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Facoltà di Ingegneria

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Approccio Energetico per la Valutazione della Risposta Sismica delle Strutture Mediante la Analisi Statica Non Lineare

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Introduction

Energy-Based Approach

At first, this concept had been proposed by Housner (1956) and Bertero, al. (1988) provided its **mathematical formulation** using by the **Energy-Balance Equation**

- Input Energy (E_I)
  - Absorbed Energy (E_a)
    - Spring En. (E_s)
    - Kinetic En. (E_k)
  - Dissipated Energy (E_d)
    - Damping En. (E_ξ)
    - Hysteretic En. (E_h)

Obtained through the integration of the **equation of motion**

$$m \cdot \ddot{x}_A + c \cdot \dot{x}_R + f_s(x_R) = 0$$

The integration can be done in two ways:

Energy-Balance Equation (**absolute terms**):

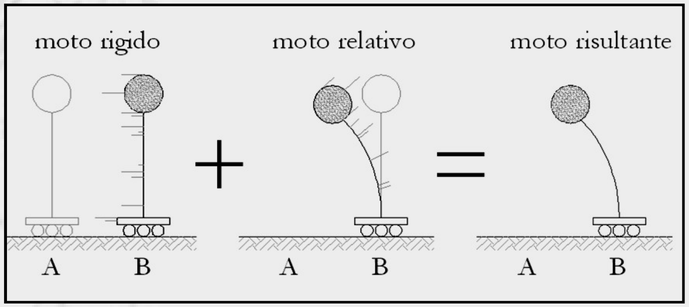
$$\int m \cdot d\dot{x}_a \cdot \frac{dx_a}{dt} + \int c \cdot \dot{x}_r \cdot dx_r + \int f_s \cdot dx_r = \int m \cdot \ddot{x}_a \cdot dx_t$$

$$\Rightarrow \quad E_I = E_s + E_k + E_\xi + E_h$$

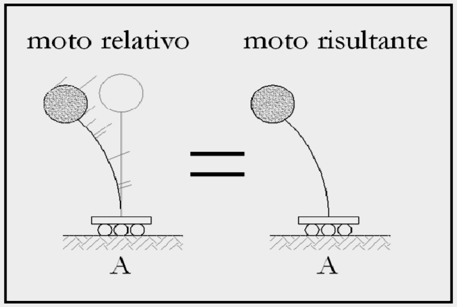
Energy-Balance Equation (**relative terms**):

$$\int m \cdot \ddot{x}_r \cdot dx_r + \int c \cdot \dot{x}_r \cdot dx_r + \int f_s \cdot dx_r = -\int m \cdot \ddot{x}_t \cdot dx_r$$

$$\Rightarrow \quad \hat{E}_I = E_s + \hat{E}_k + E_\xi + E_h$$



(absolute)



(relative)

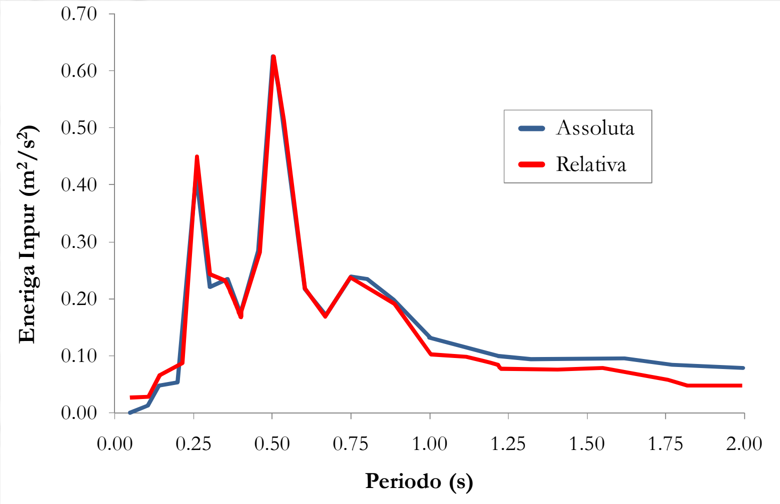
The difference between an absolute and relative approach is

$$E_I = E_s + E_k + E_\xi + E_h \qquad \text{(Absolute)}$$

$$\hat{E}_I = E_s + \hat{E}_k + E_\xi + E_h \qquad \text{(Relative)}$$

$$E_I - \hat{E}_I = E_k + \hat{E}_k$$

The difference is represented by the **kinetic energy** due to the **motion of ground**



This difference increases for low and high values of period

For mid-values of period this difference is negligible

Since **Non Linear Static Analysis** (**NLSA**) has been adopted, both energy-balance equations converge to the same form:

$$E_I = E_s + \cancel{E_k} + \cancel{E_\xi} + E_h \quad \Rightarrow \quad E_I = E_s + E_h \quad \text{(Absolute)}$$

$$\hat{E}_I = E_s + \cancel{\hat{E}_k} + \cancel{E_\xi} + E_h \quad \Rightarrow \quad \hat{E}_I = E_s + E_h \quad \text{(Relative)}$$

$$E_I - \hat{E}_I = 0$$

because Kinetic (E_k) and Damping (E_ξ) Energies depend on velocity (dx/dt) that is null in a static analysis

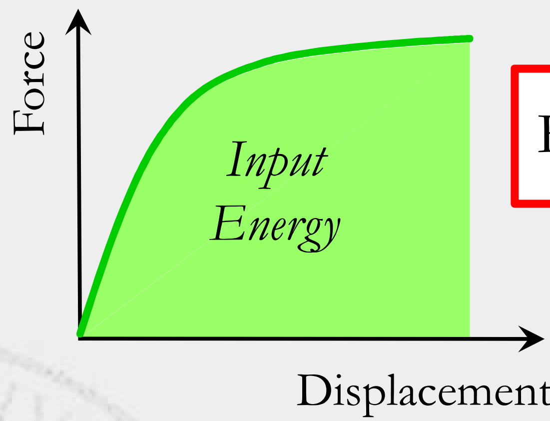
Eventually, **Absolute/Relative Input Energy** is equal to absorbed energy composed by both spring (**elastic**) and hysteretic (**inelastic**) contributions

$$\boxed{E_I = \hat{E}_I = E_a = E_s + E_h = \int f_s \cdot dx_r}$$

Introduction

Pseudo-Energy parameter

In NLSA, the **Input Energy** is represented by the area enclosed by the pushover curve (force-displacement plane)



$$E_I = \int f_s \cdot dx_r$$

The **energy-based concept** can be proficiently utilized in Non Linear Static Analysis

Input Energy (E_I)

- Absorbed Energy (E_a)
  - Spring En. (E_s)
  - Kinetic En. (E_k)
- Dissipated Energy (E_d)
  - Damping En. (E_ξ)
  - Hysteretic En. (E_h)

Introduction
Pushover Analysis
Structural Response
Seismic Demand
Non Linear Procedures
SDOF Systems
2D-MDOF Systems
3D-MDOF Systems
Conclusions

Non Linear Static Analysis (Pushover)

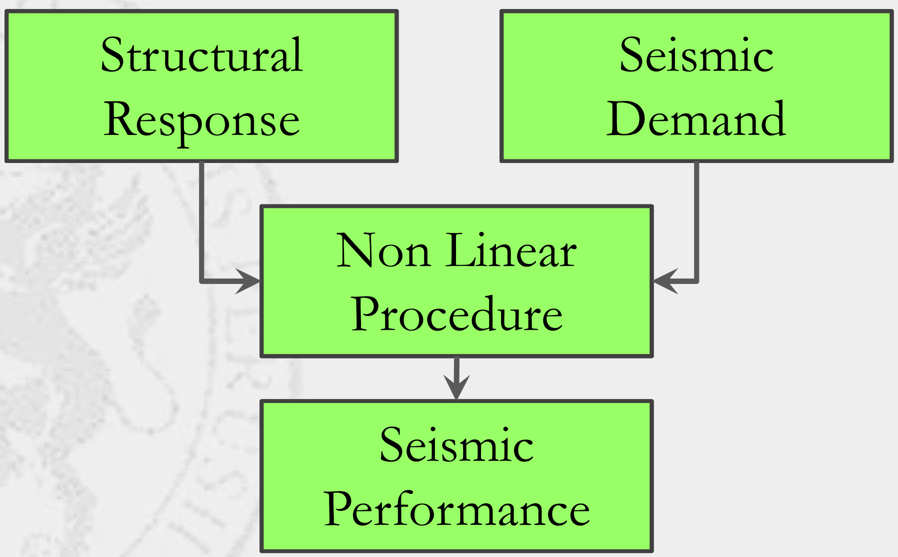
Pushover Analysis Method

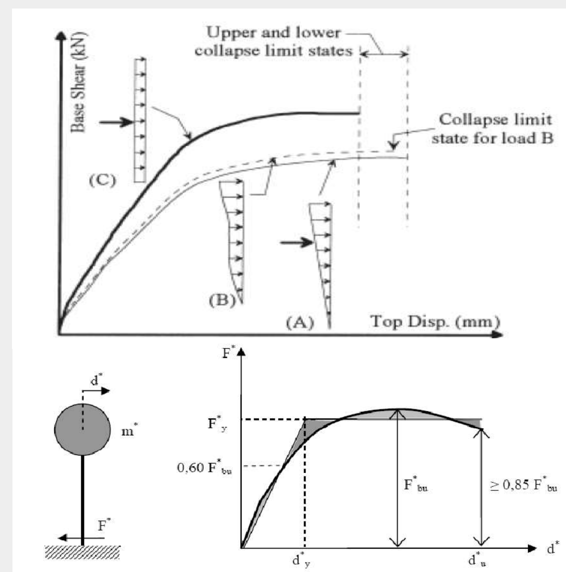
Non Linear Static Analysis procedure

Non Linear Static Analysis (NLSA) or Pushover is an useful tool to **investigate non linear response of structural systems**

Several methodologies are provided by literature and seismic codes:

- **N2 Method (Eurocode 8, OPCM 3274, NTC 08)**
- CMDM (FEMA 356)
- CSM (ATC-40)
- CMDM, CSM (FEMA 440)





Pushover Analysis Method
Non Linear Static Analysis procedure

Pushover procedure is characterized by **critical steps** when it is utilized to evaluate seismic response of structures

Typically, issues related to this type of analysis are:

- Problematic since dynamics behaviors are represented by means of static equivalent response
- Definition of a unique point of system in order to represent entire structure response
- Equipollence between real MDOF system and equivalent SDOF one
- Comparison between seismic demand and structural capacity
- Lateral force distribution used to represent seismic effects on structural masses
- Fraction of total mass which participates to seismic response

The procedures here proposed tent to overcome the difficulties and uncertainness mentioned above

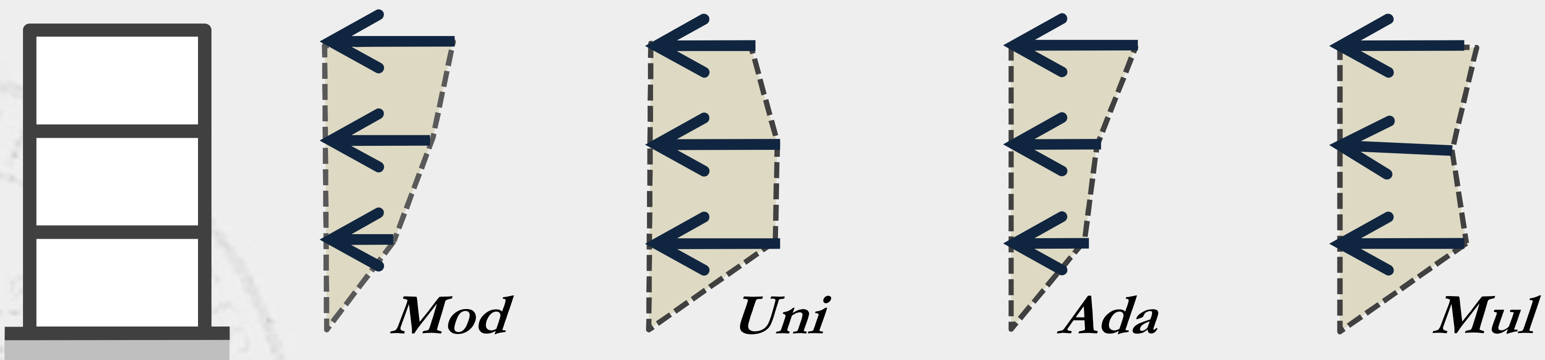
Structural Response of System

Structural Response
Lateral Force Distribution

Since a reliable numeric model of system has been defined, a **Lateral Force Distribution** (**LFD**) must be applied to the structure to represent the effect of seismic excitation

In this study, four (**4**) different configurations are considered:

$$\text{LFD} \propto [M]\cdot\{\varphi\}_1 \qquad [M]\cdot\{1\} \qquad [M]\cdot\{\varphi\}_{1,k} \qquad [M]\cdot\{\varphi\}_{eq}$$



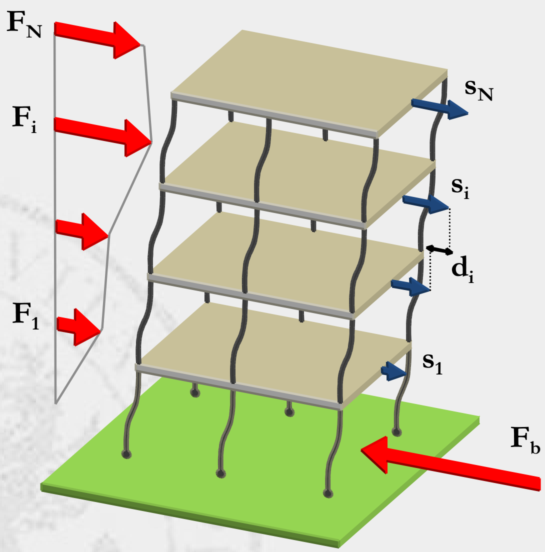
$$\text{LFD} \propto \begin{Bmatrix} m_1 \cdot \varphi_{1,1} \\ m_2 \cdot \varphi_{1,2} \\ \dots \\ m_N \cdot \varphi_{1,N} \end{Bmatrix} \qquad \begin{Bmatrix} m_1 \\ m_2 \\ \dots \\ m_N \end{Bmatrix} \qquad \begin{Bmatrix} m_1 \cdot \varphi_{1,1} \\ m_2 \cdot \varphi_{1,2} \\ \dots \\ m_N \cdot \varphi_{1,N} \end{Bmatrix}_k \qquad \begin{Bmatrix} m_1 \cdot \varphi_{eq,1} \\ m_2 \cdot \varphi_{eq,2} \\ \dots \\ m_N \cdot \varphi_{eq,N} \end{Bmatrix}$$

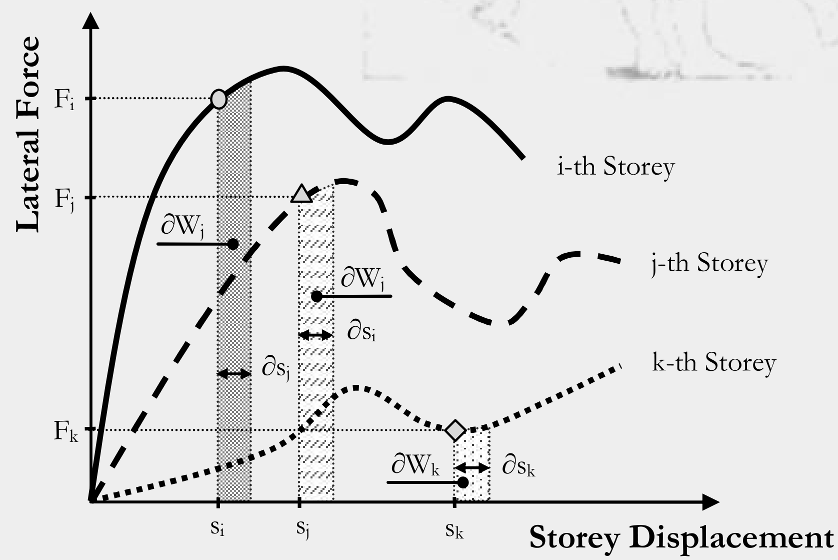
Structural Response

Energy-Based Structural Response

Knowledge of displacements, storey drifts, applied lateral forces and base shear is available since NL analysis has been performed

An **energy-representation of structural response** can be provided by means of processing information mentioned above



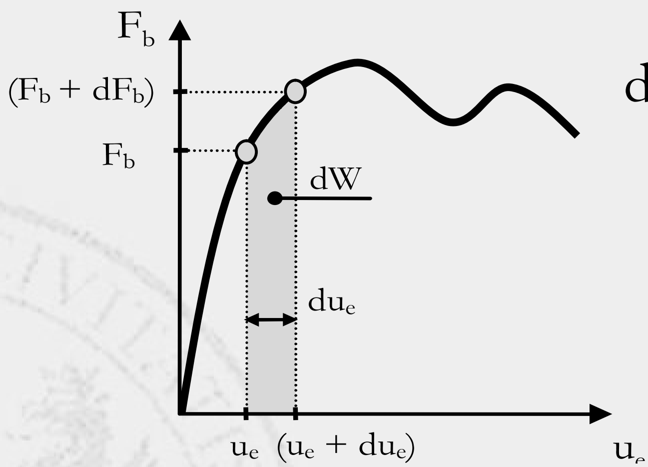


$$W = W(t) = \int_0^t dW = \int_0^t \sum_{i=1}^{N} F_i \cdot \partial s_i \cong \sum_{i=1}^{N} \sum_{k=1}^{p} \left(\frac{F_i^{(k)} + F_i^{(k+1)}}{2} \right) \cdot \left(s_i^{(k+1)} - s_i^{(k)} \right)$$

Same-Energy Displacement

Through the use of last formula, the **work done** by lateral forces applied to the system (or **energy absorbed**) is known at each step

An incremental parameter can be introduced, defined by the ratio of incremental work done and base shear at kth step



$$dW = F_b \cdot du_e \Rightarrow du_e = \frac{dW}{F_b}$$ *Continuous System*

$$\Delta u_e^{(k)} = \frac{\Delta W^{(k)}}{F_b^{(k)}}$$ *Discrete System*

The sum of each $\Delta u_e^{(k)}$ allows to know, at pth step, the value of

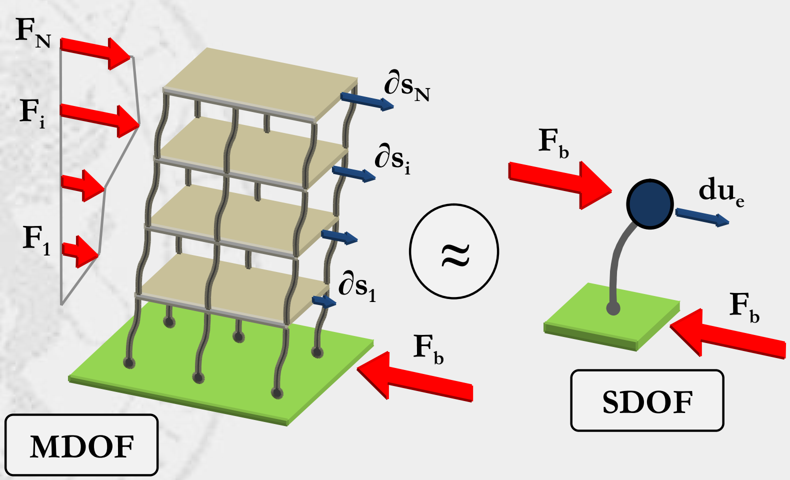
$$\boxed{u_e^{(p)} = u_e(p) = \sum_{k=1}^{p} \Delta u_e^{(k)} = \sum_{k=1}^{p} \frac{\Delta W^{(k)}}{F_b^{(k)}}}$$

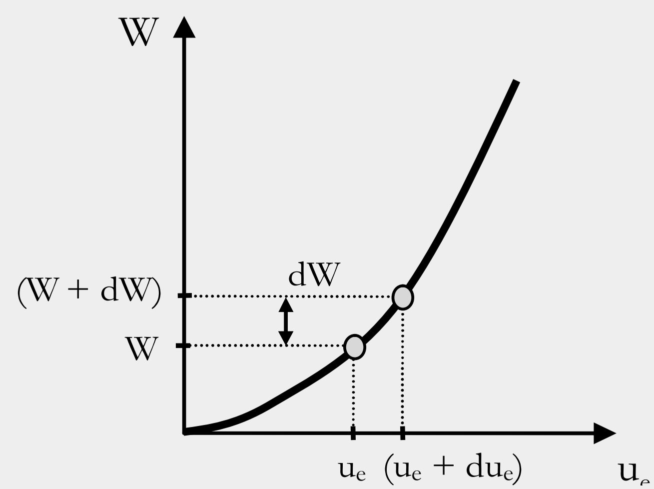
Same-Energy Displacement (equivalent SDOF)

