

# Task C

## Rapid and low-cost in-situ building vulnerability assessment

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# On-site campaign in Thessaloniki, Greece

AUTH, September-October 2015

Building of the Faculty of Philosophy



5-story RC frame with masonry walls  
and elevator shaft








Administration building



8-story RC frame with a RC shaft

# On-site campaign in Cologne, Germany

(November-December 2015)

| NN | School                            |  | General information   |
|----|-----------------------------------|--|---|
| 1  | Humboldt-Gymnasium                |    | Year of construction - 1956<br>Number of schoolchildren - 1200<br>Structural system – mixed, RC, masonry              |
| 2  | Alfred-Müller-Armack Berufskolleg |    | Year of construction - 2007<br>Number of pupils – 3000 (800)<br>Structural system – masonry shear walls               |
| 3  | Henry-Ford-Realschule             |    | Year of construction – ca. 1965<br>Number of schoolchildren - 850<br>Structural system – mixed, RC, masonry           |
| 4  | Berufskolleg Ehrenfeld            |    | Year of construction – ca. 1960<br>Number of schoolchildren - not specified<br>Structural system – mixed, RC, masonry |
| 5  | Otto-Lilienthal-Schule            |    | Year of construction - 1969<br>Number of schoolchildren – not specified<br>Structural system – mixed, RC, masonry     |
| 6  | Gymnasium Thusnelda-straße        |   | Year of construction - 1960s<br>Number of schoolchildren - 843<br>Structural system – mixed, RC, masonry              |
| 7  | Gymnasium Kreuzgasse              |  | Year of construction – not specified<br>Number of schoolchildren - 979<br>Structural system – mixed, RC, masonry      |

# School buildings, Cologne, Germany



RC frame, masonry in-fill and shear walls



Mixed: RC, masonry



Masonry shear walls



Mixed: RC, masonry

# School buildings, Cologne, Germany



well-structured

Mixed: RC, masonry



“strange”

Mixed: RC, masonry



front side

RC frame, in-fill walls, shear walls



back side

shear wall, masonry

# On-site campaign in L'Aquila, Italy

(May-June 2016)

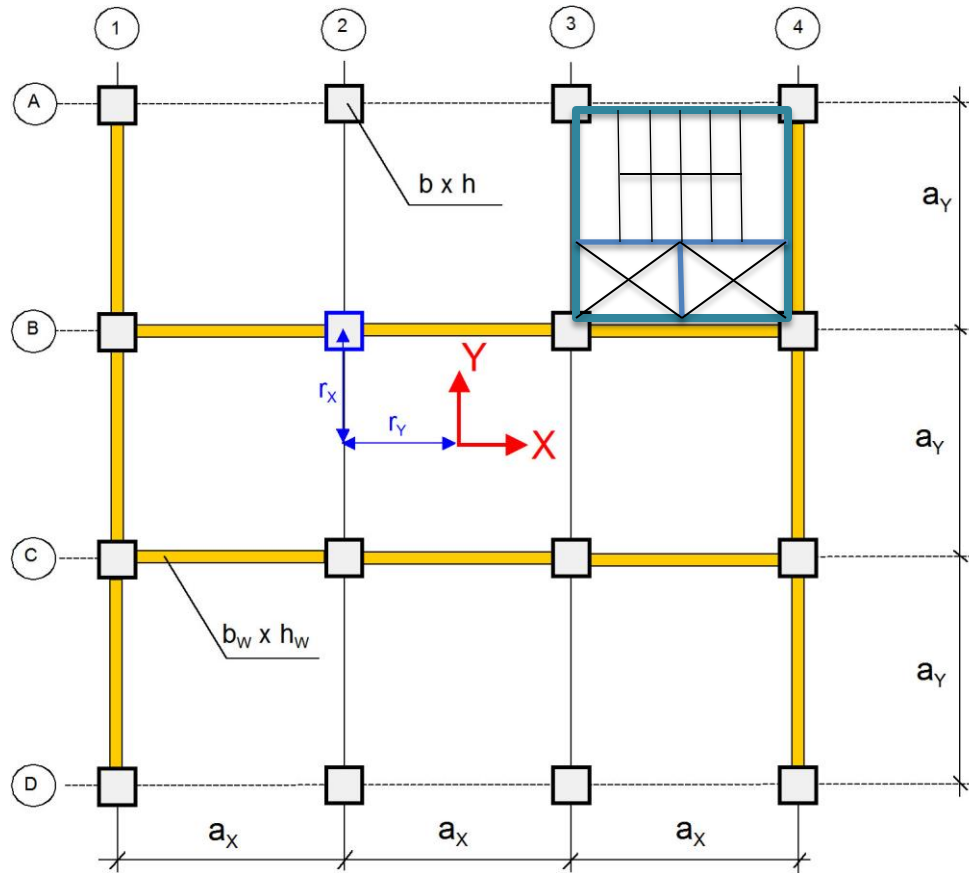


Partly damaged building since 2009  
RC frame, in-fill walls



| No. | Data type   | Ranking |
|-----|---|---------|
| 1   | Lateral load-resisting system and material of bearing structures  | 1       |
| 2   | Overall dimensions and shape of the building  | 1       |
| 3   | Presence and location of separation lines   | 1       |
| 4   | Presence of irregularities (physical or geometrical / in plan or in elevation)  | 1       |
| 5   | Dimensions and location of structural elements (columns, walls, slabs)  | 1       |
| 6   | Cross-sections of the structural members and their material properties (strength, elastic moduli, specific density)   | 1       |
| 7   | Year of construction (modification)   | 2       |
| 8   | Occupancy of the building   | 2       |
| 9   | Non-structural elements and other building components, which can contribute to the stiffness and/or mass distribution | 2       |
| 10  | State of the preservation of the building (structural system)   | 2       |
| 11  | Depth and type of foundation  | 2       |
| 12  | Local soil conditions   | 2       |
| 13  | Position of the building with respect to the neighboring buildings  | 2       |

# Typical structural members



## Structural members

- Columns
- Girders
- Walls
- Slabs
- Shafts (lift, stairs)

with their

- Position
- Dimensions
- Material properties

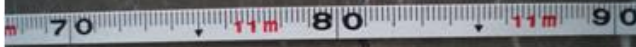


# Data collection tools

Laser distance meter on tripod



Rule / Measuring tape



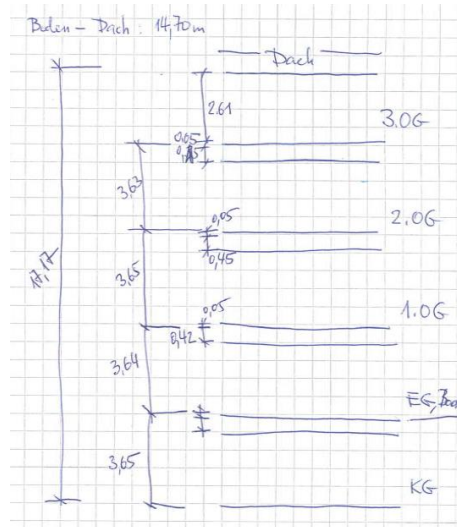
Schmidt hammer



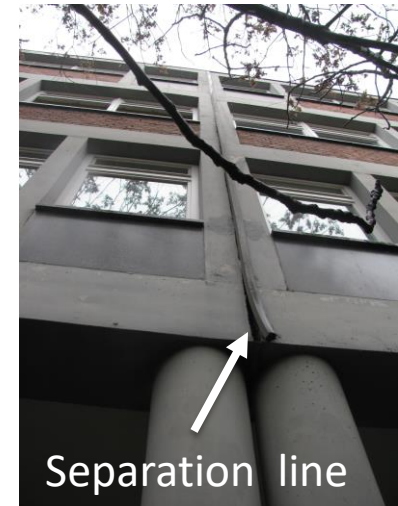
Reinforcement detector



Engineering sketches

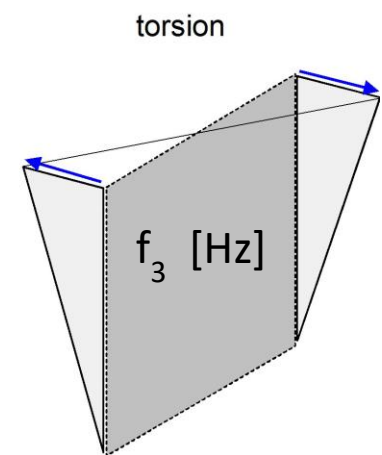
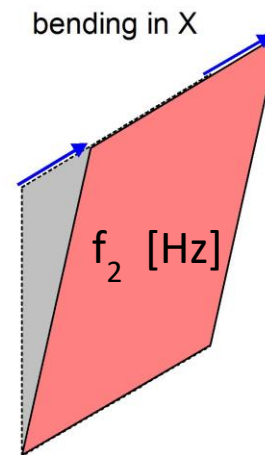
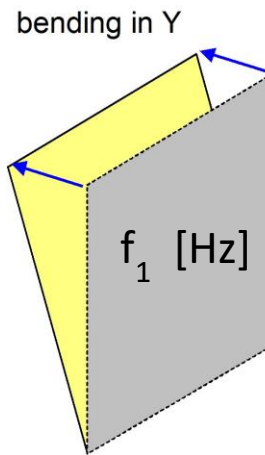
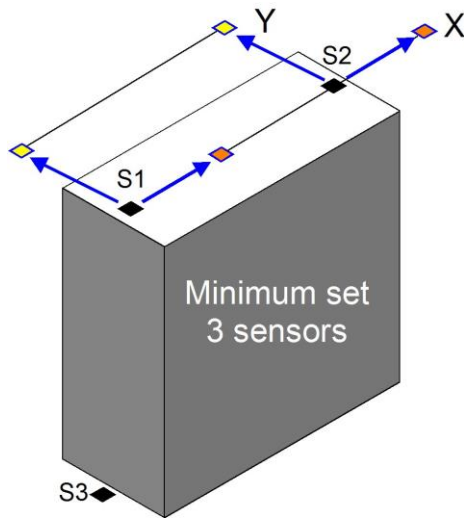
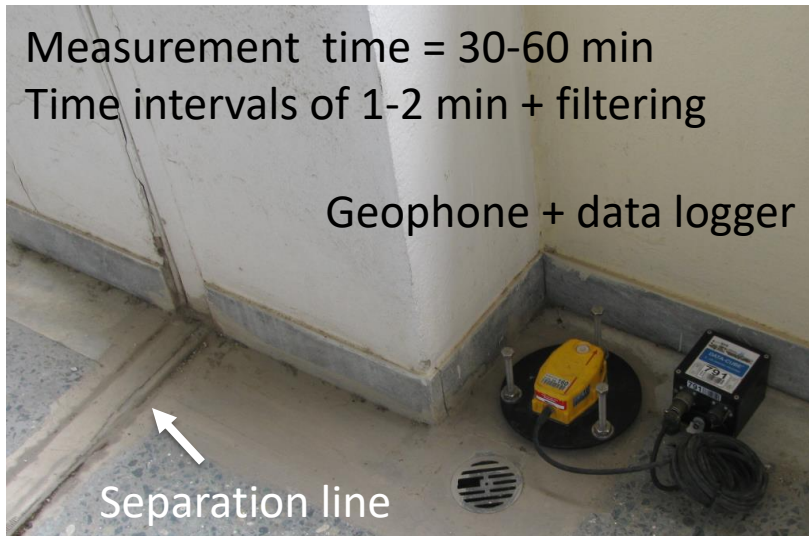


On-site pictures



Separation line

# Ambient vibration measurements



Result: Natural frequencies and mode shapes

# Data input in MS Excel

1<sup>st</sup> sheet = user interface

|    | A                                  | B                                      | C                                      | D                                    | E                                    | F   | G                                     | H   | I                                     | J                              | K                                     | L        | M |
|----|------------------------------------|--|--|--------------------------------------|--------------------------------------|---|---------------------------------------|---|---------------------------------------|--------------------------------|---------------------------------------|----------|---|
| 1  | <b>Building</b>                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 2  | Number of Stories                  |  | Length X [m]                           |                                      | E-Modulus [MN/m <sup>2</sup> ]       |   | Poisson's ratio                       |   | E-Modulus, Walls [MN/m <sup>2</sup> ] | Meas./Calc. Frequency, X [Hz]  |                                       |          | 0 |
| 3  | Total Height                       |  | Length Y [m]                           |                                      | Stiffness Ratio                      |   | Number of Column Types                |   |                                       | Meas./Calc. Frequency, Y [Hz]  |                                       |          | 0 |
| 4  |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 5  | <b>Uniform Grid of Columns</b>     |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 6  | Current Story                      | Total number of columns in X-direction | Total number of columns in Y-direction | Bay Width, X [m]                     | Bay Width, Y [m]                     | Cross-section Width, X [m]                    | Cross-section Width, Y [m]            | Diameter [m] (if round cross-section, else 0) | First Column Coordinate, X [m]        | First Column Coordinate, Y [m] | Material Density [kN/m <sup>3</sup> ] | Einfügen |   |
| 7  |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 8  |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 9  | <b>Non-uniform Grid of Columns</b> |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 10 | Current Story                      | Column Coordinate, X [m]               | Column Coordinate, Y [m]               | Cross-section Width, X [m]           | Cross-section Width, Y [m]           | Diameter [m] (if round cross-section, else 0) | Material Density [kN/m <sup>3</sup> ] | Einfügen                                      |                                       |                                |                                       |          |   |
| 11 |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 12 |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 13 | <b>Hollow Shaft</b>                |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 14 | Current Story                      | X-coordinate (center) [m]              | Y-coordinate (center) [m]              | Cross-section Width, X [m]           | Cross-section Width, Y [m]           | Wall Thickness, X [m]                         | Wall Thickness, Y [m]                 | Material Density [kN/m <sup>3</sup> ]         | Einfügen                              |                                |                                       |          |   |
| 15 |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 16 |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 17 | <b>Walls</b>                       |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 18 | Current Story                      | First Point Coordinate in Plan, X1 [m] | First Point Coordinate in Plan, Y1 [m] | End Point Coordinate in Plan, X1 [m] | End Point Coordinate in Plan, Y1 [m] | Wall Thickness, [m]                           | Material Density [kN/m <sup>3</sup> ] | Einfügen                                      |                                       |                                |                                       |          |   |
| 19 |                                    |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 20 | <b>Number of Elements</b>          |  |  |                                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |
| 21 | Story                              | Number of columns                      | Number of shafts                       | Number of walls                      |                                      |   |                                       |   |                                       |                                |                                       |          |   |

