SIBYL

*Se*I*s*mic monitoring and vu*l*nera*B*ilit*Y* framework for civi*L* protection

Preliminary results for the Thessaloniki applications (Assessment of the selected buildings)

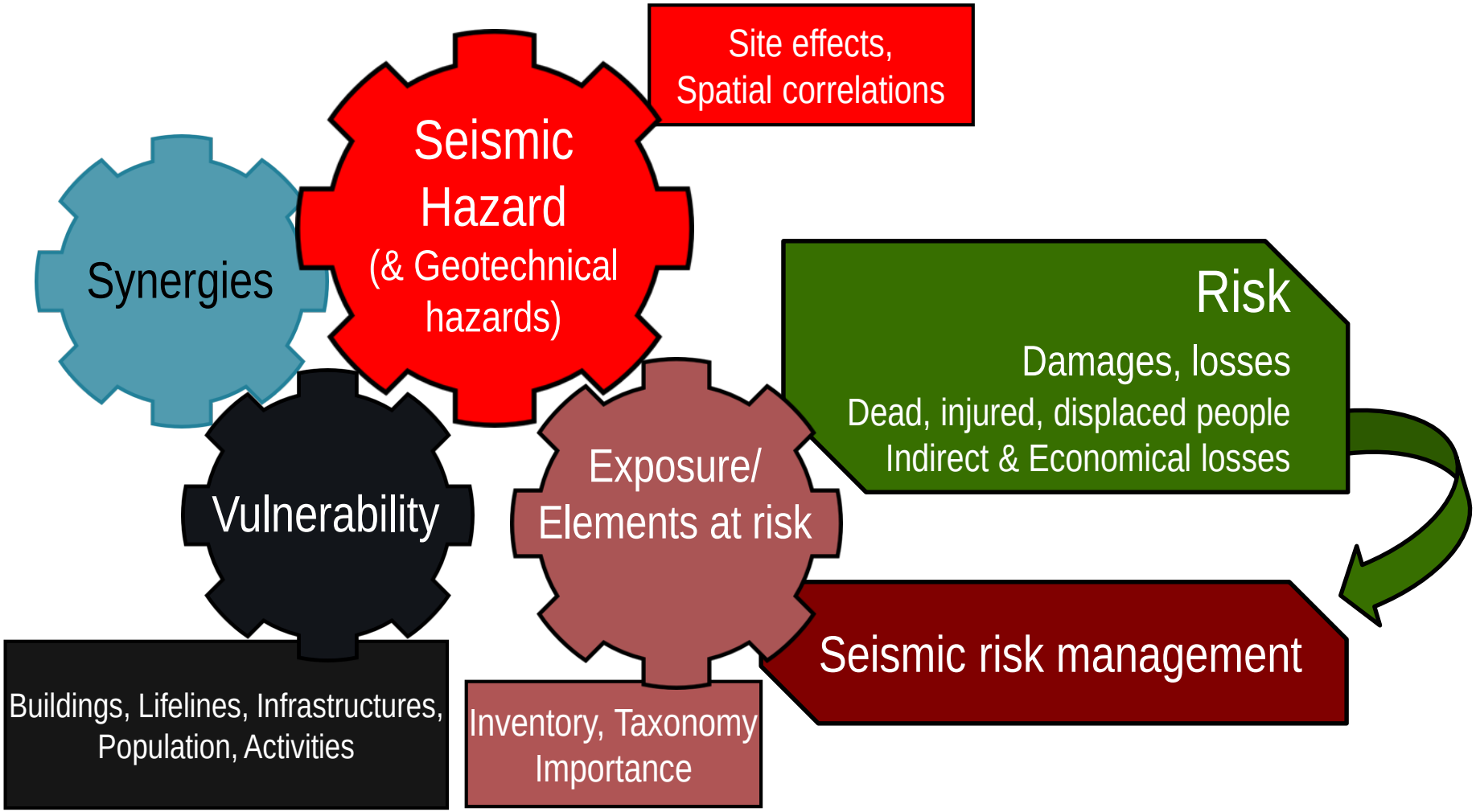
Sotiria Karapetrou
Stavroula Fotopoulou
Maria Manakou
Evagelia Yfadidou
Ioannis Thomaidis
Kyriazis Pitilakis

Aristotle University of Thessaloniki

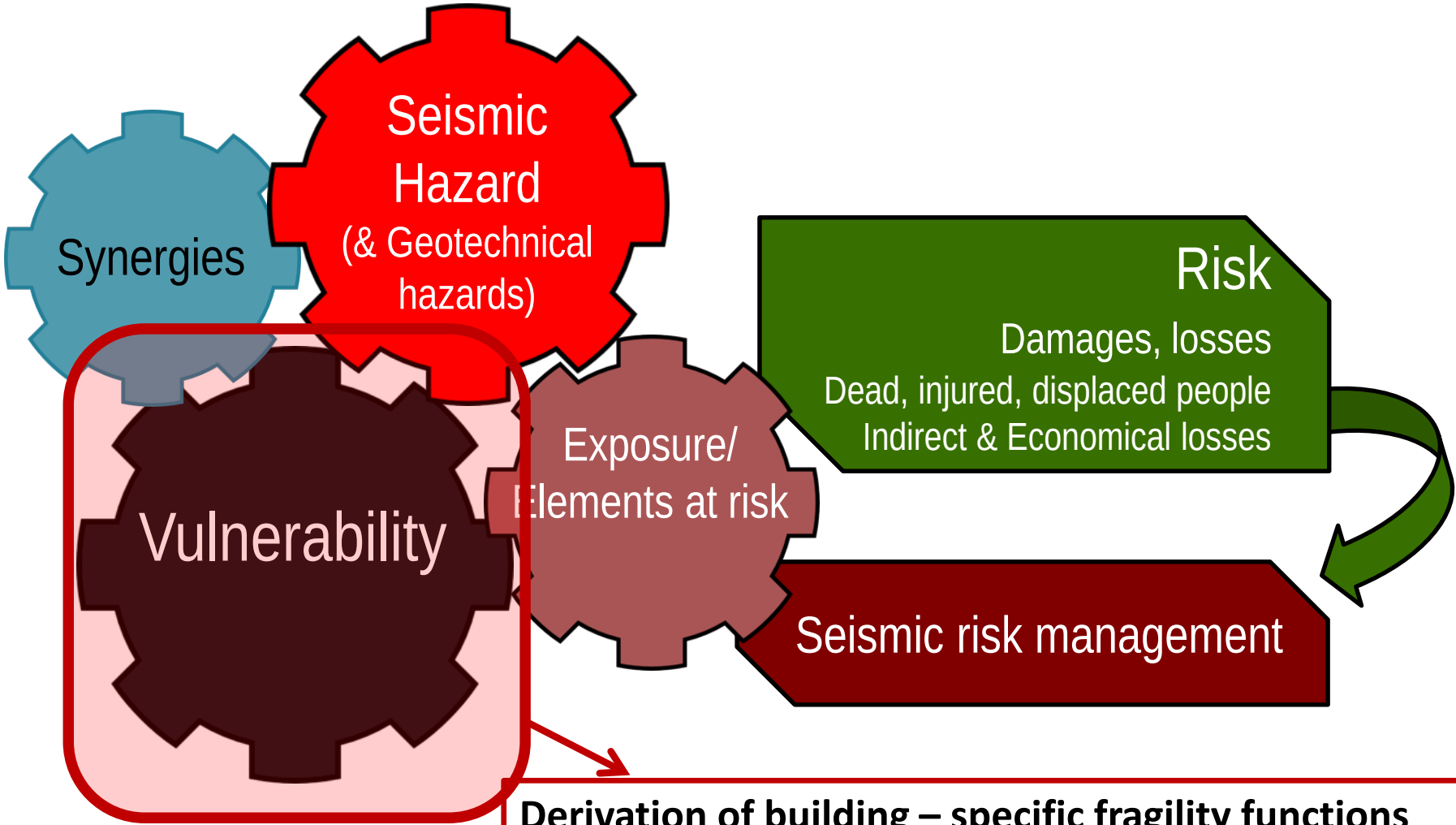
Introduction

- **Task C: "Rapid and low in-situ building vulnerability assessment"**
- **Seismic vulnerability assessment of selected buildings using field monitoring data**
- **Detailed modeling of the buildings**
- **Comparison with the simplified integral structural model (TU-Berlin)**
- **Thessaloniki applications→ 3 buildings at the AUTh campus:**
  - ✓ **AHEPA hospital (REAKT, http://www.reaktproject.eu/)**
  - ✓ **Administration**
  - ✓ **Faculty of Philosophy**

Introduction



Introduction



Derivation of building – specific fragility functions which are used in the framework of vulnerability and risk assessment

Introduction

Aim: Derivation of building-specific fragility curves using field monitoring data

Experimental procedure

Field measurements → Estimation of the actual dynamic behavior

Analytical procedure

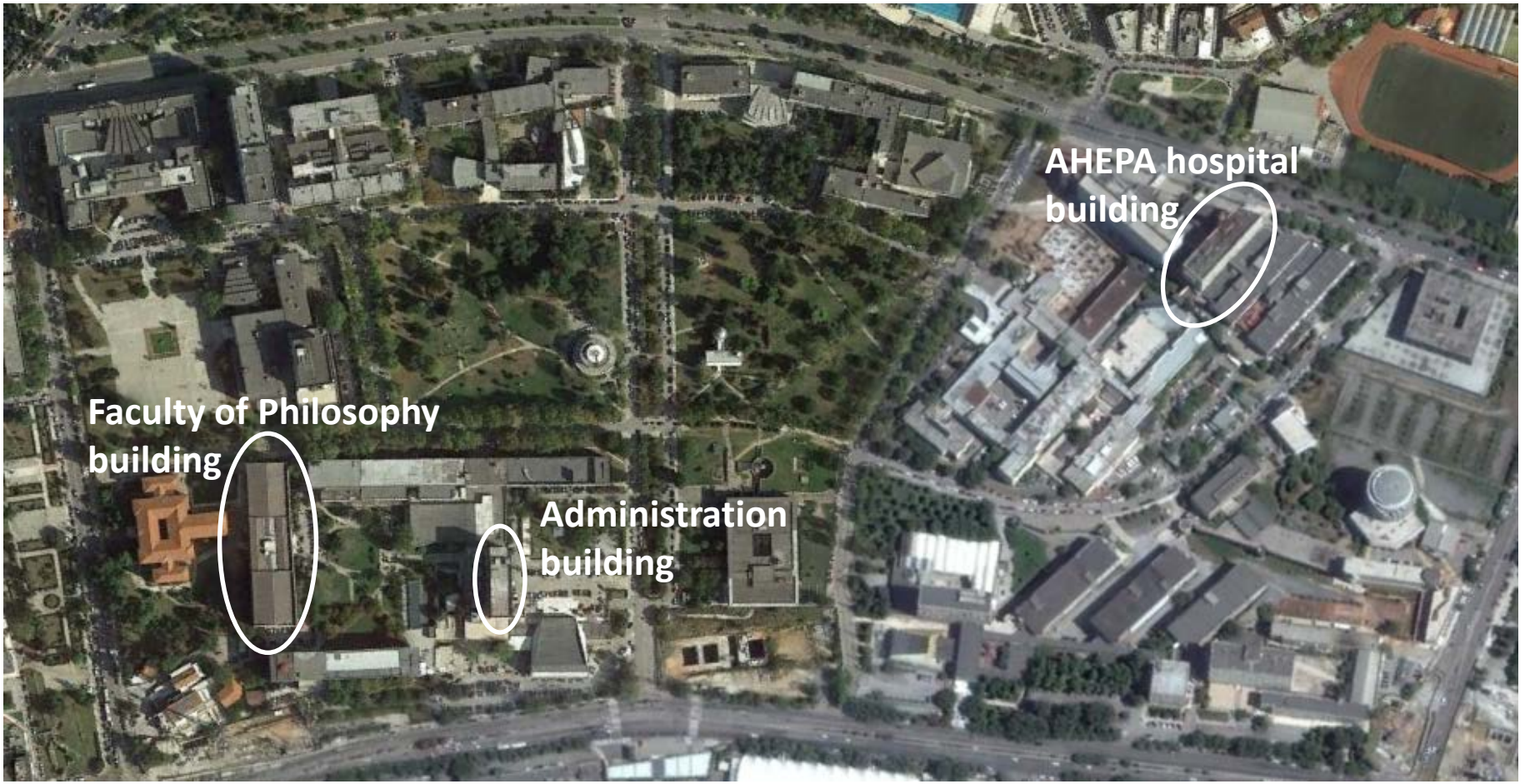
Numerical model → Estimation of the dynamic behavior

Update of the numerical model

Nonlinear analyses

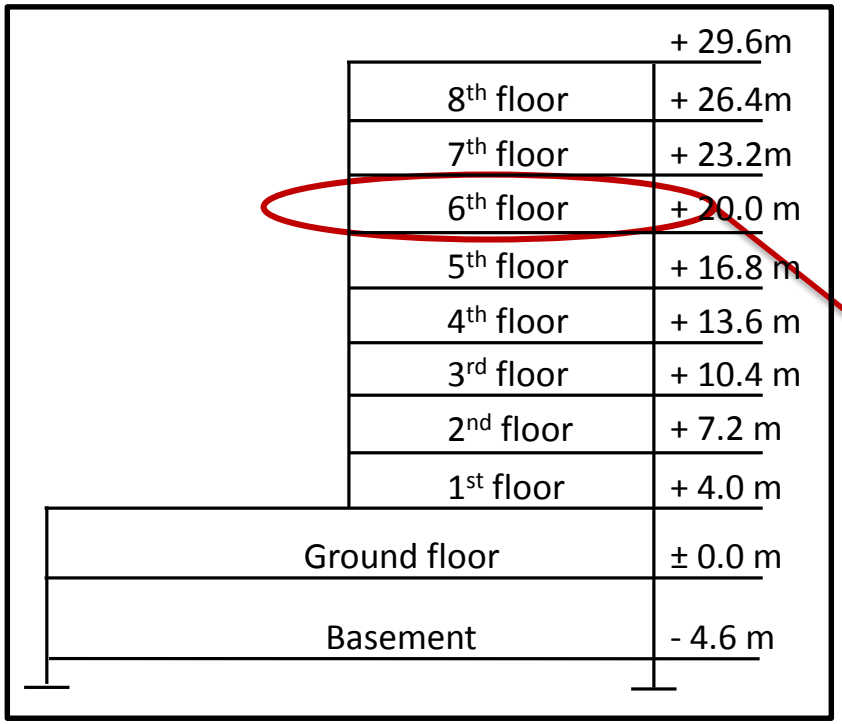
Derivation of fragility curves

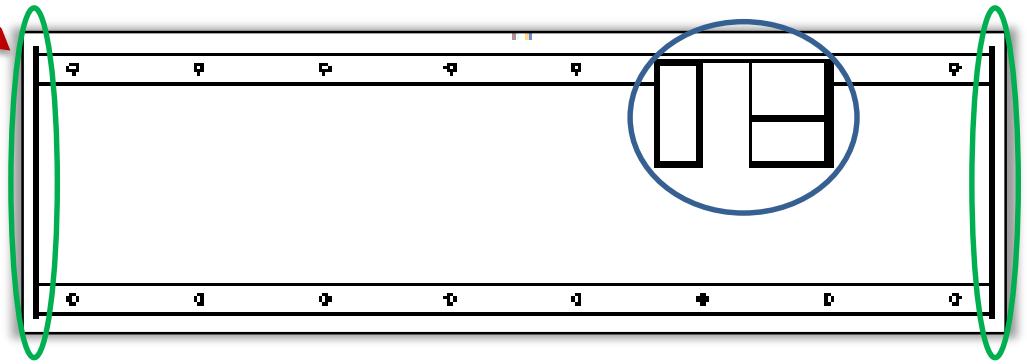
Description of the Thessaloniki applications



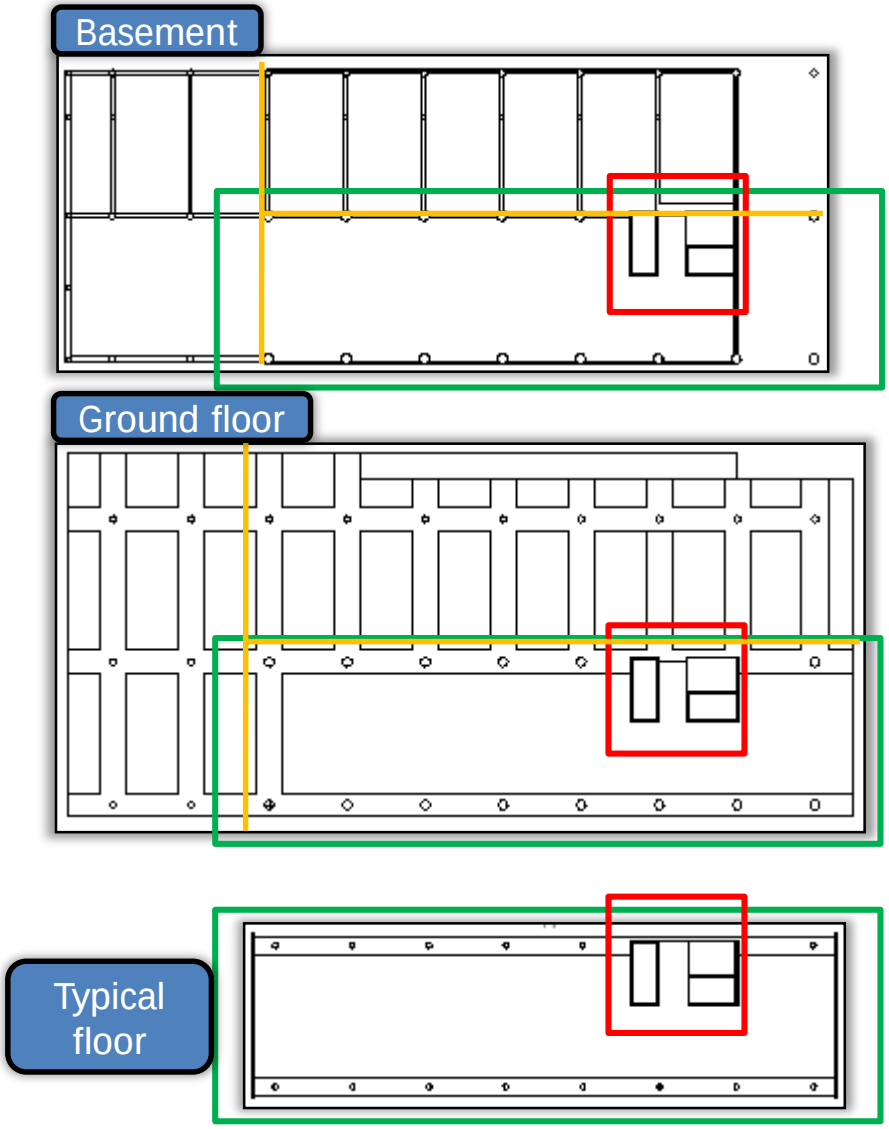
Administration building - Description

- ✓ Built in 1964 (Royal Decree of 1959)
- ✓ 9-storey with basement
- ✓ Dual force resisting mechanism:
  frames + core walls
- ✓ Frontal walls between the 2nd and 8th floor
- ✓ Peripheral walls in the basement
- ✓ Foundation: mainly isolated footings without tie beams; soil type B (EC8)