Structural Response
Energy-Based Structural Response

The introduction of this parameter allows to achieve **several benefits** for what concerns Non Linear Static Analysis:

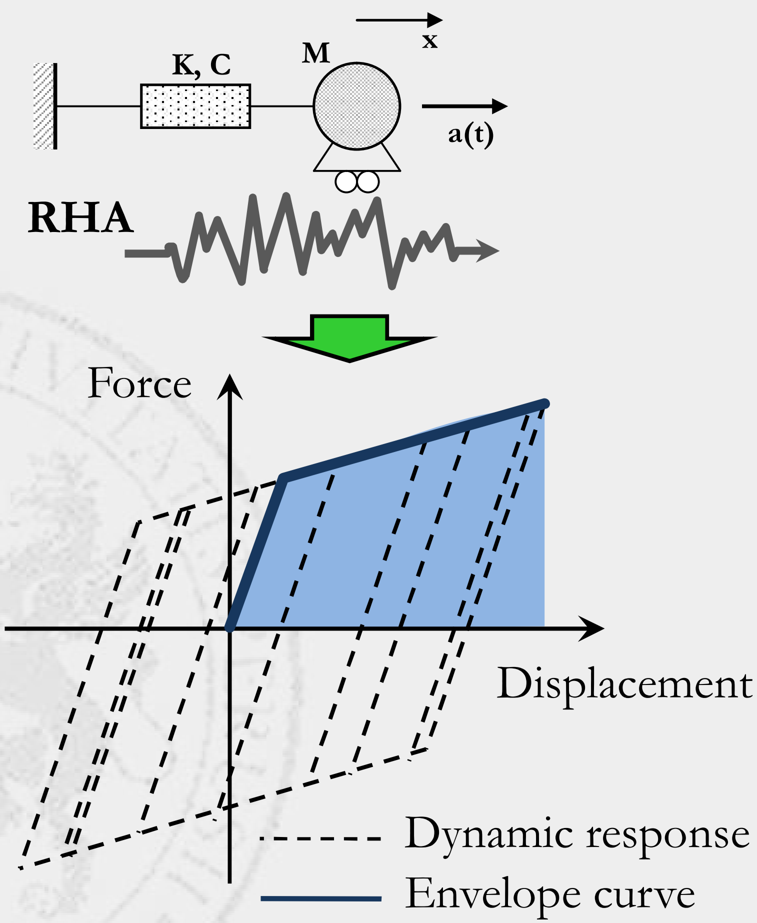
- **Arbitrary choice of control point** (rooftop CM) is avoided
- **Univocal displacement** for entire system is defined
- Parameter provides a direct **relationship** between **seismic excitation** (represented by lateral forces) and **structural response** (represented by storey displacements)
- An immediate **equivalence in terms of energy** is obtained between MDOF and SDOF systems

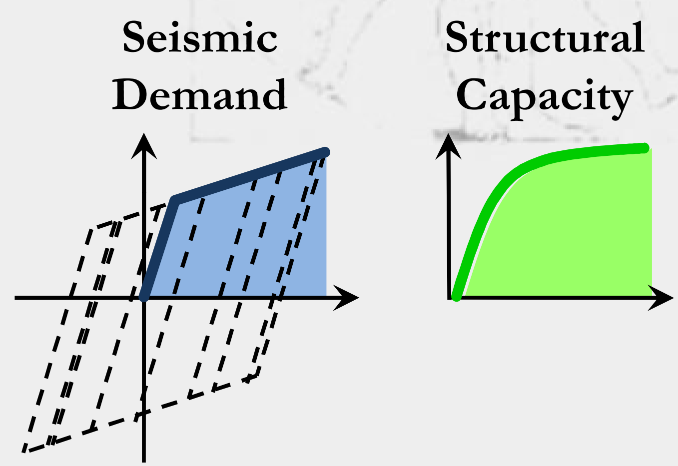




Energy-Based Seismic Demand

In order to represent an **energy-based seismic input** consistent with the response evaluated using by Non Linear Static Analysis, a parameter here called **Pseudo-Energy** has been introduced





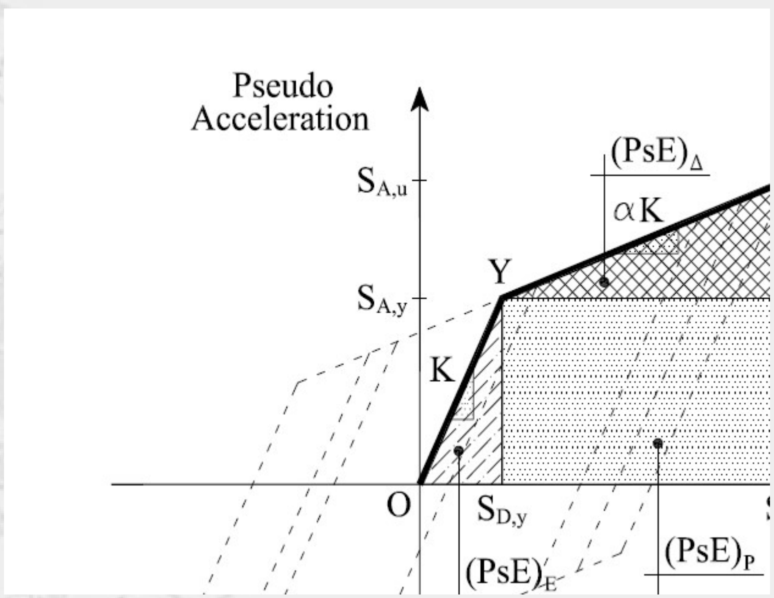
Providing **Demand** and **Capacity** in this energy format, **RHA and NLSA responses are congruent**

Seismic Demand

Pseudo-Energy Parameter

Starting from spectral displacement (S_D) and pseudo-acceleration (S_A), when period (T), ductility (μ) and hardening factor (α) are known, **Pseudo-Energy** (**PsE**) can be computed as

$$\boxed{PsE(T,\mu,\alpha) = S_A(T,\mu,\alpha) \cdot S_D(T,\mu,\alpha) \cdot \left[\frac{\alpha-1}{2\mu^2} + \frac{1-\alpha}{\mu} + \frac{\alpha}{2}\right]}$$



This relationship is valid, in general, for **ESH systems**

- Elastic behavior $\mu = 1.0$
- For EPP systems $\alpha = 0.0$

Seismic Demand

Pseudo-Energy Spectra

Using the definition of Pseudo-energy (PsE), the **seismic spectra** can be defined to represent seismic input in a NLS procedures

In this study, three (3) different approaches have been considered with this aim:

- **Direct method**: a large number of accelerograms is considered in order to calculate demand spectra
- **Indirect method**: starting from elastic spectra provided by codes, inelastic spectra are computed utilizing modification factors proposed in literature
- **Semi-direct method**: a restricted numbers of accelerograms is take into account to calculate inelastic demand spectra

Introduction
Pushover Analysis
Structural Response
Seismic Demand
Non Linear Procedures
SDOF Systems
2D-MDOF Systems
3D-MDOF Systems
Conclusions

Direct Method:

A number as large as possible of accelerograms should be taken into account to create a database where time histories can be selected

Each recorded or simulated (not generated) accelerogram should be characterized by most important seismic parameters

$$\text{Accel.} = \text{Accel.}\left\{ \text{Soil; Epicentral Distance; Magnitude; } \ldots \right\}$$

Since the range of each parameter has been defined, a group of accelerograms can be selected and relative spectra can be computed

Paper:

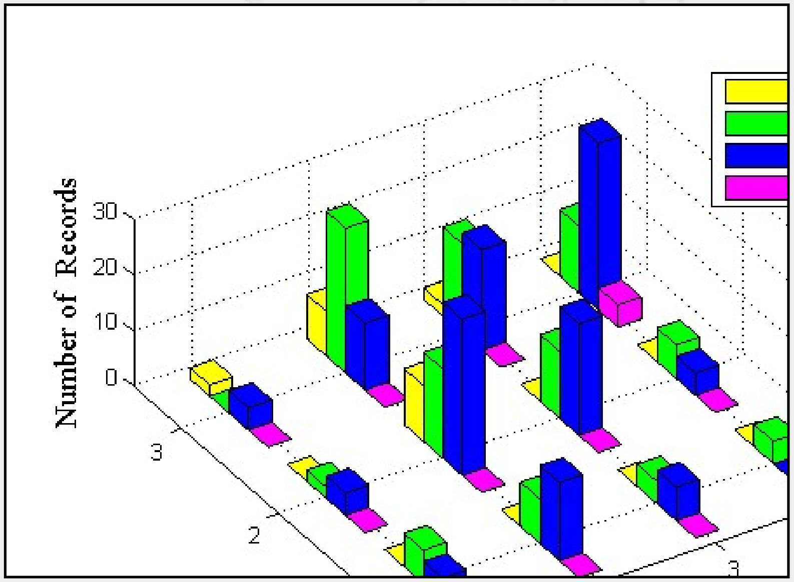
Tomassoli, Mezzi - "***Energy-Based Criterion for the Evaluation of Seismic Input Spectra for Non Linear Static Analyses***"
14th ECEE, 2010

An application of this method is also reported in Appendix B

A set of 149 accelerograms correspondents to 32 events occurred in Mediterranean area has been selected from the NGA-PEER database

Accelerograms categorized by:

- Soil Type (V_{S30})
- Epicentral Distance (D)
- Magnitude (M)



Spectral **SDOF models** utilized:

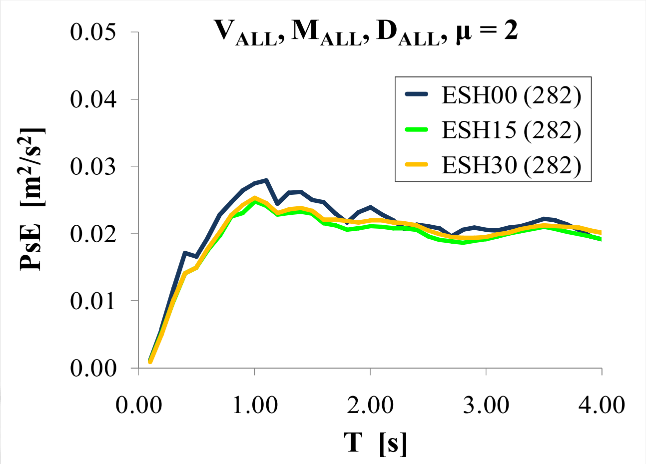
- ESH (α = 0%, 15%, 30%)
- Ductility values (μ= 1, 2, 4, 6)

Seismic Demand

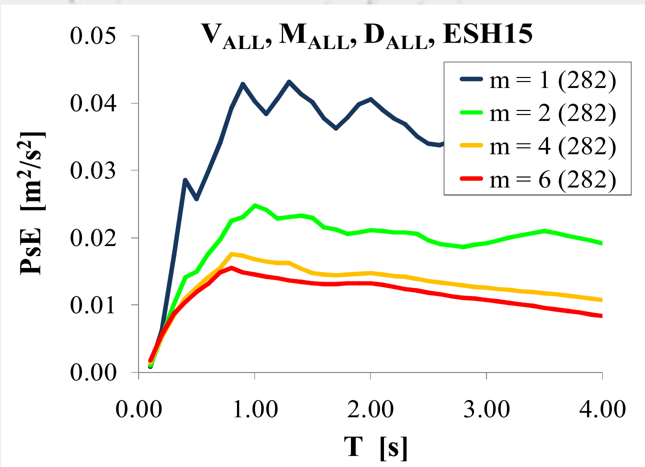
Energy Spectra - Direct Method

The **influence** of these parameters **on seismic demand spectra**, proposed in terms of **pseudo-energy**, has been investigated

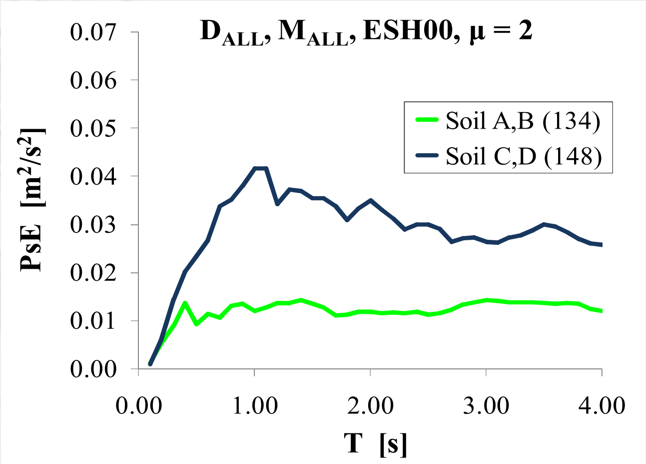
Hysteretic Model



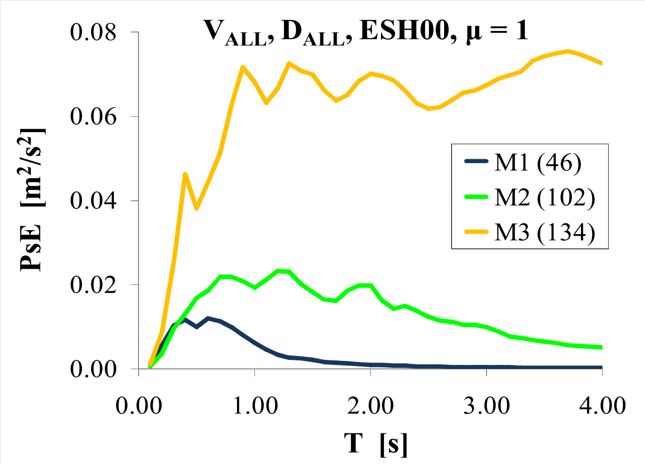
Ductility Value



Type of Soil



Magnitude



Indirect Method:

Starting from **elastic seismic demand spectra** in terms of displacement and pseudo-acceleration, and using by appropriated **modification factors** present in literature, **inelastic ps-energy spectra** can be determined

This approach is very useful for **practical purposes** when elastic spectra provided by codes are chosen

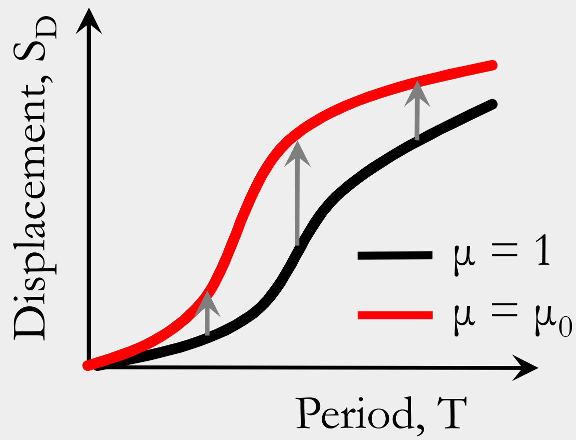
Anyway, reliable **modification factors** are needed to move from elastic to inelastic representation of spectra

An exhaustive explanation of this procedure is reported in Appendix A of the dissertation

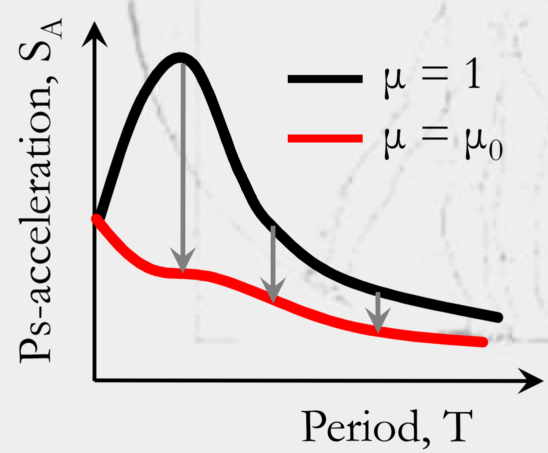
Seismic Demand

Energy Spectra - Indirect Method

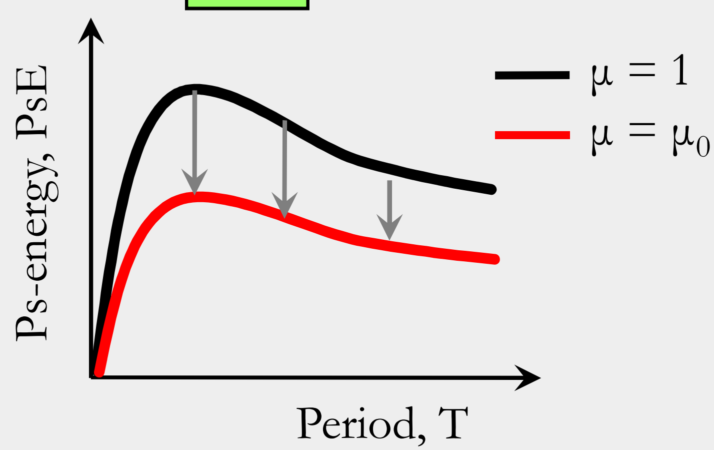
Steps to do in order to provide inelastic pseudo-energy spectrum are



Displacement Modifications Factors (R_δ)
(Miranda)



Strength Reduction Factors (R)
(Newmark – Hall)



Seismic Demand

Energy Spectra - Indirect Method

Introduction

Pushover Analysis

Structural Response

Seismic Demand

Non Linear Procedures

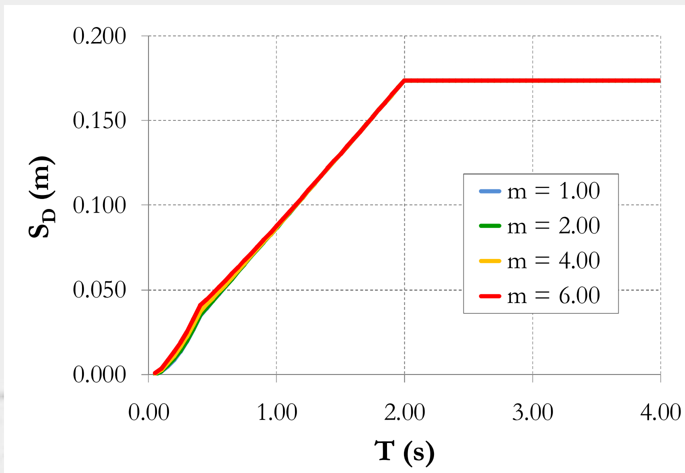
SDOF Systems

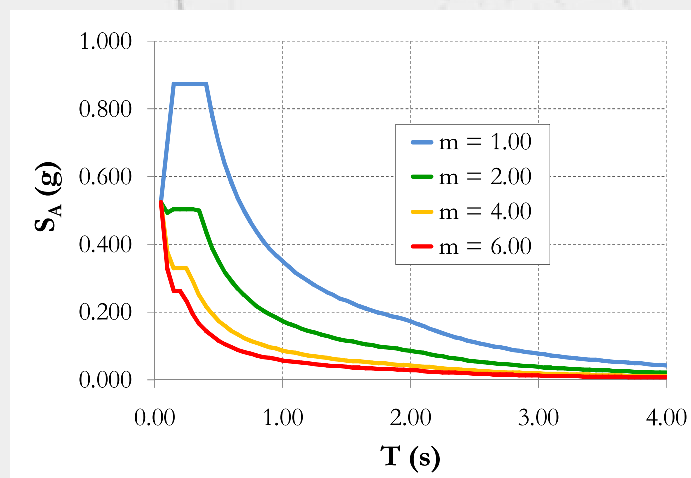
2D-MDOF Systems

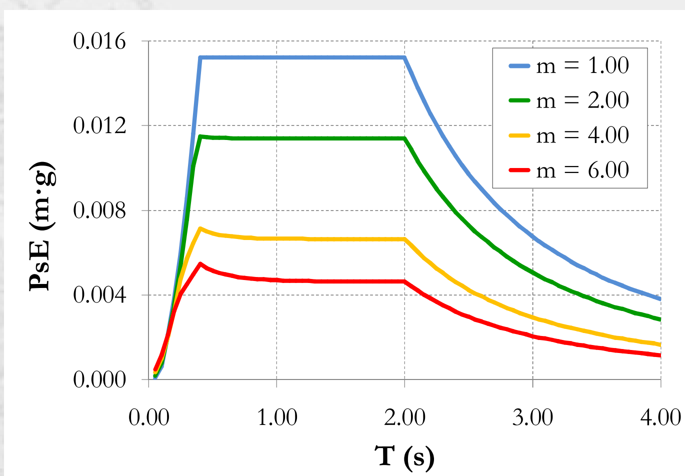
3D-MDOF Systems

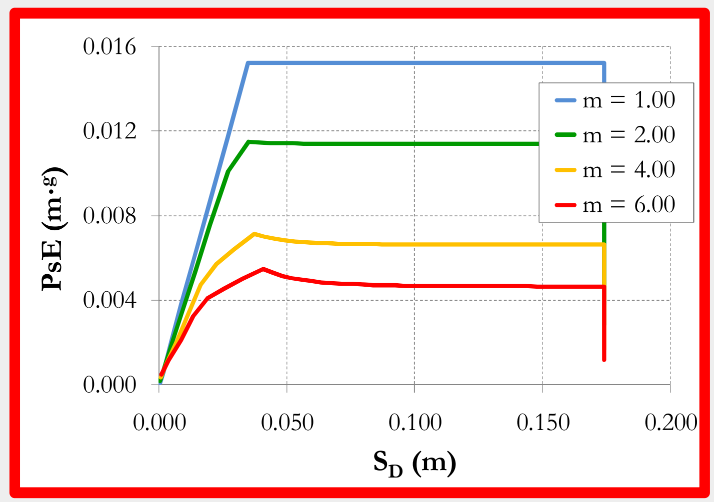
Conclusions

Examples of spectra, according to **Eurocode 8**, for a soil B and valued of ductility of μ = 1, 2, 4, 6, are reported below









