**CATANIA E IL TERREMOTO: PREVENIRE O RICOSTRUIRE ?**

**11 Gennaio 2017**
**Aula Magna - Di3A, Via Santa Sofia, 98**

# Seismic vulnerability of Catania multi-storey buildings:

- **High fidelity model for seismic response prediction**
- **Innovative and traditional strategies**

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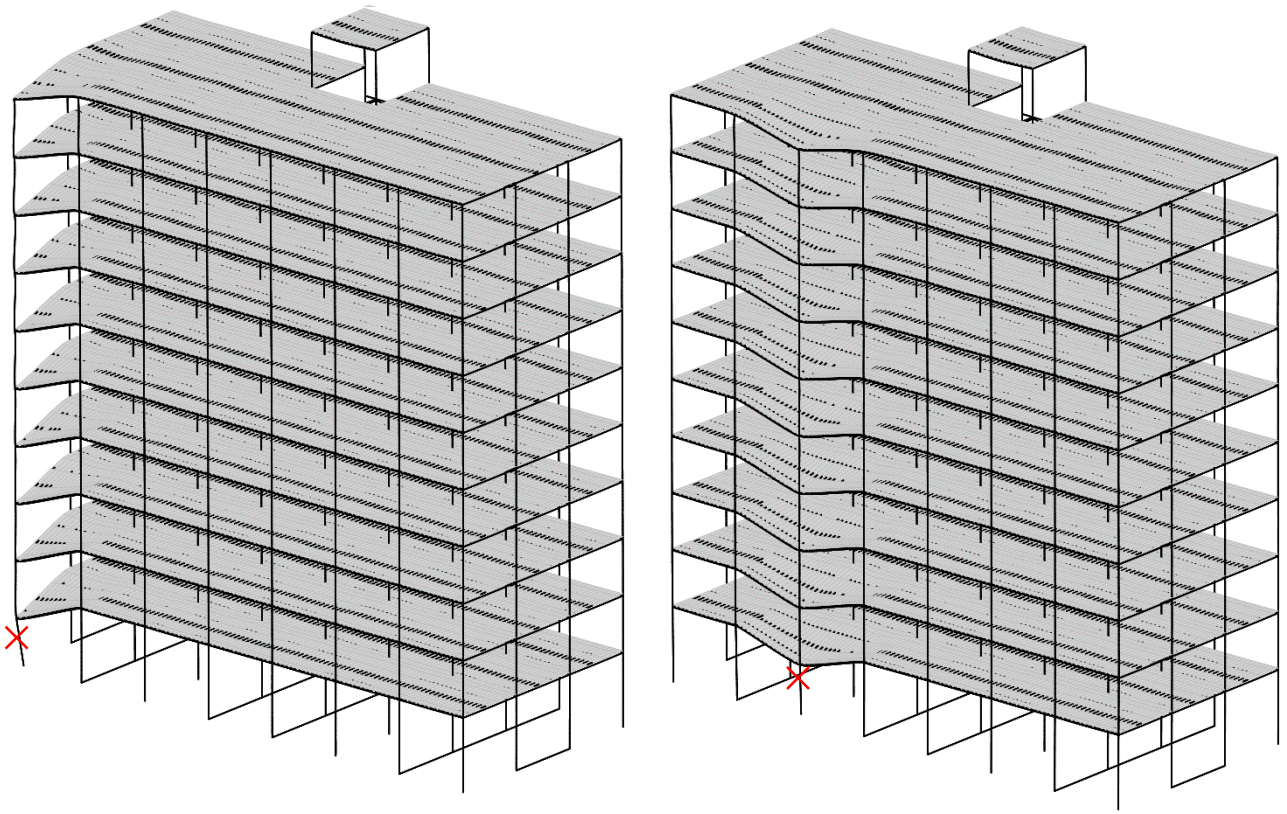
# High fidelity 3D nonlinear dynamic analysis: Benefits and importance

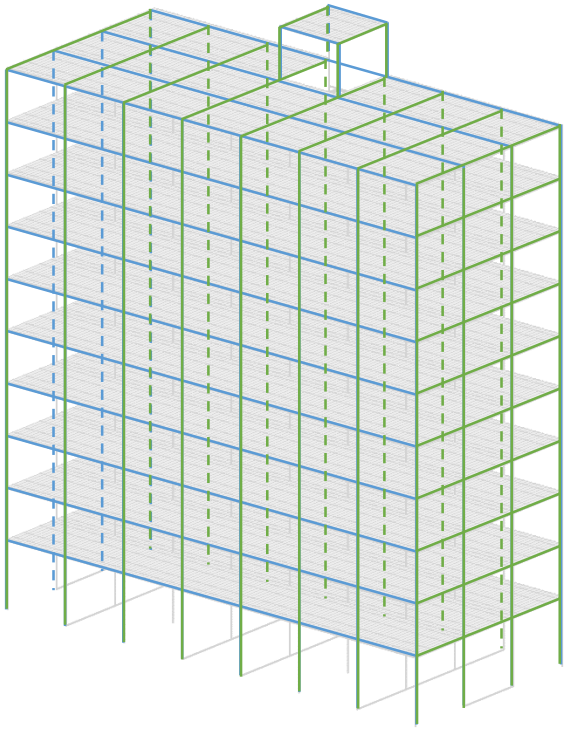
- Most realistic simulation
  - 3D: simultaneous seismic actions in 3 directions, interaction of different planar frames within building, torsional effects, …
  - High fidelity: combined response of 3D frame, floor slabs, infill panels, retrofitting system, …
  - Nonlinear: geometric nonlinearity, inelastic material response, internal force interactions under tri-directional seismic action, …
  - Dynamic: inertia effects, damping, disproportionate collapse, …
- Best prospect for reliable seismic assessment and optimal retrofitting for regular and irregular buildings

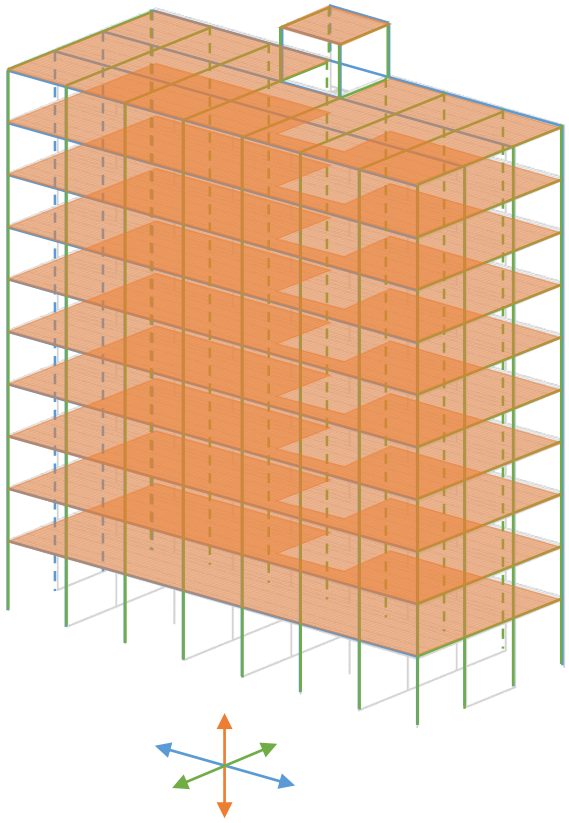
Onset of disproportionate collapse captured with 3D nonlinear dynamic analysis

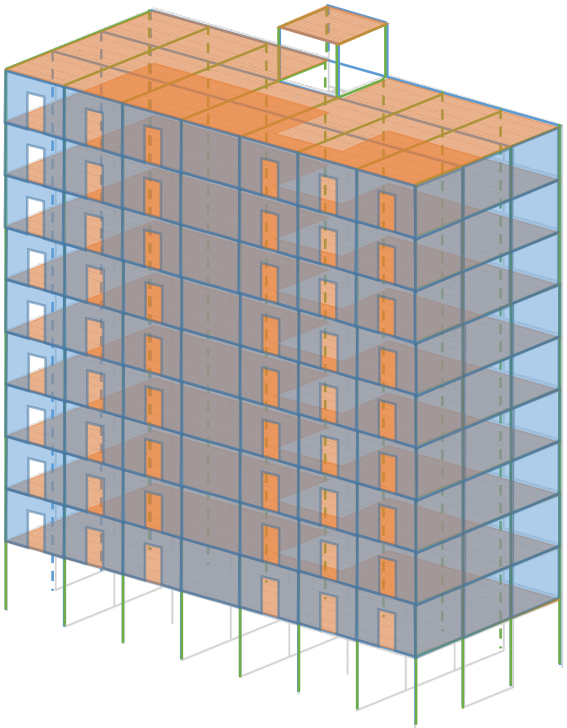


# High fidelity 3D nonlinear dynamic analysis: Requirements

- Earthquake records
- Information on structural and non-structural components
- Modelling of retrofitting system
- Reduction of computational demands

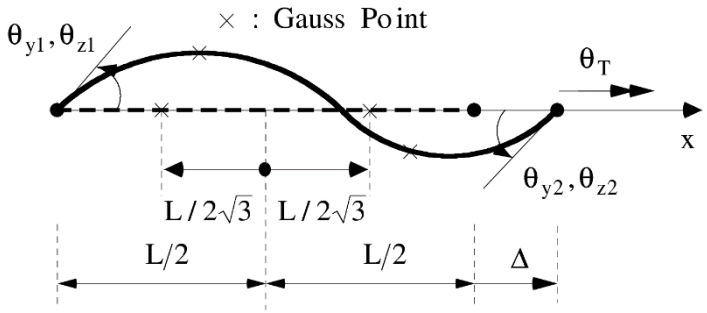


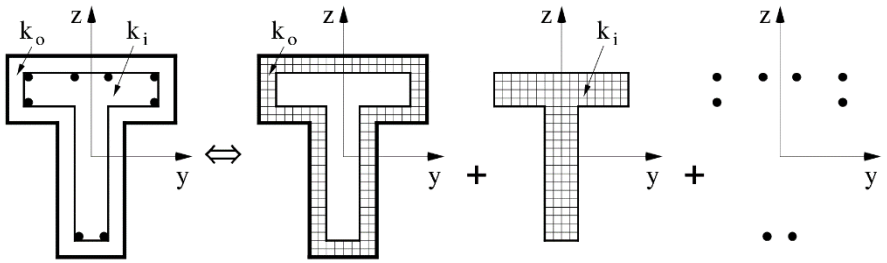




# Advanced nonlinear analysis program ADAPTIC: Existing modelling capabilities

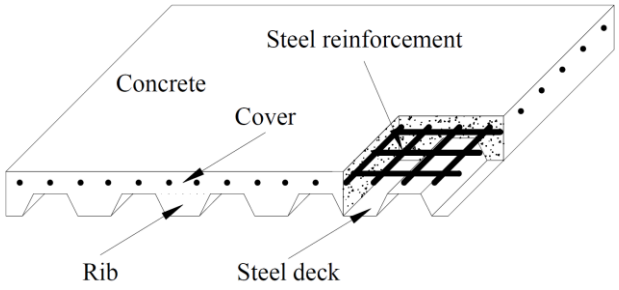
- Interactions of 3D frame, floor slabs and lateral resistance system
  - Geometric and material nonlinearity
- Modelling of frame members with 1D elements
  - Fibre elements with nonlinear material models

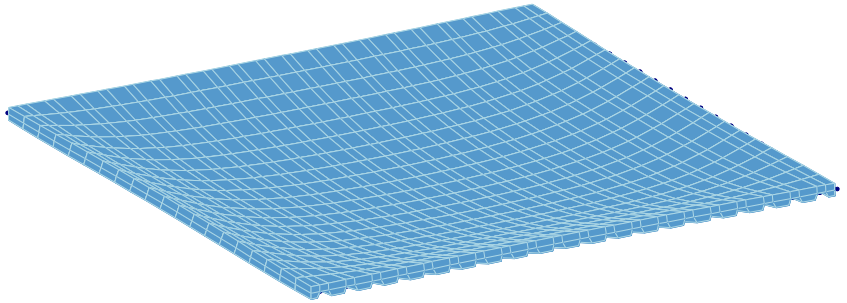


# Advanced nonlinear analysis program ADAPTIC: Existing modelling capabilities

- Modelling of floor slabs and shear walls with 2D elements

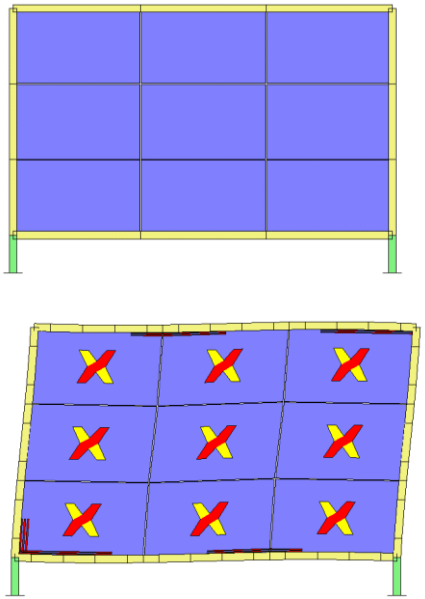


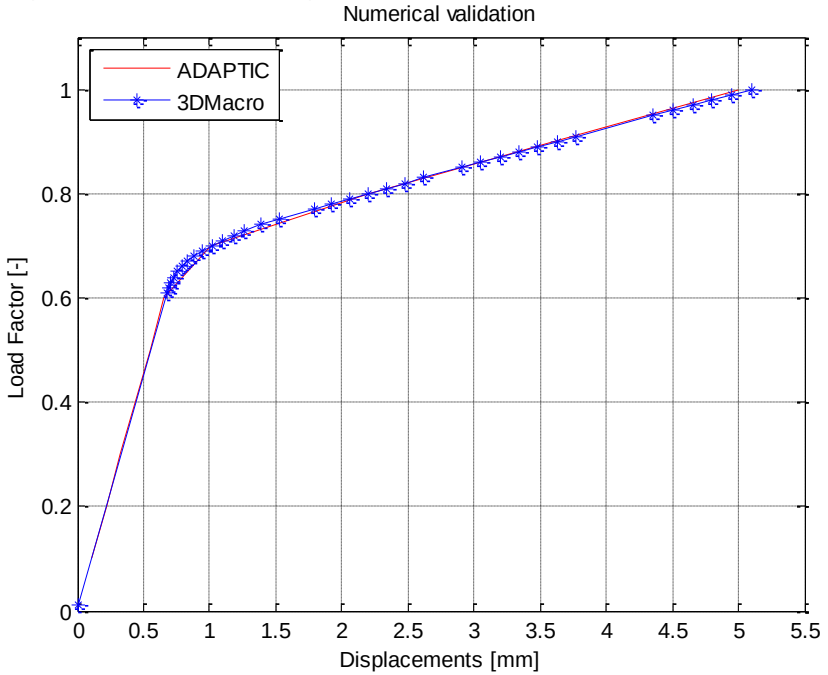



- Step-by-step time-integration scheme
  - Accuracy, stability and dissipation of higher modes using HHT

# Advanced nonlinear analysis program ADAPTIC: New modelling capabilities

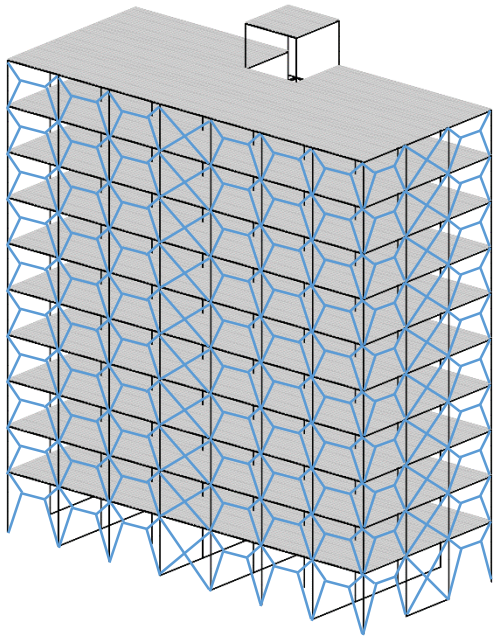
- Macro-element for masonry infill compared with the 3DMacro model





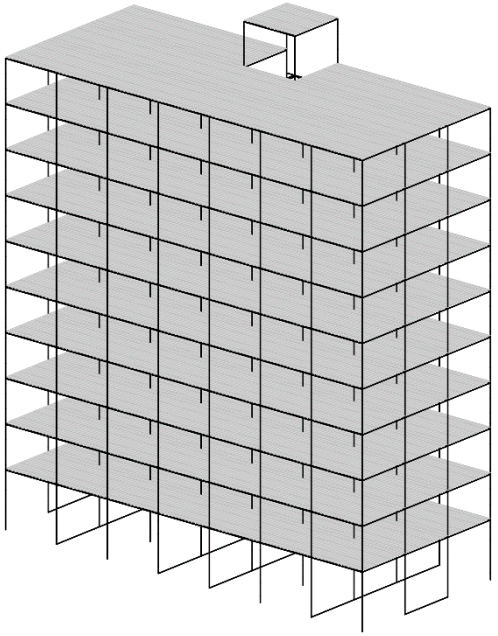
# Advanced nonlinear analysis program ADAPTIC: New modelling capabilities

- Staged construction for retrofitting systems
  - Retrofitting system should not take dead and imposed loads from original building structure



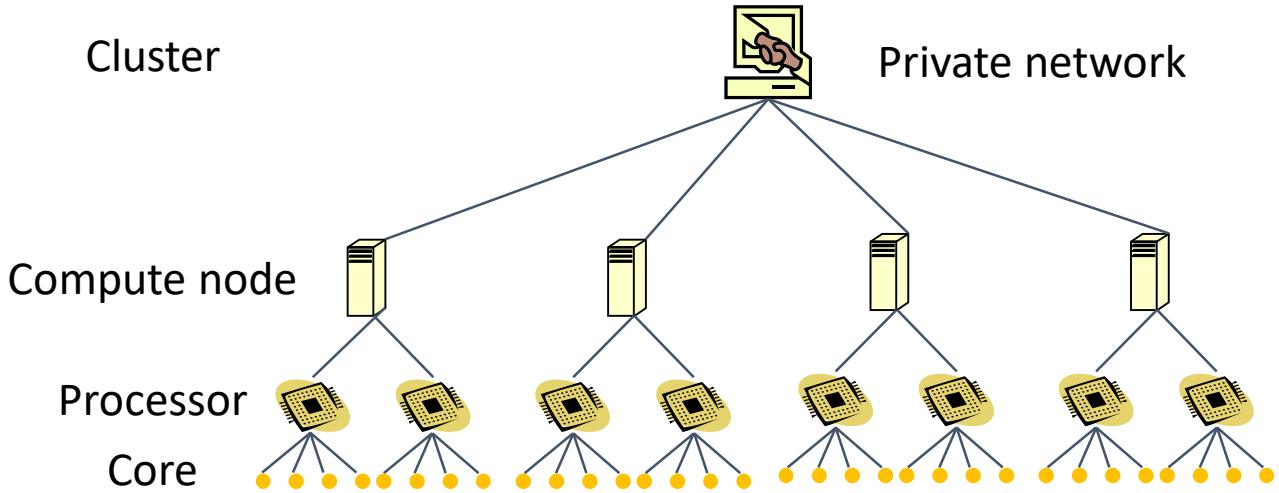
# Advanced nonlinear analysis program ADAPTIC: Partitioned modelling for efficient analysis

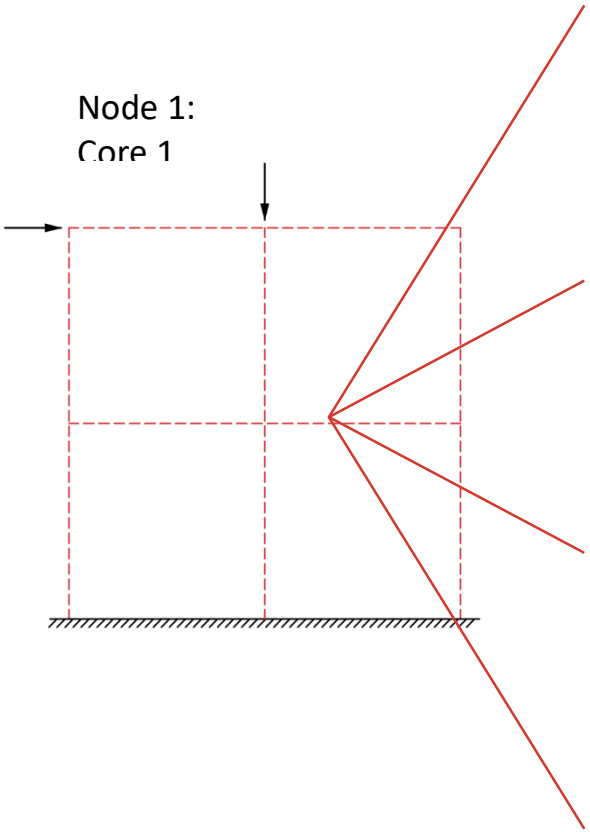
- Structural model without infill
  - > 110,000 nonlinear elements
  - > 34,000 nodes
  - > 15,000 time-steps
- Conventional monolithic model is computationally prohibitive