# Linear model check and tuning in MS Excel

|   | A                 | B    | C            | D    | E                              | F     | G                      | H   | I                                     | J                             | K    | L | M           |
|---|-------------------|------|--------------|------|--------------------------------|-------|------------------------|-----|---------------------------------------|-------------------------------|------|---|-------------|
| 1 | <b>Building</b>   |      |              |      |                                |       |                        |     |                                       |                               |      |   |             |
| 2 | Number of Stories | 5    | Length X [m] | 33.6 | E-Modulus [MN/m <sup>2</sup> ] | 33000 | Poisson's ratio        | 0.2 | E-Modulus, Walls [MN/m <sup>2</sup> ] | Meas./Calc. Frequency, X [Hz] | 1.72 |   | 1.601816004 |
| 3 | Total Height      | 29.5 | Length Y [m] | 25.5 | Siffness Ratio                 | 2     | Number of Column Types | 1   | 5000                                  | Meas./Calc. Frequency, Y [Hz] | 1.6  |   | 1.767334209 |

|    | A                         | B                 | C                | D               | E | F | G | H | I | J | K | L | M |
|----|---------------------------|-------------------|------------------|-----------------|---|---|---|---|---|---|---|---|---|
| 20 | <b>Number of Elements</b> |                   |                  |                 |   |   |   |   |   |   |   |   |   |
| 21 | Story                     | Number of columns | Number of shafts | Number of walls |   |   |   |   |   |   |   |   |   |
| 22 | 1                         | 32                | 1                | 2               |   |   |   |   |   |   |   |   |   |
| 23 | 2                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |
| 24 | 3                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |
| 25 | 4                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |
| 26 | 5                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |

Frequency difference < 20% => OK, **green**  
 Frequency difference > 20% => modify, **red**

**uncertainties**

| <b>Stiffnesses [MN/m]</b> |             |             |  |
|---------------------------|-------------|-------------|--|
| Story                     | Kx          | Ky          |  |
| 1                         | 1224.574208 | 1867.018663 |  |
| 2                         | 7560.66339  | 4861.827031 |  |
| 3                         | 7560.66339  | 4861.827031 |  |
| 4                         | 7560.66339  | 4861.827031 |  |
| 5                         | 9420.398476 | 6396.379231 |  |

| <b>Masses and Weights</b> |                   |                                   |                  |                    |             |
|---------------------------|-------------------|-----------------------------------|------------------|--------------------|-------------|
| Story                     | Story Mass [kN/m] | Slab density [kN/m <sup>3</sup> ] | Story Height [m] | Slab Thickness [m] | Weight [kN] |
| 1                         | 364.95            | 50                                | 5.8              | 0.4                | 19961.415   |
| 2                         | 783               | 50                                | 5.1              | 0.4                | 20816.1     |
| 3                         | 783               | 50                                | 5.1              | 0.4                | 20816.1     |
| 4                         | 783               | 50                                | 5.1              | 0.4                | 20385.45    |
| 5                         | 783               | 50                                | 4                | 0.4                | 18545.4     |

| <b>Calculated Frequencies [Hz]</b> |             |             |  |
|------------------------------------|-------------|-------------|--|
| Mode                               | X           | Y           |  |
| 1                                  | 1.601816004 | 1.767334209 |  |
| 2                                  | 6.634602475 | 5.789989168 |  |
| 3                                  | 12.08460813 | 9.984985082 |  |
| 4                                  | 16.45251741 | 13.38894828 |  |
| 5                                  | 18.87130599 | 15.29247381 |  |

| <b>Earthquake Forces</b> |            |                       |             |
|--------------------------|------------|-----------------------|-------------|
| lambda                   | 1          | Spectral acceleration | 2.45        |
| Weight [kN]              | 100524.465 | Shear Force Fges [MN] | 246.2849393 |

| <b>Column cross-sections</b> |             |             |            |                    |
|------------------------------|-------------|-------------|------------|--------------------|
| Current No.                  | X-Width [m] | Y-Width [m] | Radius [m] | Concrete cover [m] |
| 1                            | 0.5         | 0.75        | 0          | 0.03               |

| <b>Shaft cross-sections</b> |             |             |                       |                       |
|-----------------------------|-------------|-------------|-----------------------|-----------------------|
| Current No.                 | X-Width [m] | Y-Width [m] | Wall Thickness, X [m] | Wall Thickness, Y [m] |
| 1                           | 1.7         | 3.9         | 0.15                  | 0.15                  |

| <b>Concrete Properties</b> |       |
|----------------------------|-------|
| Strength [MPa]             | 30    |
| Reinforcement ratio        | 0.015 |
| Tens. strength [MPa]       | 2.2   |

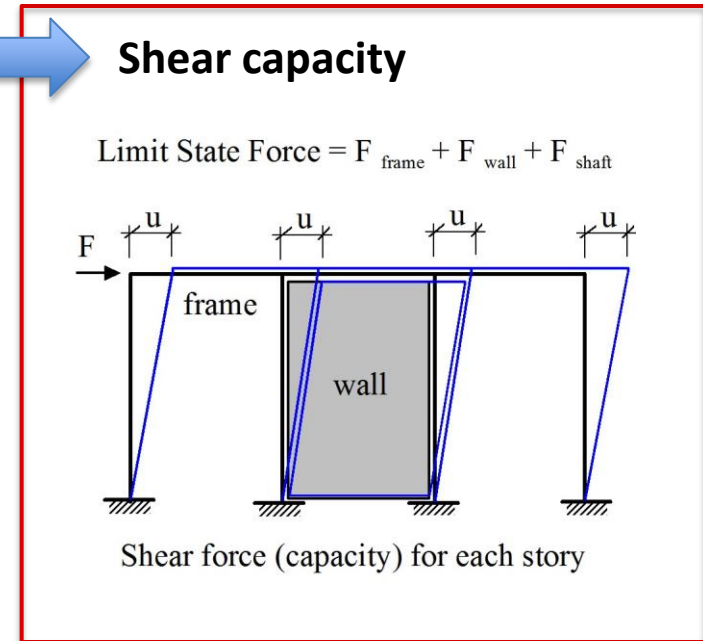
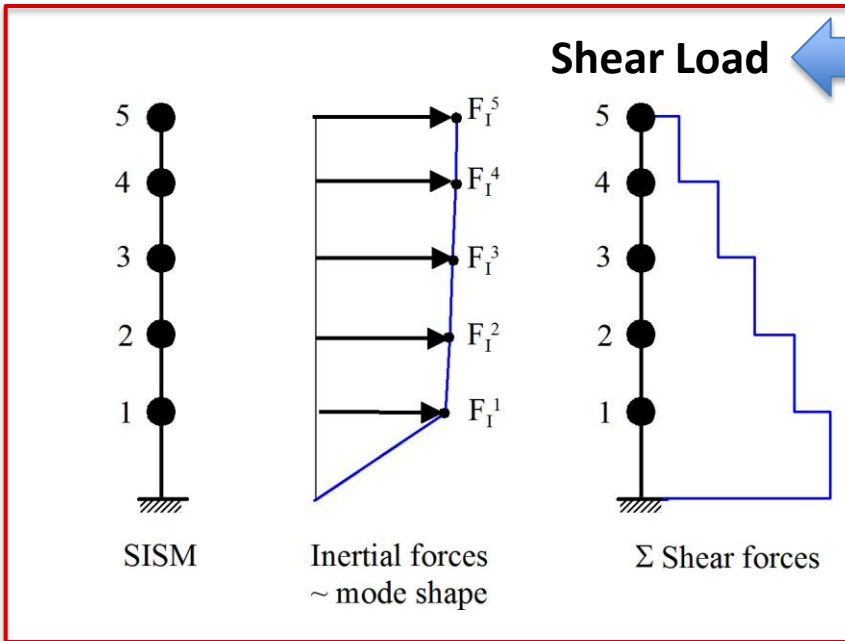
# Earthquake loading and capacity

|    | G                         | H                 | I                                 | J                | K                  | L           |
|----|---------------------------|-------------------|-----------------------------------|------------------|--------------------|-------------|
| 26 |                           |                   |                                   |                  |                    |             |
| 32 | <b>Masses and Weights</b> |                   |                                   |                  |                    |             |
| 33 | Story                     | Story Mass [kN/m] | Slab density [kN/m <sup>3</sup> ] | Story Height [m] | Slab Thickness [m] | Weight [kN] |
| 34 | 1                         | 364.95            | 50                                | 5.8              | 0.4                | 19961.415   |
| 35 | 2                         | 783               | 50                                | 5.1              | 0.4                | 20816.1     |
| 36 | 3                         | 783               | 50                                | 5.1              | 0.4                | 20816.1     |
| 37 | 4                         | 783               | 50                                | 5.1              | 0.4                | 20385.45    |
| 38 | 5                         | 783               | 50                                | 4                | 0.4                | 18545.4     |
| 44 | <b>Earthquake Forces</b>  |                   |                                   |                  |                    |             |
| 45 | lambda                    | 1                 | Spectral acceleration             | 2.45             |                    |             |
| 46 | Weight [kN]               | 100524.465        | Shear Force Fges [MN]             | 246.2849393      |                    |             |

|                               | I           | J           | K |
|-------------------------------|-------------|-------------|---|
| <b>Earthquake Forces [MN]</b> |             |             |   |
| Story                         | Force x     | Force y     |   |
| 1                             | 40.65073695 | 32.41949512 |   |
| 2                             | 48.11448874 | 45.06529491 |   |
| 3                             | 52.54018378 | 54.0222851  |   |
| 4                             | 54.40175504 | 58.98240049 |   |
| 5                             | 50.57777474 | 55.79546364 |   |

Total earthquake force

$$F_I = \lambda m S_d = \sum F_I^k$$



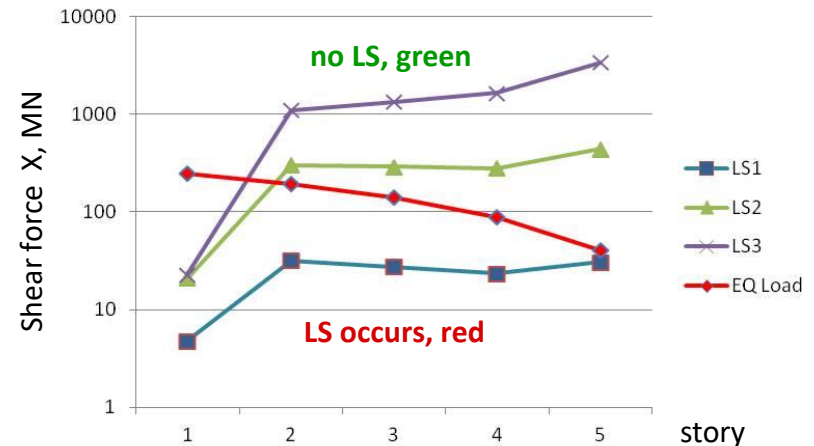
Considered limit states:

LS1: cracks (IO = immediate occupancy)

LS2: yielding (DL = damage limitation)

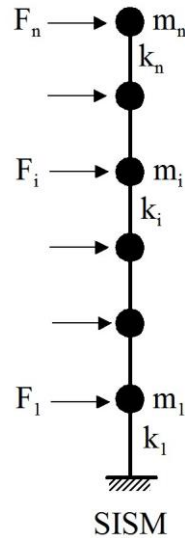
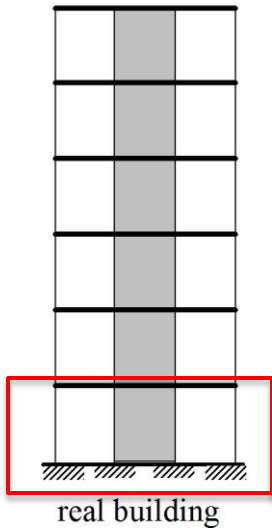
LS3: collapse (NC = near collapse)