Semi-direct Method:

This method takes into consideration both approaches (direct and indirect) previously proposed

This approach is also very useful for **practical purposes** since elastic/inelastic reference spectrum, provided by codes, is considered

The procedure is based, in general, on the following steps:

1. Define a reference spectrum in terms of a specific parameter ($S_{D,e}$, $S_{D,\mu}$, $S_{A,e}$, $S_{A,\mu}$, PsE_e, PsE_e)
2. Select a group of accelerograms characterized by scattering between mean spectrum and reference one as lower as possible
3. Calculate, for each accelerogram, its spectra in terms of displacement and pseudo-acceleration (elastic/inelastic)
4. Calculate, for each accelerogram, its pseudo-energy spectra
5. Compute the mean spectra in terms of pseudo-energy

The **selection of recorded accelerograms** characterized by a mean spectrum which matches the reference one represents the critical passage when a **reliable seismic input** for NLSA is required

Paper:

Tomassoli, Mezzi - "***Energy-based Criterion for the Selection of the Seismic Input for Inelastic Dynamic Analyses***"

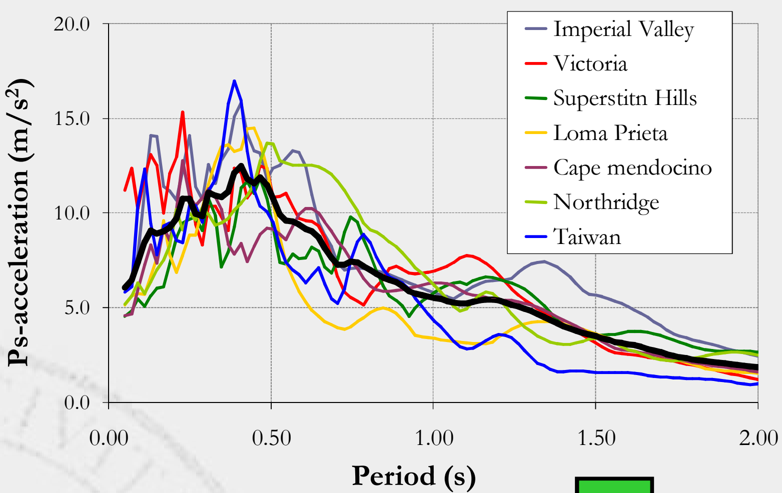
9th US Nat. and 10th Canadian Conf. on Earthquake Eng., 2010

An alternative solution is represented by adopting **generated/simulated accelerograms**, still characterized by a mean spectrum in accordance with the reference one

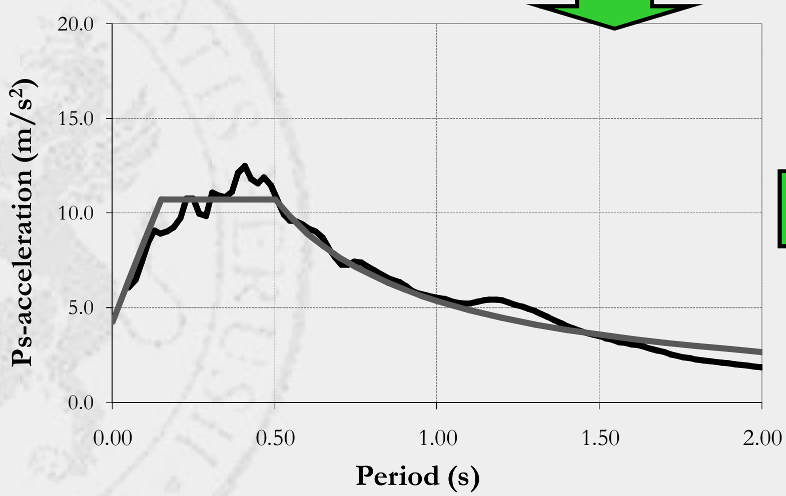
Seismic Demand

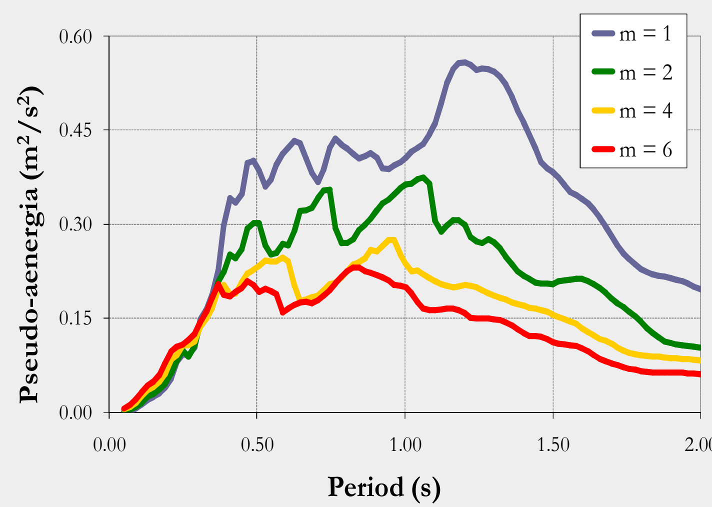
Energy Spectra - Semi-direct Method

It has been assumed a group of accelerograms where **selection procedure was based on an elastic ps-acceleration criterion**



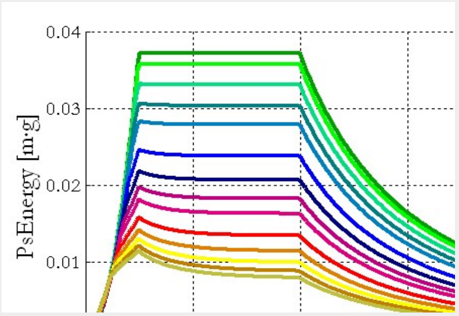
A set of **7 recorded accelerograms**, selected from NGA PEER database, has been considered to calculate **input pseudo-energy**



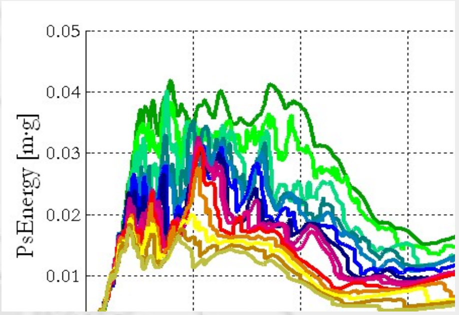


Seismic Demand
Energy Spectra

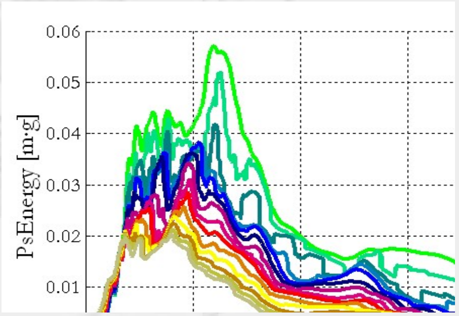
The following **scenarios** are considered in order to define seismic input spectra to be used in NLSA



Code Spectra (CodSpe):
Indirect approach has been used, adopting Newmark-Hall and Miranda modification factors [***GenAcc, RecAcc***]



Generated Spectra (GenSpe):
Semi-direct approach has been used, adopting elastic ps-acceleration criterion to generate accelerograms [***GenAcc***]

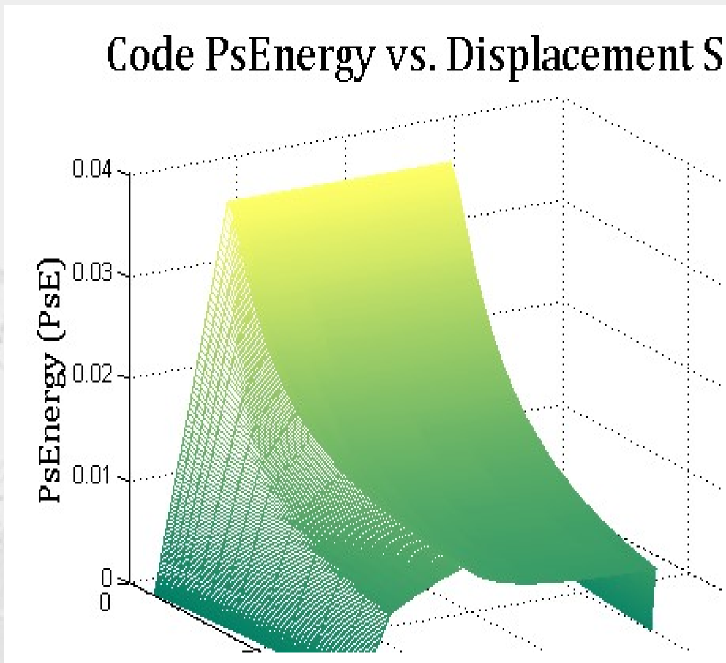


Recorded Spectra (RecSpe):
Semi-direct approach has been used, adopting elastic ps-acceleration criterion to select accelerograms [***RecAcc***]

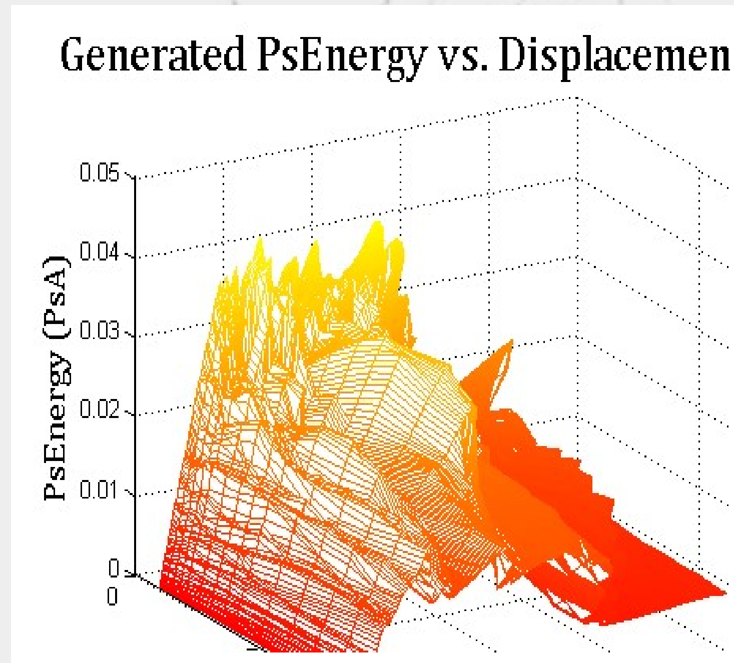
Seismic Demand

Energy Spectra

An useful representation of seismic demand is to report ps-energy parameter in (3D) form of **Energy–Displacement–Ductility Response Spectrum** (**EDμRS**)



Code Spectra



Generated Spectra

Non Linear Static Procedures to Determine Seismic Performance

Non Linear Procedure

Non Linear Static Procedure and Performance Point

Since both **system capacity** and **seismic demand** are defined, a procedure to compare them is required in order to evaluate the **performance** of structure

As a benchmark, **N2-Method** proposed by Eurocode (**EC8-N2**) is adopted

The **Energy-Based NLSA** estimates the performance point providing two different approaches or **procedures**

Procedure Energy-A:

Through the use of its bi-linearization, the energy capacity curve intersects spectral surface in the performance point

Procedure Energy-B:

The performance point is reached by means of a preliminary elastic pushover

In Energy-Based Procedures, in order to make capacity curve consistent with spectral surface, a value of **Effective Seismic Mass** must be chosen

The following values of effective mass have been considered:

- Equivalent first mode mass* (Ec8): $m^* = [M] \cdot \{\varphi\}_1$

- First mode mass (modal analysis): $$m_I = \frac{\left(\{\varphi\}_1^{\,T} \cdot [M] \cdot \{\varphi\}_1\right)^2}{\left(\{\varphi\}_1^{\,T} \cdot [M] \cdot \{\varphi\}_1\right)}$$

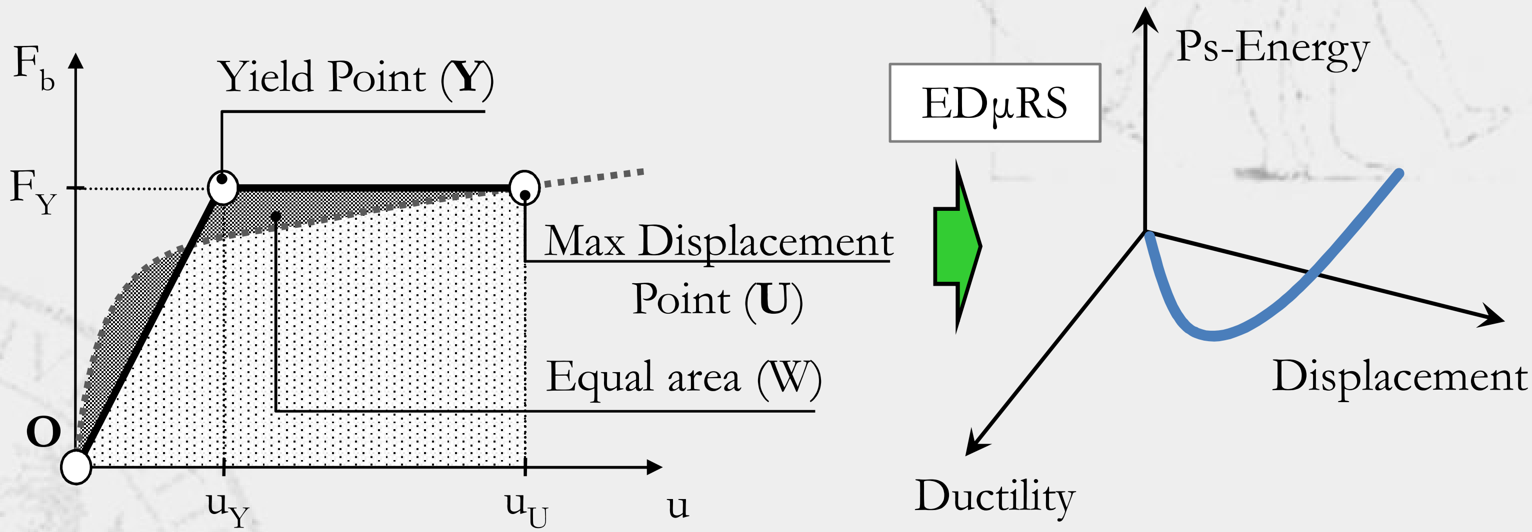
- Total mass: $$m_{tot} = \sum_{i=1}^{N} \frac{\left(\{\varphi\}_i^{\,T} \cdot [M] \cdot \{\varphi\}_i\right)^2}{\left(\{\varphi\}_i^{\,T} \cdot [M] \cdot \{\varphi\}_i\right)}$$

Non Linear Procedure

Non Linear Static Procedure and Performance Point

Procedure Energy-A:

This procedure is base on bi-linearization of capacity curve with the aim of knowing **μ-value** at each step of pushover



At each step of NLSA, values of **same-energy displacement** (**u**), **pseudo-energy** (**w**), and **ductility** (**μ**) are known

Energy Capacity Curve can be plotted in **EDμRS** (3D) and its intersection with spectral surface represents the performance point

Procedure Energy-A:

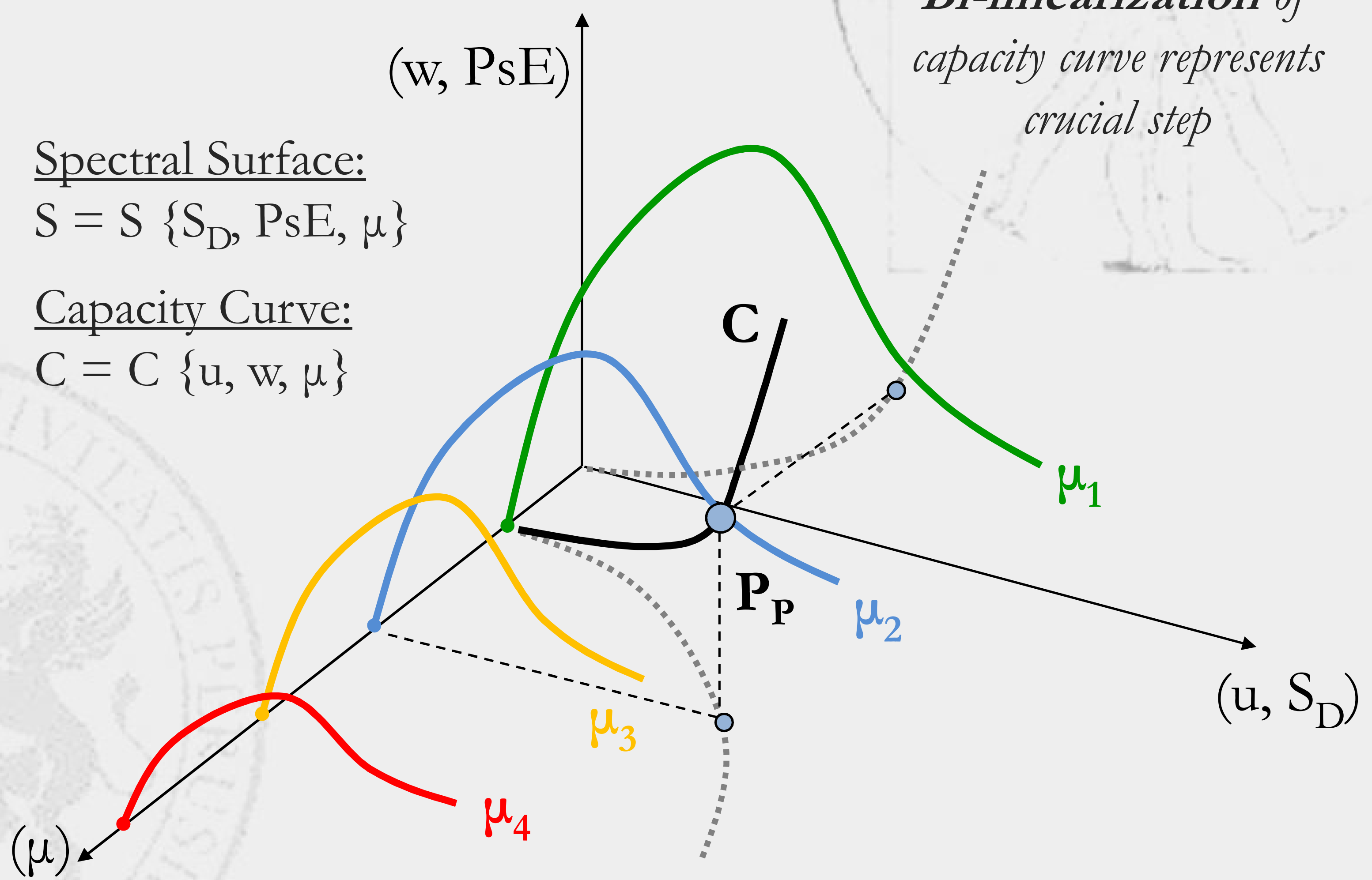
Spectral Surface:

$S = S\ \{S_D, PsE, \mu\}$

Capacity Curve:

$C = C\ \{u, w, \mu\}$

***Bi-linearization** of capacity curve represents crucial step*



Procedure Energy-B:

This procedure is base on a preliminary elastic pushover analysis (≈ linear static analysis) with the aim of knowing **T-value** when ductility $\boldsymbol{\mu = 1.0}$ (elastic case)

Since elastic performance has been evaluated, the period $\mathbf{T = T_e}$ is defined

Moving from the elastic performance point, the intersection of **constant-period curve** and energy capacity curve represents the inelastic performance point