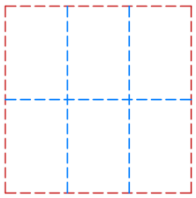


# Advanced nonlinear analysis program ADAPTIC: Partitioned modelling for efficient analysis

**Scalable hierarchic distributed memory and computing power**

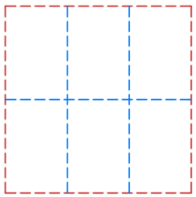




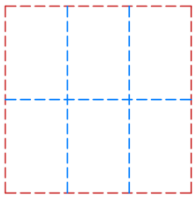
Node 1:
Core 2

Node 1: Cores 3-8



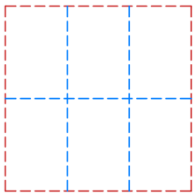
Node 2:
Core 1

Node 2: Cores 2-7



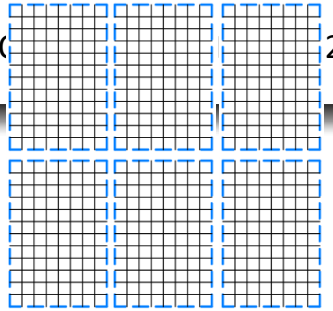
Node 3:
Core 2

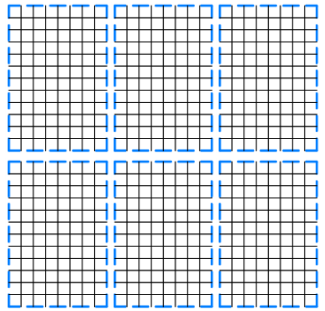
Node 3: Cores 2-7

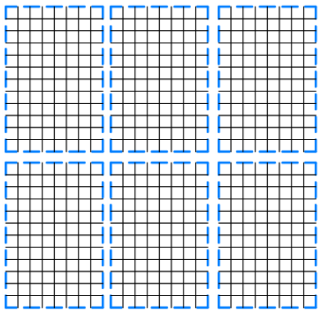


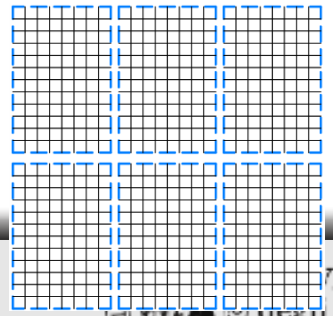
Node 4:
Core 2

Node 4: Cores 2-7



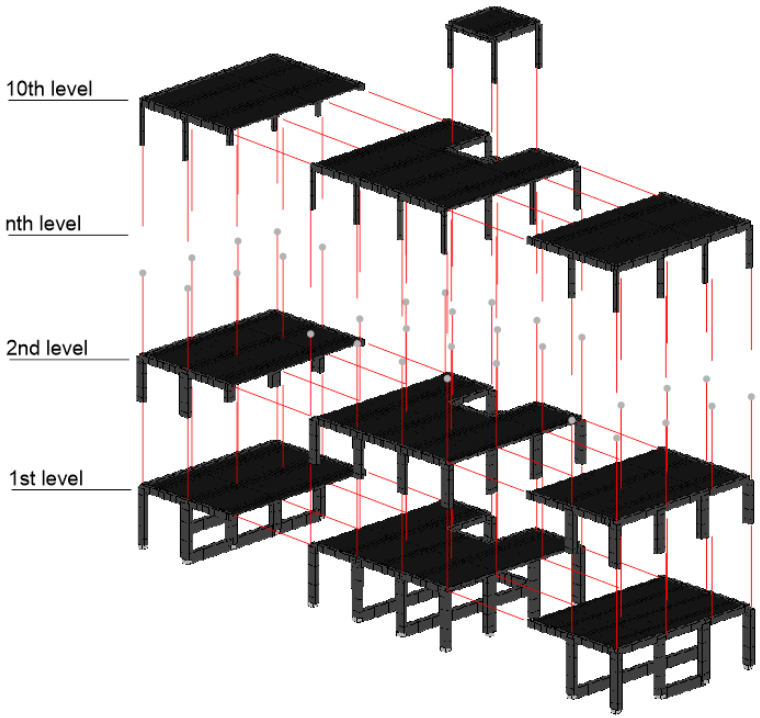




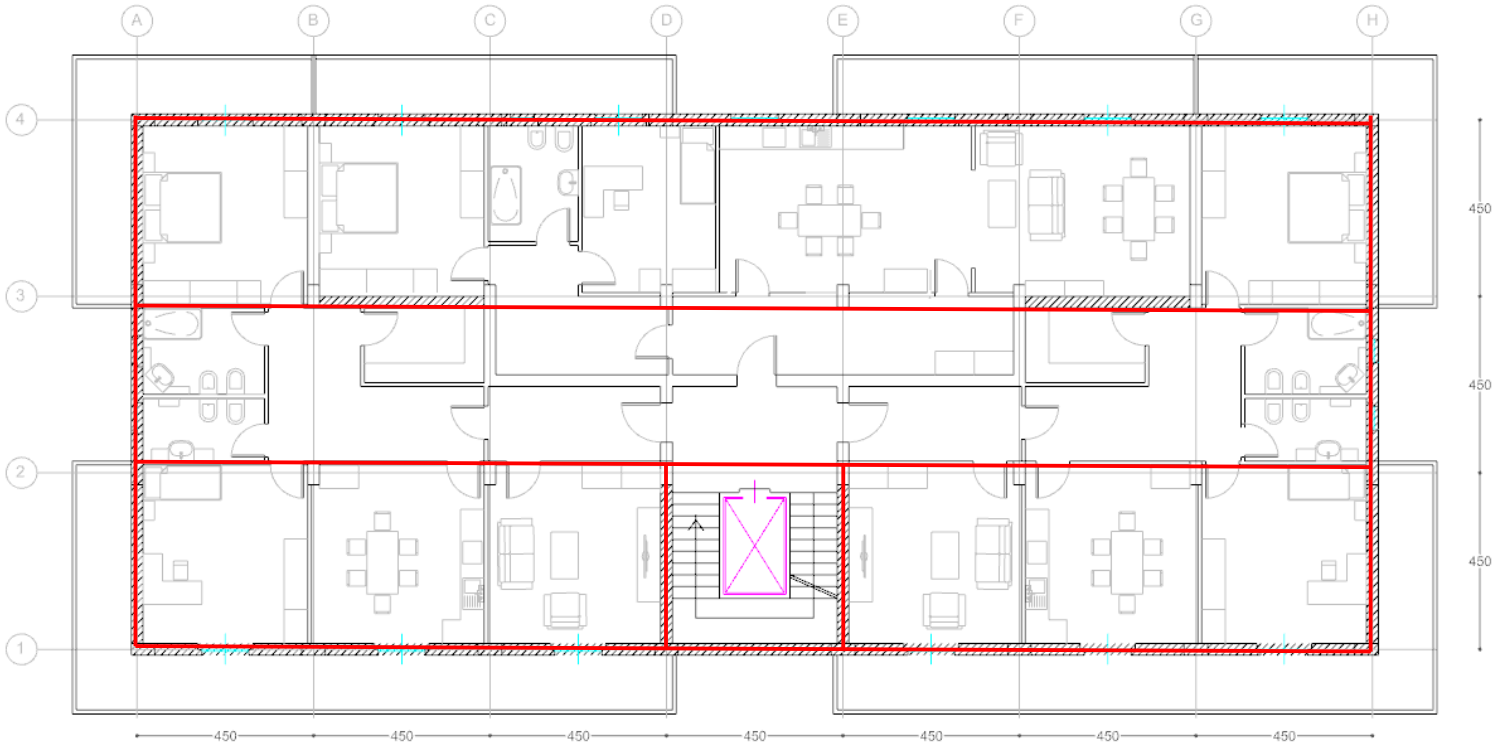


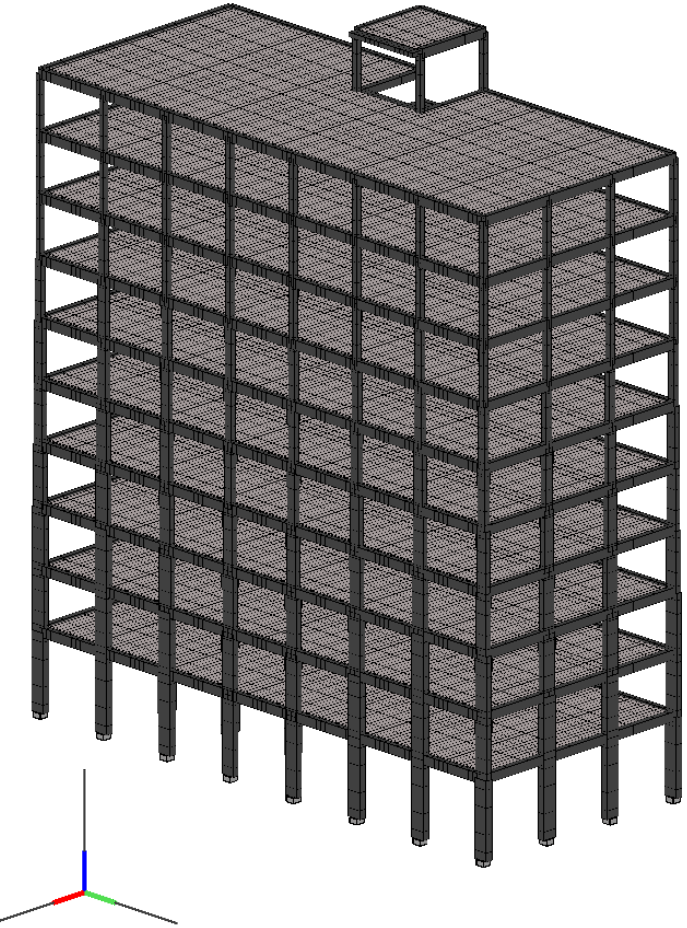
# Advanced nonlinear analysis program ADAPTIC: Partitioned modelling for efficient analysis

- Catania building case study
- 31 partitions used
- Typical high fidelity 3D nonlinear dynamic analysis takes 2-3 days
- A conventional model would take several weeks



# Generic floor plan

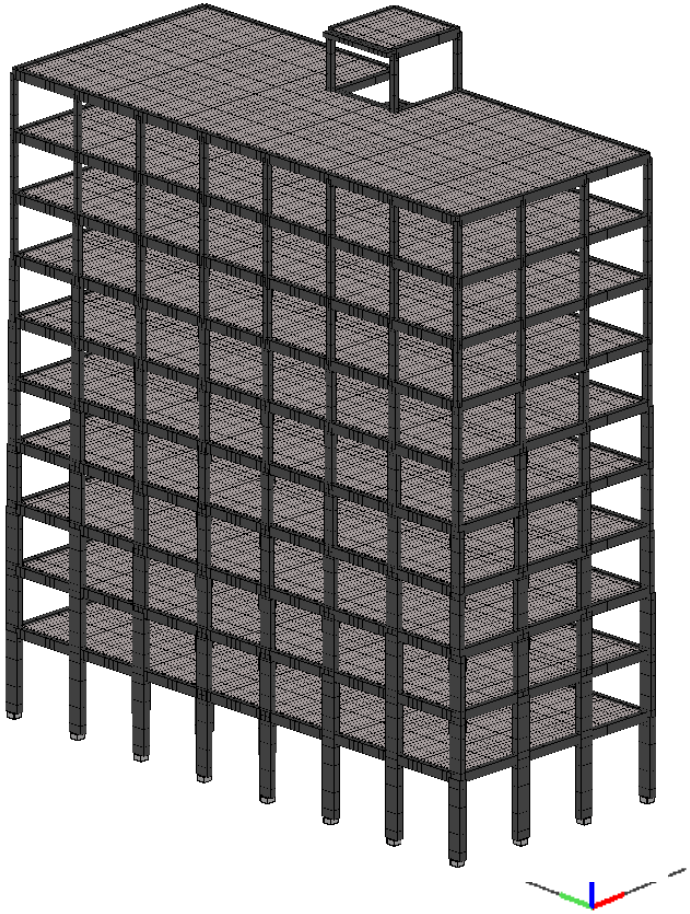




## 3D HIGH FIDELITY MODEL FOR SEISMIC ASSESSMENT

- Non Linear Dynamic Analyses
- 7 Accelerograms with 3 acceleration components

- Elasto-Plastic Beam-Column and Slab Elements allowing for the spread of plasticity and geometric non linearity.
- Specific Nonlinear Material Relationships for Steel Reinforcements and Concrete (with softening)
- Macromodel elements for description of the unreinforced masonry infilled walls and frame interaction
- **Staged Construction allowing the contribute of the Unreinforced Masonry Walls and their interaction with the surrounding frames**

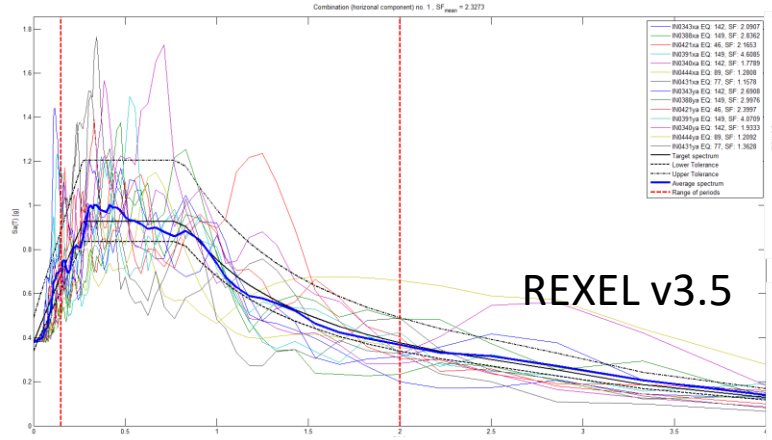


## 3D HIGH FIDELITY MODEL FOR RETROFITTED STRUCTURE

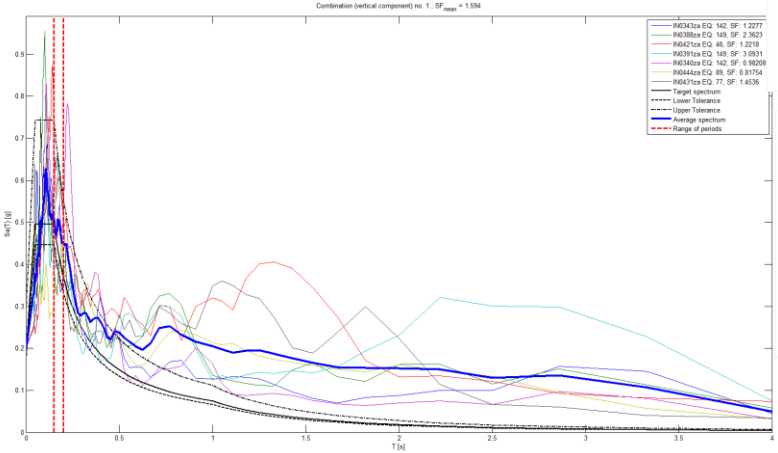
**Analysis of structural performance according to Italian Seismic Code (D.M. 14 Gennaio 2008 and Circolare 2 -02-2009, 617)**

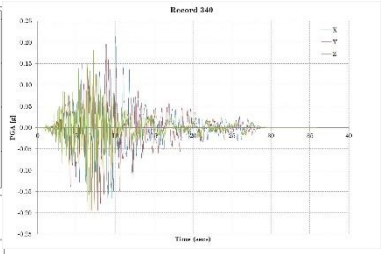
- **Horizontal displacements**
- **Interstorey drifts**
- **Ductile mechanisms** (chord rotation)
- **Brittle mechanisms** (shear failure)

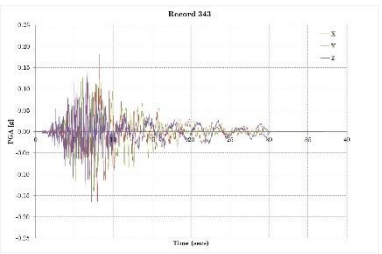
**§ 3.2.3.6 NTC08**
**C3.2.3.6 circolare**
**§ 7.3.4.2 NTC08**

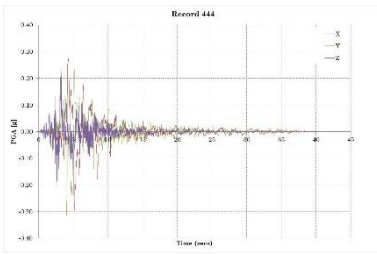


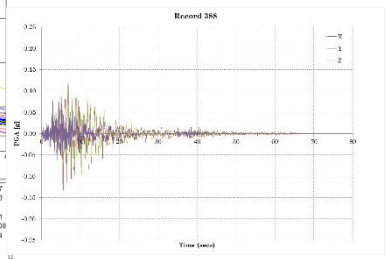
REXEL v3.5

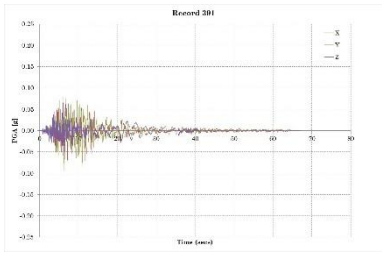


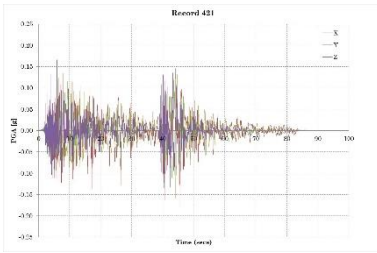


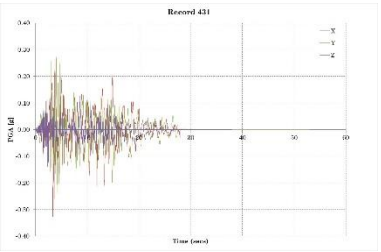



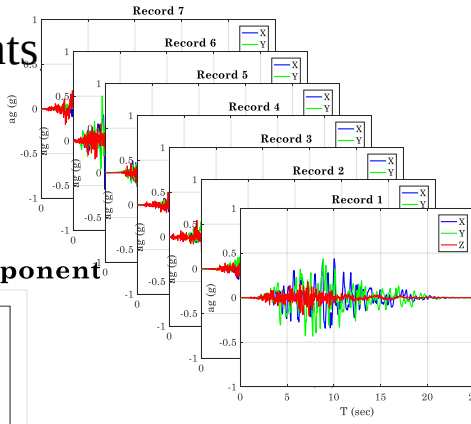



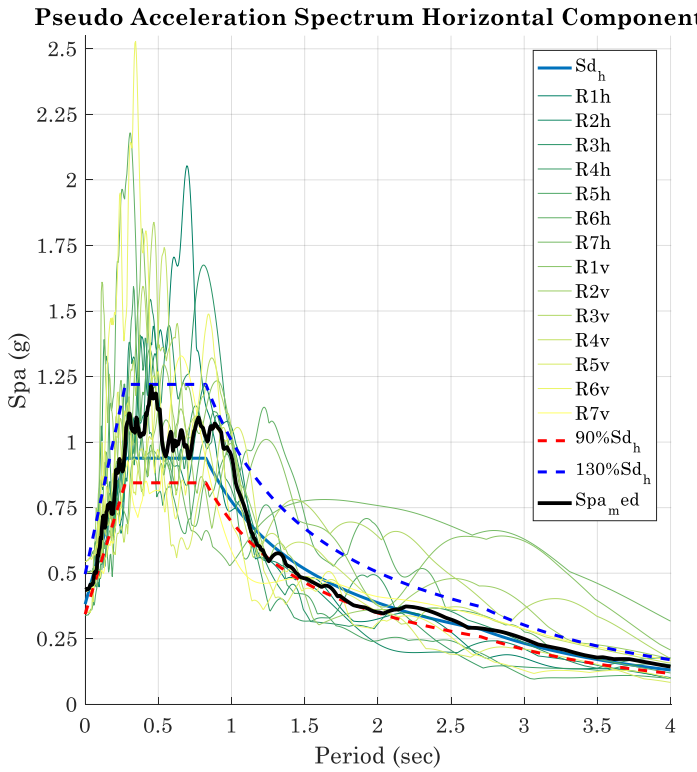



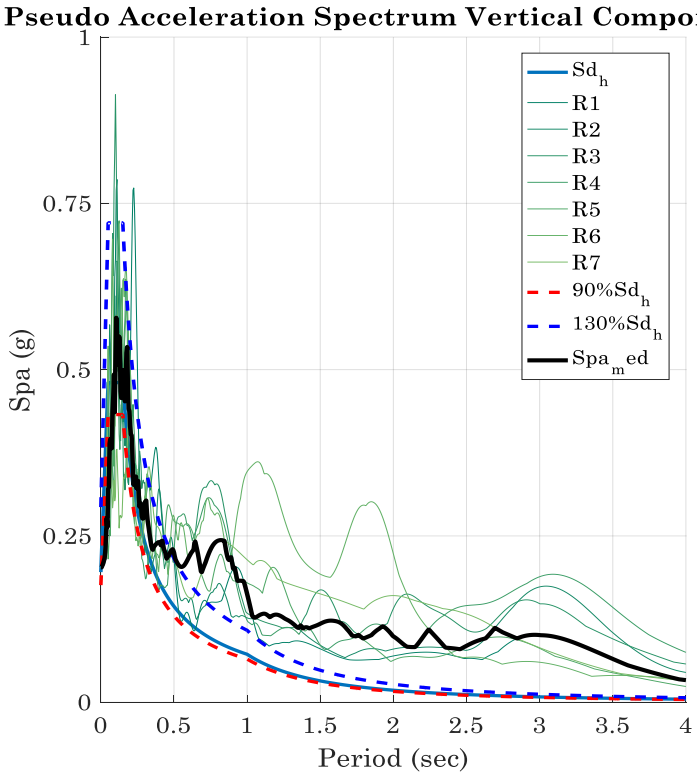




Iervolino I., Galasso C., Cosenza E. (2009). REXEL: computer aided record selection for code-based seismic structural analysis. Bulletin of Earthquake Engineering, 8:339-362. DOI 10.1007/s10518-009-9146-1