Limit states are determined individually for each story by comparing the EQ shear force with corresponding limit state force.



|     | A                                      | B             | C              | D                                      | E              | F                  | G                             | H              | I              | J              | K |
|-----|--|---------------|----------------|--|----------------|--------------------|-------------------------------|----------------|----------------|----------------|---|
| 67  | <b>Stiffnesses for LS2 (DL) [MN/m]</b> |               |                | <b>Stiffnesses for LS3 (NC) [MN/m]</b> |                |                    | <b>Earthquake Forces [MN]</b> |                |                |                |   |
| 68  | Story                                  | Kx            | Ky             | Story                                  | Kx             | Ky                 | Story                         | Force x        | Force y        |                |   |
| 69  | 1                                      | 372.4023786   | 827.4240258    | 1                                      | 82.26828406    | 273.7881038        | 1                             | 40.65073695    | 32.41949512    |                |   |
| 70  | 2                                      | 4797.979814   | 2957.408525    | 2                                      | 3245.500734    | 1785.880412        | 2                             | 48.11448874    | 45.06529491    |                |   |
| 71  | 3                                      | 4755.07782    | 2878.319765    | 3                                      | 3224.925779    | 1719.394627        | 3                             | 52.54018378    | 54.0222851     |                |   |
| 72  | 4                                      | 4708.255894   | 2788.379897    | 4                                      | 3208.667273    | 1667.673076        | 4                             | 54.40175504    | 58.98240049    |                |   |
| 73  | 5                                      | 5959.617656   | 3761.467554    | 5                                      | 4126.531119    | 2399.274547        | 5                             | 50.57777474    | 55.79546364    |                |   |
| 79  |  |               |                |  |                |                    |                               |                |                |                |   |
| 235 | <b>Limit state assessment</b>          |               |                |  |                |                    |                               |                |                |                |   |
| 236 | <b>X-direction</b>                     |               |                |  |                | <b>Y-direction</b> |                               |                |                |                |   |
| 237 | Story                                  | EQ Force [MN] | LS1 Force [MN] | LS2 Force [MN]                         | LS3 Force [MN] | Story              | EQ Force [MN]                 | LS1 Force [MN] | LS2 Force [MN] | LS3 Force [MN] |   |
| 238 | 1                                      | 246.2849393   | 4.746546254    | 20.78882127                            | 22.87858781    | 1                  | 246.2849393                   | 6.131266703    | 33.37581799    | 38.69791476    |   |
| 239 | 2                                      | 195.7071645   | 31.89646838    | 301.1644601                            | 1102.459691    | 2                  | 190.4894756                   | 17.95616911    | 133.1247826    | 312.3054249    |   |
| 240 | 3                                      | 141.3054095   | 27.6340501     | 290.0644197                            | 1334.017535    | 3                  | 131.5070751                   | 15.019346      | 123.3464814    | 384.473826     |   |
| 241 | 4                                      | 88.76522569   | 23.37163172    | 279.5643801                            | 1652.873636    | 4                  | 77.48479003                   | 12.08252286    | 113.6312262    | 500.433487     |   |
| 242 | 5                                      | 40.65073695   | 30.49733346    | 441.6718571                            | 3431.459118    | 5                  | 32.41949512                   | 15.44320505    | 186.2155253    | 1274.251465    |   |

# Simplified integral structural model (SISM)



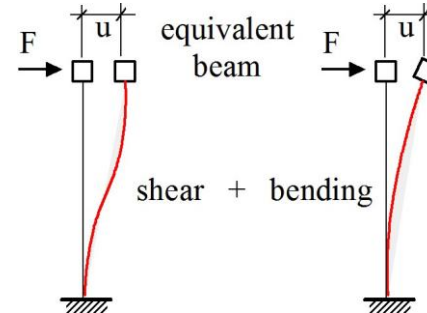
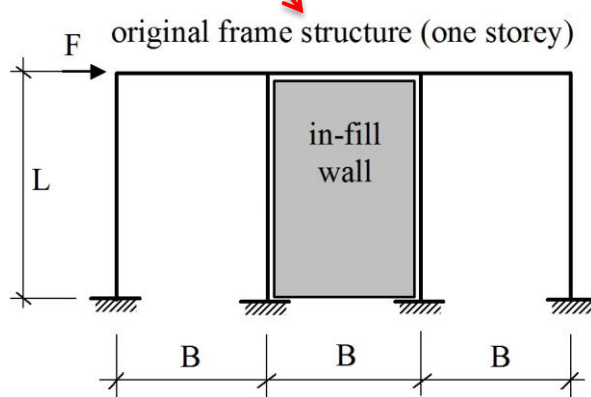
Stiffness matrix  $K = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix}$

Mass matrix  $M = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}$

Modal analysis:  $(K - \Omega M)\Phi = 0$

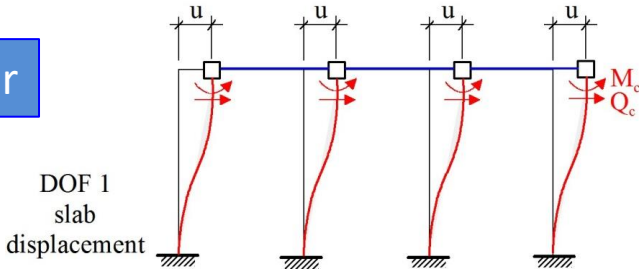
**Linear model check and improvement** is done by comparison of measured and calculated eigenfrequencies and mode shapes.

Each story will be replaced by an equivalent beam element with stiffness  $k_i$  and mass  $m_i$ . Both bending and shear deformations are taken into account.

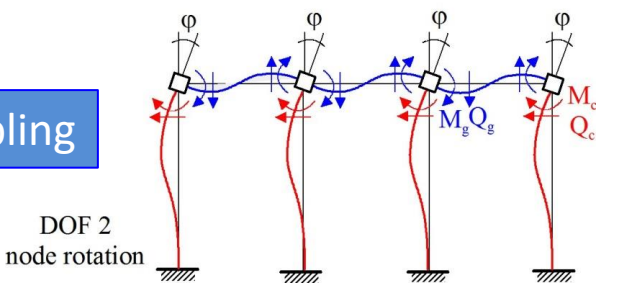


# Linear SISM: Frame part

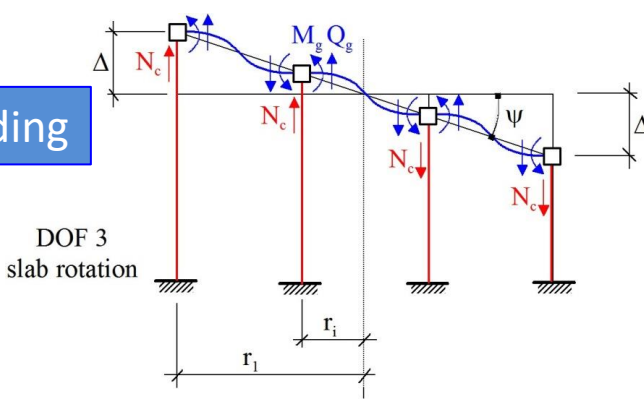
shear



coupling



bending



Stiffness relation with 3 coupled DOF

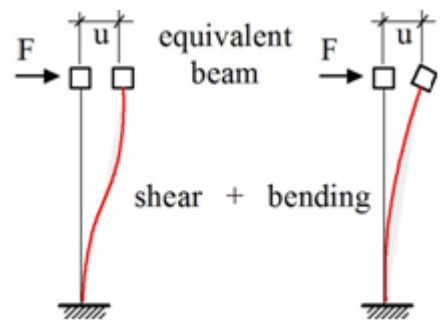
$$\begin{bmatrix} K_{uu} & K_{u\phi} & \cancel{K_{u\psi}} \\ K_{\phi u} & K_{\phi\phi} & K_{\phi\psi} \\ \cancel{K_{\psi u}} & K_{\psi\phi} & K_{\psi\psi} \end{bmatrix} \cdot \begin{bmatrix} u \\ \phi \\ \psi \end{bmatrix} = \begin{bmatrix} F \\ 0 \\ 0 \end{bmatrix}$$

Solution

$$\begin{bmatrix} u \\ \phi \\ \psi \end{bmatrix} = \begin{bmatrix} K_{uu} & K_{u\phi} & 0 \\ K_{\phi u} & K_{\phi\phi} & K_{\phi\psi} \\ 0 & K_{\psi\phi} & K_{\psi\psi} \end{bmatrix}^{-1} \cdot \begin{bmatrix} F \\ 0 \\ 0 \end{bmatrix}$$

Integral equivalent story stiffness

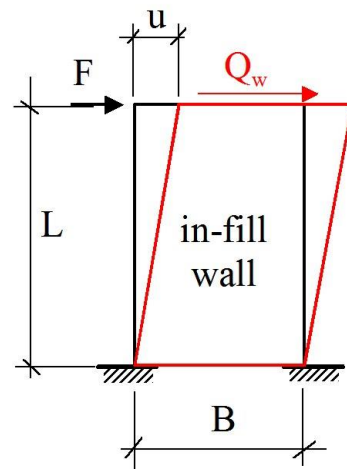
$$K_{uu}^* = \frac{F}{u} = \frac{1}{u} \neq K_{uu}$$





# Linear SISM: shear walls and shafts

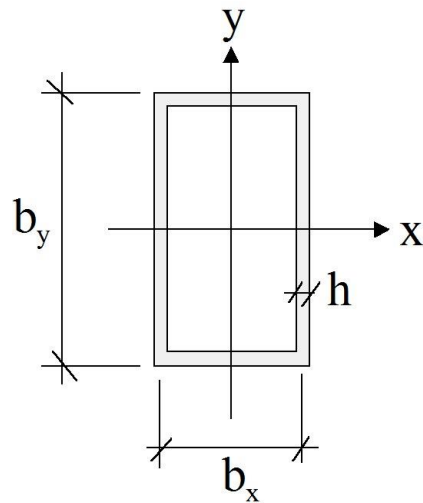
Wall:



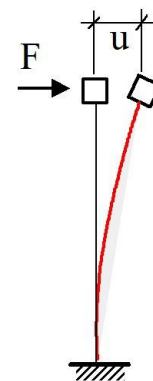
$$K_u = \frac{F}{u} = \frac{E \cdot B \cdot h}{L} \left[ \frac{1}{\frac{4L^2}{B^2} + \frac{4+5\nu}{2}} \right]$$

h: wall thickness

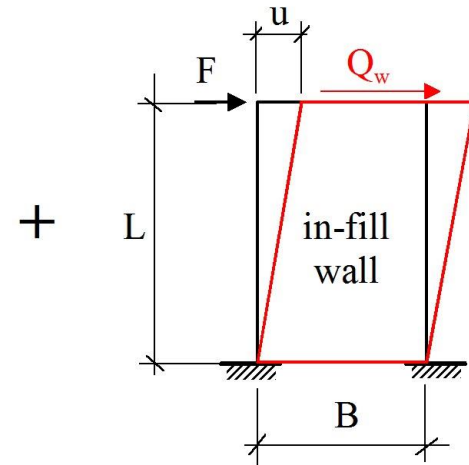
Shaft:



cross-section of hollow shaft



beam (bending)



walls (shear)

# Nonlinear SISIM

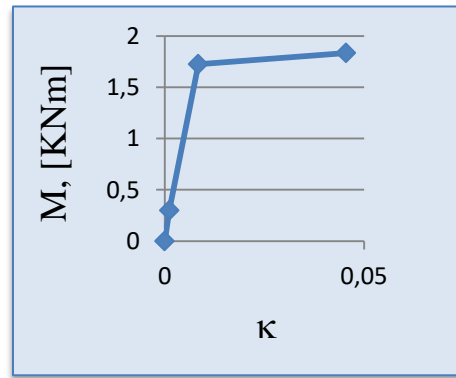
Considered limit states:

LS1: cracks (IO = immediate occupancy)

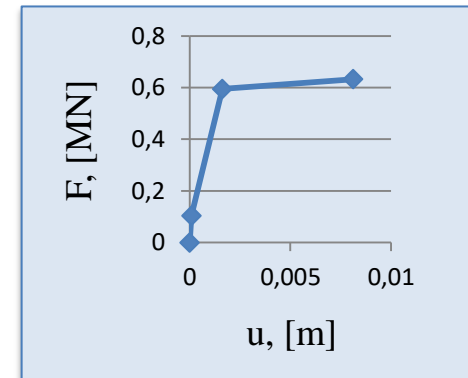
LS2: yielding (DL = damage limitation)

LS3: collapse (NC = near collapse)

