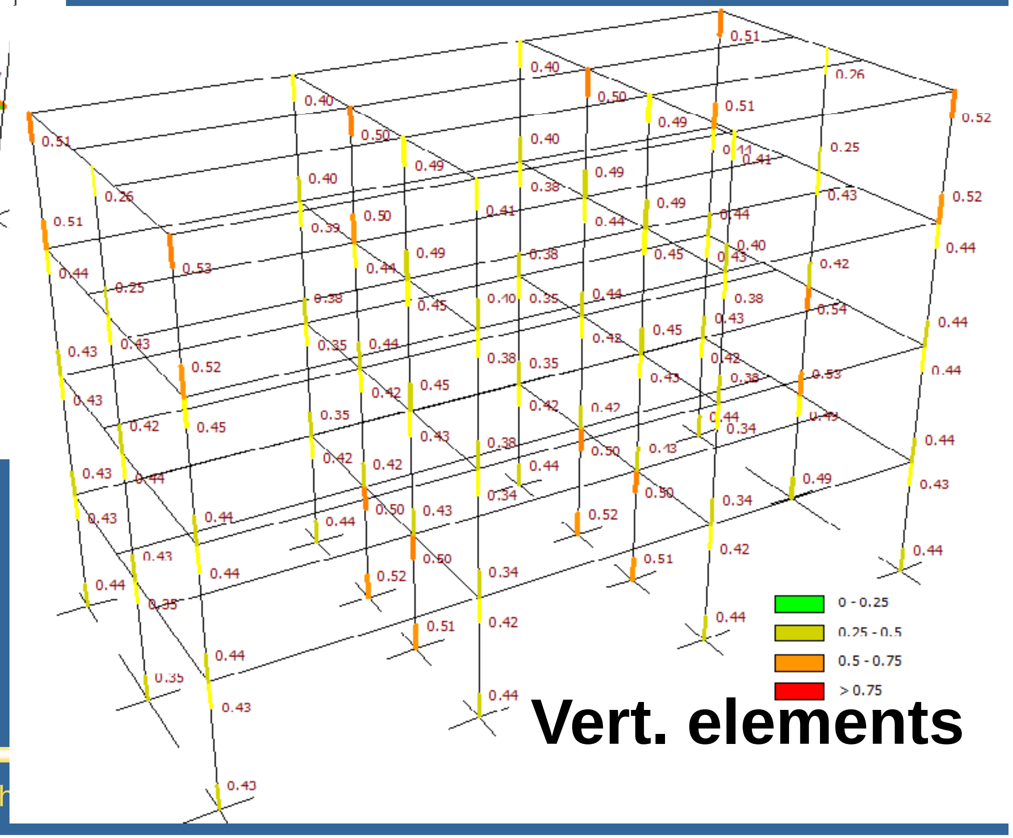
Shear *damage index for Significant Damage - Nonlinear dynamic analysis,* ***uplifting*** *footings* ***w/ tie-beams*** *(av/ge over 14 records, 0.25g)*





Shear *damage index for Significant Damage, nonlinear dynamic analysis,* ***uplifting*** *footings,* ***no tie-beams*** *(av/ge over 14 records, 0.25g)*

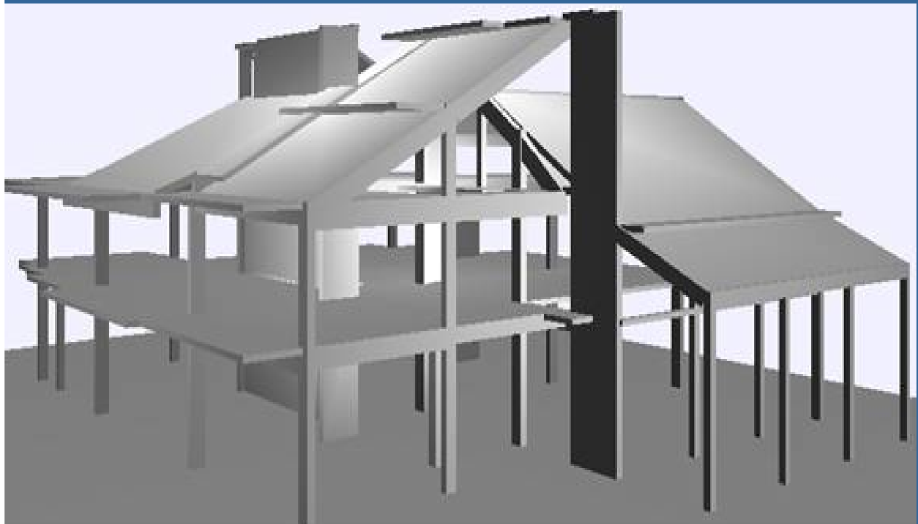




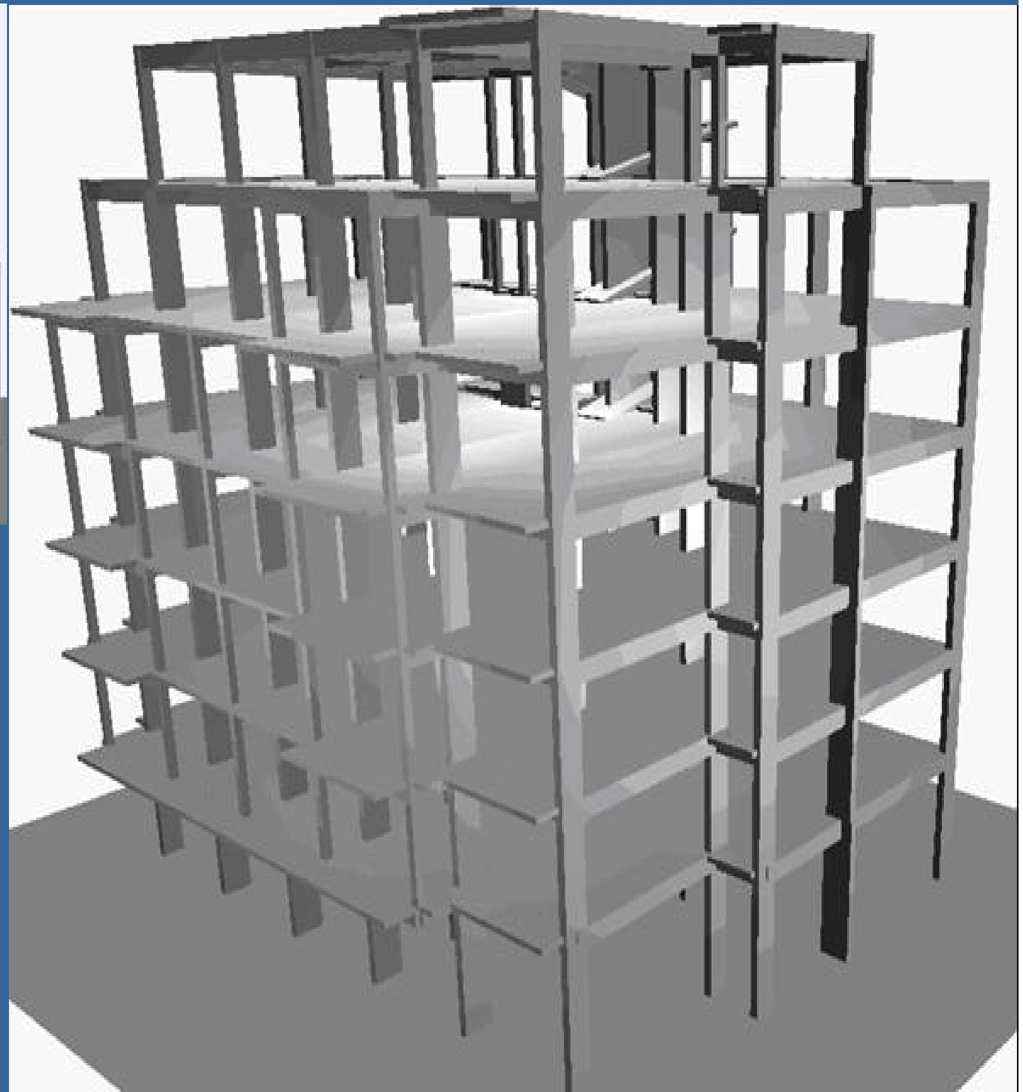
Conclusions from analysis with fixed or uplifting footings, with or w/o tie-beams

- Rocking of the foundation is beneficial for the walls, but increases the demand on columns, particularly at the base
- Damage index values are smaller at the base of the walls without tie-beams
- Columns: the maximum damage index values are at the base of the exterior columns in building with tie-beams or at the interior frames in building without tie-beams
- Uplifting does not have a major effect on beams.