# Response spectra of the seven records in the two horizontal components average spectrum and elastic spectrum



# ITALIAN SEISMIC CODE

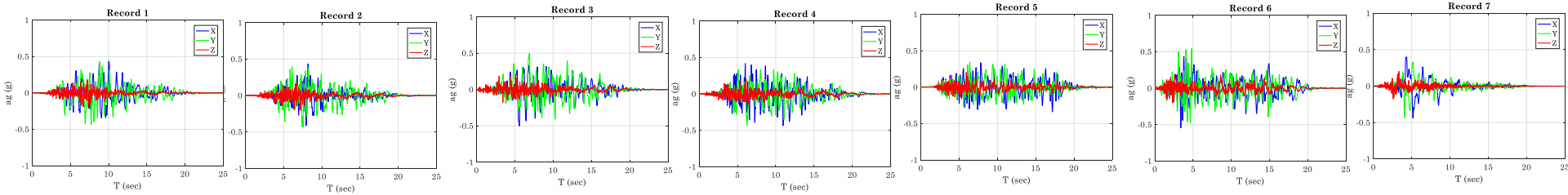
## C8A.6. VALUTAZIONE DELLE ROTAZIONI DI COLLASSO DI ELEMENTI DI STRUTTURE IN CALCESTRUZZO ARMATO E ACCIAIO

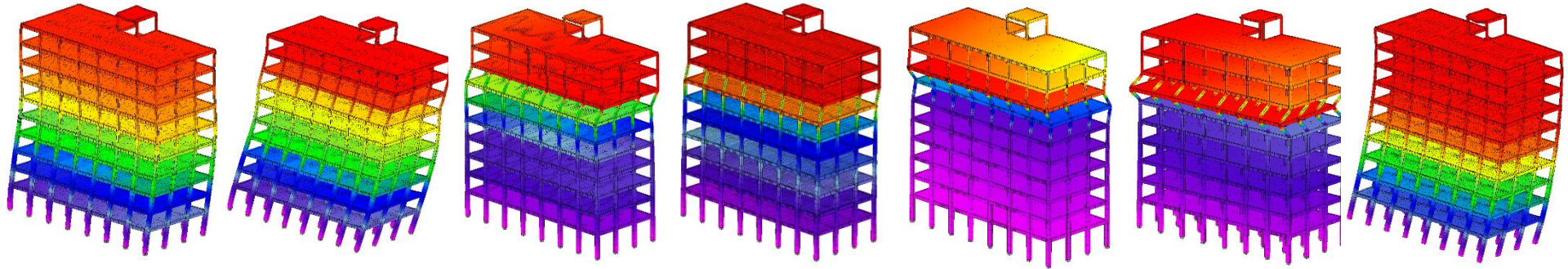
## C8A.6.1 ELEMENTI DI STRUTTURE IN CALCESTRUZZO ARMATO

$$\theta_u = \frac{1}{\gamma_{el}} 0{,}016 \cdot (0{,}3^{\nu}) \left[ \frac{\max(0{,}01;\omega')}{\max(0{,}01;\omega)} f_c \right]^{0.225} \left( \frac{L_V}{h} \right)^{0{,}35} 25^{\left( \alpha \rho_{sx} \frac{f_{yw}}{f_c} \right)} (1{,}25^{100\rho_d}) \qquad \text{(C8A.6.1)}$$

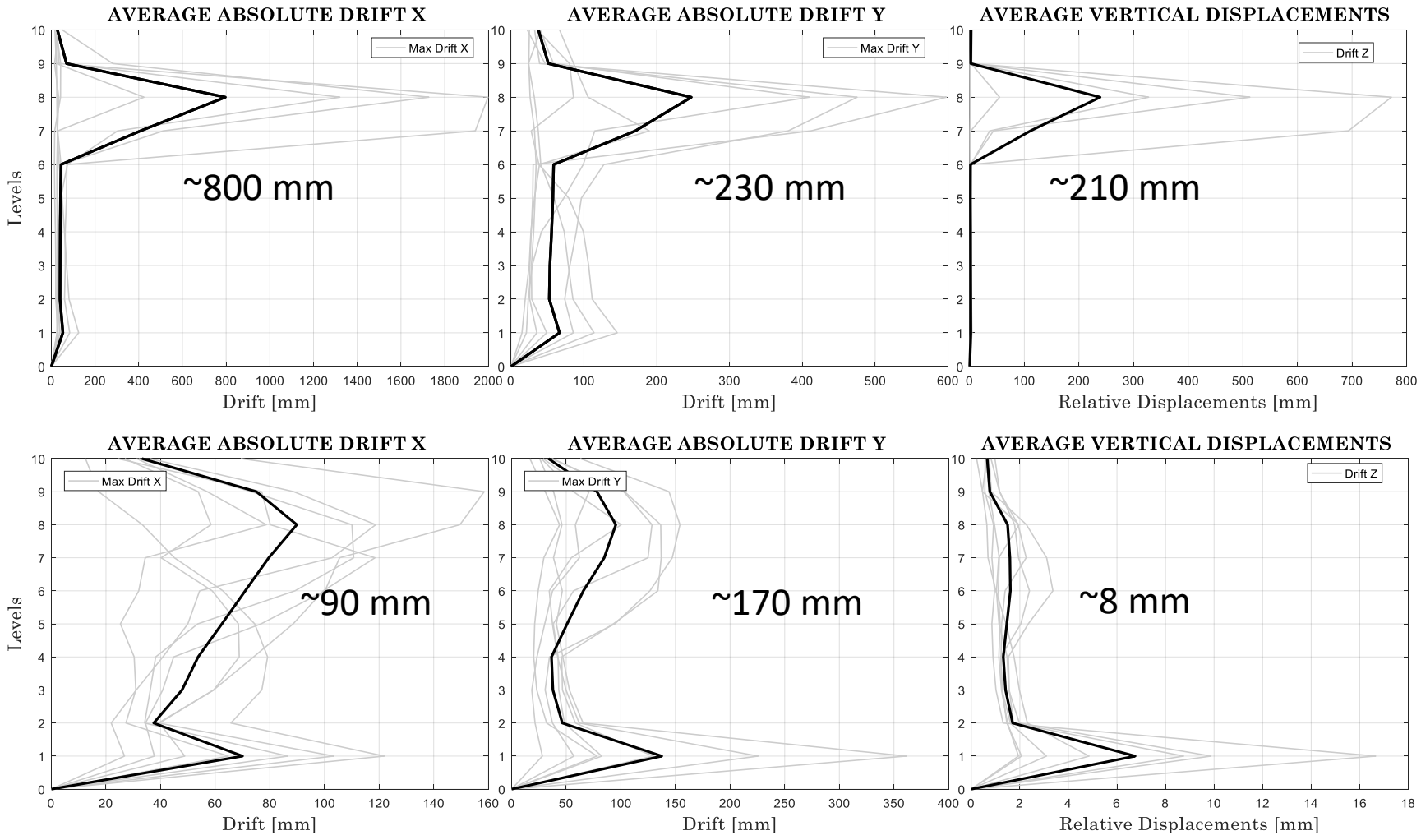
## C8.7.2.5 Modelli di capacità per la valutazione di edifici in cemento armato

- La resistenza a taglio si valuta come per il caso di nuove costruzioni
- contributo del conglomerato al massimo pari a quello relativo agli elementi senza armature trasversali resistenti a taglio.
- Le resistenze dei materiali media divise per il fattore di confidenza e per il coefficiente parziale del materiale.



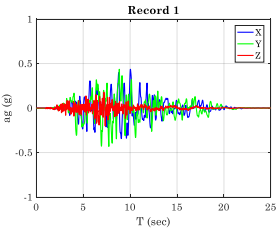



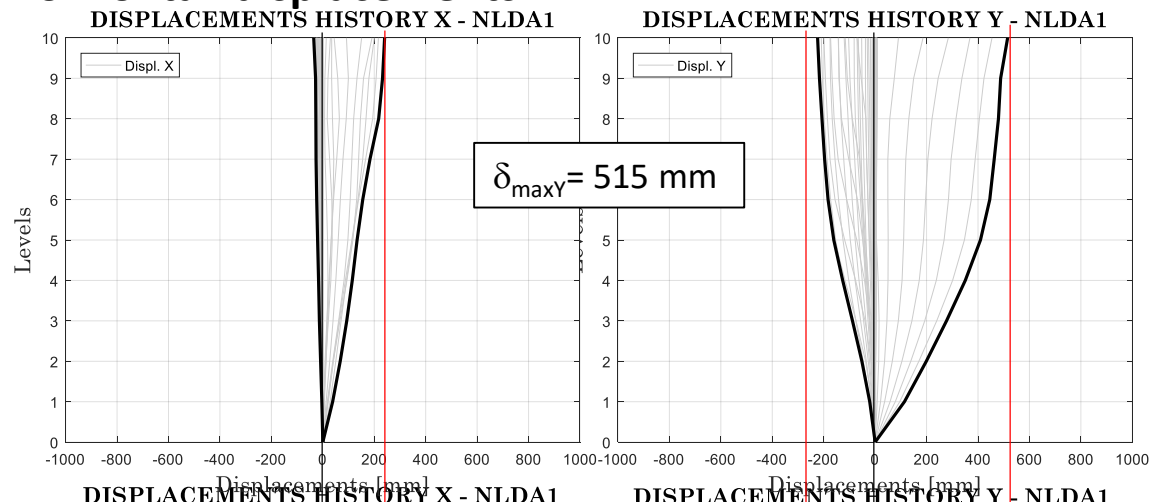
| | | | | | | |
|---|---|---|---|---|---|---|
| ≥ 0,649 m | ≥ 0,841 m | ≥ 0,503 m | ≥ 1,214 m | ≥ 1,451 m | ≥ 1,926 m | ≥ 0,505 m |
| 0,595 m | 0,771 m | 0,461 m | 1,113 m | 1,330 m | 1,766 m | 0,463 m |
| 0,541 m | 0,701 m | 0,419 m | 1,012 m | 1,209 m | 1,605 m | 0,421 m |
| 0,487 m | 0,631 m | 0,377 m | 0,911 m | 1,088 m | 1,445 m | 0,378 m |
| 0,433 m | 0,561 m | 0,335 m | 0,809 m | 0,967 m | 1,284 m | 0,336 m |
| 0,379 m | 0,491 m | 0,293 m | 0,708 m | 0,846 m | 1,124 m | 0,294 m |
| 0,325 m | 0,421 m | 0,252 m | 0,607 m | 0,725 m | 0,963 m | 0,252 m |
| 0,270 m | 0,351 m | 0,210 m | 0,506 m | 0,605 m | 0,803 m | 0,210 m |
| 0,216 m | 0,280 m | 0,168 m | 0,405 m | 0,484 m | 0,642 m | 0,168 m |
| 0,162 m | 0,210 m | 0,126 m | 0,304 m | 0,363 m | 0,482 m | 0,126 m |
| 0,108 m | 0,140 m | 0,084 m | 0,202 m | 0,242 m | 0,321 m | 0,084 m |
| 0,054 m | 0,070 m | 0,042 m | 0,101 m | 0,121 m | 0,161 m | 0,042 m |
| ≤ 0,000 m | ≤ 0,000 m | ≤ 0,000 m | ≤ 0,000 m | ≤ 0,000 m | ≤ 0,000 m | ≤ 0,000 m |

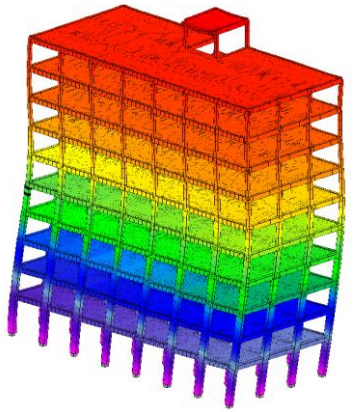

AVERAGE ABSOLUTE DRIFT X
Max Drift X
~800 mm
Levels
Drift [mm]
AVERAGE ABSOLUTE DRIFT Y
Max Drift Y
~230 mm
Drift [mm]
AVERAGE VERTICAL DISPLACEMENTS
Drift Z
~210 mm
Relative Displacements [mm]
AVERAGE ABSOLUTE DRIFT X
Max Drift X
~90 mm
Levels
Drift [mm]
AVERAGE ABSOLUTE DRIFT Y
Max Drift Y
~170 mm
Drift [mm]
AVERAGE VERTICAL DISPLACEMENTS
Drift Z
~8 mm
Relative Displacements [mm]