Administration building - Description



- ✓ **Torsional effects**

  Center of mass → x=20.06m , y=5.24m

  Center of rigidity → x=25.10m , y=6.31m

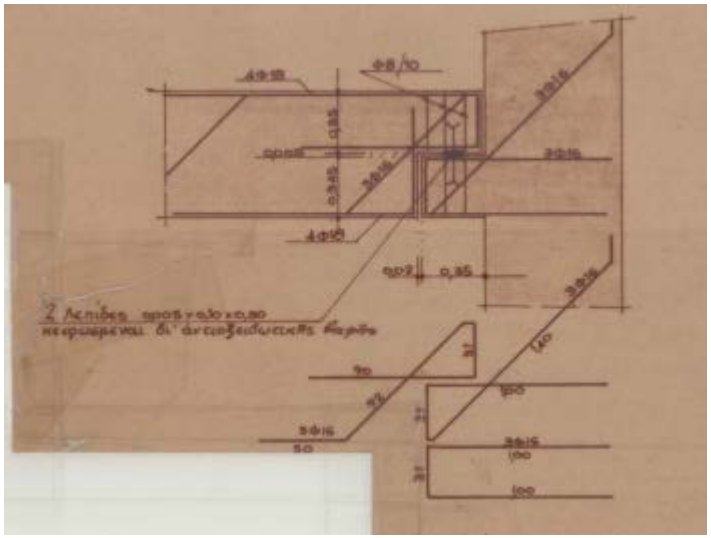
- ✓ Irregular in elevation (EC8)

- ✓ Irregular in plan (EC8)

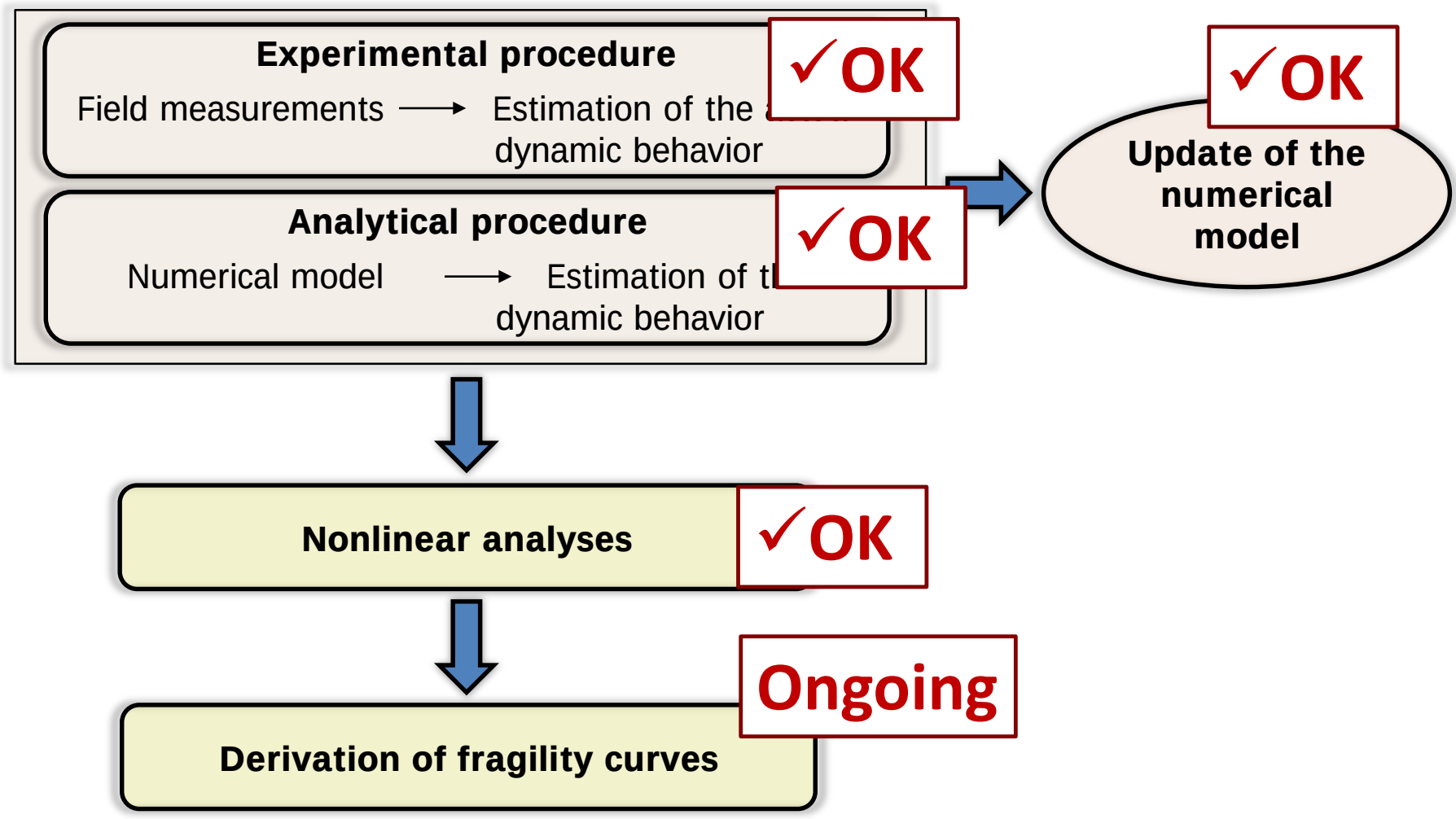
  $e_{ox} > 0.3r_x$

  $e_{oy} > 0.3r_y$

- ✓ Joints at the basement and ground floor level



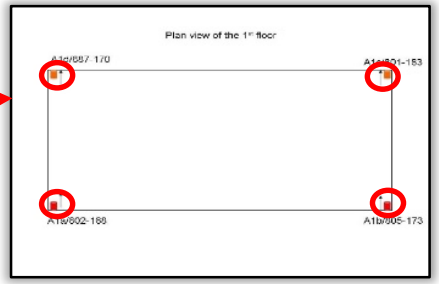
Administration building – Evolution of work in SIBYL



Temporary instrumentation array

- **September/October 2015: ambient noise measurements (TU Berlin, GFZ, AUTh)**
- **Duration of the measurements at each building: approx. 20 hours**
- **Sensors: 38 CUBE digitizers connected to 4.5Hz geophones**
- **Sampling rate: 400 Hz**

Administration building – Measurements

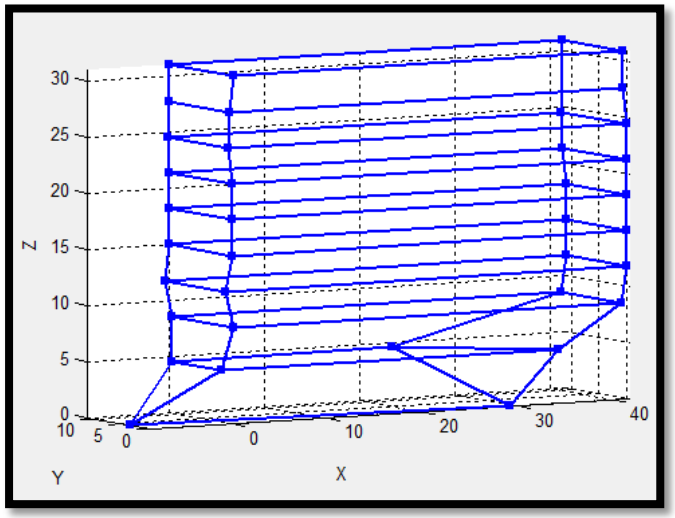


4 in each floor

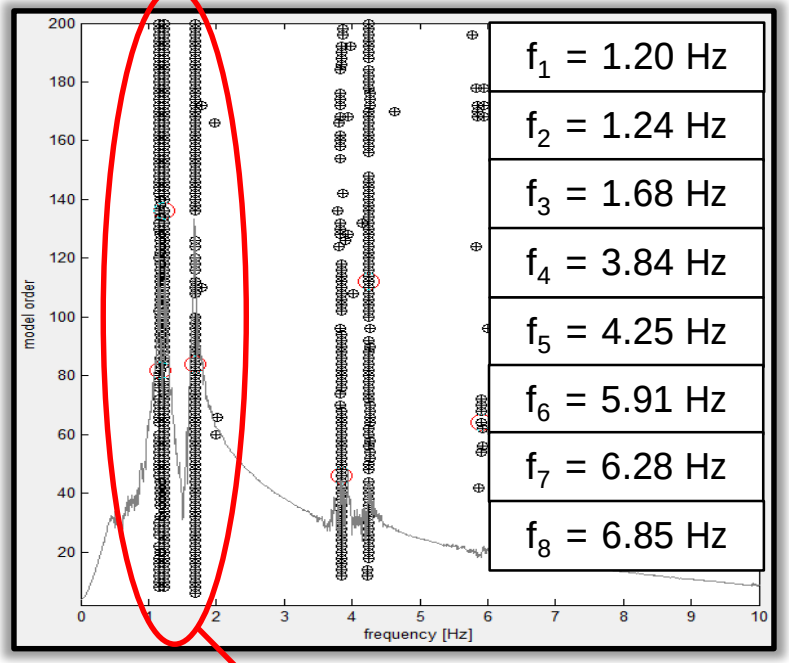
4 in the ground floor

2 in the basement

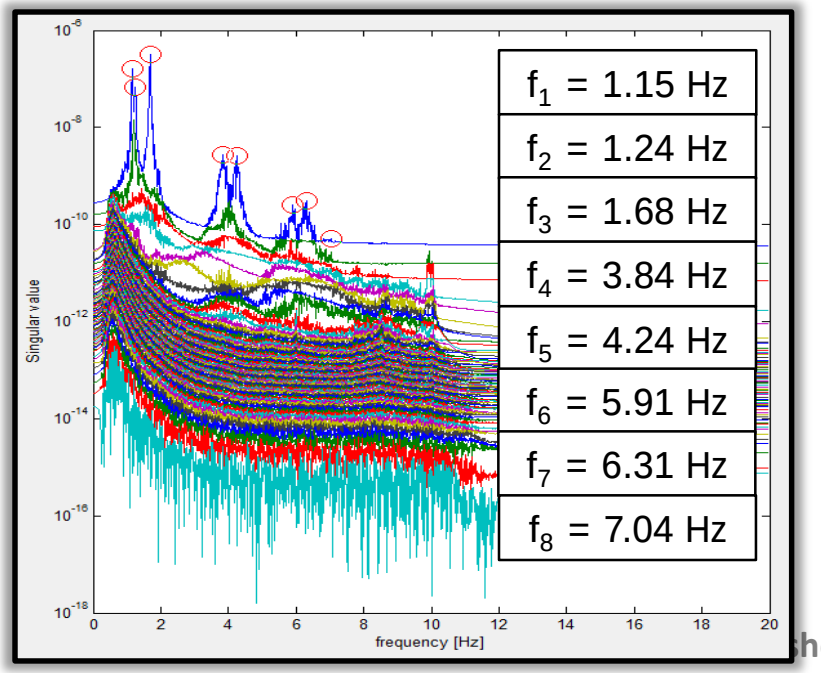
Administration building – Operational modal analysis (MACEC 3.2)

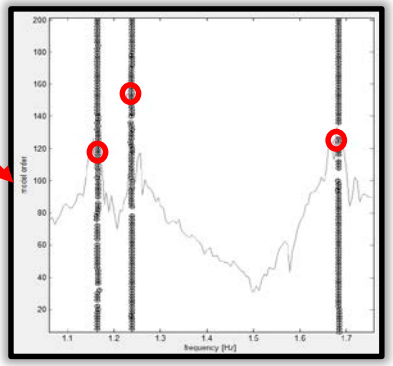


SSI



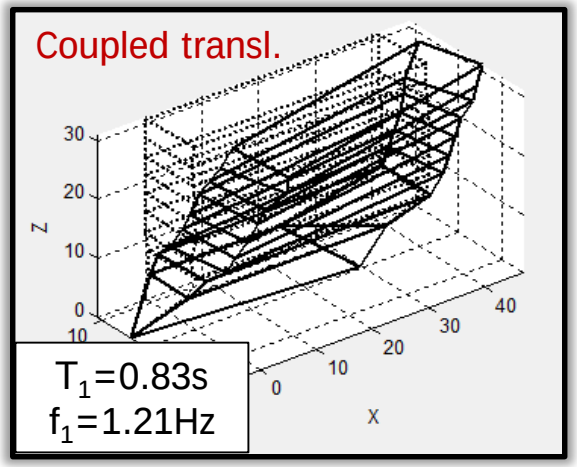
FDD

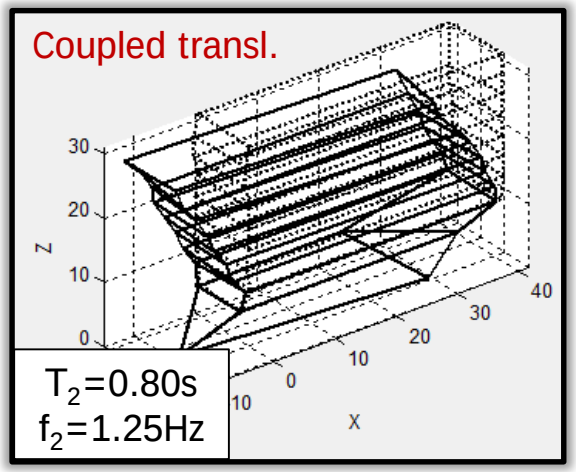


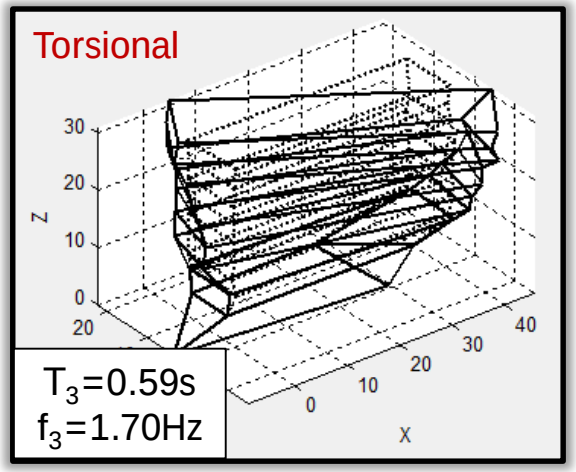


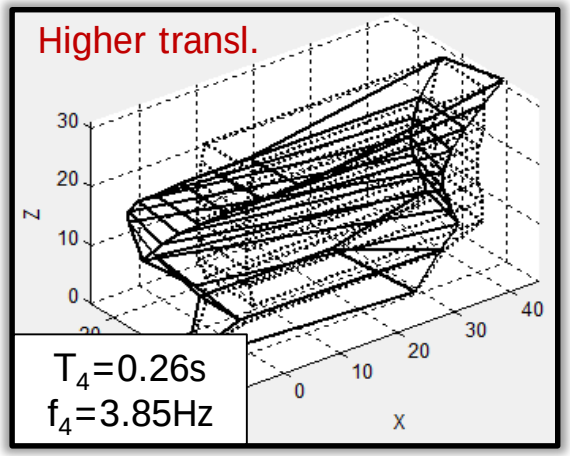
Administration building – Operational modal analysis (MACEC 3.2)

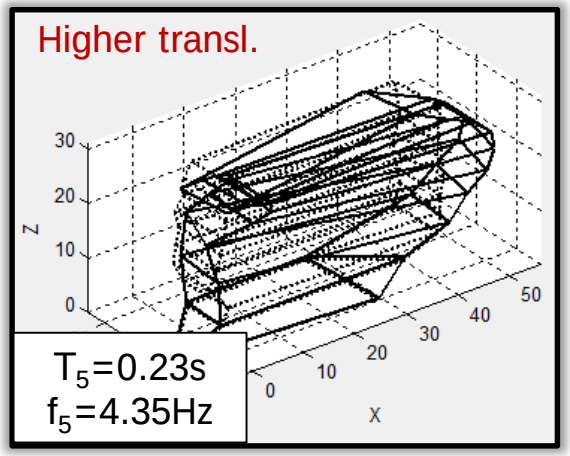
- **Modes (frequencies/periods and shapes)**











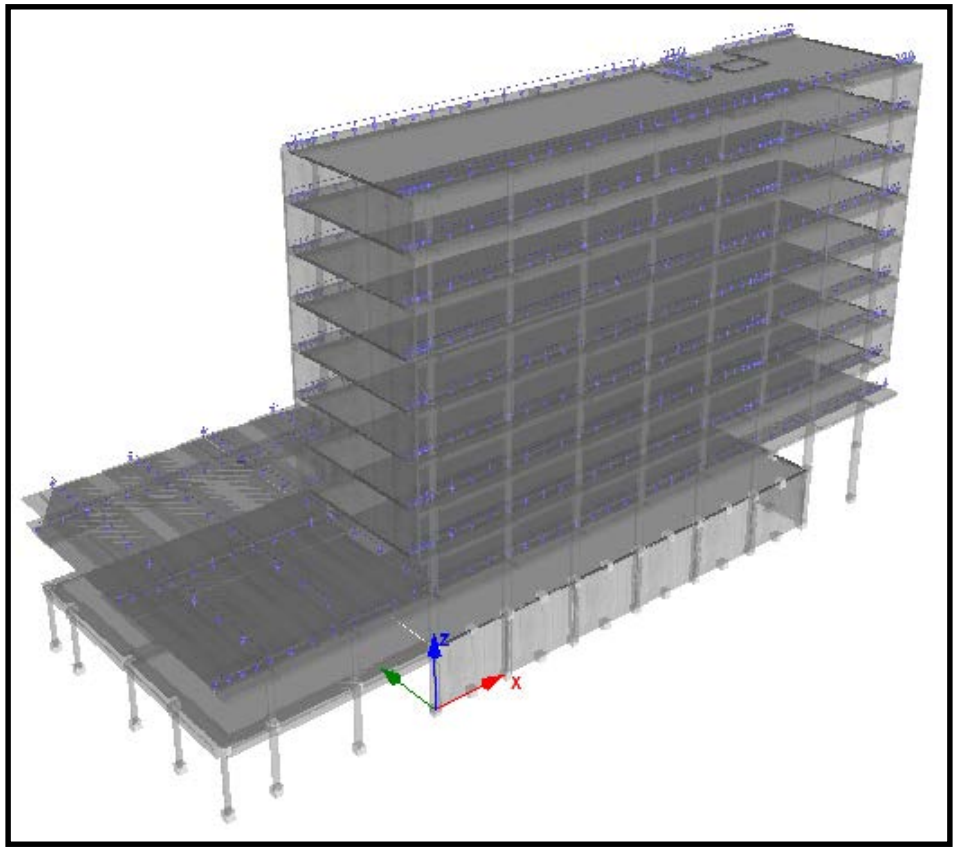
Administration building – Operational modal analysis (MACEC 3.2)