Seismic assessment and retrofit of 2 real irregular buildings

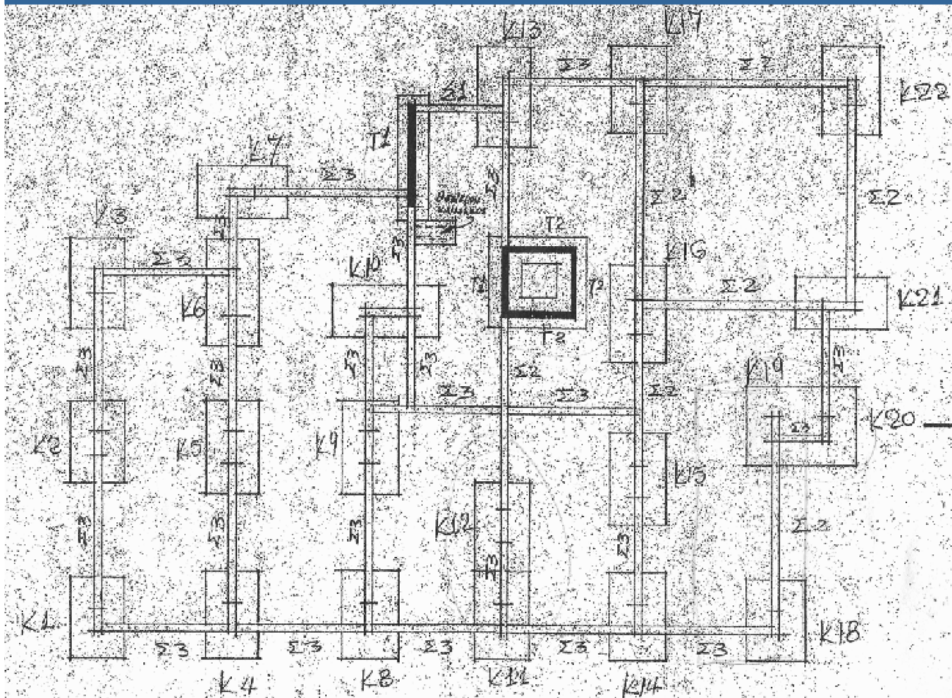


2-storey building
with inclined roofs

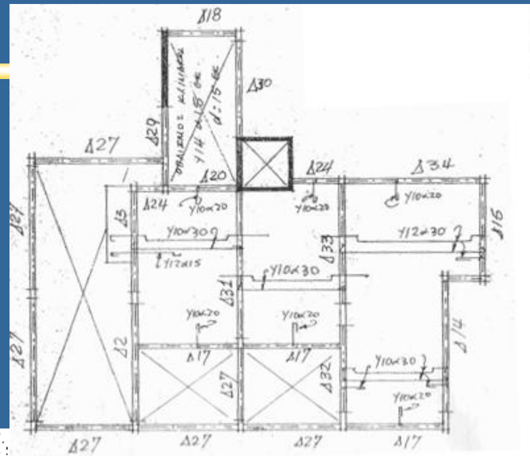


7-storey building
with 2 set-backs

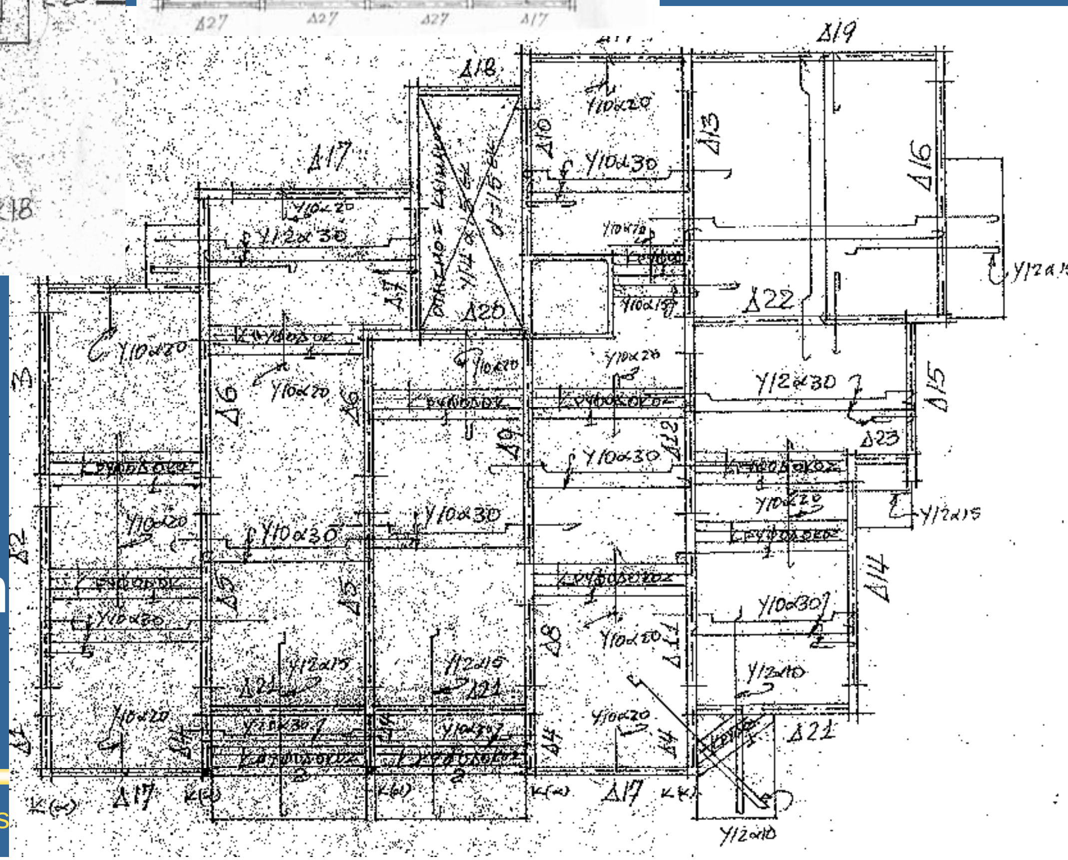
7-storey building



Foundation plan

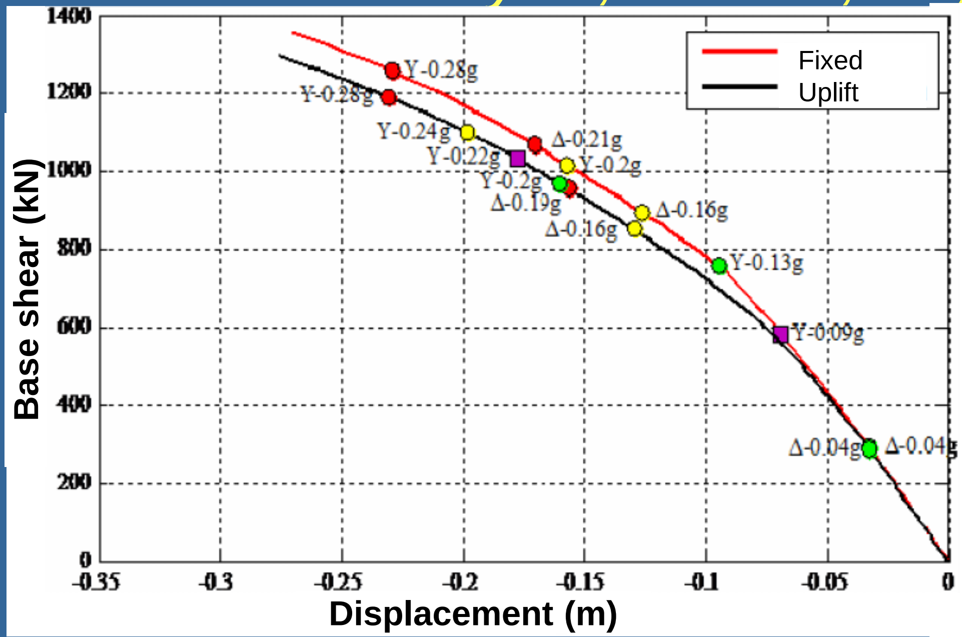


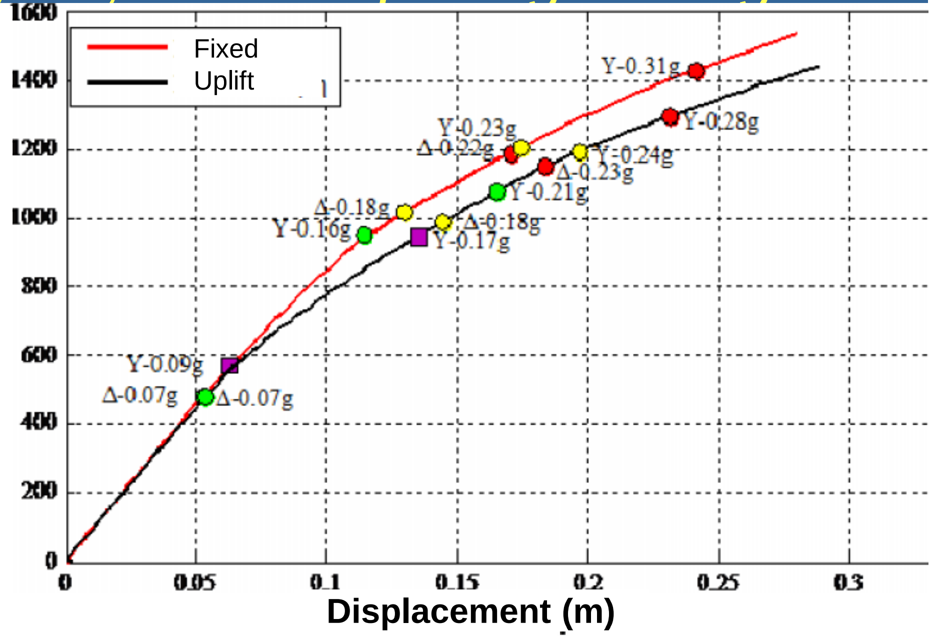
2nd setback



1st - 5th storey plan

Pushover analysis, as-built, ±X, ±Y, fixed v uplifting footings



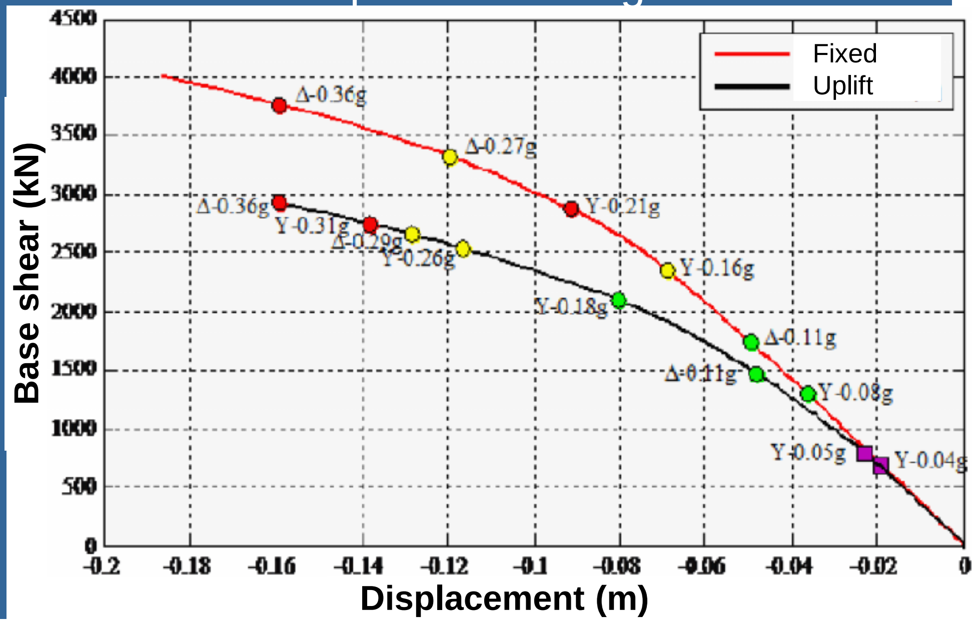


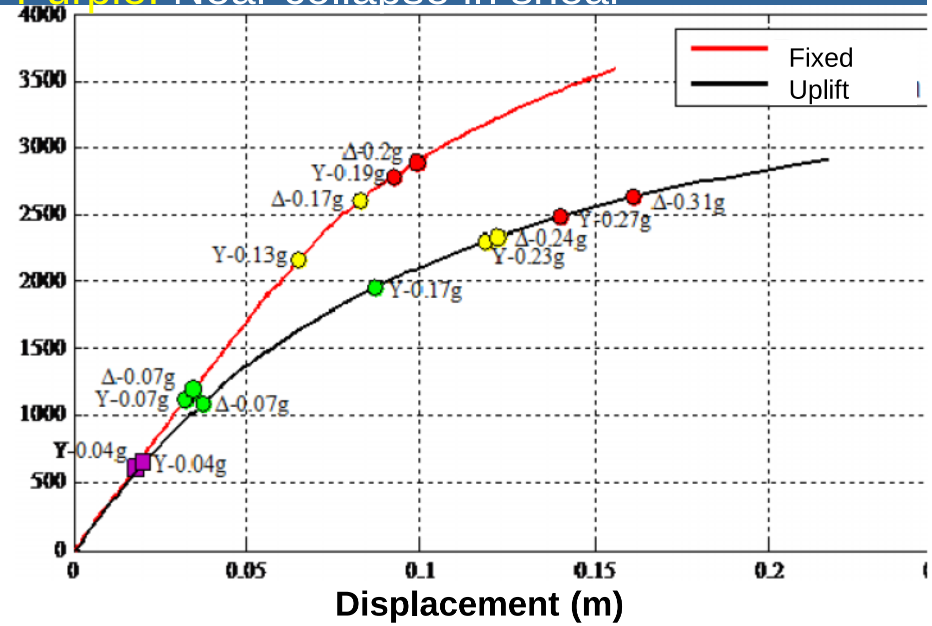
Green: Damage Limitation per EC8–3

Red: Near Collapse in bending

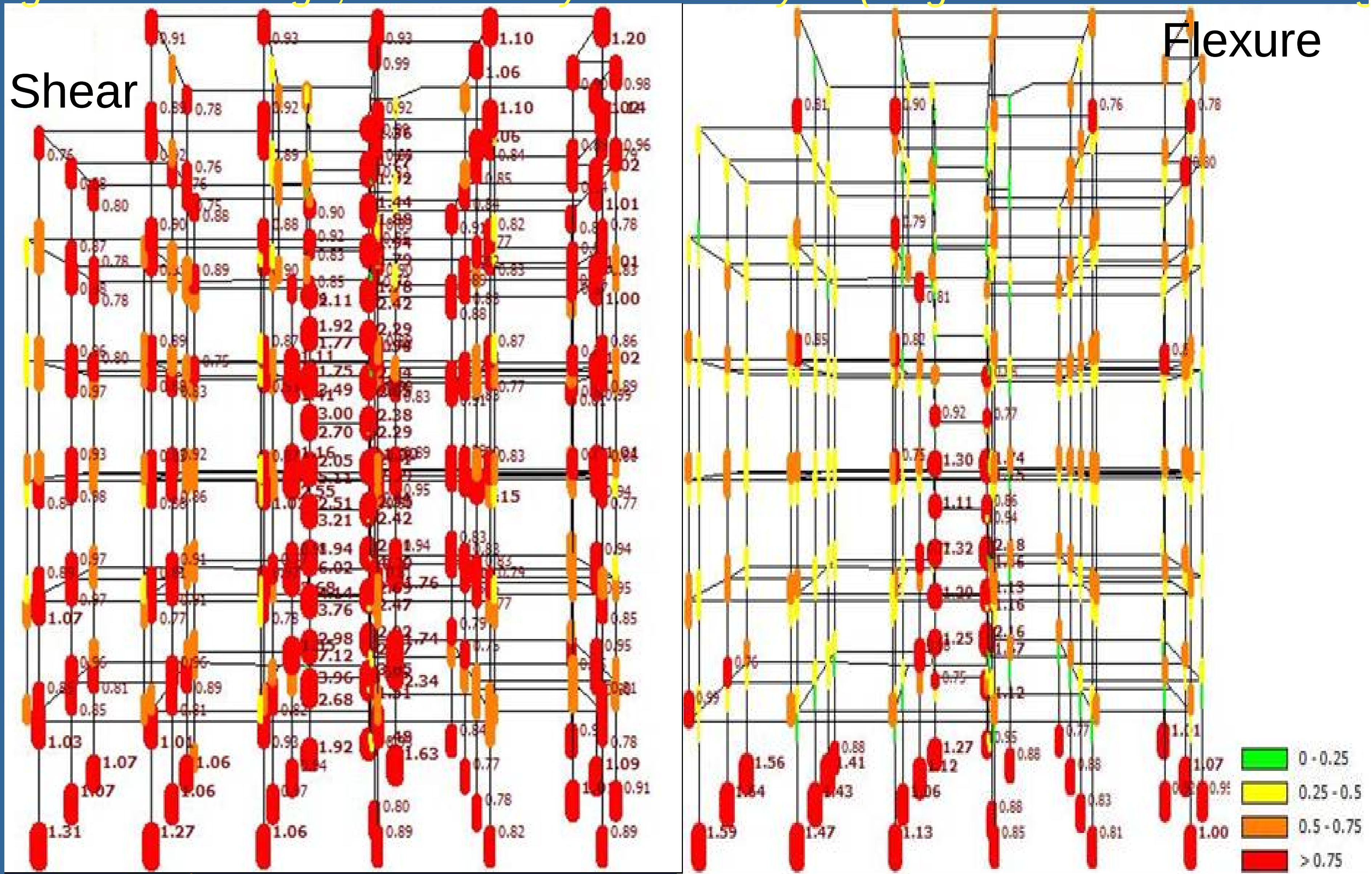
Yellow: Significant Damage per EC EK8–3

Purple: Near collapse in shear

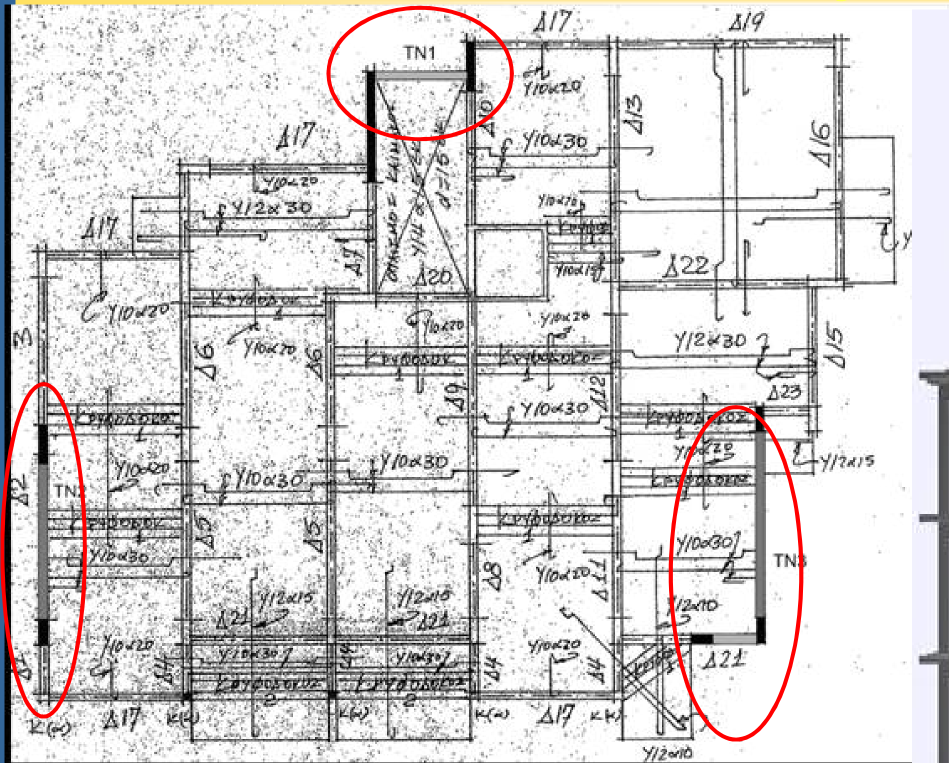


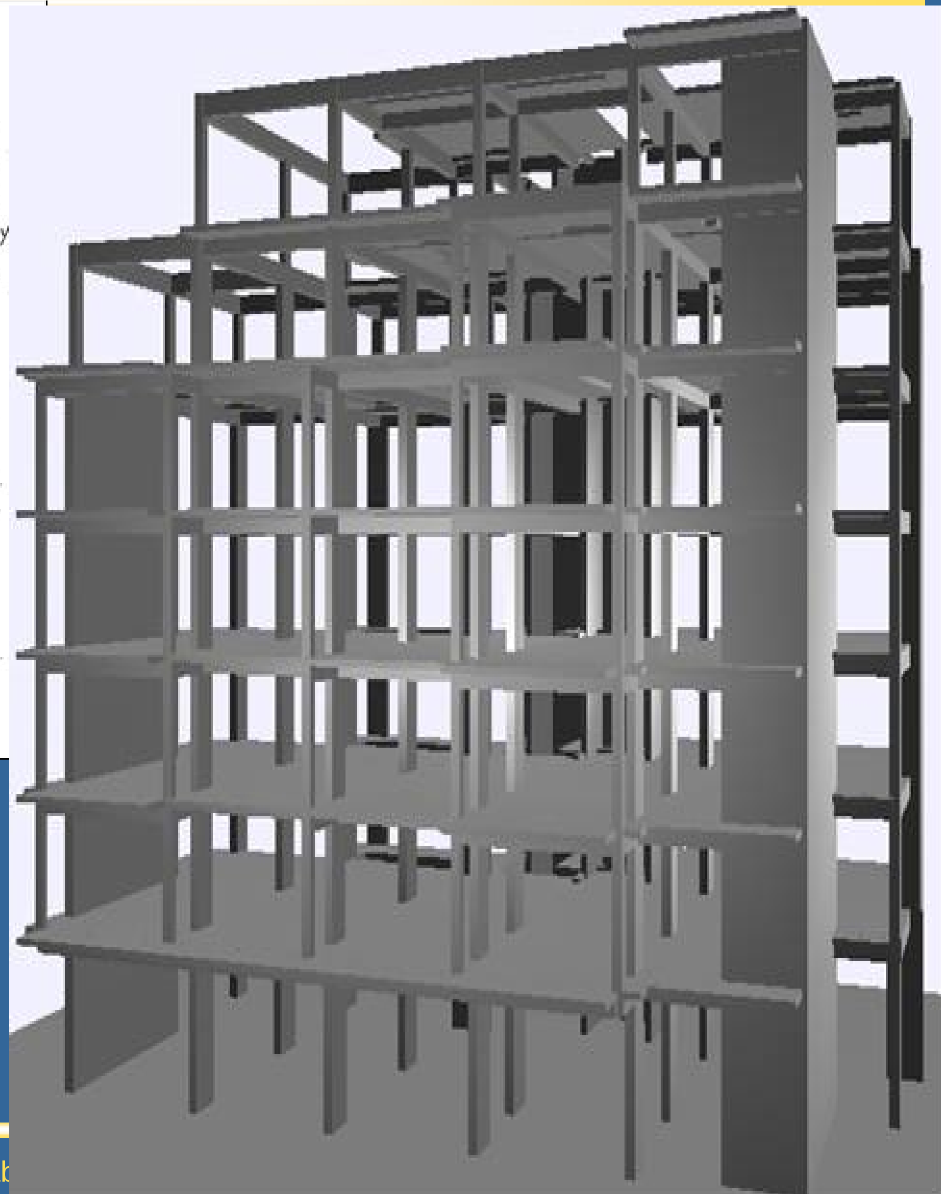


Shear & flexural damage index of vertical elements - as-built building for Significant Damage, nonlinear dynamic analysis (av/ge over 14 records 0.25g