Moment-curvature relationship



Force-displacement relationship



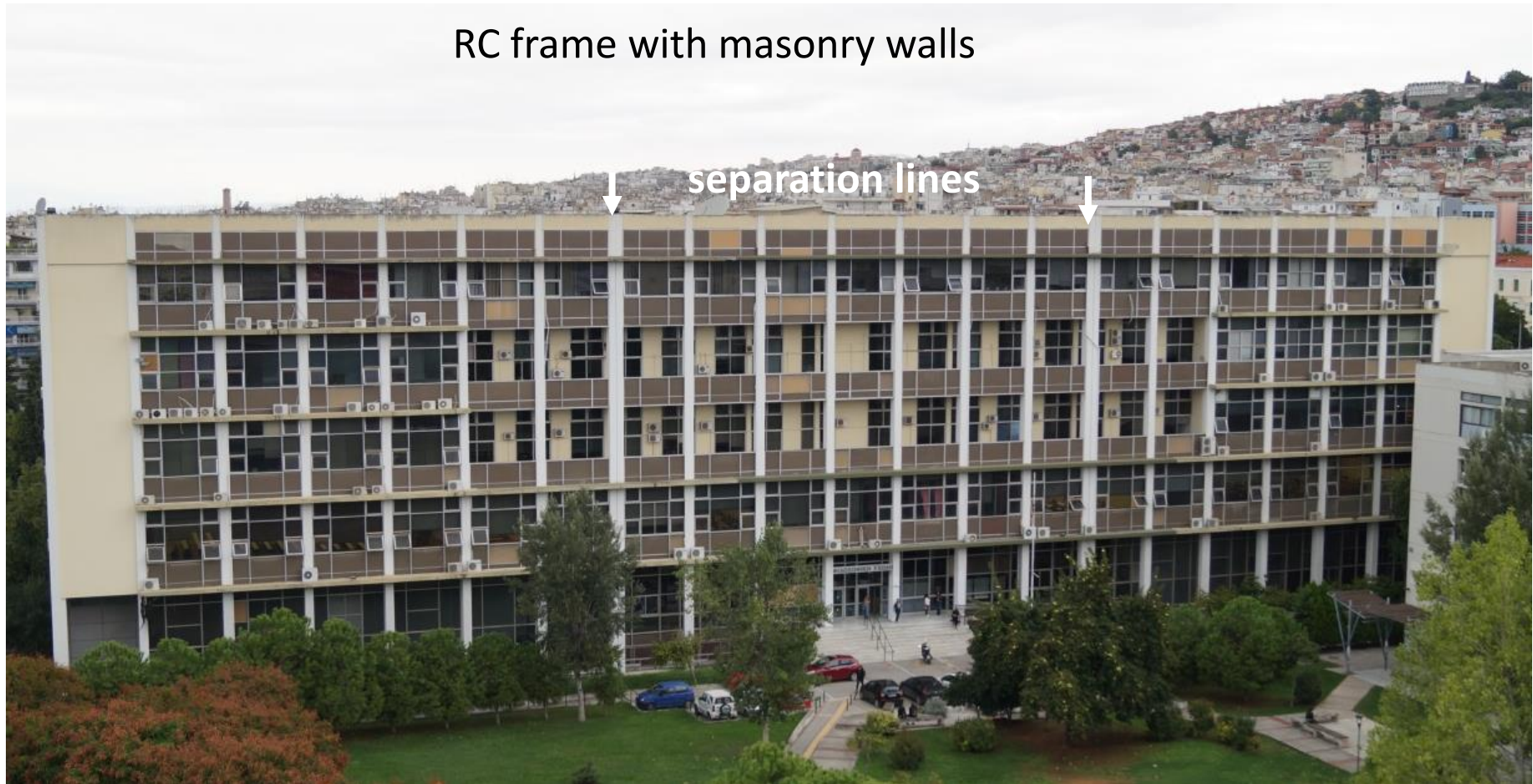
Frame Shaft:

Mechanical model

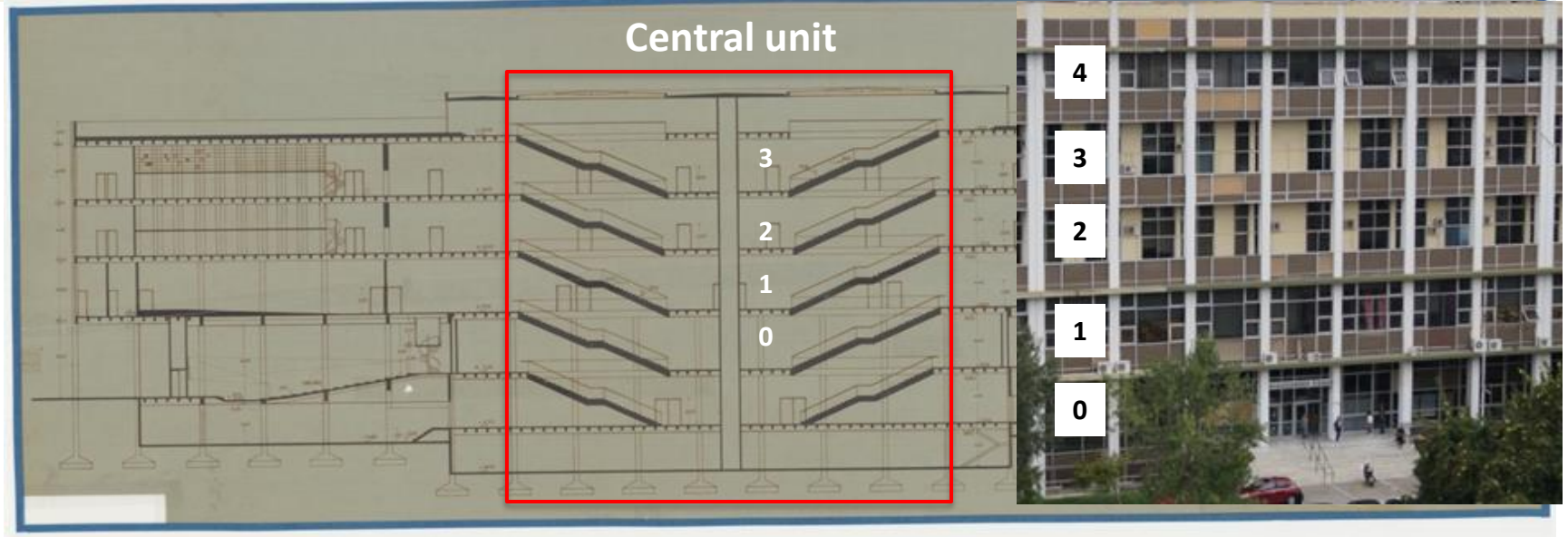
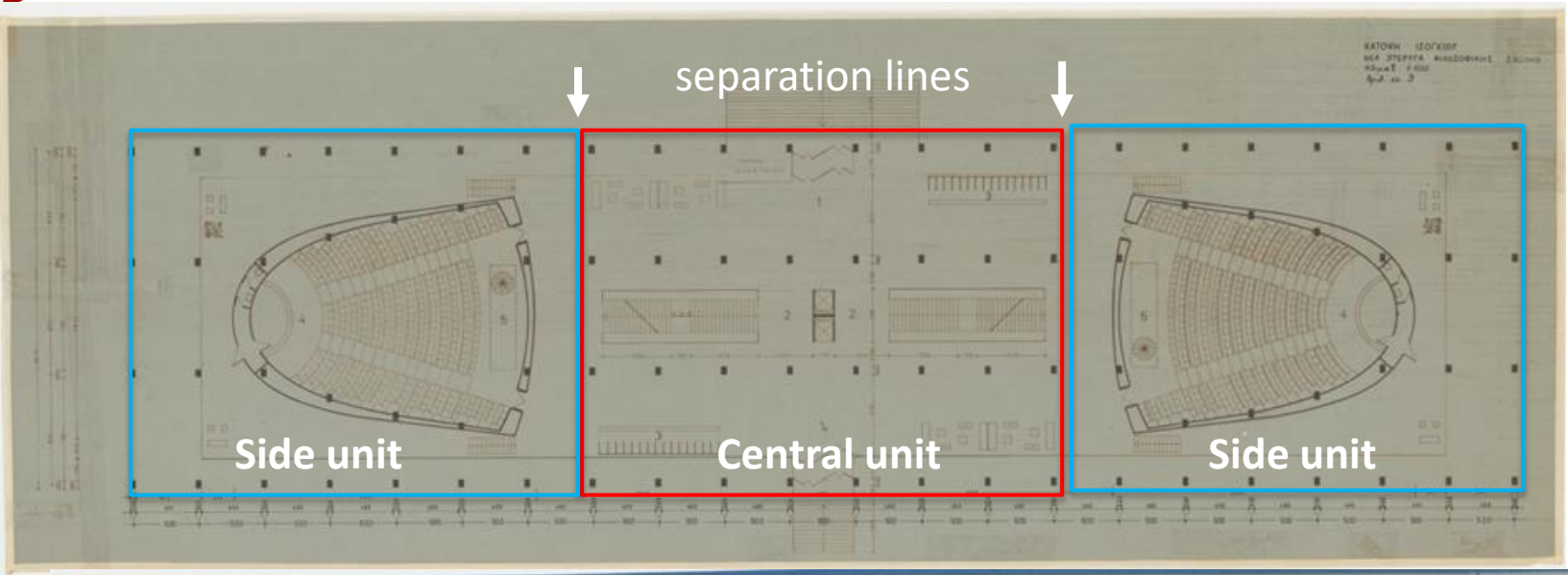
Wall:

Empirical model

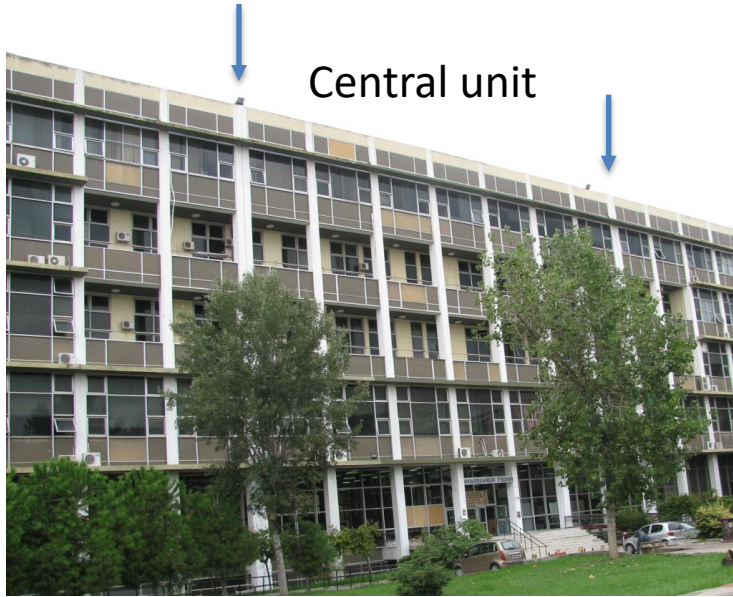
$$K_w = \begin{cases} 1.0 K_w & \text{for LS1} \\ 0.7 K_w & \text{for LS2} \\ 0.5 K_w & \text{for LS3} \end{cases}$$