# NLDA 1 • Horizontal displacements

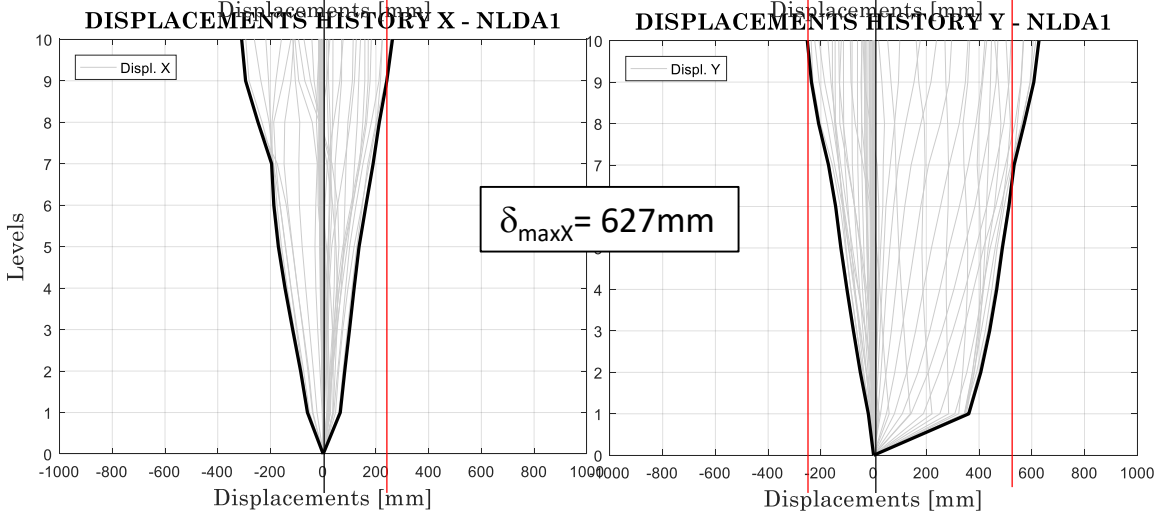
***Bare Structure***

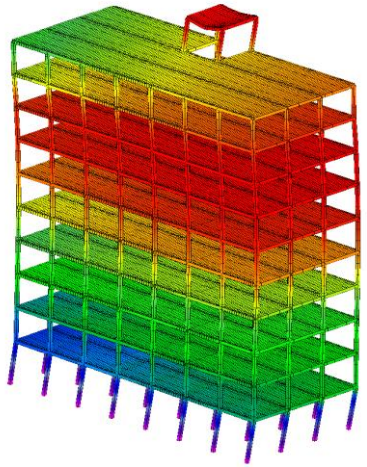


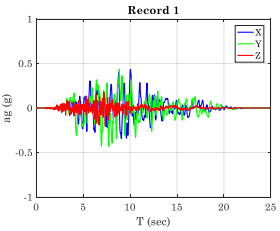
***Infilled Structure***

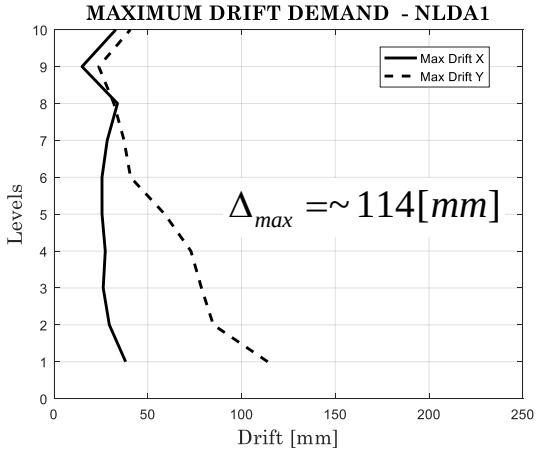


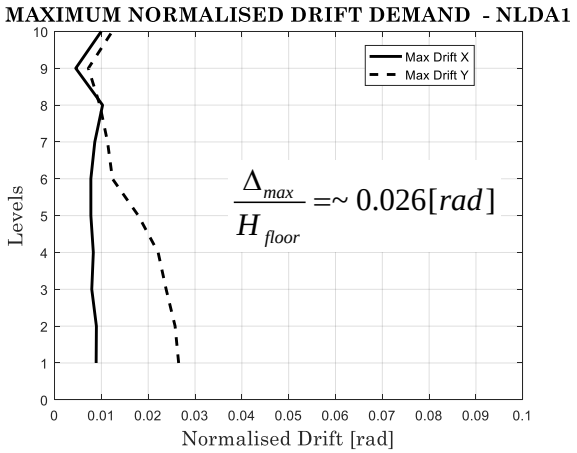



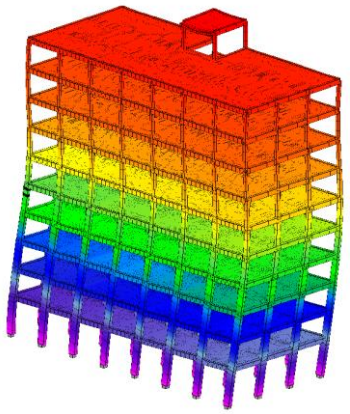
# NLDA 1 • Interstorey drifts

***Bare Structure***

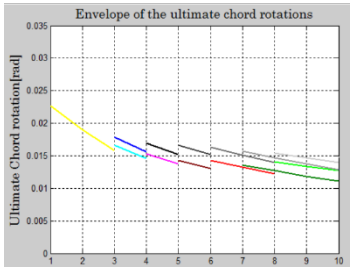


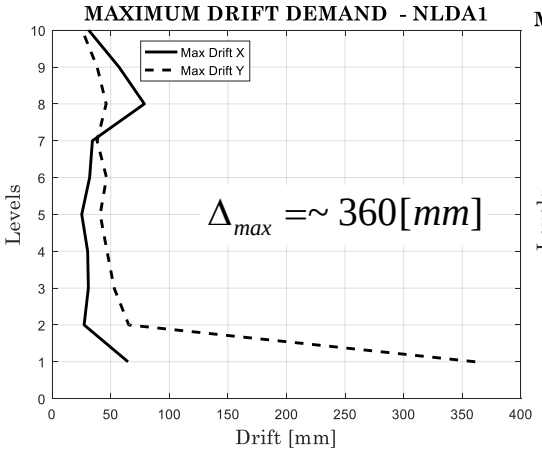



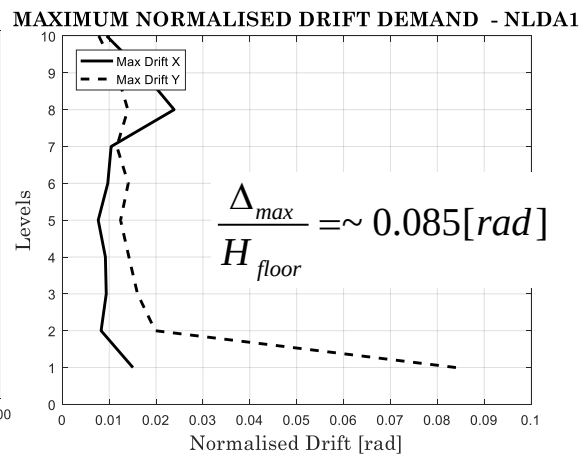



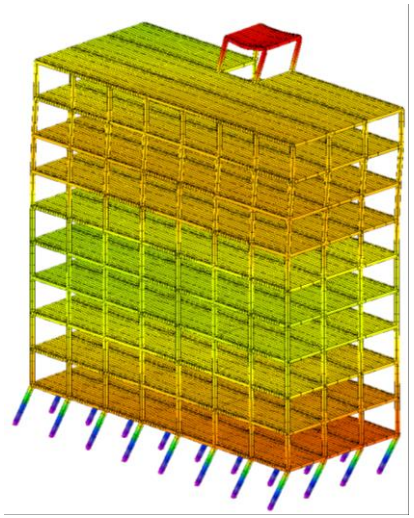



***Infilled Structure***



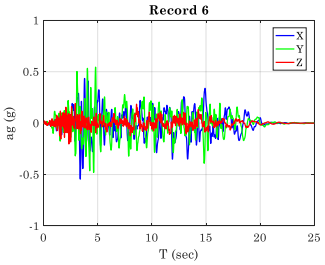



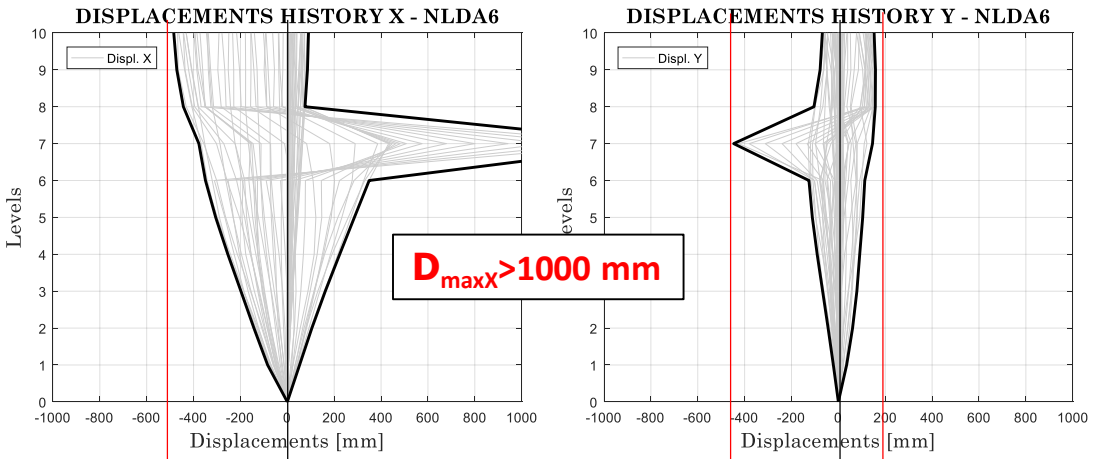



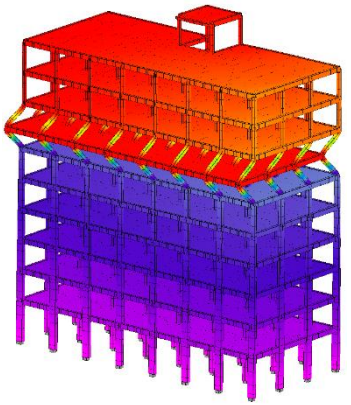
# NLDA 6 • Horizontal displacements

***Bare Structure***




$D_{maxX}$>1000 mm



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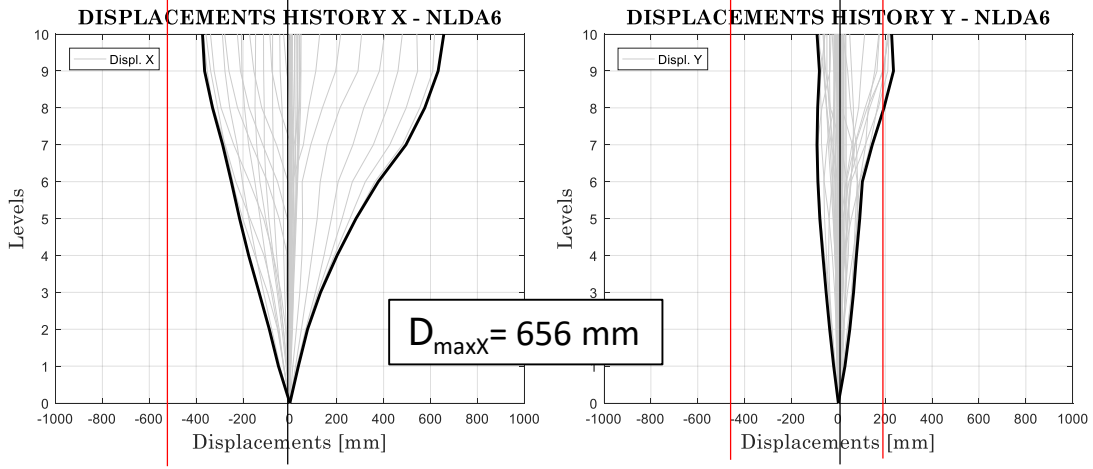
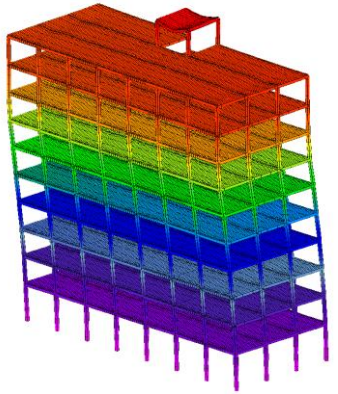
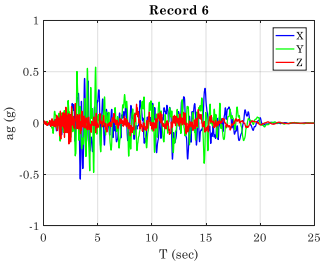


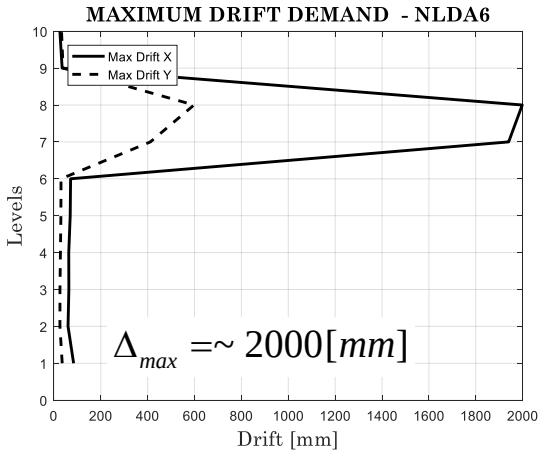

$D_{maxX}$= 656 mm

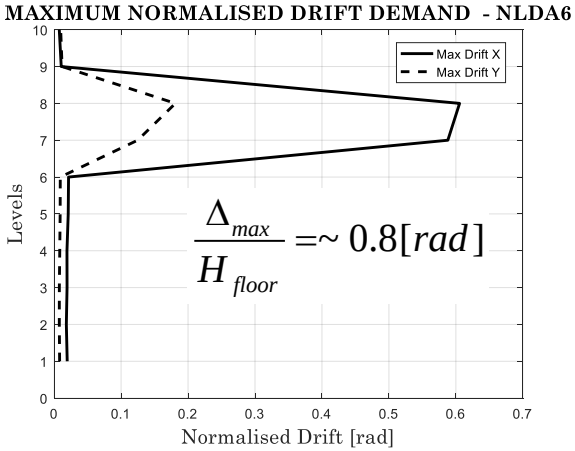


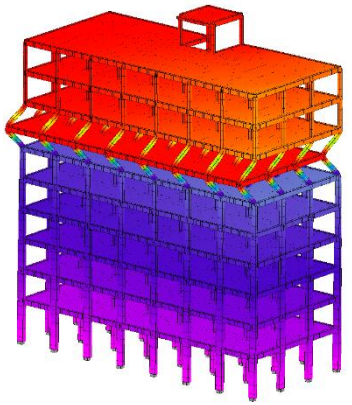
# NLDA 6 • Interstorey drifts

***Bare Structure***



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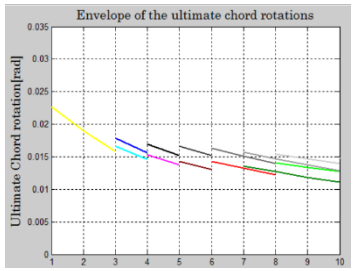
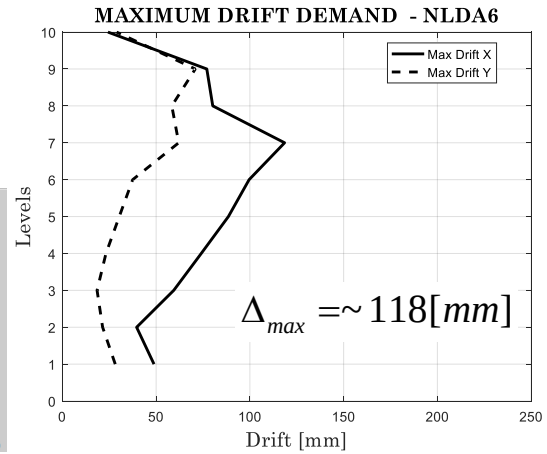
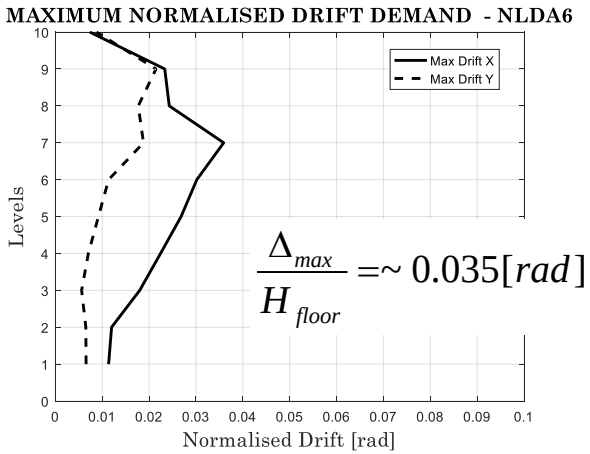
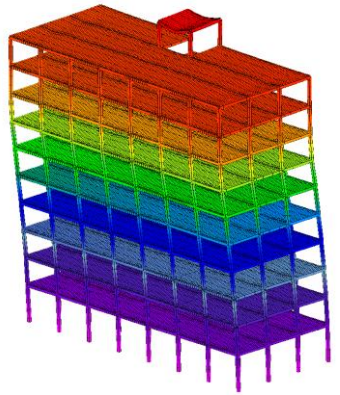


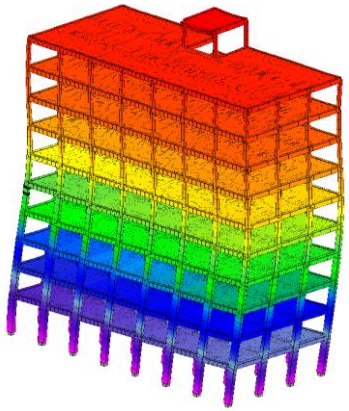



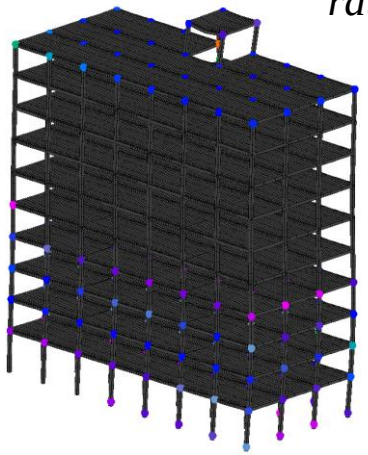



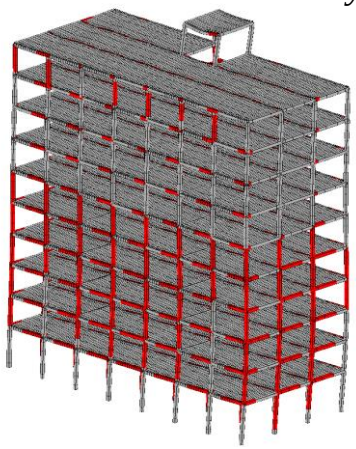



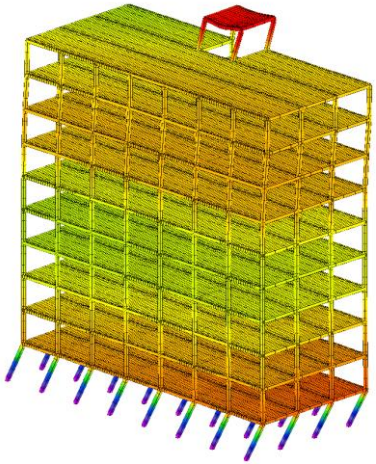
$\theta_{ratio} >> 1$

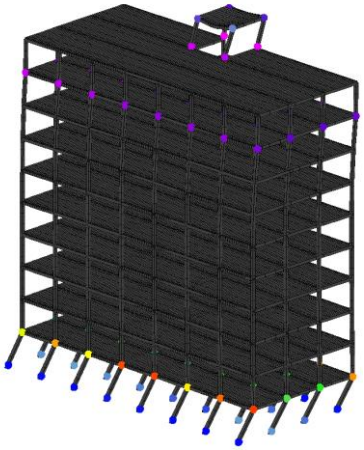
$V_{y,ratio} >> 1$

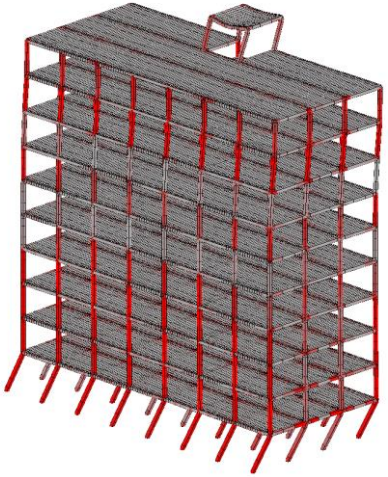








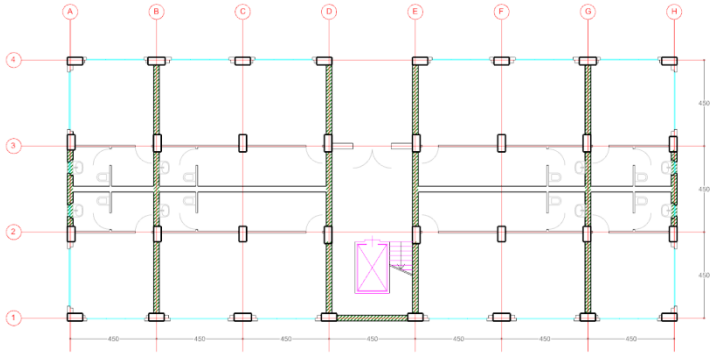




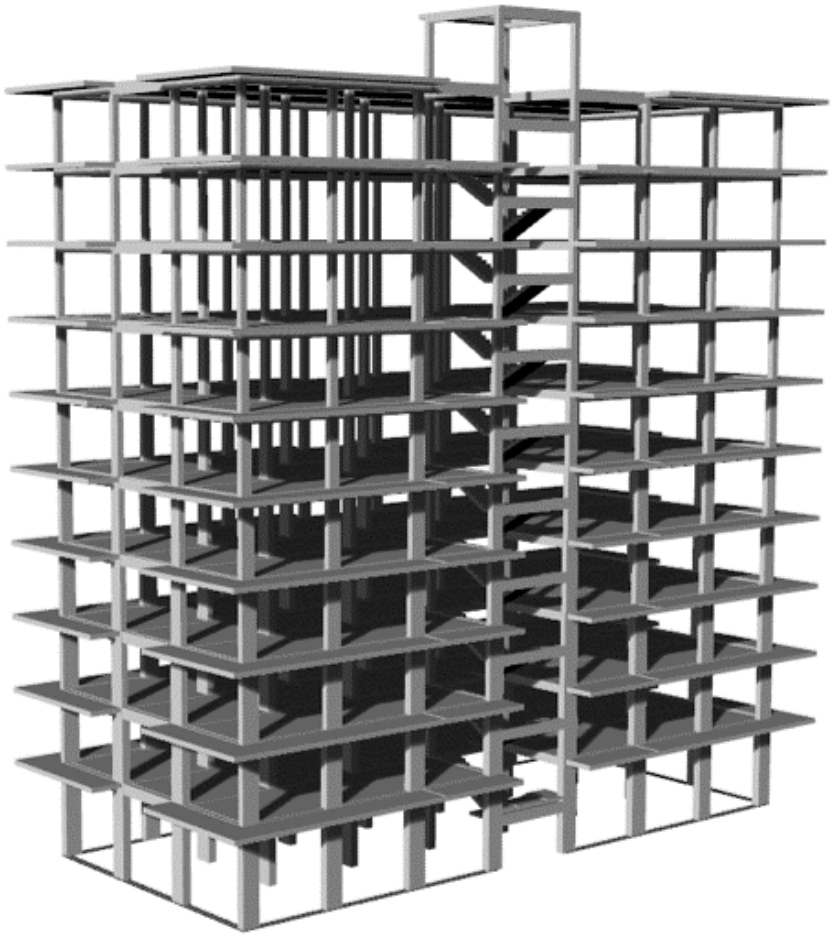
**Considerations:**

- The columns section optimization, only under vertical loads, deeply influences the global dynamic response in absence of infilled frames
- The contribute of the hollow brick walls changes the global structural response and the collapse modality
- In both the models a considerable demand in terms of displacements, floor drifts, chord rotations and shear forces has been found
- According to the values, that the ratios have reached, a localised strengthening could not be enough