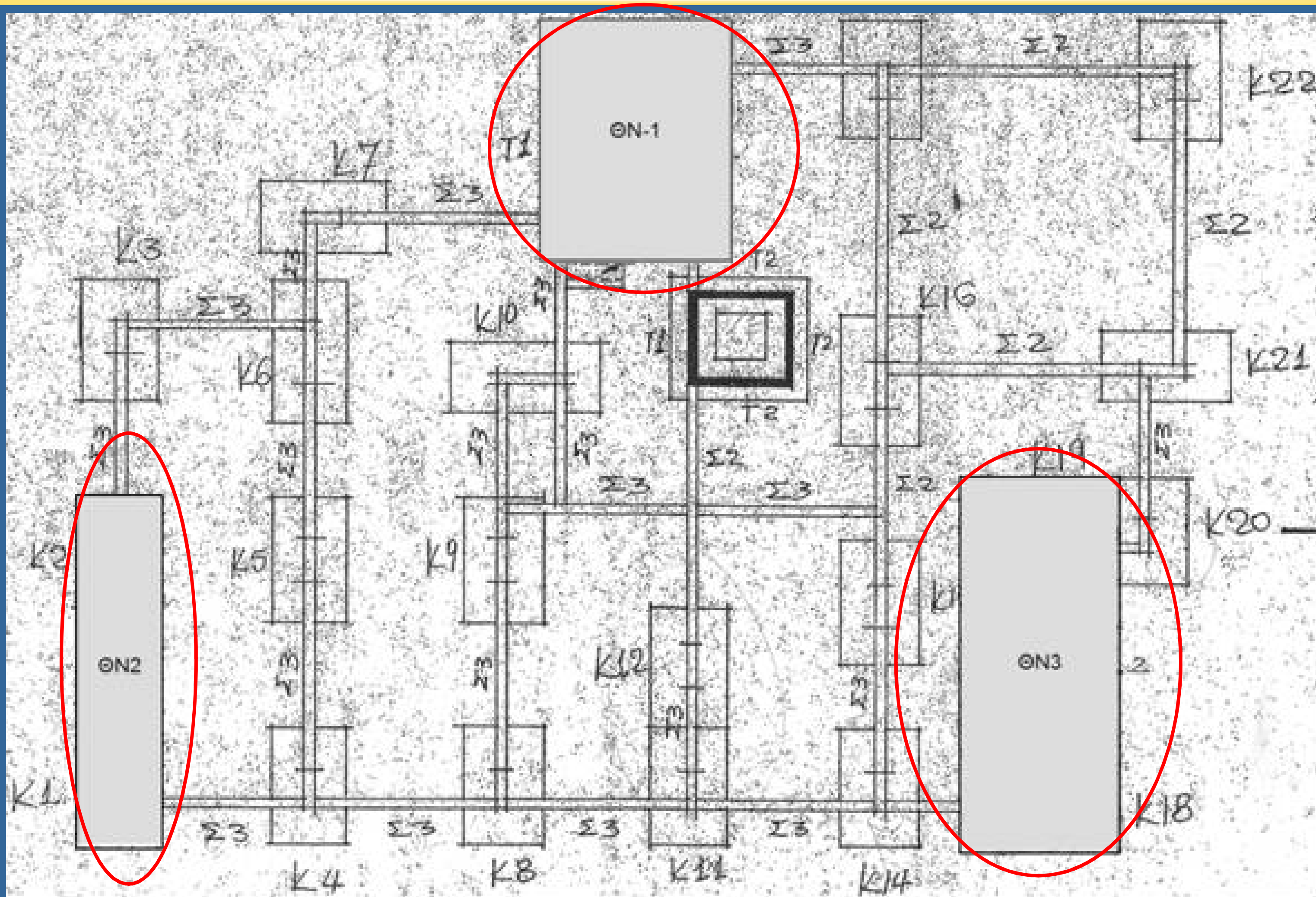


Seismic retrofit of 7-storey building with new walls

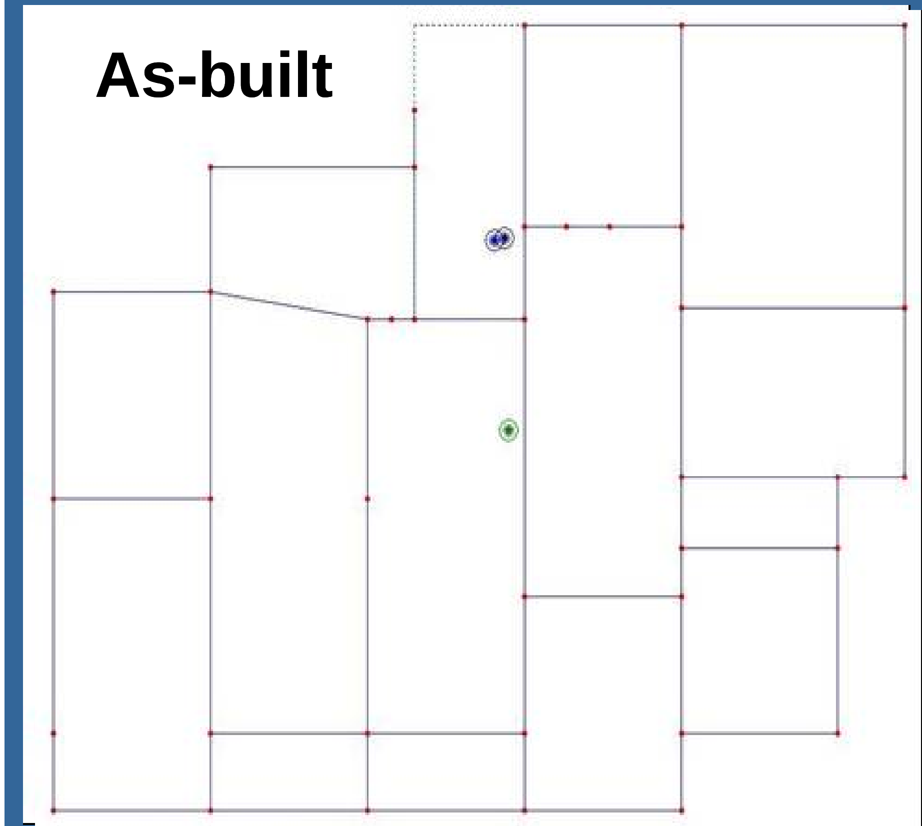


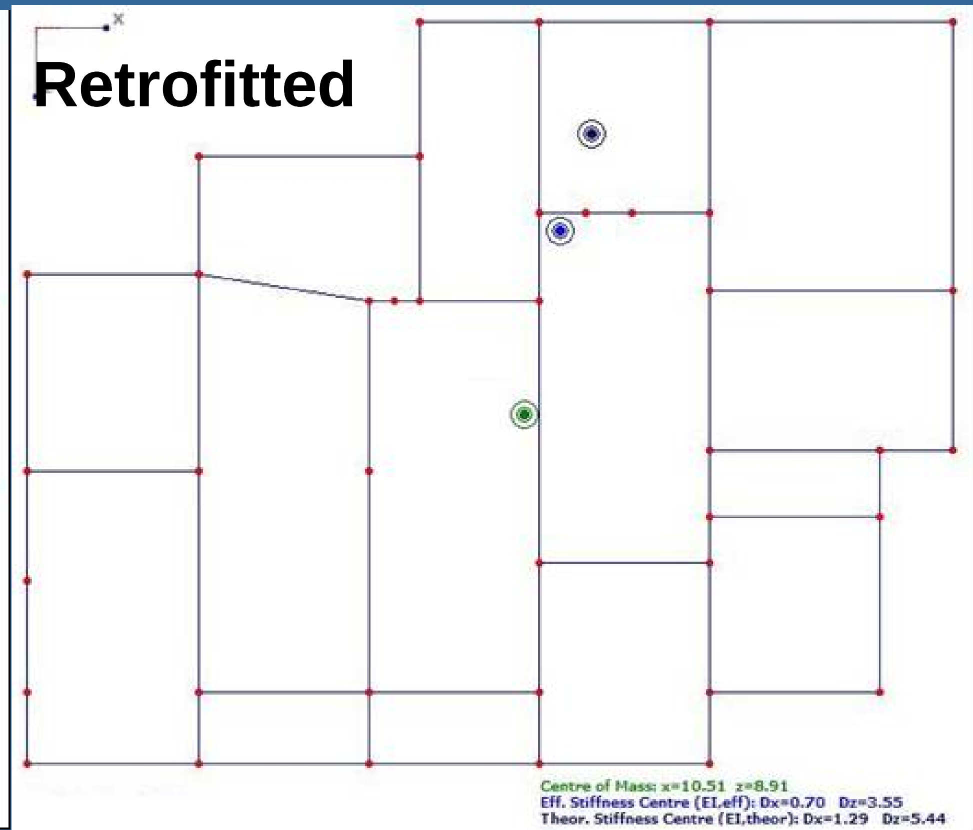


Foundation of new walls



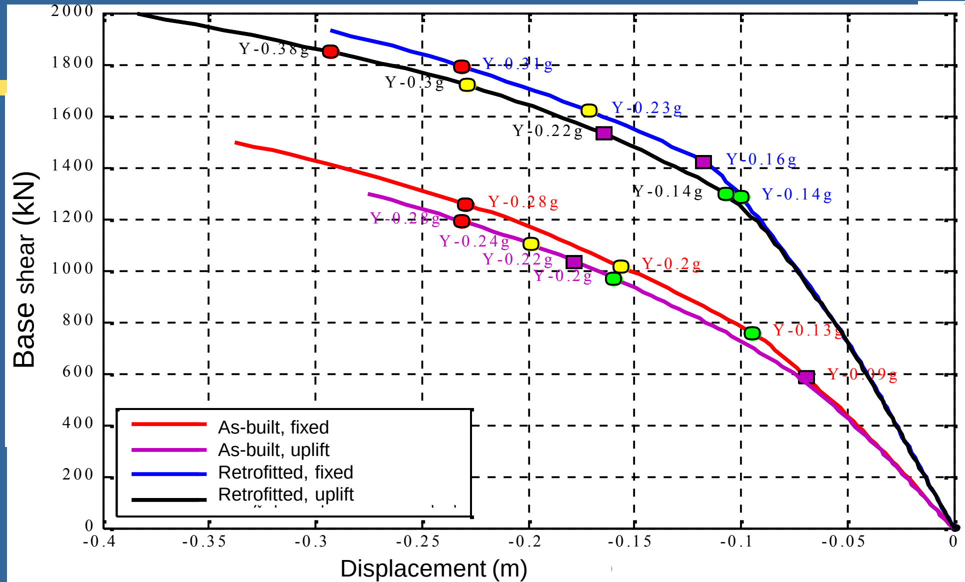
Static eccentricity between C.M. and C.S.

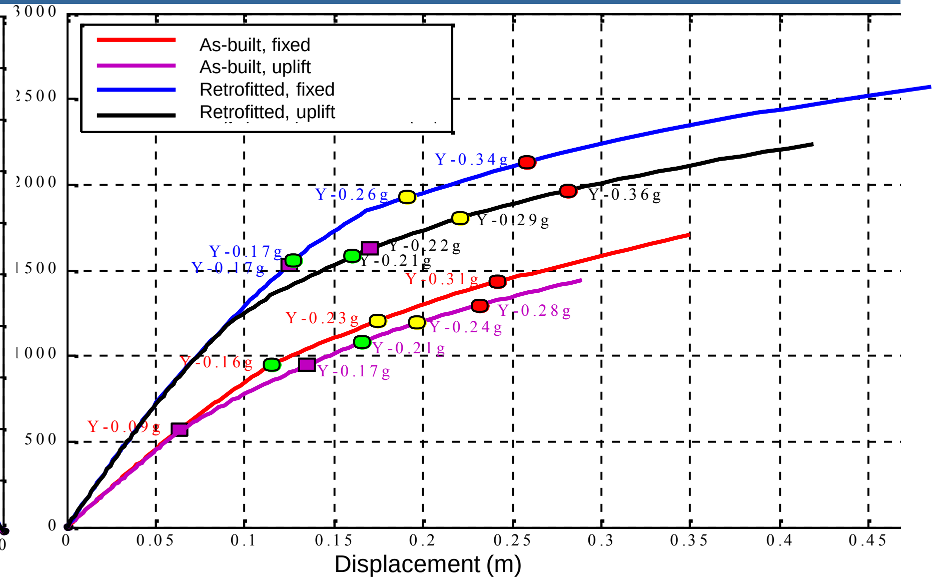




- No improvement (the contrary).
- But, although as-built building is torsionally flexible (torsional mode T > 1st translational mode T), the retrofitted one is not !

Pushover analysis, as built v retrofitted, ±X, ±Y, fixed v uplifting footings
*PGA at 1st exceedance of Limit State in **vertical elements***