# Original design drawings

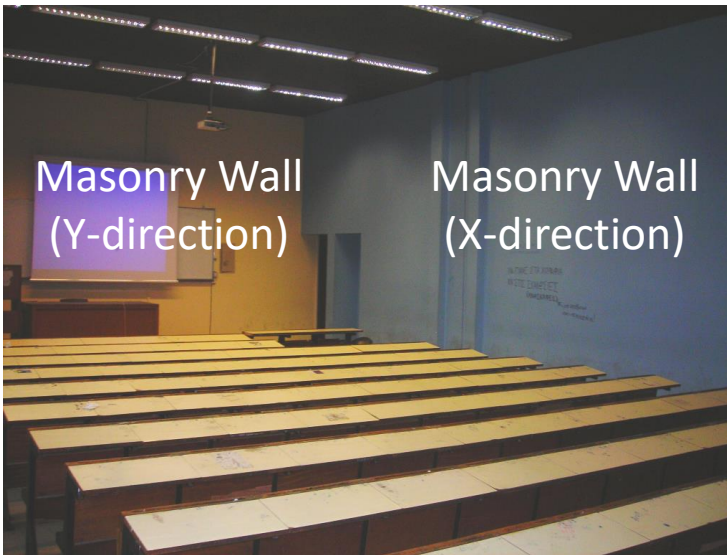


# Faculty building AUTH

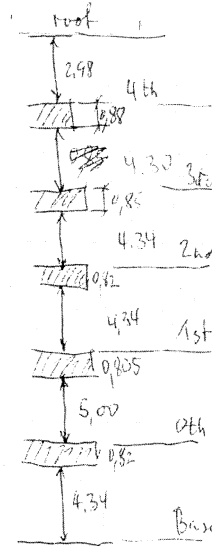


RC columns

Separation line



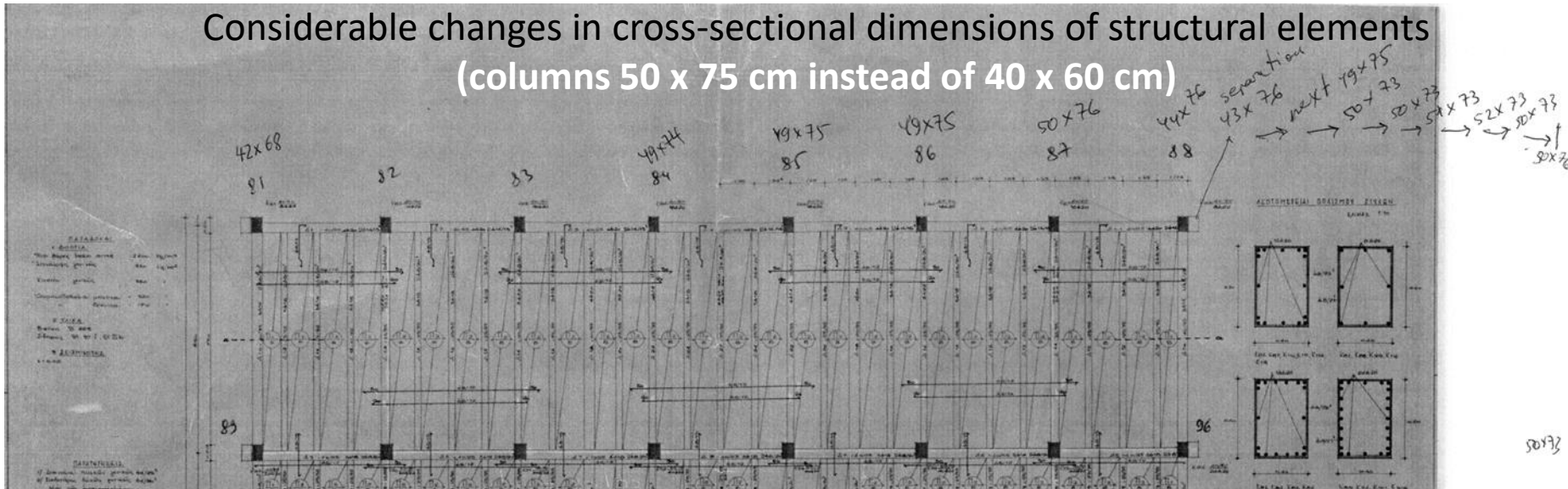
# In-situ structural survey and data collection



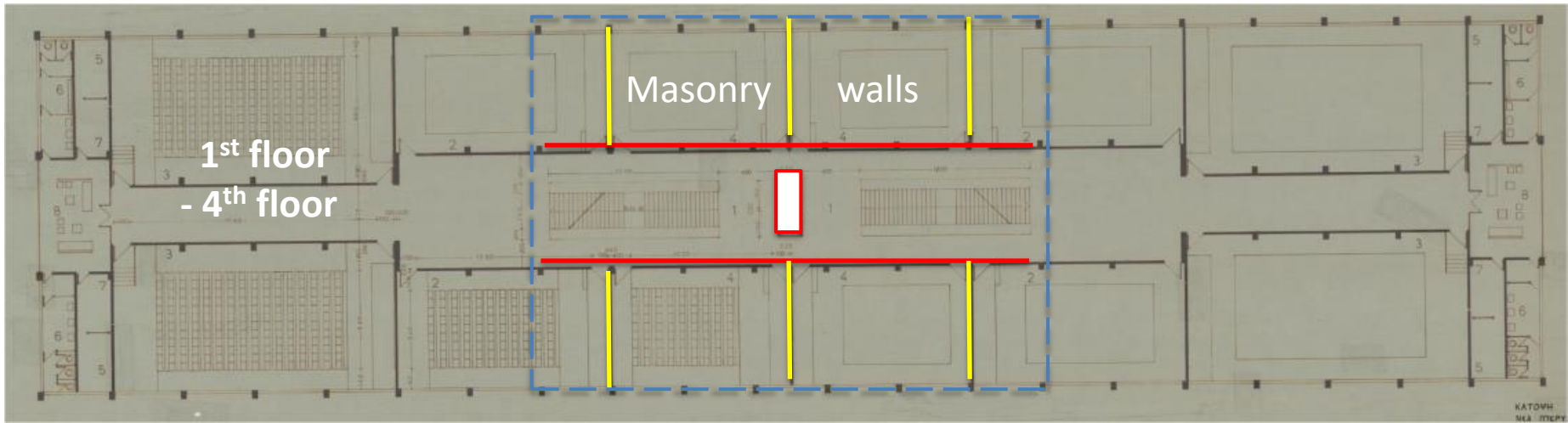
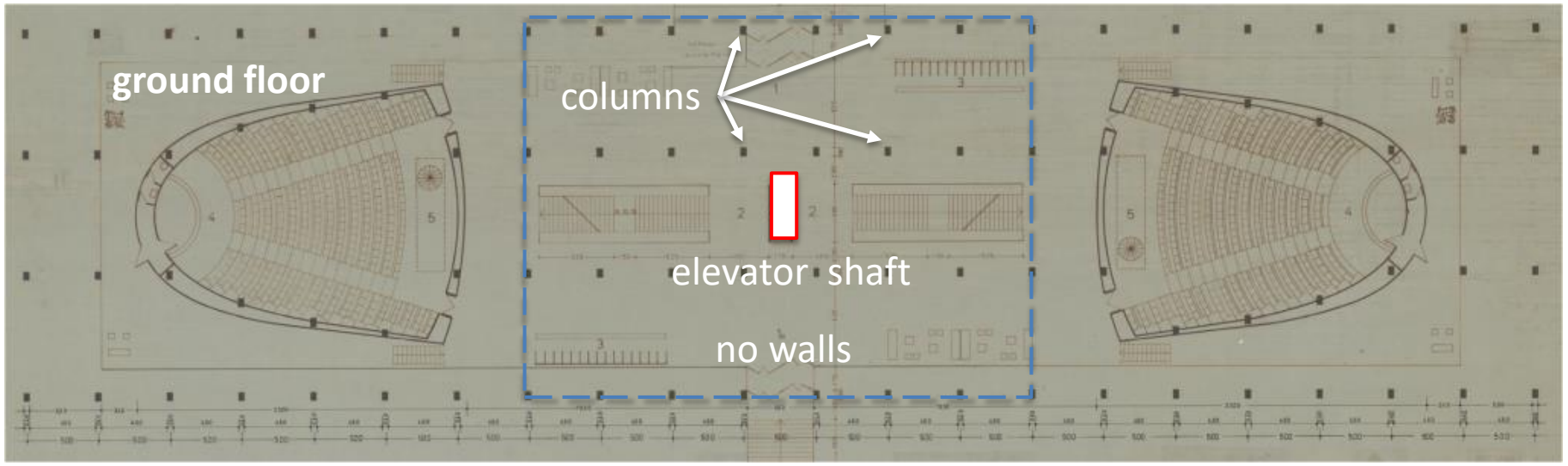
← One additional story detected

Structural modification  
20 years after construction

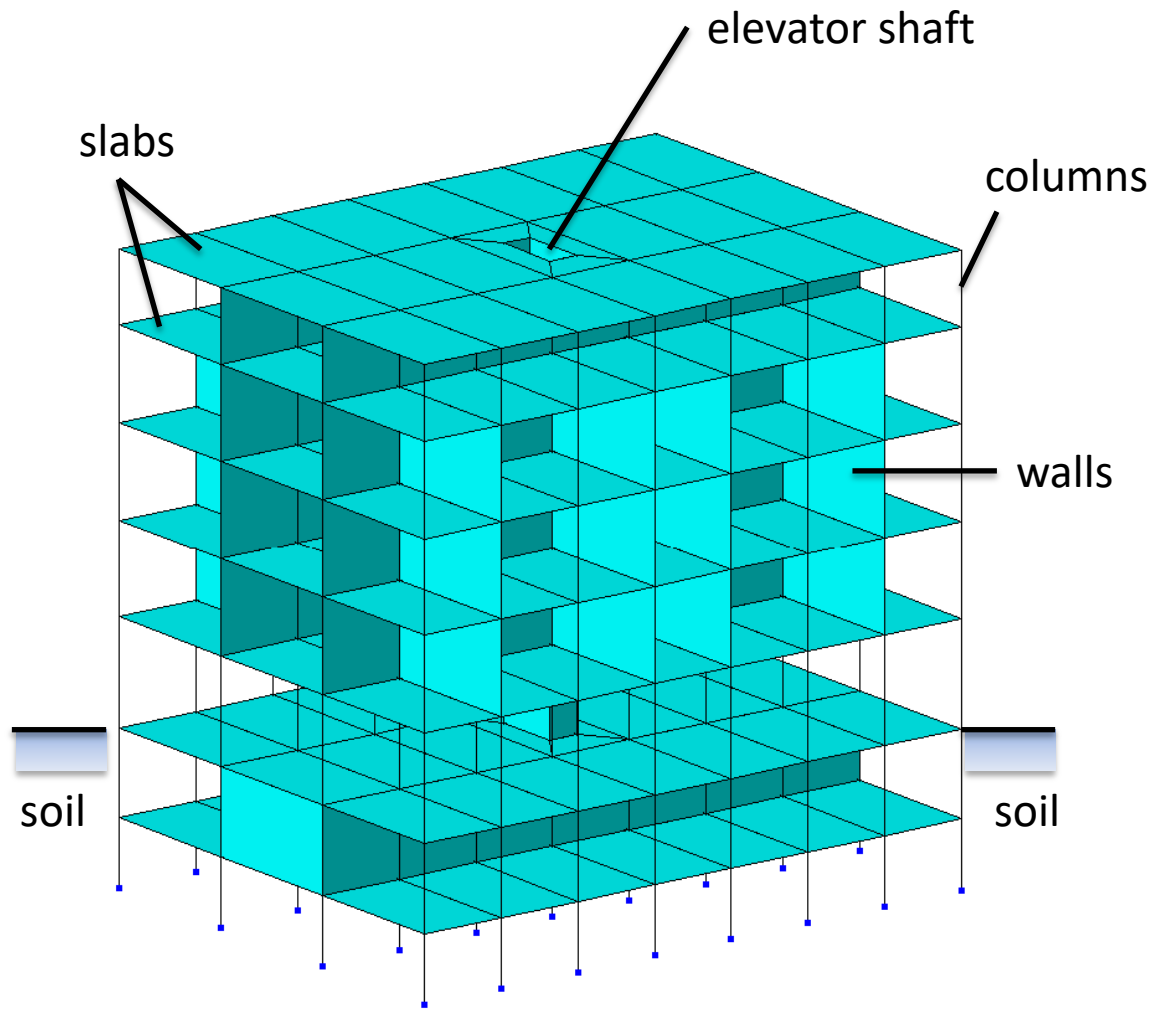
Considerable changes in cross-sectional dimensions of structural elements  
(columns 50 x 75 cm instead of 40 x 60 cm)