- **Modes (frequencies/periods and shapes)**
  - ✓ **Variation of the fundamental frequencies**

Frequencies (Hz)	Recording 13:00-14:00	Recording 18:00-19:00	Recording 23:00-24:00	Recording 6:00-7:00
f_1	1.21	1.20	1.20	1.20
f_2	1.25	1.25	1.25	1.25
f_3	1.70	1.69	1.70	1.70
f_4	3.85	3.88	3.91	3.91
f_5	4.35	4.26	4.27	4.29

Administration building – Numerical modeling

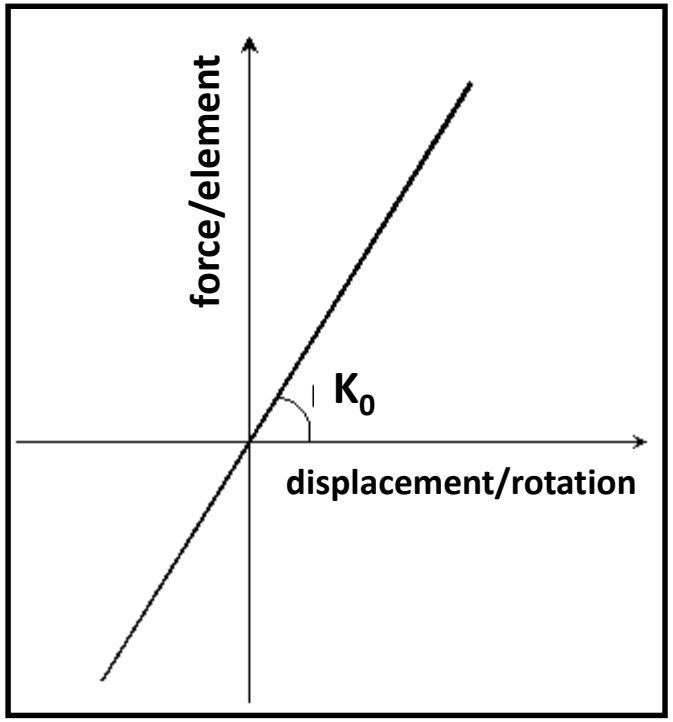
- **SeismoStruct (SeismoSoft, v. 7)**
  - ✓ Beam/Columns: frame elements
  - ✓ Peripheral concrete walls – Core walls: equivalent beam-column model
  - ✓ Total mass: 7219 tn
  - ✓ Concrete strength: B300 -> C20/25
  - ✓ Steel strength: StIIIb -> S400
  - ✓ Fixed base conditions
  - ✓ Translational degrees of freedom of the building nodes are fixed at the basement level
  - ✓ Joints at the basement and the ground floor level simulated through **link elements**



Administration building – Finite Element Updating

- **SeismoStruct (SeismoSoft, v. 7)**

Link element in SeismoStruct



Updating procedure:

✓ Sensitivity modal analysis

✓ Extensive investigation of the stiffness parameter K_0 of the link elements

✓ Selection of the best finite element model that reflects the measured response based on the Modal Assurance Criterion (MAC)

$$MAC_{ij} = \frac{(\varphi_j^T \varphi_{Ei})^2}{(\varphi_j^T \varphi_j)(\varphi_{Ei}^T \varphi_{Ei})}$$

φ_j eigenvector *j* from numerical model

φ_{Ei} eigenvector *i* from field monitoring test

- **Best model (MAC>0.8)**: $K_0 = 10^4$kN/m for the *translational* DOFs
  $K_0 = 10^6$kNm/rad for the *rotational* DOFs

Administration building – Finite Element Updating

- **SeismoStruct (SeismoSoft, v. 7)**

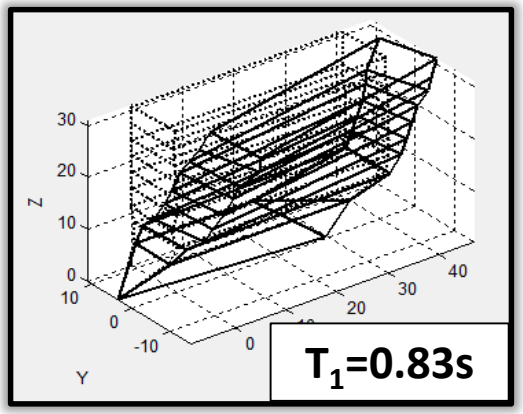
Link element in SeismoStruct: connection with nearby structures

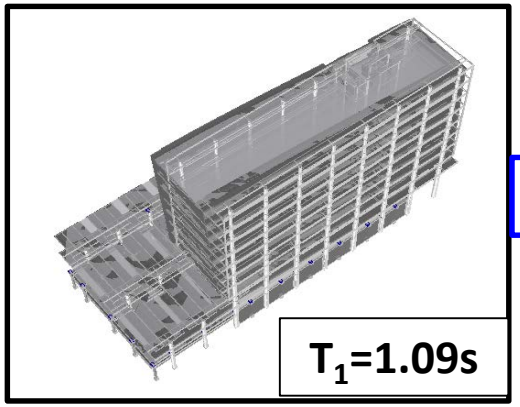
- **Best model (MAC>0.8)**: $K_0 = 10^6$kN/m for the *translational* DOFs
  $K_0 = 10^6$kNm/rad for the *rotational* DOFs

Administration building – Finite Element Updating

- **Comparison with measured response**

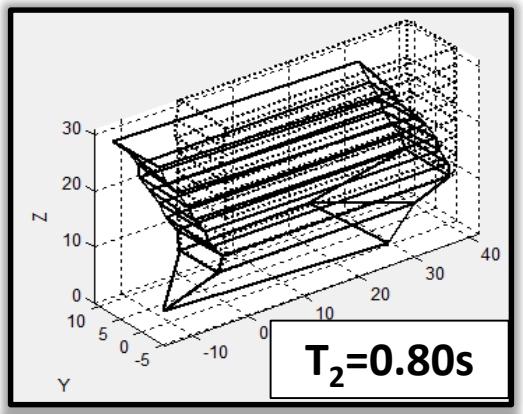
1st mode
Coupled translational along the transverse direction

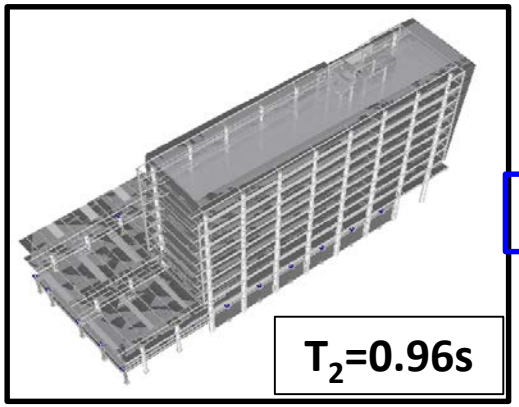




MAC=0.89

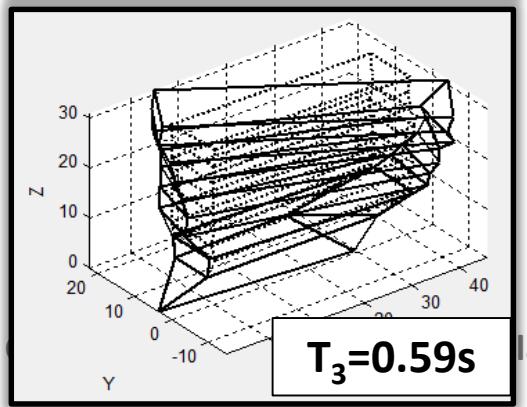
2nd mode
Coupled translational along the longitudinal direction

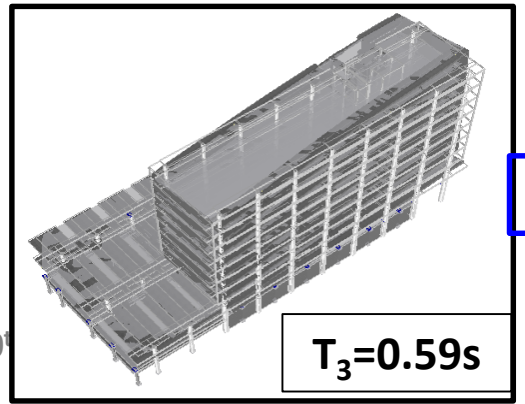




MAC=0.90

3rd mode
Torsional



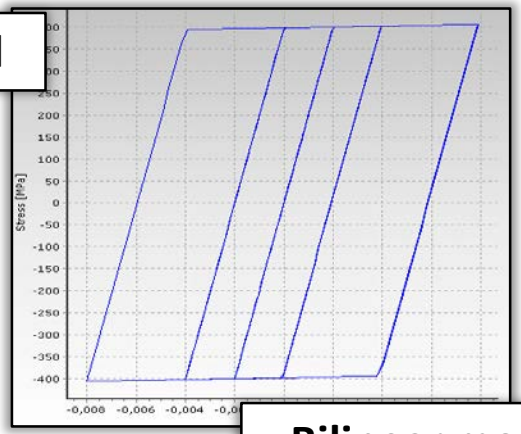


MAC=0.87

Administration building – Nonlinear modeling

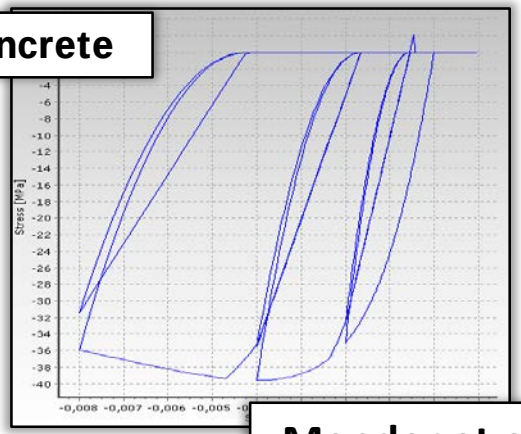
- ✓ Nonlinear numerical modeling – **SeismoStruct (SeismoSoft, v. 7)**
- ✓ Force- and displacement based formulations
- ✓ Geometric nonlinearity
- ✓ Material inelasticity

Steel



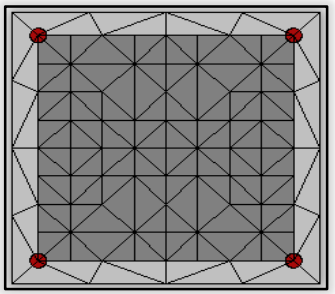
Bilinear model

Concrete



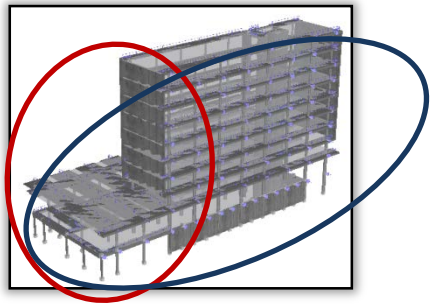
Mander et al. (1988)

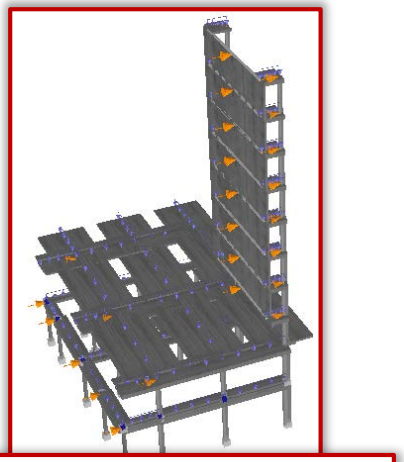
- ✓ Distributed plasticity along the structural elements (fiber based approach)



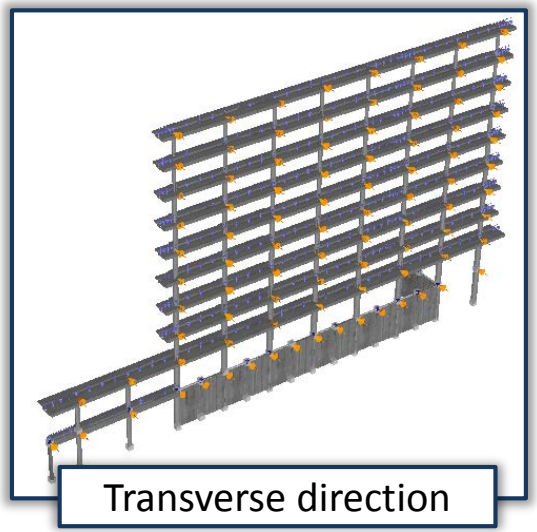
Administration building – Pushover analysis

✓ longitudinal (x) and transverse (y) direction





Longitudinal direction

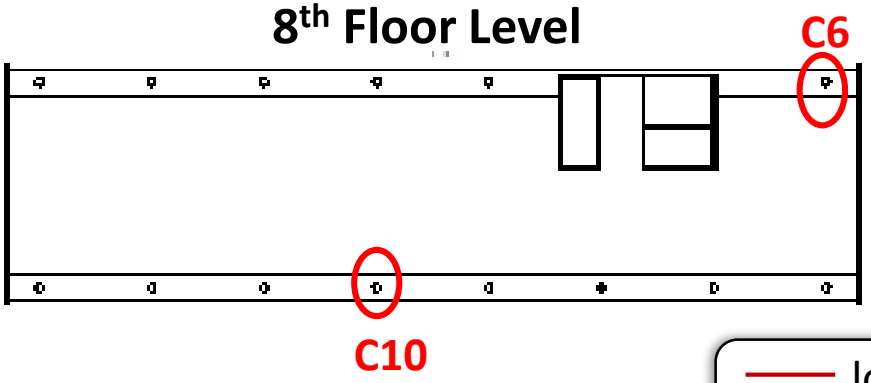


Transverse direction

✓ Force distribution along the height according to EC8

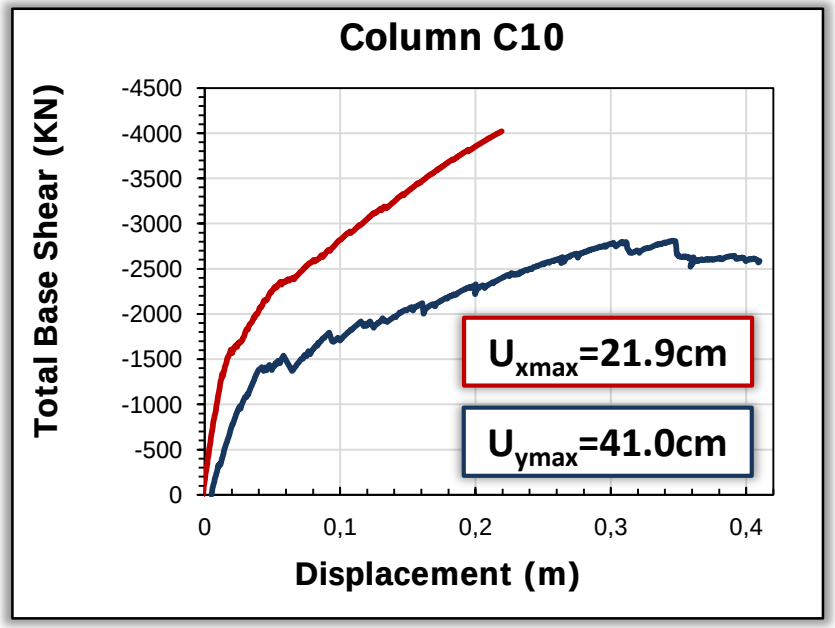
$$F_i = F_b \frac{m_i z_i}{\sum m_i z_i}$$

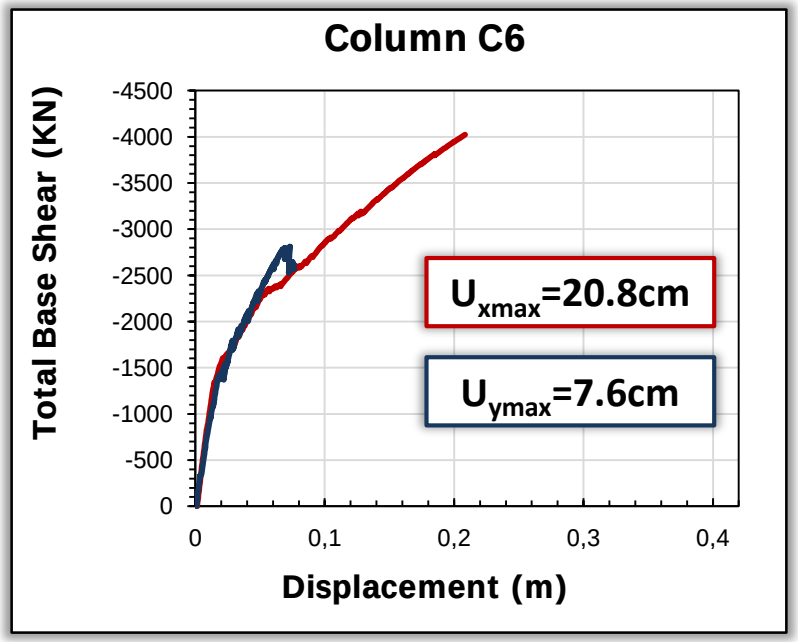
Administration building – Pushover analysis



- ✓ Total base shear versus displacement
- ✓ Control point **C6** and **C10** located at top floor level

longitudinal
transverse





Administration building – IDA: Selection of the input motion

- 10 real ground motion records from the ESMD (http://www.isesd.hi.is) referring to stiff soil conditions according to EC8 (soil type B)