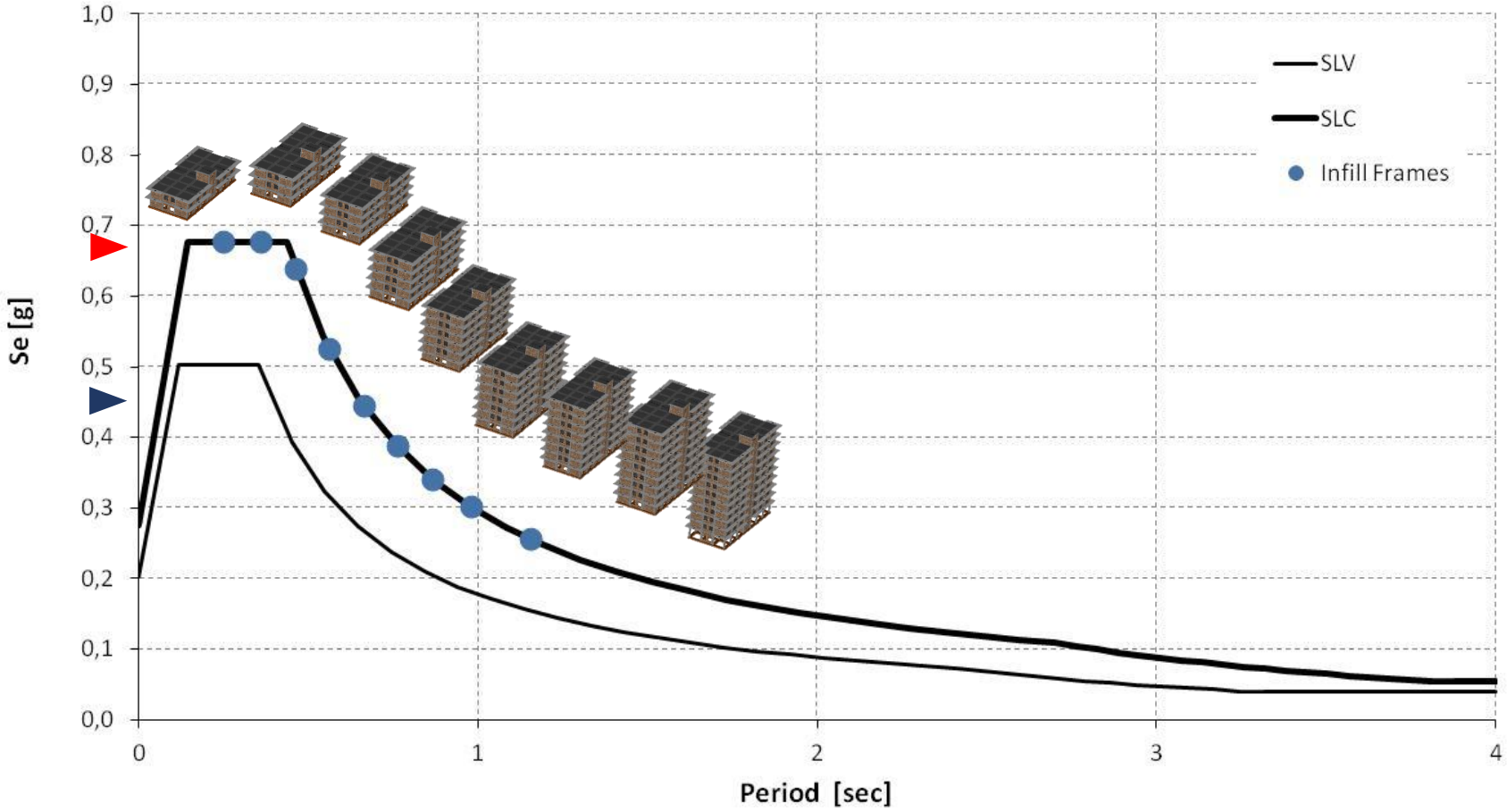
# Parametric analysis of the case study

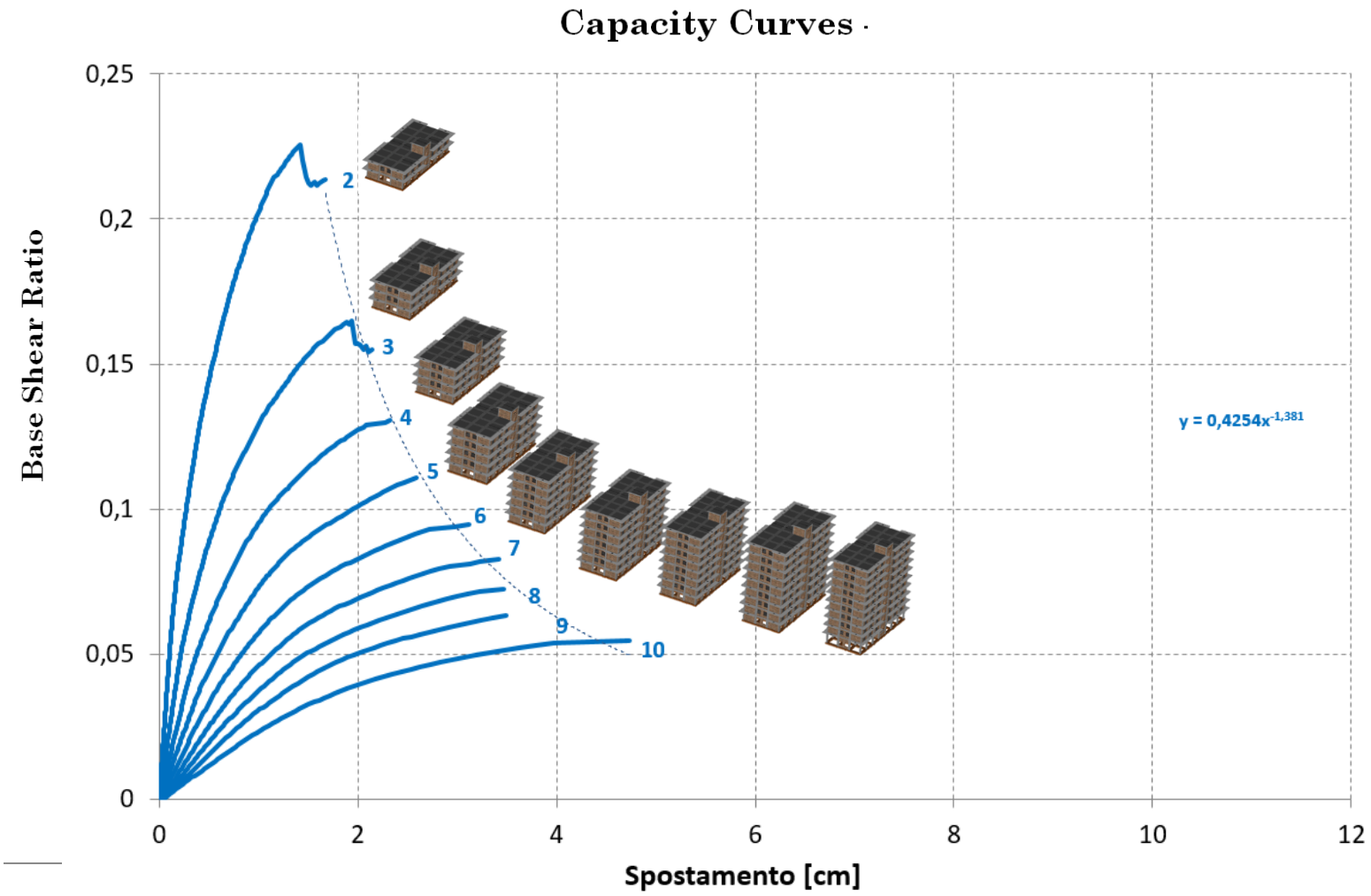


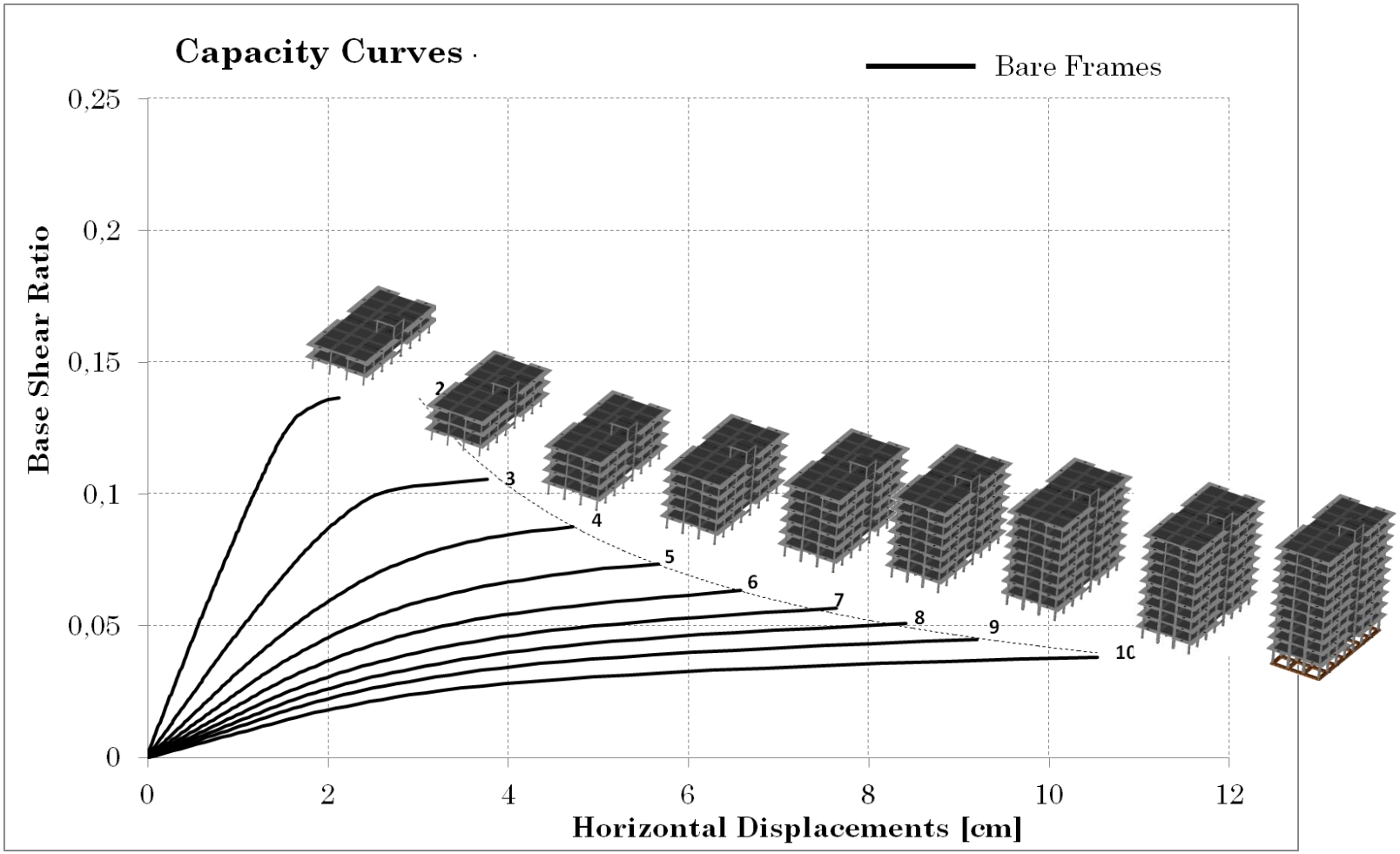
Ground Floor and Collocation of the Infill Frames

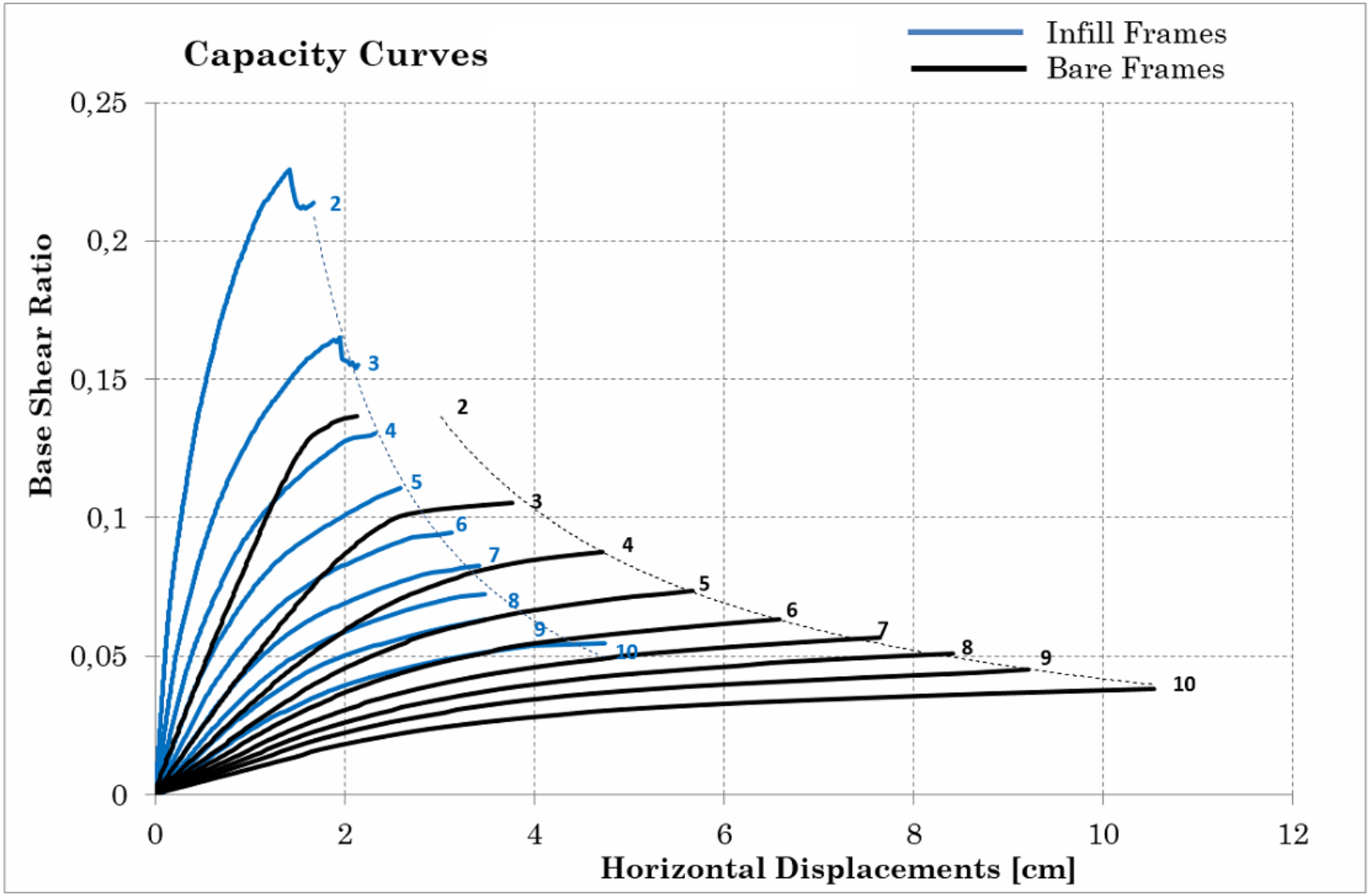


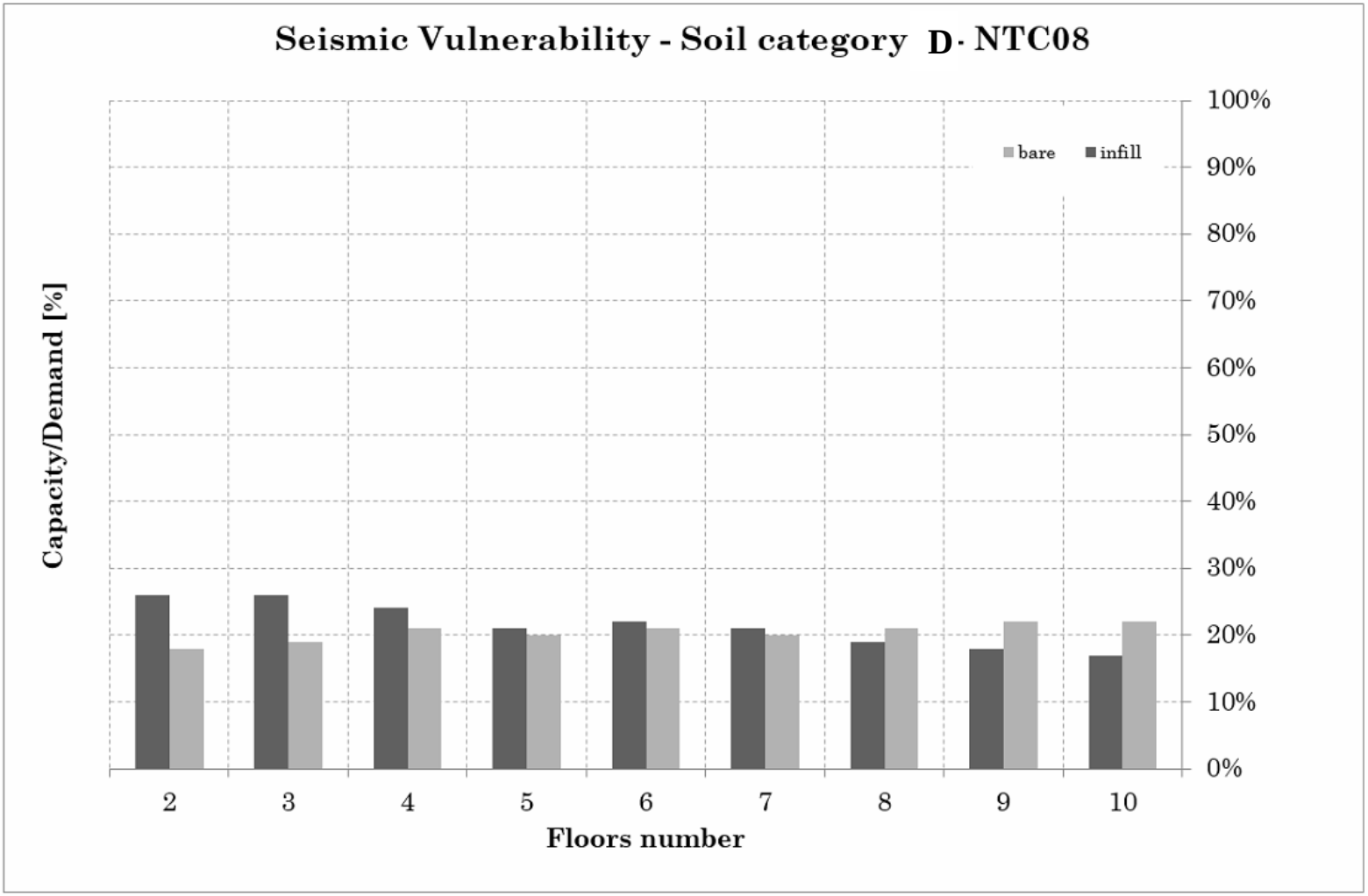
## Elastic spectrum and variation of the seismic demands

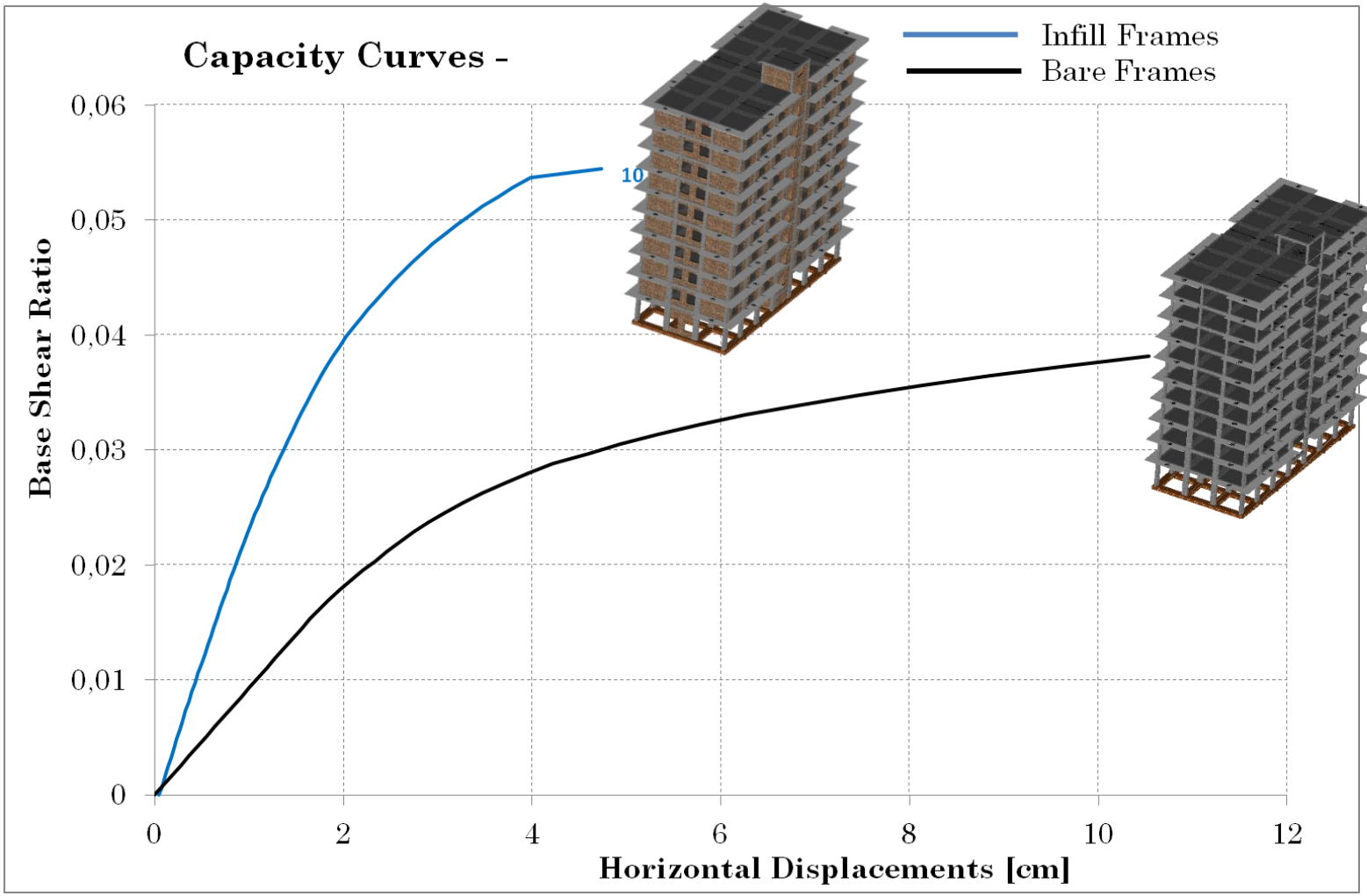



Capacity Curves
Base Shear Ratio
0,25
0,2
0,15
0,1
0,05
0
0
2
4
6
8
10
12
Spostamento [cm]
2
3
4
5
6
7
8
9
10
y = 0,4254x-1,381