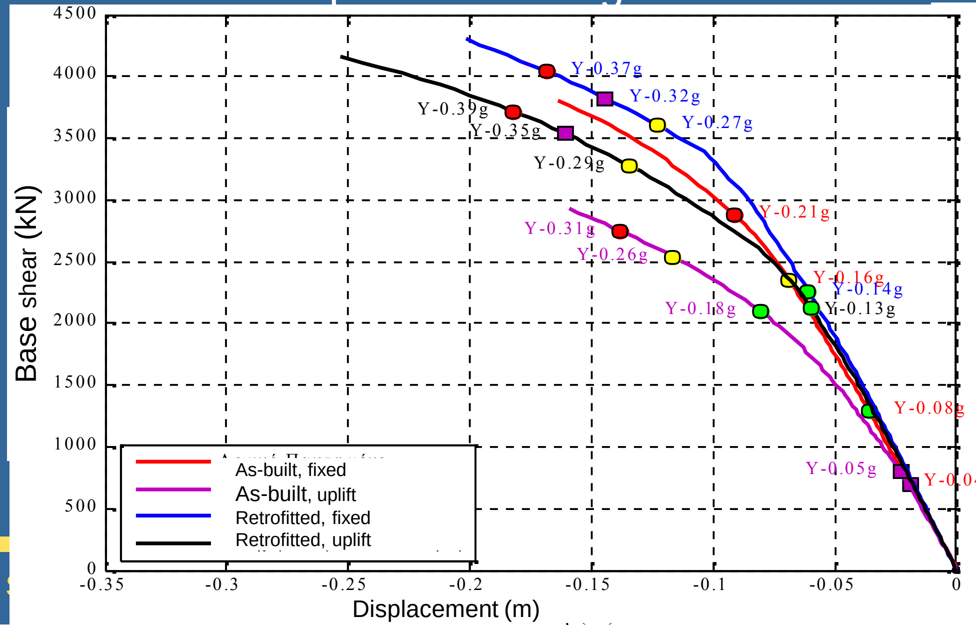


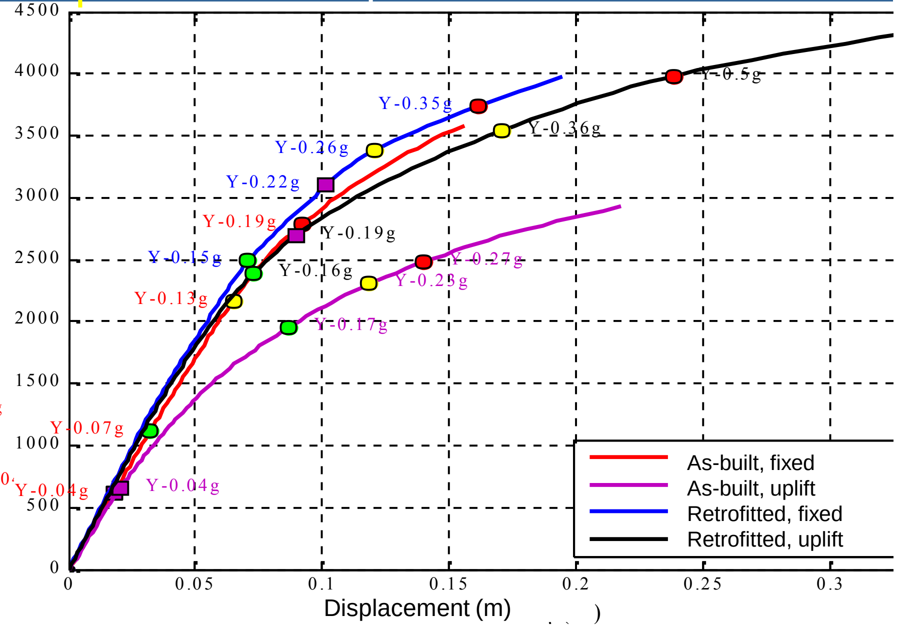
Green: Damage Limitation per EC8-3

Yellow: Significant Damage per EC8-3

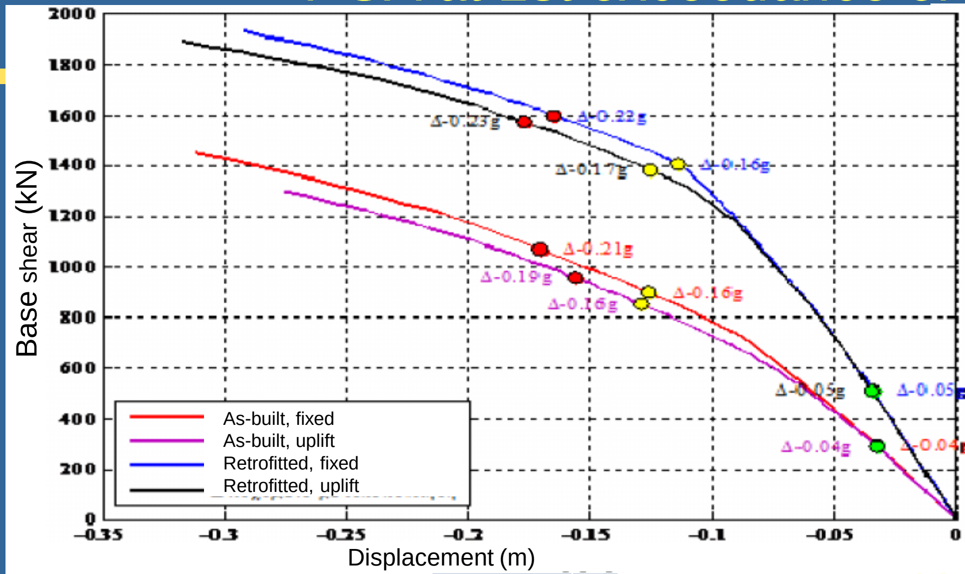
Red: Near Collapse in bending

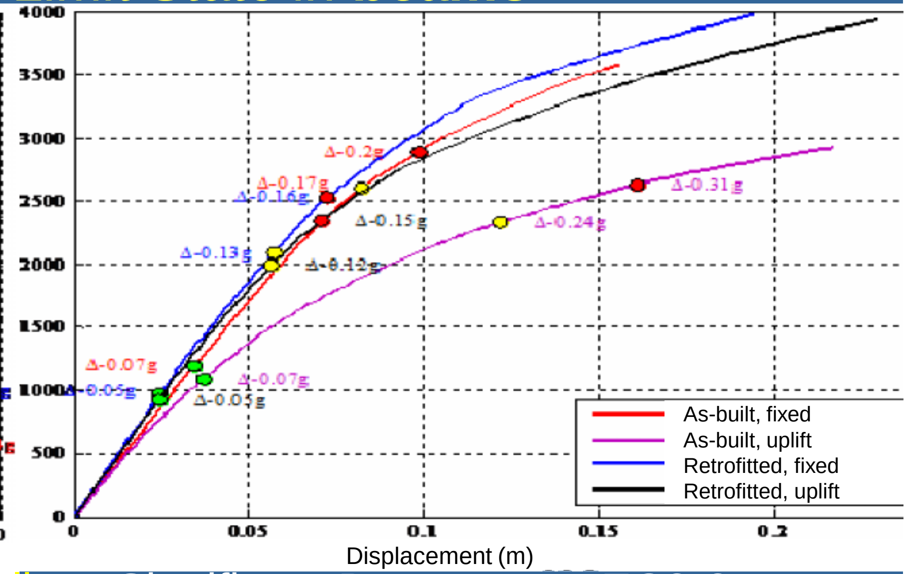
Purple: Near collapse in shear





*Pushover analysis, as built v retrofitted, ±X, ±Y, fixed v uplifting footings PGA at 1st exceedance of Limit State in **beams***