- Selection criteria

  ✓ Moment magnitude: 5.5<Mw<6.5

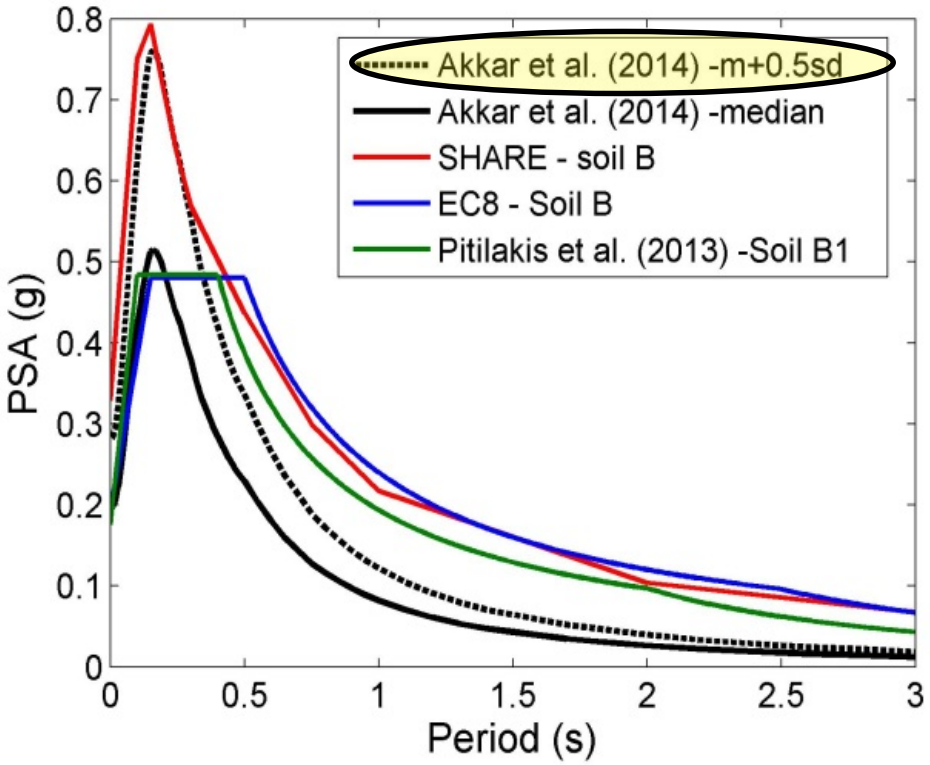
  ✓ Epicentral distance: 0<R<45km

  ✓ Average acceleration spectra of the set to be of minimal "epsilon" (*Baker and Cornell, 2005*) at 0<T<2.0sec with respect to the corresponding 5% damped median plus 0.5 standard deviations *Akkar et al. (2014) spectrum*

- Optimization procedure for the record selection using REXEL software (*Iervolino et al., 2010*)

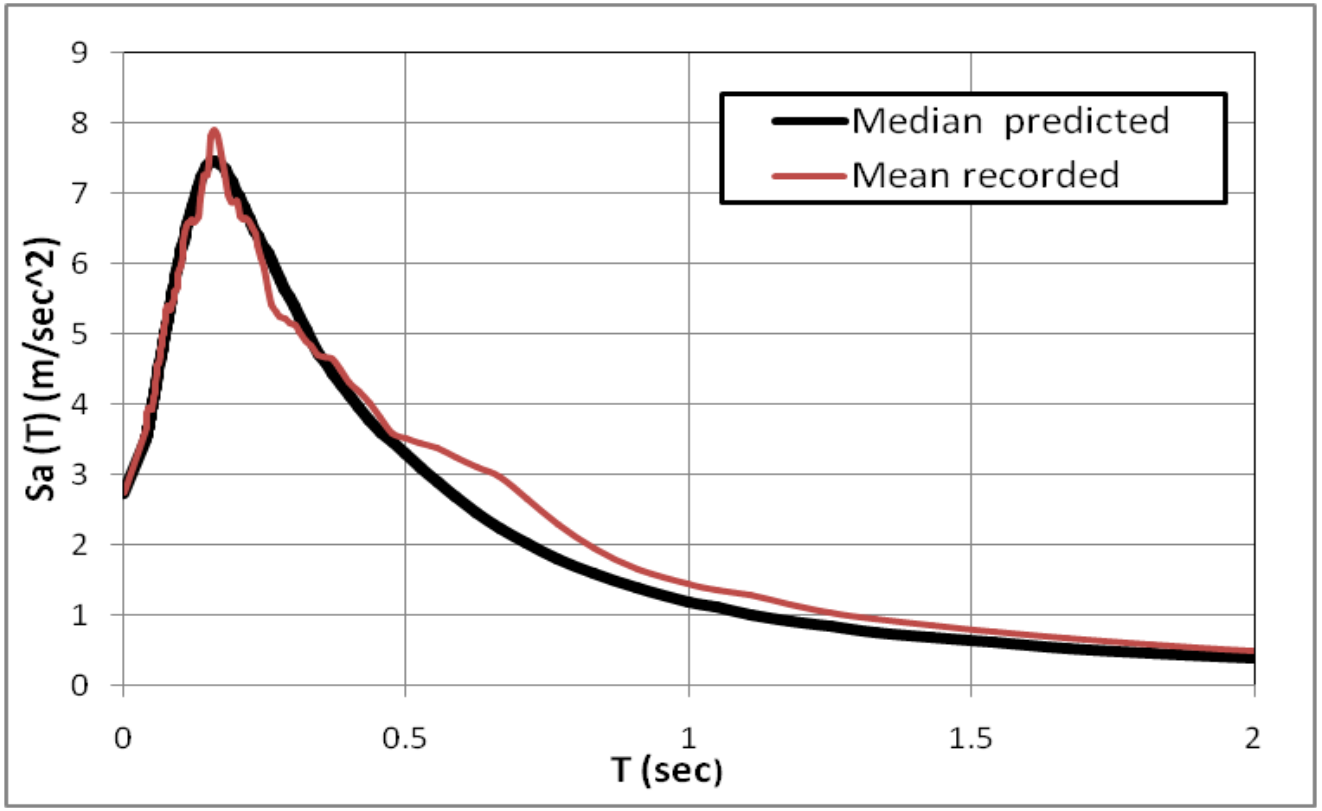
Administration building – IDA: Selection of the input motion

- Disaggregation of the probabilistic seismic hazard analysis PSHA results for the Aristotle University area (Papaioannou, 2004)
- Most significant contribution to the seismic hazard : Anthemountas fault system (i.e. normal fault)
- For the 475 years scenario max annual exceedance probability for a certain PGA value with M_w=5.675, R_{epi}=11.67km, R_{jb}=5km, R_{rup}=10km
- Selected GMPE which describes the sufficiently the hazard of the studied area: Akkar et al. (2014)



Administration building – IDA: Selection of the input motion

- Mean elastic response spectrum of the input motions in comparison with the corresponding reference spectrum proposed by *Akkar et al. (2014) plus 0.5 standard deviations*



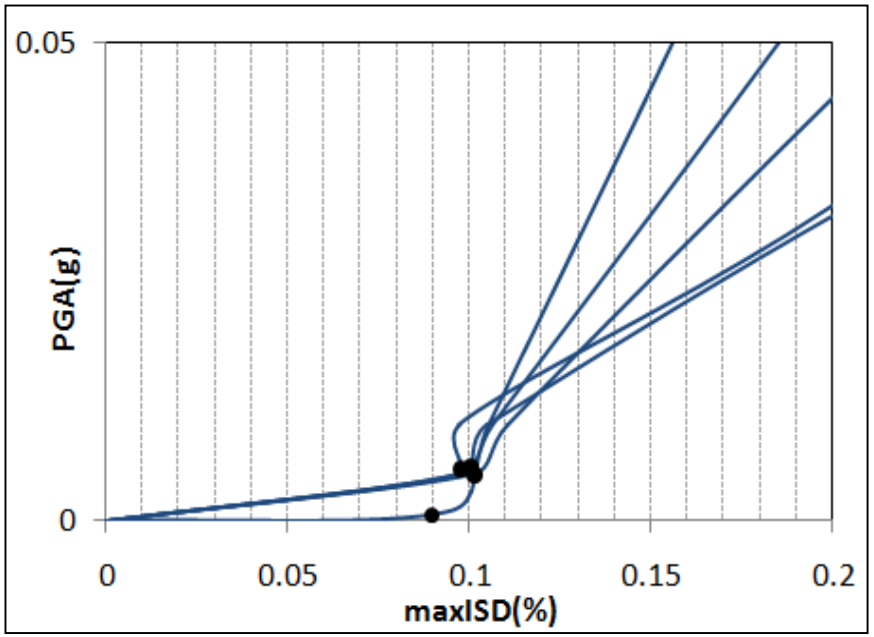
Administration building – IDA: Preliminary results

- Parametric analysis method by *Vamvatsikos and Cornell (2002)*: the structural model is subjected to a series of nonlinear dynamic analyses under a suite of multiply scaled ground motion records covering the range from elasticity to global dynamic instability

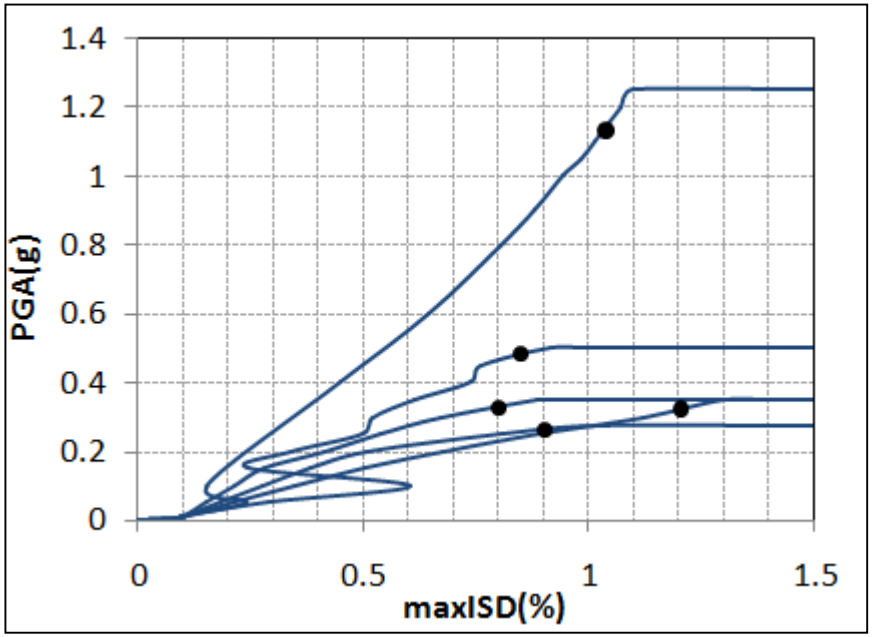
Total number of analyses: 126

- ✓ **EDP: max interstorey drift ratio maxISD**
- ✓ **IM: peak ground acceleration**

Immediate Occupancy



Collapse Prevention



Administration building – IDA: Preliminary results

- Two – parameter lognormal cumulative distribution functions:

$$P[DS / IM] = \Phi\left(\frac{ln(IM) - ln(\overline{IM})}{\beta}\right)$$

where :

Φ: the standard normal cumulative distribution function

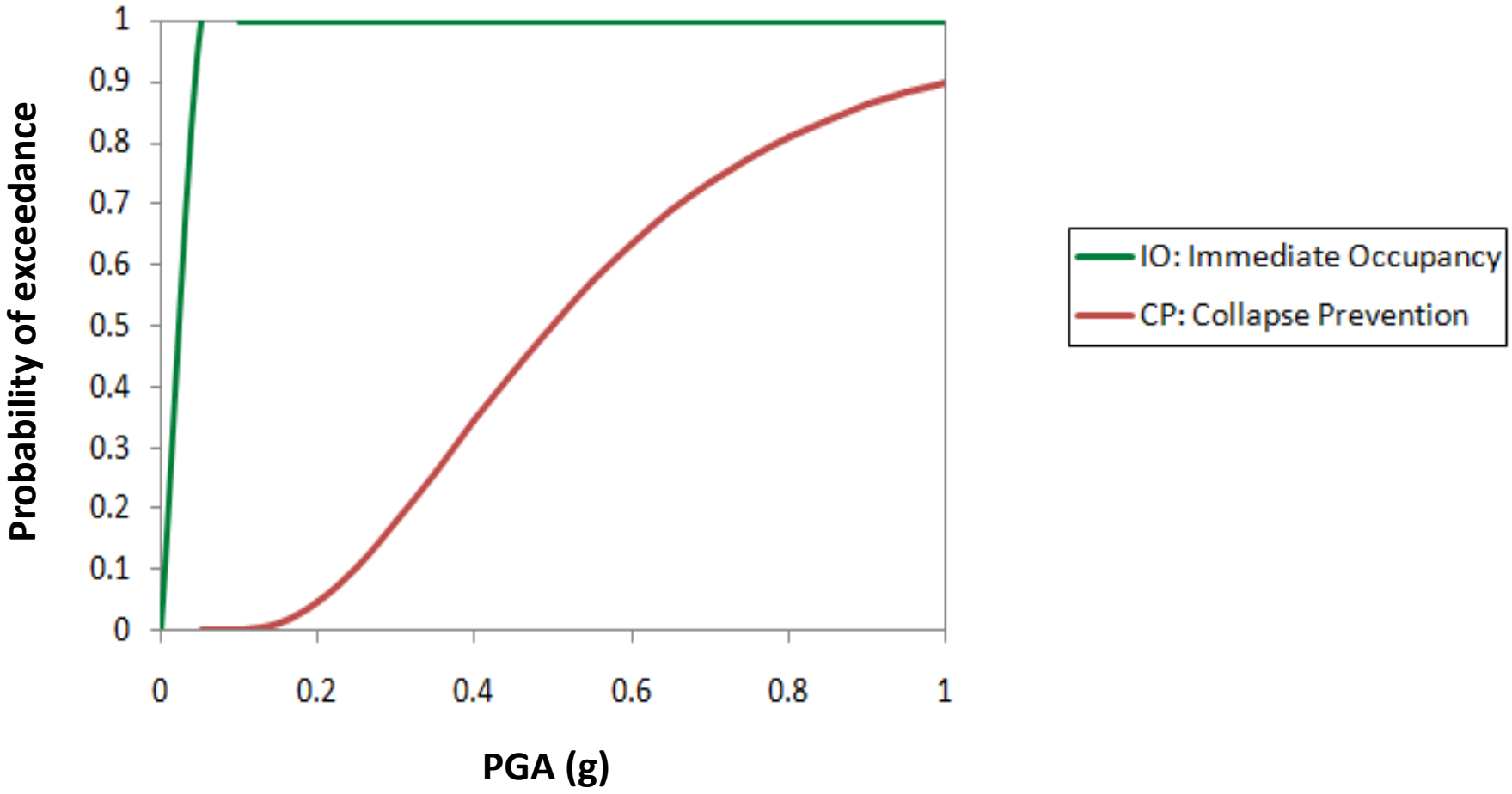
IM: the intensity measure of the earthquake expressed in terms of PGA (in units of *g)*

$\overline{IM}$ and β: the median values and log-standard deviations respectively of the building fragilities

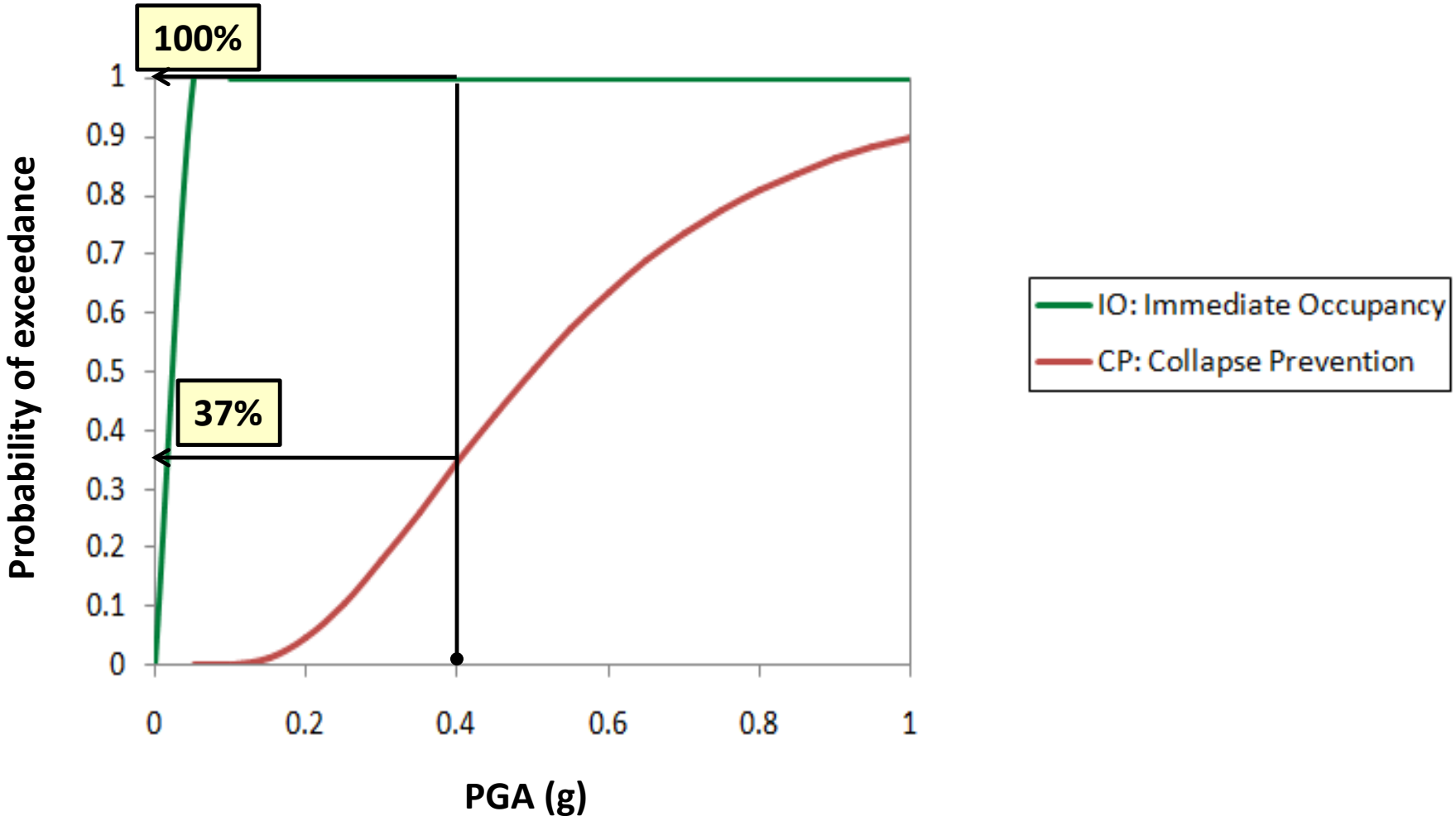
- ✓ β: demand; capacity (HAZUS); definition of the damage states