Introduction

Pushover Analysis

Structural Response

Seismic Demand

Non Linear Procedures

SDOF Systems

2D-MDOF Systems

3D-MDOF Systems

Conclusions

<u>Procedure Energy-B:</u>

Preliminary linear analysis *is required to evaluate elastic performance*

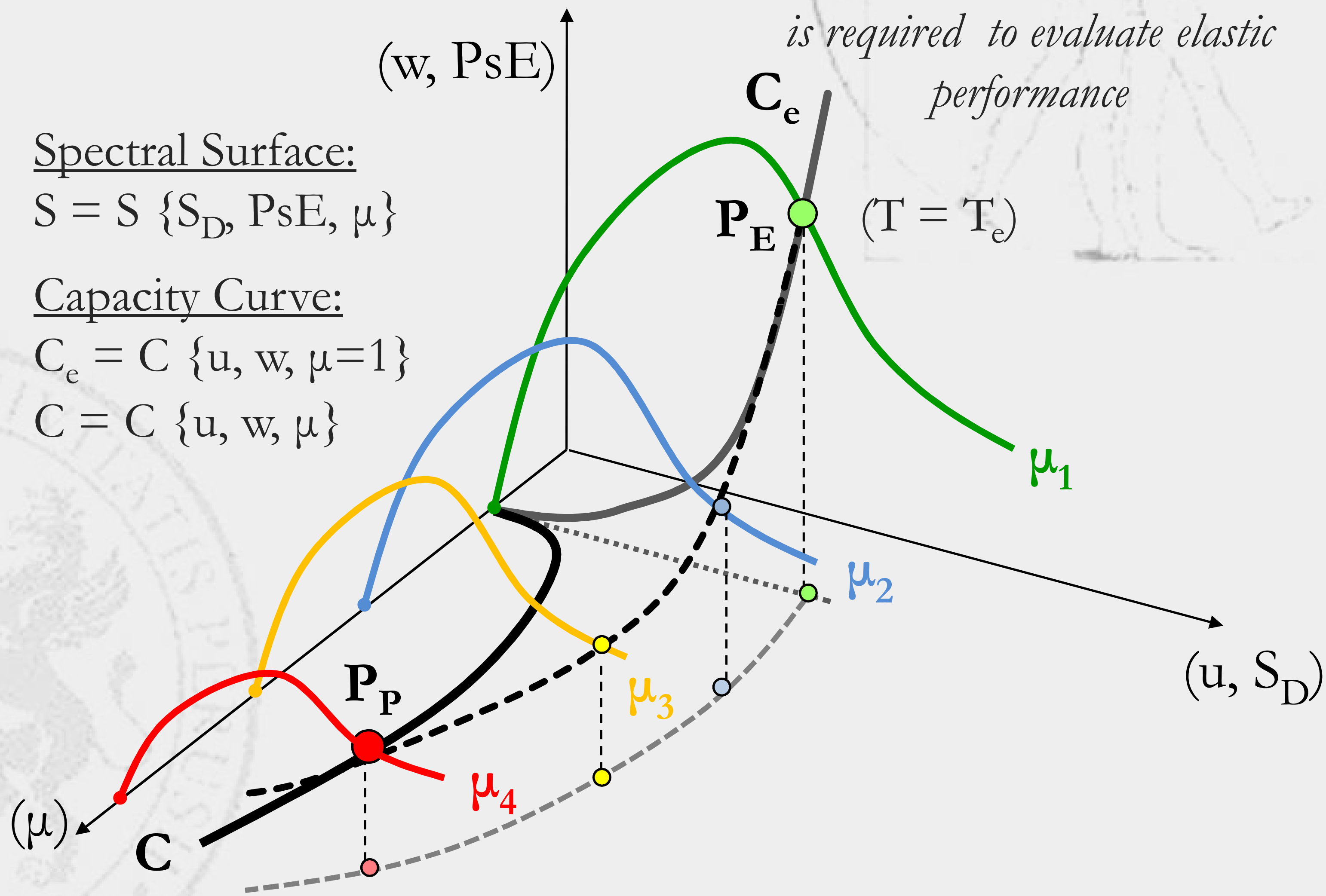
<u>Spectral Surface:</u>

$S = S\ \{S_D, PsE, \mu\}$

<u>Capacity Curve:</u>

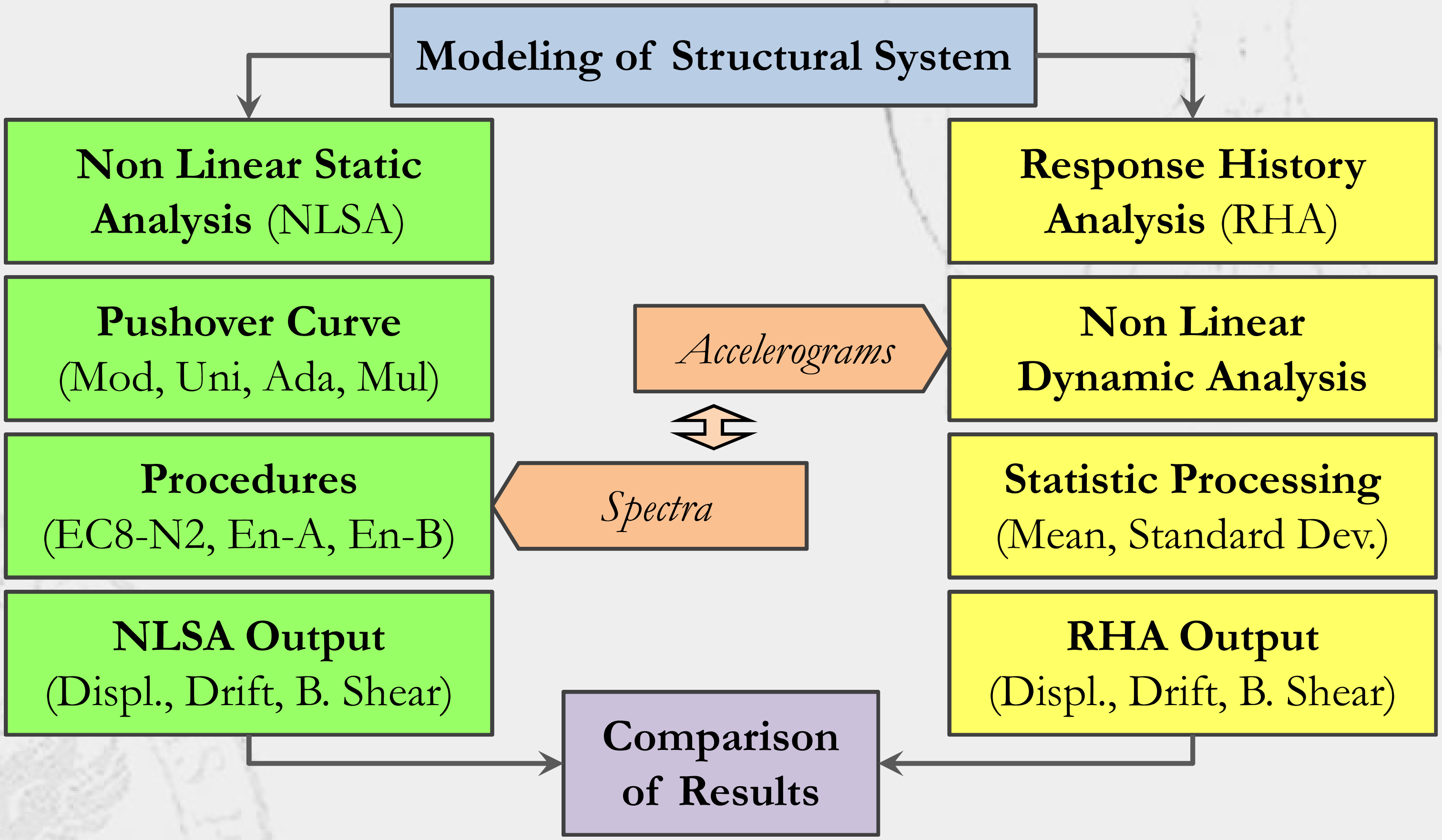
$C_e = C\ \{u, w, \mu=1\}$

$C = C\ \{u, w, \mu\}$



Non Linear Procedure

Assessment of Reliability of NLS Methodologies



$$\varepsilon = 100 \cdot \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} \left(\frac{P_{push}^{(i)} - P_{time}^{(i)}}{P_{time}^{(i)}} \right)^2}$$

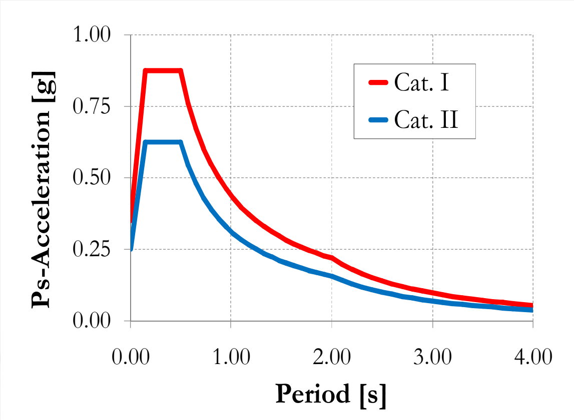
Error Parameter

Evaluation of SDOF System Response

SDOF Systems

Procedures Assessment by means of SDOF systems

For the analysis of response of **SDOF systems** the following assumptions have been adopted:

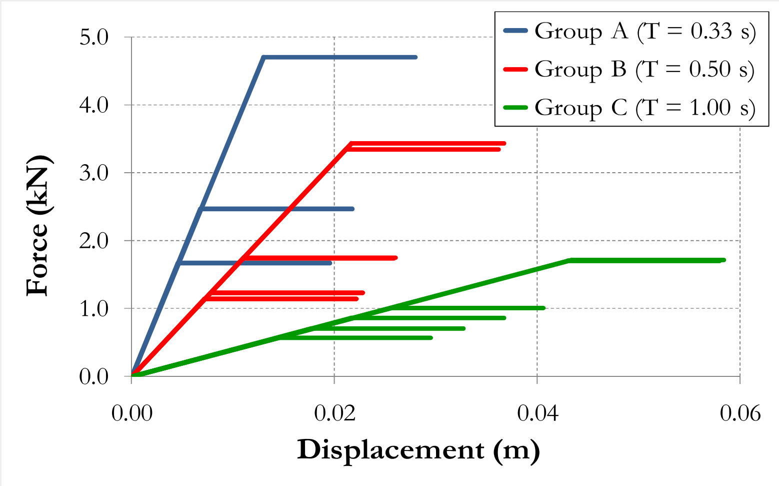


Two seismic scenarios:

Seismic Zone = I, II
Peak Gr. Accel., PGA = 0.35·g, 0.25·g
Soil Condition = B
Equivalent Damping, ξ = 5%
(Group of 9-generated acceler. each)

Three groups of SDOFs:

A = {A1, A2, A3}, T_A = 0.33 s
B = {B1, …, B6 }, T_B = 0.50 s
C = {C1, …, C6 }, T_C = 1.00 s



SDOF Systems

Procedures Assessment by means of SDOF systems

Since a SDOF system has been adopted, some simplifications can be achieved for what concerns the NLSA parameters

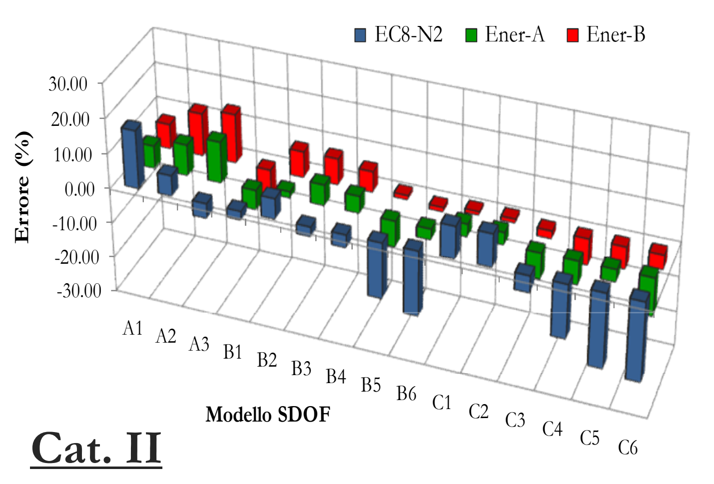
- **Lateral Force Distr.** = {Mod, Uni, Ada, Mul} ≈ {One force}
- **Effective Seismic Mass** = $\{m^*, m_I, m_{tot}\} \approx \{m_{SDOF}\}$

Due to the properties of SDOF models, **results** obtained from both **NLSA** and **RHA** can be **directly compared**

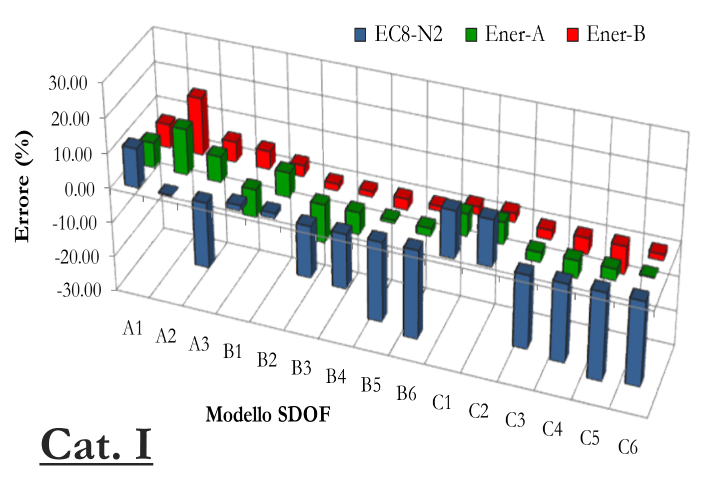
The following parameters have been considered:

- Maximum Displacement (**u**)
- Yield Displacement ($\mathbf{u_Y}$)
- Base Shear (Yield Force) ($\mathbf{F_b}$)
- Period (**T**)
- Ductility (**μ**)
- Strength Reduction Factor (**R**)

<u>ε-displacement:</u> comparison between NLSAs and RHA in terms of maximum displacement u_{max} of system



<u>Cat. II</u>



<u>Cat. I</u>

In general, energy-based methods provide a better solution in comparison with N2-EC8

This is true for cat. I. On the contrary, it is not so clear since Cat. II has been considered

This trend is recognizable for the higher values of T (0.5, 1.0 s) but not for the lower period (0.3 s)

SDOF Systems

Procedures Assessment by means of SDOF systems

Introduction

Pushover Analysis

Structural Response

Seismic Demand

Non Linear Procedures

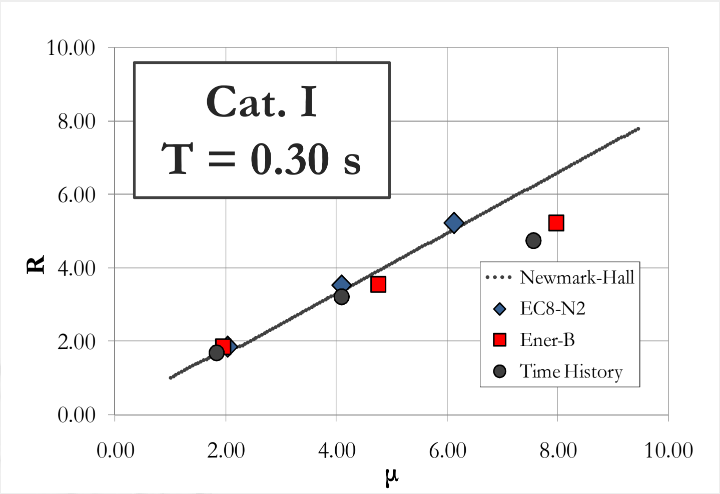
SDOF Systems

2D-MDOF Systems

3D-MDOF Systems

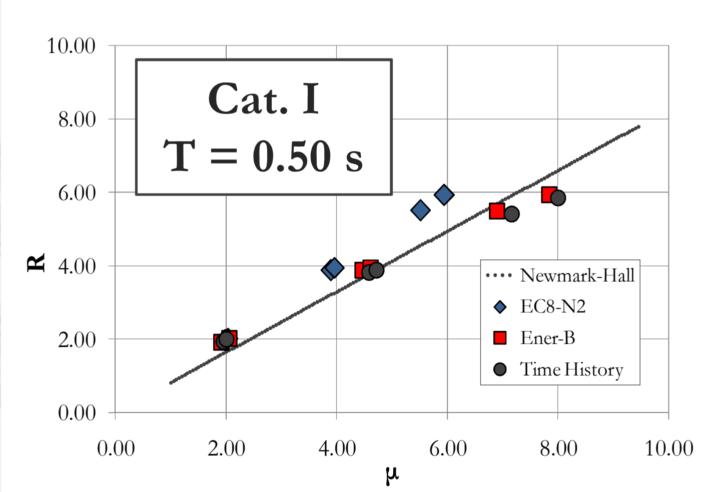
Conclusions

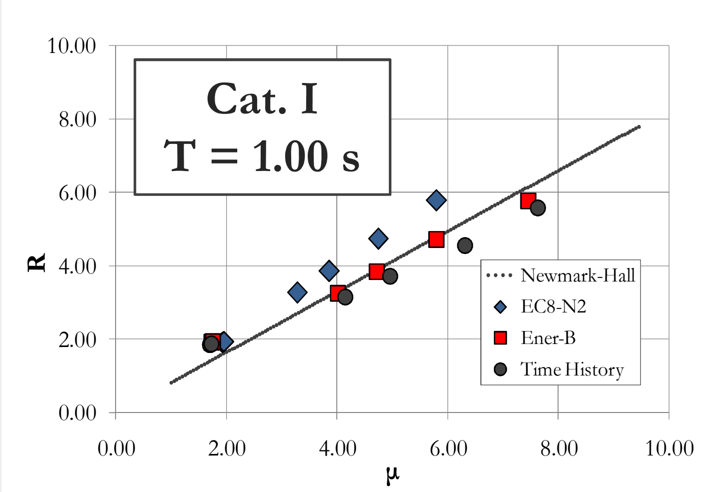
R-μ values: comparison between NLSAs and RHA when couples strength reduction factor/ductility (R-μ) are considered



The Energy-B procedure tends to be comparable with RHA results. On the contrary, N2-EC8 does not and its tendency is opposite

When R and μ increase, scattering with RHA increase as well



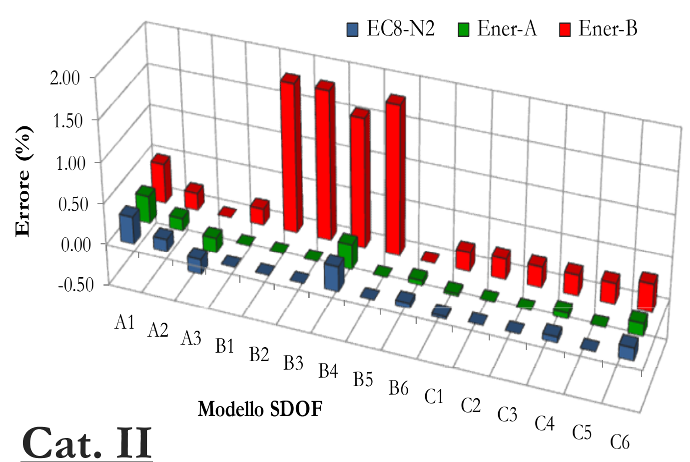


Introduction
Pushover Analysis
Structural Response
Seismic Demand
Non Linear Procedures
SDOF Systems
2D-MDOF Systems
3D-MDOF Systems
Conclusions

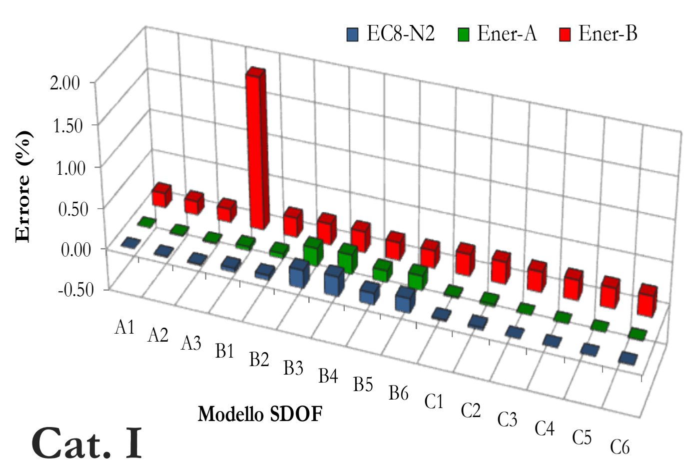
SDOF Systems

Procedures Assessment by means of SDOF systems

ε-period: comparison between NLSAs and Modal Analysis in terms of period T of system



Cat. II



Cat. I

Both N2-EC8 and Energy-A procedures are based on bi-linearization that gives

$$T = 2\pi \cdot \sqrt{\frac{m_{eff}}{k^*}}$$

Energy-B gives T, in an indirect way, using by evaluation of elastic performance and consequently the error is slightly higher

