RISPOSTA SISMICA E PROGETTAZIONE SEMPLIFICATA DI STRUTTURE DOTATE DI DISSIPATORI VISCOSI

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Presentation outline

- Background
- Previous studies
- The "five-step procedure" (2010)
- The "direct five-step procedure" (2016-2018)
- Applicative example
- Conclusions and future developments

OBJECTIVES

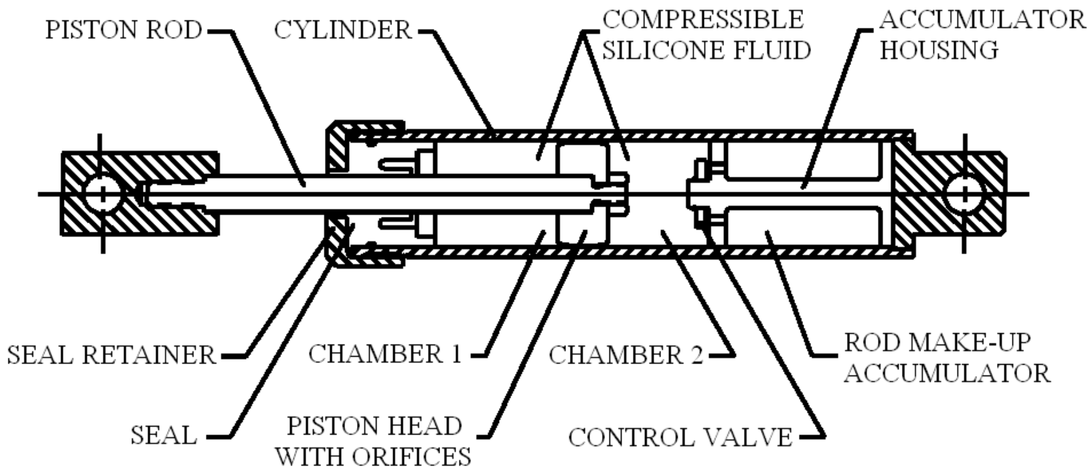
To develop an easy method for preliminary quick design of structures equipped with dampers (for the wide diffusion of their use)

To give fully-analytical tools to the professional engineers for the control of the results of non-linear TH analyses

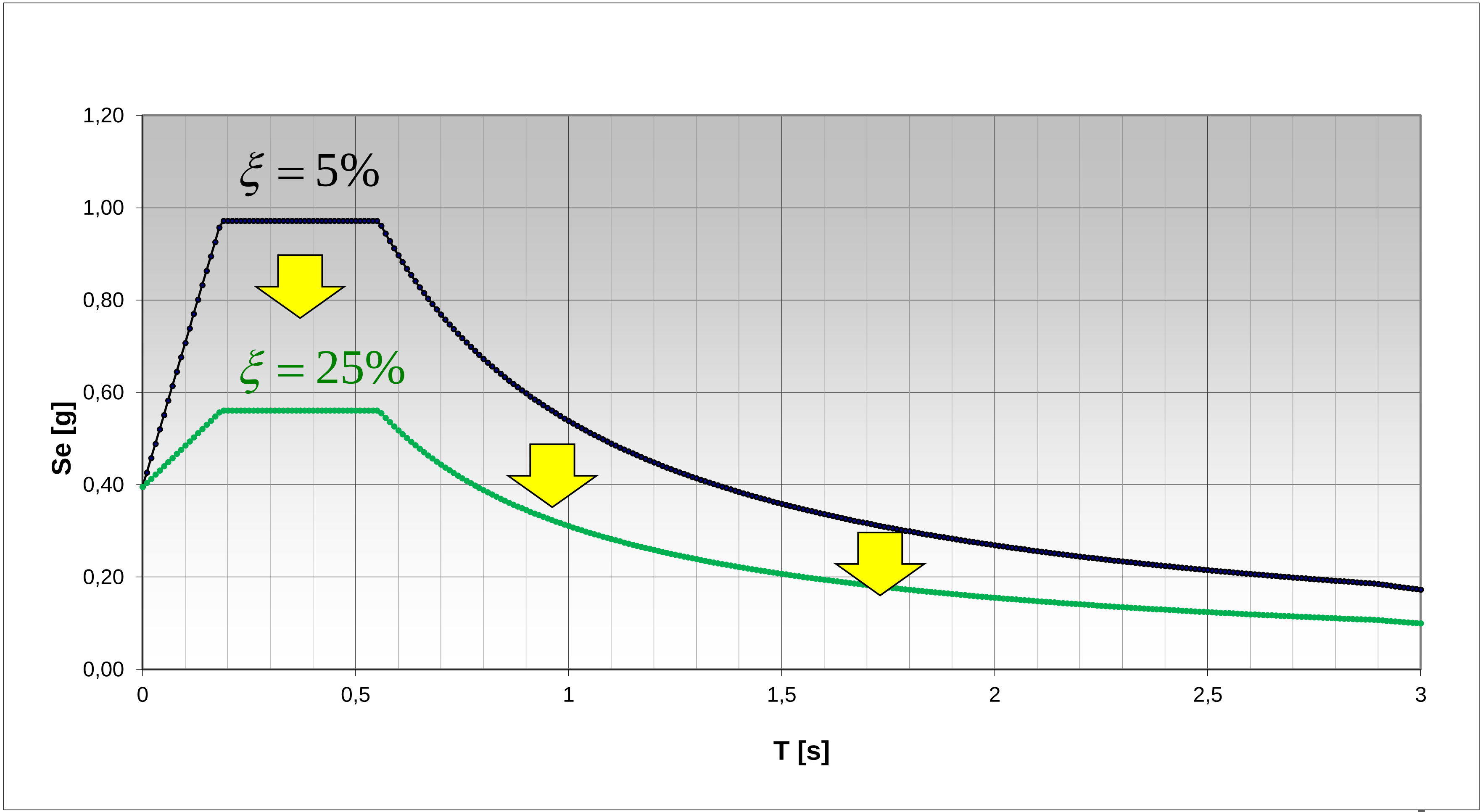
Background

Viscous dampers

energy is dissipated in the guise of **heat** through the passage of a **viscous silicone fluid** (stable w.r.t. temperature) across the piston head with orifices

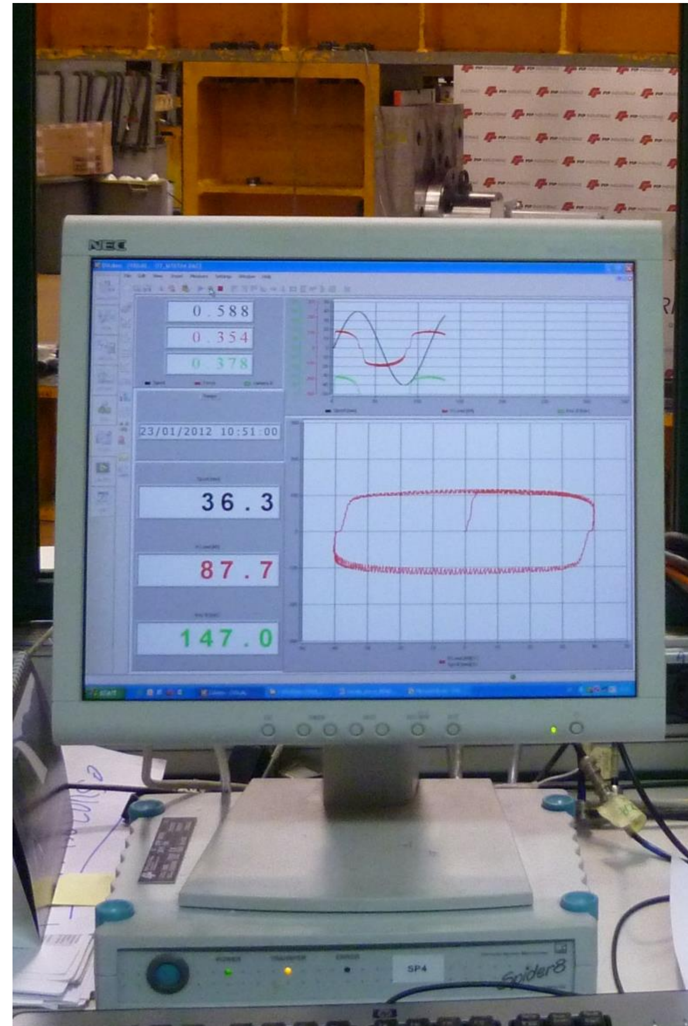


Benefits provided by viscous dampers

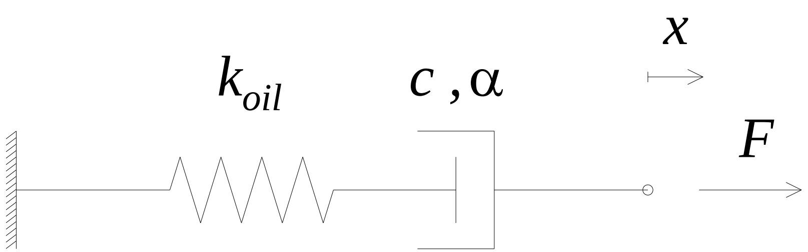


Viscous dampers

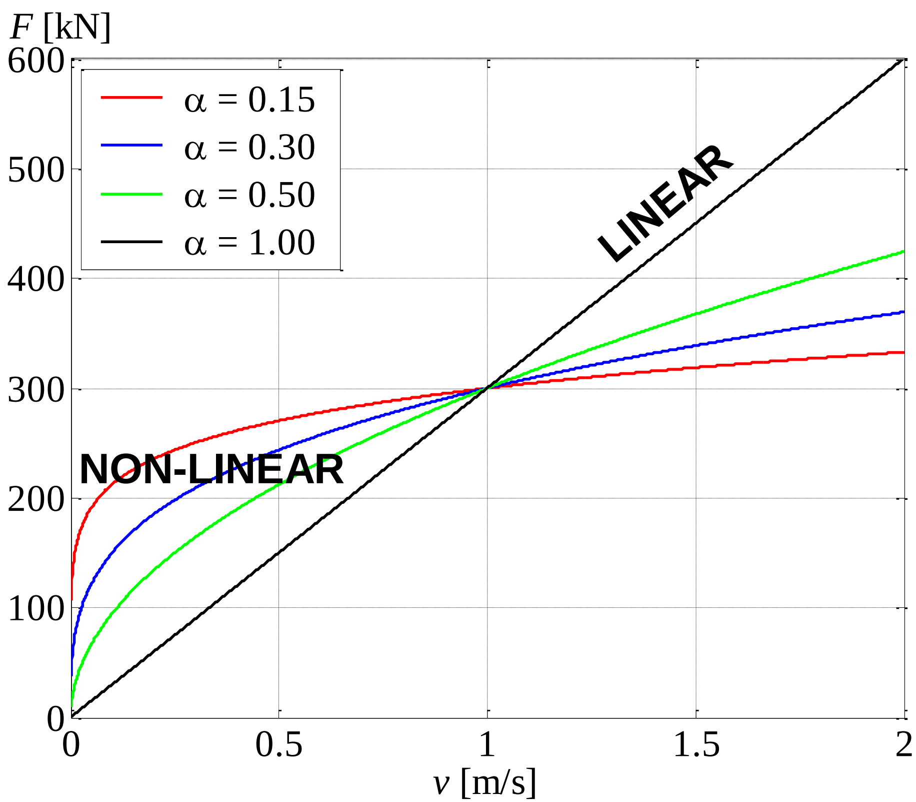
constant velocity tests



Viscous dampers



$$F = k_{oil} \cdot x = c \cdot v^{\alpha}$$

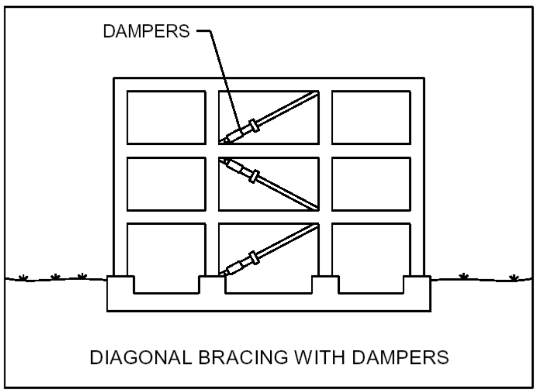


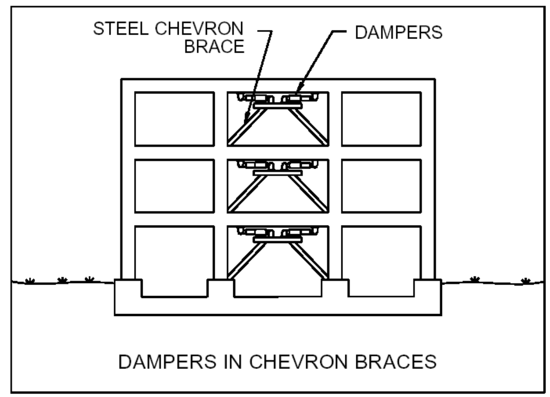
$$\alpha \cong 0.15$$

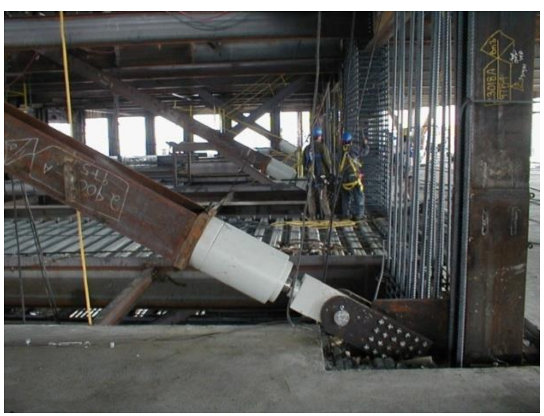
$$k_{oil} = \frac{F_{\max}}{5\% \left(\frac{x_{\max}}{2} \right)}$$

Effectiveness

- The **effectiveness** of fluid viscous dissipative devices in reducing the seismic demand on the structural elements has been demonstrated by a number of research works and real applications since the 1980s.





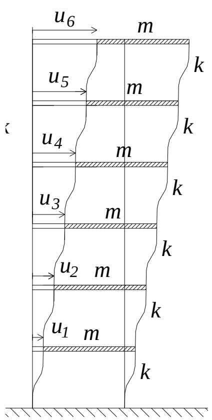


Seismic Dampers installed at the Hotel Woodland, in Woodland, California
Force = 100,000 lbs., Stroke = +/- 2 inches
Production = 16 pieces

Effectiveness

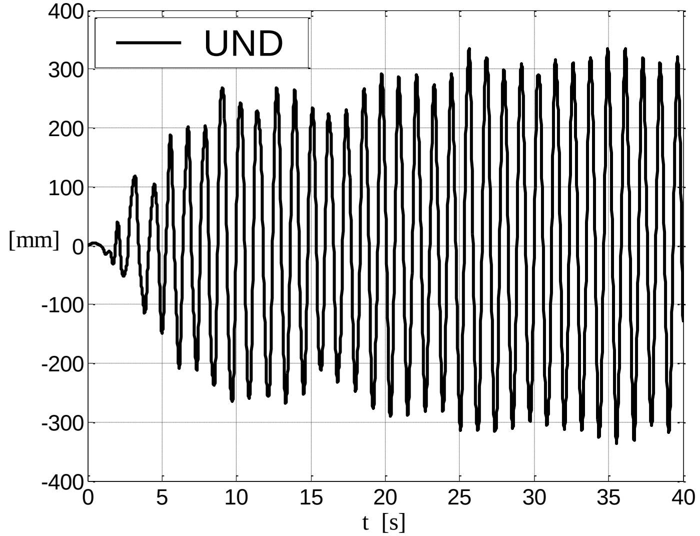
6-DOF

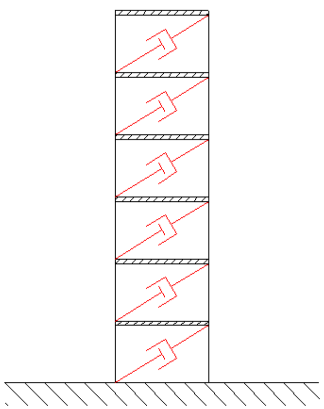
$\bar{c} = 4.452 \cdot 10^6 \ N \cdot s / m$



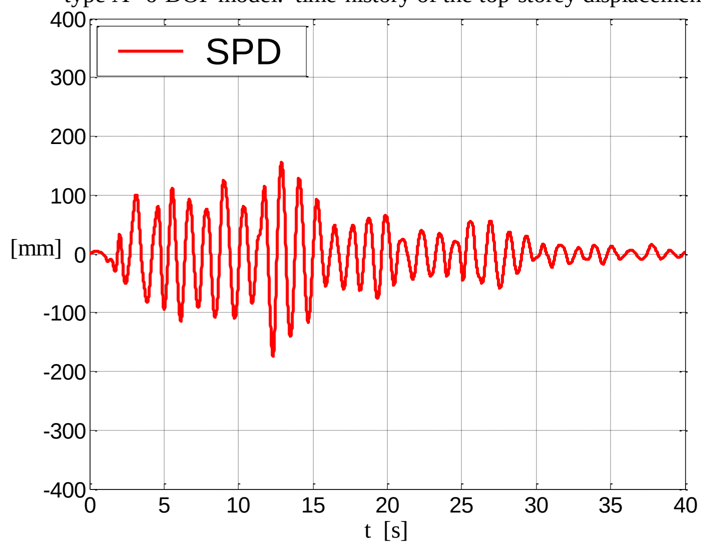
$T_1 = 1.17$s

type A' 6-DOF model: time-history of the top-storey displacement





type A' 6-DOF model: time-history of the top-storey displacement



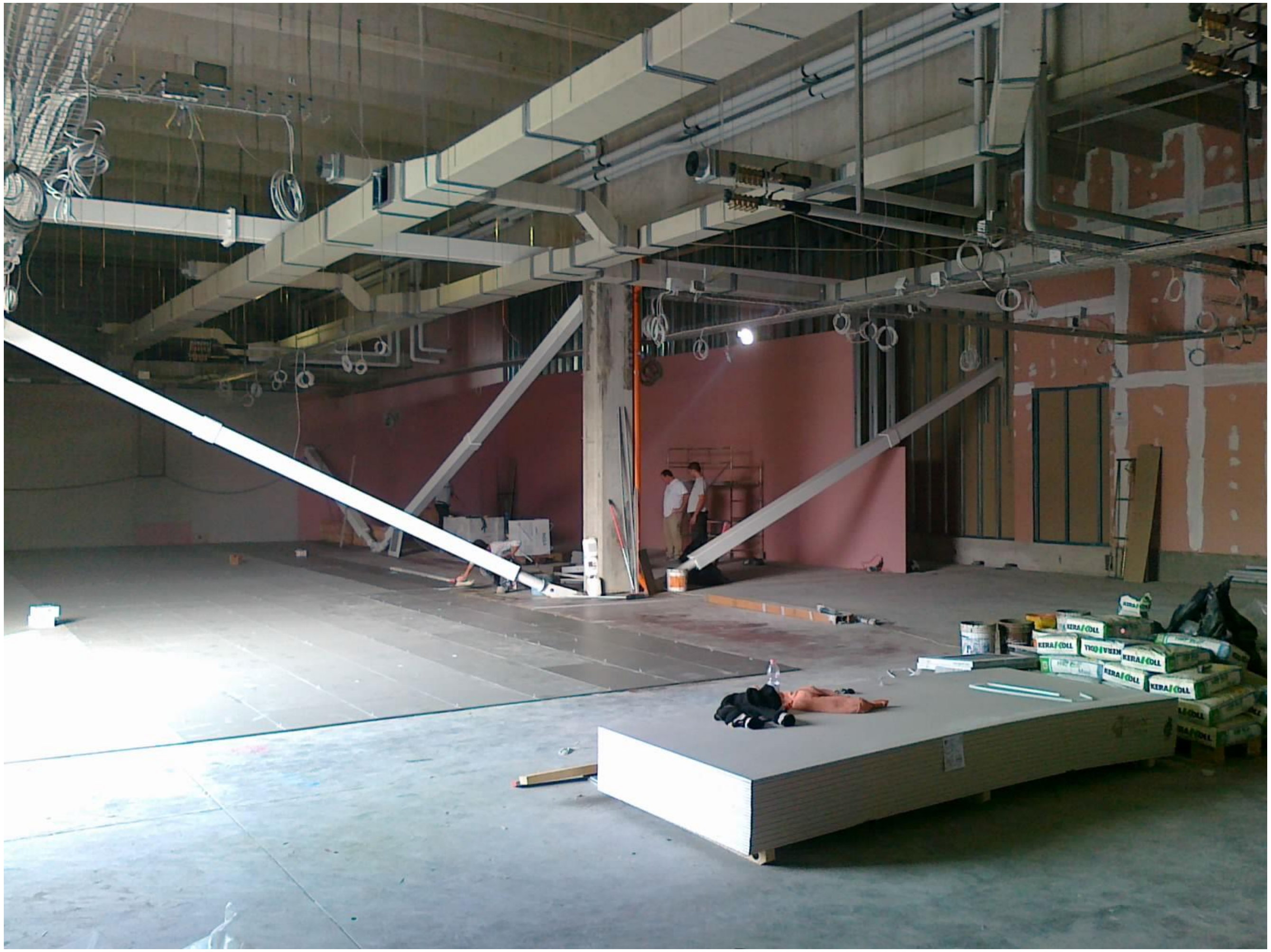
top-storey displacement response

El Centro 1940

scaled to

PGA = 0.3*g*

Real application



pictures courtesy of Ing. Franco Baroni, Studio Ceccoli & Associati, Bologna

dampers manufactured by FIP, Padova, Italy

Real application

pictures courtesy of Ing. Franco Baroni, Studio Ceccoli & Associati, Bologna

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Real application

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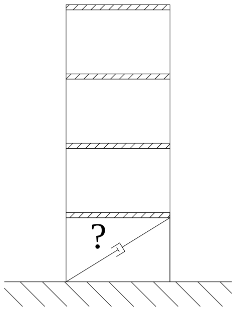
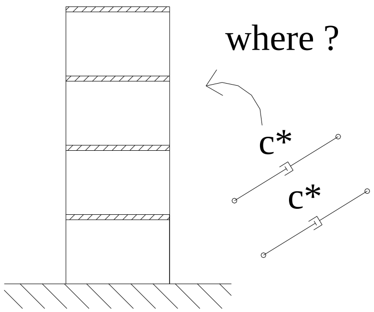
In the scientific literature:

- **Sophisticated numerical algorithms for dampers optimization** (Takewaki 1997, 2000 and 2009, Shukla and Datta 1999, Lopez Garcia 2001, Singh and Moreschi 2002, Levy and Lavan 2006, ...)