DS: the damage state

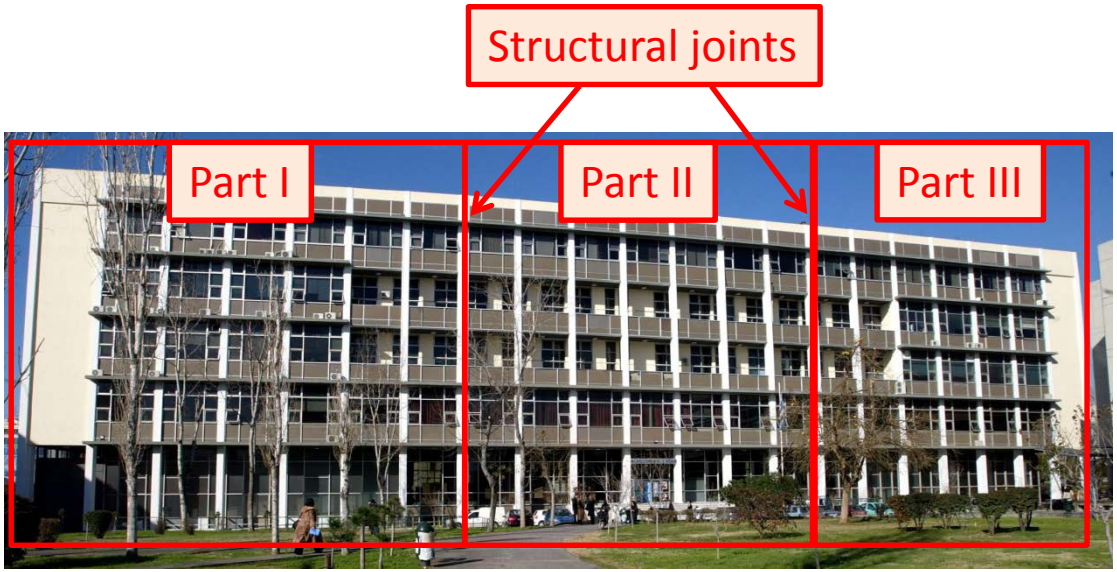
Incremental Dynamic Analysis IDA – Preliminary fragility curves

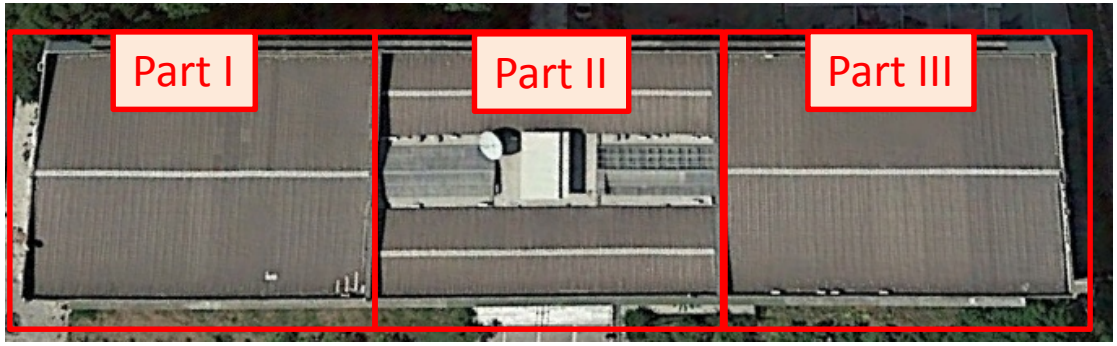


Incremental Dynamic Analysis IDA – Preliminary fragility curves



Faculty of Philosophy building - Description



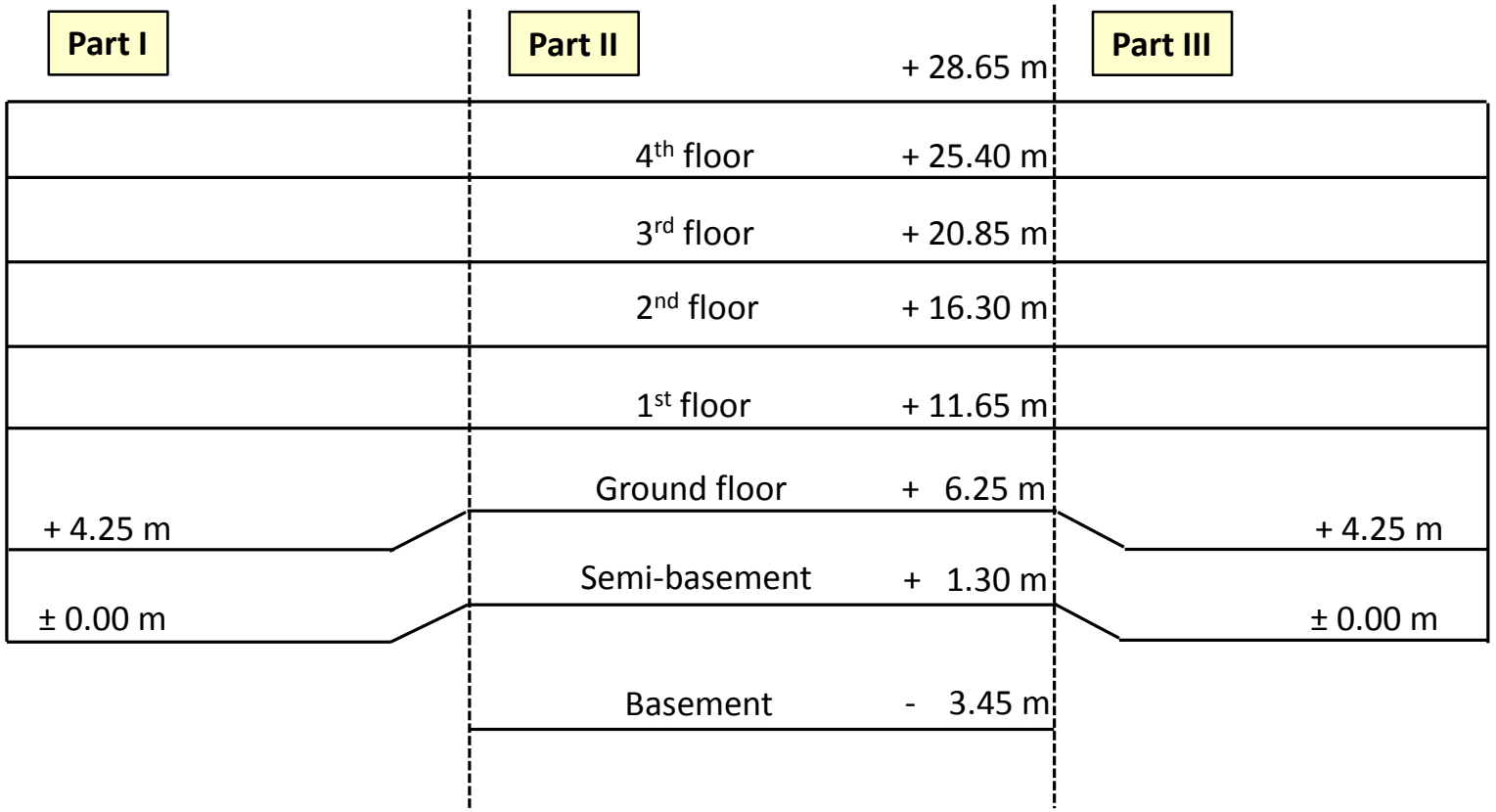


✓ Oblong plan with length 105m and width 25.5m

✓ Structural joints per 35m

✓ Divided in three parts with length 35m and width 25.5m

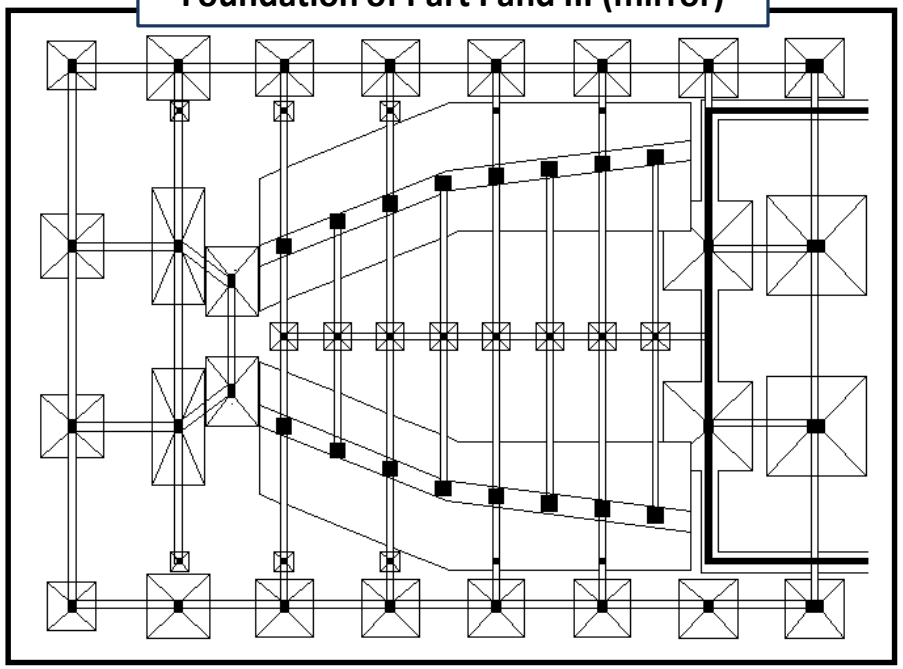
Faculty of Philosophy building - Description



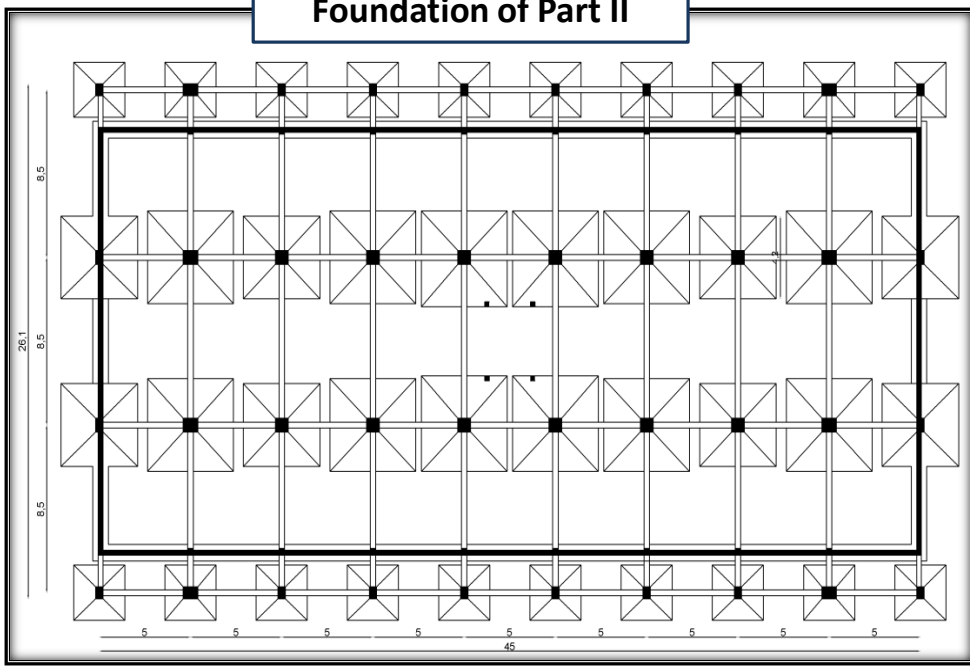
- ✓ Built in 1965 (Royal Decree of 1959)
- ✓ Construction of additional floor (last floor) in 1984 – No plans available
- ✓ Moment resisting frame system
- ✓ External infill panels along the longitudinal direction in the 2nd and 3rd floors

Faculty of Philosophy building - Description

Foundation of Part I and III (mirror)



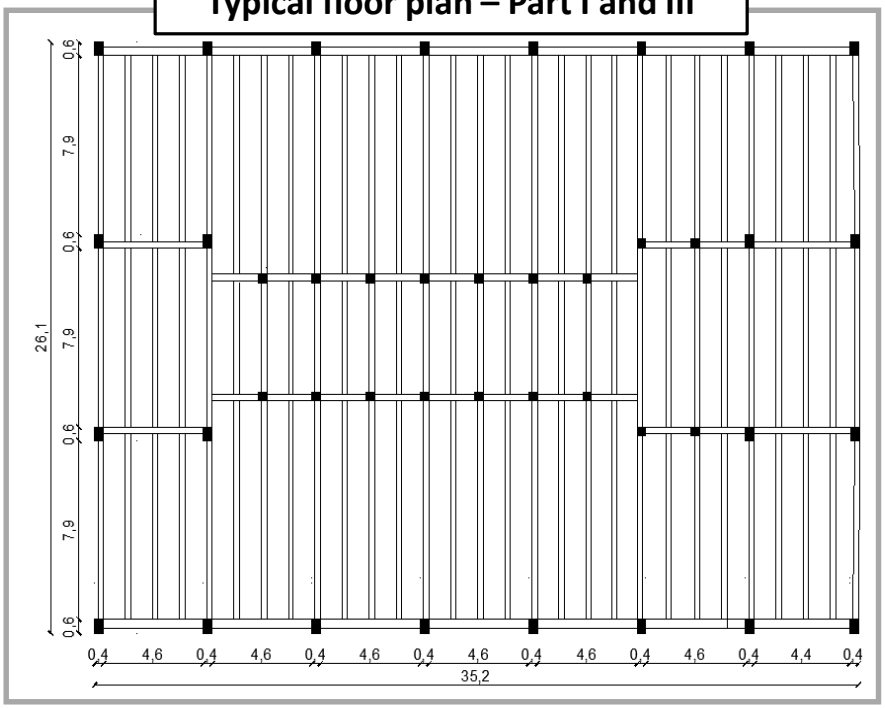
Foundation of Part II



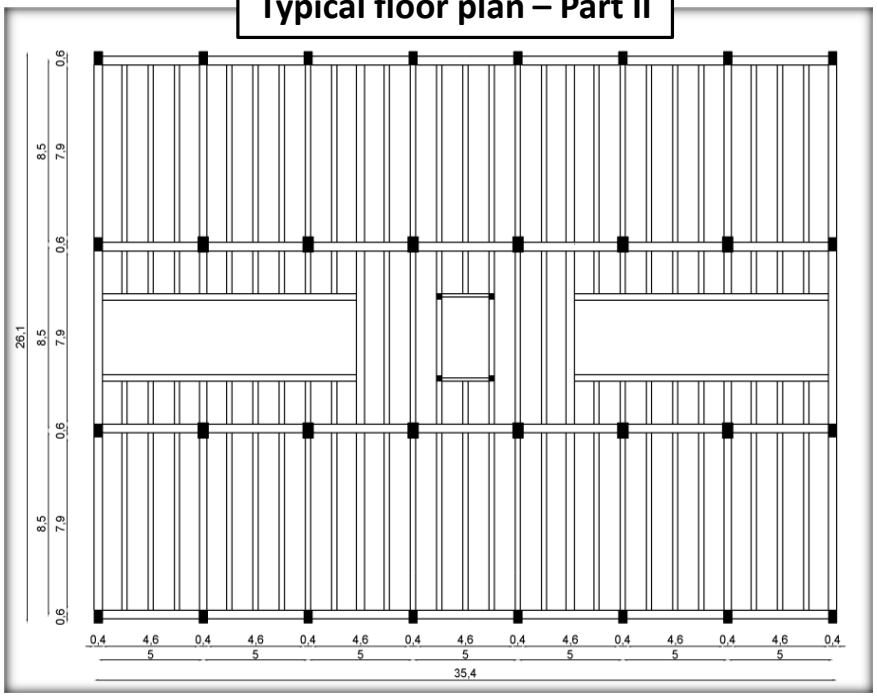
- ✓ Peripheral walls in the basement
- ✓ Isolated footings and strip footings
- ✓ Foundation soil: stiff clay -> Soil type B (EC8)