All procedures provide in all cases an accurate estimation of period

Introduction

Pushover Analysis

Structural Response

Seismic Demand

Non Linear Procedures

SDOF Systems

2D-MDOF Systems

3D-MDOF Systems

Conclusions

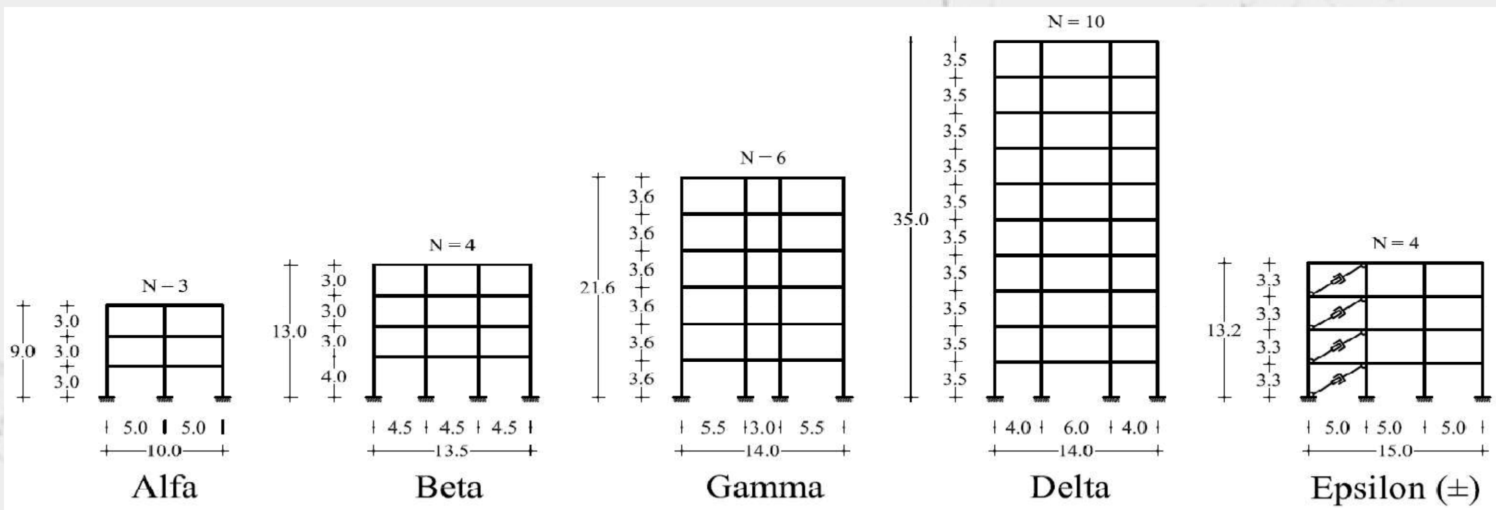
Evaluation of 2D-MDOF System Response

Introduction
Pushover Analysis
Structural Response
Seismic Demand
Non Linear Procedures
SDOF Systems
2D-MDOF Systems
3D-MDOF Systems
Conclusions

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

The following **2D-MDOF** systems have been considered in order to assess the reliability of the energy-based NLSAs proposed



Model	# Floors	# Bays	m_{tot} (t)	m* (%)	m_I (%)	Period (s)	Γ Factor	Ductil. Class	Design R
Alfa	3	2	83.4	66.5	85.3	0.462	1.282	High	5.85
Beta	4	3	144.6	64.8	86.6	0.509	1.336	High	5.85
Gamma	6	3	327.6	50.2	72.7	0.624	1.448	High	5.85
Delta	10	3	602.9	48.7	71.8	1.064	1.476	High	5.85
Eps (+)	4	3	160.9	68.8	86.4	0.500	1.257	High	5.85
Eps (–)	4	3	160.9	68.8	86.4	0.500	1.257	High	5.85

Introduction

Pushover Analysis

Structural Response

Seismic Demand

Non Linear Procedures

SDOF Systems

2D-MDOF Systems

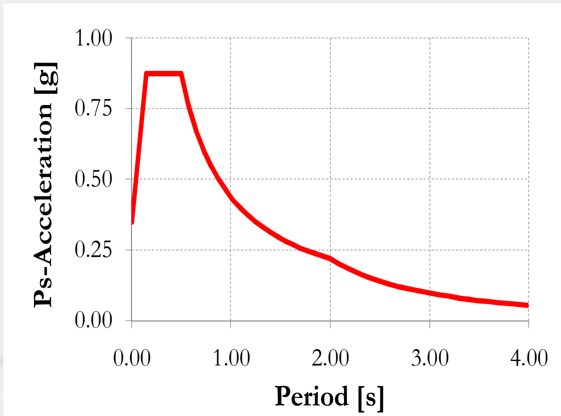
3D-MDOF Systems

Conclusions

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

For what concerns the **seismic input**, the following assumptions have been adopted to perform NLSA and RHA



<u>Seismic Demand Spectrum:</u>

Seismic Zone = I

Peak Gr. Acceleration, PGA = 0.35·g

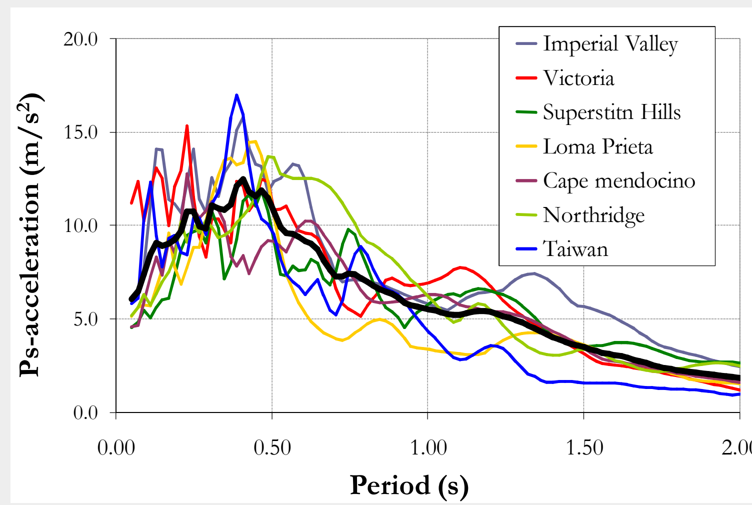
Soil Condition = B

Equivalent Damping, ξ = 5%

<u>Two 7-accelerograms groups:</u>

Gen_Acc = {7-Generated Accel.}

Rec_Acc = {7-Recorded Accel.}



2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Since a 2D-MDOF system has been adopted, the following parameters, which characterize estimated solution, are considered

- **Lateral Force Distr.** = {Mod, Uni, Ada, Mul} **[4 options]**
- **Effective Seismic Mass** = {m*, m_I, m_{tot}} **[3 options]**
- **Procedure** = {N2-EC8, En-A, En-B} **[1+2 options]**
- **Seismic Spectra** = {Cod_Spe, Gen_Spe, Rec_Spe} **[3 options]**
- **Group of Accelerograms** = {Gen_Acc, Rec_Acc} **[2 options]**

For each **scenario** (**combination of cases**), results obtained from both **NLSA** and **RHA** are compared in terms of

- Storey Displacement ($\mathbf{s_i}$)
- Storey Drift ($\mathbf{d_i}$)
- Base Shear ($\mathbf{F_b}$)

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Cases available for what concerns **NLSAs**:

When the **energy-based methodologies** have been taken into account, each NLSA is characterized by

$$\mathrm{NLSA}_{\mathrm{Energy}} = \begin{Bmatrix} \mathrm{Mod} \\ \mathrm{Uni} \\ \mathrm{Ada} \\ \mathrm{Mul} \end{Bmatrix} \times \begin{Bmatrix} m^* \\ m_I \\ m_{tot} \end{Bmatrix} \times \begin{Bmatrix} \mathrm{Ener\ A} \\ \mathrm{Ener\ B} \end{Bmatrix} = \{4\} \times \{3\} \times \{2\} = 24 \text{ cases}$$

Since the **N2-EC8 methodology**, here considered as a benchmark, has been taken into account, each NLSA is characterized by

$$\mathrm{NLSA}_{\mathrm{EC8\text{-}N2}} = \begin{Bmatrix} \mathrm{Mod} \\ \mathrm{Uni} \\ \mathrm{Ada} \\ \mathrm{Mul} \end{Bmatrix} \times \{m^*\} \times \{\mathrm{N2\text{-}EC8}\} = \{4\} \times \{1\} \times \{1\} = 4 \text{ cases}$$

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Cases available for what concerns **RHAs**:

When the **non linear dynamic analyses** have been taken into account, each RHA is characterized by

$$\text{RHA} = \begin{Bmatrix} \text{Cod\_Sp} \\ \text{Gen\_Sp} \\ \text{Rec\_Sp} \end{Bmatrix} \oplus \begin{Bmatrix} \text{Gen\_Ac} \\ \text{Rec\_Ac} \end{Bmatrix} = \begin{Bmatrix} \text{Cod\_Sp} \oplus \text{Gen\_Ac} \\ \text{Cod\_Sp} \oplus \text{Rec\_Ac} \\ \text{Gen\_Sp} \oplus \text{Gen\_Ac} \\ \text{Rec\_Sp} \oplus \text{Rec\_Ac} \end{Bmatrix} = 4 \text{ cases}$$

The RHA cases proposed above derive from the fact that **seismic demand spectra** and **groups of accelerograms** must be **consistent**

Total Scenarios = $[(24+4)_{NLSA}] \times [4_{RHA}] \times [6_{Models}] = 672$

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

At first, a "**Relative Comparison**" between responses are made

Each seismic performance, estimated by means of NLSA, is characterized by N parameters

One at the time, (N-1) parameters are fixed and the results, when the Nth parameter varies, are considered

Example:

Model "Alfa"
Displacement Error ε (Table 8.3.1.III, page 88)
(N-1) fixed parameters are: effective mass, NL procedure
Nth parameter is Lateral Force distribution
Seismic scenario are four (4)
Cases available are 112 grouped in (4·7) 28 sub-scenarios

Procedures Assessment by means of 2D-MDOF systems

Spect.	Accel.	LFD	m* N2	m* EnA	m* EnB	m_I EnA	m_I EnB	m_{tot} EnA	m_{tot} EnB
Cod	Gen	Mod	83.0	49.1	15.2	76.9	45.5	94.0	69.0
		Uni	75.0	44.0	3.7	72.6	30.5	97.9	52.1
		Ada	82.5	49.8	13.5	78.0	44.4	93.2	69.4
		Mul	73.1	48.3	12.2	77.0	41.5	93.2	65.1
	Rec	Mod	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Uni	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Ada	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Mul	25.6	7.6	19.2	28.4	2.9	40.2	19.8
Gen	Gen	Mod	83.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	56.3
		Uni	75.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	63.5
		Ada	83.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55.9
		Mul	73.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	48.8
Rec	Rec	Mod	32.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	37.6
		Uni	27.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21.3
		Ada	32.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	37.7
		Mul	25.6	13.9	4.9	28.5	12.4	s.n.t.	36.3

1st 2nd 3rd 4th 5th 6th 7th

Best solution (LFD):

0/7 Modal (0%)

5/7 Uniform (71%)

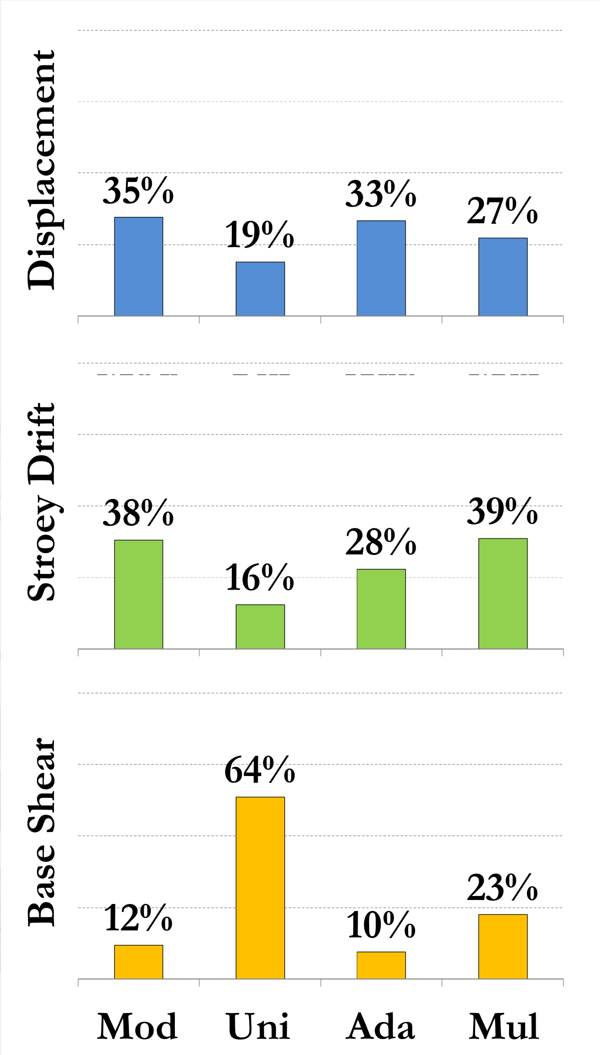
1/7 Adaptive (14%)

1/7 Multimodal (14%)

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Lateral Force Distribution (LFD) – (28·6) 168 sub-scenarios:



There is **no clear trend**, in terms of displacement or drift, that suggests to use one Lateral Force Distribution rather than another

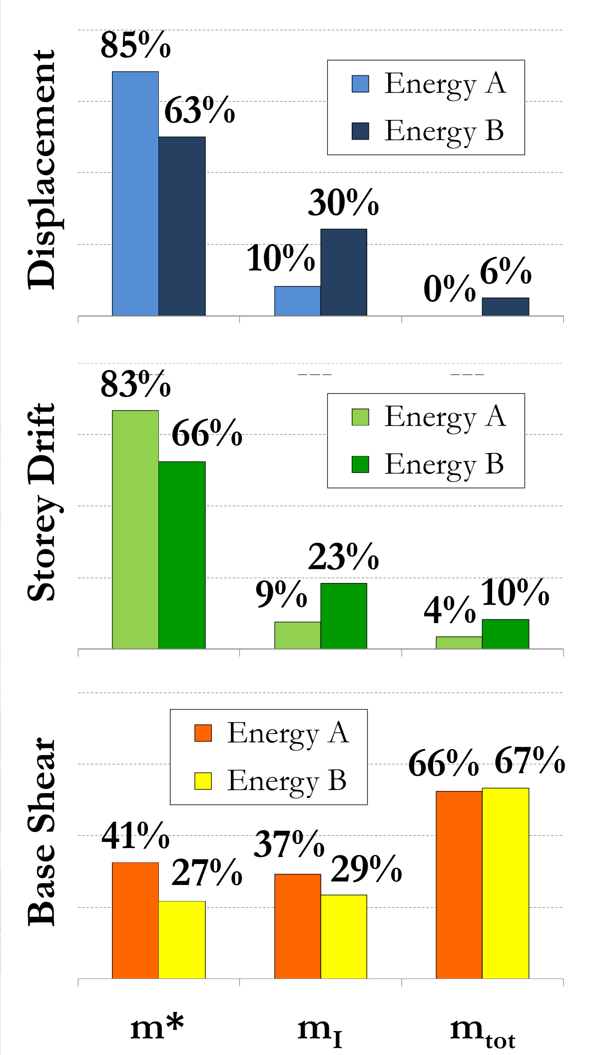
Modal, **Adaptive** and/or **Multimodal** LFD seem to be more accurate to estimate **displacement** and/or **storey drift**

On the contrary, **Uniform LFD** seems to be more accurate to estimate **base shear**

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Effective Seismic Mass – (16·6) 96 sub-scenarios:



The choice of effective mass regards only energy-based procedures, due to the fact that N2-EC8 considers always m* value

In terms of displacement and/or storey drift, results suggest to adopt **equivalent first mode mass m*** as effective seismic mass

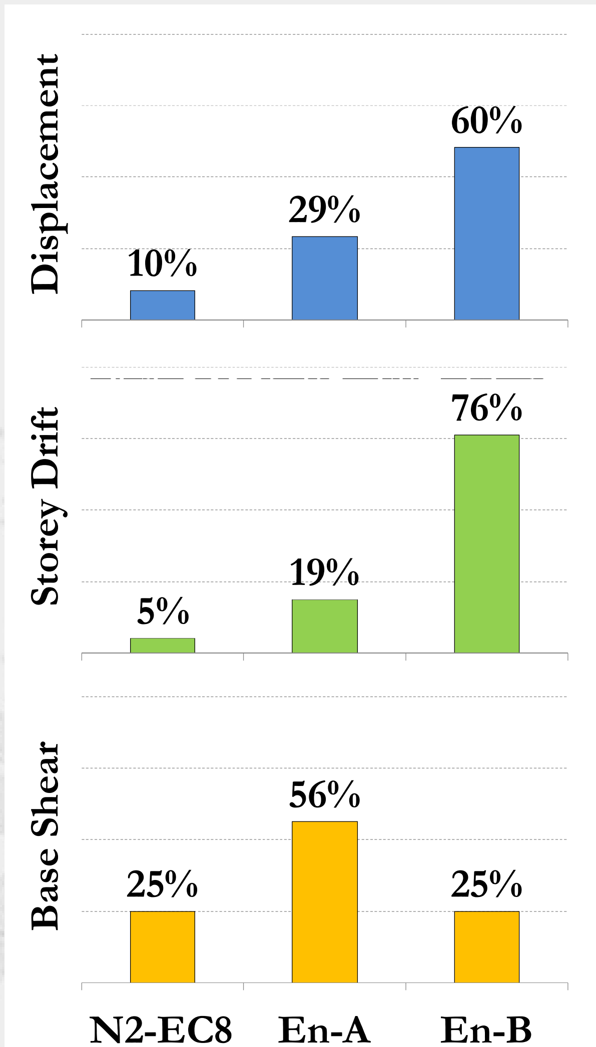
The use of **first mode mass m_I** should be taken into account for Energy-B

The value of **total mass m_{tot}** is more reliable for evaluation of base shear

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Non Linear Procedure – (16·6) 96 sub-scenarios:



Since the comparisons have been made in terms of displacement and/or storey drift, the **energy-based** methodologies represent a **robust tool** to estimate seismic response

In particular, the **Energy-B** procedure provides a more accurate solution than Energy-A

On the contrary, when base shear has been chooses as a comparison parameter, **Energy-A** appears to be more accurate than other two methods

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Secondly, an "**Absolute Comparison**" between responses are made

Each seismic performance, estimated by means of NLSA, is characterized by N parameters

One at the time, the combinations of all N-parameters are considered in order to infer which one provides the best solution

Example:

Model "Alfa"

Displacement Error ε (Table 8.3.1.III, page 88)

Combination of all parameters is considered (LFD, procedure, mass)

Seismic scenario are four (4)

Cases available are 112 grouped in 4 sub-scenarios

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Introduction

Pushover Analysis

Structural Response

Seismic Demand

Non Linear Procedures

SDOF Systems

2D-MDOF Systems

3D-MDOF Systems

Conclusions

Spect.	Accel.	LFD	m*			m_I		m_{tot}	
			N2	EnA	EnB	EnA	EnB	EnA	EnB
Cod	Gen	Mod	83.0	49.1	15.2	76.9	45.5	94.0	69.0
		Uni	75.0	44.0	3.7	72.6	30.5	97.9	52.1
		Ada	82.5	49.8	13.5	78.0	44.4	93.2	69.4
		Mul	73.1	48.3	12.2	77.0	41.5	93.2	65.1
	Rec	Mod	32.7	8.6	17.5	[illegible]	5.8	40.7	22.6
		Uni	27.4	5.6	24.8	[illegible]	6.0	43.9	11.0
		Ada	32.3	8.7	18.7	[illegible]	5.1	40.1	22.8
		Mul	25.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	19.8
Gen	Gen	Mod	83.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	56.3
		Uni	75.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	63.5
		Ada	83.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55.9
		Mul	73.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	48.8
Rec	Rec	Mod	32.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	37.6
		Uni	27.4	9.4	17.3	35.3	11.2	48.9	21.3
		Ada	32.7	14.3	11.4	30.2	15.2	56.9	37.7
		Mul	25.6	13.9	4.9	28.5	12.4	s.n.t.	36.3

1^{st}

Best Solution:

Energy-B NLSA

Effective Mass m*

Uniform LFD

Best Combination – (4·6) 24 sub-scenarios

Best combination among 24 available evaluated using by **ε-displacement** comparison

Parameters			Response		Total Scenarios
LFD	NL Procedure	Effective Mass	Positive Cases	Percentage (%)	
Uni	Energy-B	m*	6	25.0%	24
Mul	Energy-A	m*	5	20.8%	24
Mul	Energy-B	m*	3	12.5%	24
Mul	Energy-B	m_I	3	12.5%	24
Unif	Energy-A	m*	2	8.3%	24