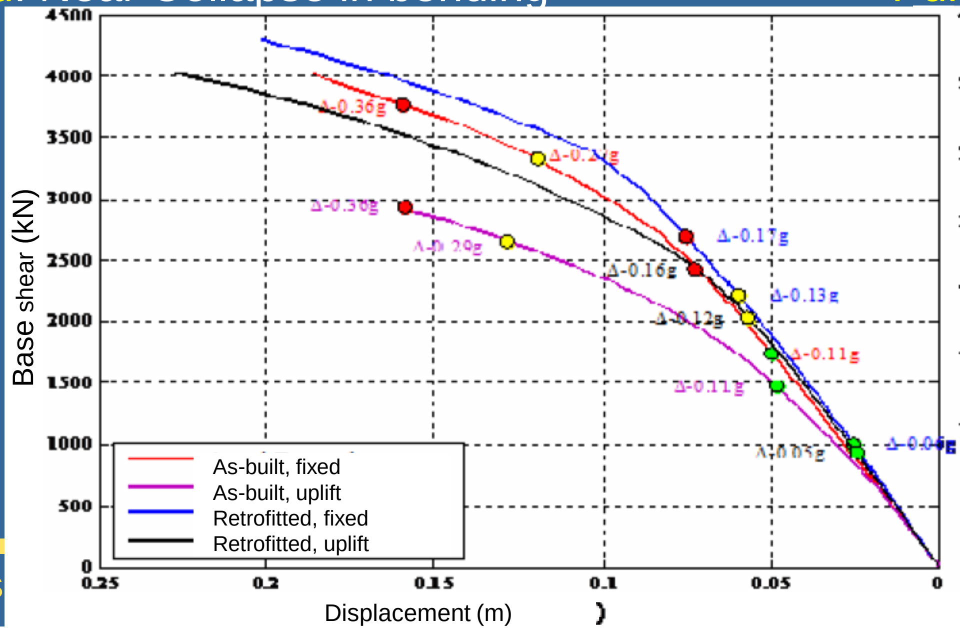


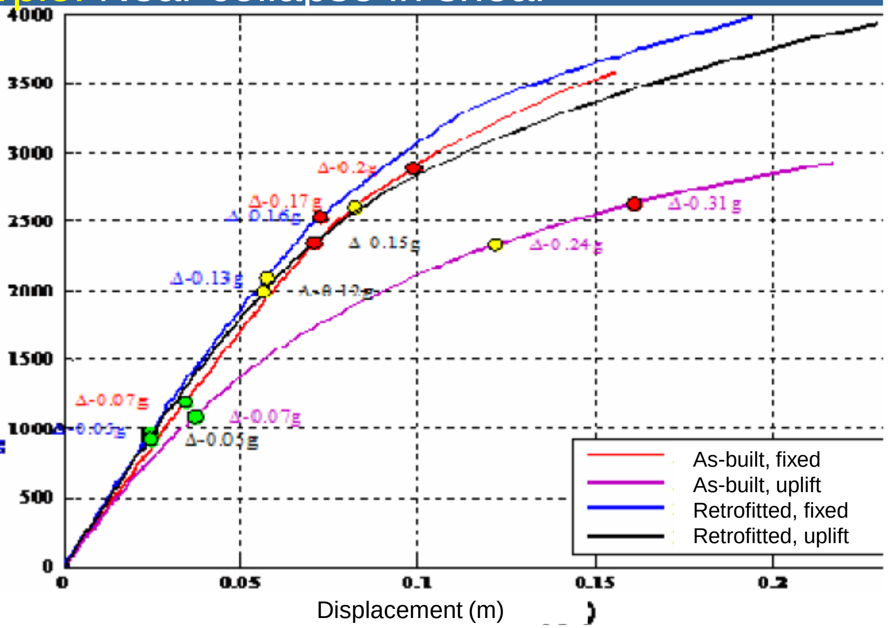
Green: Damage Limitation per EC8-3

Red: Near Collapse in bending

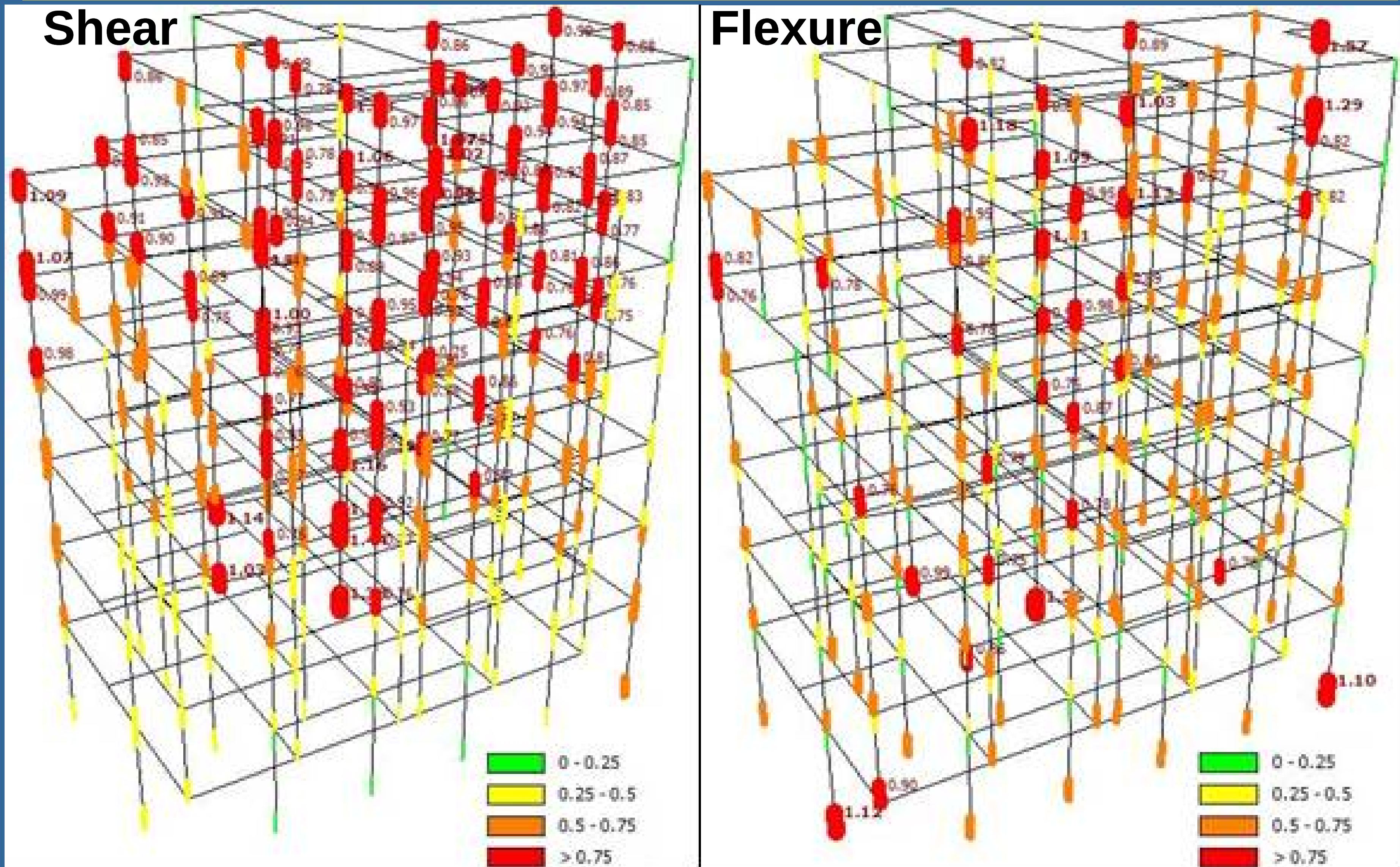
Yellow: Significant Damage per EC8-3

Purple: Near collapse in shear



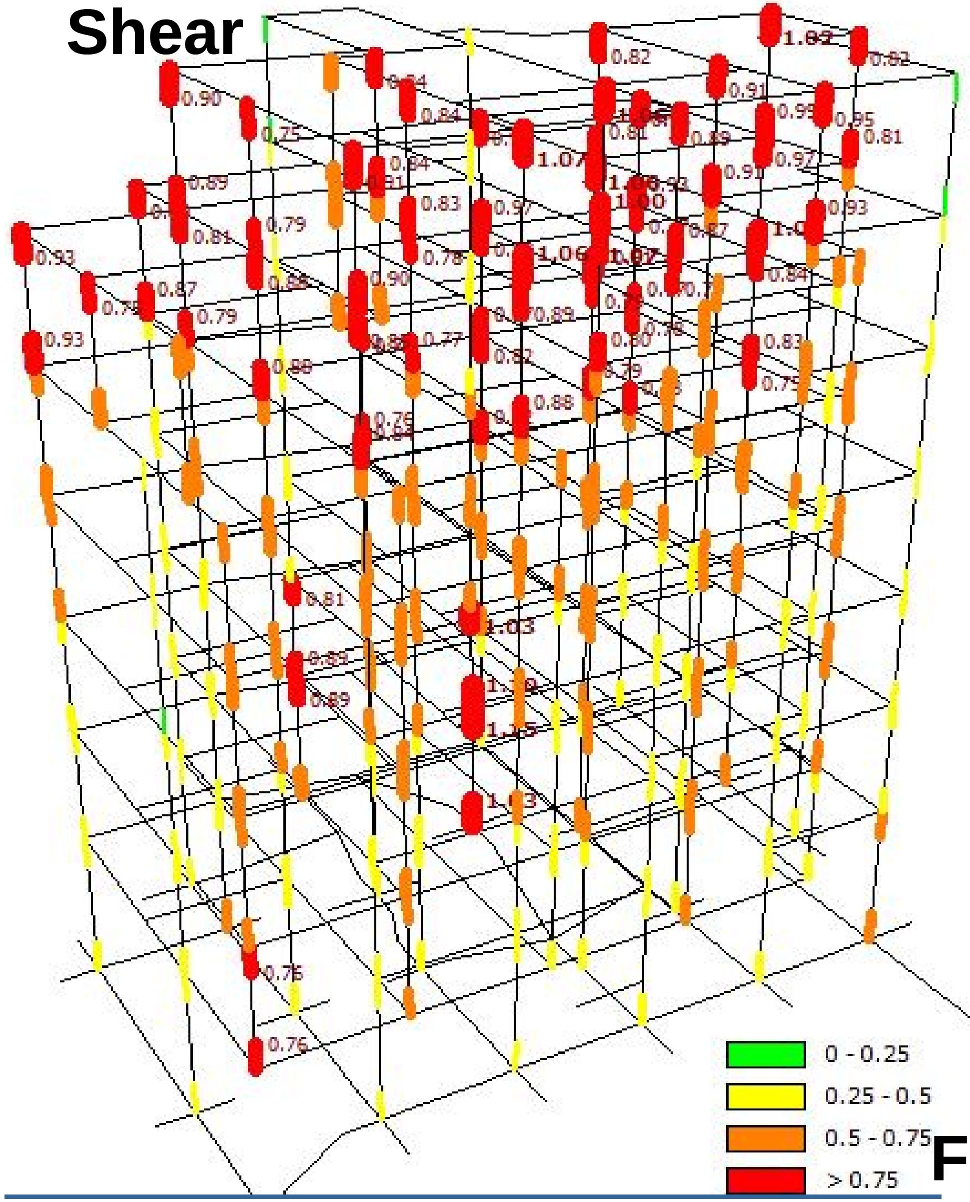


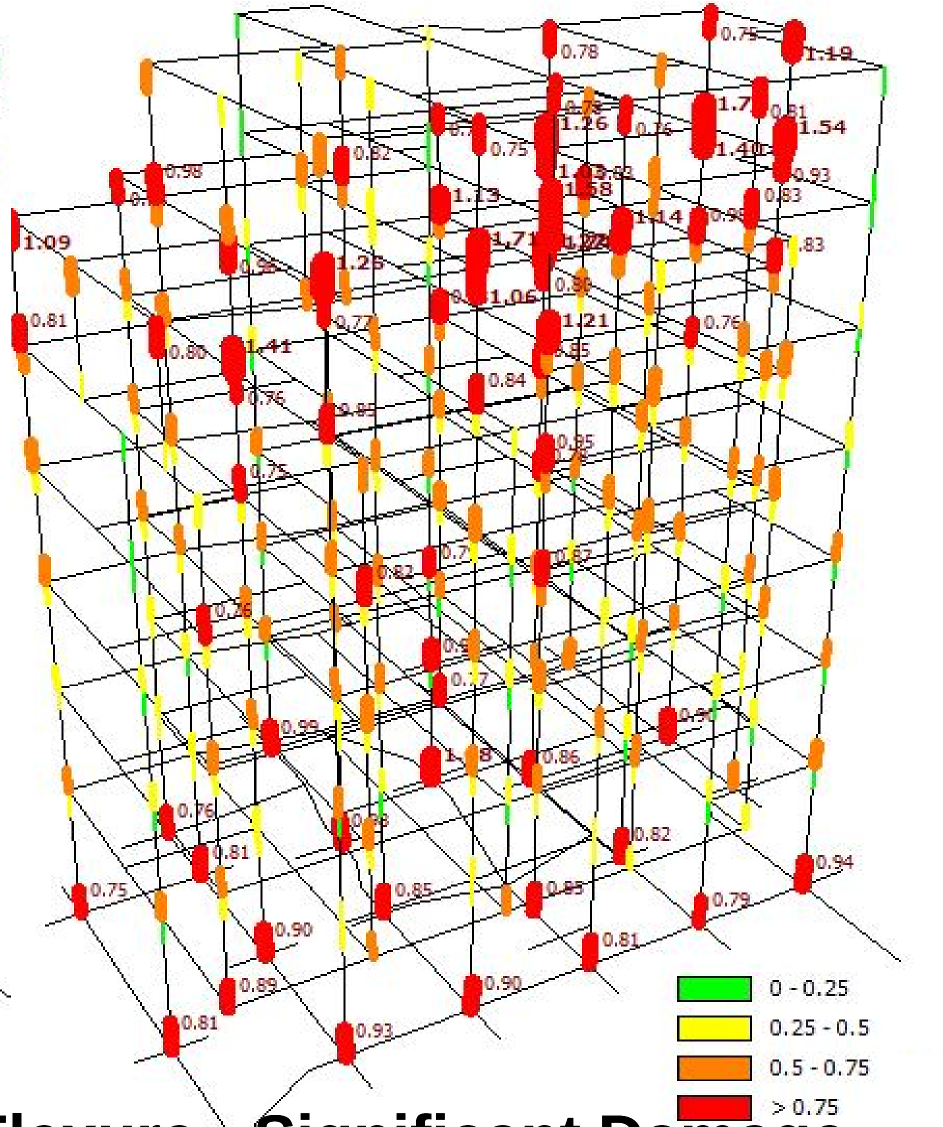
*Shear & flexural DI of **vertical elements** in retrofitted building for Significant Damage, nonlinear dynamic analysis (**fixed** footings, av/ge over 14 records 0.25g)*



*Shear & flexural DI of **vertical elements** in retrofitted building, Significant Damage, nonlinear dynamic analysis (**uplifting** footings, av/ge over 14 records 0.25g)*

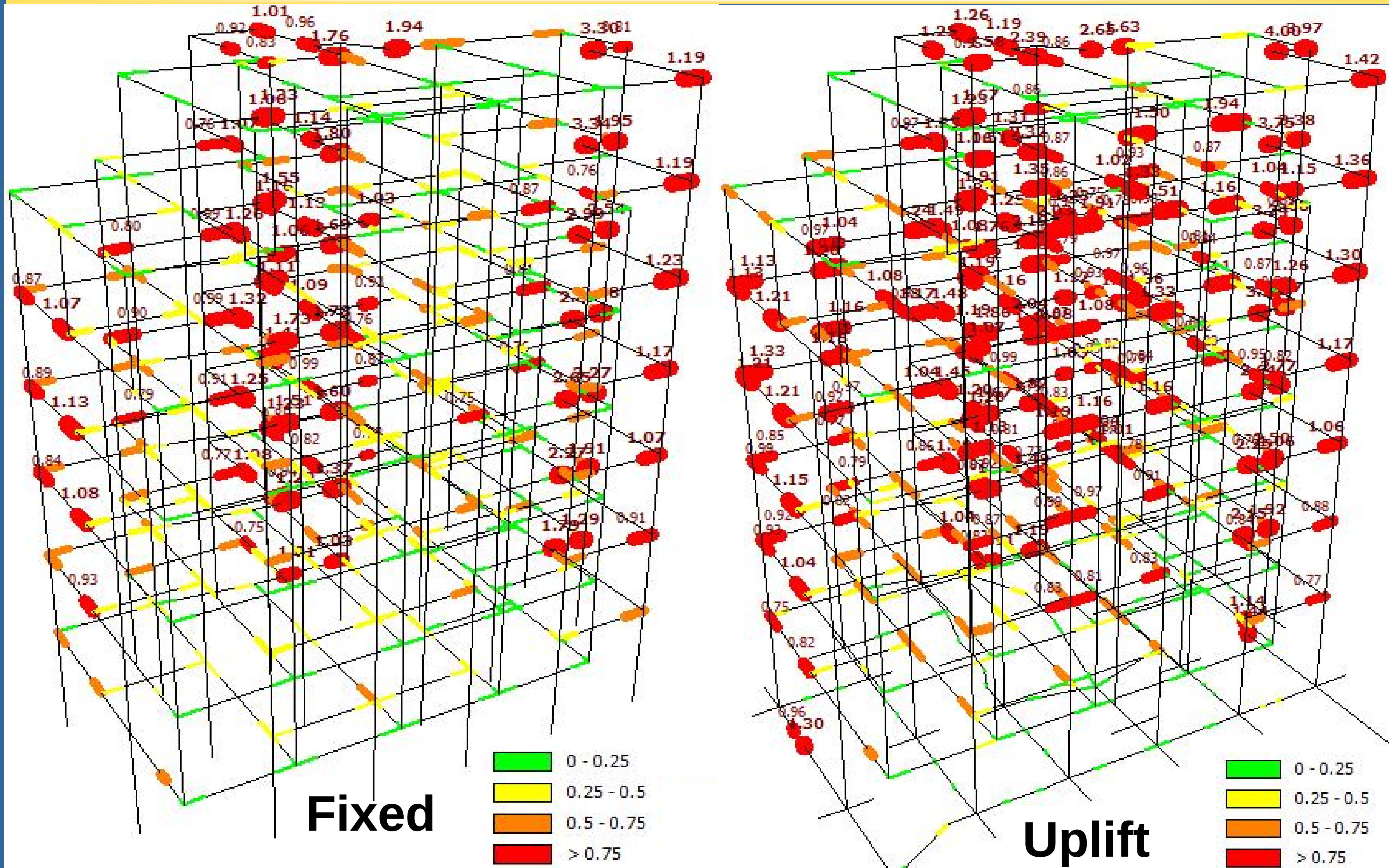
Shear





Flexure - Significant Damage

*Flexural DI in **beams** of retrofitted building for Significant Damage, nonlinear dynamic analysis (fixed v uplifting footings, av/ge over 14 records, 0.25g)*



Conclusions from retrofitted 7-storey building with fixed or uplifting footings

Fixed footings

- New walls TN2, TN3, the elevator wall & some columns of the setbacks, don't meet the flexure limit at Significant Damage LS.
- New wall TN1 fails in shear.
- More damage in beams compared to the as-built building.

Uplifting footings

- Although column DI-values increase, "Significant Damage" LS is met, except for few columns at the setbacks.
- Wall DI-values drop < 1.0, except for elevator shaft wall (DI=1.08)
- Elevator wall & few columns of top floor ~fail to meet shear LS.
- Flexural damage in beams increases significantly.

In both cases CFRPs are added to fix the local shortfalls

*Cost of retrofitting 7-storey building for **fixed** footings*

Cost of added walls:

@ 90€ /m³ concrete
@ 1€ /kg steel
epoxy grouting: @ 9€/Φ20mm dowel
@ 7€/Φ12mm dowel

Wall	Starter bars plus dowels	Dowels doubling as starter bars
TN1	13600 €	9300 €
TN2	12700 €	8400 €
TN3	26200 €	19500 €
Total	**52500 €**	**37200 €**

Cost of adding CFRPs: @ 40€/m² CFRP ply

Vertical element	Story	DI to be made <1.0	required v provided CFRP	Cost €
Column 156	7th - base	1.18	0.08mm → **1 ply 0.12mm**	20
Column 157	7th - base	1.29	0.14mm → 2 **plies 0.24mm**	40
Column 157	7th - top	1.57	0.24mm → 2 **plies 0.24mm**	40
Column 132	6th - base	1.13	0.73mm → 6 **plies 0.72mm**	260
Elevator wall	1st	1.40	**1 ply, 150mm strips / 125mm**	1150
Elevator wall	2nd	1.16	**1 ply, 100mm strips / 200mm**	370
Total				**1880**

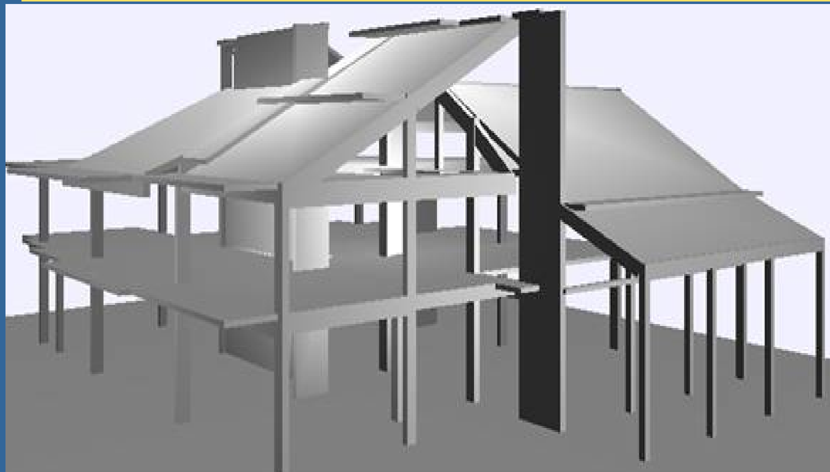
*Cost of retrofitting 7-storey building for **uplifting** footings*

Cost of added walls the same as for fixity

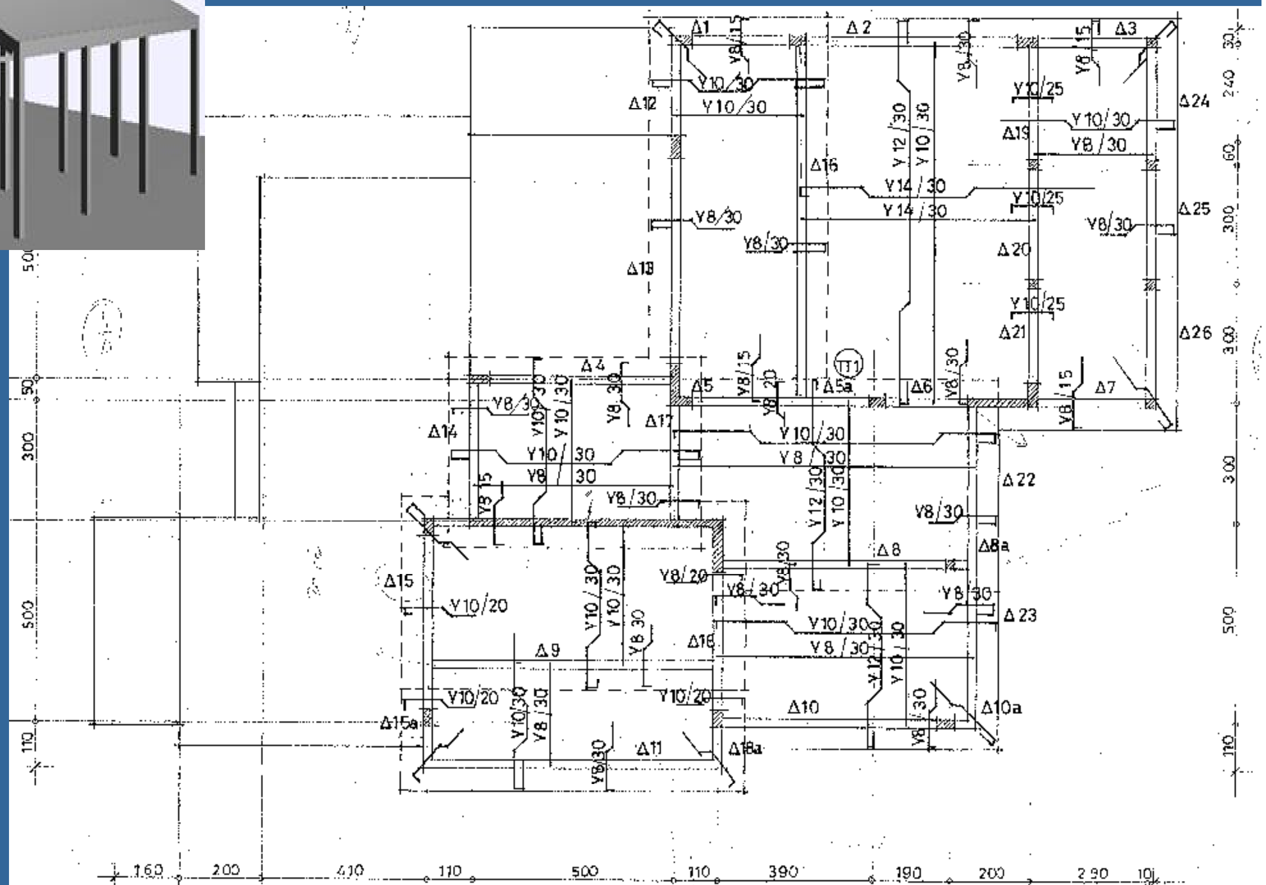
Cost of adding CFRPs, @ 40€ /m^2 CFRP ply

Vertical element	Story	DI to be made <1.0	required v provided CFRP	Cost €
Column 163	7th – base	1.71	0.52mm → **4 plies 0.48mm**	100
Column 163	6th – top	1.06	0.05mm → **1 ply 0.12mm**	30
Column 161	6th – base	1.21	0.184mm → **2 plies 0.24mm**	50
Column 161	7th – base	1.22	0.19mm → **2 plies 0.24mm**	50
Column 161	7th – top	1.26	0.22mm → **2 plies 0.24mm**	50
Column 127	6th – base	1.14	0.58mm → **5 plies 0.60mm**	200
Column 154	7th – base	1.70	0.51mm → **4 plies 0.48mm**	200
Column 154	6th – top	1.40	0.33mm → **3 plies 0.36mm**	80
Column 157	7th – base	1.54	0.24mm → **2 plies 0.24mm**	40
Elevator wall	1st	1.15	**1 ply, 100mm strips / 200mm**	500
Elevator wall	2nd	1.10	**1 ply, 100mm strips / 300mm**	250
Total				**1550**