Capacity Curves
Bare Frames
Base Shear Ratio
0,25
0,2
0,15
0,1
0,05
0
0
2
4
6
8
10
12
Horizontal Displacements [cm]
2
3
4
5
6
7
8
9
10


Capacity Curves
Infill Frames
Bare Frames
Base Shear Ratio
0,25
0,2
0,15
0,1
0,05
0
0
2
4
6
8
10
12
Horizontal Displacements [cm]
2
3
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
10


Seismic Vulnerability - Soil category D - NTC08
Capacity/Demand [%]
bare
infill
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2
3
4
5
6
7
8
9
10
Floors number


Capacity Curves -
Infill Frames
Bare Frames
Base Shear Ratio
0,06
0,05
0,04
0,03
0,02
0,01
0
0
2
4
6
8
10
12
Horizontal Displacements [cm]

# THE MAIN WEAKNESS POINTS OF EXISTING TALL STRUCTURE

- LOW RESISTANCE FOR HORIZONTAL AND VERTICAL LOADS;

- LOW LOCAL AND GLOBAL DUCTILITY;

- FRAGILE SHEAR COLLAPSE AND NODE MECHANISMS;

- POSSIBLE PRESENCE OF DAMAGE AT THE BASE COLUMN DUE TO STEEL BAR CORROSION

- POSSIBLE PROGRESSIVE COLLAPSE SCENARIO AS A CONSEQUENCE OF COLUMN LOSS EVENTS;

# POSSIBLE PRESENCE OF DAMAGE AT THE BASE COLUMN;

gli edifici esistenti, in molti casi, manifestano un **avanzato stato di degrado**, spesso localizzato in alcune zone, come i pilastri a piano terra, questo costituisce un ulteriore elemento di vulnerabilità che potrebbe innescare **il collasso progressivo dell'edificio** anche per terremoti di bassa intensità.

# POSSIBLE PROGRESSIVE COLLAPSE AS A CONSEQUENCE OF LOCAL FAILURE

I recenti terremoti hanno evidenziato l'instaurarsi di collassi parziali, anche negli edifici in calcestruzzo armato, spesso riconducibili a cedimenti strutturali di singoli elementi la cui crisi ha innescato **collasso progressivi** simili a quelli derivati da esplosioni .

2009 L'Aquila
$M_L$= 5,8-5,9 $M_w$= 6,3

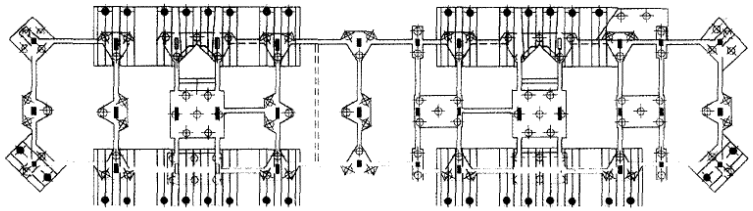
1977 Vrancea Romania
$M_w$= 7,2

2008 Sichuan Cina
$M_w$= 7,9

# TRADITIONAL RETROFITTING SOLUTIONS


10

**Fig. 10.** Selected retrofitting system. RC stiffening cores and corner elements.



11

**Fig. 11.** Strengthening of the foundation system.

**Repair and retrofit of a six storey reinforced concrete building damaged by the earthquake in south-east Sicily on the 13th December 1990**

**G. Oliveto[a] & L.D. Decanini[b]**

[a]*Istituto di Scienza delle Costruzioni, Università di Catania, Catania, Italy*
[b]*Dipartimento di Ingegneria Strutturale e Geotecnica, Università degli Studi di Roma "La Sapienza", Rome, Italy*

(Received 9 December 1996; accepted 12 March 1997)

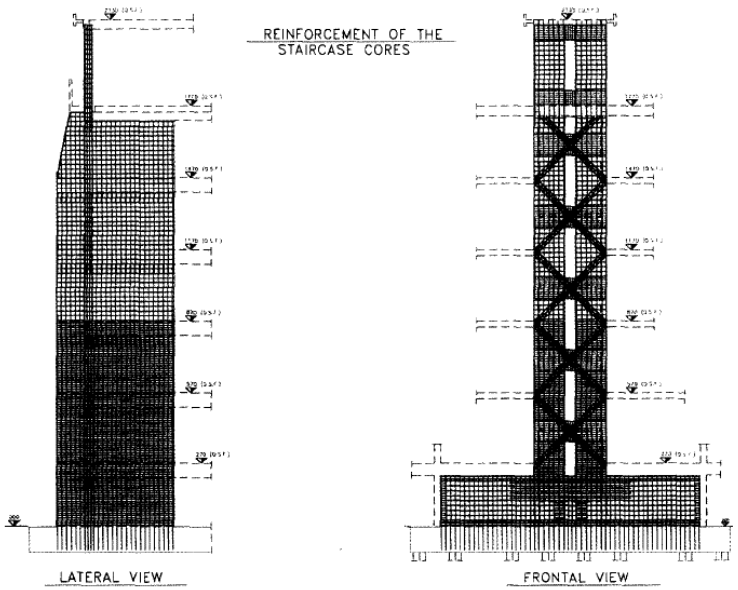
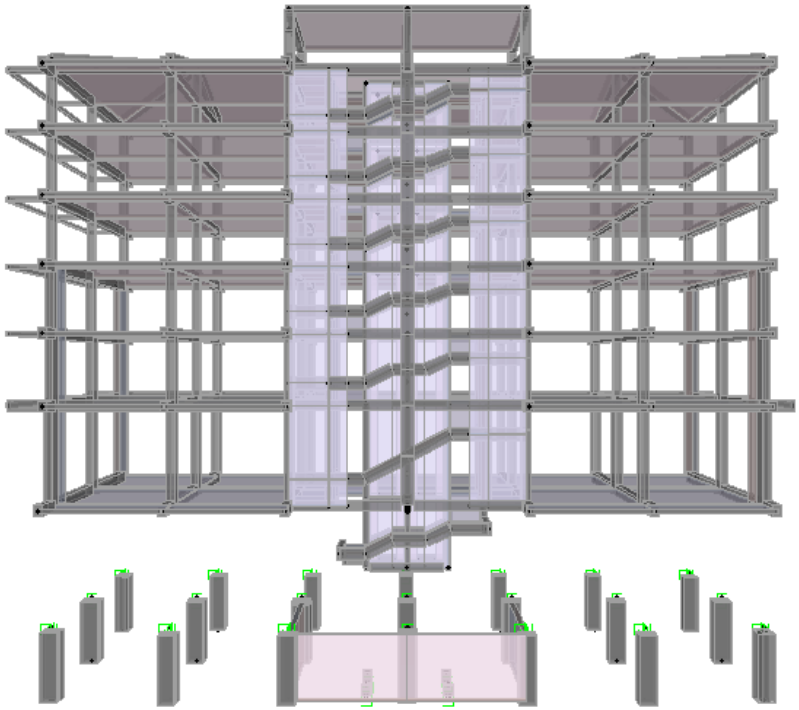
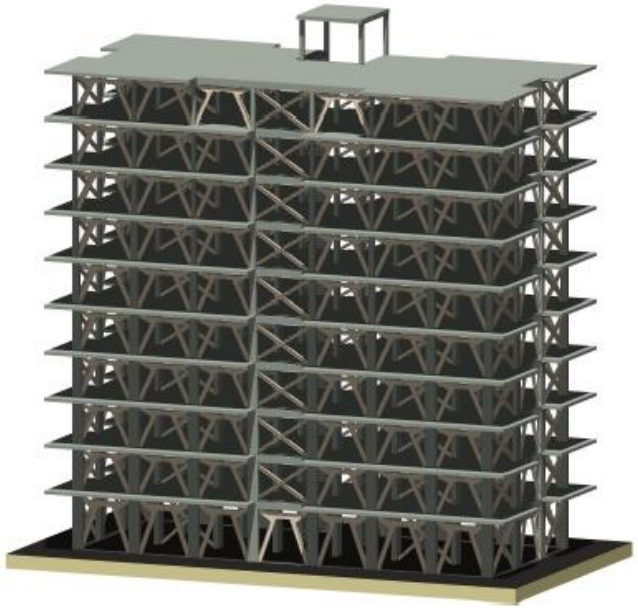



**Fig. 12.** Ductility endowment to stiffening cores.

# INNOVATIVE RETROFITTING SOLUTIONS



SEISMIC ISOLATION

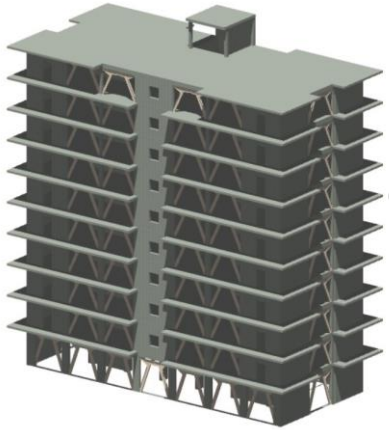


BUCKLING RESTRAINED DISSIPATIVE BRACING

ECCENTRIC BRACED SYSTEM

# THE SOLUTIONS THAT HAVE BEEN INVESTIGATED

CONCRETE SHEAR (OR STEEL WALLS)



CONCRETE SHEAR (OR STEEL WALLS)

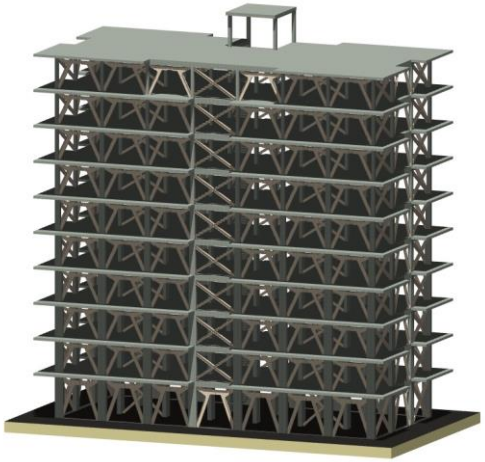
+

ECCENTRIC BRACED SYSTEM

CONCENTRIC DIAGONAL BRACINGS

+

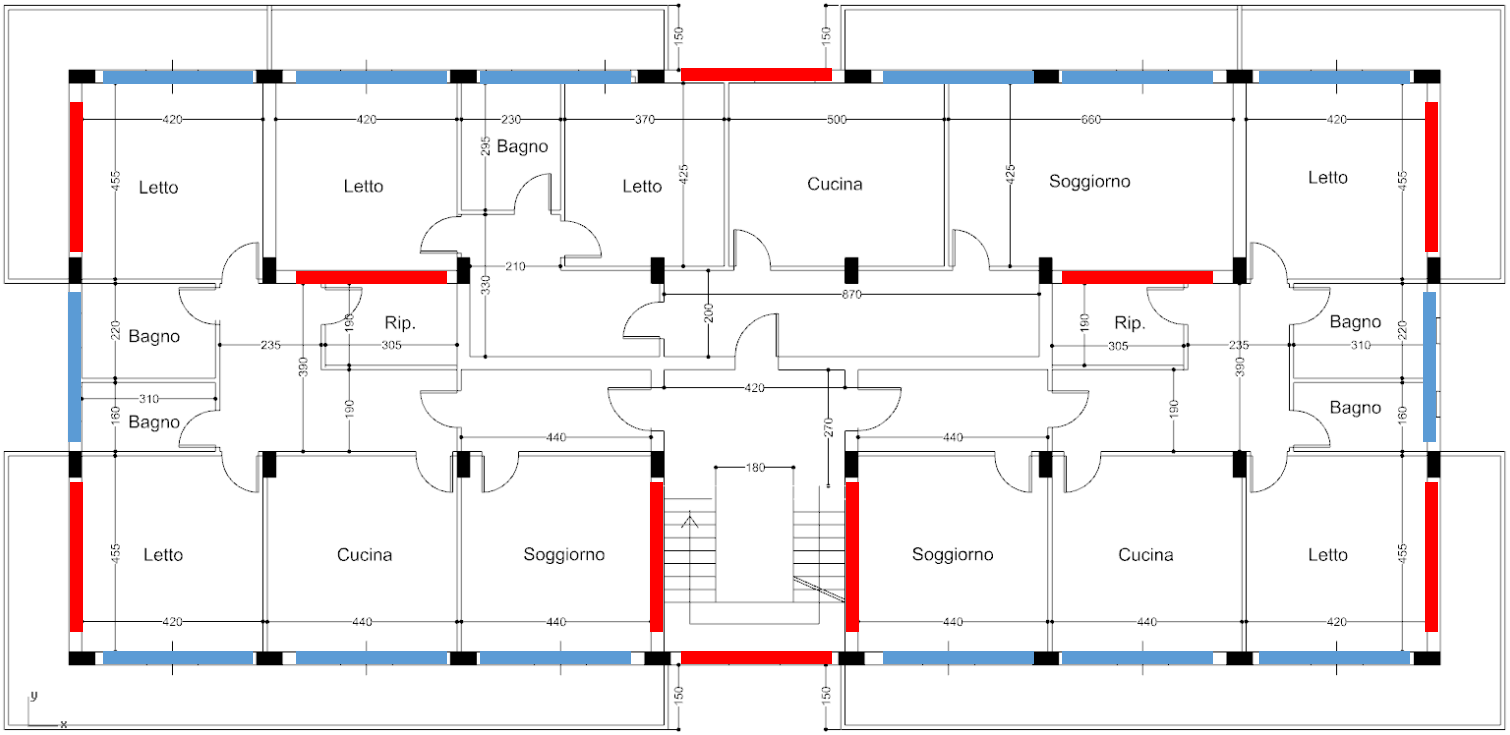
ECCENTRIC BRACED SYSTEM

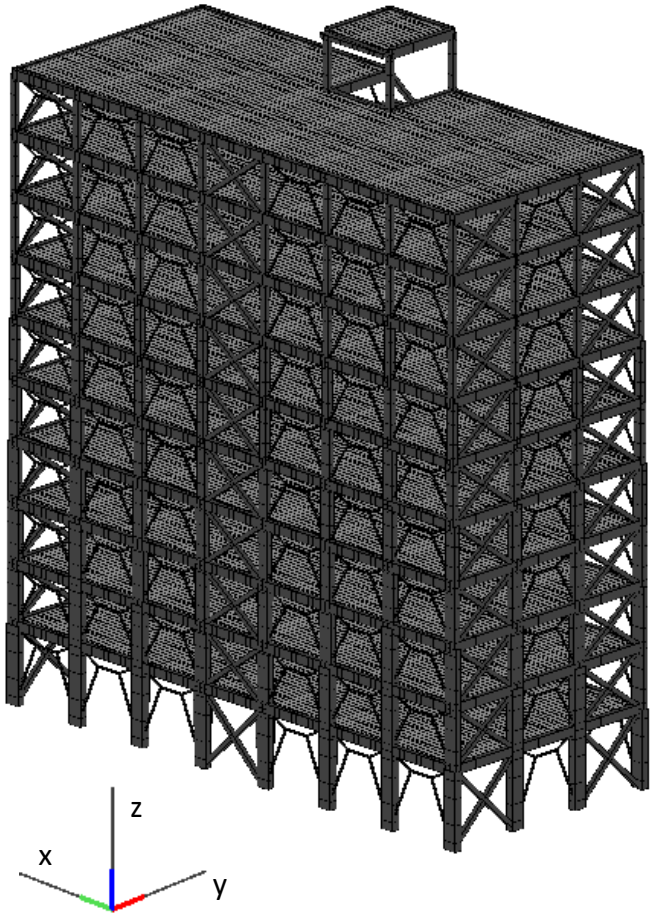


Generic floor plan and retrofit systems distribution

Concentric Bracing Systems

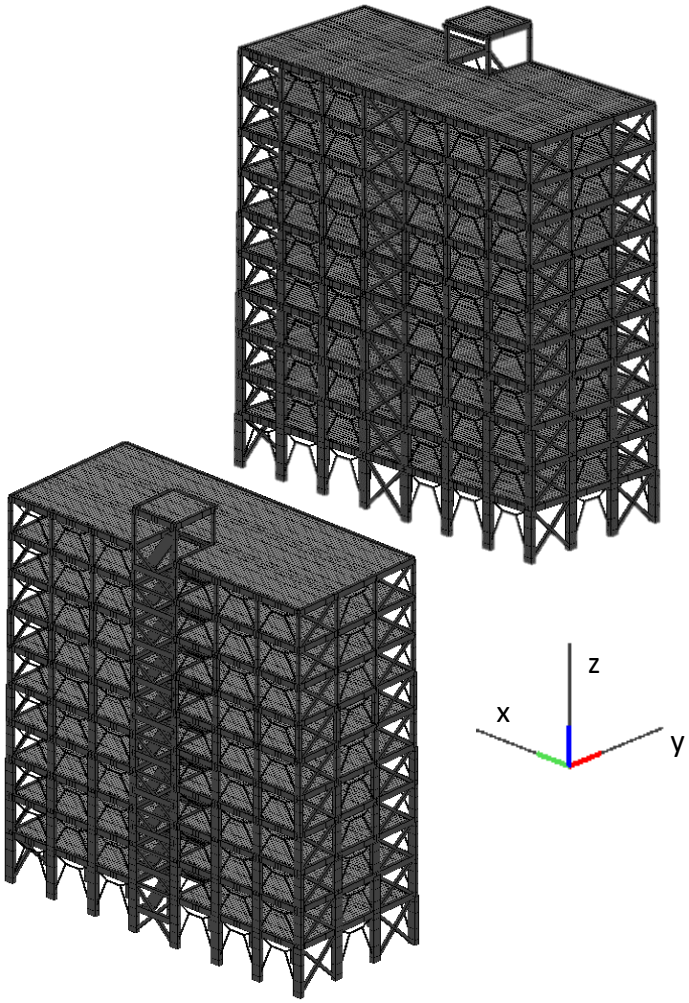
Eccentric Bracing Systems withDissipative Shear Links






## 3D HIGH FIDELITY MODEL FOR THE RETROFITTED STRUCTURE

- Nonlinear Dynamic Analysis
- 7 Accelerograms with 3 acceleration components
- Elasto-Plastic Beam-Column and Slab Elements allowing for the spread of plasticity and geometric nonlinearity
- Specific Nonlinear Material Relationships for Steel Reinforcements and Concrete (with softening)
- **Detail modelling for retrofitting elements**
- **Staged construction procedure allowing different construction phases**