Combo = {Mul LFD} × {Ener. Procedures} × {m*}

Introduction
Pushover Analysis
Structural Response
Seismic Demand
Non Linear Procedures
SDOF Systems
2D-MDOF Systems
3D-MDOF Systems
Conclusions

Best Combination – (4·6) 24 sub-scenarios

Best combination among 24 available evaluated using by **ε-drift** comparison

Parameters			Response		Total Scenarios
LFD	NL Procedure	Effective Mass	Positive Cases	Percentage (%)	
Mul	Energy-A	m*	6	25.0%	24
Mod	Energy-B	m*	5	20.8%	24
Ada	Energy-A	m*	3	12.5%	24
Ada	Energy-A	m_I	3	12.5%	24
Mul	Energy-A	m_I	3	12.5%	24

Combo = {Mul/Mod LFD} × {Ener. Procedures} × {m*}

Introduction
Pushover Analysis
Structural Response
Seismic Demand
Non Linear Procedures
SDOF Systems
2D-MDOF Systems
3D-MDOF Systems
Conclusions

Best Combination – (4·5) 20$^{(*)}$ sub-scenarios

Best combination among 24 available evaluated using by **ε-base shear** comparison [* *Epsilon (±) models are symmetric*]

Parameters			Response		Total Scenarios
LFD	NL Procedure	Effective Mass	Positive Cases	Percentage (%)	
Uni	Energy-B	m*	6	30.0%	20
Uni	Energy-B	m_{tot}	4	20.0%	20
Uni	Energy-A	m*	2	10.0%	20
Uni	Energy-A	m_I	2	10.0%	20
Uni	Energy-A	m_{tot}	2	10.0%	20

Combo = {Uni LFD} × {Ener. Procedures} × {?}

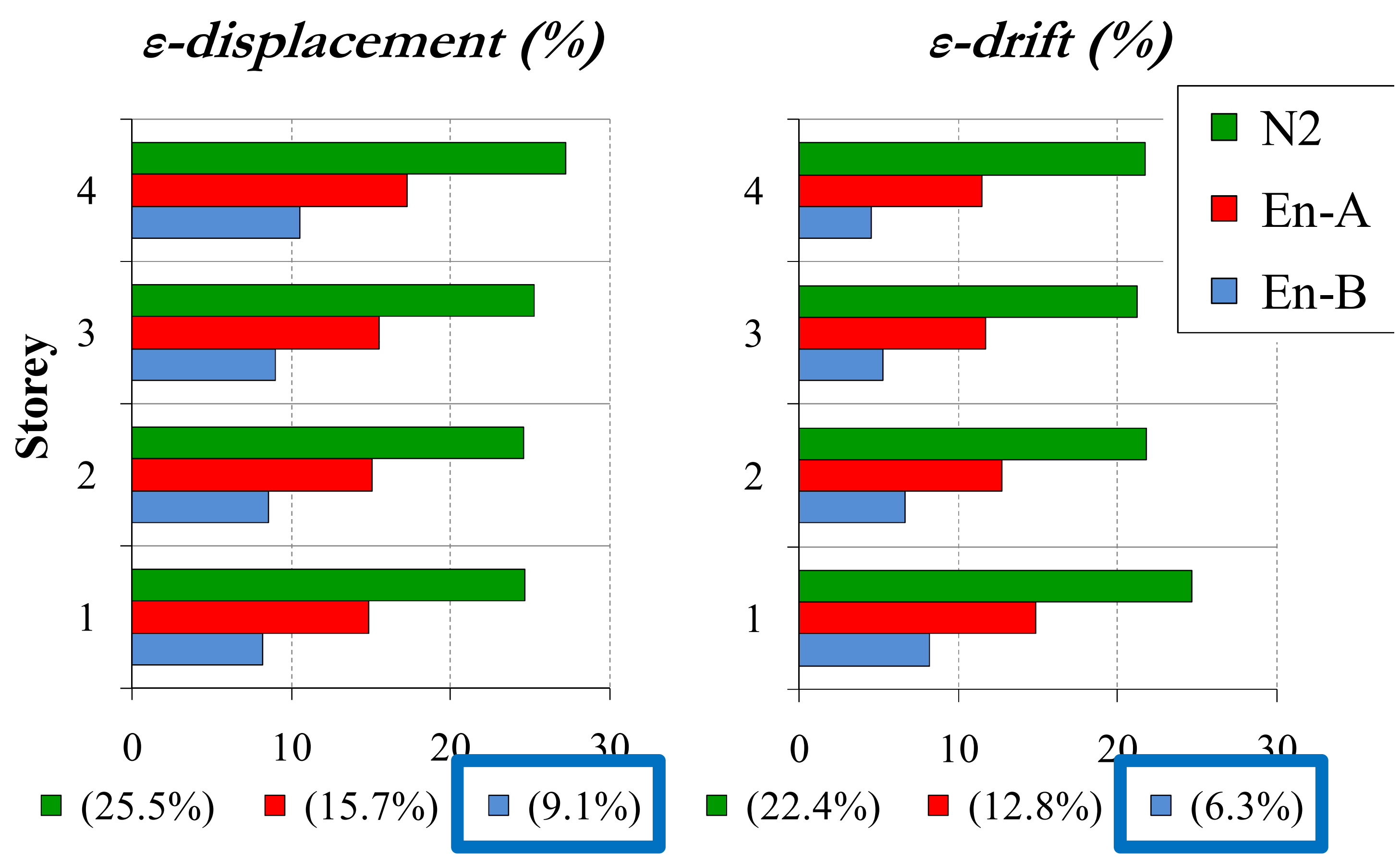
2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Finally, for what concerns the assumption of parameters in order to evaluate the seismic response of system, the analyzed data suggests to

- Use lateral force distribution based on a **modal dynamic criterion** (**Multimodal LFD**) to represent inertial effect on structural seismic masses
- Adopt **equivalent first mode mass** (**m***) as effective mass
- Utilize **energy-based procedures** (**Energy-A**, **Energy-B**) to determine performance point

<u>Example</u>: **Model "Beta"** and **Generated Spectra**

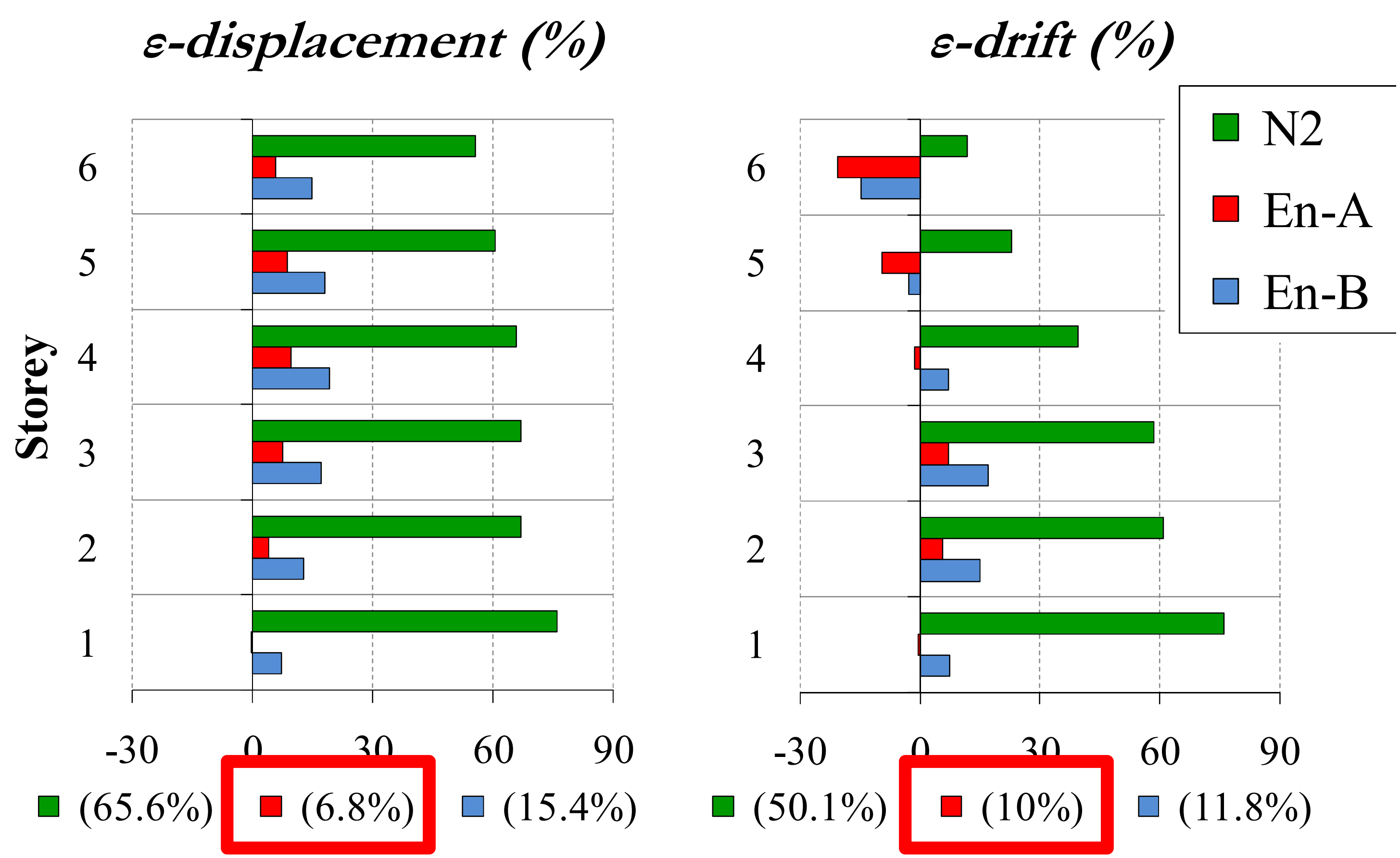


Multimodal + m*

2D-MDOF Systems

Procedures Assessment by means of 2D-MDOF systems

Example: **Model "Gamma"** and **Generated Spectra**



Multimodal + m*

Evaluation of 3D-MDOF System Response

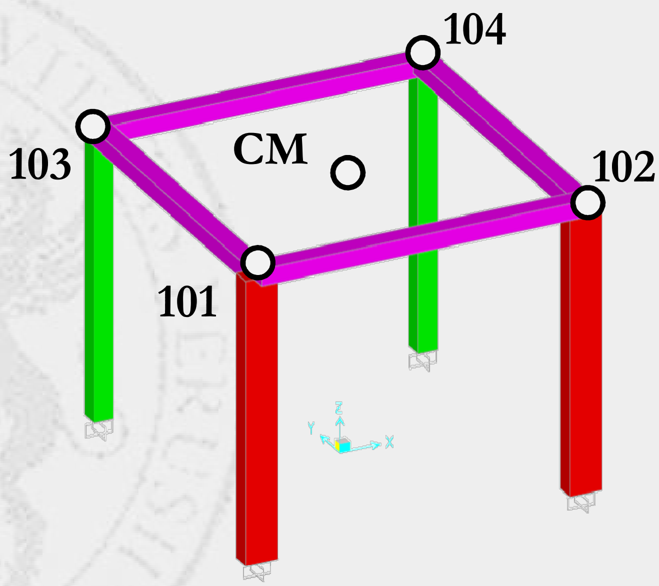
3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

The following **3D-MDOF** system has been considered to assess the reliability of the energy-based NLSAs proposed

Code	Element	Color	Cross-section (cm x cm)	Length (m)
P1, P2	Column	red	50 x 30	5.00
P3, P4	Column	green	30 x 30	5.00
T	Beam	magenta	30 x 30	5.00

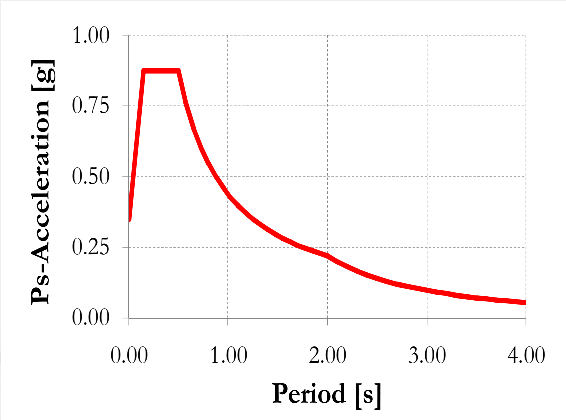
Mode	Period (s)	Part. M (t)	Part. M (%)
1st	0.5655	55.55	100.0
2nd	0.5492	27.46	49.4
3rd	0.3888	28.09	50.6



Taking into account the fact that 3D-MODF has one floor, **base shear** and **displacement of 101, 102, 103, 104** and **CM points** are considered to represent the **structural response**

Introduction
Pushover Analysis
Structural Response
Seismic Demand
Non Linear Procedures
SDOF Systems
2D-MDOF Systems
3D-MDOF Systems
Conclusions

For what concerns the **seismic input**, the following assumptions have been adopted to perform NLSA and RHA



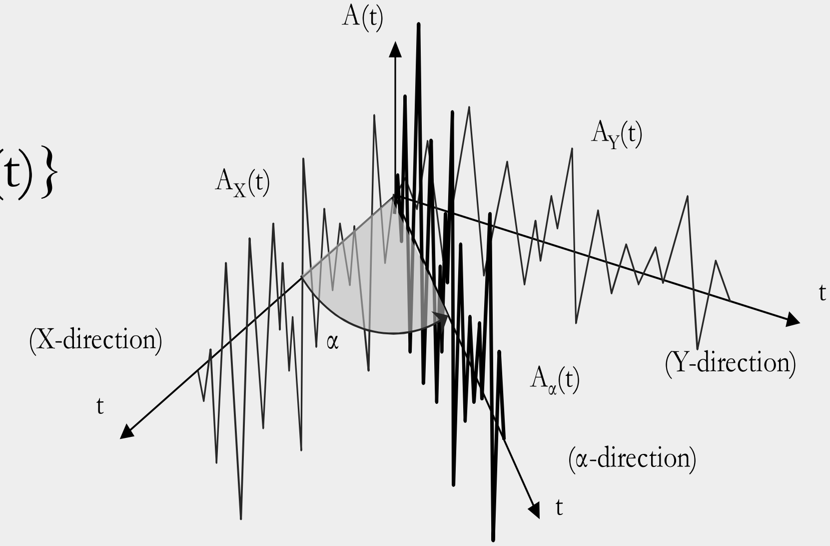
Seismic Demand Spectrum:

Seismic Zone = I
Peak Gr. Acceleration, PGA = 0.35·g
Soil Condition = B
Equivalent Damping, ξ = 5%

Accelerograms:

Multidir. = {7 gener. $A_X(t)+A_Y(t)$}

Each component is generated in accordance with elastic PsA spectrum



3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

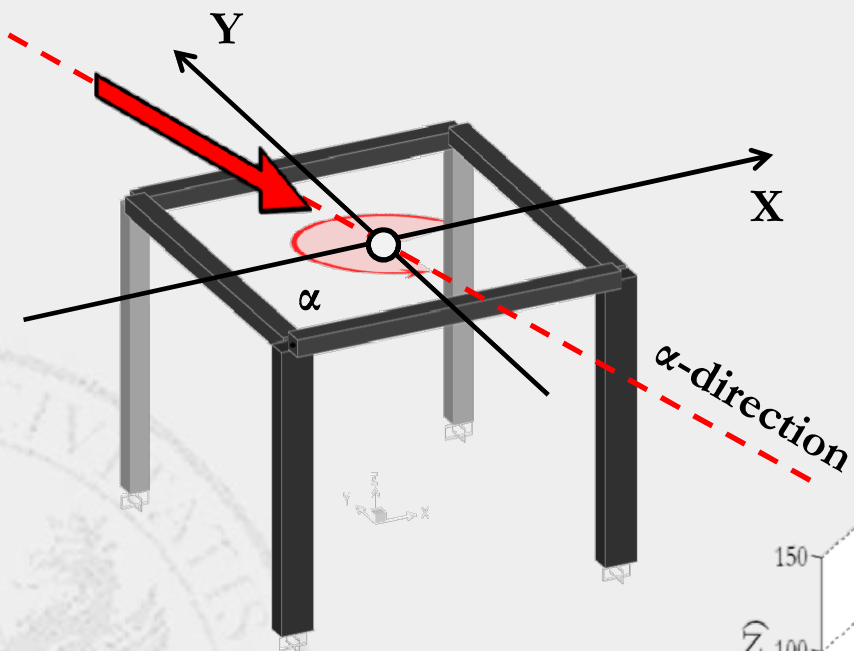
When the 3D-MDOF system has been adopted, some simplifications can be achieved for what concerns the NLSA parameters

- **Lateral Force Distr.** = {Mod, Uni, Ada, Mul} ≈ {One force, α}
- **Effective Seismic Mass** = $\{m^*, m_I, m_{tot}\} \approx \{m_{MDOF}\}$

Due to the properties of the 3D-MDOF model, the **results** obtained from both **NLSAs** and **RHAs** are compared in terms of

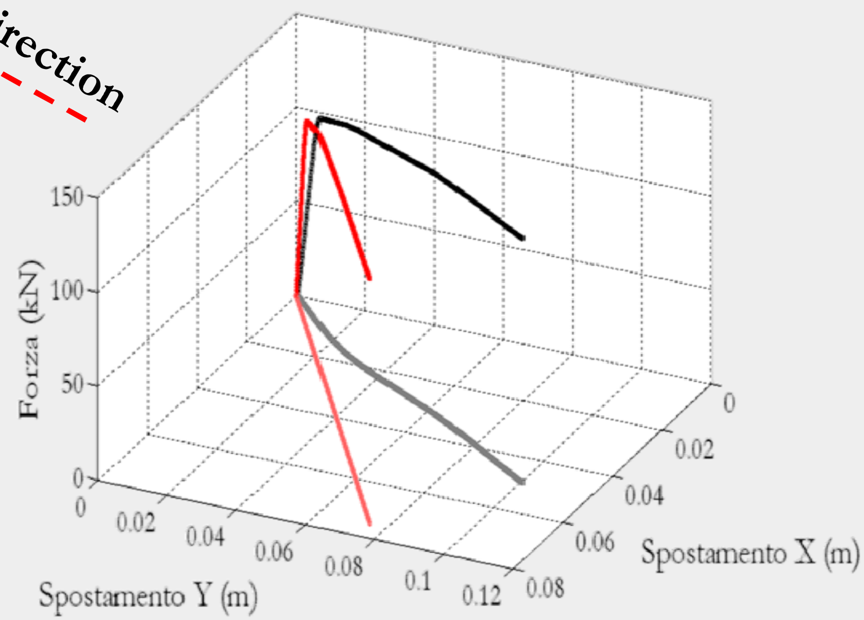
- Displacement ($\mathbf{u}_i$) ≡ Storey Drift ($\mathbf{d}_i$)
- Base Shear ($\mathbf{F}_b$)

The **Lateral Force** used in NLSA has been applied to the system through the use of **α-angle** parameter



The parameter represented by **α-angle** allows to compare NLSA and RHA along the **α-direction**

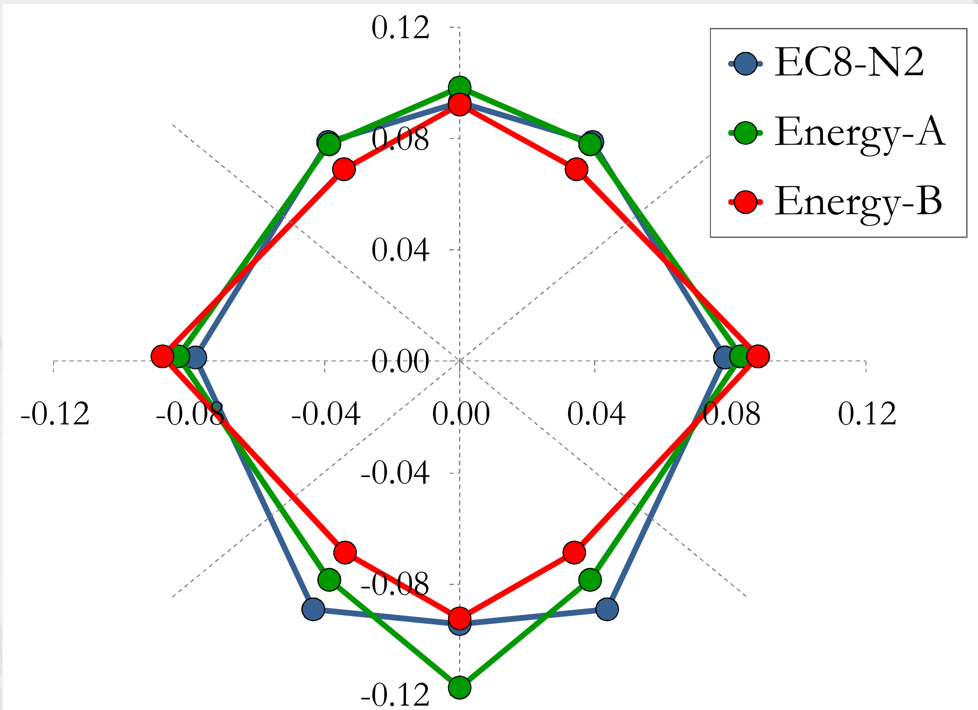
NLSA is performed along generic α-direction that allows to "**project**" analysis response in **Z−α-direction plane**