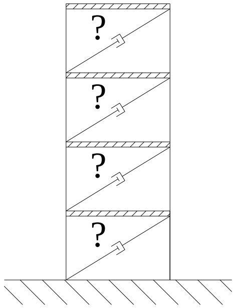


- **Computational expertise and time** (beyond the typical availabilities of the designers) are needed



- **Numerical results** which do not provide physical insight into the matter.

- The issue of developing **simple/analytical methods** in order to size and locate the viscous dampers is still open.



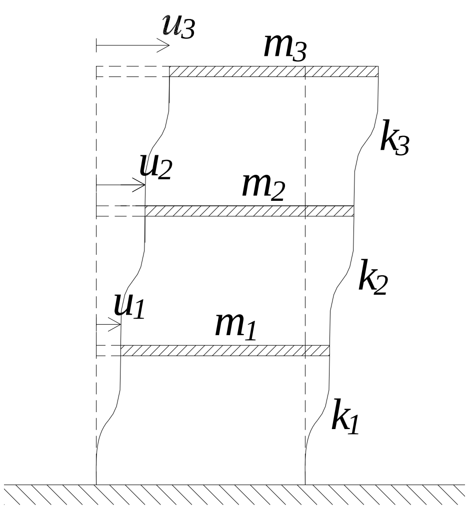
(like equivalent static analysis vs. non-linear time-history analysis)

Design procedures

- **report NCEER-92-0032 (Constantinou and Symans 1992)**
- **report MCEER-00-0010 (Ramirez et al. 2000)**
- **ASCE 7 (2005) Chapter 18**, which is grounded on the MCEER-00-0010 approach and on the works by Ramirez et al. (2002a and b, and 2003) and by Whittaker et al. (2003), contains systematic procedures for design and analysis of building with damping systems (***use of the residual mode approach***).
- **Lopez-Garcia 2001** developed a simple **algorithm** for optimal damper configuration (placement and properties) in MDOF structures, assuming a constant inter-storey height and a straight-line first modal shape.
- **Christopoulos and Filiatrault (2006)** suggested a design approach for estimating the damping coefficients of added viscous dampers consisting in a ***trial and error procedure*****.**
- **Silvestri et al. 2010** → **"five-step procedure"**

Previous studies

Insight into the Rayleigh damping



$$\underset{\sim}{\mathbf{m}}\,\underline{\ddot{\mathbf{u}}} + \underset{\sim}{\mathbf{c}}\,\underline{\dot{\mathbf{u}}} + \underset{\sim}{\mathbf{k}}\,\underline{\mathbf{u}} = -\underset{\sim}{\mathbf{m}}\,\underline{\mathbf{1}}\cdot \ddot{u}_g\left(t\right)$$

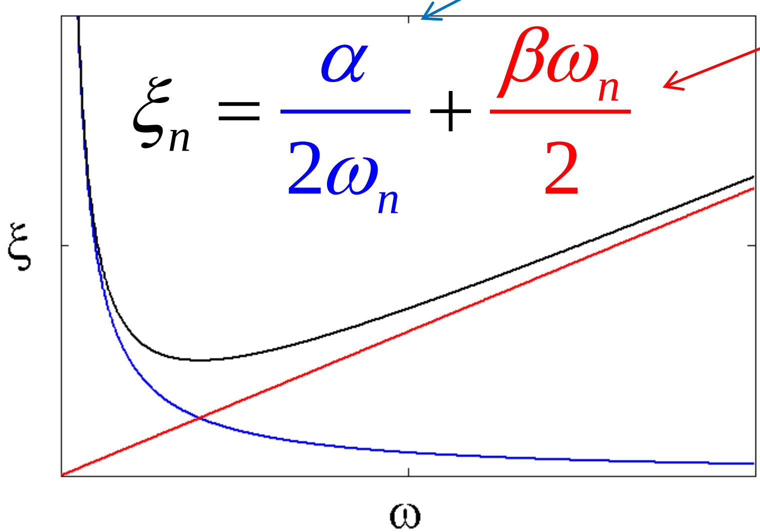
$\underline{\mathbf{u}}$ physical coordinates vector

$\underset{\sim}{\mathbf{m}}$ mass matrix

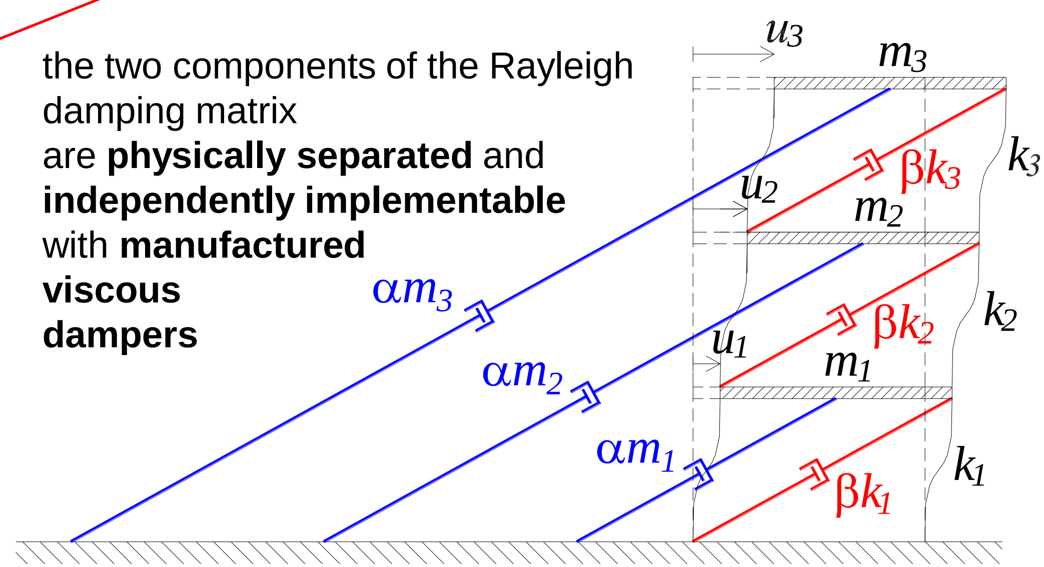
$\underset{\sim}{\mathbf{k}}$ stiffness matrix

$$\underset{\sim}{\mathbf{c}} = \alpha \underset{\sim}{\mathbf{m}} + \beta \underset{\sim}{\mathbf{k}}$$

$$\underset{\sim}{\mathbf{c}} = \alpha \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} + \beta \begin{bmatrix} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix}$$



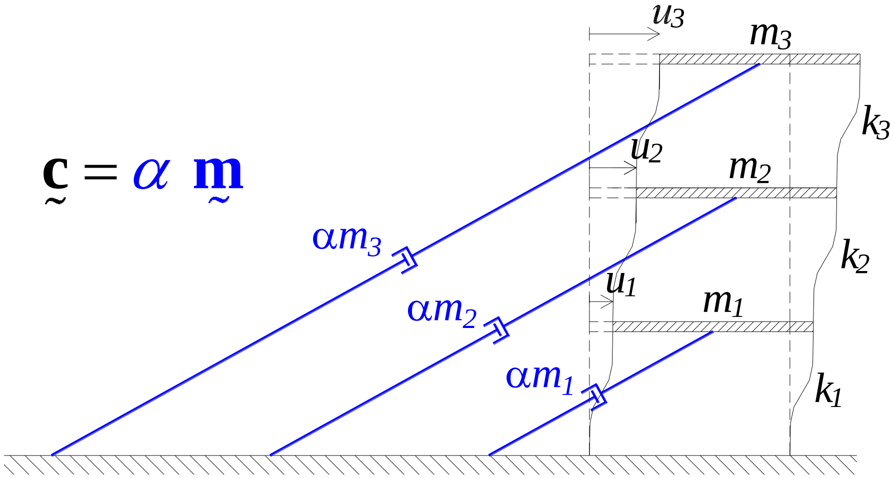
the two components of the Rayleigh damping matrix are **physically separated** and **independently implementable** with **manufactured viscous dampers**

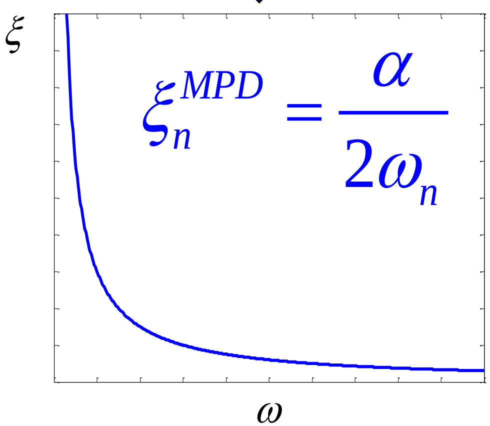


Properties of MPD and SPD systems (1)

Mass Proportional Damping system

$$\underset{\sim}{\mathbf{c}} = \alpha\ \underset{\sim}{\mathbf{m}}$$

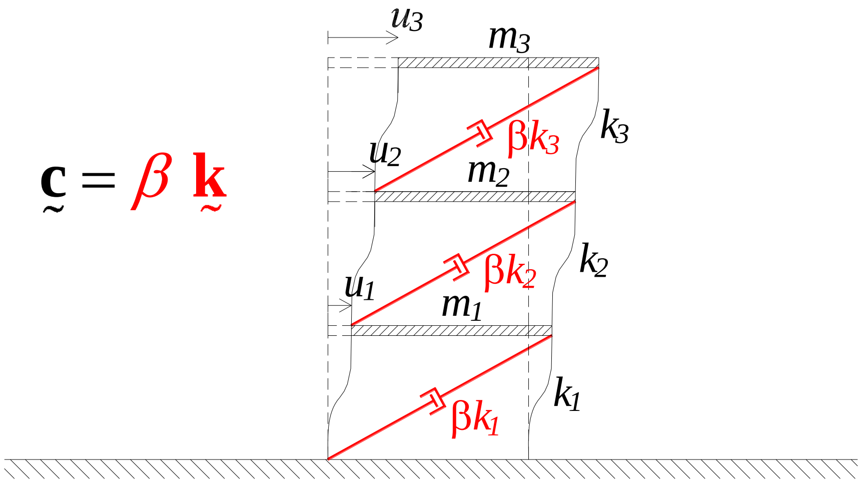


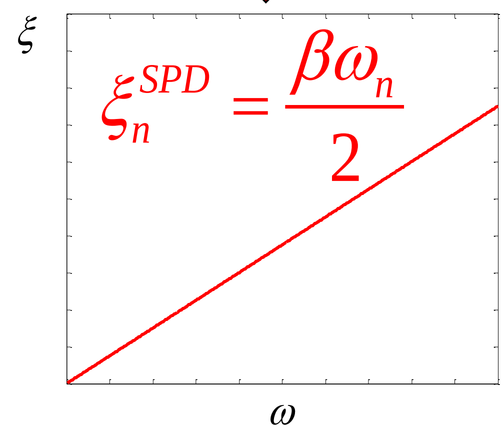


$$\xi_n^{MPD} = \frac{\alpha}{2\omega_n}$$

Stiffness Proportional Damping system

$$\underset{\sim}{\mathbf{c}} = \beta\ \underset{\sim}{\mathbf{k}}$$





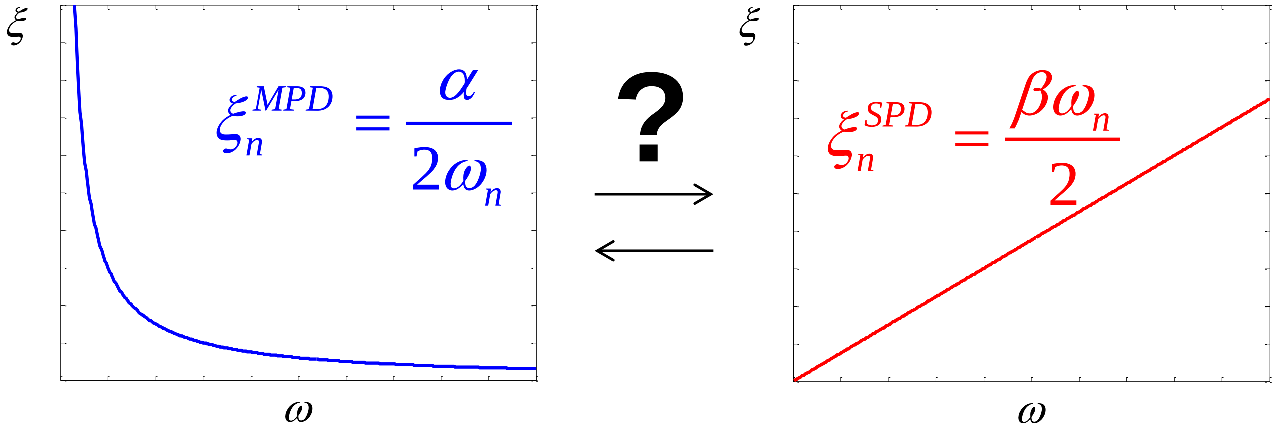
$$\xi_n^{SPD} = \frac{\beta\omega_n}{2}$$

Properties of MPD and SPD systems (2)

HP:

The two systems have equal total damping:

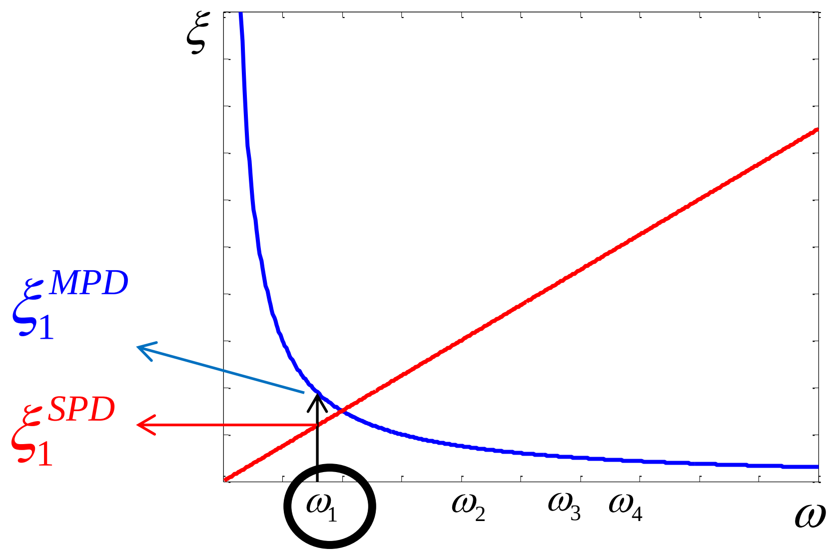
$$c_{tot} = \sum c_i$$



QUESTION:

How the modal damping ratios of the SPD system and the "corresponding" MPD system are related to each other?

$$\xi_1^{MPD} \; \overset{?}{\gtrless} \; \xi_1^{SPD}$$

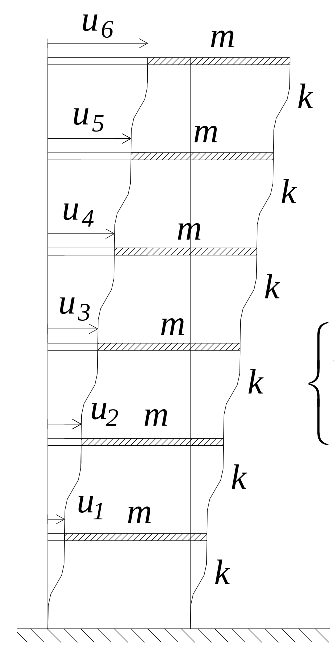


Properties of MPD and SPD systems (3)

From basic dynamics:

$$\frac{\xi_i^{SPD}}{\xi_i^{MPD}} = \frac{\frac{\beta}{2}\omega_i}{\frac{\alpha}{2\omega_i}} = \frac{\beta}{\alpha}\omega_i^2 = \dots$$

HP1) structures characterised by constant values of lateral stiffness *k* and storey mass *m*



$$\begin{cases} k = \text{cost} \\ m = \text{cost} \end{cases}$$

HP2) equal "total cost" constraint

$$\left.\begin{aligned} \bar{\alpha} &= \frac{\bar{c}}{\sum_{i=1}^{N} m_i} = \frac{\bar{c}}{Nm} \\ \bar{\beta} &= \frac{\bar{c}}{\sum_{i=1}^{N} k_i} = \frac{\bar{c}}{Nk} \end{aligned}\right\} \bar{\alpha} m = \bar{\beta} k \;\Rightarrow\; \frac{\bar{\beta}}{\bar{\alpha}} = \frac{m}{k} = \frac{1}{\omega_0^2} \qquad \left(\omega_0 = \sqrt{\frac{k}{m}}\right)$$

$$\frac{\xi_i^{SPD}}{\xi_i^{MPD}} = \frac{\frac{\bar{\beta}}{2}\omega_i}{\frac{\bar{\alpha}}{2\omega_i}} = \frac{\bar{\beta}}{\bar{\alpha}}\omega_i^2 = \frac{\omega_i^2}{\omega_0^2} = \dots$$

$$\frac{\xi_i^{SPD}}{\xi_i^{MPD}} = \frac{\frac{\bar{\beta}}{2}\omega_i}{\frac{\bar{\alpha}}{2\omega_i}} = \frac{\bar{\beta}}{\bar{\alpha}}\omega_i^2 = \frac{\omega_i^2}{\omega_0^2} = \Omega_i^2 = \Lambda_i$$

Properties of MPD and SPD systems (4)

$$\frac{\xi_i^{SPD}}{\xi_i^{MPD}} = \frac{\frac{\bar{\beta}}{2}\omega_i}{\frac{\bar{\alpha}}{2\omega_i}} = \frac{\bar{\beta}}{\bar{\alpha}}\omega_i^2 = \frac{\omega_i^2}{\omega_0^2} = \Omega_i^2 = \Lambda_i$$

→ eigenproblem

The matrix $\underset{\sim}{\mathbf{A}}_N = \frac{1}{\omega_0^2}\underset{\sim}{\mathbf{k}}_N \underset{\sim}{\mathbf{m}}_N^{-1} = \begin{bmatrix} 2 & -1 & 0 & \dots & & & 0 \\ -1 & 2 & -1 & 0 & \dots & & 0 \\ 0 & -1 & 2 & \dots & \dots & & \dots \\ \dots & 0 & \dots & \dots & & & \dots \\ & & \dots & & \dots & -1 & 0 \\ & & & & -1 & 2 & -1 \\ 0 & \dots & & \dots & 0 & -1 & 1 \end{bmatrix}$ has eigenvalues Λ_i

if $\Lambda_i < 1 \Rightarrow \xi_i^{SPD} < \xi_i^{MPD}$ → The *i*-th damping ratio of the SPD system is less then the "corresponding" one of the MPD system (the two systems with same total damping)

Properties of MPD and SPD systems (5)

- It can be demonstrated:

$$\frac{\xi_1^{SPD}}{\xi_1^{MPD}} = \Lambda_1 < 1$$

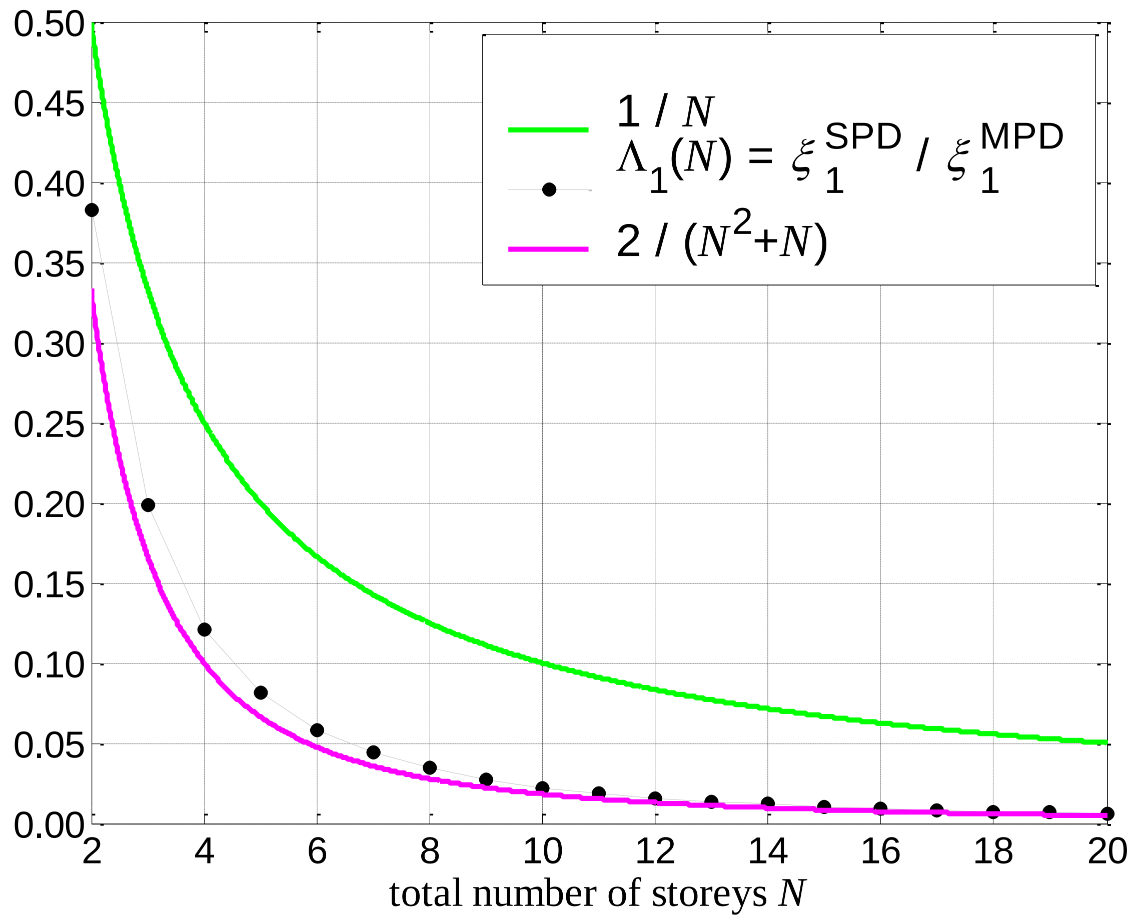
- Upper bound:

$$\frac{\xi_1^{SPD}}{\xi_1^{MPD}} < \frac{1}{N}$$

- Approximation:

$$\frac{\xi_1^{SPD}}{\xi_1^{MPD}} \cong \frac{2}{N(N+1)}$$

*



Trombetti & Silvestri 2006 (JSV)