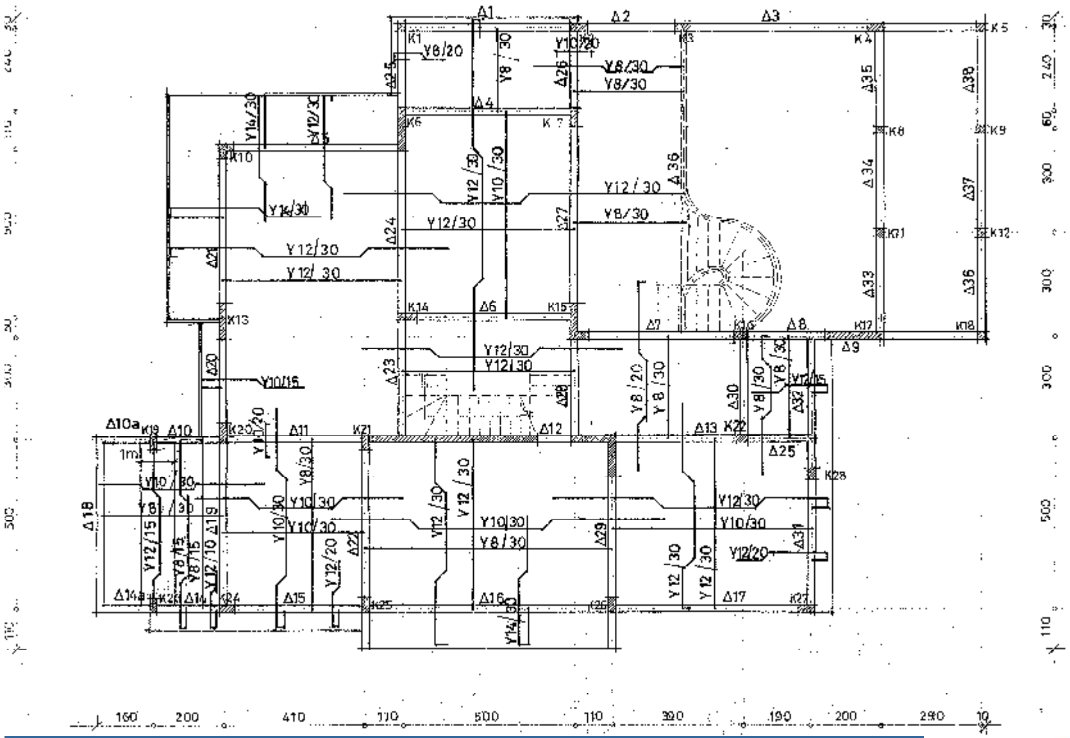
2-storey building



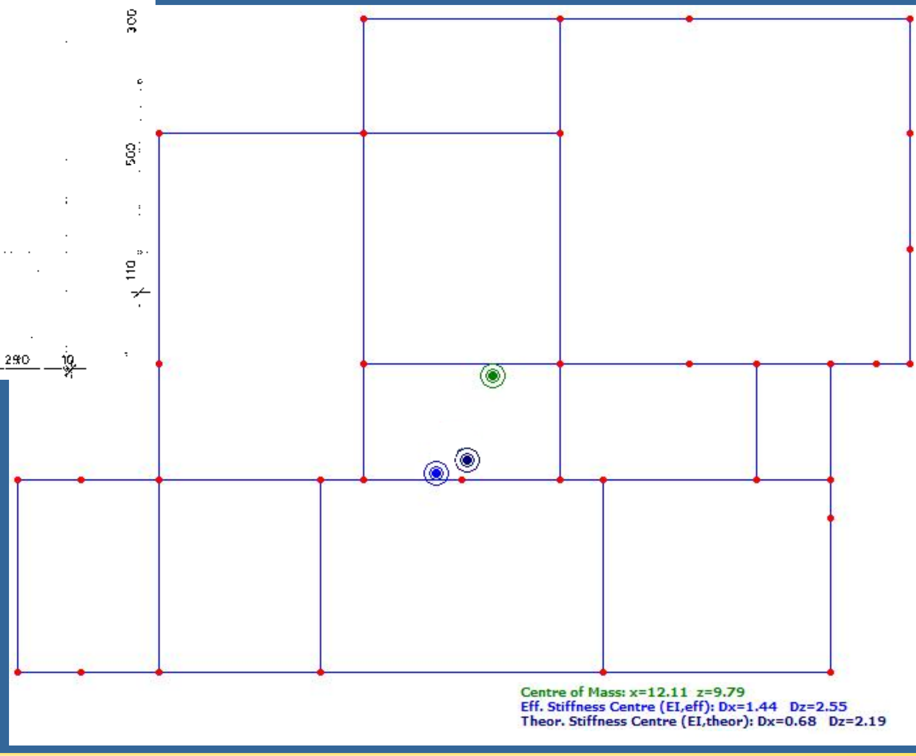
2nd storey



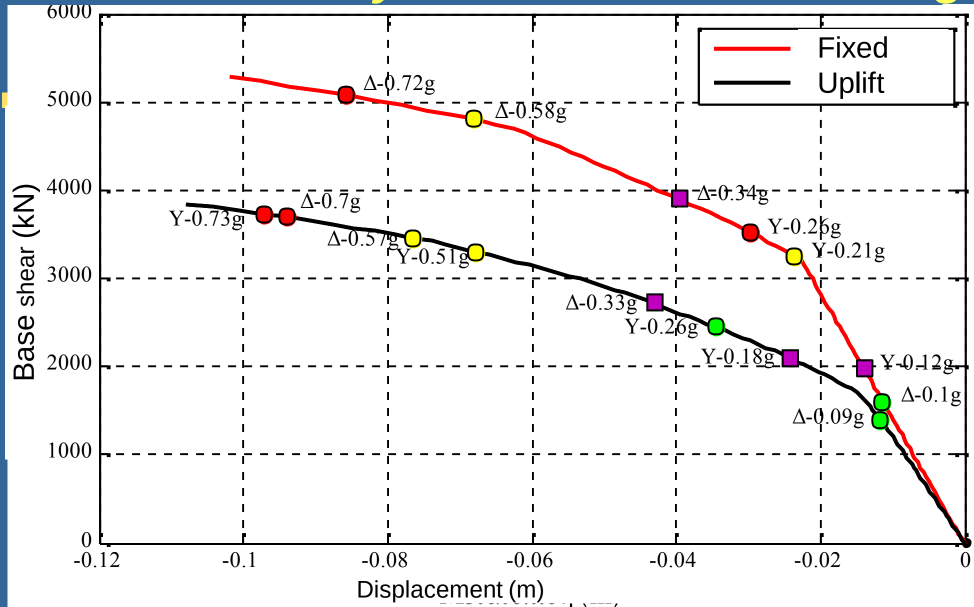
1st-storey slab – C.M. and C.S.

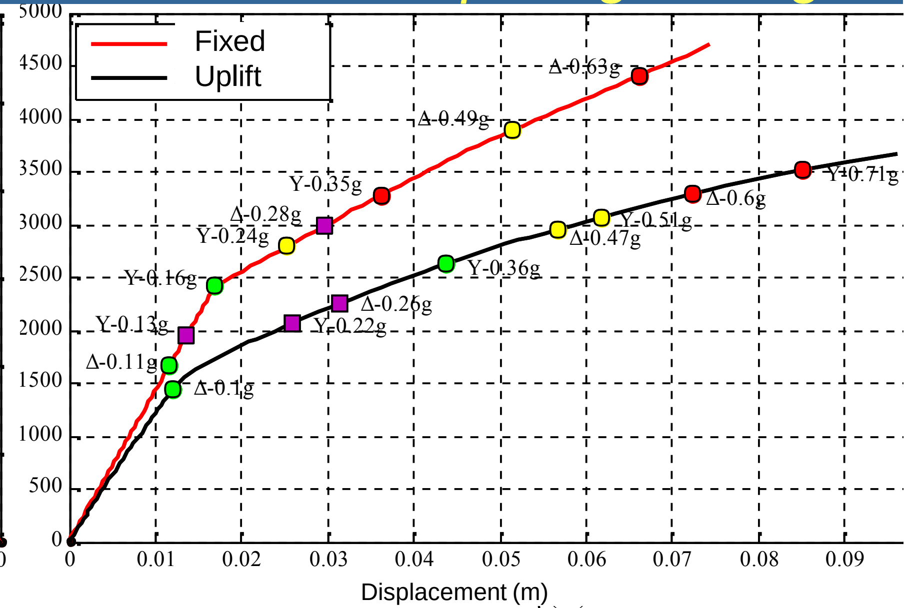


Torsionally flexible:
Torsional mode T > T of 1st translational mode in both directions



Pushover analysis of as-built building, ±X, ±Y, fixed v uplifting footings



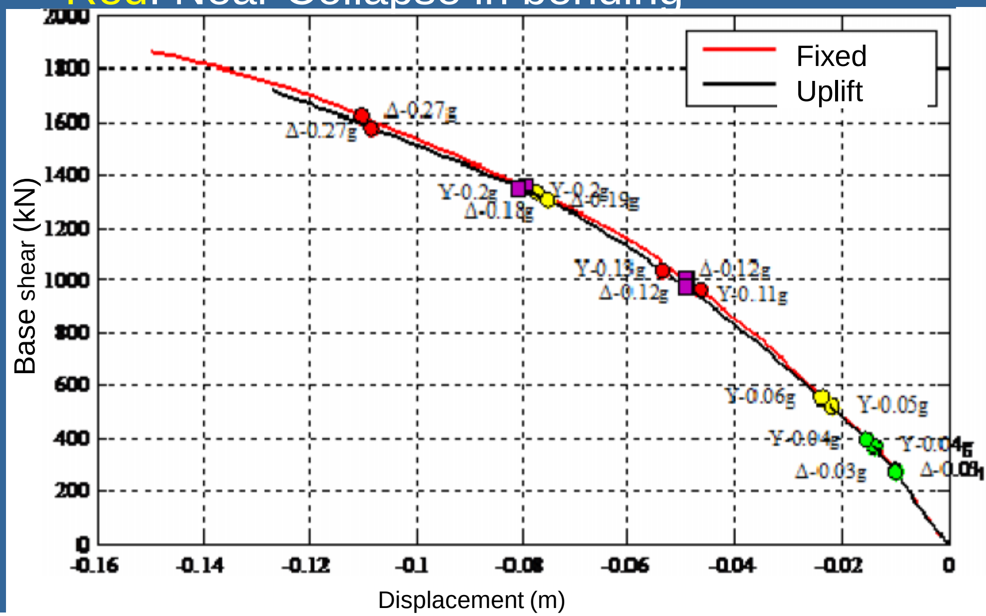


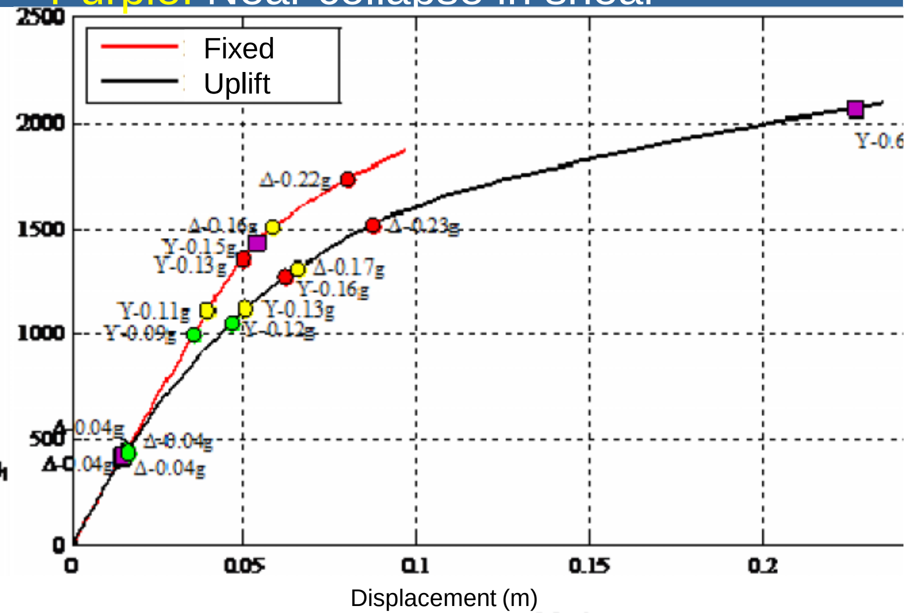
Green: Damage Limitation per EC8-3

Yellow: Significant Damage per EC8-3

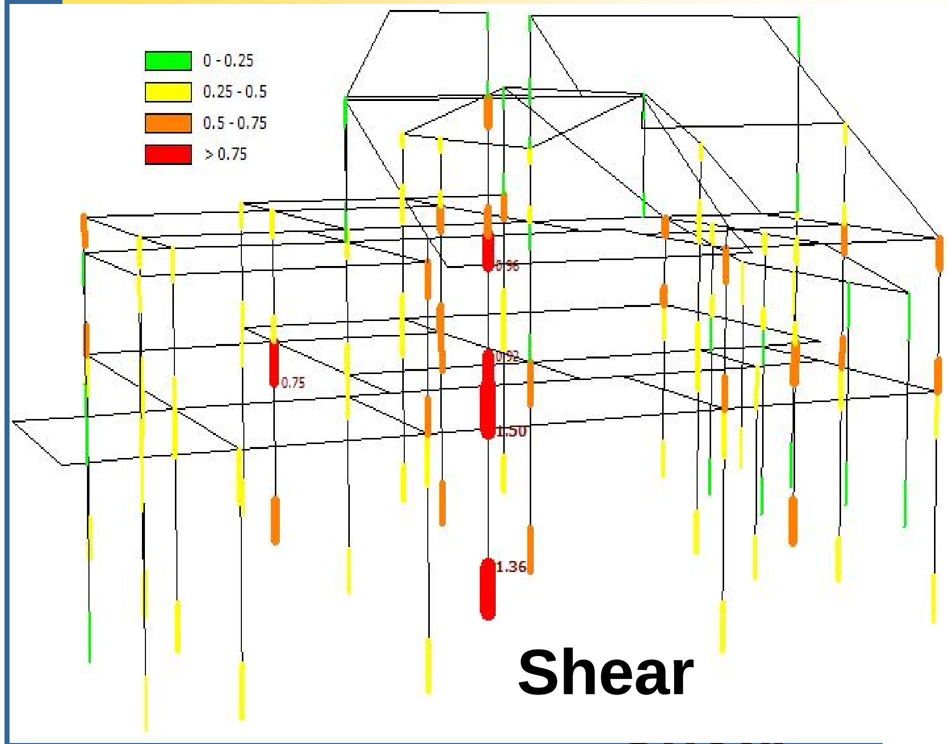
Red: Near Collapse in bending

Purple: Near collapse in shear

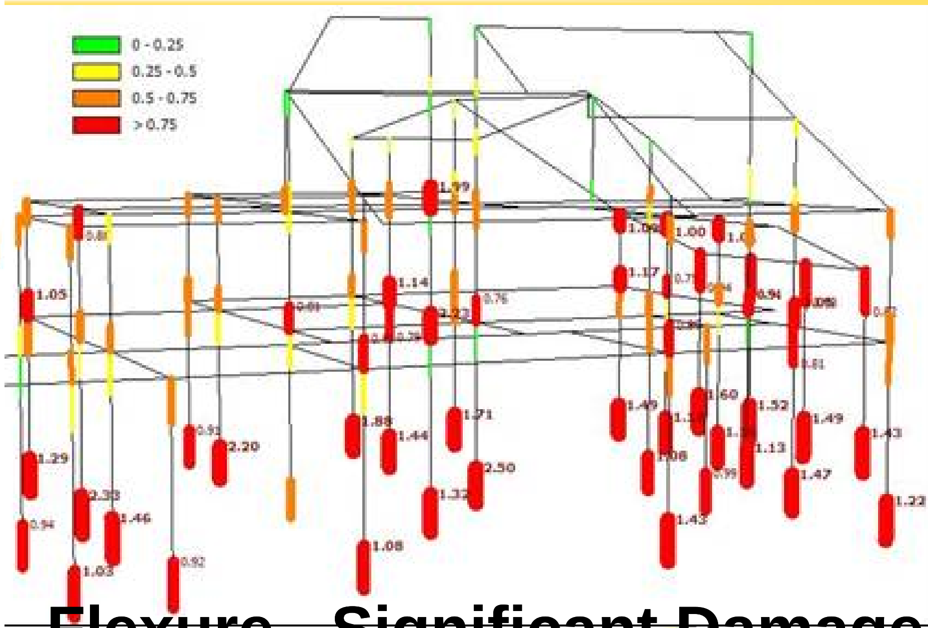




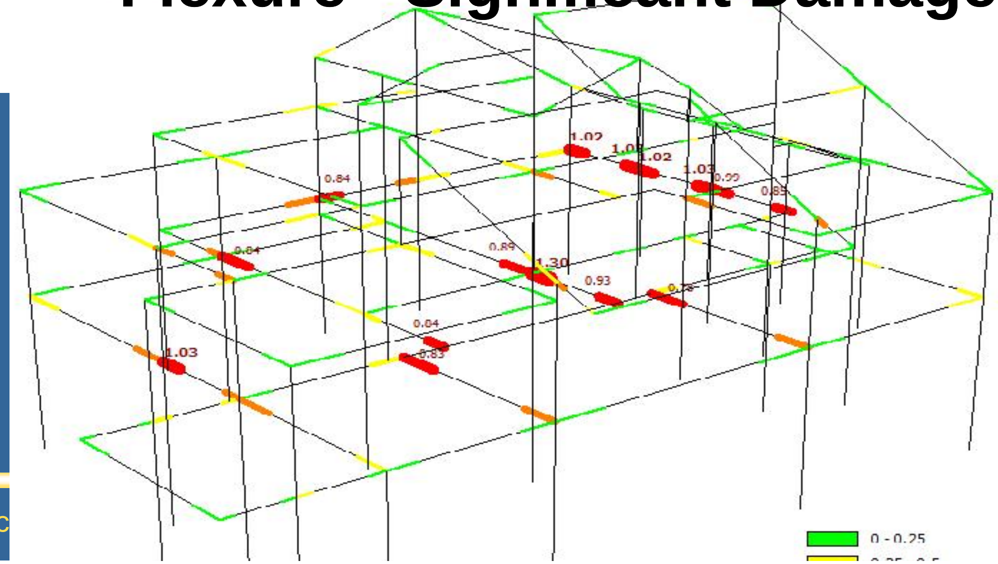
Shear & flexural damage index in as-built building, Significant Damage, nonlinear dynamic analysis (fixed footings, av/ge over 14 records 0.25g)