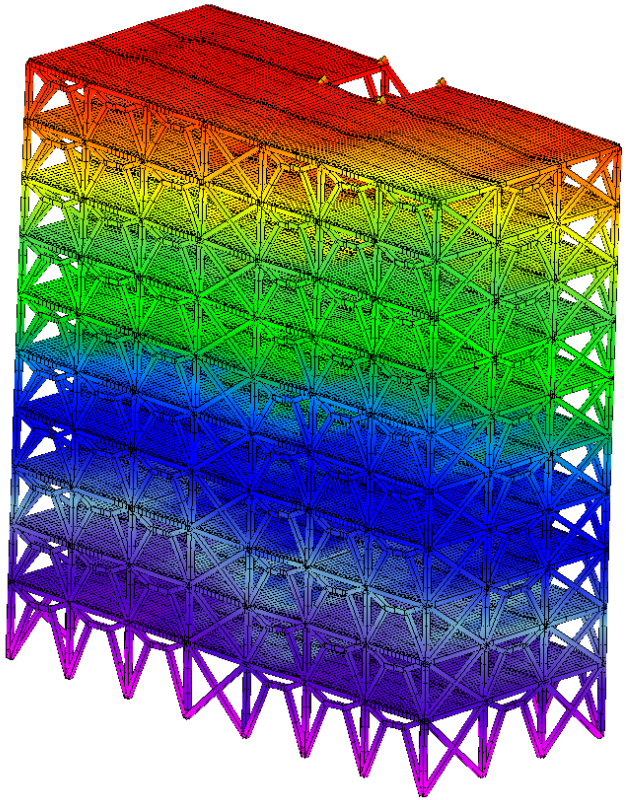


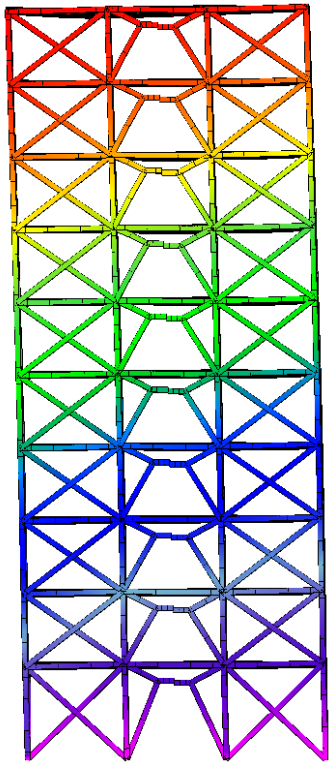

3D HIGH FIDELITY MODEL FOR THE RETROFITTED STRUCTURE

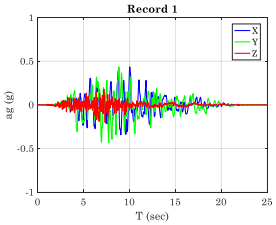
## Analysis of structural performance

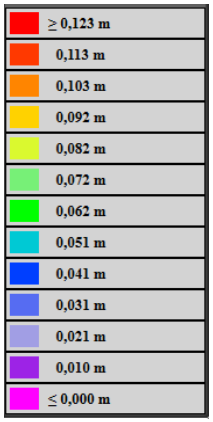
- **Horizontal displacements**
- **Inter-storey drifts**
- **Ductile mechanisms** (chord rotation)
- **Brittle mechanisms** (shear failure)