Properties of MPD and SPD systems (6)

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On the modal damping ratios of shear-type structures equipped with Rayleigh damping systems

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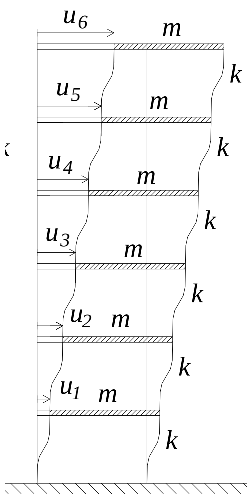
Abstract

The effects of added manufactured viscous dampers upon shear-type structures are analytically investigated here for the class of Rayleigh damping systems. The definitions of mass proportional damping (MPD) and stiffness proportional damping (SPD) systems are briefly recalled and their physical counterpart is derived. From basic physics, a detailed mathematical demonstration that the first modal damping ratio of a structure equipped with the MPD system is always larger than the first modal damping ratio of a structure equipped with the SPD system is provided here. All results are derived for the class of structures characterised by constant values of lateral stiffness and storey mass, under the equal "total size" constraint. The paper also provides closed form demonstrations of other properties of modal damping

Seismic response of MPD and SPD systems

6-DOF

$\bar{c} = 4.452 \cdot 10^6 \; N \cdot s / m$

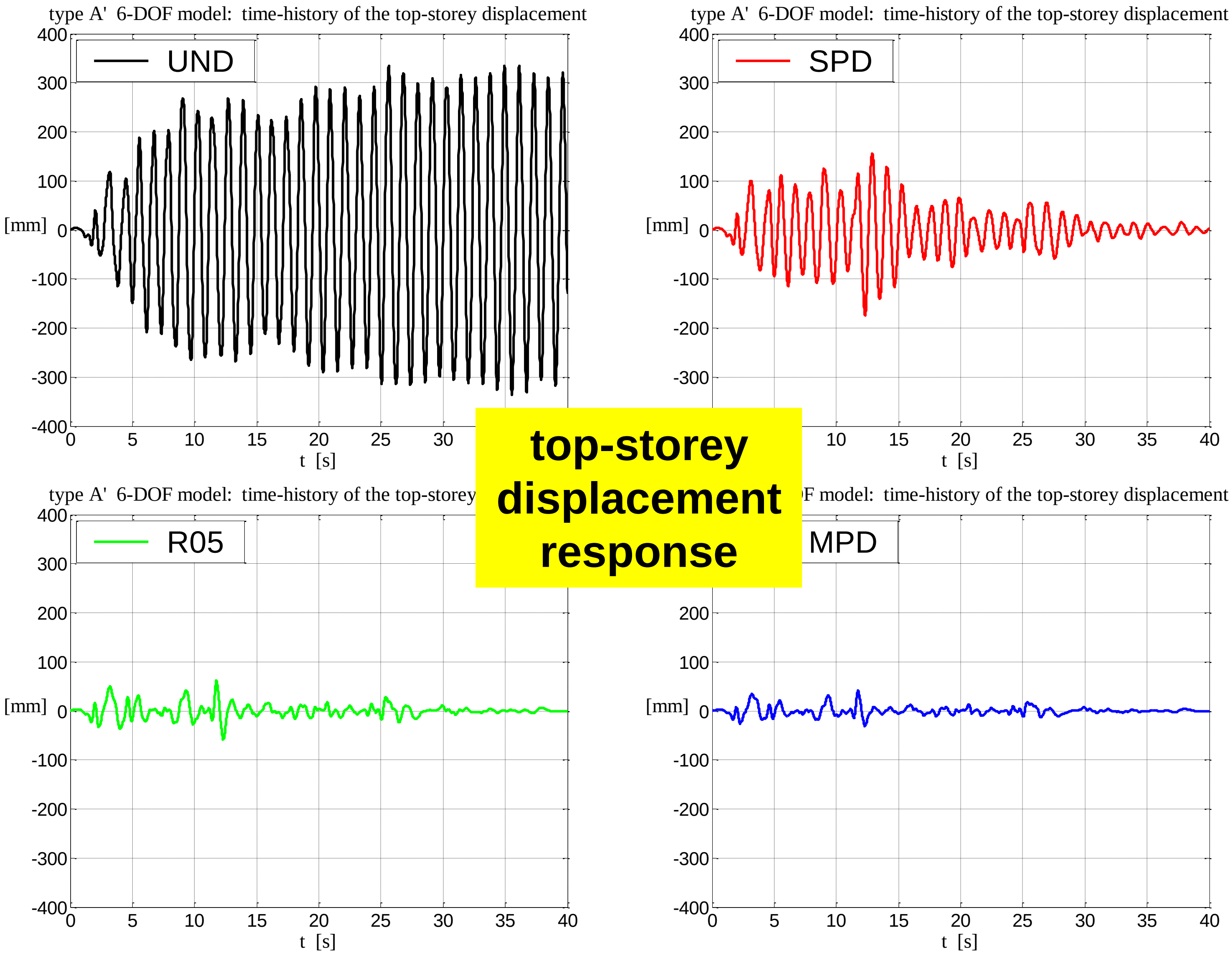


$T_1 = 1.17\text{s}$

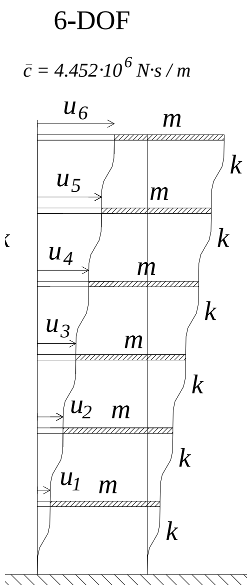
El Centro 1940

scaled to

PGA = 0.3*g*



Seismic response of MPD and SPD systems



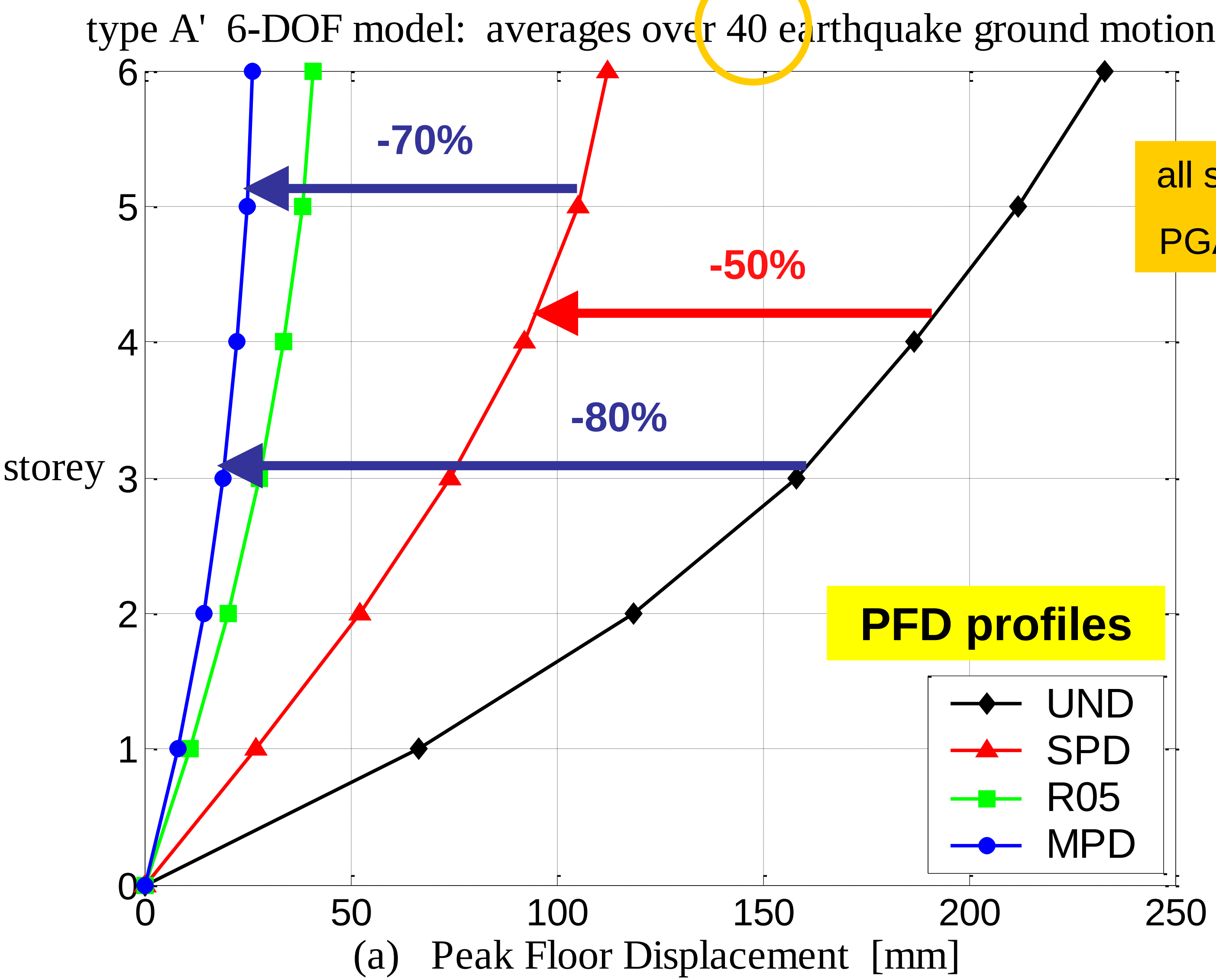
$T_1 = 1.17$s

$\xi_1^{MPD} = 86\%$

$\xi_1^{SPD} = 5\%$

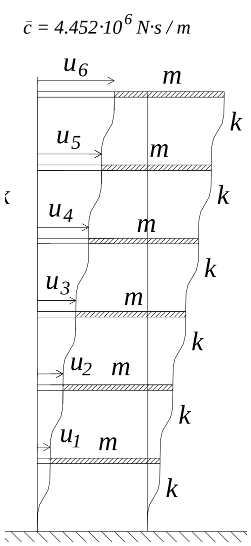
$\xi_2^{MPD} = 29\%$

$\xi_2^{SPD} = 15\%$

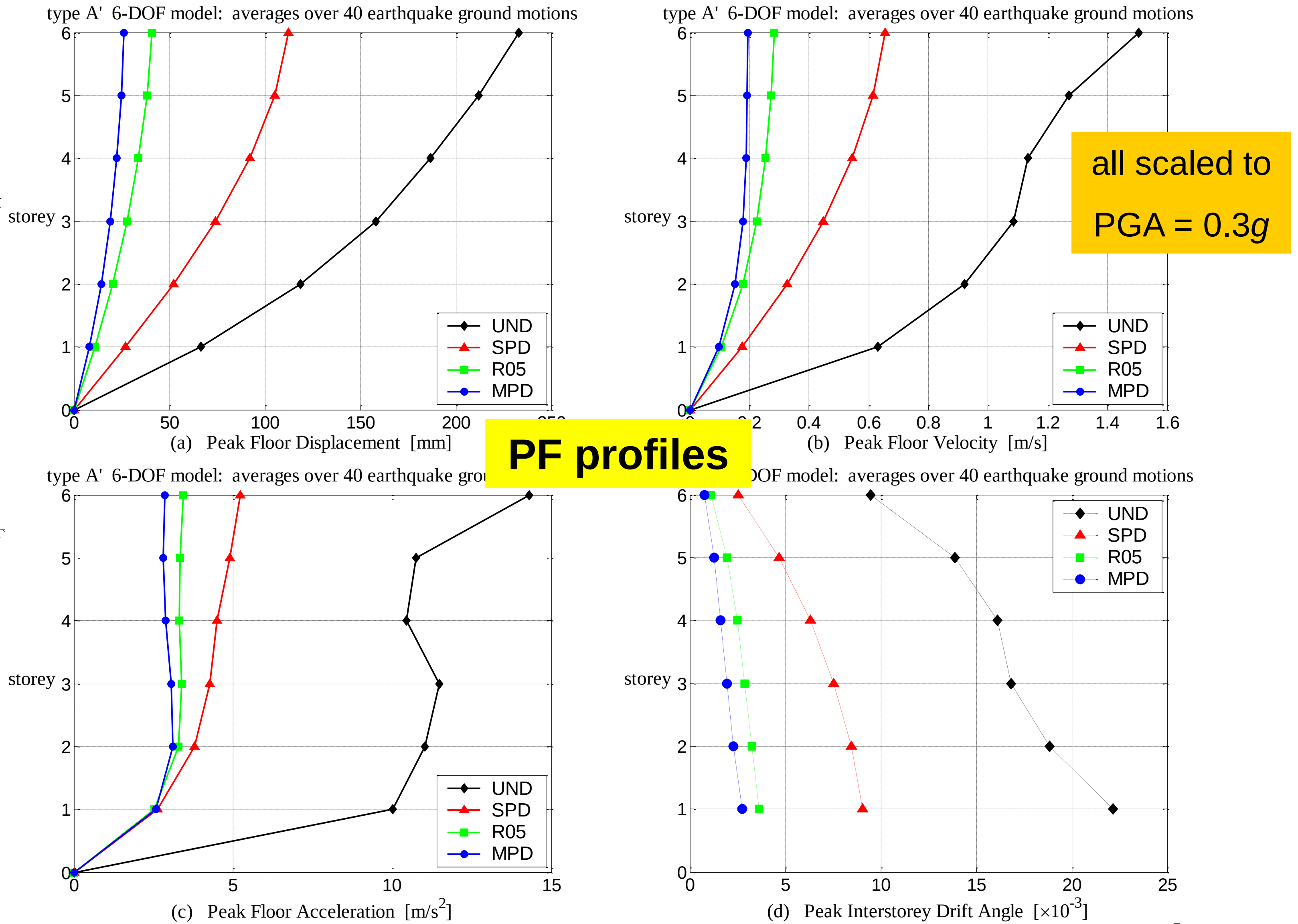


Seismic response of MPD and SPD systems

6-DOF



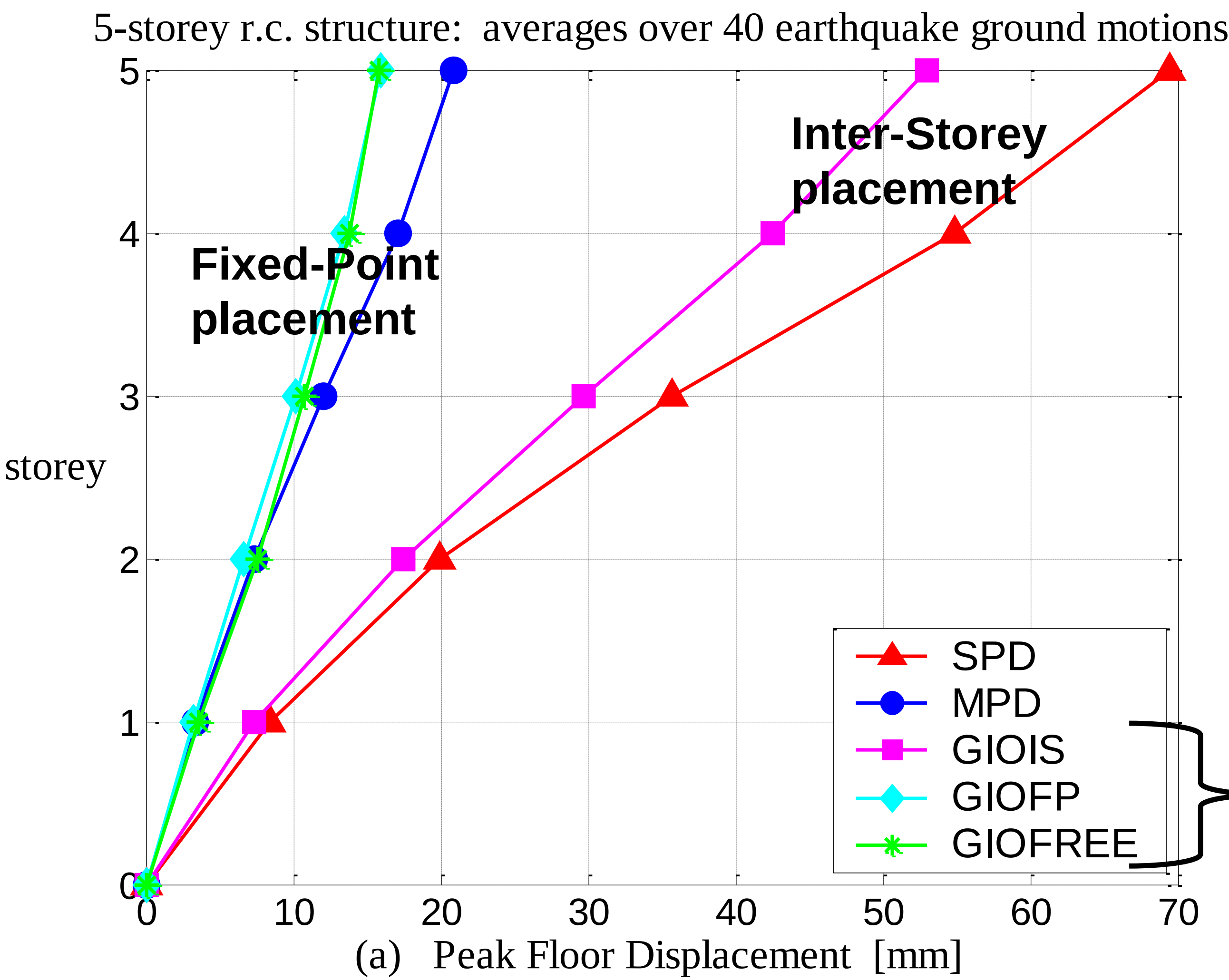
$T_1 = 1.17$s



all scaled to PGA = 0.3*g*

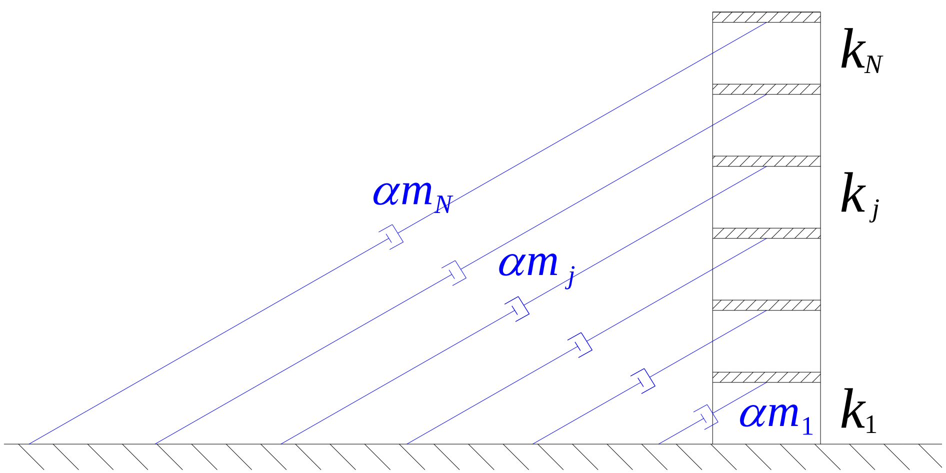
PF profiles

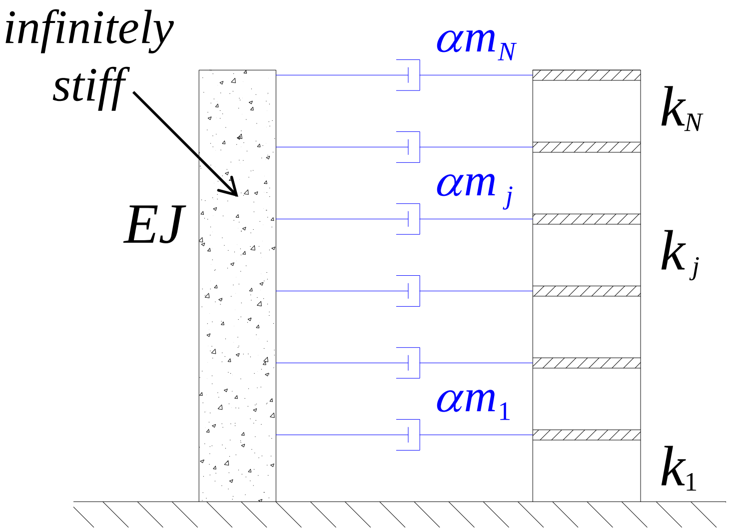
Seismic response of Genetically Identified Optimal (GIO) systems



Objective function: *average of the standard deviations of the interstory drift angles.*

Implementation of MPD systems





DIRECT IMPLEMENTATION

Use of long buckling-resistant braces (mega-braces, unbonded braces, prestressed steel cables, ...)