# Main structural members of the central unit



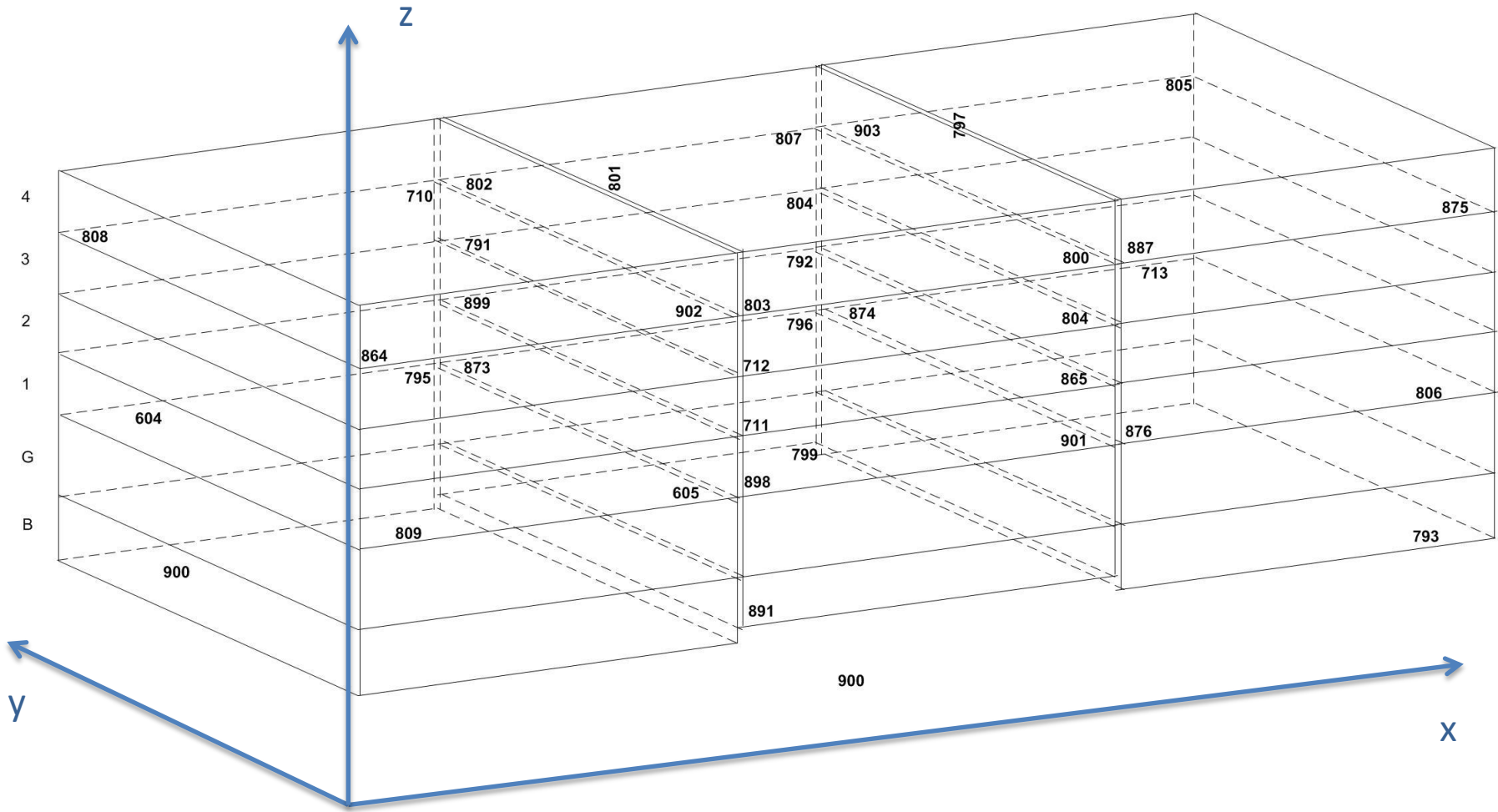
# Summary: main structural elements

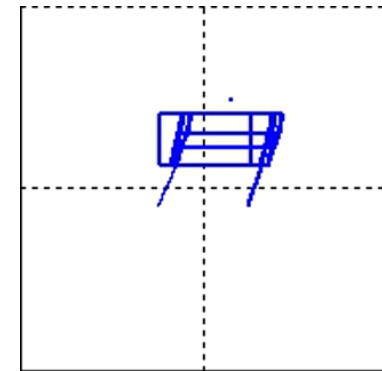
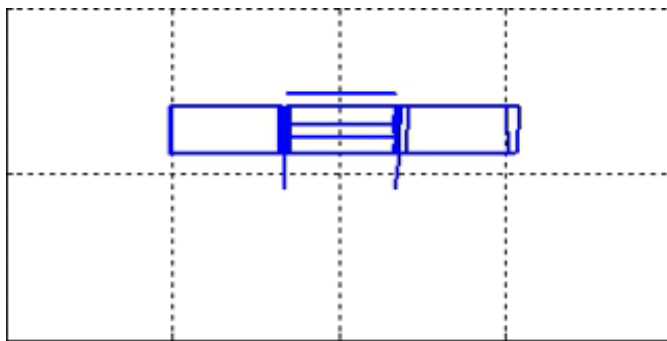
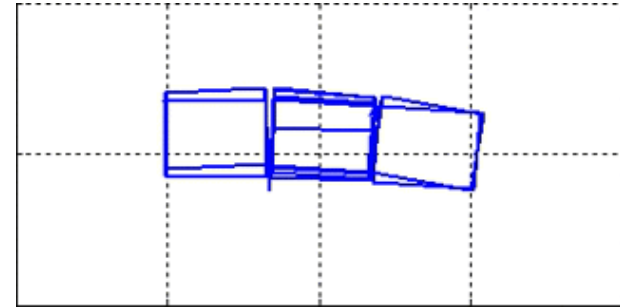
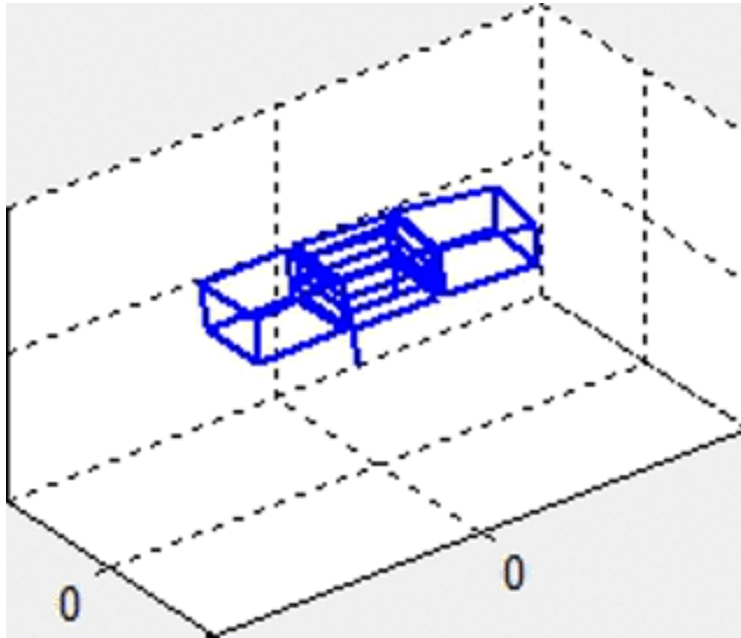


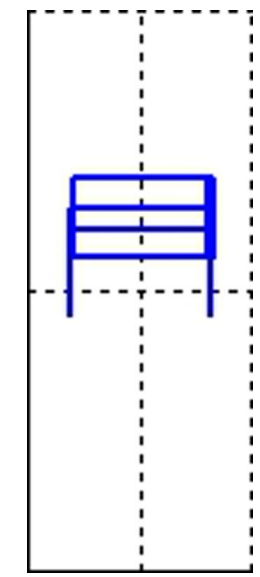
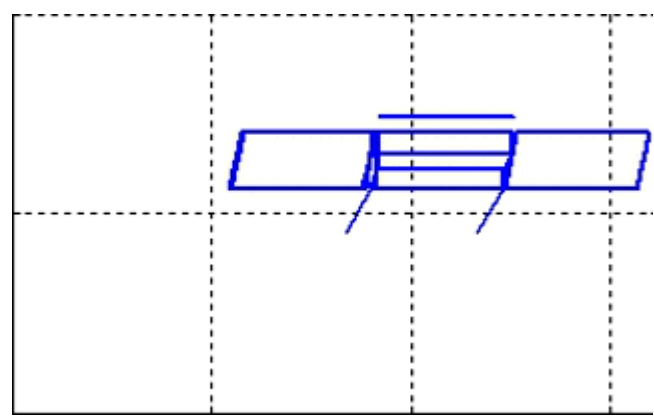
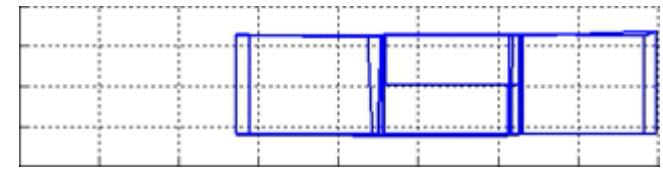
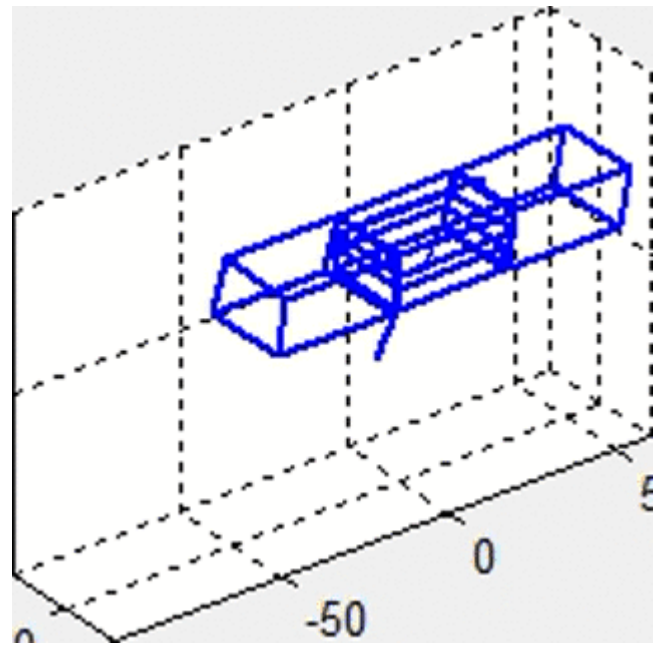
Basement is not considered

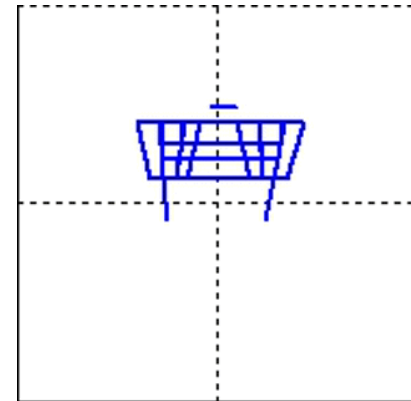
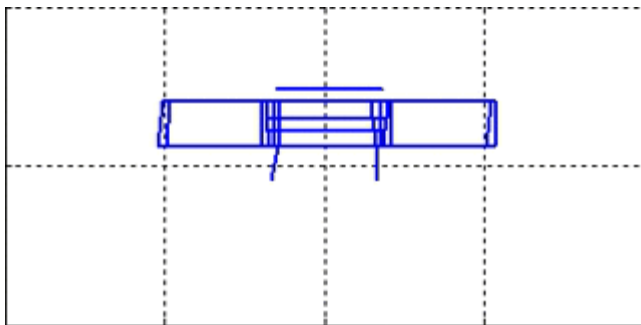
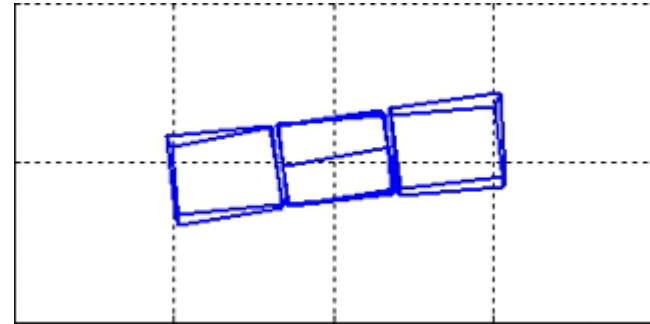
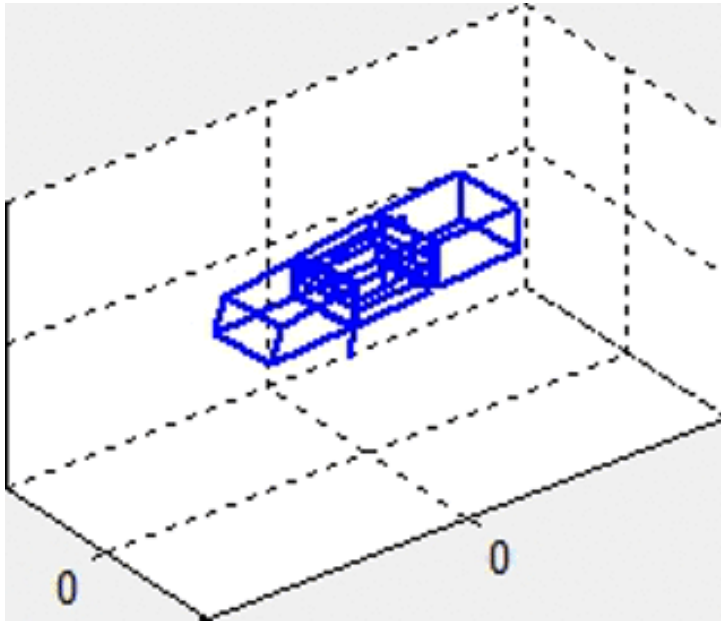


# Spatial arrangement of sensors









# Model check by use of vibration monitoring

|   | A                 | B    | C            | D    | E                              | F     | G                      | H   | I                                     | J                             | K    | L | M           |
|---|-------------------|------|--------------|------|--------------------------------|-------|------------------------|-----|---------------------------------------|-------------------------------|------|---|-------------|
| 1 | <b>Building</b>   |      |              |      |                                |       |                        |     |                                       |                               |      |   |             |
| 2 | Number of Stories | 5    | Length X [m] | 33.6 | E-Modulus [MN/m <sup>2</sup> ] | 33000 | Poisson's ratio        | 0.2 | E-Modulus, Walls [MN/m <sup>2</sup> ] | Meas./Calc. Frequency, X [Hz] | 1.72 |   | 1.601816004 |
| 3 | Total Height      | 29.5 | Length Y [m] | 25.5 | Siffness Ratio                 | 2     | Number of Column Types | 1   | 5000                                  | Meas./Calc. Frequency, Y [Hz] | 1.6  |   | 1.767334209 |

measured

calculated

|    | A                         | B                 | C                | D               | E | F | G | H | I | J | K | L | M |
|----|---------------------------|-------------------|------------------|-----------------|---|---|---|---|---|---|---|---|---|
| 20 | <b>Number of Elements</b> |                   |                  |                 |   |   |   |   |   |   |   |   |   |
| 21 | Story                     | Number of columns | Number of shafts | Number of walls |   |   |   |   |   |   |   |   |   |
| 22 | 1                         | 32                | 1                | 2               |   |   |   |   |   |   |   |   |   |
| 23 | 2                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |
| 24 | 3                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |
| 25 | 4                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |
| 26 | 5                         | 32                | 1                | 8               |   |   |   |   |   |   |   |   |   |