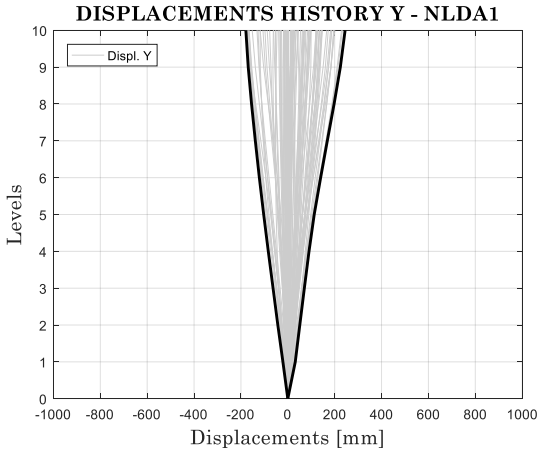
## NLDA 1 • Horizontal displacements

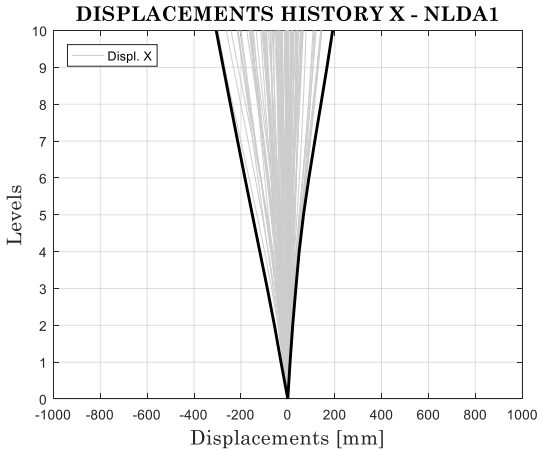






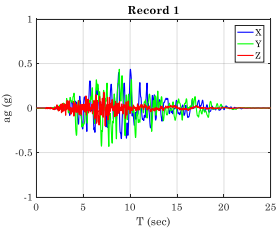



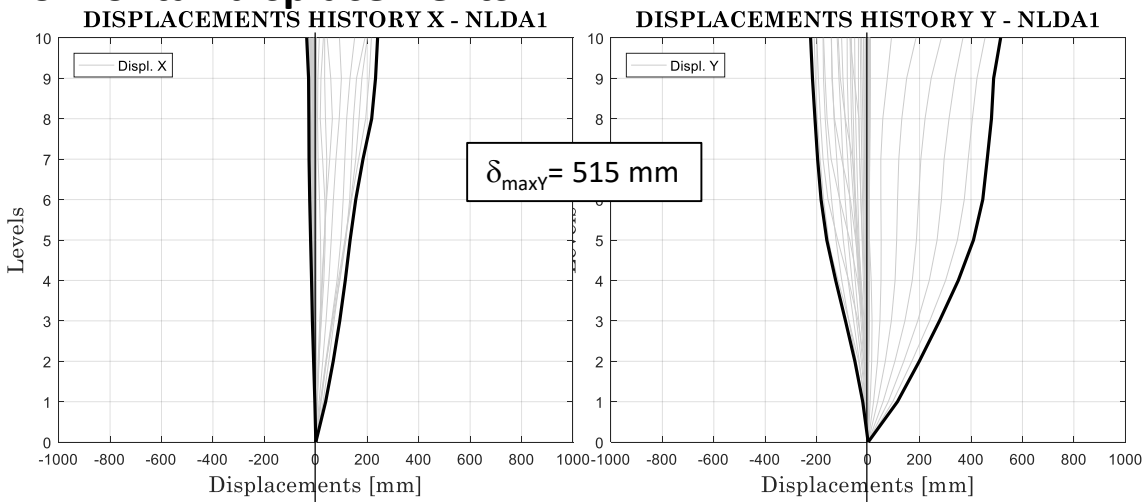



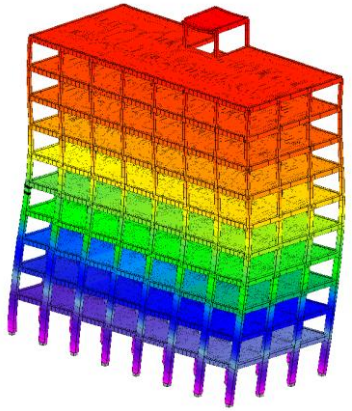

**Maximum horizontal displacements, $\delta_{max}$ = 305 mm**

# NLDA 1 • Horizontal displacements

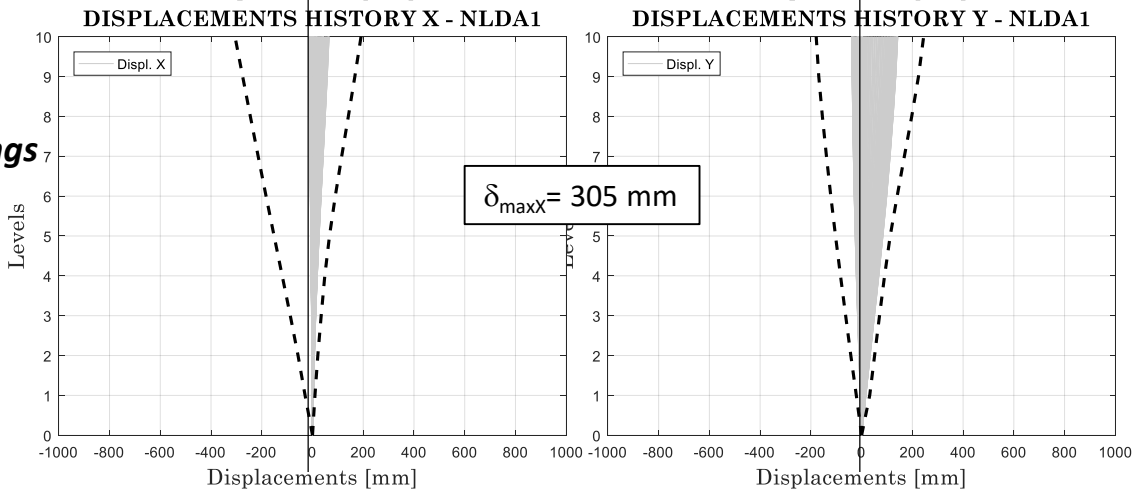
***Existing buildings***

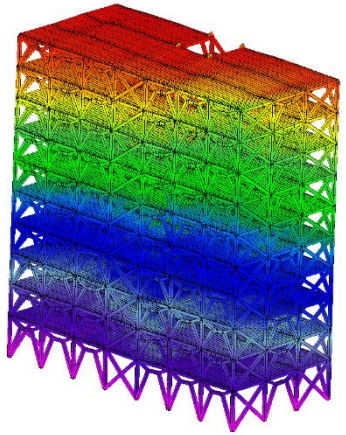


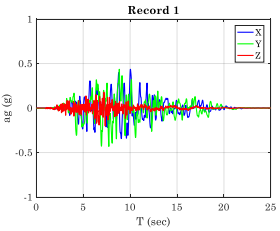
***Retrofitted buildings***

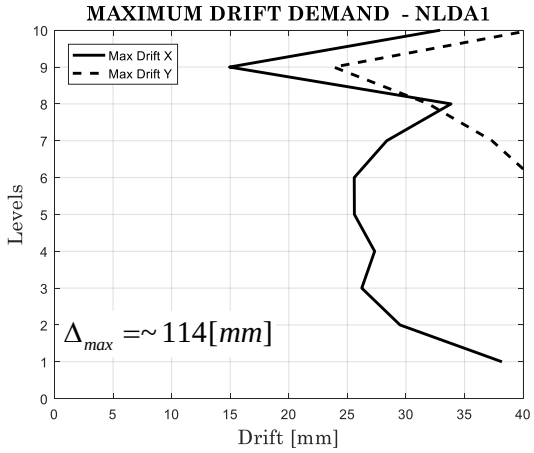


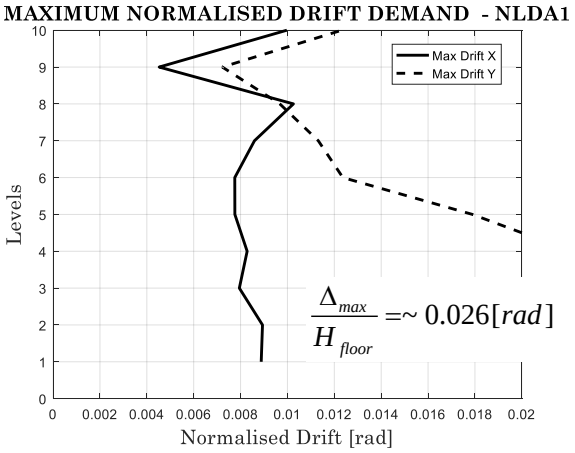



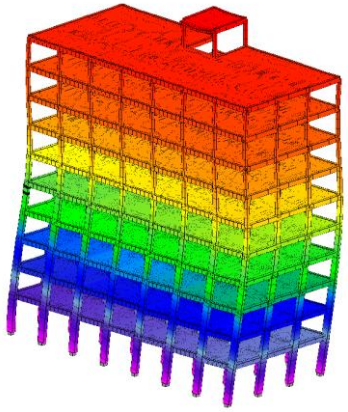
# NLDA 1 • Interstorey drifts

***Existing buildings***

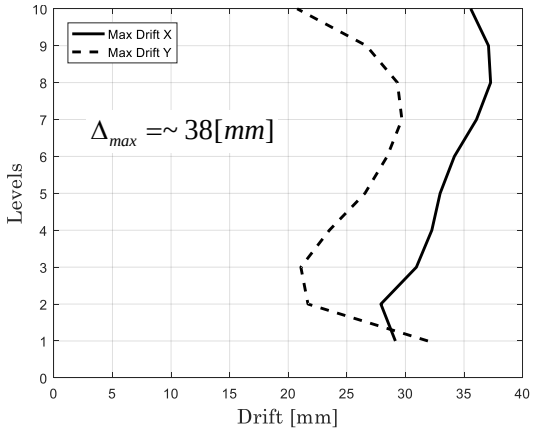


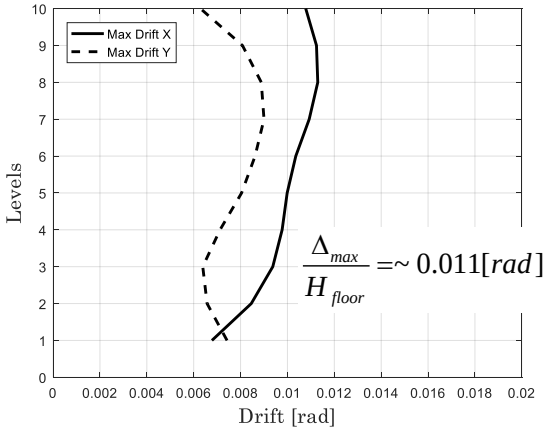



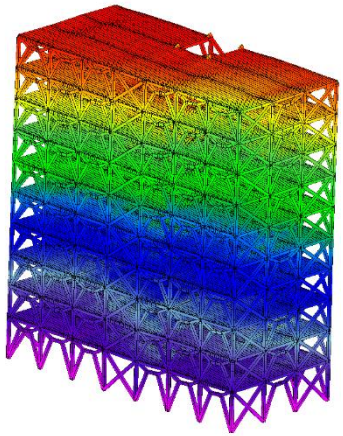



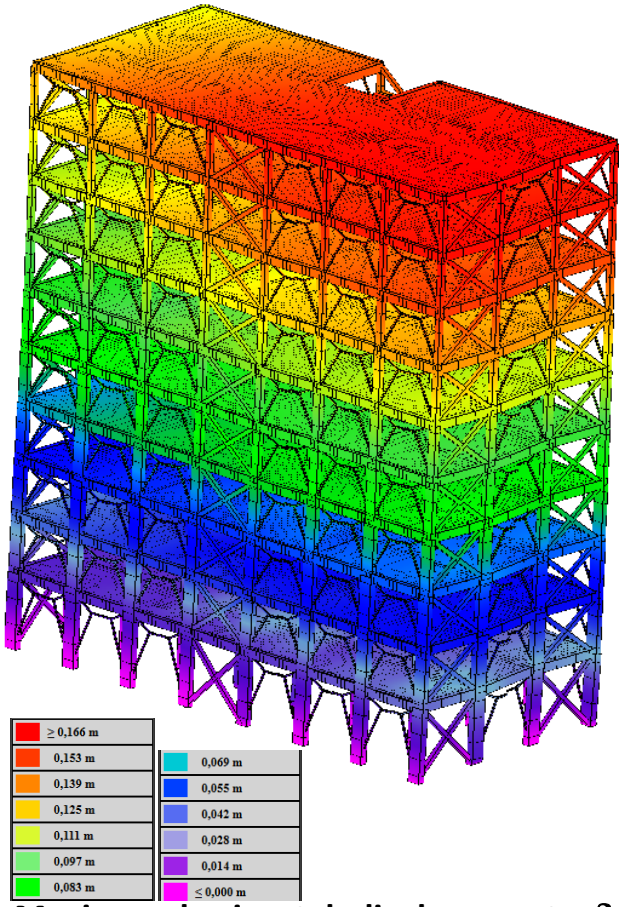
***Retrofitted buildings***

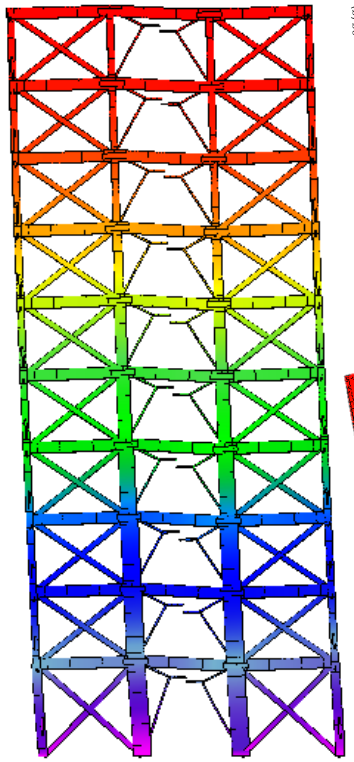


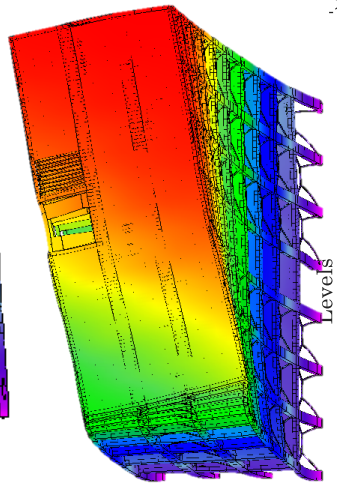



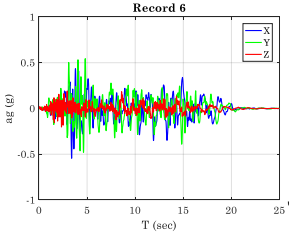



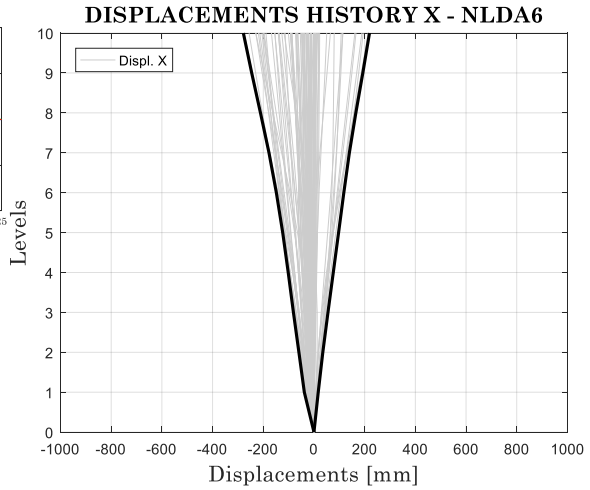
# NLDA 6 • Horizontal displacements

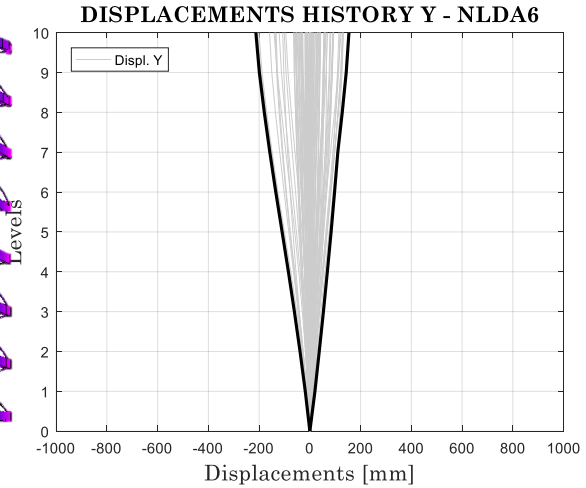






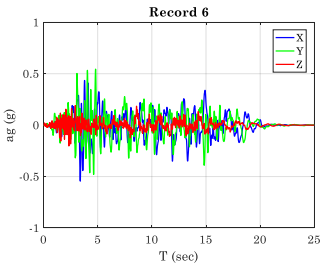



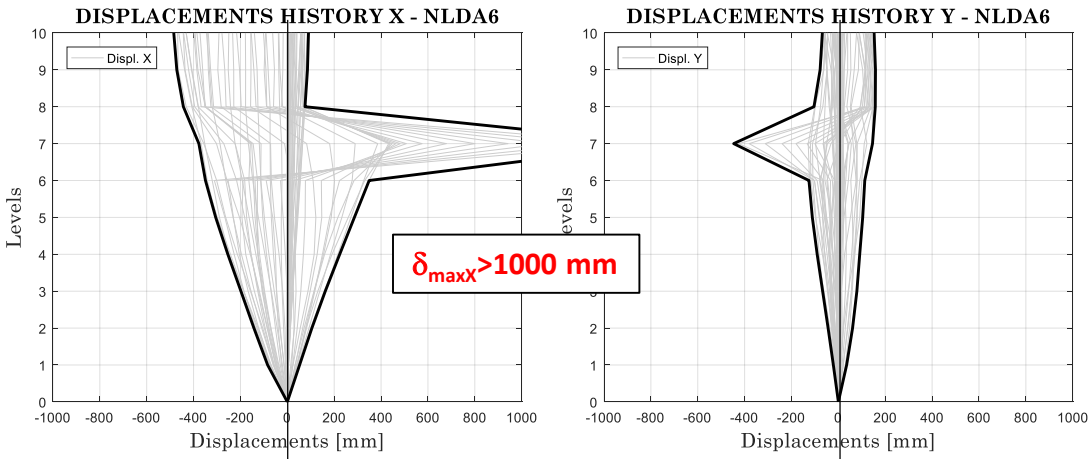



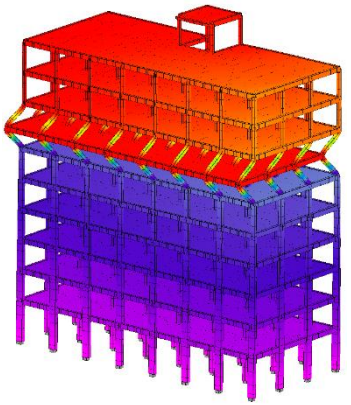

**Maximum horizontal displacements, $\delta_{max}$ = 278 mm**

# NLDA 6 • Horizontal displacements

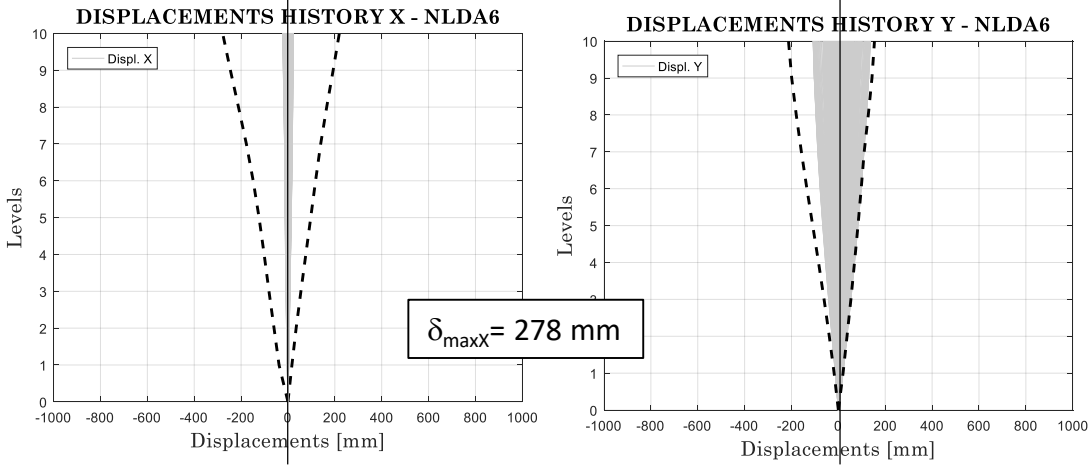
***Existing buildings***

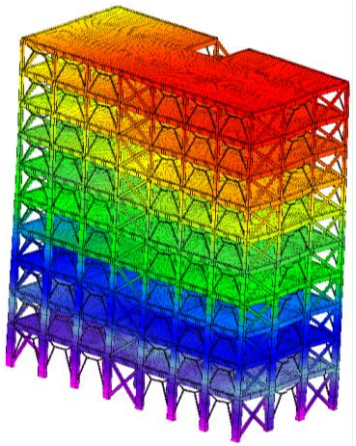


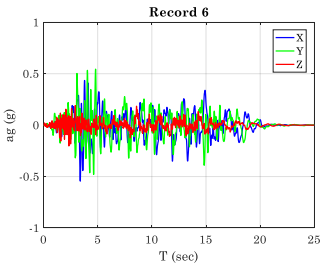
***Retrofitted buildings***

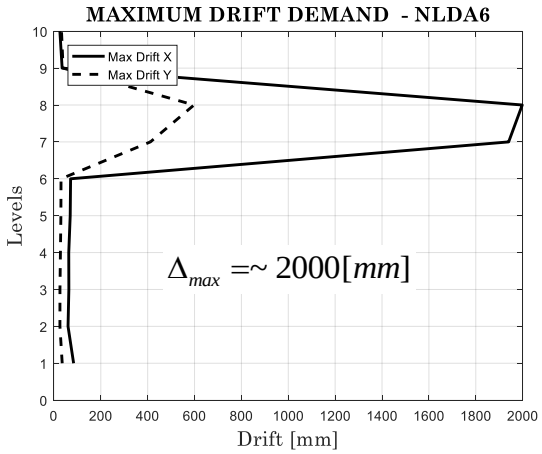


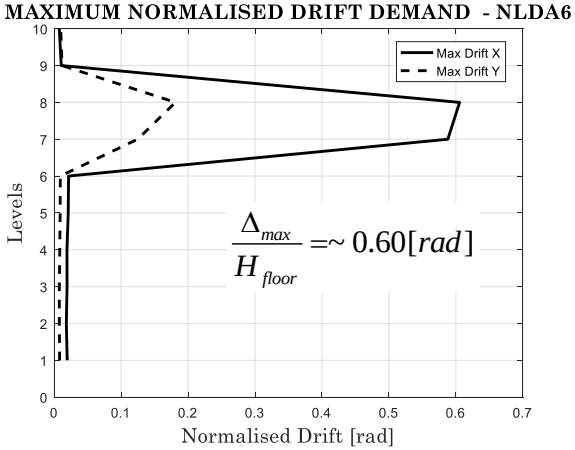



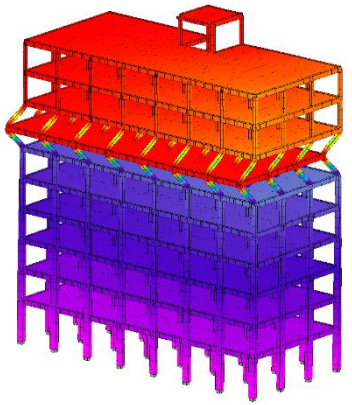
# NLDA 6 • Interstorey drifts

***Existing buildings***

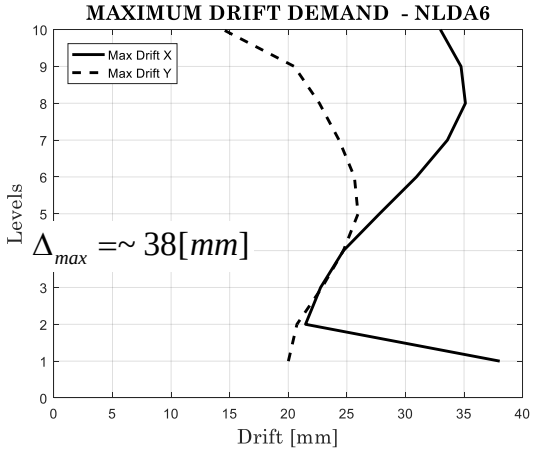


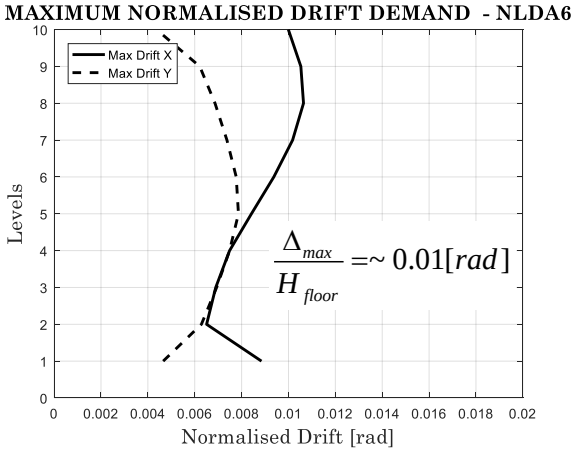



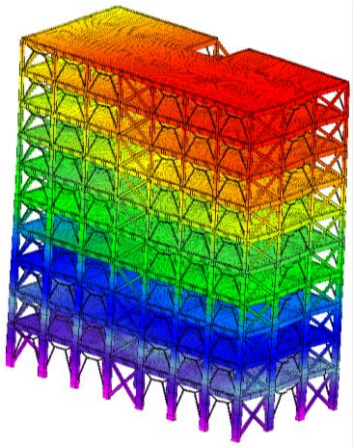



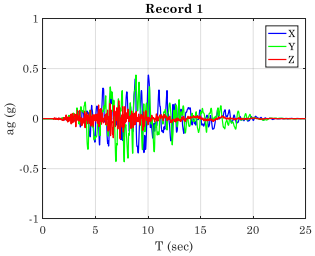
***Retrofitted buildings***



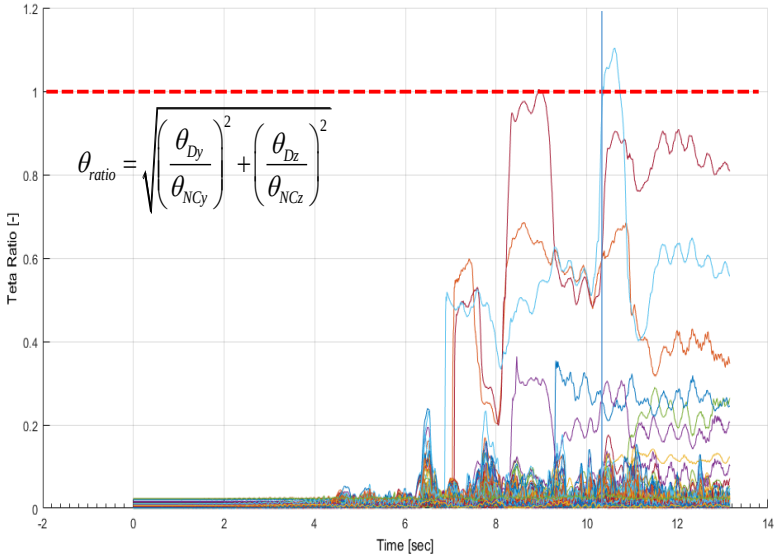



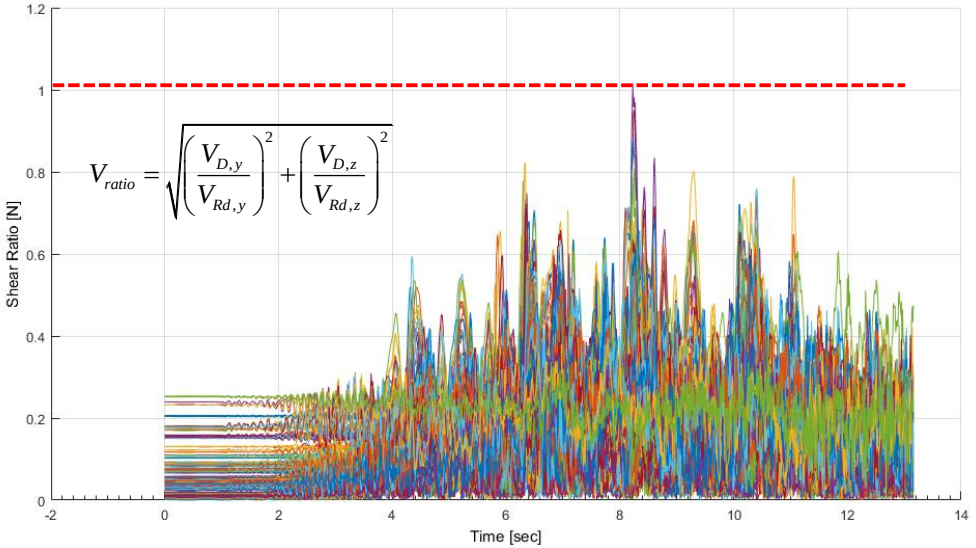
## NLDA 1



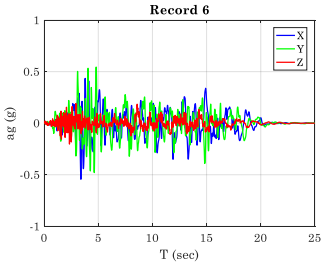

- **Ductile mechanisms** (chord rotation)




- **Brittle mechanisms** (shear failure)

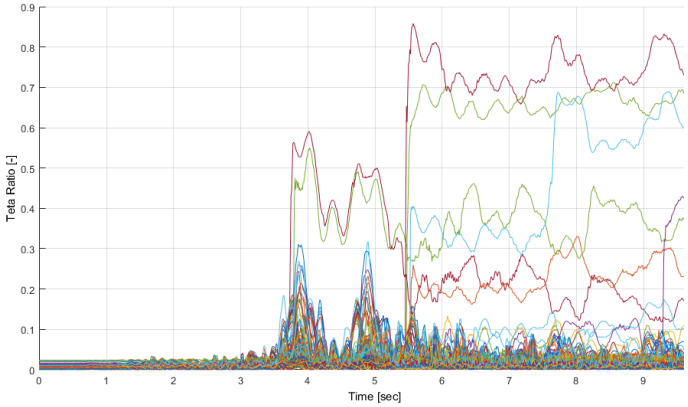


## NLDA 6



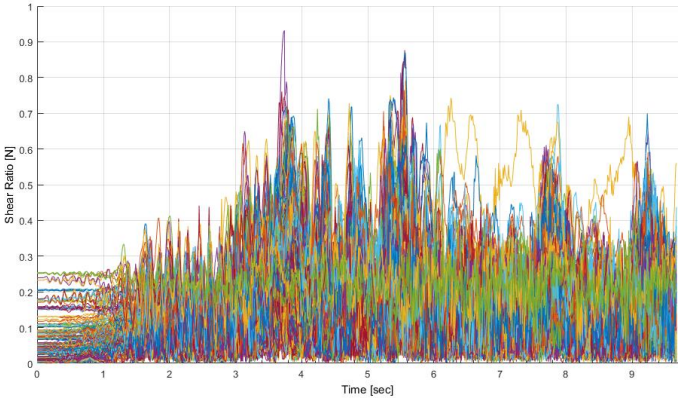

- **Ductile mechanisms** (chord rotation)

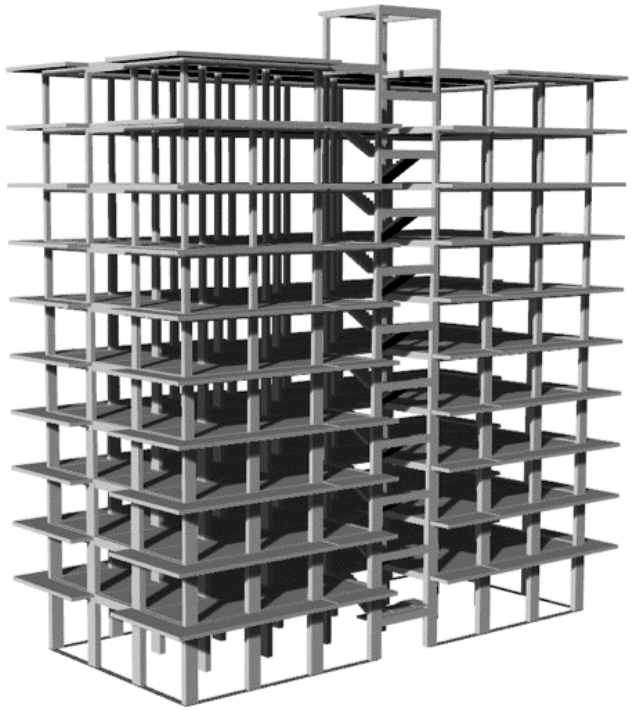
$$\theta_{ratio} = \sqrt{\left(\frac{\theta_{Dy}}{\theta_{NCy}}\right)^2 + \left(\frac{\theta_{Dz}}{\theta_{NCz}}\right)^2}$$



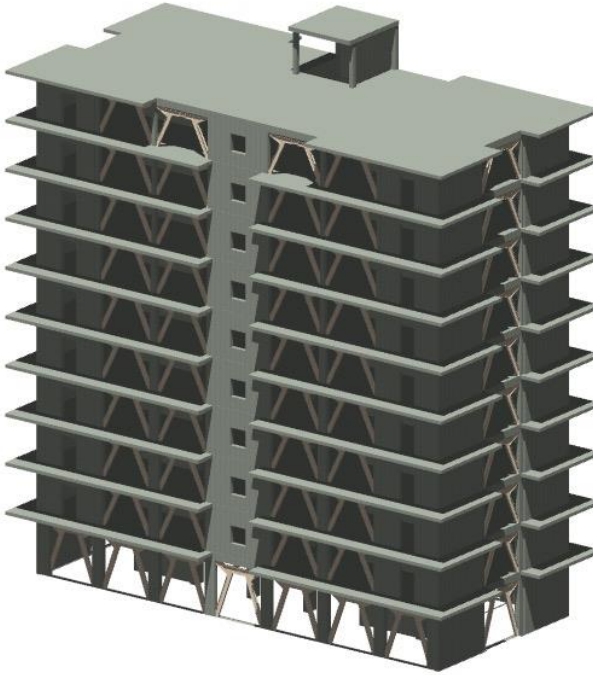

- **Brittle mechanisms** (shear failure)

$$V_{ratio} = \sqrt{\left(\frac{V_{D,y}}{V_{Rd,y}}\right)^2 + \left(\frac{V_{D,z}}{V_{Rd,z}}\right)^2}$$

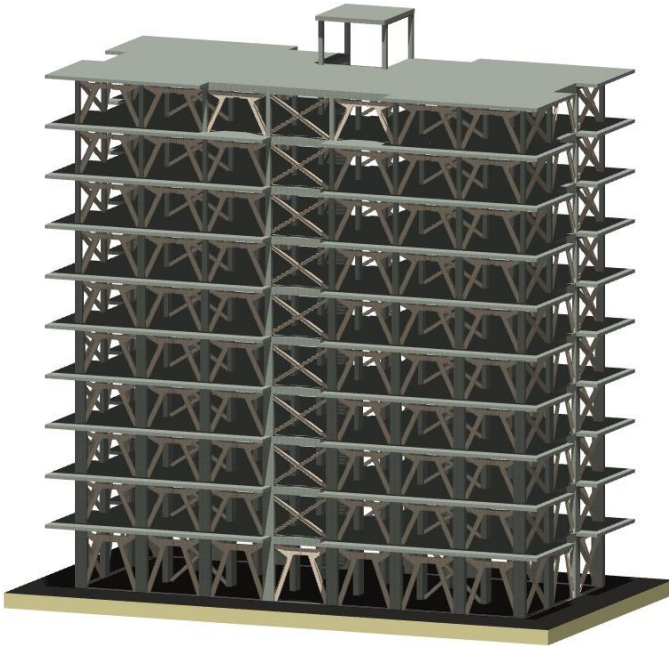




Edificio Esistente



Edificio Rinforzato con controventi eccentrici e setti in cemento armato



Edificio Rinforzato con controventi concentrici e eccentrici


4 Via Piave
Catania, Sicilia
Street View - lug 2016
ANNA
Glamour
ANNA
Via Piave
Google


4 Via Piave
Catania, Sicilia
Street View - lug 2016
ANNA
Glamour
ANNA
30%
Via Piave
Google

# ADVANTAGES OF THE ADOPTED SOLUTION

- GOOD RATIO: (COST OF RETROFITTING)/(COST OF RECONSTRUCTION)

- REDUCED DOWNTIME;

- USE OF STEEL MODULAR SOLUTIONS ENABLING FAST CONSTRUCTION ;

- POSSIBILITY TO REPAIR THE BUILDING AFTER MODERATE EARTHQUAKE

- SYNERGY BETWEEN SEISMIC PERFORMANCE AND ENERGY EFFICIENCY ;

# CONCLUSIONS

- The proposed solutions offers an effective protection to the existing structure
- High-fidelity numerical descriptions represents fundamental vehicles to assess the effectiveness of any strengthening measure
- Future research will be devoted to the optimisation of the proposed solution leading to cost savings