INDIRECT IMPLEMENTATION

Dampers placed between the structure and a very stiff vertical lateral-resistant element

Properties of MPD and SPD systems (7)

$$\underset{\sim}{\mathbf{c}} = \alpha \, \underset{\sim}{\mathbf{m}}$$

$$\xi_1^{MPD} = \frac{\alpha}{2\omega_1} \qquad \alpha = 2 \cdot \xi_1^{MPD} \cdot \omega_1$$

$$\underset{\sim}{\mathbf{c}} = 2 \cdot \xi_1^{MPD} \cdot \omega_1 \cdot \underset{\sim}{\mathbf{m}}$$

$$c_{storey,j} = 2 \cdot \xi_1^{MPD} \cdot \omega_1 \cdot m_j$$

m_j is easy to be calculated

$$c_{tot,MPD} = 2 \cdot \xi_1^{MPD} \cdot \omega_1 \cdot m_{tot}$$

$$\underset{\sim}{\mathbf{c}} = \beta \, \underset{\sim}{\mathbf{k}}$$

$$\xi_1^{SPD} = \frac{\beta \omega_1}{2} \qquad \beta = \frac{2 \cdot \xi_1^{SPD}}{\omega_1}$$

$$\underset{\sim}{\mathbf{c}} = \frac{2 \cdot \xi_1^{SPD}}{\omega_1} \cdot \underset{\sim}{\mathbf{k}}$$

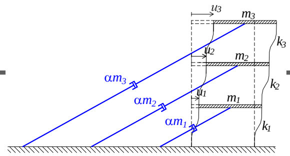
$$c_{storey,j} = \frac{2 \cdot \xi_1^{SPD}}{\omega_1} \cdot k_j$$

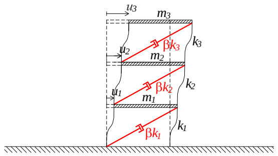
k_j is not so immediate ...

$$c_{tot,SPD} = \ldots$$

?

Properties of MPD and SPD systems (8)





$$c_{tot,MPD} = 2 \cdot \xi_1^{MPD} \cdot \omega_1 \cdot m_{tot}$$

$$\xi_1^{MPD} = \frac{c_{tot}}{2 \cdot \omega_1 \cdot m_{tot}}$$

$$c_{tot,SPD} = 2 \cdot \xi_1^{SPD} \cdot \omega_1 \cdot m_{tot} \cdot \frac{N(N+1)}{2}$$

$$\xi_1^{SPD} = \frac{c_{tot}}{2 \cdot \omega_1 \cdot m_{tot}} \cdot \frac{2}{N(N+1)}$$

$$\xi_1^{SPD} \frac{N(N+1)}{2} = \frac{c_{tot}}{2 \cdot \omega_1 \cdot m_{tot}}$$

$$\xi_1^{MPD} \cong \xi_1^{SPD} \frac{N(N+1)}{2}$$

*

$$\frac{\xi_1^{SPD}}{\xi_1^{MPD}} \cong \frac{2}{N(N+1)}$$

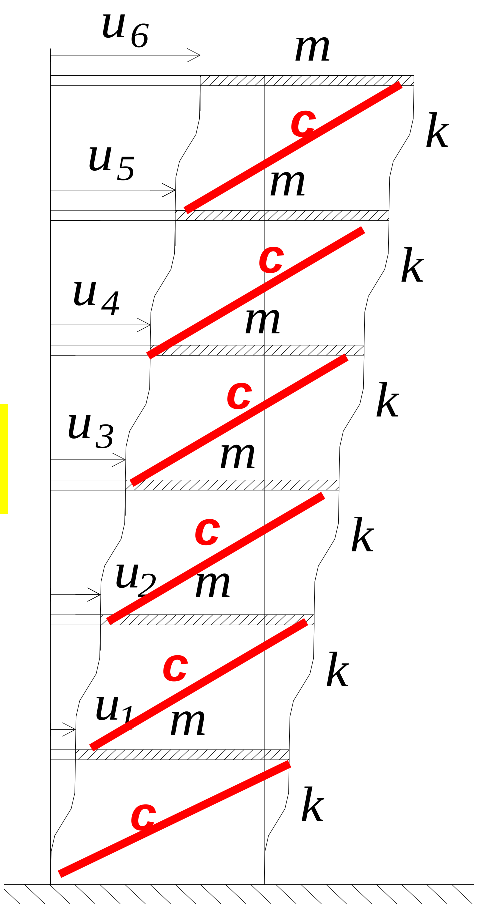
Properties of MPD and SPD systems (9)

If a target damping ratio is looked for: $\xi_1^{SPD} = \bar{\xi}$

the **fundamental results** are:

$$c_{tot,SPD} = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot N(N+1)$$

$$c_{storey,SPD} = \frac{c_{tot,SPD}}{N} = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot (N+1)$$ **



The above equations allow to size the damping coefficients of each damper of an inter-storey dampers system, in order to get a target damping ratio $\bar{\xi}$, **by simply knowing:**

- **the total mass m_{tot}**
- **the fundamental period of vibration T_1 (or ω_1)**
- **the total number of storeys N**

The five-step procedure (2010)

Design strategy

- The design philosophy is **<u>to limit the structural damages</u>** under severe earthquakes.

- The structural elements (columns and beams) should remain **<u>in the elastic phase</u>**.

- Let's keep the **<u>ductility resources</u>** of columns and beams **<u>as an additional property</u>** to withstand very severe and unexpected earthquakes.

The five-step procedure for inter-storey dampers placement

DESIGN PROCESS

STEP 1: performance objectives ⇨ $\bar{\eta} \rightarrow \bar{\xi}$

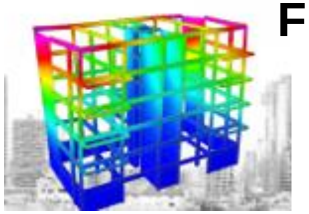
$$\bar{\eta} = \sqrt{\frac{10}{5+\bar{\xi}}}$$

STEP 2: linear dampers ⇨ $\bar{\xi} \rightarrow \bar{c}_L$

$$c_L = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot \left(\frac{N+1}{n} \right)$$

STEP 3: linear TH analyses ⇨ structural response

FEM



⇨ v_{max}

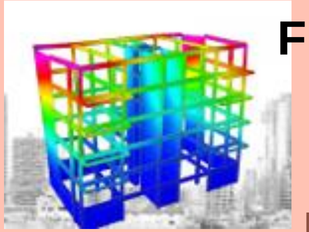
STEP 4: non-linear dampers ⇨ $\bar{c}_L \rightarrow \begin{cases} \bar{c}_{NL} \\ \bar{\alpha} \\ \bar{k}_{oil} \end{cases}$

$$c_{NL} = c_L \cdot (\chi \cdot v_{max})^{1-\alpha}$$

VERIFICATION

STEP 5: non-linear TH analyses ⇨ structural response

FEM



Silvestri et al. 2010 (JEE)

The five-step procedure for inter-storey dampers placement

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A Five-Step Procedure for the Dimensioning of Viscous Dampers to Be Inserted in Building Structures

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and TOMASO TROMBETTI

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Viscous dampers have widely proved their effectiveness in mitigating the effects of the seismic action upon building structures. In view of the large impact that use of such dissipative devices is already having and would most likely have soon in earthquake engineering applications, this article presents a practical procedure for the seismic design of building structures equipped with viscous dampers, which aims at providing practical tools for an easy identification of the mechanical characteristics of the manufactured viscous dampers which allow to achieve target levels of performances. Selected numerical applications are developed with reference to simple, but yet relevant, cases.

Keywords Added Viscous Dampers; Seismic Design; Design Procedure; Nonlinear Modeling; Damping Ratio

Starting point

$\bar{\eta}$

$$\bar{\eta} = \frac{V_{base,\xi}}{V_{base,\xi=5\%}}$$

$$\bar{\eta} = \frac{M_{Ed,\xi}}{M_{Ed,\xi=5\%}}$$

$$\bar{\eta} = \frac{\delta_{top-storey,\xi}}{\delta_{top-storey,\xi=5\%}}$$

EXAMPLE:

If the bending moment action at the base of a column is $M_{Ed,\xi=5\%}$ = 1000 kNm and if the bending moment resistance is M_{Rd} = 500 KNm

then

we want that dampers lead to $M_{Ed,\xi}$ = 500 kNm

$$\bar{\eta} = \frac{500}{1000} = 0.5$$

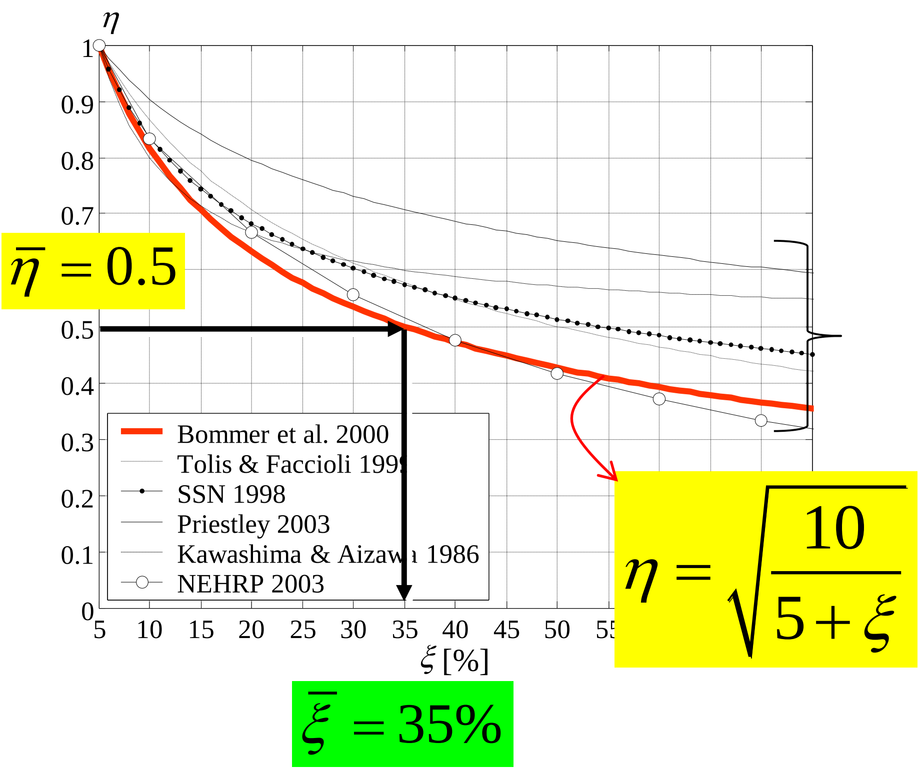
$$\bar{\eta} = \frac{\text{target seismic demand (i.e. capacity/strength or acceptable action or drift)}}{\text{actual seismic demand with no dampers}}$$

Step 1

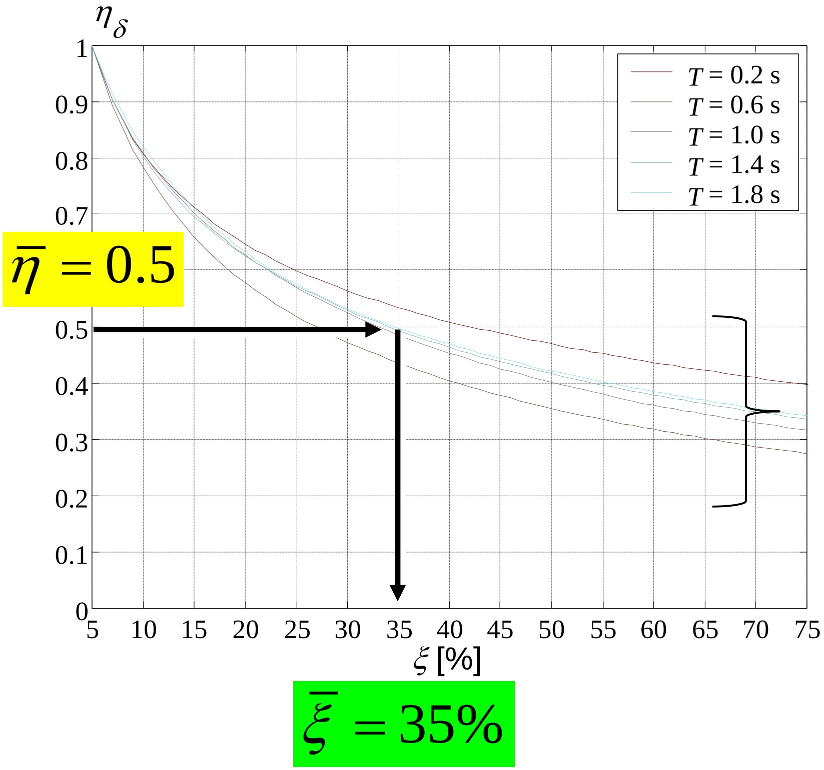
$\bar{\eta} \longrightarrow \bar{\xi}$

Some available formulations to relate $\bar{\eta} \longrightarrow \bar{\xi}$

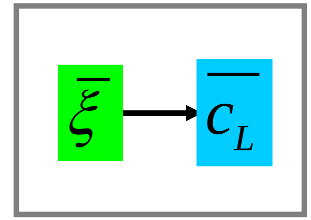
Cardone, Dolce, Rivelli (ANIDIS 2007)



mean SDOF response from T-H analyses

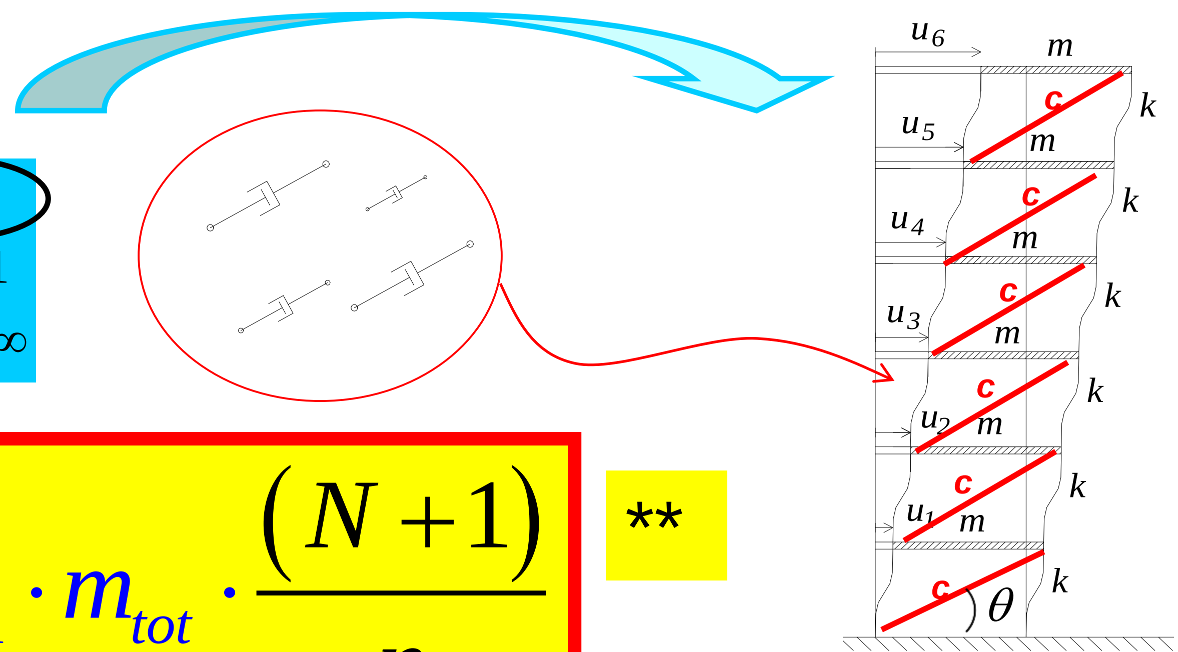


Step 2



Preliminary sizing of linear viscous damper using analytical formula **

$$\begin{cases} c_L \\ \alpha = 1 \\ k_{oil} = \infty \end{cases}$$



$$c_L = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot \frac{(N+1)}{n}$$

**

$$c_{L,\text{inclined}} = c_{L,\text{horizontal}} \cdot \left(\frac{1}{\cos^2 \theta} \right)$$

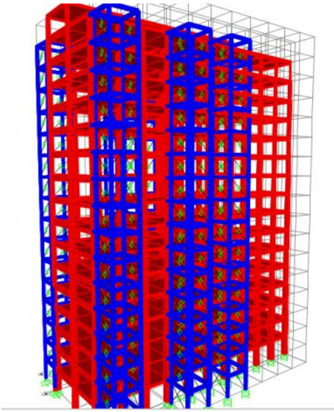
n = number of dampers at a given storey in a given direction

Step 3

FEM
simulations

After linear viscous dampers are dimensioned

$$c_L = \overline{c_L} \quad , \quad \alpha = 1 \quad , \quad k_{oil} = \infty$$



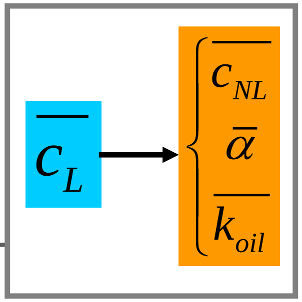
Linear TH dynamic analyses are necessary in order to:

1. Verify by means of **snap-back tests** that the actual damping properties of the model are in line with the expected ones (e.g. **target damping ratio is achieved**) $\overline{\xi}$

2. Calculate the **maximum working velocities of the linear dampers** v_{max}

3. Calculate **the maximum damper piston-strokes** x_{max}

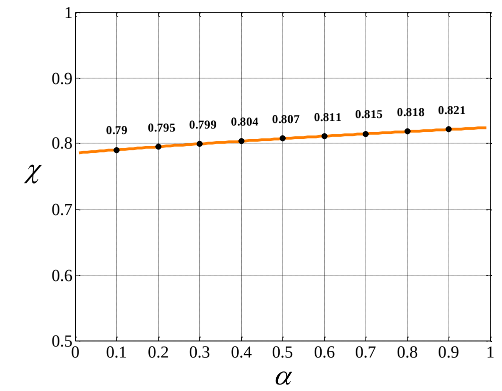
Step 4



ENERGETIC APPROACH:

equal energy dissipated over a full cycle of harmonic motion

$$E_{d,L} = E_{d,NL} \longrightarrow \overline{c_{NL}} = \overline{c_L} \cdot \left(\chi \cdot v_{\max}\right)^{1-\bar{\alpha}}$$

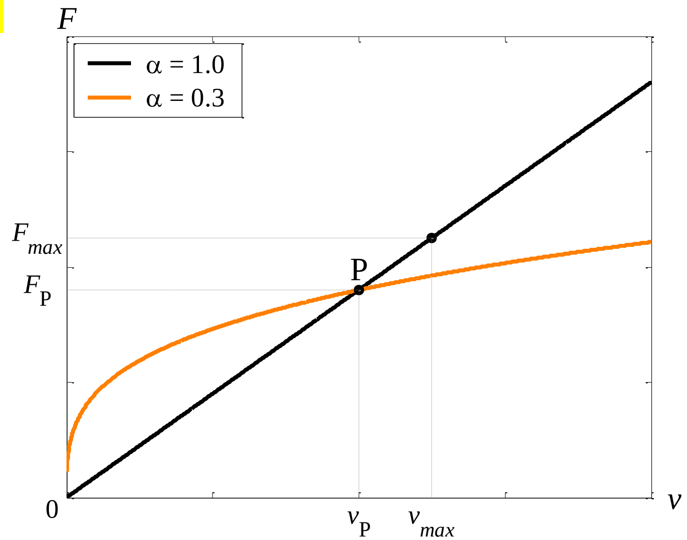


$$\chi = \left(\frac{\sqrt{\pi}}{2} \frac{\Gamma\left(\frac{\bar{\alpha}+3}{2}\right)}{\Gamma\left(\frac{\bar{\alpha}+2}{2}\right)} \right)^{\frac{1}{1-\bar{\alpha}}} \cong 0.8 \quad , \quad \forall \alpha$$

REFERENCE POINT P:

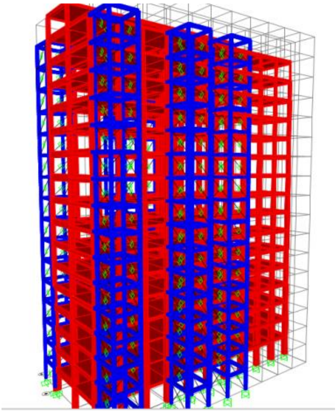
$$v_P = 0.8 \cdot v_{\max}$$

$$F_P = 0.8 \cdot \overline{c_L} \cdot v_{\max}$$



Step 5

FEM
simulations



After non-linear viscous dampers are dimensioned

$$c_{NL} = \overline{c_{NL}} \quad , \quad \alpha = \bar{\alpha} \quad , \quad k_{oil} = \overline{k_{oil}} \geq 10 \cdot c_L \cdot \omega_1$$

Non-linear TH dynamic analyses are necessary in order to:

1. Verify the effectiveness of the non-linear dampers in reducing the global structural response (e.g. **target damping ratio is achieved, maximum forces in the structural elements are acceptable**)

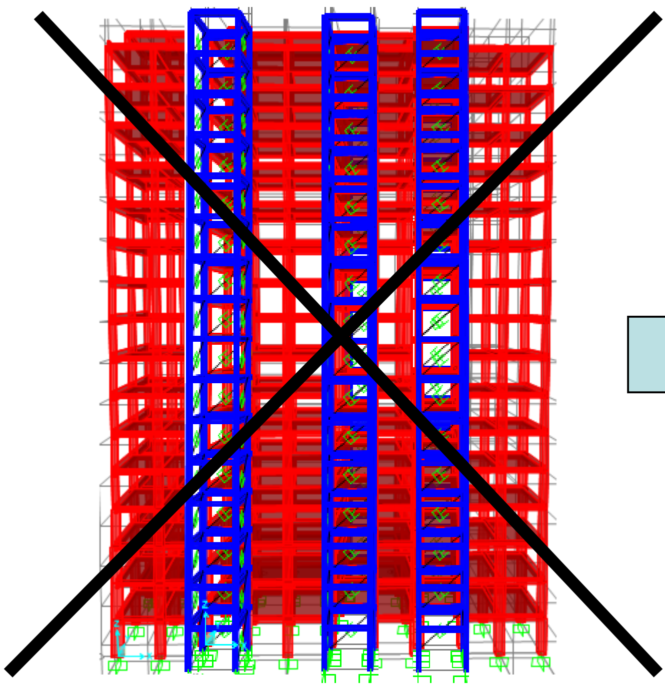
2. Evaluate the **maximum damper forces in the non-linear dampers**

3. Evaluate **the maximum strokes in the non-linear dampers**

The direct five-step procedure (2016-2018)

A step forward:
a <u>direct</u> five-step procedure

The challenge:
Can we directly design (at least PRELIMINAR SIZING) the viscous dampers and the frames without performing TH dynamic analyses?