Faculty of Philosophy building - Description

Typical floor plan – Part I and III

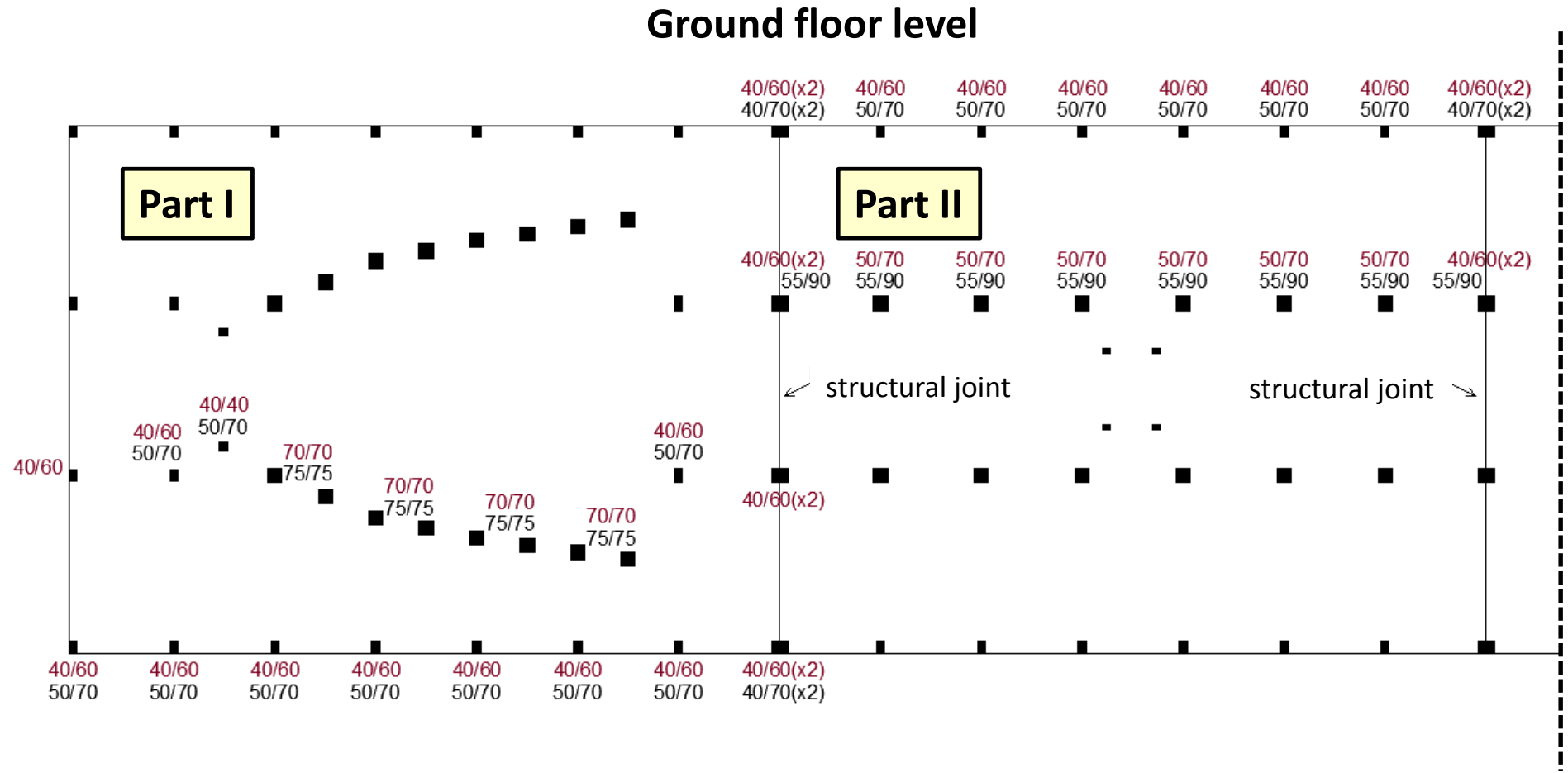


Typical floor plan – Part II



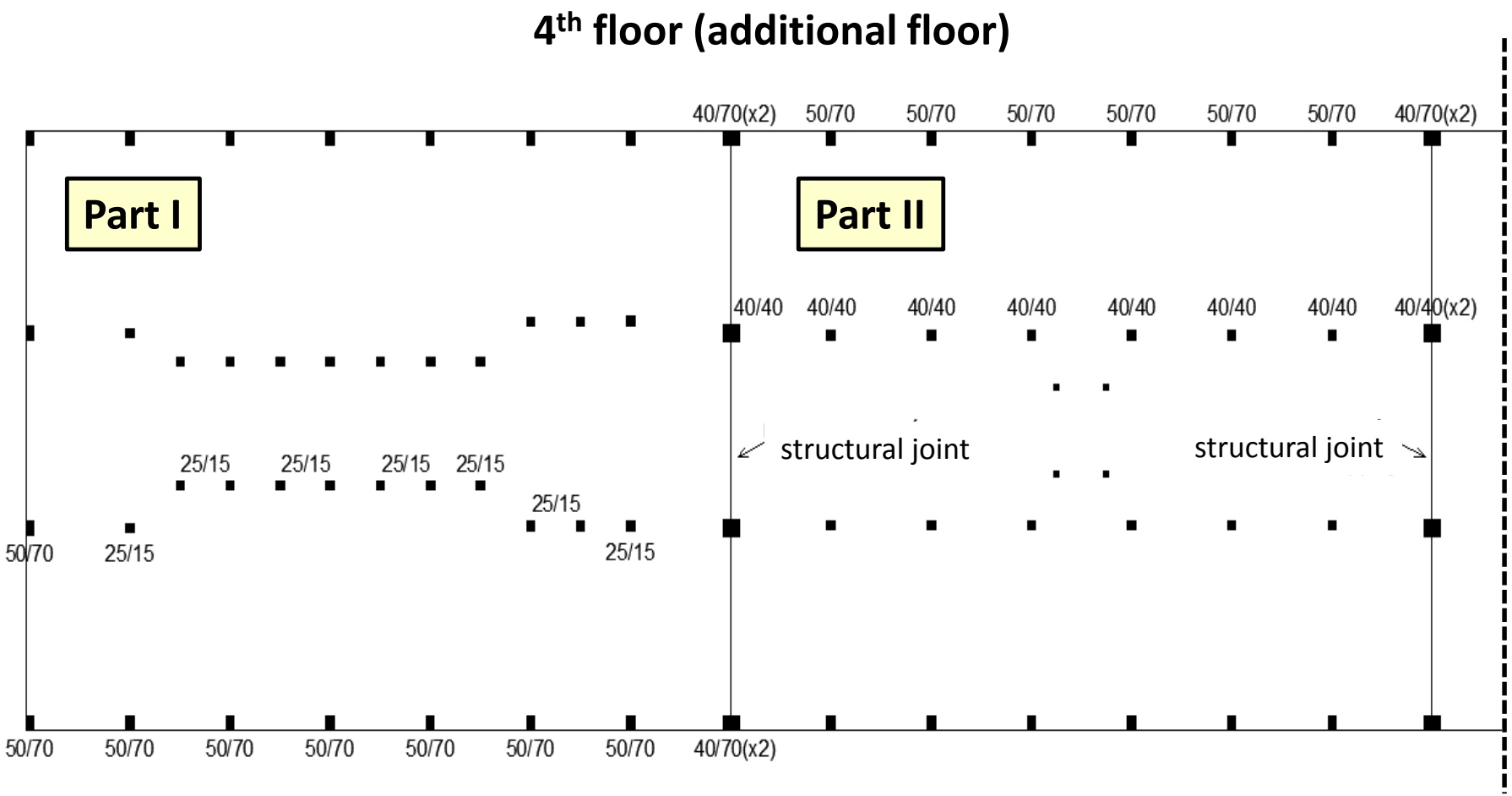
Faculty of Philosophy building - Description

- ✓ In situ measurements: dimensions of structural elements, reinforcement detection, concrete cover, floor heights

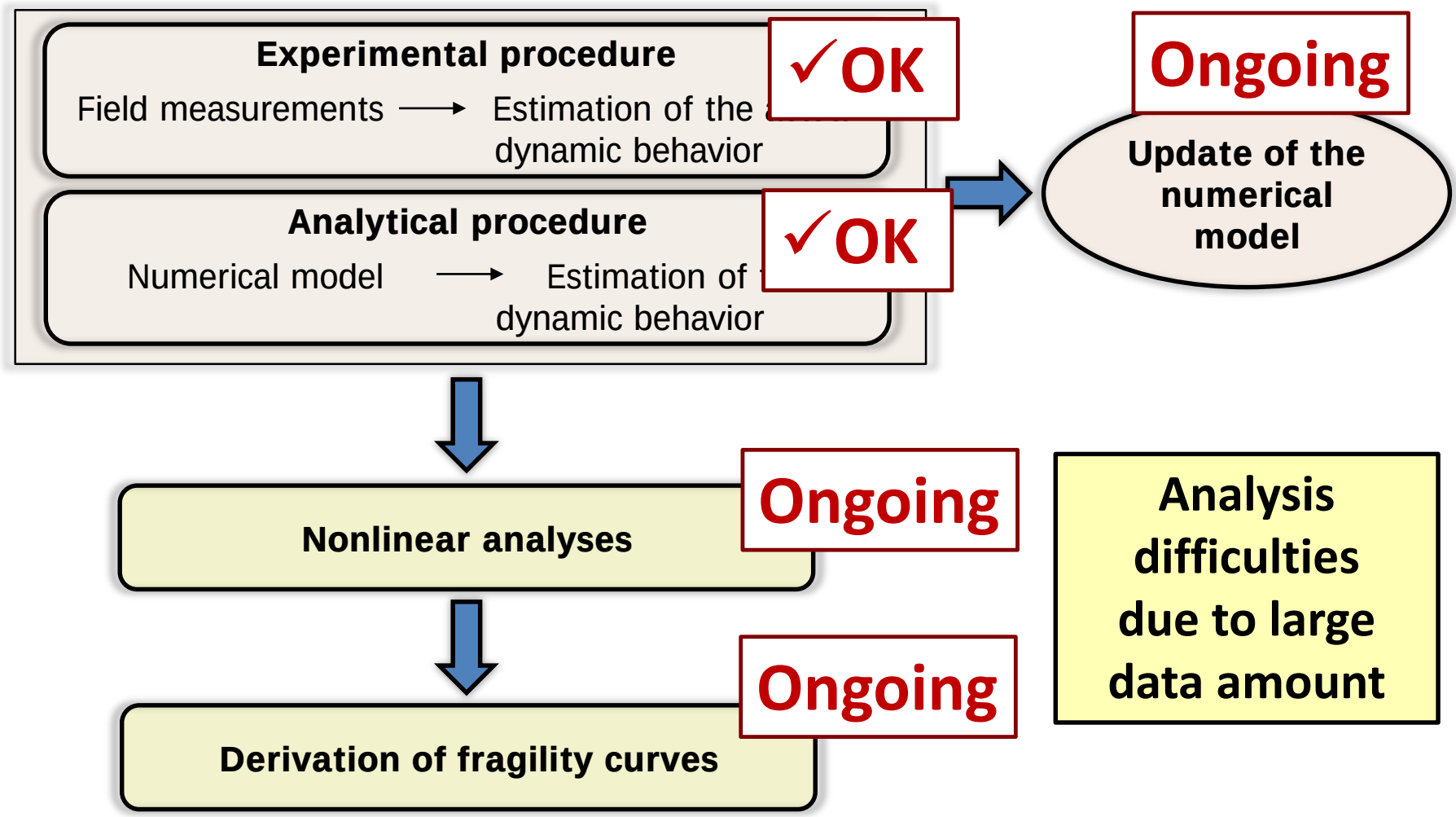


Faculty of Philosophy building - Description

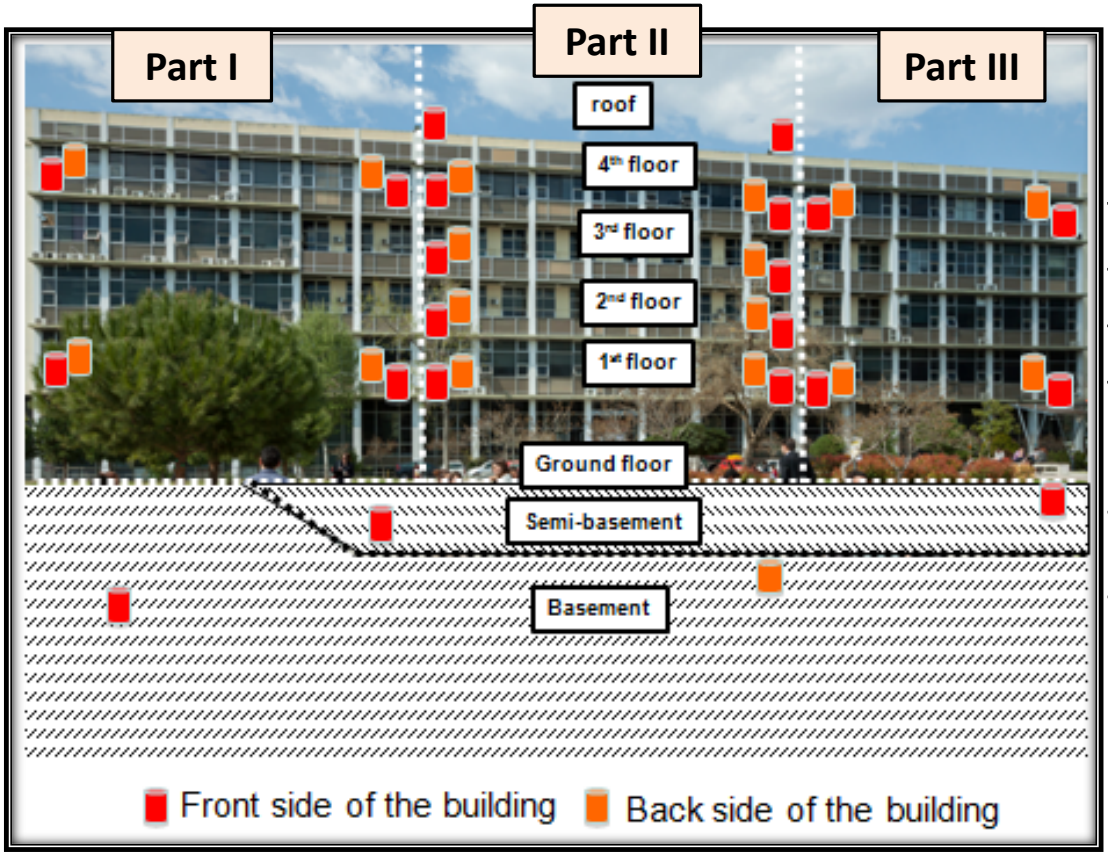
- ✓ In situ measurements: dimensions of structural elements, reinforcement detection, concrete cover, floor heights