3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

The pushover analyses have been performed for α angle from 0° to 360° (**Δα = 45°**)



Response of **CM** (**X/Y-displacement**) evaluated using by pushover analyses

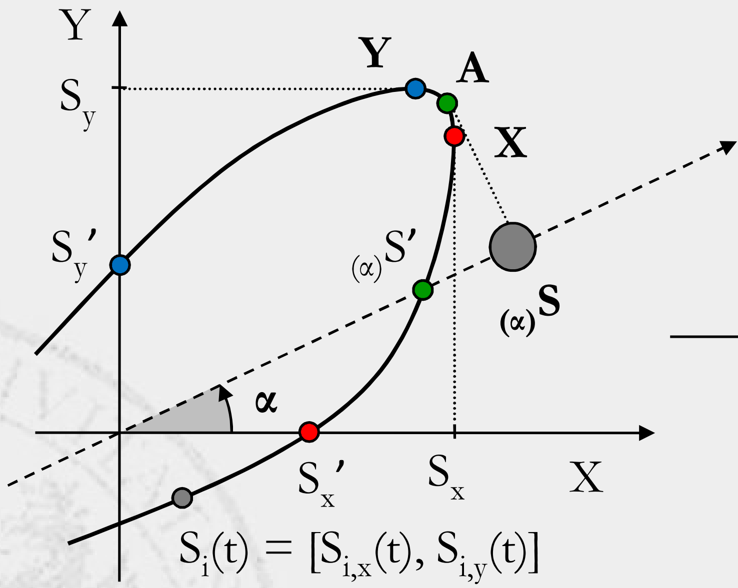
Each pushover result can be **represented by a point** in X-Y plane

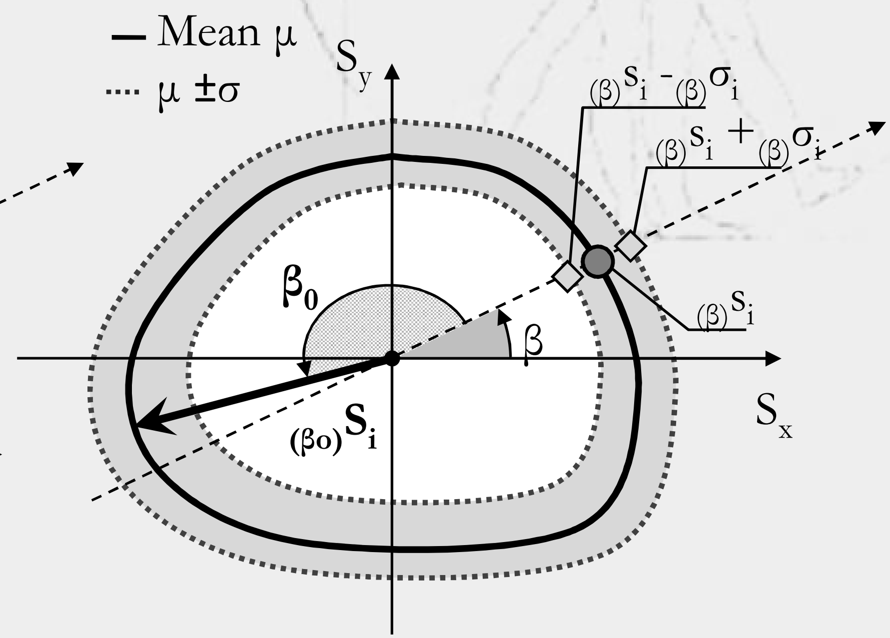
Since a number of solutions have been evaluated, the "**solution ellipse**" can be plotted

3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

The results obtained from RHA can be represented in a plane using a curve S = S(t)





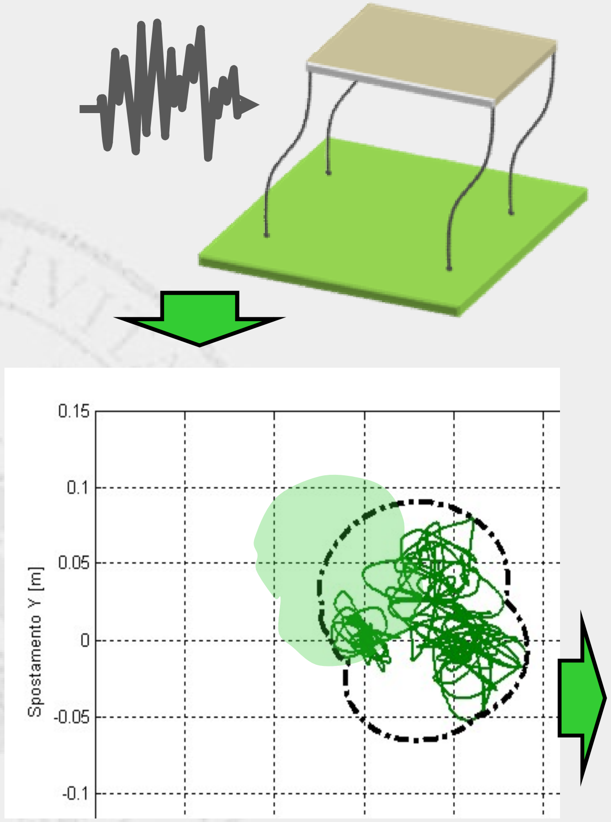
Using the **"projection" procedure**, for a fixed direction α = β, it is possible to compute the **mean** and **standard deviation** values processing results from each of 7 accelerograms

3D-MDOF Systems

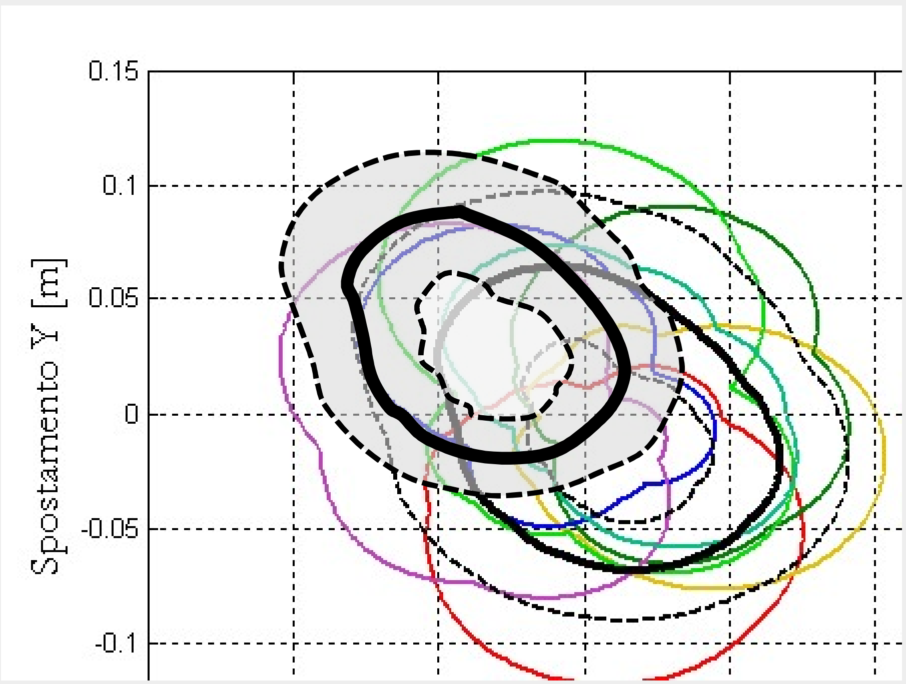
Procedures Assessment by means of 3D-MDOF system

The procedure of projection is necessary for:

- Statistic processing of RHA output
- Comparison between NLSAs and RHA results



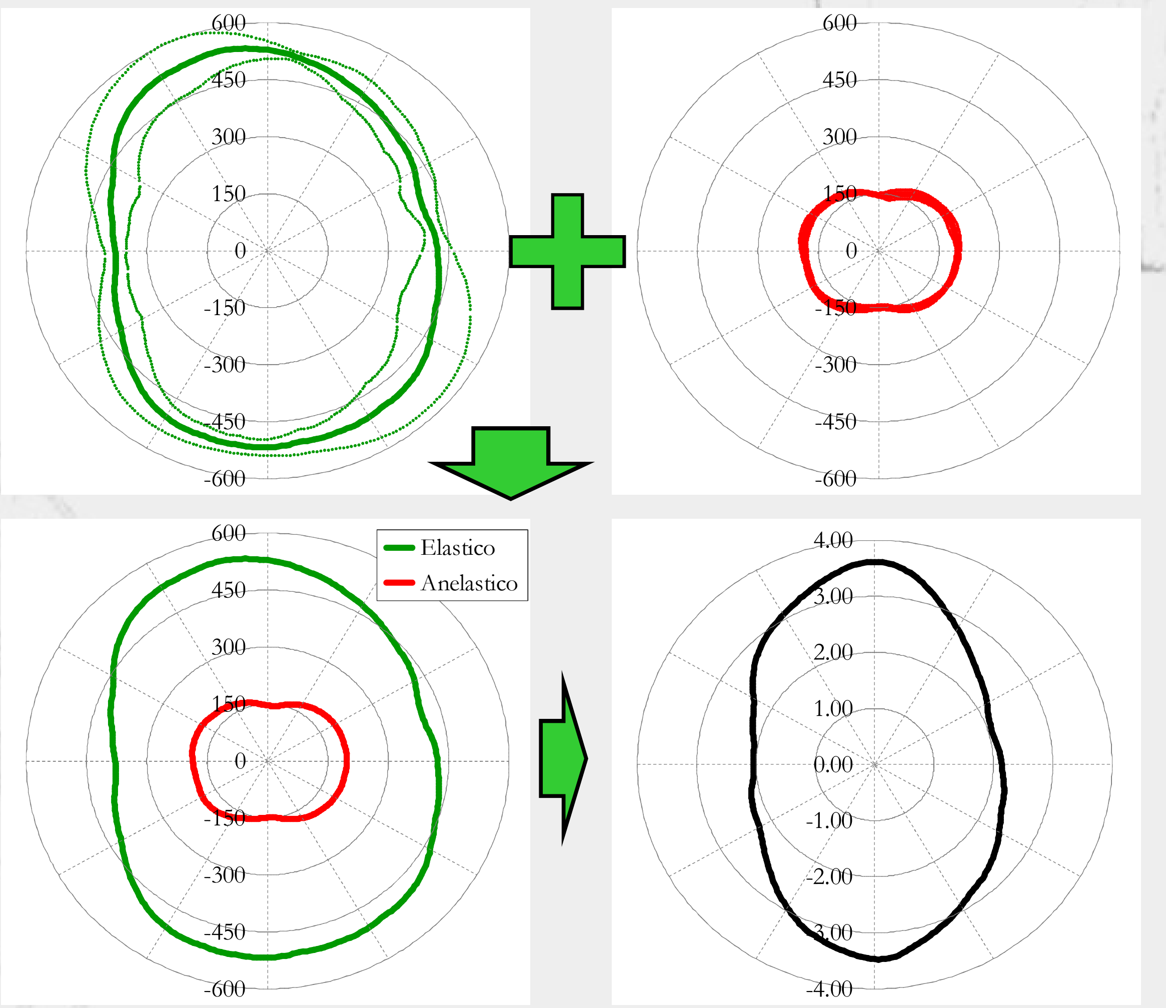
Mean response



3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

Comparison between **elastic** and **inelastic** mean responses in terms of **base shear**



Introduction

Pushover Analysis

Structural Response

Seismic Demand

Non Linear Procedures

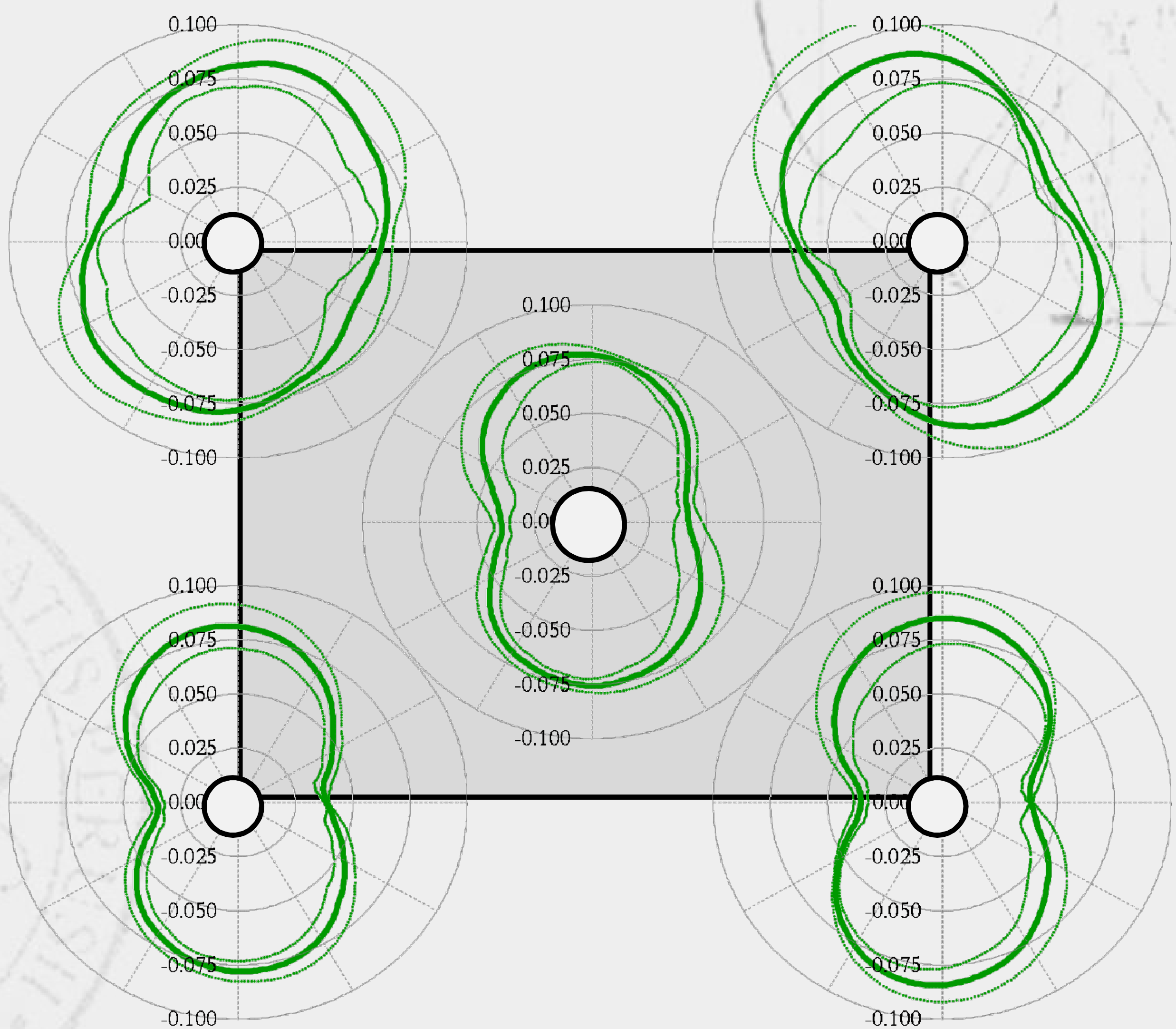
SDOF Systems

2D-MDOF Systems

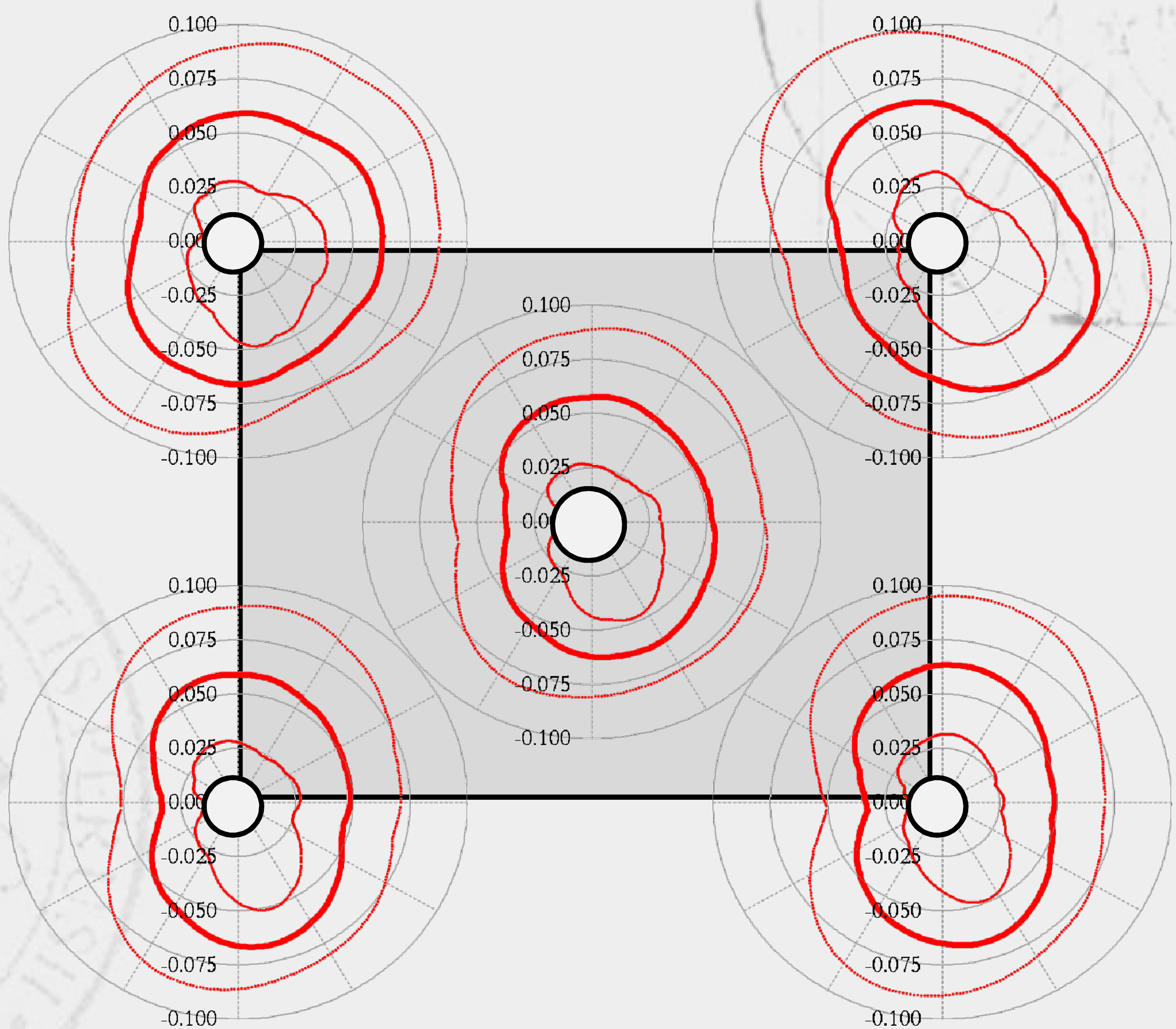
3D-MDOF Systems

Conclusions

Mean response in terms of **displacement** for **elastic behavior**



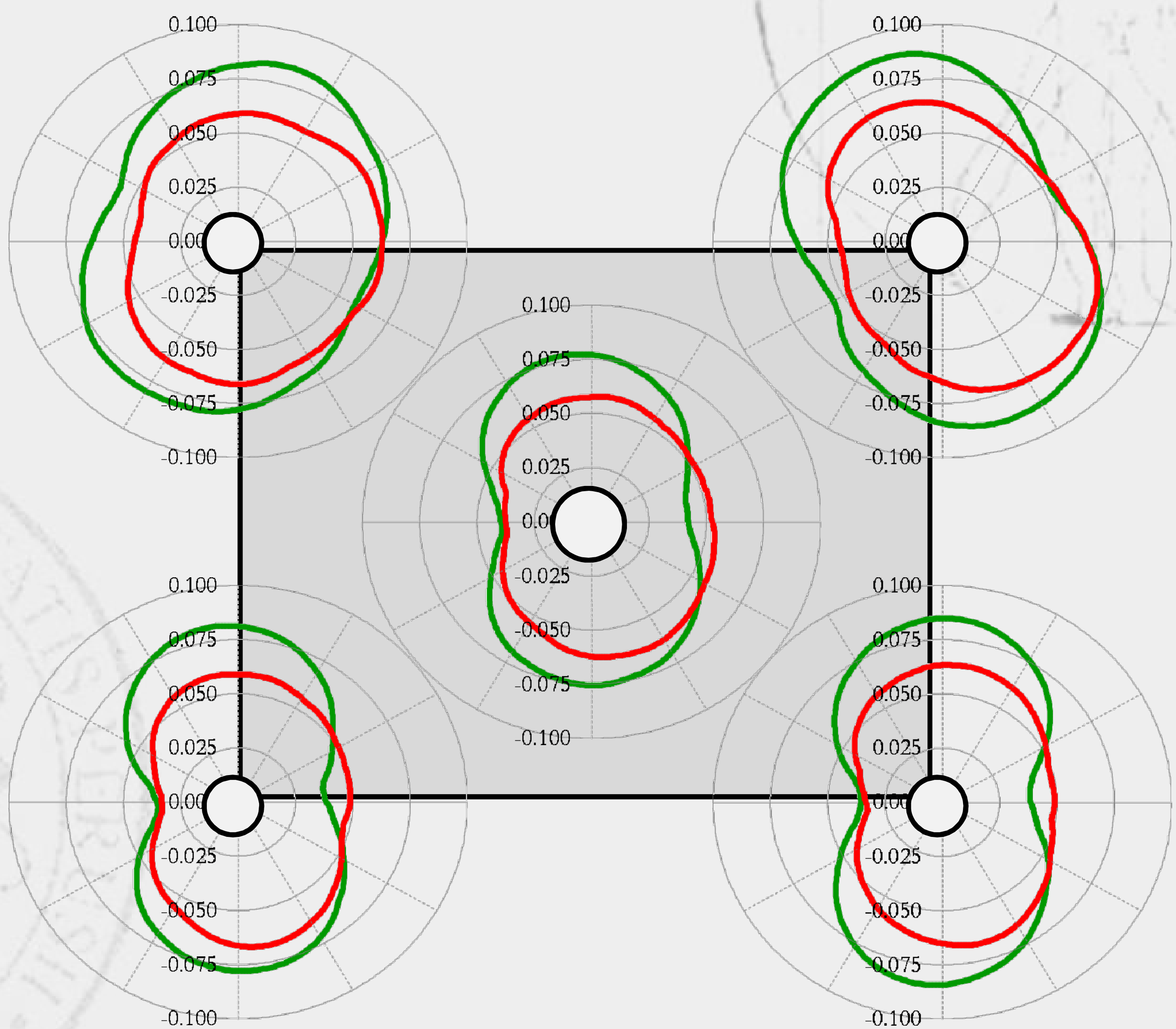
Mean response in terms of **displacement** for **inelastic behavior**