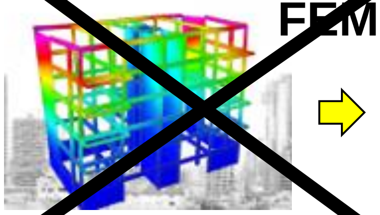
The five-step procedure for inter-storey dampers placement

DESIGN PROCESS

STEP 1: performance objectives ⇨ $\bar{\eta} \rightarrow \bar{\xi}$ $\bar{\eta} = \sqrt{\dfrac{10}{5+\bar{\xi}}}$

STEP 2: linear dampers ⇨ $\bar{\xi} \rightarrow \overline{c_L}$ $c_L = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot \left(\dfrac{N+1}{n}\right)$

STEP 3: linear TH analyses ⇨ structural response

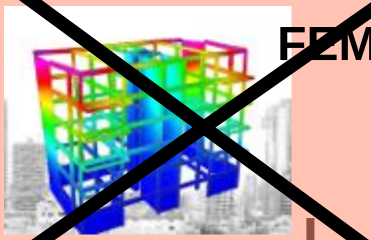


⇨ v_{max}

STEP 4: non-linear dampers ⇨ $\overline{c_L} \rightarrow \begin{cases} \overline{c_{NL}} \\ \bar{\alpha} \\ \overline{k_{oil}} \end{cases}$ $c_{NL} = c_L \cdot (\chi \cdot v_{max})^{1-\alpha}$

VERIFICATION

STEP 5: non-linear TH analyses ⇨ structural response



Silvestri et al. 2010 (JEE)

The five-step procedure for inter-storey dampers placement

DESIGN PROCESS

STEP 1: performance objectives ⇨ $\bar{\eta} \rightarrow \bar{\xi}$ $\quad \bar{\eta} = \sqrt{\dfrac{10}{5+\bar{\xi}}}$

STEP 2: linear dampers ⇨ $\bar{\xi} \rightarrow \overline{c_L}$ $\quad c_L = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot \left(\dfrac{N+1}{n}\right)$

STEP 3: linear TH analyses ⇨ structural response

1. Estimation of inter-storey velocities

STEP 4: non-linear dampers ⇨ $\overline{c_L} \rightarrow \begin{cases} \overline{c_{NL}} \\ \bar{\alpha} \\ \overline{k_{oil}} \end{cases}$ $\quad c_{NL} = c_L \cdot \left(\chi \cdot v_{\max}\right)^{1-\alpha}$

VERIFICATION

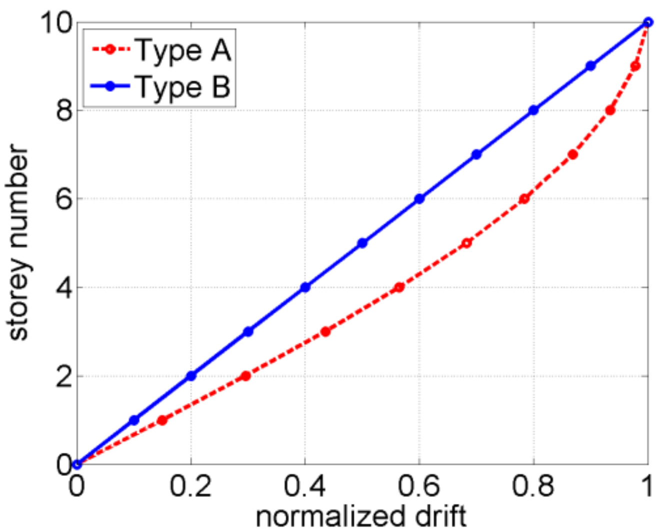
STEP 5: non-linear TH analyses ⇨ structural response

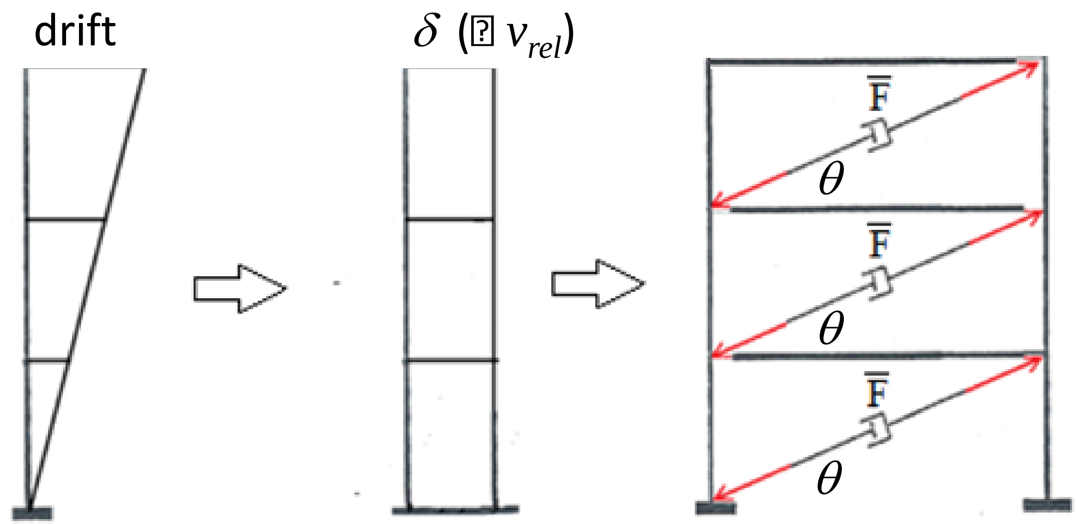
2. Equivalent Static Analysis (ESA)

Silvestri et al. 2010 (JEE)

1. Inter-storey velocities and damper forces

Analytical Estimations Based On First Mode Response





B

$$\delta_{\max} = \frac{S_{e,\xi}(T_1)}{\omega_1^2} \cdot \frac{2}{(N+1)} \Rightarrow v_{\max} = \frac{S_{e,\xi}(T_1)}{\omega_1} \cdot \frac{2}{(N+1)} \cdot \cos\theta \Rightarrow F_{D\max} = \frac{2 \cdot \xi \cdot m_{tot} \cdot S_{e,\xi}(T_1)}{\cos\theta}$$

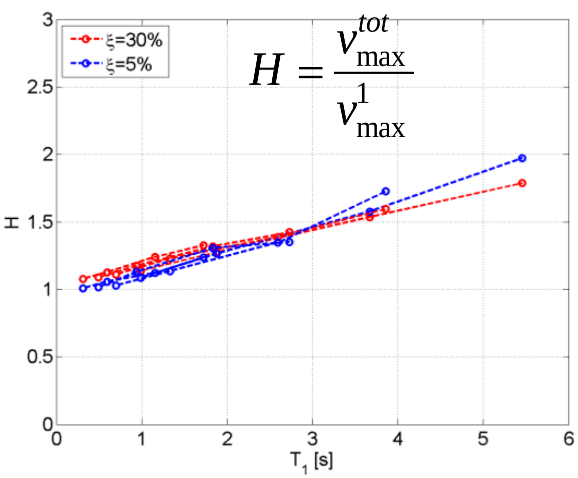
A

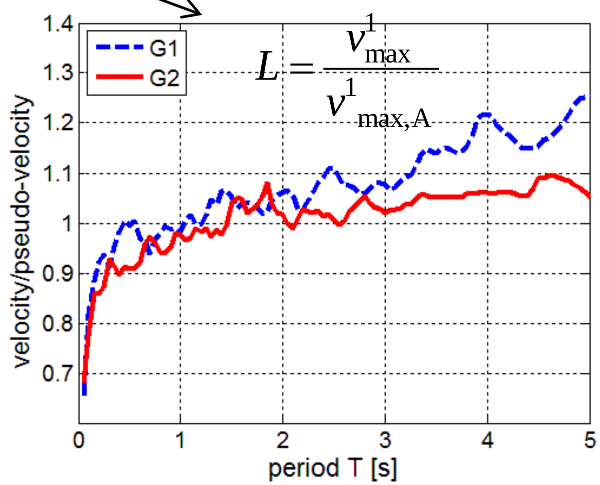
$$\delta_{\max} = \frac{S_{e,\xi}\left(T_1\right)}{\omega_1^2} \frac{12N}{\left(2+5N+5N^2\right)} \Rightarrow \ldots$$

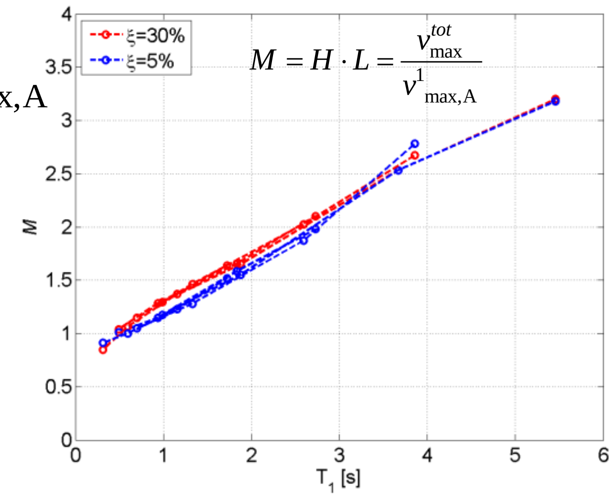
Palermo et al. 2016 (BEE)

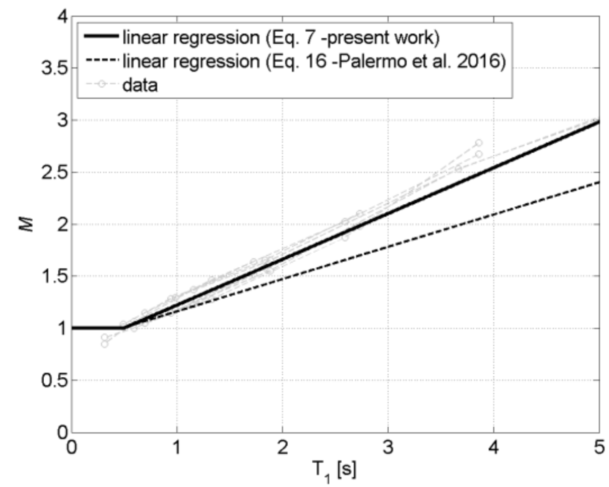
1. Higher modes contribution

$$v^{tot}_{max} = \left(\frac{v^{tot}_{max}}{v^{1}_{max}}\right) \cdot \left(\frac{v^{1}_{max}}{v^{1}_{max,A}}\right) \cdot v^{1}_{max,A} = H \cdot L \cdot v^{1}_{max,A} = M \cdot v^{1}_{max,A}$$







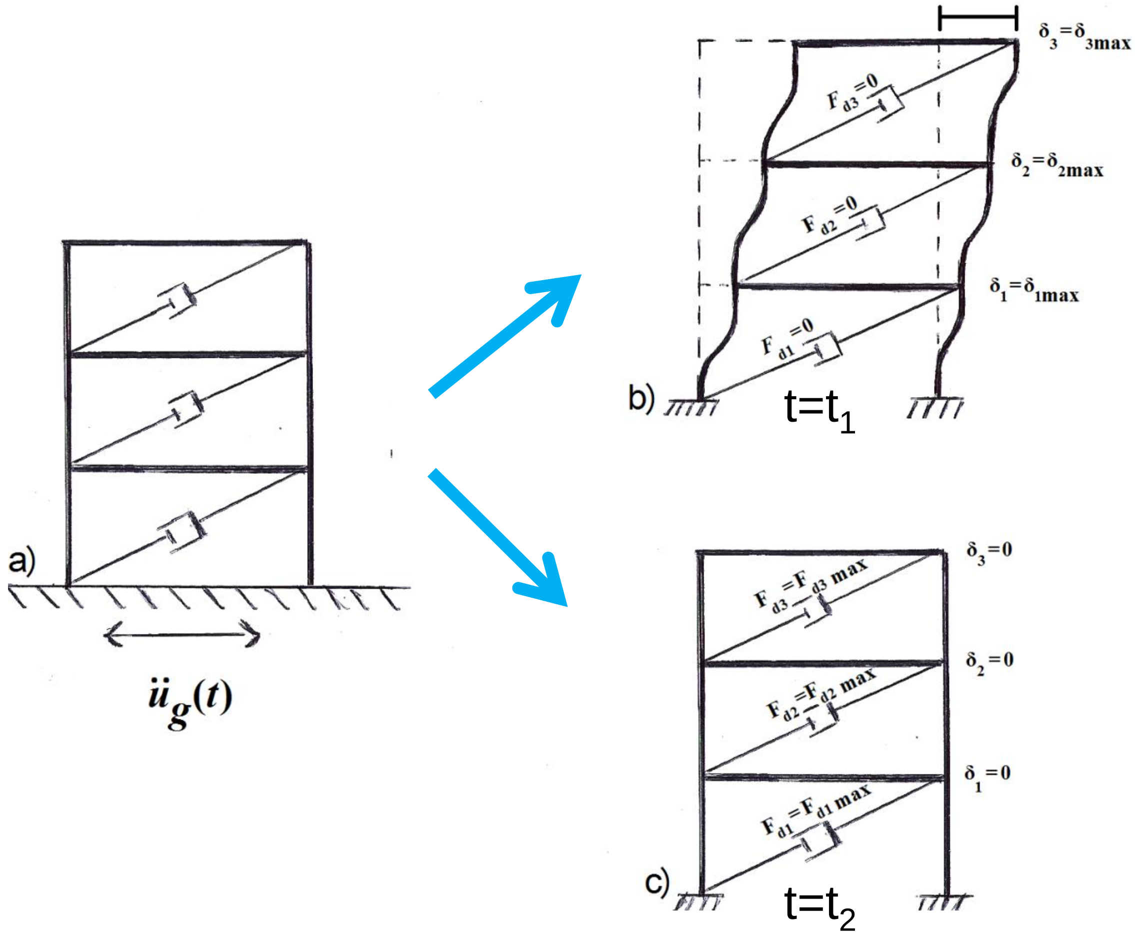


$$v^{tot}_{max,A} = \begin{cases} \dfrac{12N}{(2+5N+5N^2)} \cdot \dfrac{S_a(T_1)}{\omega_1} & \text{for } T_1 \le 0.5s \\ (0.44 \cdot T_1 + 0.78) \cdot \dfrac{12N}{(2+5N+5N^2)} \cdot \dfrac{S_a(T_1)}{\omega_1} & \text{for } 0.5 < T_1 \le 5.0s \end{cases}$$

correction factor *M*

Palermo et al. 2017 (SDEE)

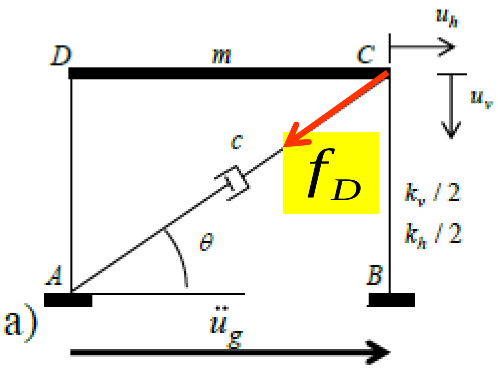
2. Equivalent Static Analysis for damped structures



Maximum Lateral Displacement Configuration (ESA1)

Maximum Velocity (Max Damper Force) Configuration (ESA2)

2. The rationale behind ESA: the damped frame



dynamic equations

$$\begin{cases} f_{Ih} + f_{Dh} + f_{Sh} = 0 \\ f_{Iv} + f_{Dv} + f_{Sv} = 0 \end{cases}$$

two coupled equations (due to the damper)

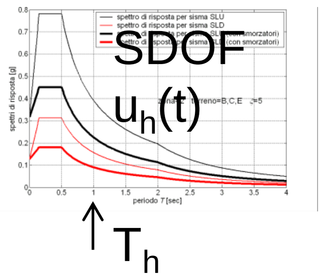
$$\begin{cases} m\ddot{u}_h + c_h\dot{u}_h + c_{hv}\dot{u}_v + k_h u_h = -m\ddot{u}_g(t) \\ m\ddot{u}_v + c_{hv}\dot{u}_h + c_v\dot{u}_v + k_v u_v = 0 \end{cases}$$

k_v □ k_h

$\dot{u}_v$ can be neglected in the first equation

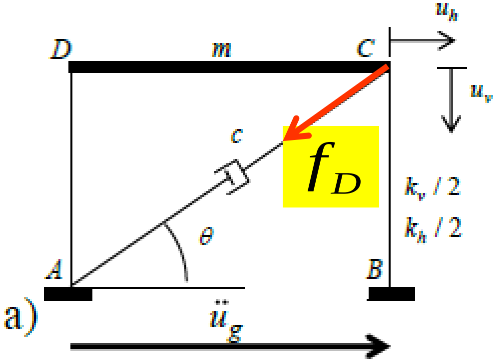
first equation (only in the horizontal d.o.f.)

$$m\ddot{u}_h + c_h\dot{u}_h + k_h u_h = -m\ddot{u}_g(t)$$



Palermo et al. 2018 (BEE)

2. The rationale behind ESA: the damped frame



u_h is obtained
and the damper force is obtained as:

$$c_h \dot{u}_h(t) = f_{Dh}(t) = f_D(t) \cdot \cos\theta$$

$$f_D(t) = \frac{c_h \dot{u}_h(t)}{\cos\theta}$$

second equation

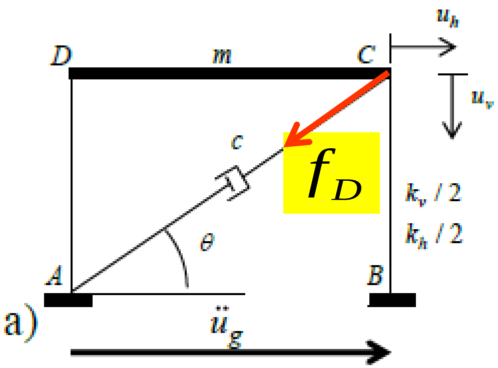
$$m\ddot{u}_v + c_v \dot{u}_v + k_v u_v = -c_{hv} \dot{u}_h = -f_{Dv}(t) = -f_D(t) \cdot \sin\theta$$

$$m\ddot{u}_v + c_v \dot{u}_v + k_v u_v = -f_{Dv}(t)$$

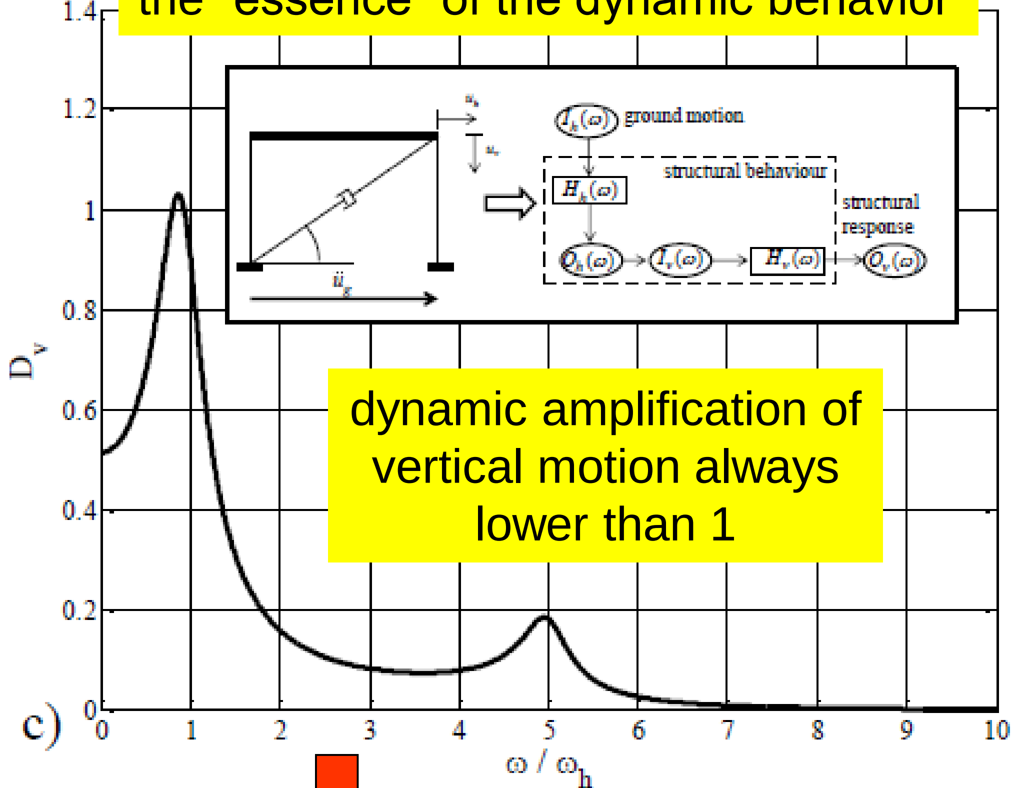
the input for the vertical d.o.f. is given by the damper force (coupled response)

Palermo et al. 2018 (BEE)

2. The rationale behind ESA: the damped frame



k_v □ k_h



the second dynamic equation can be treated as a static equation

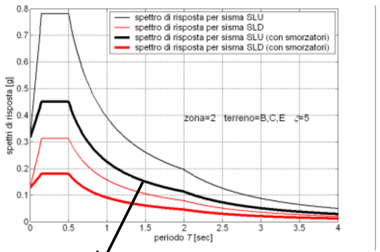
$$\cancel{m\ddot{u}_v} + \cancel{c\dot{u}_v} + k_v u_v = -f_{Dv}(t)$$

axial force in the column

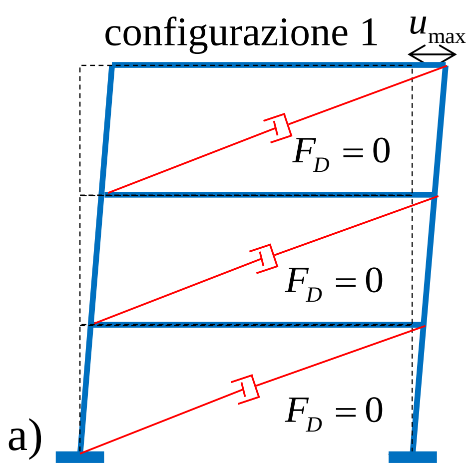
$$k_v u_{v,\max} = -f_{Dv,\max}$$

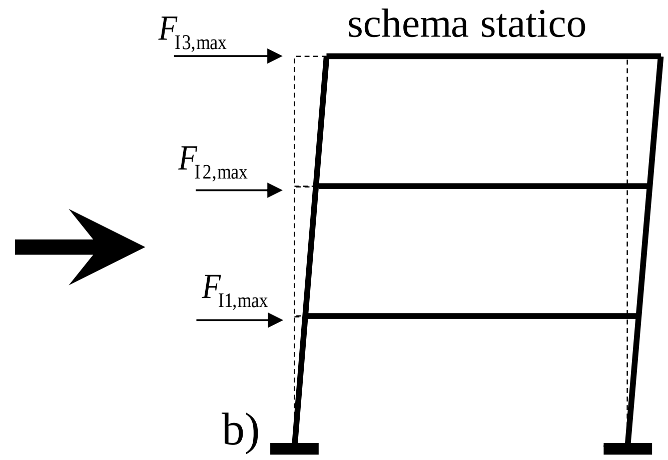
Palermo et al. 2018 (BEE)