### Stiffnesses [MN/m]

| Story | Kx          | Ky          |
|-------|-------------|-------------|
| 1     | 1224.574208 | 1867.018663 |
| 2     | 7560.66339  | 4861.827031 |
| 3     | 7560.66339  | 4861.827031 |
| 4     | 7560.66339  | 4861.827031 |
| 5     | 9420.398476 | 6396.379231 |

### Masses and Weights

| Story | Story Mass [kN/m] | Slab density [kN/m <sup>3</sup> ] | Story Height [m] | Slab Thickness [m] | Weight [kN] |
|-------|-------------------|-----------------------------------|------------------|--------------------|-------------|
| 1     | 364.95            | 50                                | 5.8              | 0.4                | 19961.415   |
| 2     | 783               | 50                                | 5.1              | 0.4                | 20816.1     |
| 3     | 783               | 50                                | 5.1              | 0.4                | 20816.1     |
| 4     | 783               | 50                                | 5.1              | 0.4                | 20385.45    |
| 5     | 783               | 50                                | 4                | 0.4                | 18545.4     |

### Calculated Frequencies [Hz]

| Mode | X           | Y           |
|------|-------------|-------------|
| 1    | 1.601816004 | 1.767334209 |
| 2    | 6.634602475 | 5.789989168 |
| 3    | 12.08460813 | 9.984985082 |
| 4    | 16.45251741 | 13.38894828 |
| 5    | 18.87130599 | 15.29247381 |

### Earthquake Forces

|             |            |                       |             |
|-------------|------------|-----------------------|-------------|
| lambda      | 1          | Spectral acceleration | 2.45        |
| Weight [kN] | 100524.465 | Shear Force Fges [MN] | 246.2849393 |

Input AUTH, GFZ

### Column cross-sections

| Current No. | X-Width [m] | Y-Width [m] | Radius [m] | Concrete cover [m] |
|-------------|-------------|-------------|------------|--------------------|
| 1           | 0.5         | 0.75        | 0          | 0.03               |

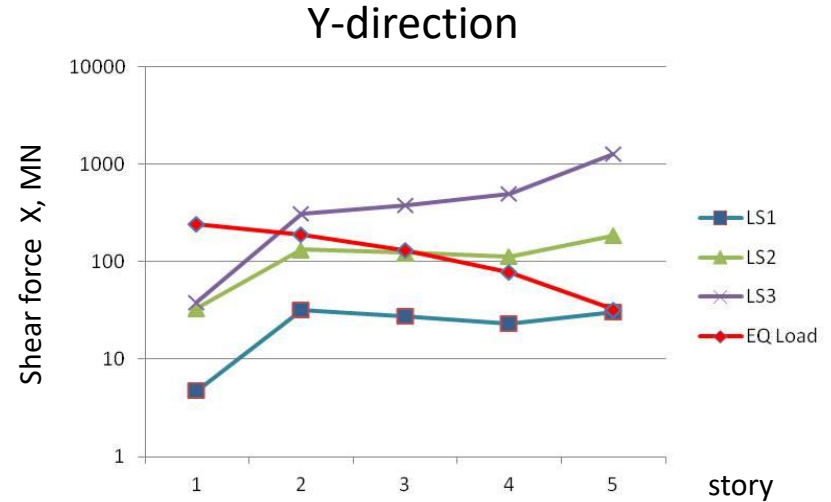
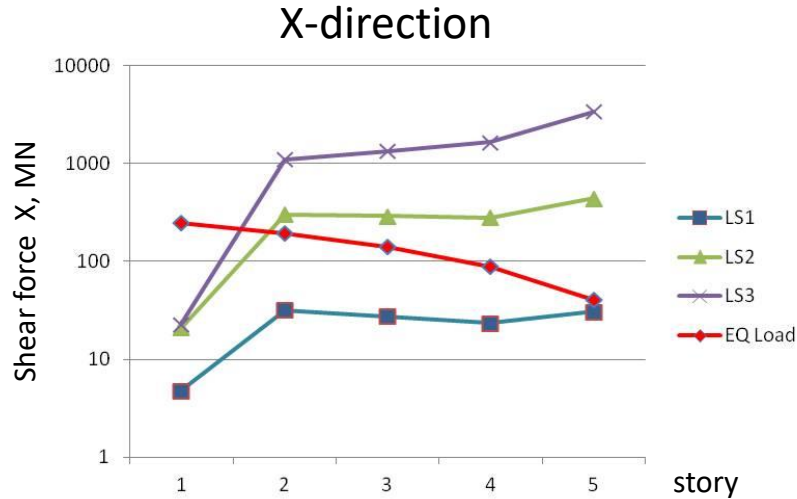
### Shaft cross-sections

| Current No. | X-Width [m] | Y-Width [m] | Wall Thickness, X [m] | Wall Thickness, Y [m] |
|-------------|-------------|-------------|-----------------------|-----------------------|
| 1           | 1.7         | 3.9         | 0.15                  | 0.15                  |

### Concrete Properties

|                      |       |
|----------------------|-------|
| Strength [MPa]       | 30    |
| Reinforcement ratio  | 0.015 |
| Tens. strength [MPa] | 2.2   |

# Vulnerability assessment



#### Earthquake Forces

|             |            |                       |             |
|-------------|------------|-----------------------|-------------|
| lambda      | 1          | Spectral acceleration | 2.45        |
| Weight [kN] | 100524.465 | Shear Force Fges [MN] | 246.2849393 |

The design value of PGA is taken from the response spectrum according to AUTH investigations on-site.

#### 235 Limit state assessment

##### 236 X-direction

| Story | EQ Force [MN] | LS1 Force [MN] | LS2 Force [MN] | LS3 Force [MN] |
|-------|---------------|----------------|----------------|----------------|
| 1     | 246.2849393   | 4.746546254    | 20.78882127    | 22.87858781    |
| 2     | 195.7071645   | 31.89646838    | 301.1644601    | 1102.459691    |
| 3     | 141.3054095   | 27.6340501     | 290.0644197    | 1334.017535    |
| 4     | 88.76522569   | 23.37163172    | 279.5643801    | 1652.873636    |
| 5     | 40.65073695   | 30.49733346    | 441.6718571    | 3431.459118    |

##### Y-direction

| Story | EQ Force [MN] | LS1 Force [MN] | LS2 Force [MN] | LS3 Force [MN] |
|-------|---------------|----------------|----------------|----------------|
| 1     | 246.2849393   | 6.131266703    | 33.37581799    | 38.69791476    |
| 2     | 190.4894756   | 17.95616911    | 133.1247826    | 312.3054249    |
| 3     | 131.5070751   | 15.019346      | 123.3464814    | 384.473826     |
| 4     | 77.48479003   | 12.08252286    | 113.6312262    | 500.433487     |
| 5     | 32.41949512   | 15.44320505    | 186.2155253    | 1274.251465    |

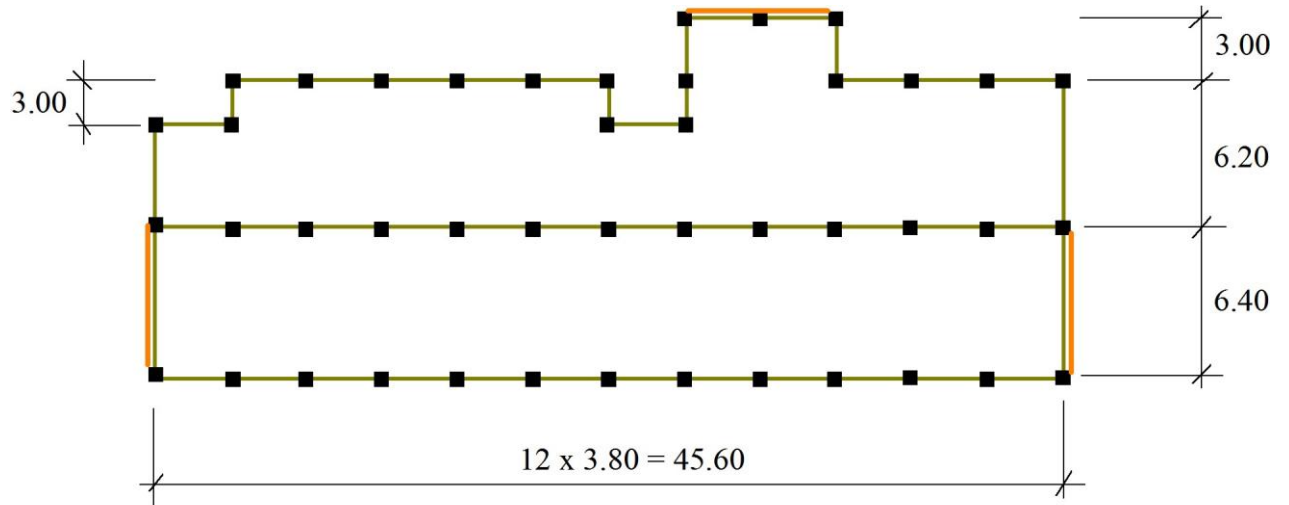
# Case study: Technical school, L'Aquila, Italy



Partly damaged building  
unoccupied since 2009  
RC frame, in-fill walls

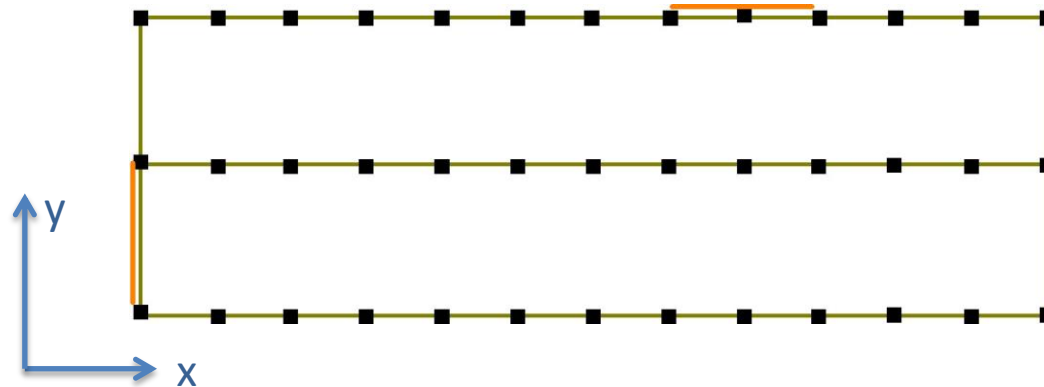


# Main structural elements



slab  $t = 0.30$   
 columns  $0.40 \times 0.40$   
 girders  $0.40 \times 0.30$

— in-fill walls  
 — girders  
 ■ columns



Simplified model



# Model check by use of vibration measurements

| Building          |      |              |      |                                |       |                        |     |                                       |                               |      |  |             |
|-------------------|------|--------------|------|--------------------------------|-------|------------------------|-----|---------------------------------------|-------------------------------|------|--|-------------|
| Number of Stories | 5    | Length X [m] | 45.6 | E-Modulus [MN/m <sup>2</sup> ] | 33000 | Poisson's ratio        | 0.2 | E-Modulus, Walls [MN/m <sup>2</sup> ] | Meas./Calc. Frequency, X [Hz] | 1.85 |  | 1.921804986 |
| Total Height      | 17.9 | Length Y [m] | 12.6 | Siffness Ratio                 | 2     | Number of Column Types | 1   | 4000                                  | Meas./Calc. Frequency, Y [Hz] | 1.65 |  | 1.683358836 |

↑ measured      ↑ calculated

| Number of Elements |                   |                  |                 |
|--------------------|-------------------|------------------|-----------------|
| Story              | Number of columns | Number of shafts | Number of walls |
| 1                  | 39                | 0                | 3               |
| 2                  | 39                | 0                | 3               |
| 3                  | 39                | 0                | 3               |
| 4                  | 39                | 0                | 3               |
| 5                  | 39                | 0                | 3               |