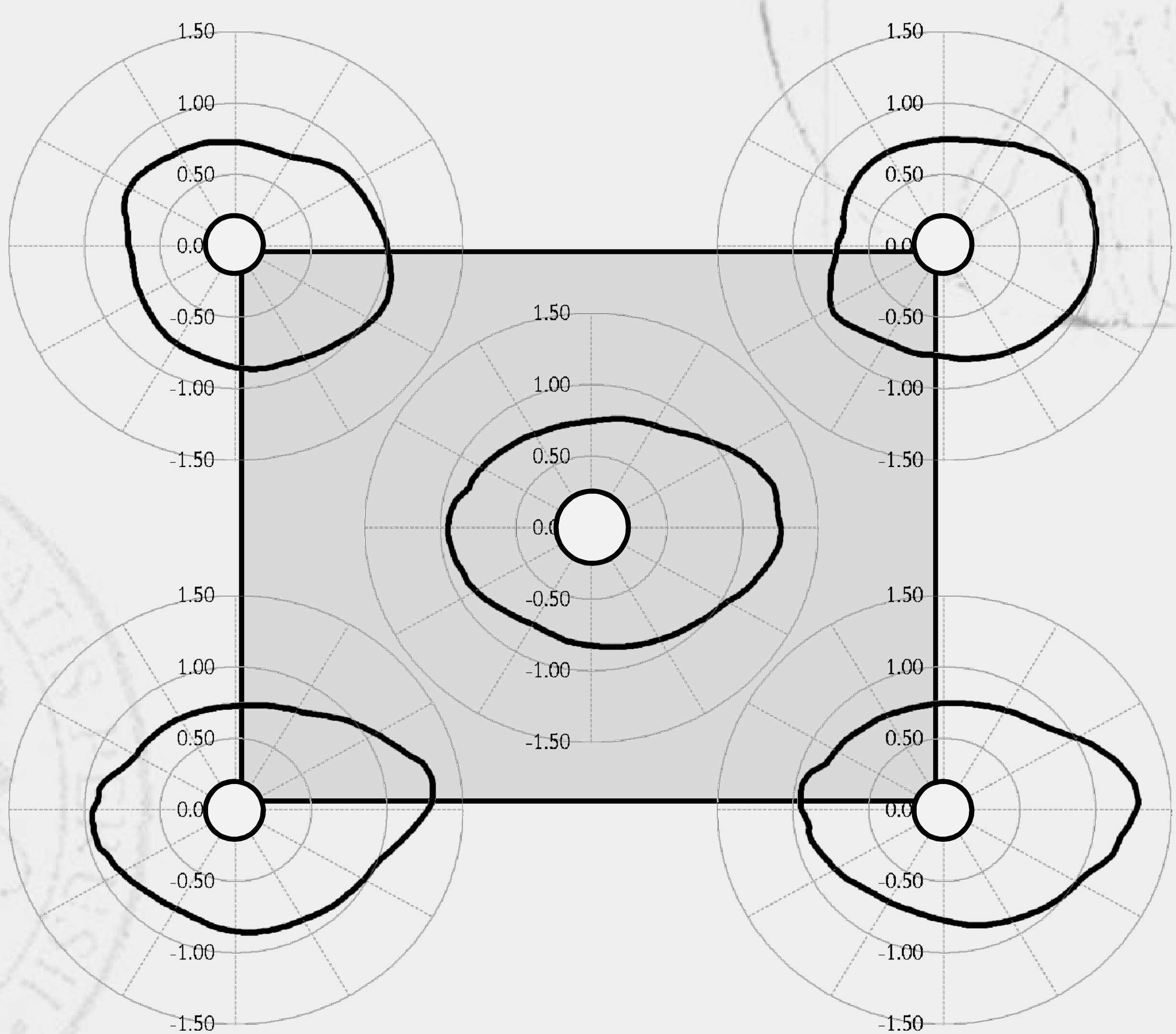
3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

Comparison between elastic and inelastic mean responses (**displ.**)



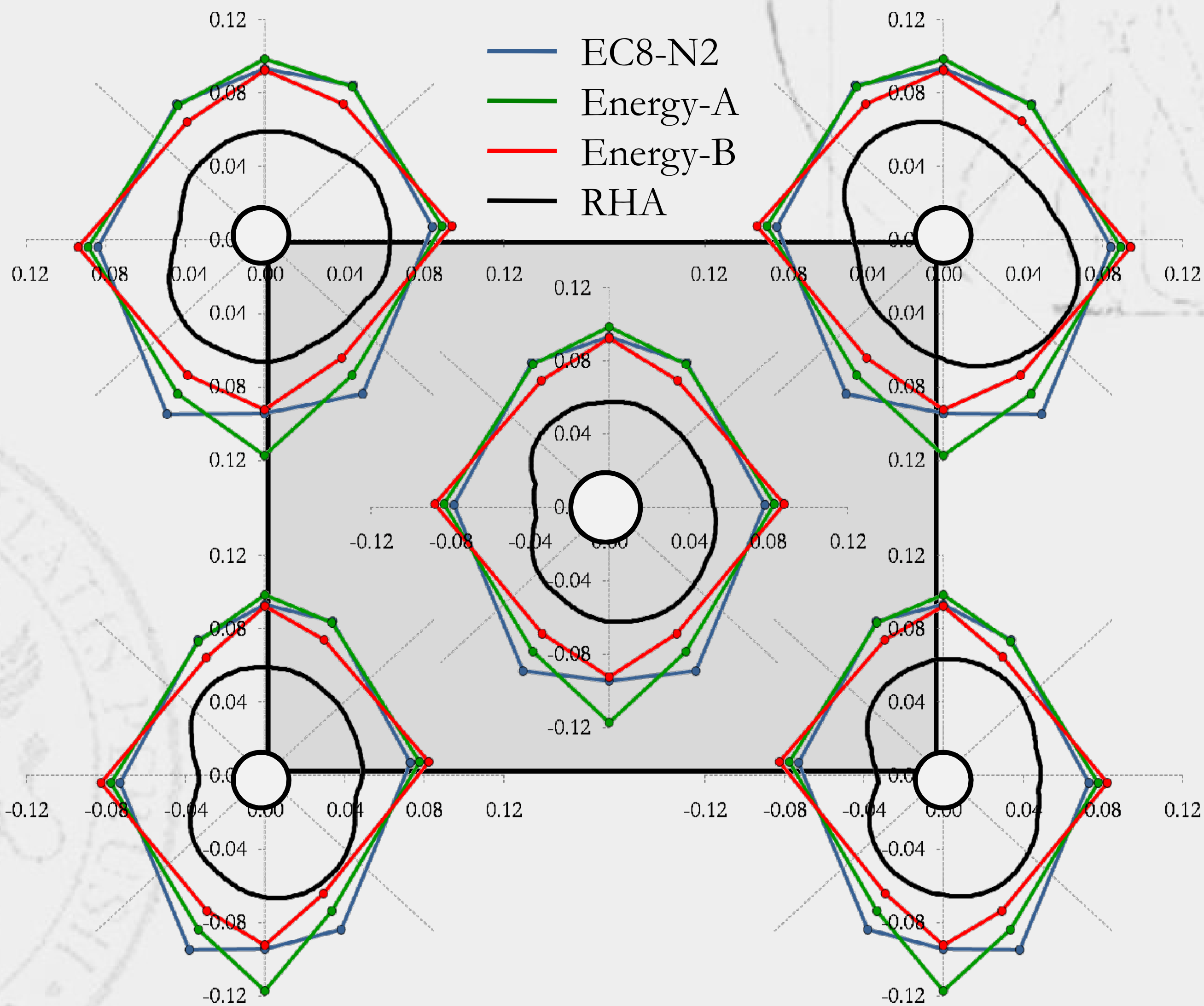
Ratio of inelastic and elastic mean **displacement**



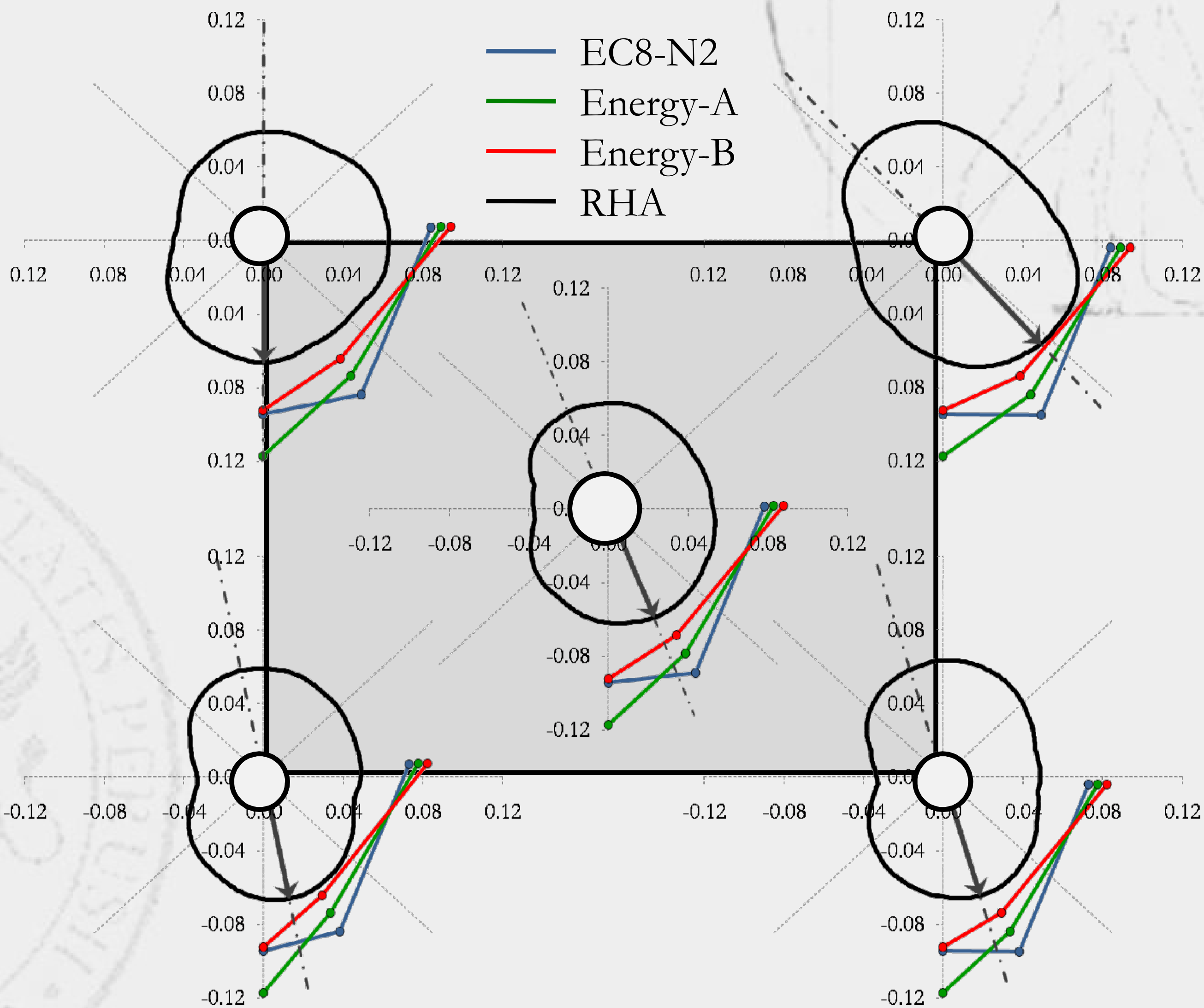
3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

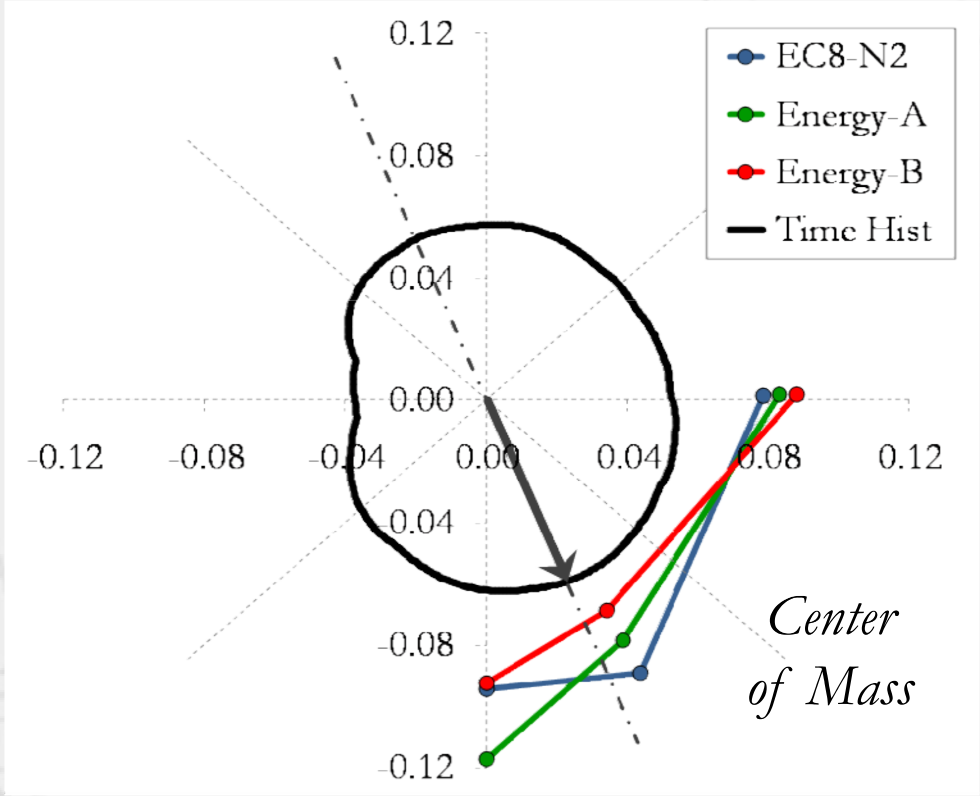
Comparison between **RHA** and **NLSAs** responses (**displacement**)



Comparison between **Max RHA** and **NLSAs** responses (**displac.**)



When a comparison has to performed, it is crucial to compare the **NLSA "Ellipse"** with the **maximum mean response of RHA**

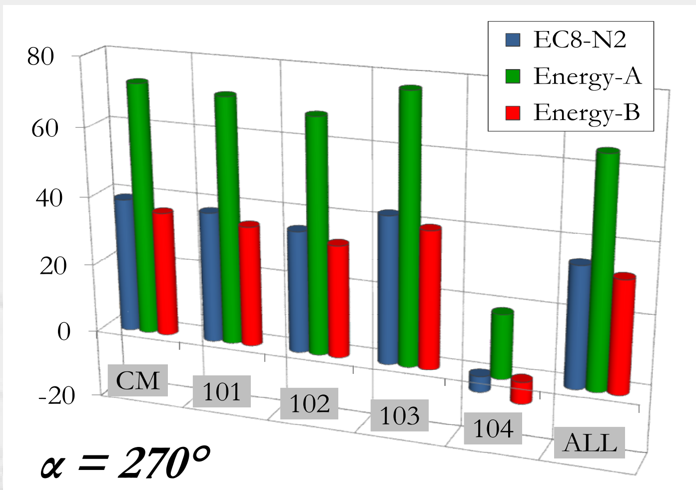


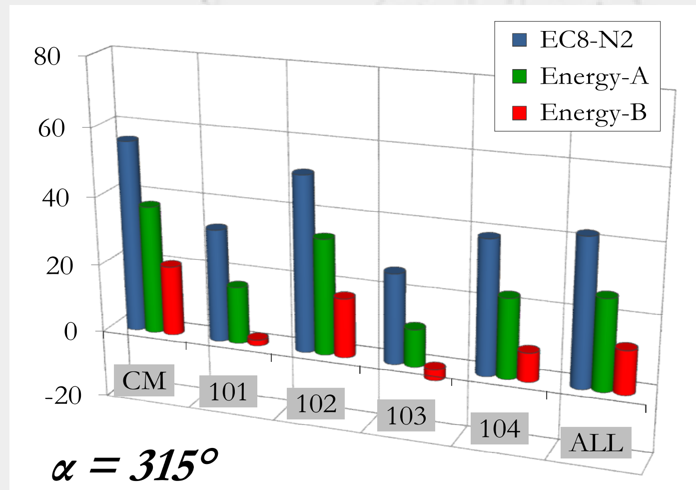
In this case, the pushover analyses, which provide a better approximation, correspond to α-angle ranging from 270 to 360°

3D-MDOF Systems

Procedures Assessment by means of 3D-MDOF system

In **terms of displacement**, when the mean RHA response is compared to estimated performance provide by NLSAs, the **error parameter** is reported below for **α = 270°** and **α = 315°**





As clearly shown by the results expressed by error parameter, when **α = 315°**, which provides the most accurate estimation, the **Energy-based approaches** (Energy B in particular) are a robust tool to evaluate non linear response of system

Conclusions

Conclusions

Main conclusions

Applying an energy-based concept to NLSA allows to achieve several benefits

1. Representation of both structural behavior and seismic demand in terms of (pseudo) energy

2. Introduction of same-energy displacement which avoids the arbitrary selection of a control point (usually rooftop CM)

3. Energy-based procedures provide a robust and accurate estimation of “conventional exact” seismic response (RHA)

4. Evaluations result be more accurate when they are express in terms of displacement and storey drift rather than base shear

Conclusions

Main conclusions

5. Encouraging and comforting results have been found for all SDOF, 2D-MDOF and 3D-MDOF systems

6. A preliminary energy-based approach has been introduced for 3D-MDOF structures, remaining several crucial aspects which require to be investigated

7. Both energy-based NL procedures (En-A, En-B) can be directly applied to practical purposes

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Approccio Energetico per la Valutazione della Risposta Sismica delle Strutture Mediante la Analisi Statica Non Lineare

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