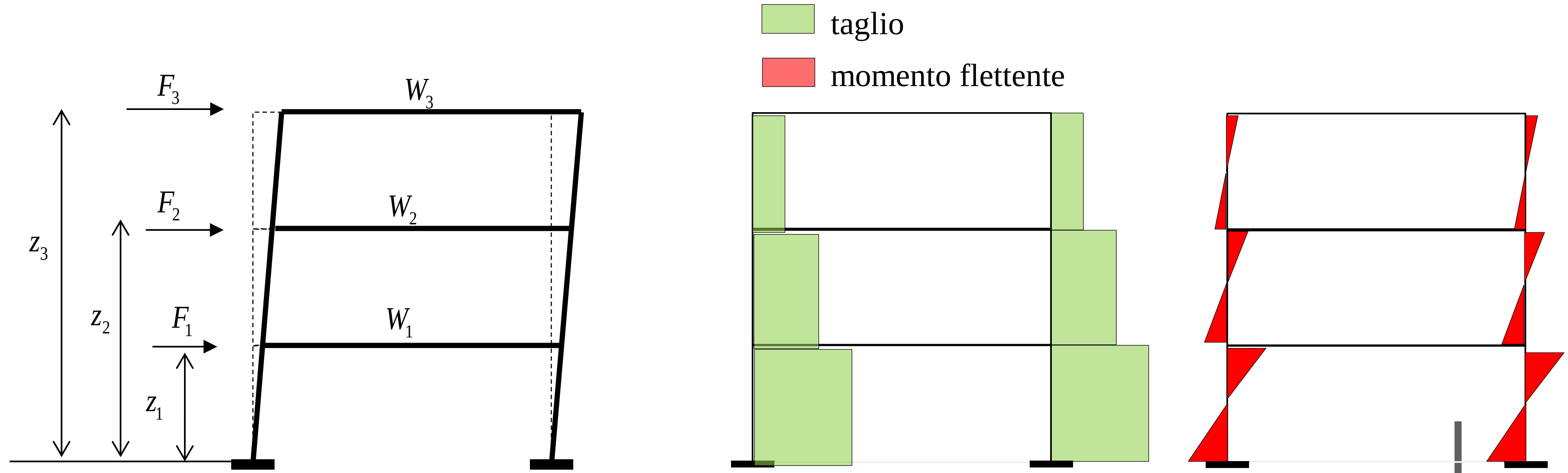
How to perform
Equivalent Static Analysis ESA1



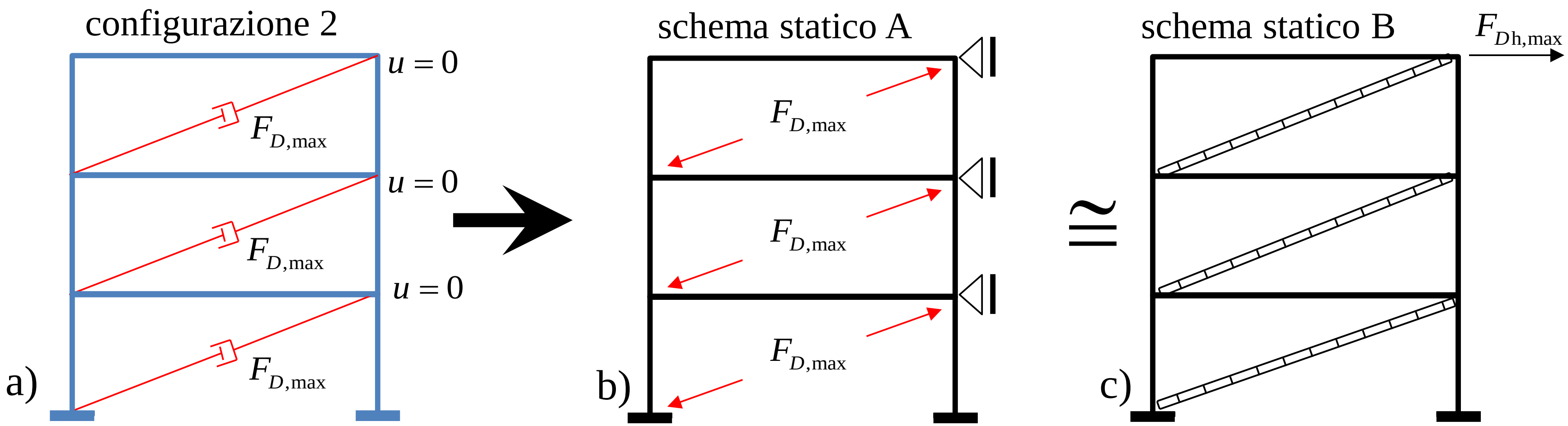
$$F_i = S_{e,\xi} \cdot \frac{W_i}{\sum_{i=1,2,\dots,N} W_i \cdot z_i}$$

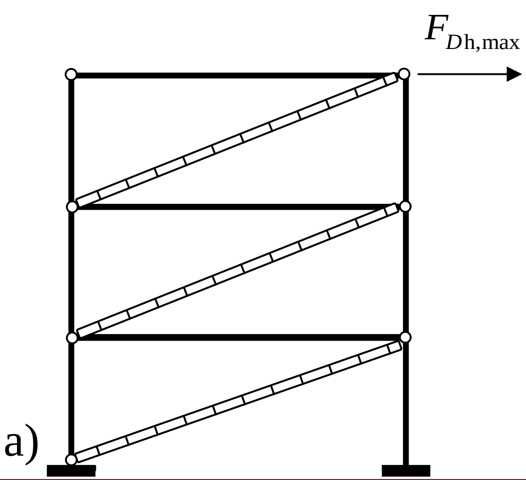


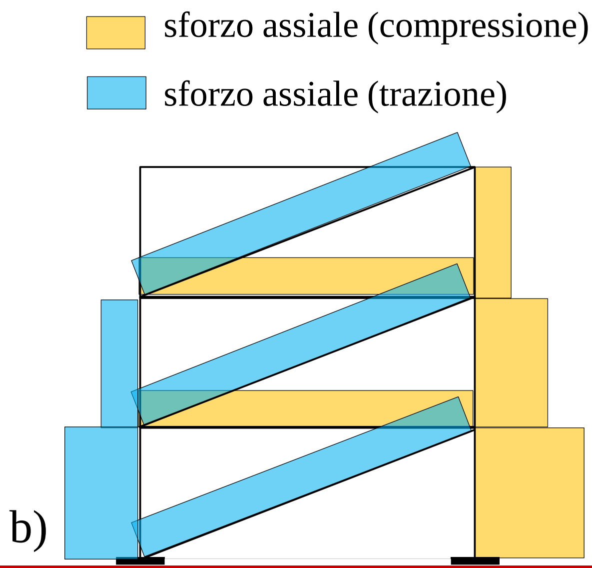


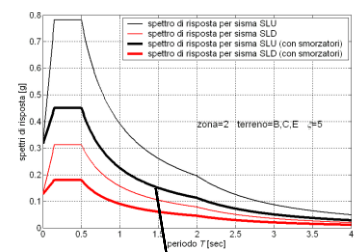


How to perform Equivalent Static Analysis ESA2





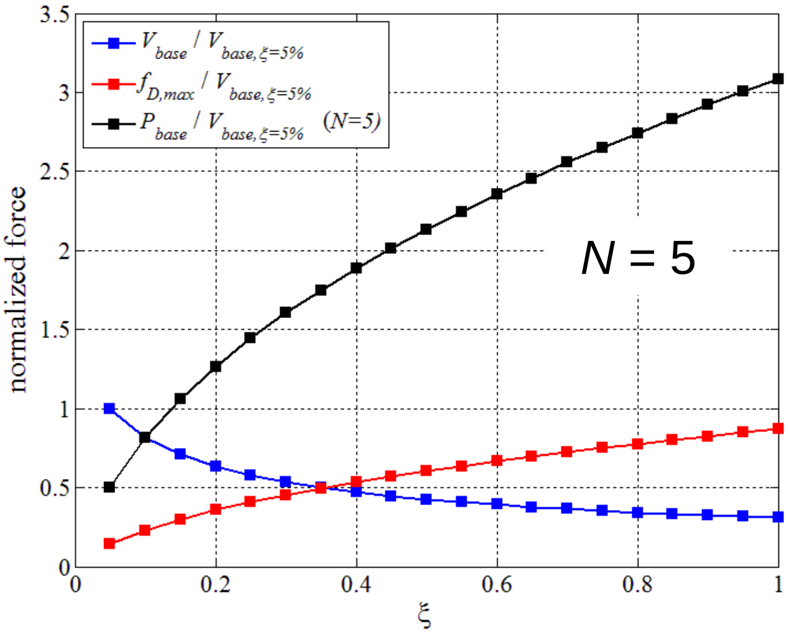


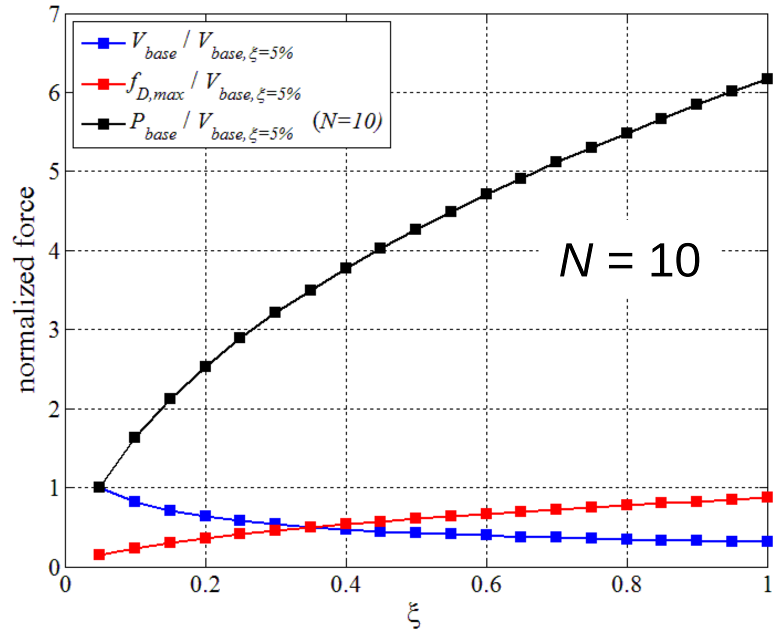


COLUMNS AXIAL FORCES DUE TO DAMPERS

$$P_{i,\max} = (N-i+1)F_{d,v,\max} = $$
$$= (N-i+1)\cdot\frac{2\cdot\xi\cdot W_{tot}}{n} S_{e,\xi} \tan\theta$$

Axial forces in the columns due to dampers





REMEMBER: For tall buildings the axial forces due to dampers may become even larger than the axial forces due to static vertical loads

The direct five-step procedure for inter-storey dampers placement

DESIGN PROCESS

STEP 1: performance objectives ⇨ $\bar{\eta} \rightarrow \bar{\xi}$

$\bar{\eta} = \sqrt{\frac{10}{5+\bar{\xi}}}$

STEP 2: linear dan

$$v_{\max} = \frac{S_{e,\xi}(T_1)}{\omega_1} \cdot \frac{2}{(N+1)} \cdot \cos\theta$$

$c_L = \bar{\xi} \cdot \omega_1 \cdot m_{tot} \cdot \left(\frac{N+1}{n}\right)$

STEP 3: ~~linear TH~~

analytical estimations

response

$v_{\max} = \frac{S_{e,\xi}(T_1)}{\omega_1} \cdot \frac{2}{(N+1)} \cdot \cos\theta$

$F_{D\max} = \frac{2 \cdot \xi \cdot m_{tot} \cdot S_{e,\xi}(T_1)}{\cos\theta}$

STEP 4: non-linear

$$F_{D\max} = \frac{2 \cdot \xi \cdot m_{tot} \cdot S_{e,\xi}(T_1)}{\cos\theta}$$

$c_{NL} = c_L \cdot (\chi \cdot v_{\max})^{1-\alpha}$

k_{oil}

VERIFICATION

STEP 5: $$P_{i,\max} = (N-i+1) \cdot \frac{2 \cdot \xi \cdot W_{tot} \cdot S_{e,\xi}}{n} \cdot \tan\theta$$

$\frac{2 \cdot \xi \cdot W_{tot} \cdot S_{e,\xi}}{n} \cdot \tan\theta$

FEM

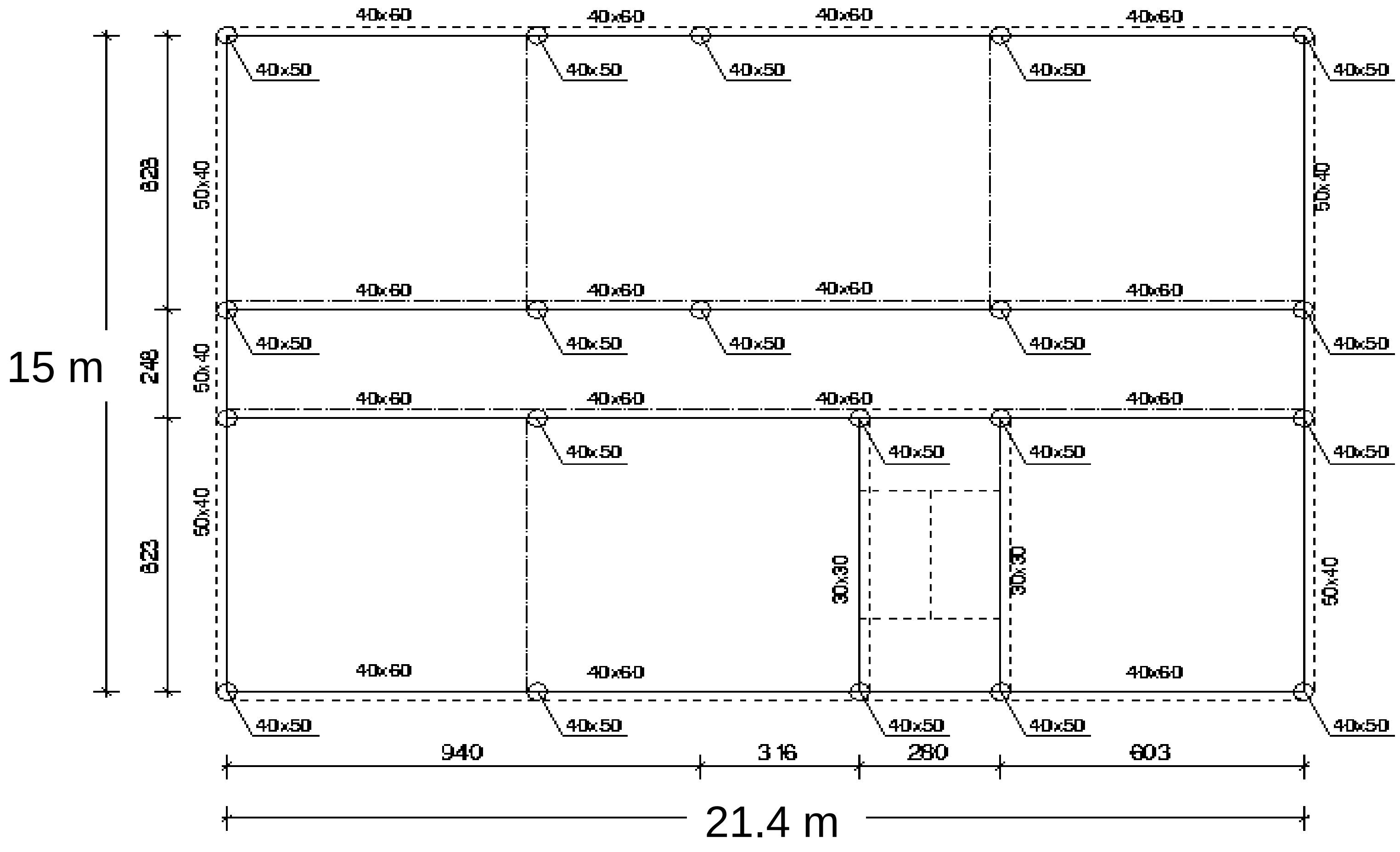
Palermo et al. 2016 (BEE)

Applicative example

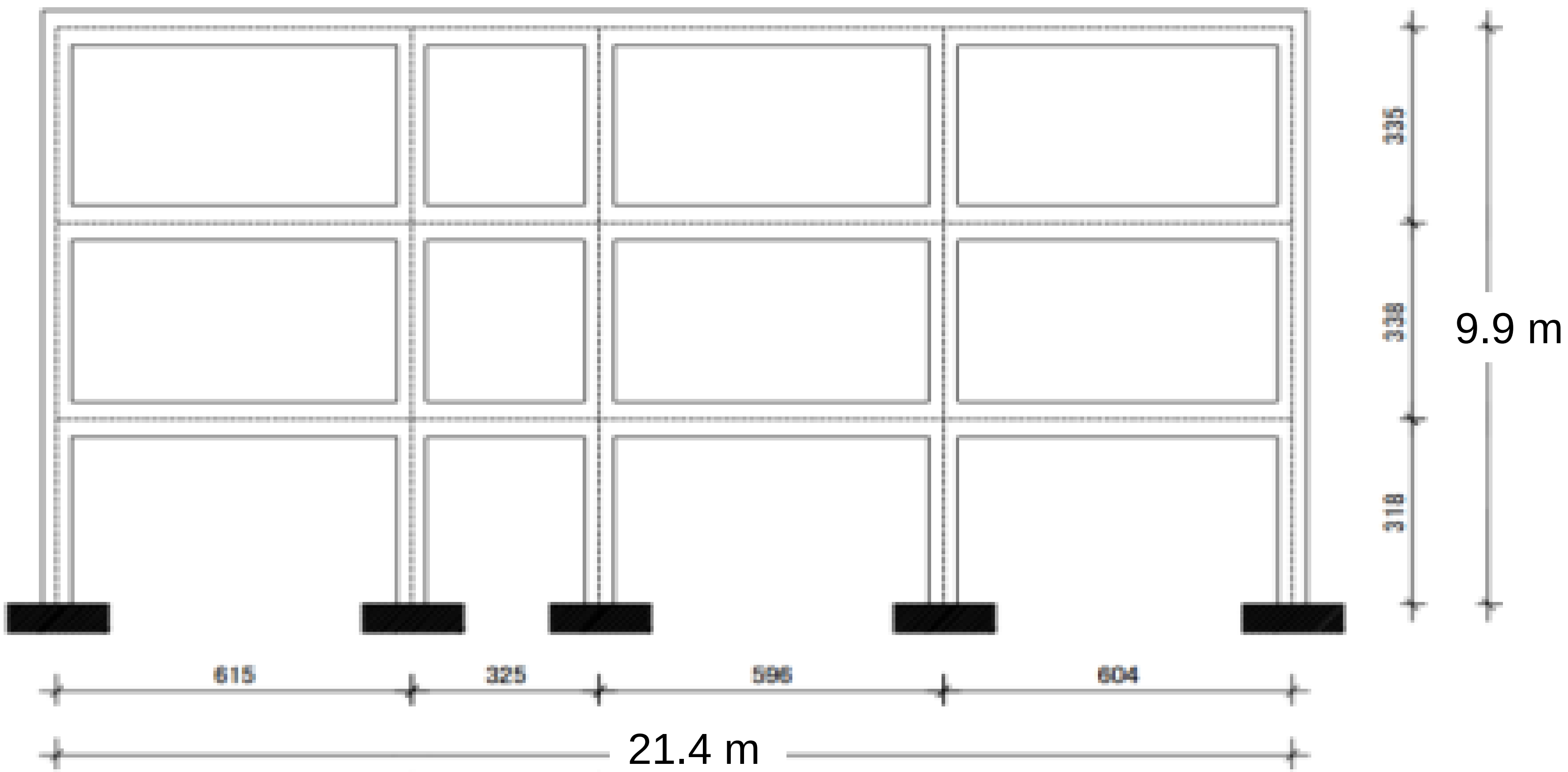
The case study

reinforced-concrete 3-storey school building
located in Bisignano (Cosenza, southern Italy)