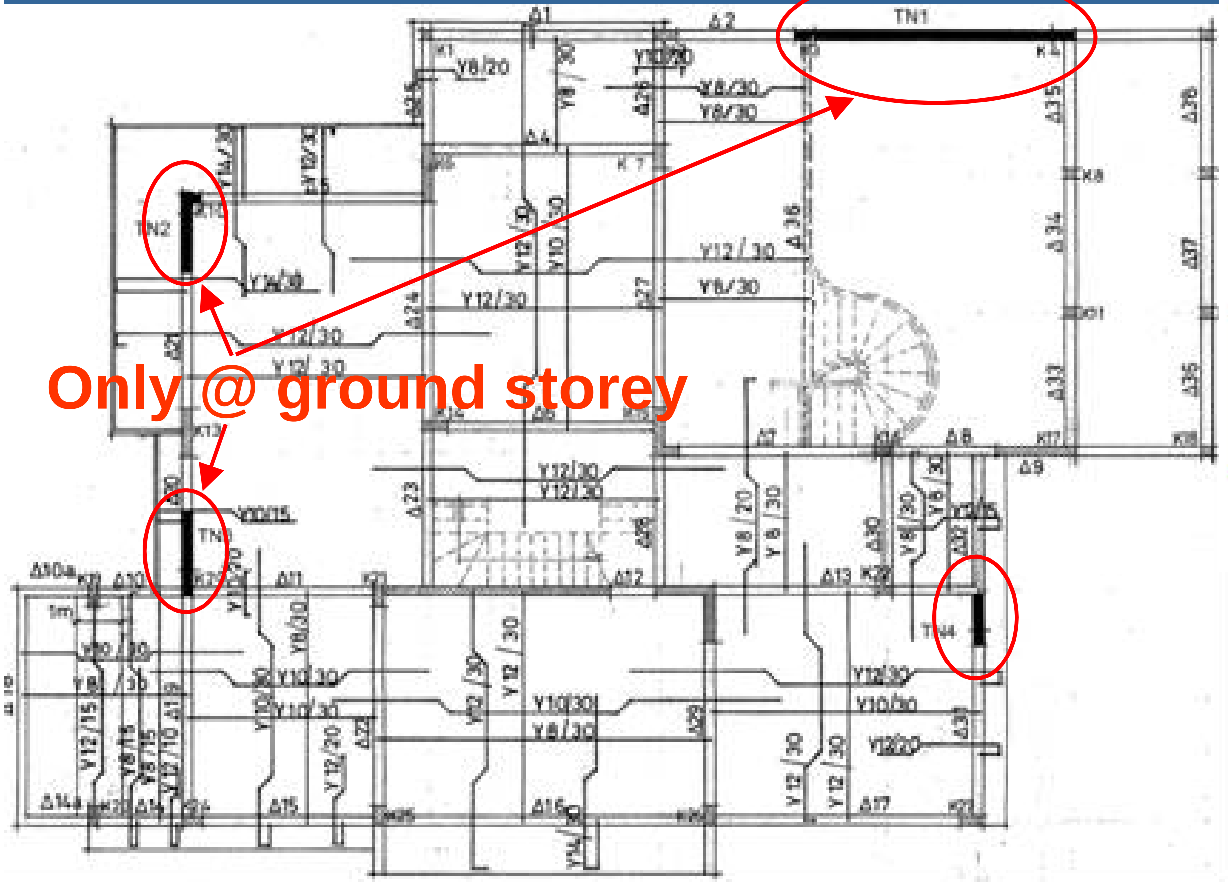
Shear

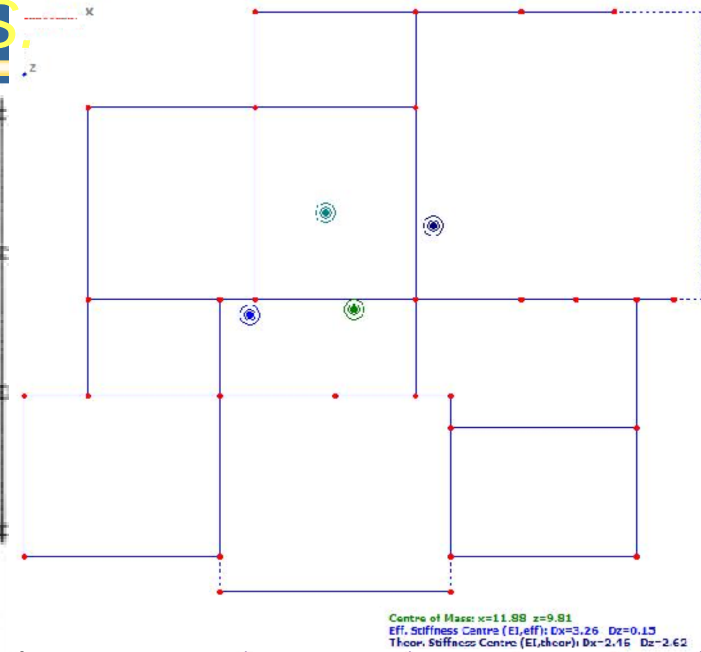


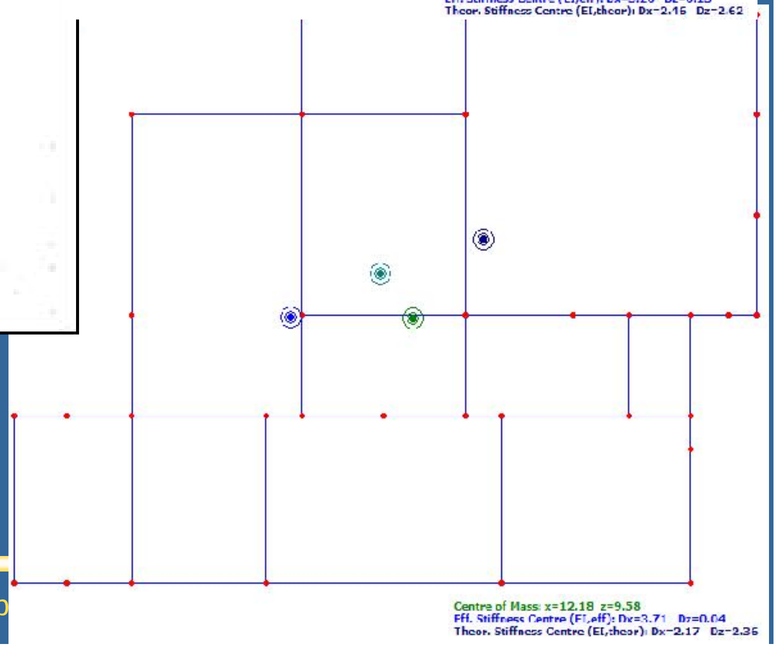
Flexure - Significant Damage



Seismic retrofit with walls - C.M. v C.S.

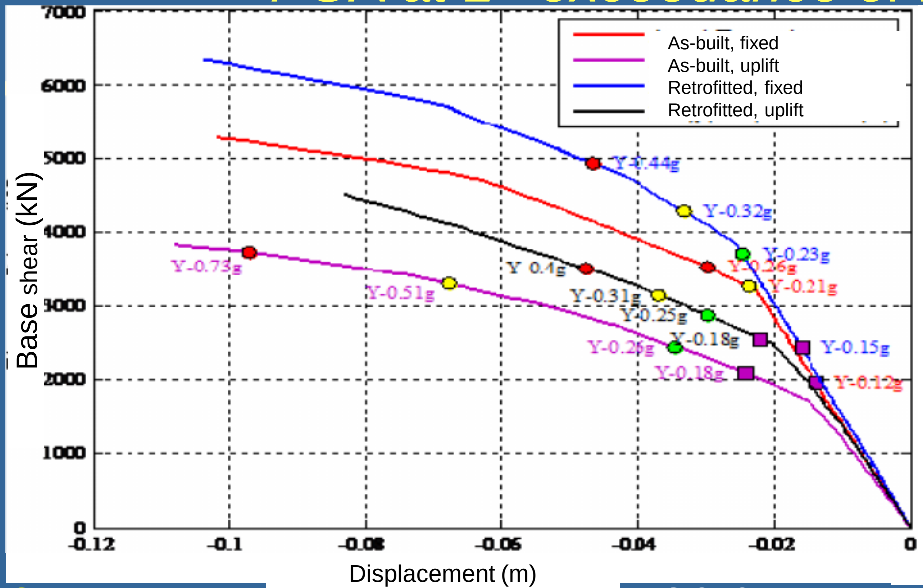


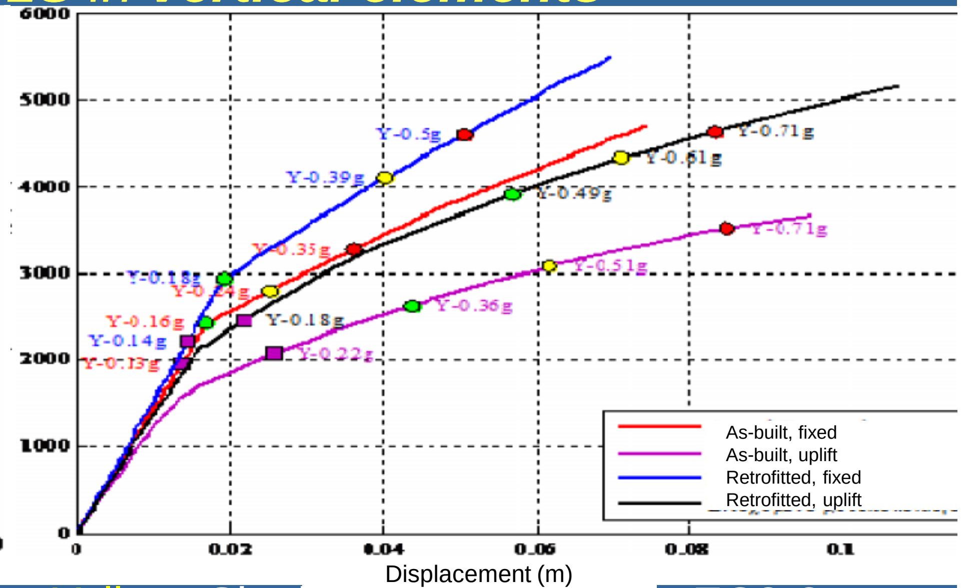




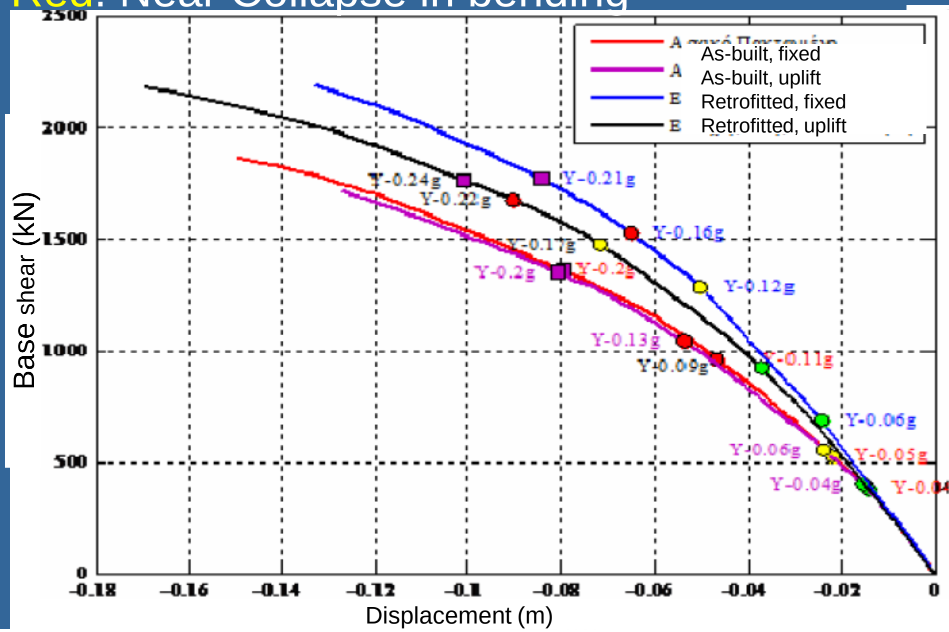
Remains torsionally flexible (torsional mode T > 1st translational mode T in one direction)

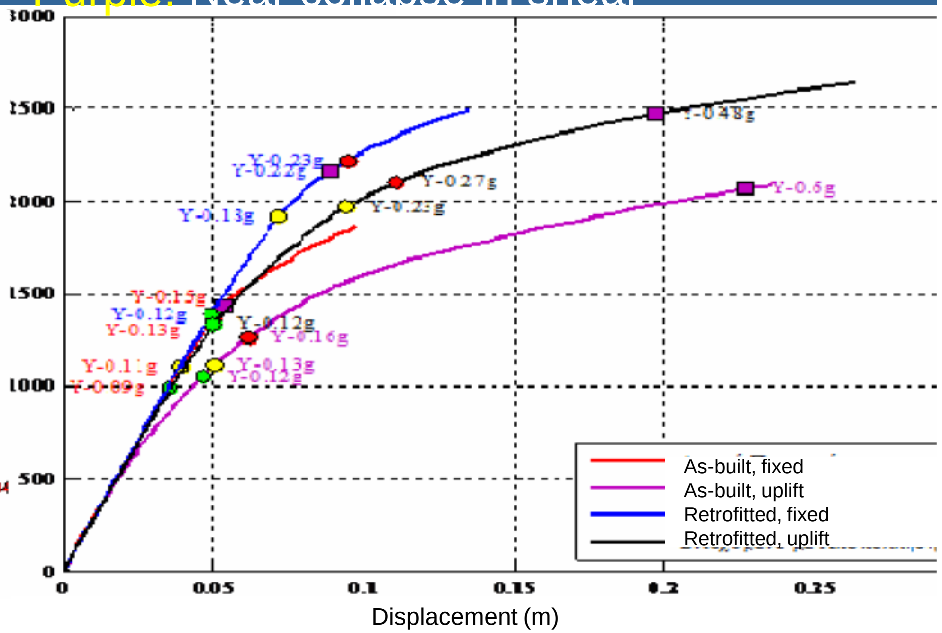
*Pushover analysis of as-built building ±X, ±Y, fixed v uplifting footings, PGA at 1st exceedance of LS in **vertical elements***