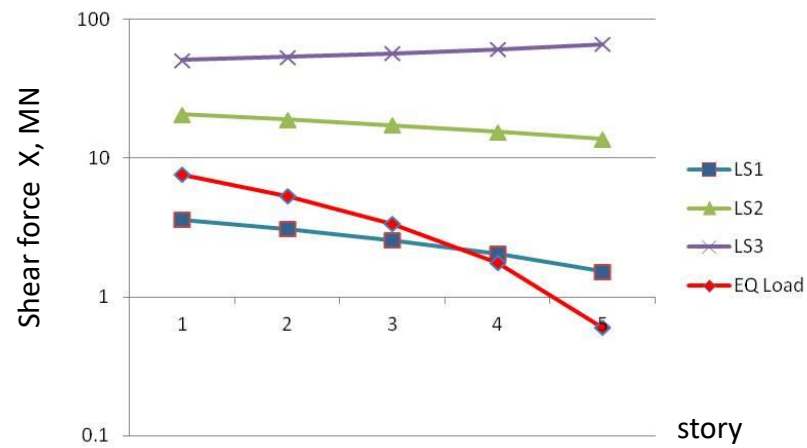
| Stiffnesses [MN/m] |             |             |
|--------------------|-------------|-------------|
| Story              | Kx          | Ky          |
| 1                  | 1383.482236 | 1061.471557 |
| 2                  | 1383.482236 | 1061.471557 |
| 3                  | 1383.482236 | 1061.471557 |
| 4                  | 1383.482236 | 1061.471557 |
| 5                  | 1383.482236 | 1061.471557 |

| Calculated Frequencies [Hz] |             |             |
|-----------------------------|-------------|-------------|
| Mode                        | X           | Y           |
| 1                           | 1.921804986 | 1.683358836 |
| 2                           | 5.624507205 | 4.926651753 |
| 3                           | 8.899745314 | 7.795517768 |
| 4                           | 11.47545625 | 10.05164979 |
| 5                           | 13.12321503 | 11.49496445 |

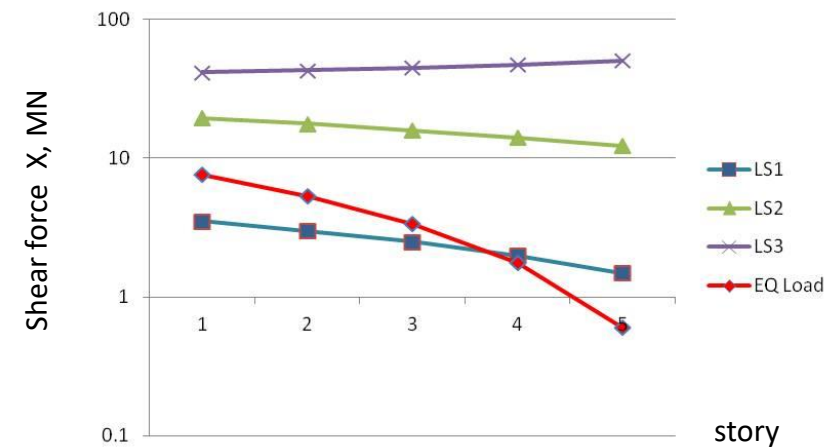
| Masses and Weights |                   |                                   |                  |                    |             |
|--------------------|-------------------|-----------------------------------|------------------|--------------------|-------------|
| Story              | Story Mass [kN/m] | Slab density [kN/m <sup>3</sup> ] | Story Height [m] | Slab Thickness [m] | Weight [kN] |
| 1                  | 197.4             | 40                                | 3.26             | 0.3                | 7479.024    |
| 2                  | 197.4             | 40                                | 3.26             | 0.3                | 7479.024    |
| 3                  | 197.4             | 40                                | 3.26             | 0.3                | 7479.024    |
| 4                  | 197.4             | 40                                | 3.26             | 0.3                | 7479.024    |
| 5                  | 197.4             | 45                                | 3.26             | 0.3                | 8048.712    |

# Vulnerability assessment at $S_d = 0.2$

## X-direction



## Y-direction



### Earthquake Forces

|             |           |                       |           |
|-------------|-----------|-----------------------|-----------|
| lambda      | 1         | Spectral acceleration | 0.2       |
| Weight [kN] | 37964.808 | Shear Force Fges [MN] | 7.5929616 |

← weak earthquake

### Limit state assessment

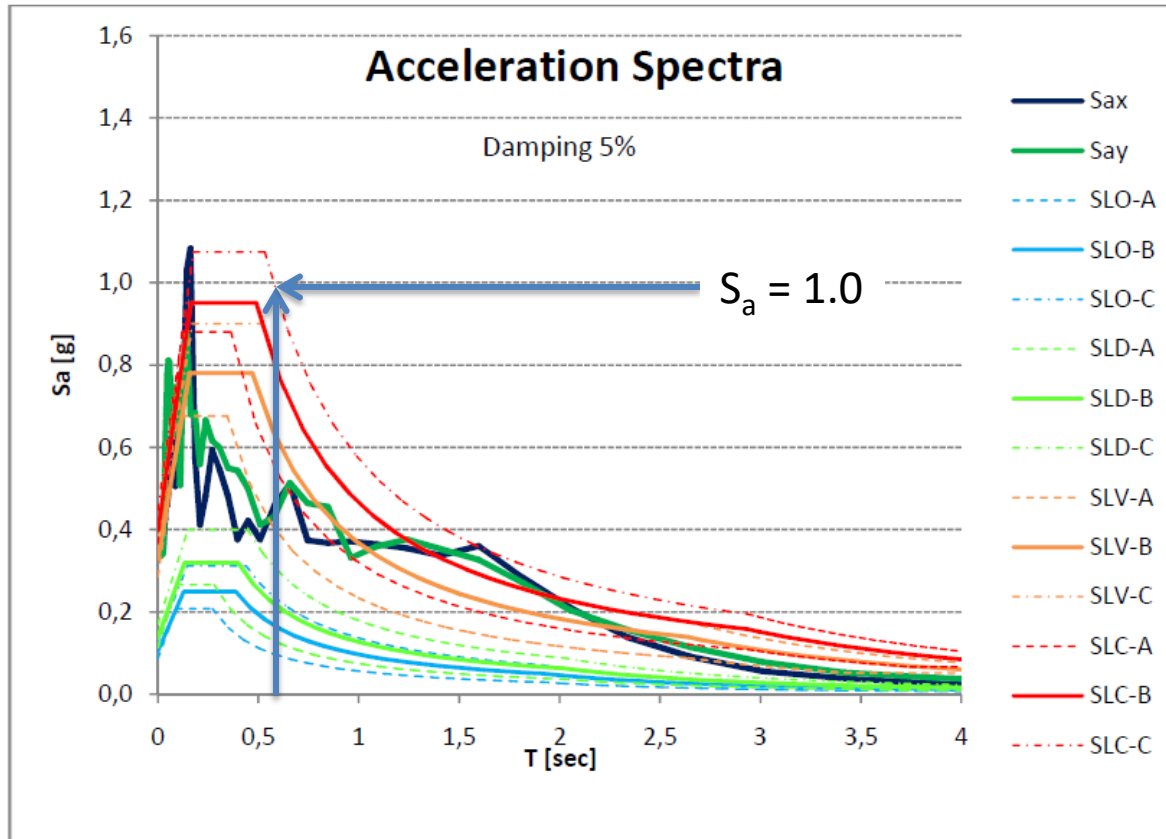
#### X-direction

| Story | EQ Force [MN] | LS1 Force [MN] | LS2 Force [MN] | LS3 Force [MN] |
|-------|---------------|----------------|----------------|----------------|
| 1     | 7.5929616     | 3.623893582    | 20.66379861    | 50.99124322    |
| 2     | 5.314472367   | 3.099581093    | 18.96430414    | 53.69999521    |
| 3     | 3.369922325   | 2.575268608    | 17.24186725    | 57.07878064    |
| 4     | 1.755473148   | 2.050956057    | 15.49226857    | 61.19380904    |
| 5     | 0.601242102   | 1.526643477    | 13.70921719    | 66.08850028    |

#### Y-direction

| Story | EQ Force [MN] | LS1 Force [MN] | LS2 Force [MN] | LS3 Force [MN] |
|-------|---------------|----------------|----------------|----------------|
| 1     | 7.5929616     | 3.509120301    | 19.48189042    | 41.47668039    |
| 2     | 5.314472367   | 3.001413451    | 17.70719499    | 42.9677038     |
| 3     | 3.369922325   | 2.493706603    | 15.91548907    | 44.94744365    |
| 4     | 1.755473148   | 1.985999692    | 14.10394802    | 47.46484746    |
| 5     | 0.601242102   | 1.478292752    | 12.2681631     | 50.55219537    |

# Response Spectrum for L'Aquila



School building

$$T_1 = 1/1.65 = 0.6 \text{ s}$$



Code:  $S_a = 1.0$

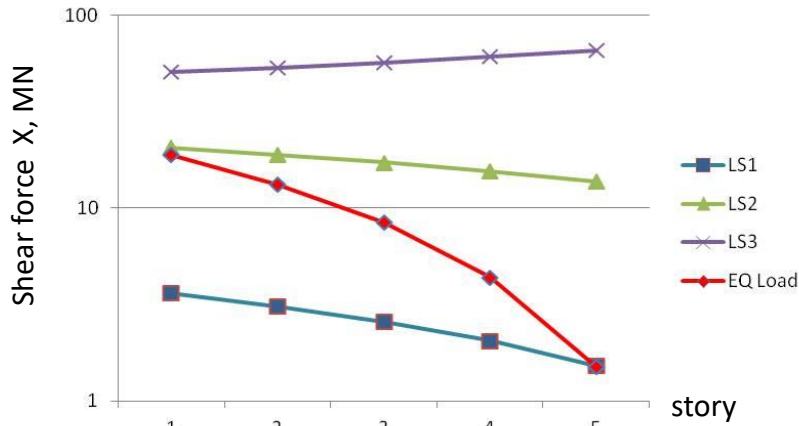
Record:  $S_a = 0.5$

Record AM043 – Earthquake Spectra Response vs. NTC2008 Elastic Spectra for Civil Buildings

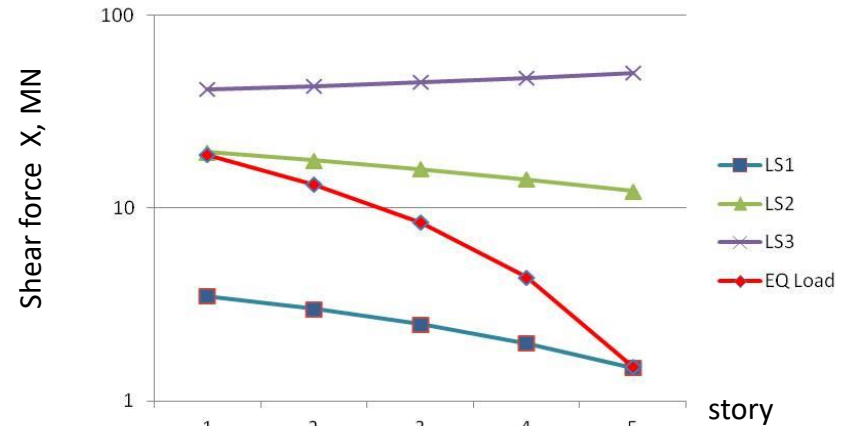
L. Petti, I. Marino (2009), Preliminary comparison between response spectra evaluated at close source for L'Aquila earthquake and elastic demand spectra according to new seismic Italian code (v.1.00), available at <http://www.reluis.it>

# Vulnerability assessment at $S_d = 0.5$ (record)

## X-direction



## Y-direction



### Earthquake Forces

|             |           |                       |           |
|-------------|-----------|-----------------------|-----------|
| lambda      | 1         | Spectral acceleration | 0.5       |
| Weight [kN] | 37964.808 | Shear Force Fges [MN] | 18.982404 |

← Record acc. to Petti, Marino (2009)

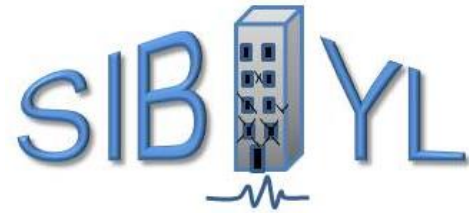
### Limit state assessment

#### X-direction

| Story | EQ Force [MN] | LS1 Force [MN] | LS2 Force [MN] | LS3 Force [MN] |
|-------|---------------|----------------|----------------|----------------|
| 1     | 18.982404     | 3.623893582    | 20.66379861    | 50.99124322    |
| 2     | 13.28618092   | 3.099581093    | 18.96430414    | 53.69999521    |
| 3     | 8.424805813   | 2.575268608    | 17.24186725    | 57.07878064    |
| 4     | 4.388682871   | 2.050956057    | 15.49226857    | 61.19380904    |
| 5     | 1.503105255   | 1.526643477    | 13.70921719    | 66.08850028    |

#### Y-direction

| Story | EQ Force [MN] | LS1 Force [MN] | LS2 Force [MN] | LS3 Force [MN] |
|-------|---------------|----------------|----------------|----------------|
| 1     | 18.982404     | 3.509120301    | 19.48189042    | 41.47668039    |
| 2     | 13.28618092   | 3.001413451    | 17.70719499    | 42.9677038     |
| 3     | 8.424805813   | 2.493706603    | 15.91548907    | 44.94744365    |
| 4     | 4.388682871   | 1.985999692    | 14.10394802    | 47.46484746    |
| 5     | 1.503105255   | 1.478292752    | 12.2681631     | 50.55219537    |



<http://www.sibyl-project.eu/>

**Thanks for your attention**