The case study



The case study



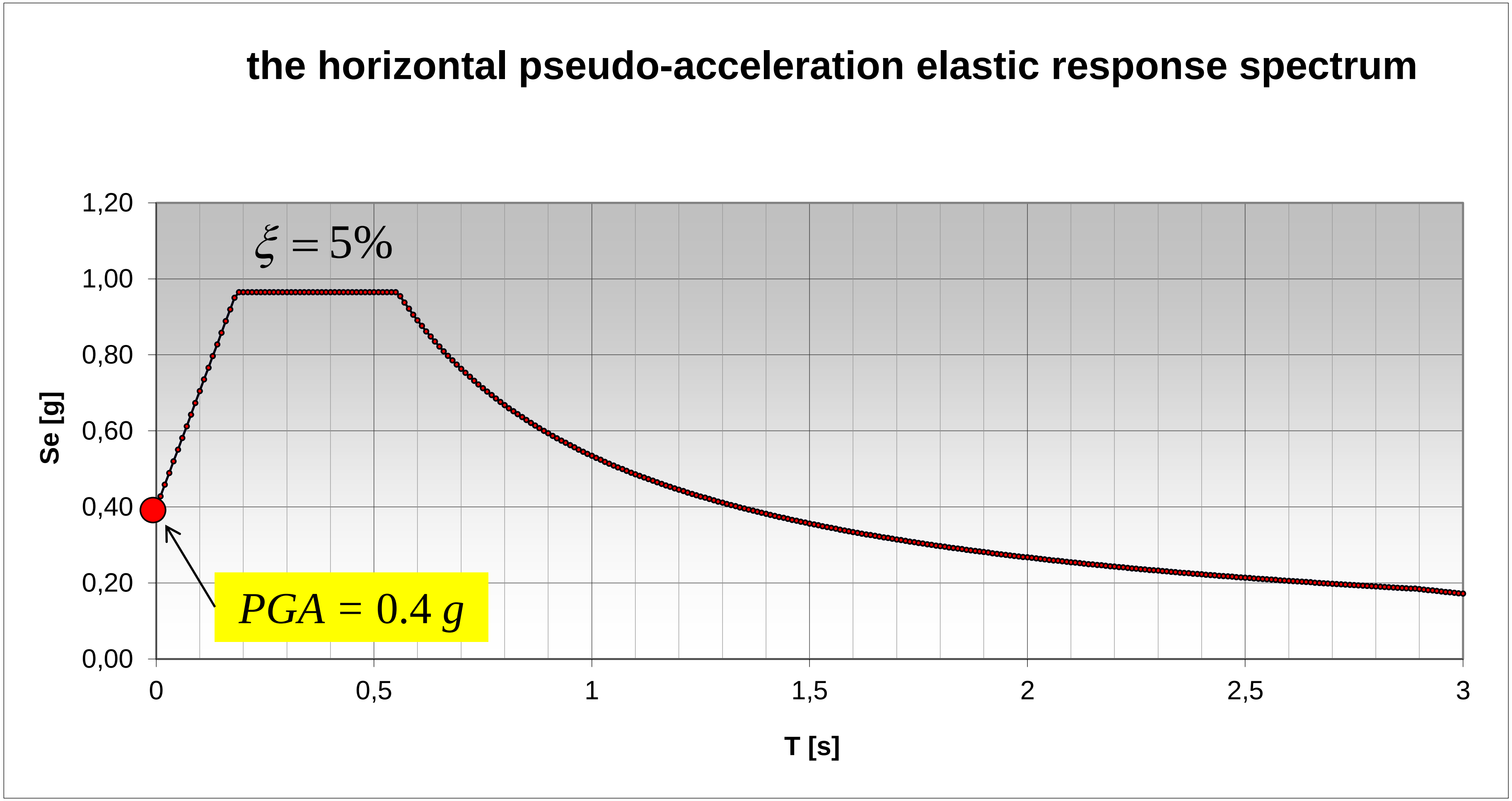
The case study

Table 1: Load analysis

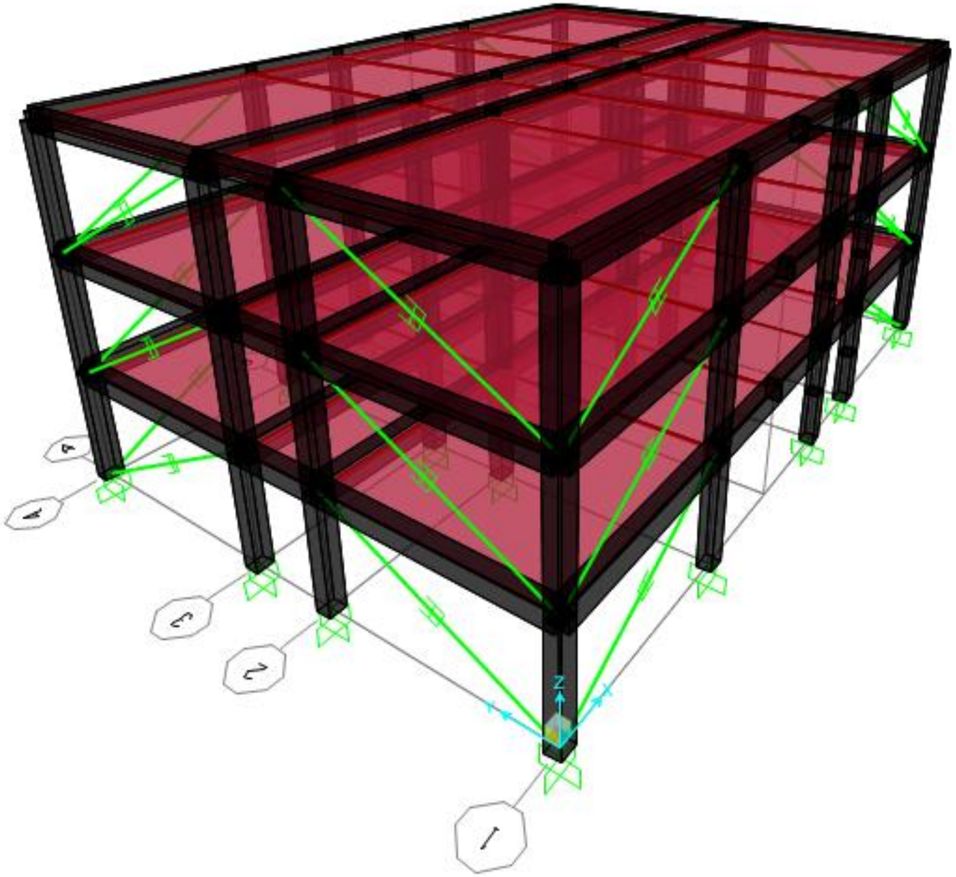
Loads	*Floor 1*	*Floor 2*	*Floor 3 (attic + roof)*
Permanent G1	3.00 kN/m^2	3.00 kN/m^2	4.00 kN/m^2
Permanent *G2*	2.00 kN/m^2	2.00 kN/m^2	3.00 kN/m^2
Imposed Loads *Q*	3.00 kN/m^2 (Ψ_2= 0.6)	3.00 kN/m^2 (Ψ_2= 0.6)	2.50 kN/m^2 (Ψ_2= 0)
TOTAL in static conditions	8.00 kN/m^2	8.00 kN/m^2	9.50 kN/m^2
TOTAL in seismic conditions	6.80 kN/m^2	6.80 kN/m^2	7.00 kN/m^2

total weight in seismic conditions
W_{tot} = 11900 kN

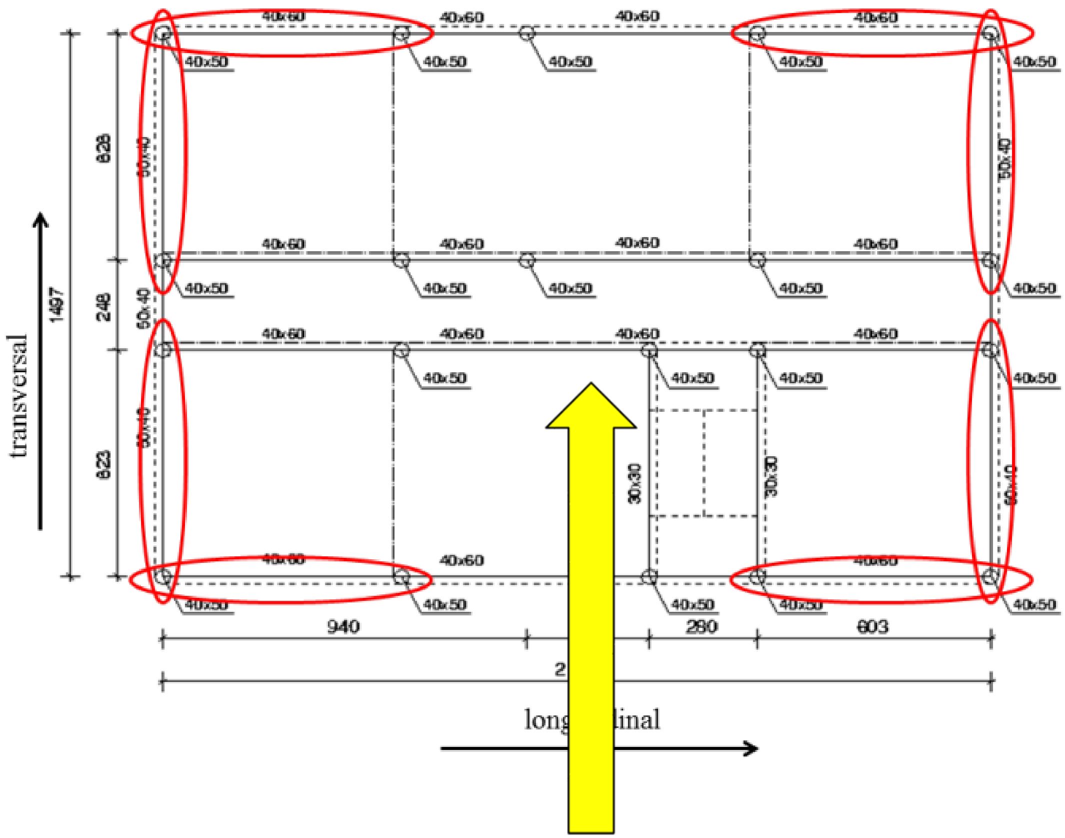
The case study



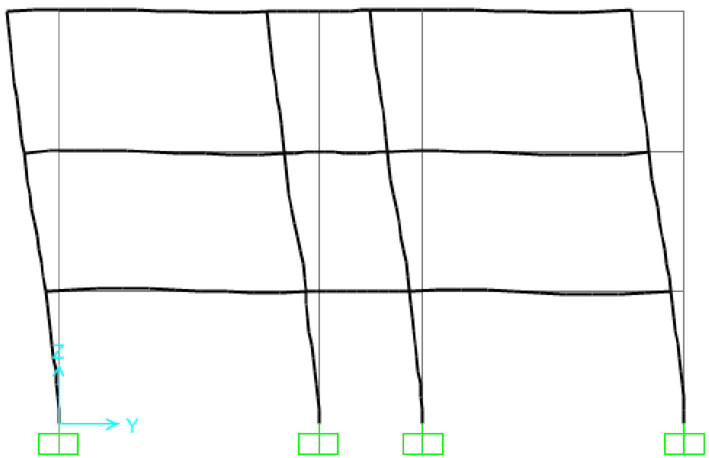
The case study



The direct five-step procedure applied to the case study



seismic action
along the transversal direction



first mode
along the transversal direction

$$T_{1,transversal} = 0.80\ s$$

Application - Step 1

STEP 1

through dampers

Assumed target damping ratio: $\bar{\xi}_{tot} = \xi_{\text{intr}} + \bar{\xi}_{visc} = 5\% + 20\% = 25\%$

Corresponding response reduction factor: $\bar{\eta} = \sqrt{\dfrac{10}{5+\bar{\xi}_{tot}}} = \sqrt{\dfrac{10}{5+25}} = 0.577$

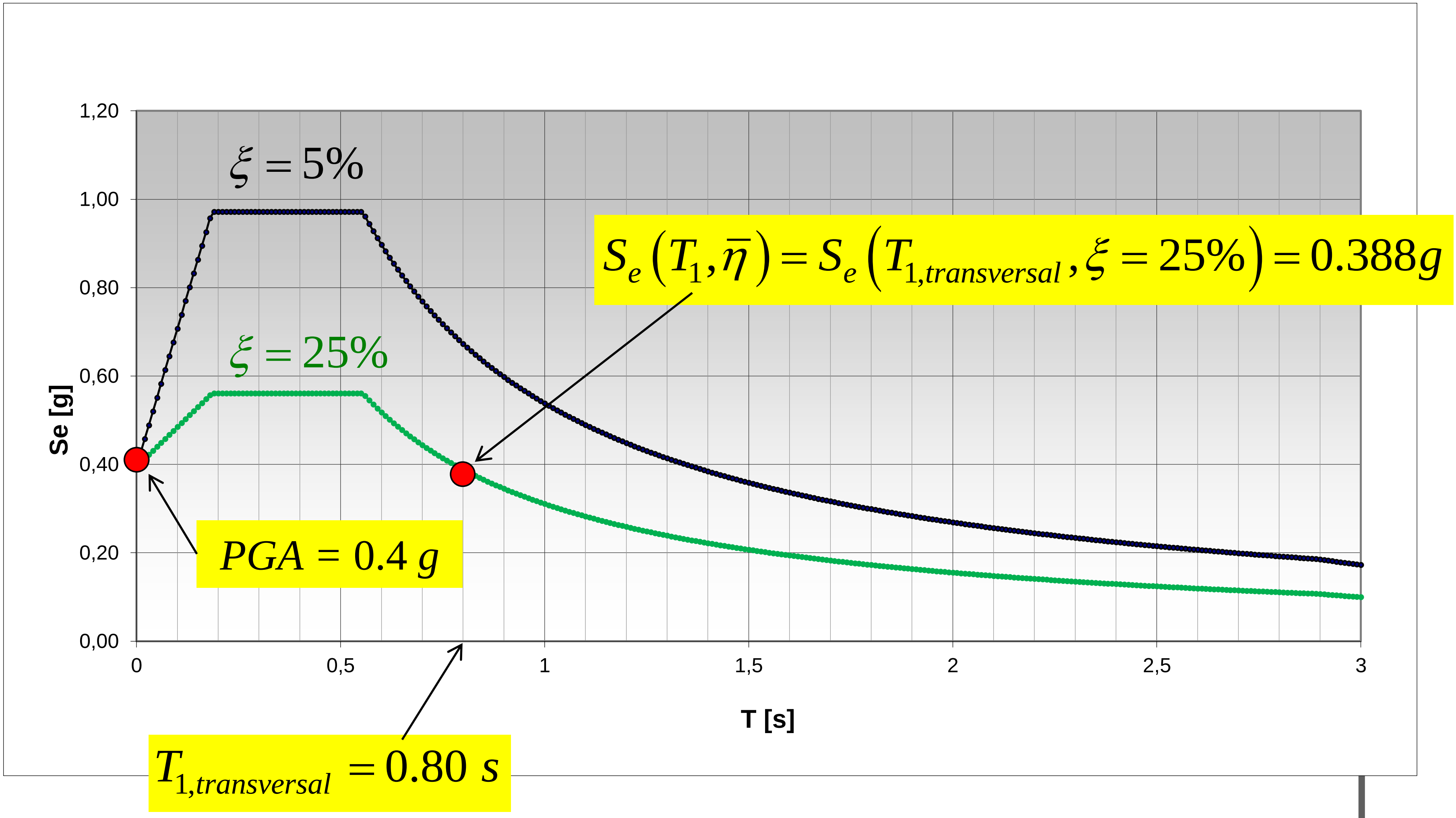
Fundamental period along the considered (transversal) direction: $T_1 = 0.80s$

Spectral acceleration:

$$S_e(T_1,\bar{\eta}) = a_g \cdot S \cdot \bar{\eta} \cdot F_o \cdot \left(\frac{T_c}{T_1}\right) =$$

$$= 0.323g \cdot 1.23 \cdot 0.577 \cdot 2.43 \cdot \frac{0.55}{0.80} = 0.388g$$

Application – Step 1



Application - Step 2

STEP 2

Number of dampers per floor placed along the longitudinal direction: $n = 4$

Damper inclination with respect to the horizontal line: $\theta = 28°$

Linear damping coefficient:

$$c_L = \bar{\xi}_{visc} \cdot \omega_1 \cdot \frac{W_{tot}}{g} \cdot \left(\frac{N+1}{n}\right) \frac{1}{\cos^2\theta} =$$

$$= 0.20 \cdot \frac{2\pi}{0.80\text{s}} \cdot \frac{11900\ \text{kN}}{9.81\ \frac{\text{m}}{\text{s}^2}} \cdot \left(\frac{3+1}{4}\right) \cdot \frac{1}{\cos^2 28°} \cong 2444 \frac{\text{kN} \cdot \text{s}}{\text{m}}$$

Application - Step 3

STEP 3

Peak damper **velocity** estimation for the equivalent linear damper:

$$v_{\max} = \frac{S_e\left(T_1, \bar{\eta}\right)}{\omega_1} \cdot \frac{2}{N+1} \cdot \cos\theta =$$

$$= \frac{0.388 \cdot 9.81 \ \dfrac{\mathrm{m}}{\mathrm{s}^2}}{\left(\dfrac{2\pi}{0.80\mathrm{s}}\right)} \cdot \frac{2}{3+1} \cdot \cos 28° \cong 0.214 \frac{\mathrm{m}}{\mathrm{s}}$$

Application - Step 3

STEP 3

Peak damper **force** estimation for the equivalent linear damper:

$$F_{L,\max} = 2 \cdot \bar{\xi}_{visc} \cdot \frac{W}{g} \cdot \frac{S_e\left(T_1, \bar{\eta}\right)}{n \cdot \cos\theta} =$$

$$= 2 \cdot 0.20 \cdot \frac{11900 \text{ kN}}{g} \cdot \frac{0.388g}{4 \cdot \cos 28°} \cong 524 \text{ kN}$$

Application - Step 3

STEP 3

Peak damper **stroke** estimation for the equivalent linear damper:

$$s_{\max} = \frac{S_e\left(T_1, \bar{\eta}\right)}{\omega_1^{\,2}} \cdot \frac{2}{N+1} \cdot \cos\theta =$$

$$= \frac{0.388g}{\left(\dfrac{2\pi}{0.80\text{s}}\right)^2} \cdot \frac{2}{3+1} \cdot \cos 28° \cong \; 2.73\text{cm}$$

Application - Step 4

STEP 4

α-exponent of the commercial damper: $\alpha = 0.15$

Non-linear damping coefficient of the commercial damper:

$$c_{NL} = c_L \cdot \left(0.8 \cdot v_{\max}\right)^{1-\alpha} =$$

$$= 2444 \frac{\mathrm{kN} \cdot \mathrm{s}}{\mathrm{m}} \cdot \left(0.8 \cdot 0.214 \frac{\mathrm{m}}{s}\right)^{1-0.15} \cong 546 \frac{\mathrm{kN} \cdot \mathrm{s}^{0.15}}{\mathrm{m}^{0.15}}$$

Minimum axial stiffness of the device (non-linear damper + supporting brace):

$$k_{axial} \geq 10 \cdot c_L \cdot \omega_1 =$$

$$= 10 \cdot 2444 \frac{\mathrm{kN} \cdot \mathrm{s}}{\mathrm{m}} \cdot \frac{2\pi}{0.80\mathrm{s}} = 1.92 \cdot 10^5 \frac{\mathrm{kN}}{\mathrm{m}} \longrightarrow 2 \cdot 10^5 \frac{\mathrm{kN}}{\mathrm{m}}$$

Application - Step 4

STEP 4

Peak damper **force** estimation for the "non-linear" damper:

$$F_{NL,\max} = 0.8^{1-\alpha} \cdot F_{L,\max} =$$

$$= 0.8^{1-0.15} \cdot 524 \text{ kN} \cong 433 \text{ kN}$$

Application - Step 5

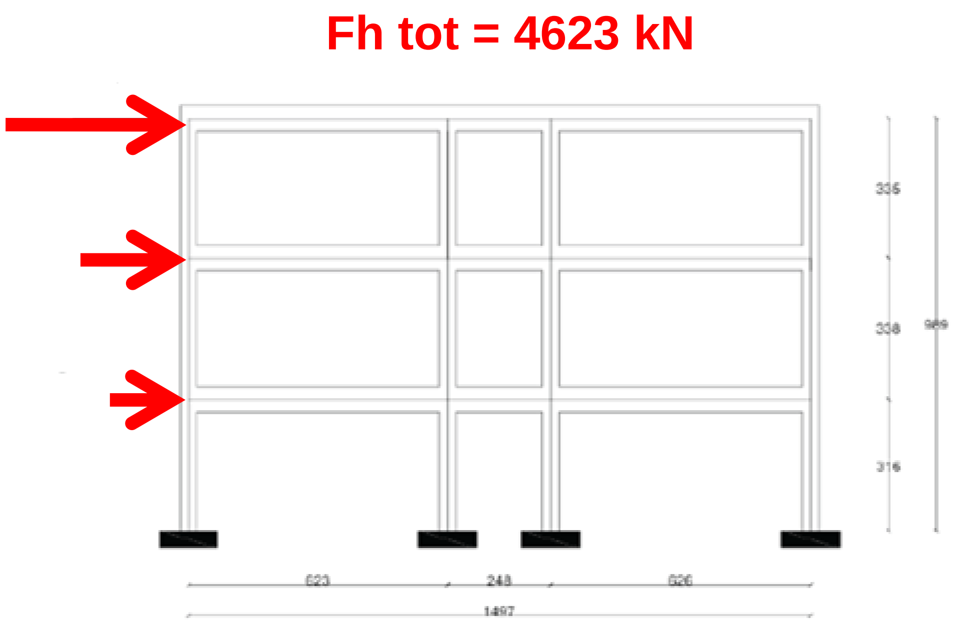


Figure 9. Static scheme to be solved for ESA1.