Faculty of Philosophy building – Evolution of work in SIBYL



Faculty of Philosophy building - Measurements



→ 12 in the 4th floor

→ 4 in the 3rd floor

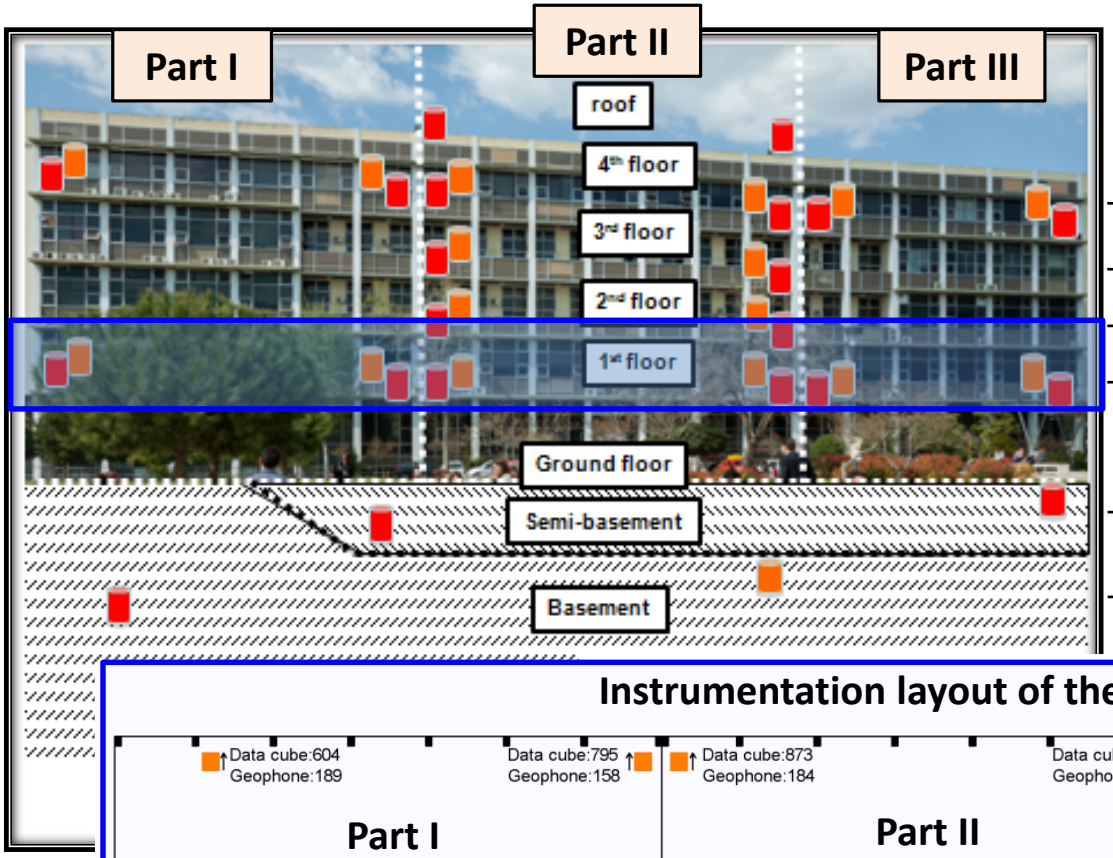
→ 4 in the 2nd floor

→ 12 in the 1st floor

→ 2 in the semi-basement

→ 2 in the basement

Faculty of Philosophy building - Measurements



→ 12 in the 4th floor

→ 4 in the 3rd floor

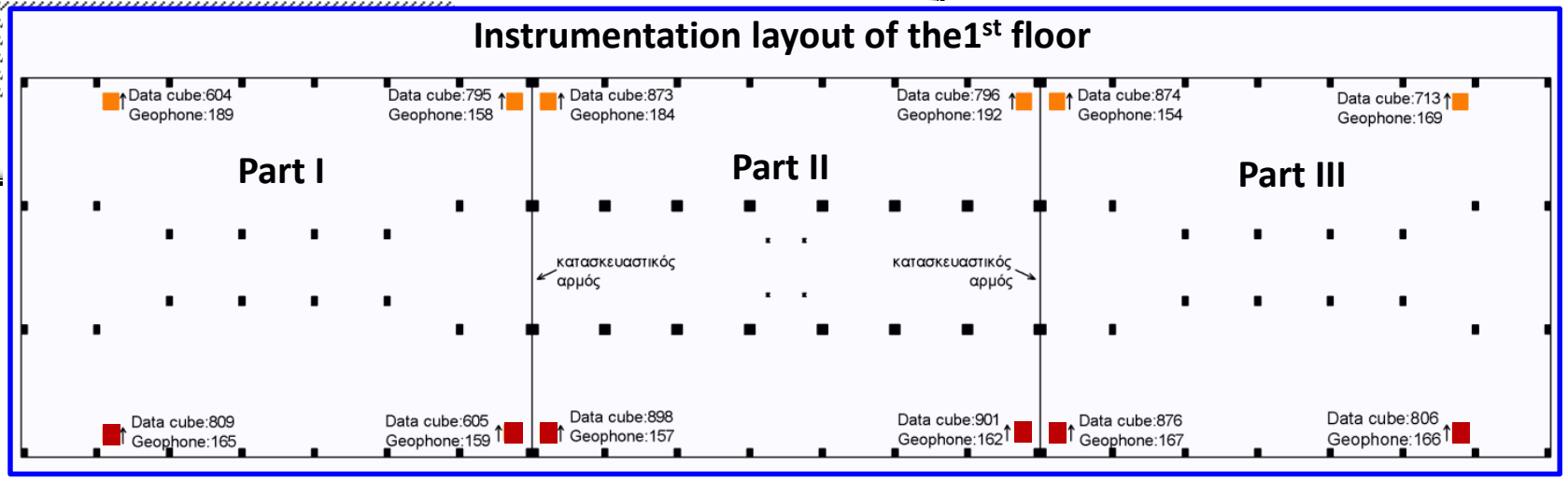
→ 4 in the 2nd floor

→ 12 in the 1st floor

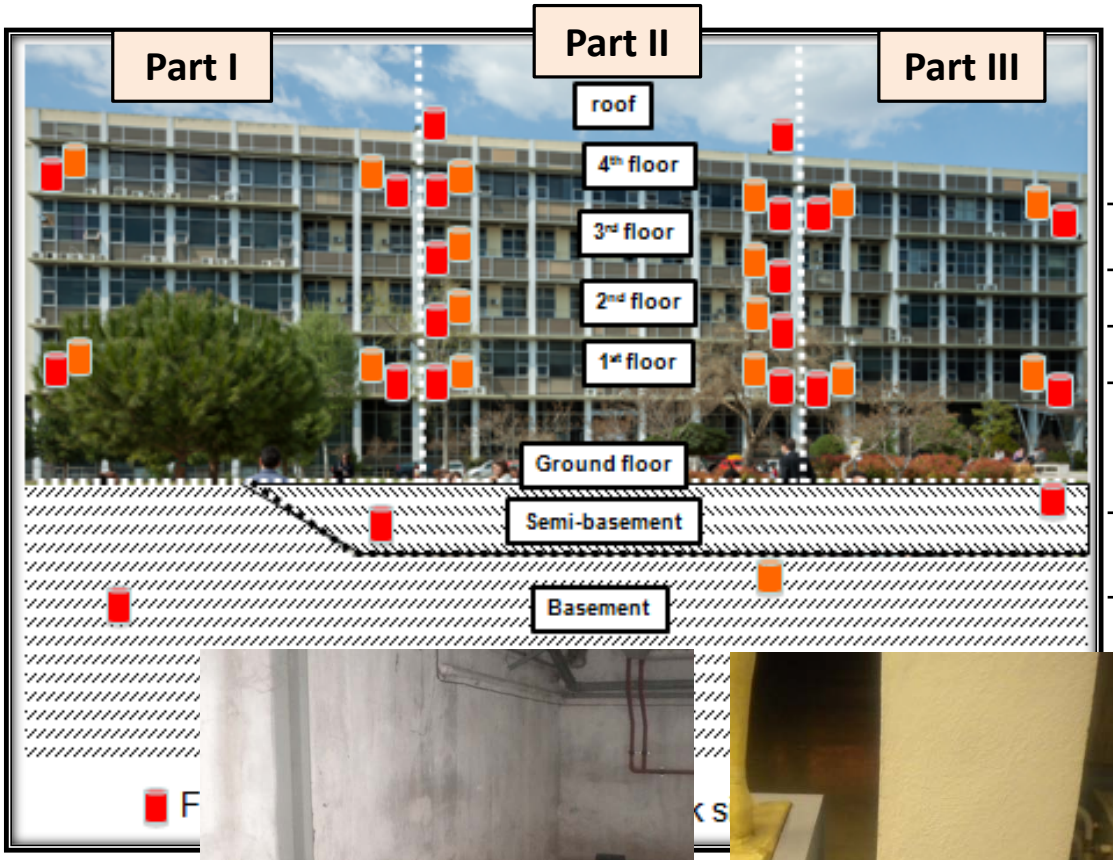
→ 2 in the semi-basement

→ 2 in the basement

Instrumentation layout of the1st floor



Faculty of Philosophy building - Measurements



→ 12 in the 4th floor

→ 4 in the 3rd floor

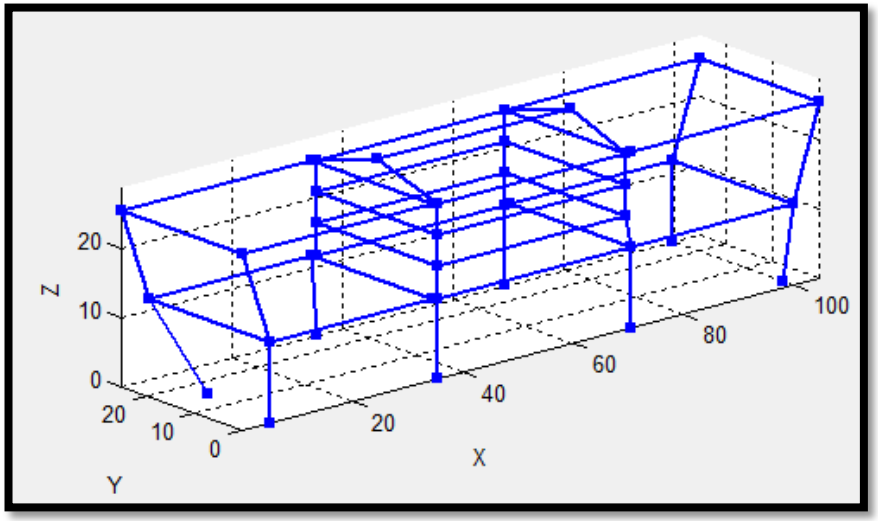
→ 4 in the 2nd floor

→ 12 in the 1st floor

→ 2 in the semi-basement

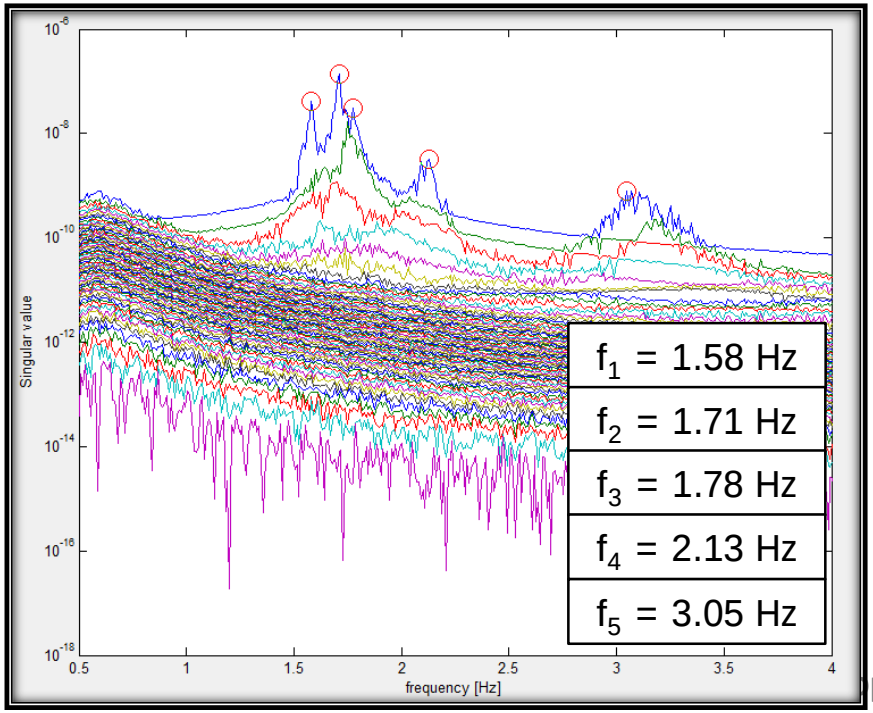
→ 2 in the basement

Faculty of Philosophy building – Operational modal analysis

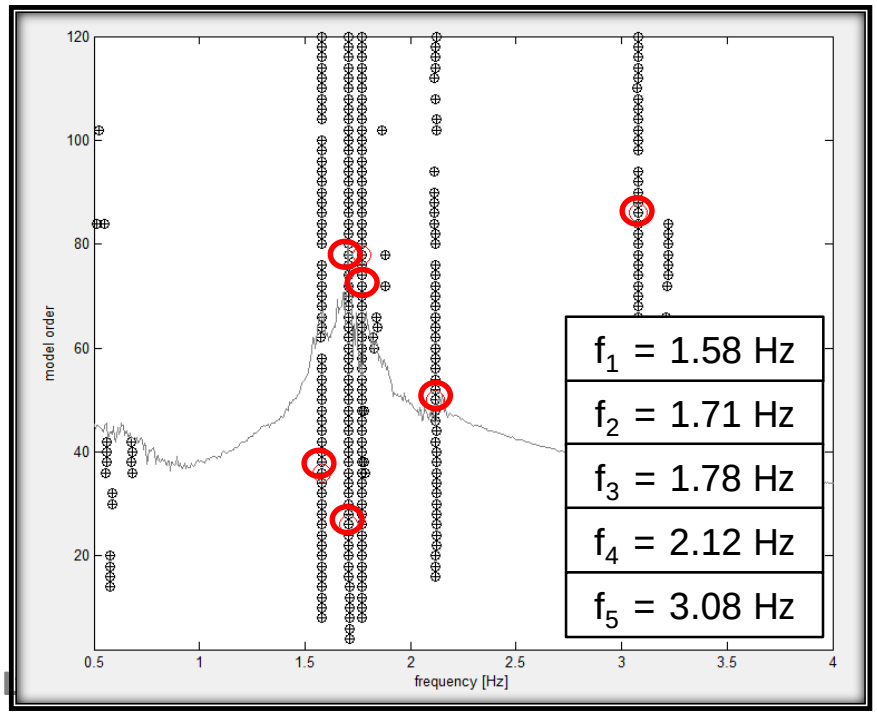


MACEC 3.2

FDD

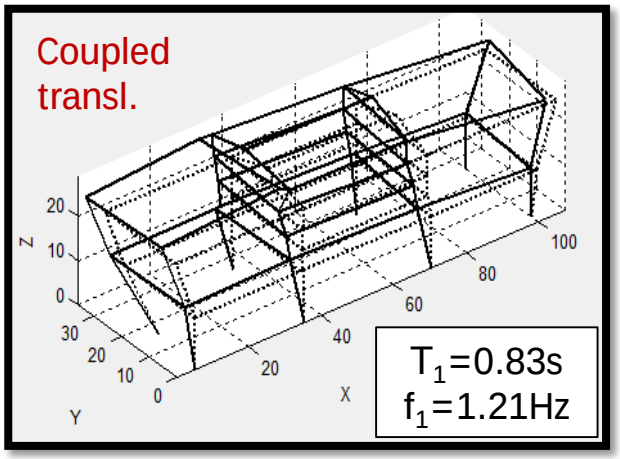


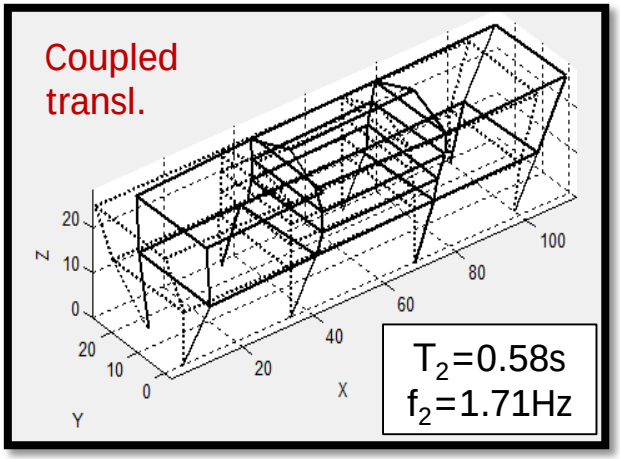
SSI

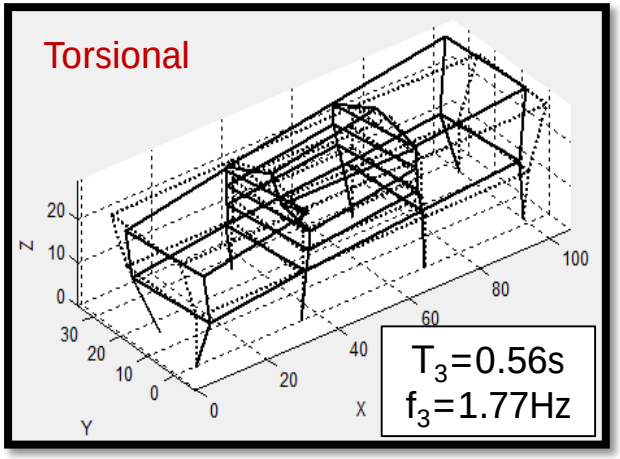


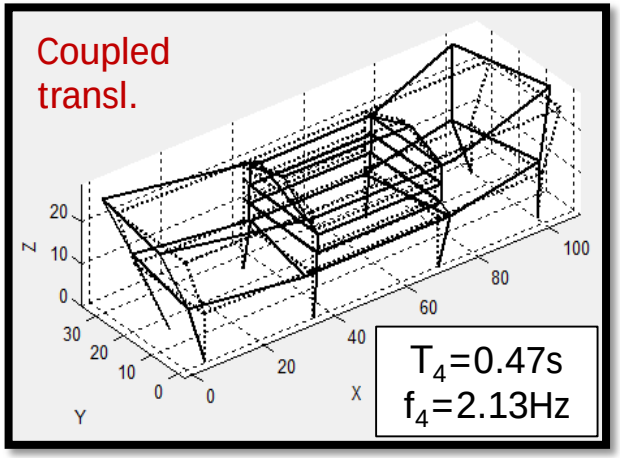
Faculty of Philosophy building – Operational modal analysis

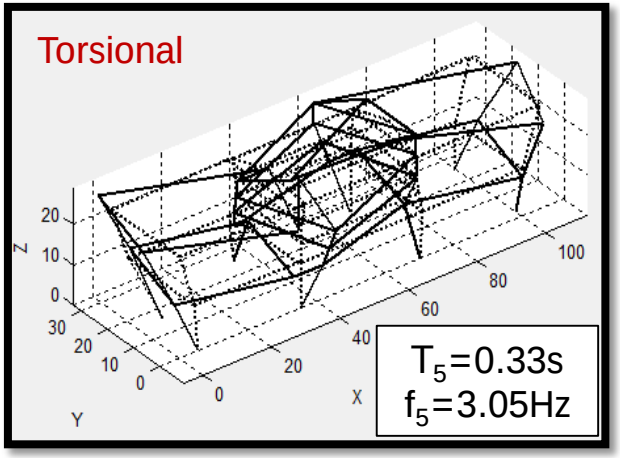
- **Modes (frequencies/periods and shapes)**











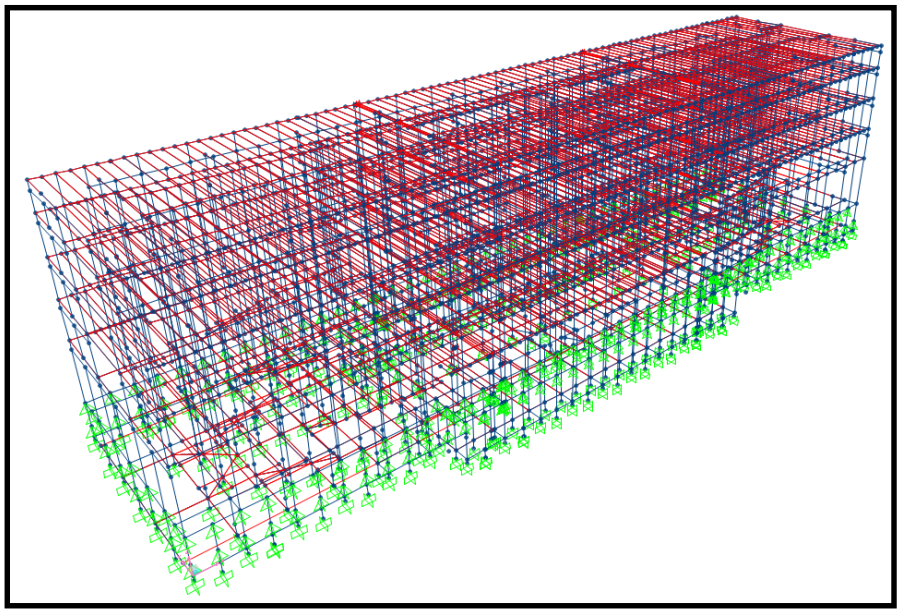
Faculty of Philosophy building – Operational modal analysis

- **Modes (frequencies/periods and shapes**
  - ✓ **Variation of the fundamental frequencies**

Frequencies (Hz)	Recording 13:00-14:00	Recording 18:00-19:00	Recording 23:00-24:00	Recording 6:00-7:00
f_1	1.58	1.58	1.60	1.58
f_2	1.71	1.71	1.74	1.75
f_3	1.78	1.78	1.79	1.78
f_4	2.13	2.28	2.28	2.14
f_5	3.05	3.30	3.33	3.32

Faculty of Philosophy building – Numerical modeling

- **SAP 2000 (Computers and Structures, Inc)**
  - ✓ Beam/Columns: frame elements
  - ✓ Peripheral concrete walls: equivalent beam-column model
  - ✓ Infill model: equivalent beam/column model
  - ✓ Total mass: 9360 tn
  - ✓ Concrete strength: B225 -> C16/20
  - ✓ Steel strength: StIIIb -> f_y=420MPa
  - ✓ Infill strength: $f_{m\theta}$=3MPa
  - ✓ Fixed base conditions
  - ✓ Translational degrees of freedom of the building nodes are fixed at the basement level
  - ✓ Joints between the building parts through link elements



Faculty of Philosophy building – Finite element updating

- **Faculty of Philosophy building – SAP**

✓ Extensive investigation of the link properties **(ongoing)**

✓ Selection of the best model based on the evaluation of **MAC (>0.8)**

✓ Link of gap element type with the following stiffness properties:

Translational DOFs

U_1= 50000kN/m

U_2= 50000kN/m

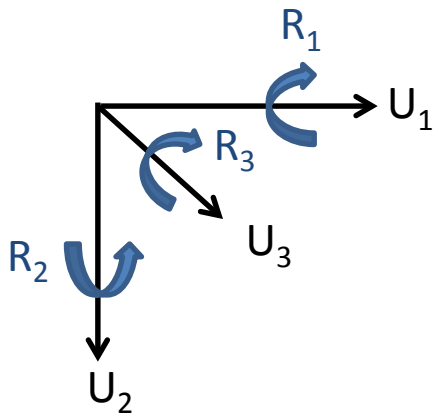
U_3 -> fixed

Rotational DOFs

R_1= 50000kNm/rad

R_2=50000kNm/rad

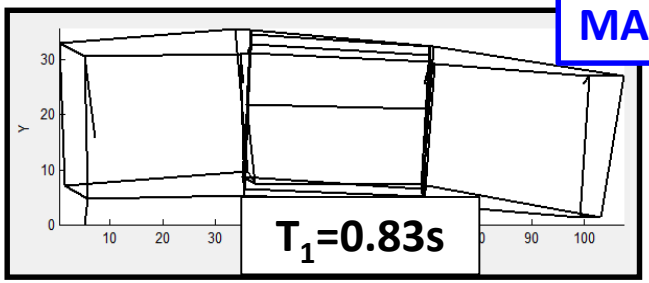
R_3=100000kNm/rad



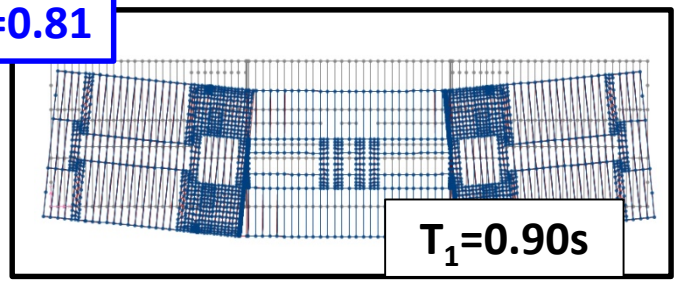
Faculty of Philosophy building – Finite element updating