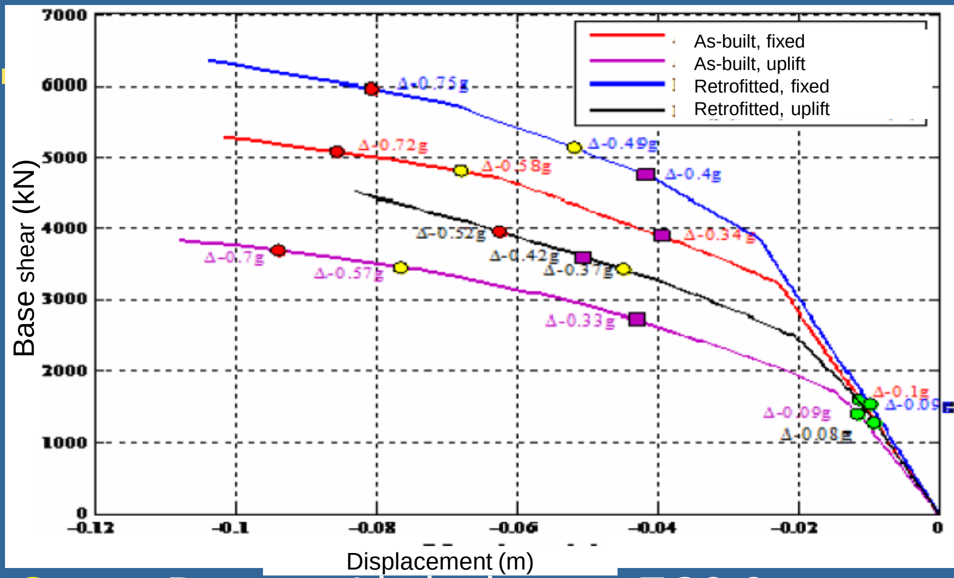


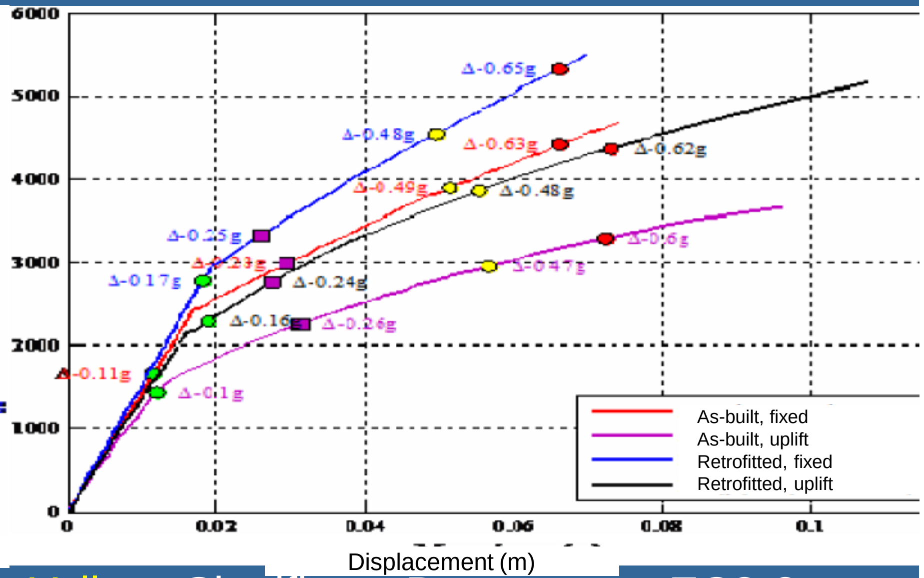
Green: Damage Limitation per EC8-3
Yellow: Significant Damage per EC8-3
Red: Near Collapse in bending
Purple: Near collapse in shear





*Pushover analysis ±X, ±Y, fixed v uplifting footings, PGA at 1st exceedance of Limit State in **beams***



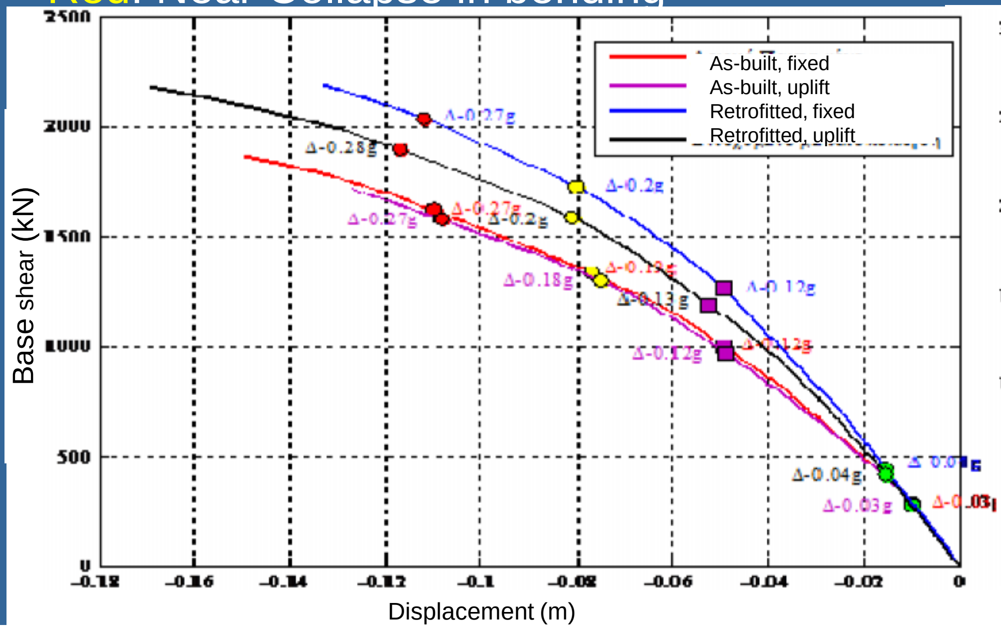


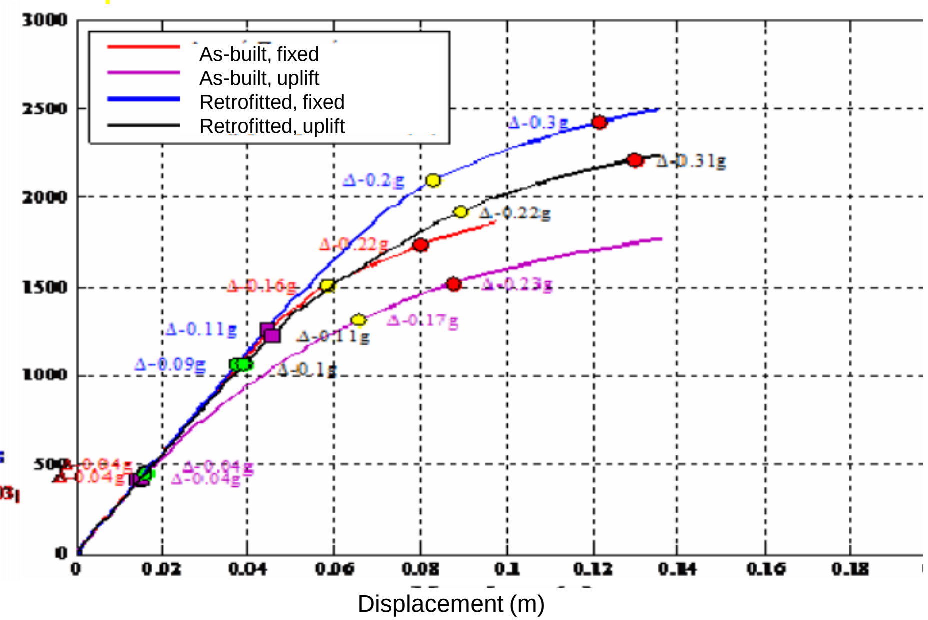
Green: Damage Limitation per EC8-3

Red: Near Collapse in bending

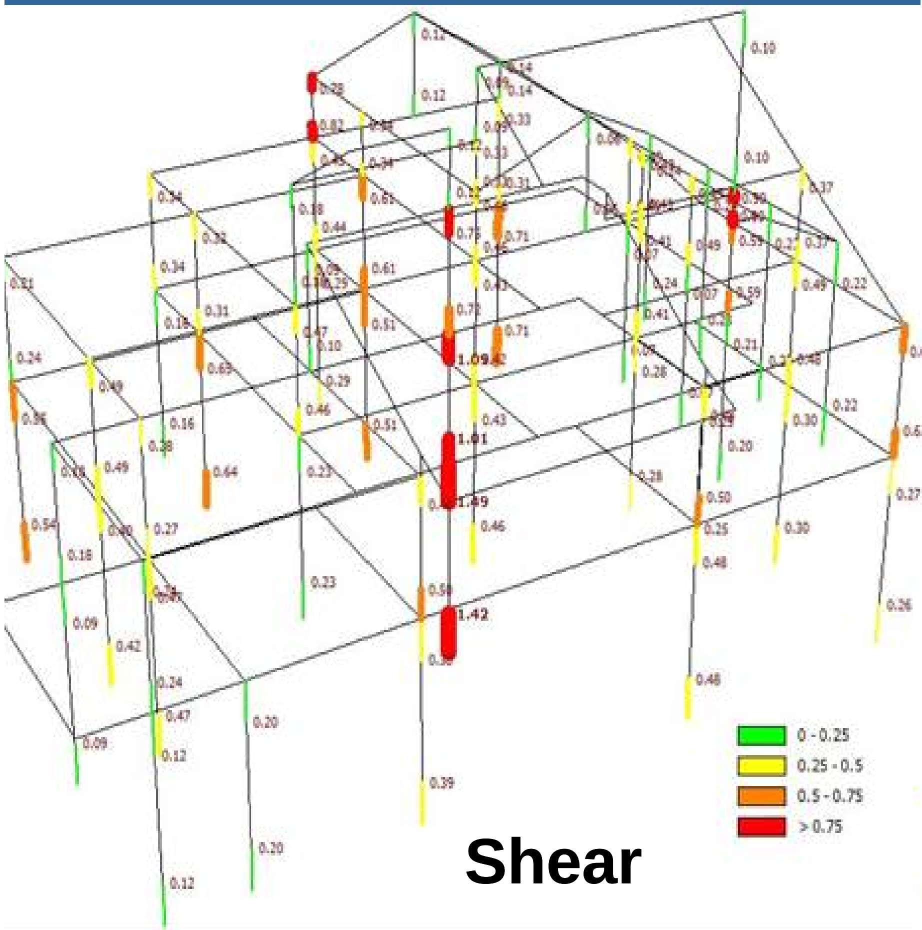
Yellow: Significant Damage per EC8-3

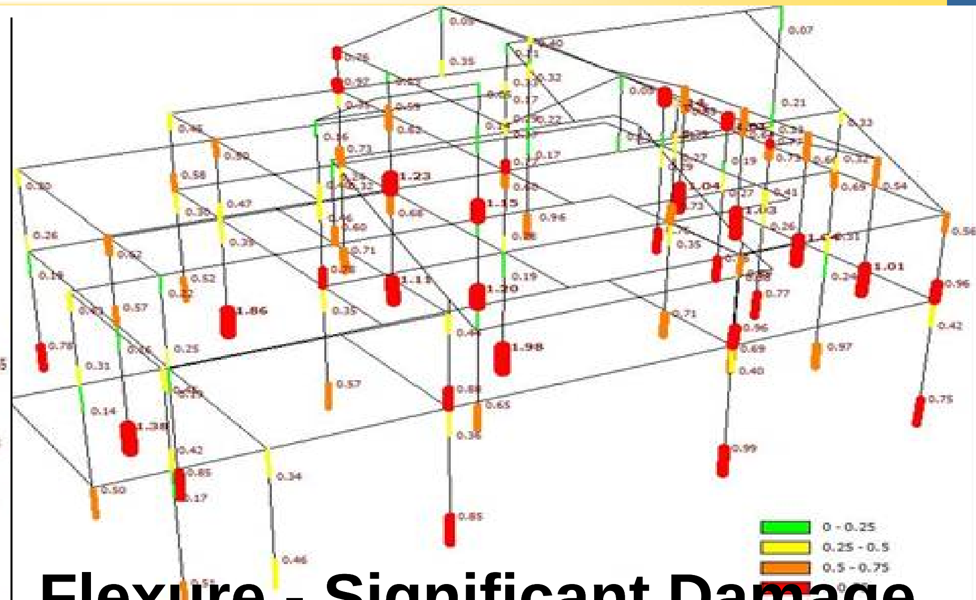
Purple: Near collapse in shear

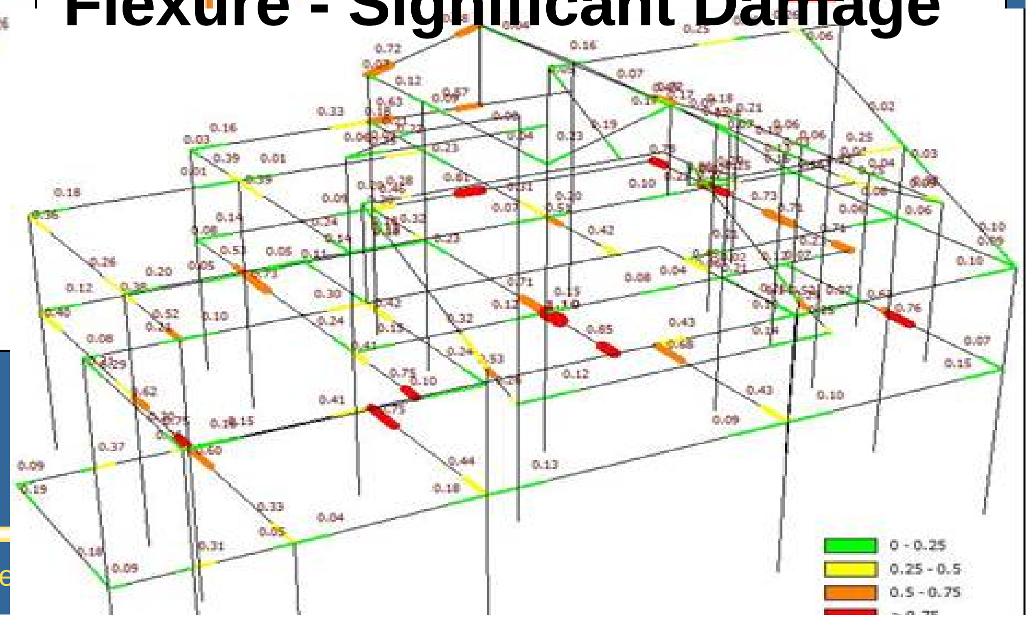




Shear & flexural damage index in retrofitted building for Significant Damage, nonlinear dynamic analysis (fixed footings, av/ge over 14 records, 0.25g)







Conclusions from retrofitted 2-storey building with fixed or uplifting footings

- Flexural damage indices at column bases are reduced compared to as-built, but the “Significant Damage” Limit State still not met.

- Adding new walls does not prevent failure of the interior large wall.

- Flexural damage indices in beams increase compared to the as-built

- Retrofit with new walls at the perimeter is insufficient. Additional retrofit of other members w/ FRP jackets is necessary; it turns out to be very cost-effective.

Cost of retrofitting 2-storey building (considered with uplifting footings)

Cost of added walls:

@ 90€ /m^3 concrete
@ 1€ /kg steel
epoxy grouting @ 9€/Φ20mm dowel
@ 7€/Φ12mm dowel

Wall	Starter bars plus dowels	Dowels doubling as starter bars
TN1	6730 €	4550 €
TN2	2470 €	2230 €
TN3	1720 €	1640 €
TN4	1230 €	1230 €
Total	**12150 €**	**9650 €**

Cost of adding CFRPs:

@ 40€ /m^2 CFRP ply

Vertical element	Story	DI to be made <1.0	required v provided CFRP	Cost €
Column 7	1st - base	1.11	0.184mm → **2 plies 0.24mm**	60
Column 7	2nd - base	1.23	0.364mm → **3 plies 0.36mm**	90
Column 17	1st - base	1.01	0.005mm → **1 ply 0.12mm**	25
Column 11	1st - base	1.04	0.02mm → **1 ply 0.12mm**	25
Column 9	1st - base	1.03	0.016mm → **1 ply 0.12mm**	25
Column 39	1st - base	1.04	0.02mm → **1 ply 0.12mm**	25
central wall	1st - base	1.49	**1 ply, 100mm strips / 125mm**	2200
central wall	2nd - base	1.09	**1 ply, 50mm strips / 250mm**	400
Total				**2850**

Thank you !