- **Comparison with measured response**

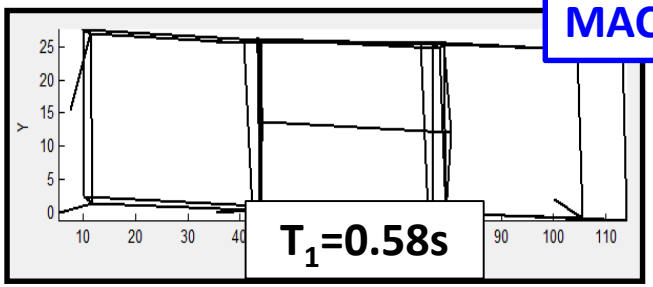
1st mode
Coupled translational along the transverse direction



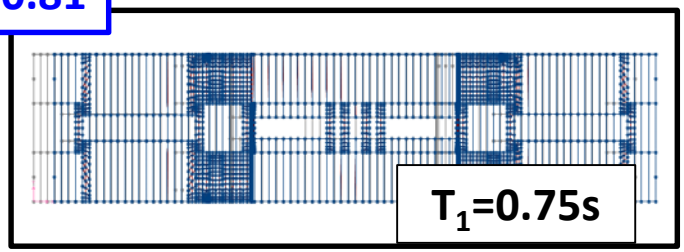
MAC=0.81



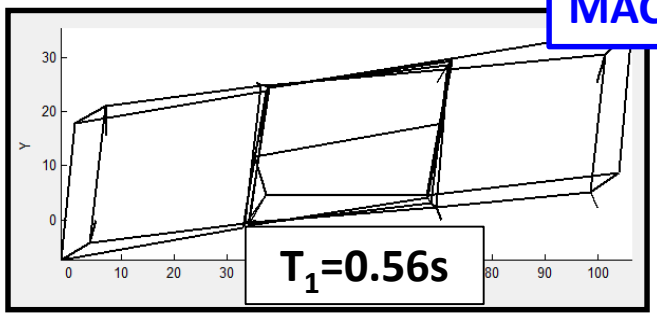
2nd mode
Coupled translational along the longitudinal direction



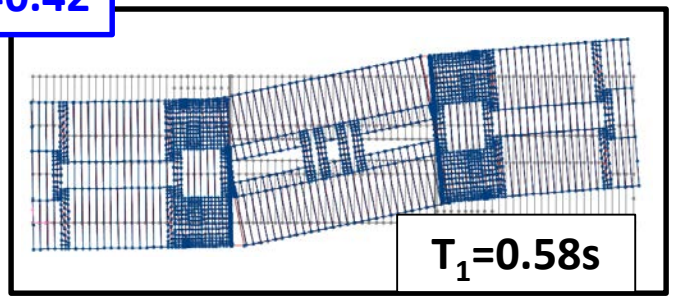
MAC=0.81



3rd mode
Torsional

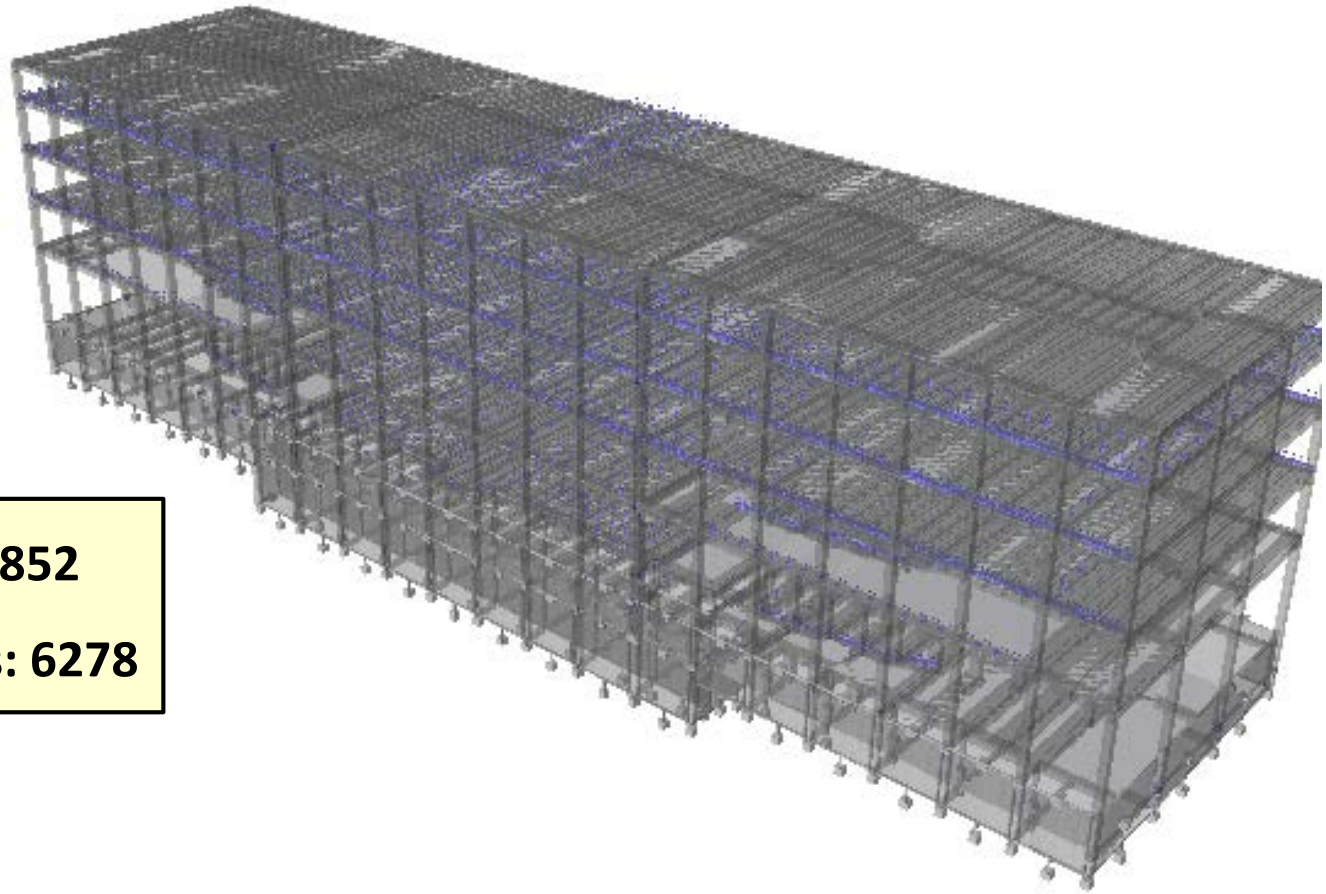


MAC=0.42



Faculty of Philosophy building – Nonlinear modeling

- **SeismoStruct (SeismoSoft, v. 7)**
  - ✓ Distributed plasticity through fibers (similar to the Administration building)
  - ✓ Academic version allows limited amount of data
  - ✓ Could not perform a simple static analysis



Number of nodes: 3852

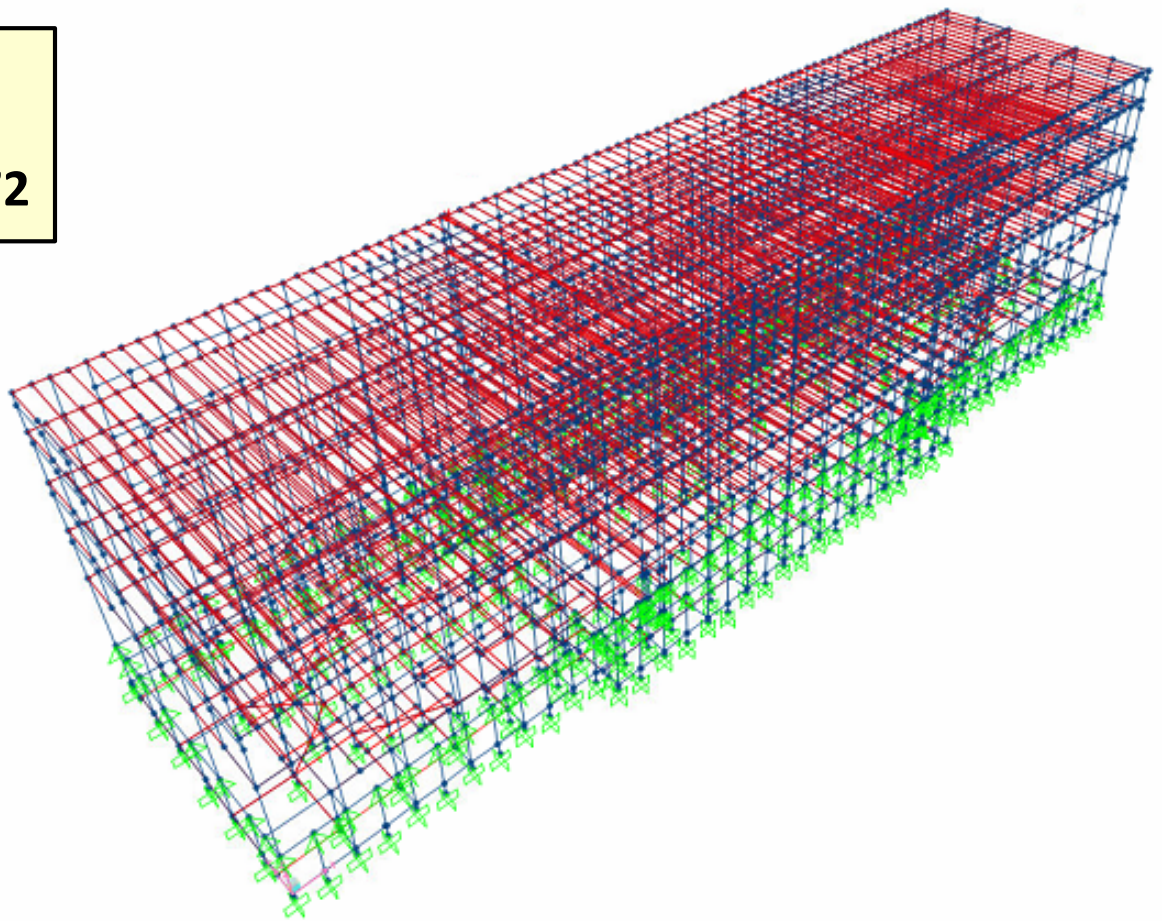
Number of elements: 6278

Faculty of Philosophy building – Nonlinear modeling

- **SAP 2000 (Computers and Structures, Inc)**
  - ✓ Lumped plasticity through hinges (automatically assigned with SAP defaults based on FEMA 356)
  - ✓ Dynamic analysis: does not run in conventional computers
  - ✓ Pushover analysis ongoing: time expensive analysis

Number of nodes: 4340

Number of elements: 7272

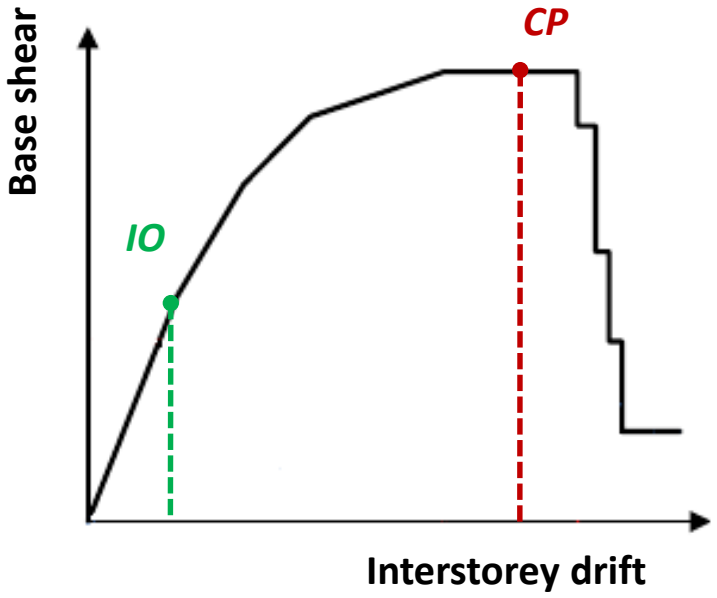


SIBYL Civil

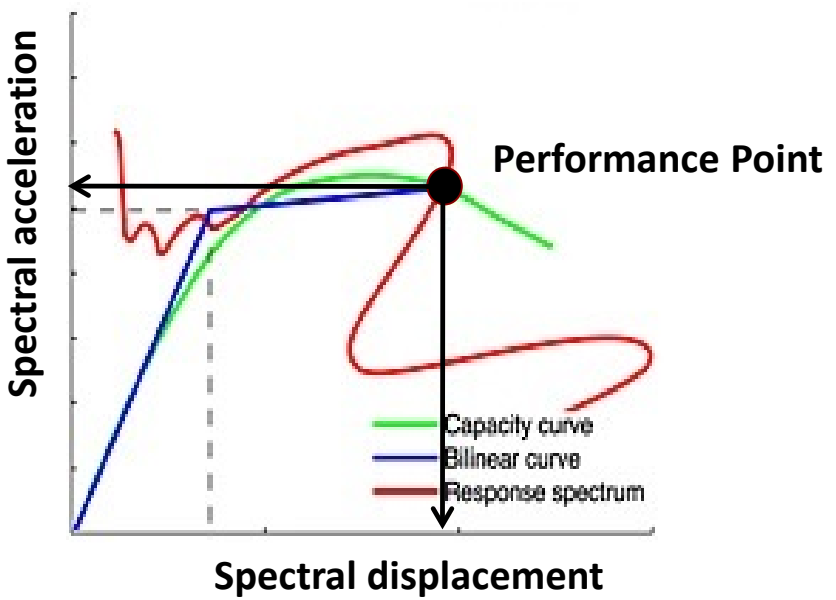
Faculty of Philosophy building – Vulnerability assessment method

- **Derivation of fragility curves based on nonlinear static analysis**

Pushover Curve



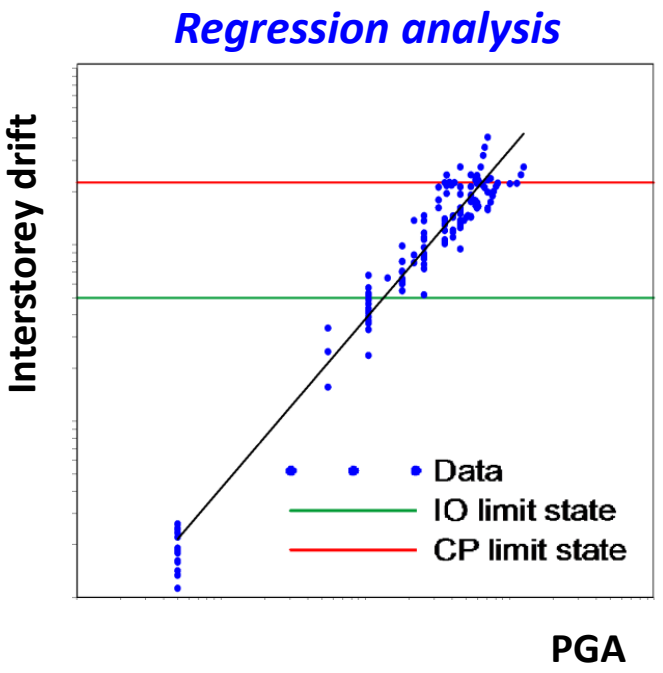
Capacity Curve – Inelastic demand spectrum

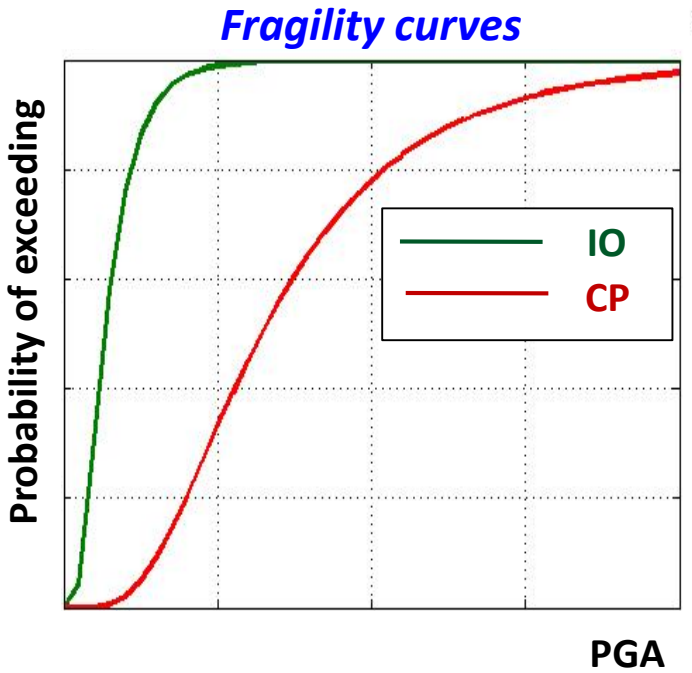


- Inelastic demand spectra will be derived using the *10 selected seismic records* described in the previous slides
- Derivation of a cloud of Performance Points = (number of records) x (number of scaling factors)
- Building-specific damage states (IO and CP) defined on the pushover curve

Faculty of Philosophy building – Vulnerability assessment method

- **Derivation of fragility curves based on nonlinear static analysis**





- Each performance point correspond to a PGA – maxISD pair
- The derived pairs are used for the regression analysis and the derivation of the fragility curves
- Consideration of uncertainties: demand (*from the analysis*); capacity (*HAZUS*); definition of the damage states (*HAZUS*)

Thessaloniki applications: Ongoing work

- **Administration building**
  - ✓ Post - processing of the results and derivation of the final fragility curves (end of June)
  - ✓ Comparison of the building-specific fragility curves with literature generic curves (end of June)

- **Faculty of Philosophy building**
  - ✓ Finalization of the updating procedure (end of June)
  - ✓ Nonlinear analysis of the updated model (end of August)
  - ✓ Derivation of building-specific fragility curves and comparison with literature generic curves (end of September)

GFZ Helmholtz Centre POTSDAM

amra ■ analysis and monitoring of environmental risk

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

TU berlin

Thank you !!!