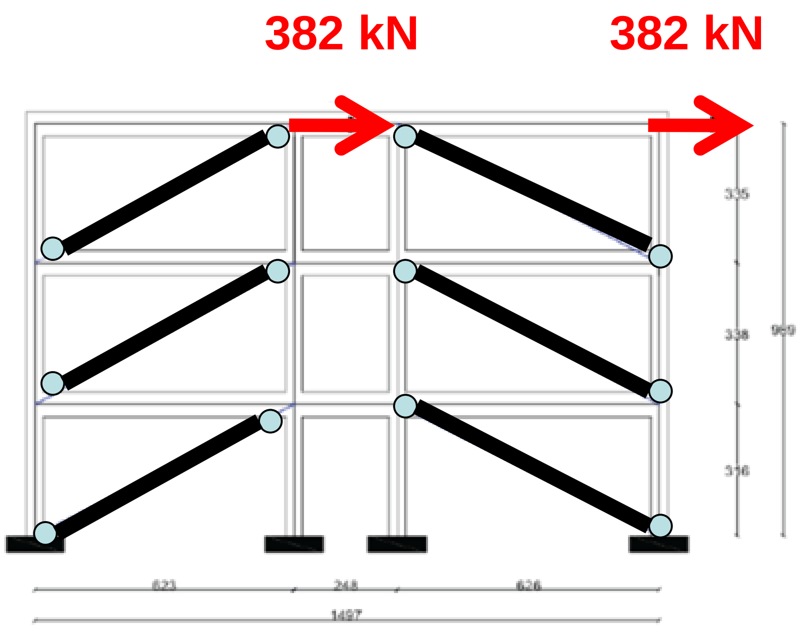


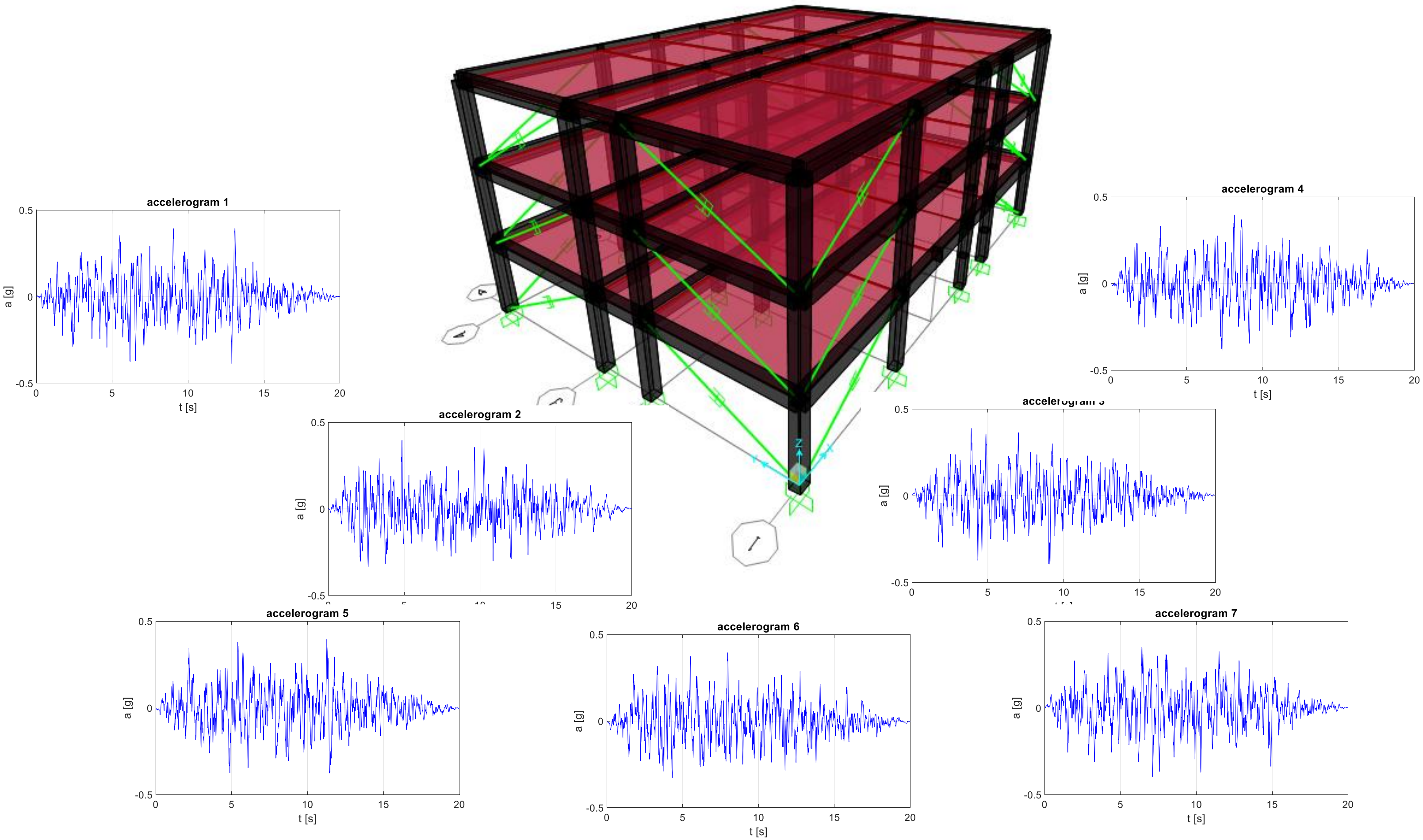
Figure 10. Static scheme to be solved for ESA2.

ESA1

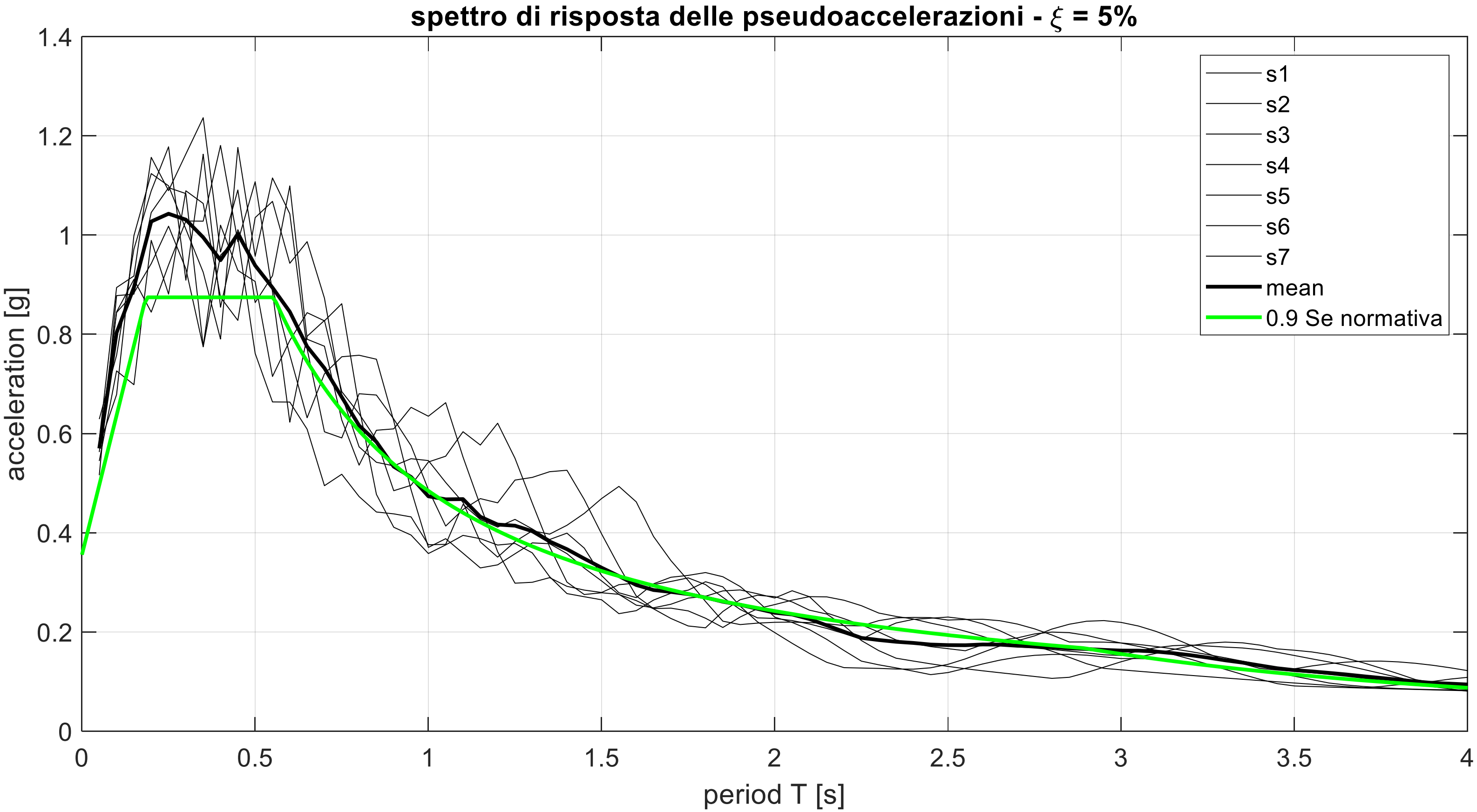
ESA2

TH verification

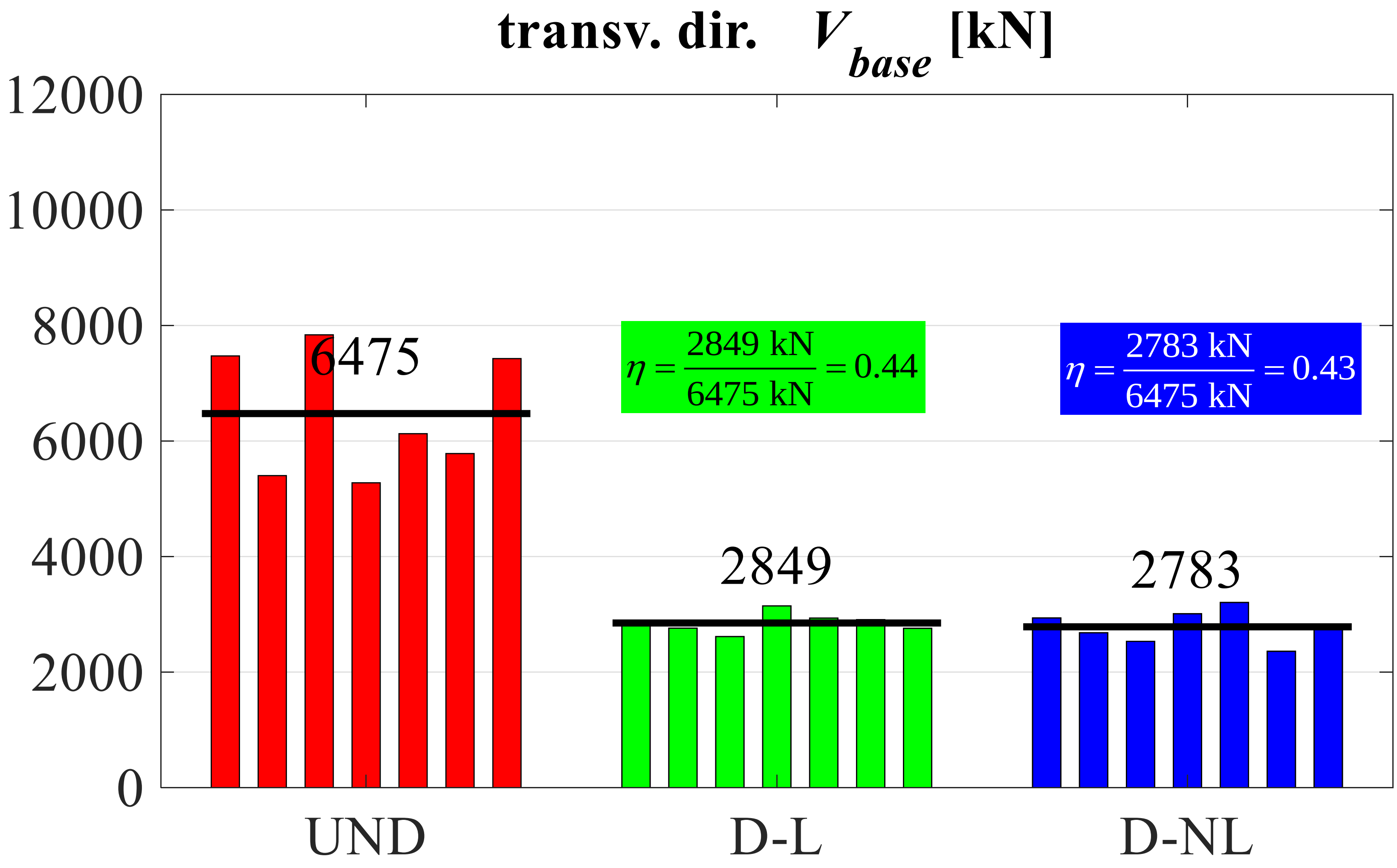
7 accelerograms which are consistent with the design spectrum:



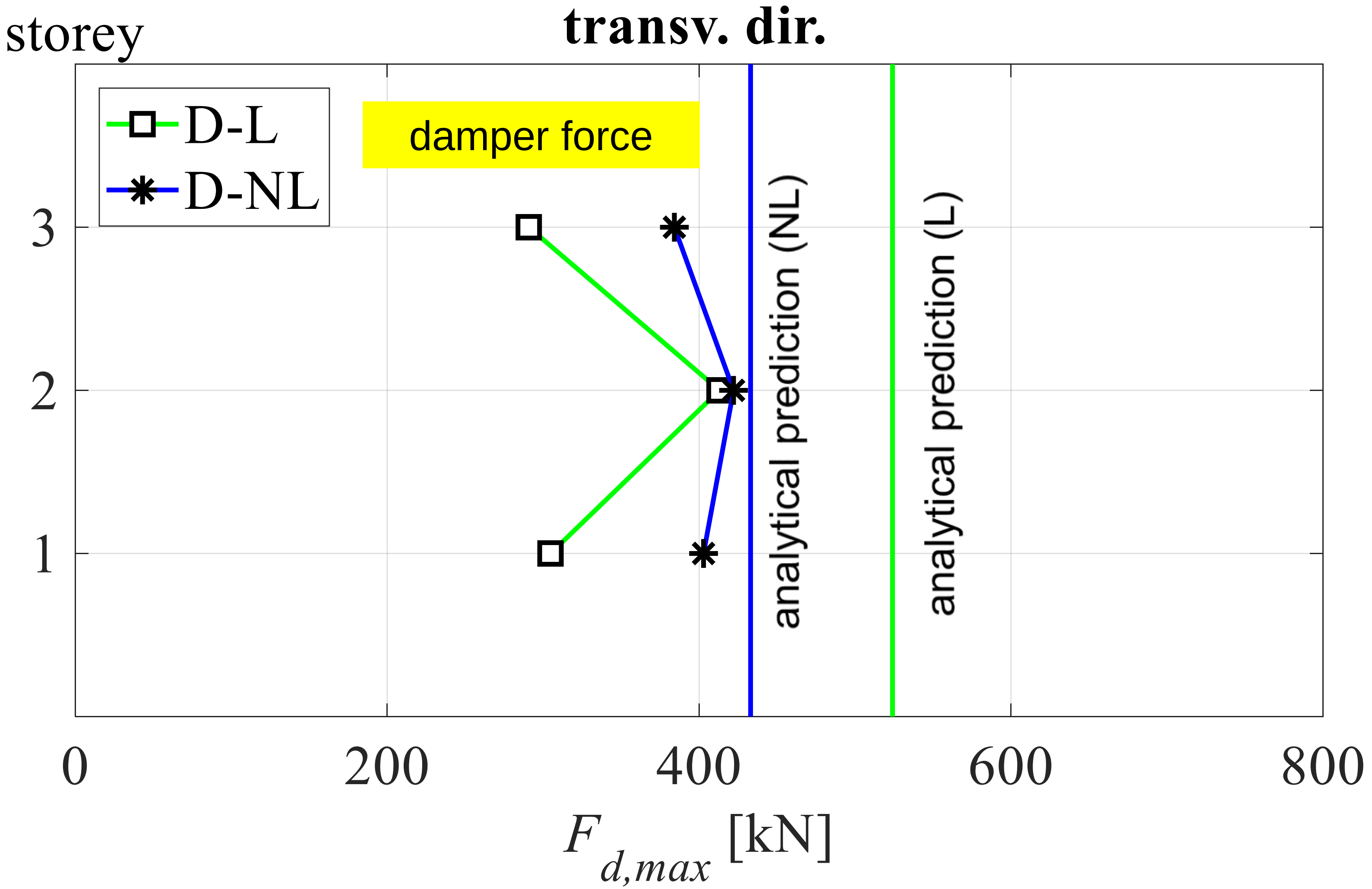
TH verification



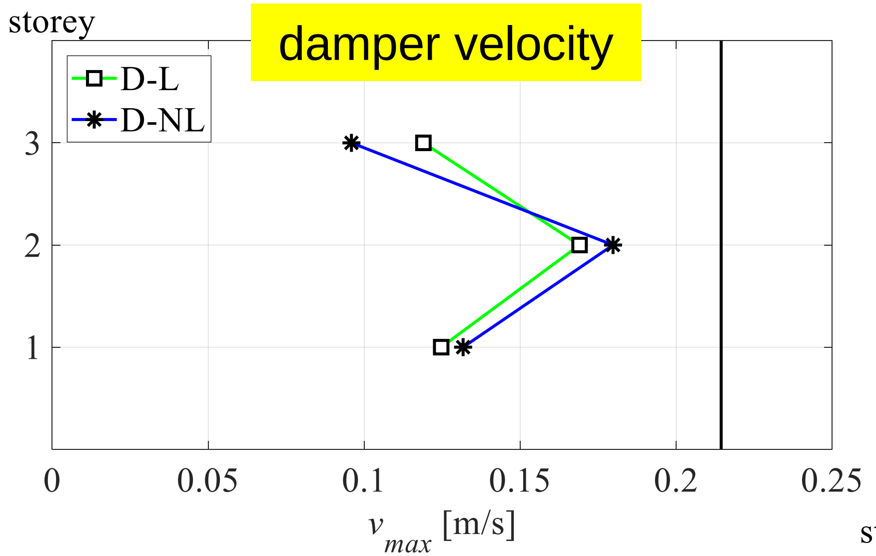
TH verification

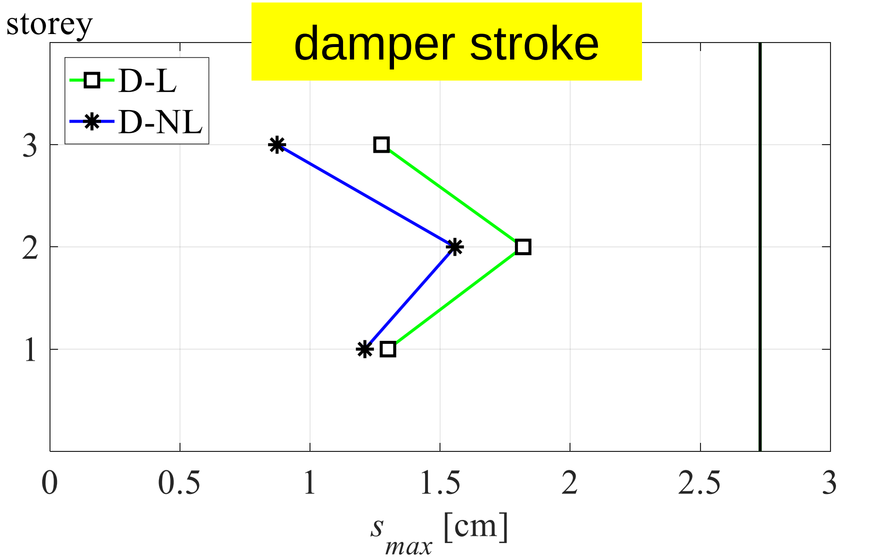


TH verification



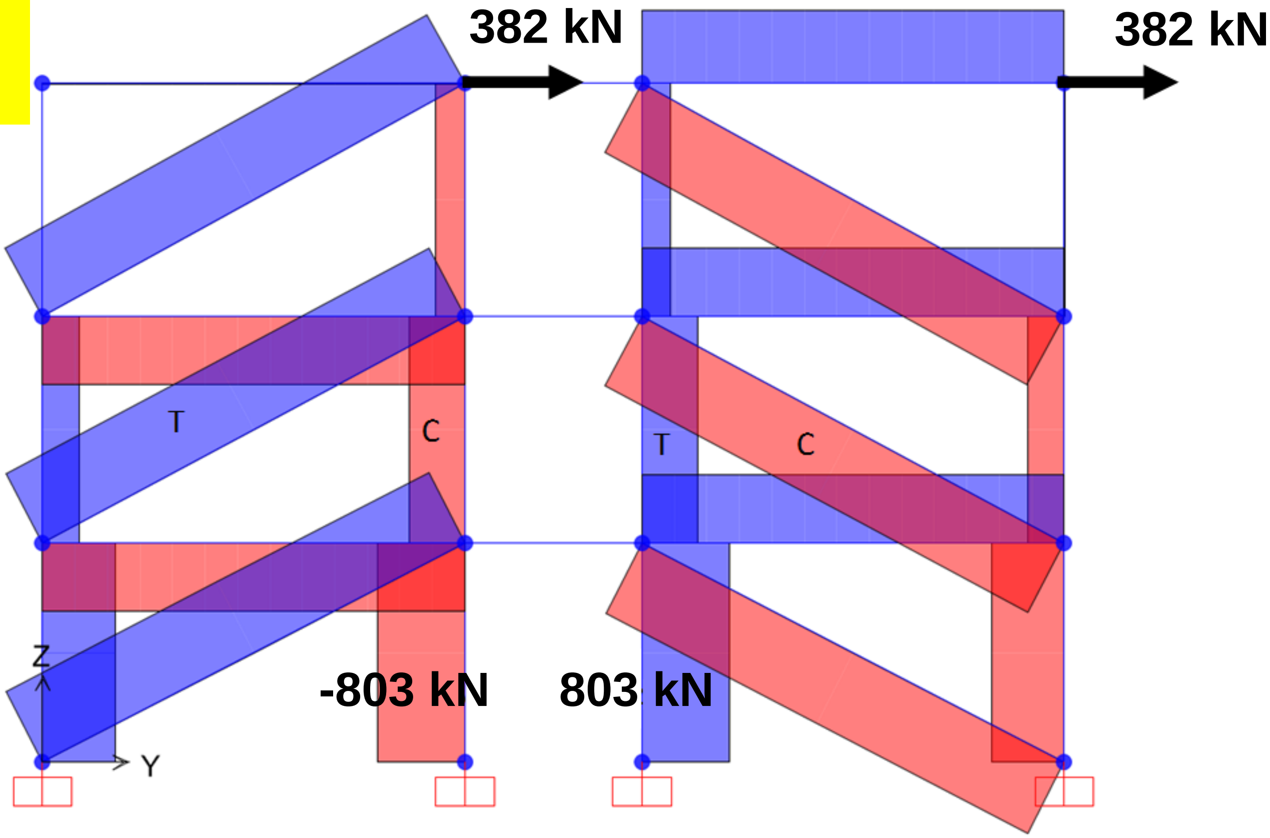
TH verification





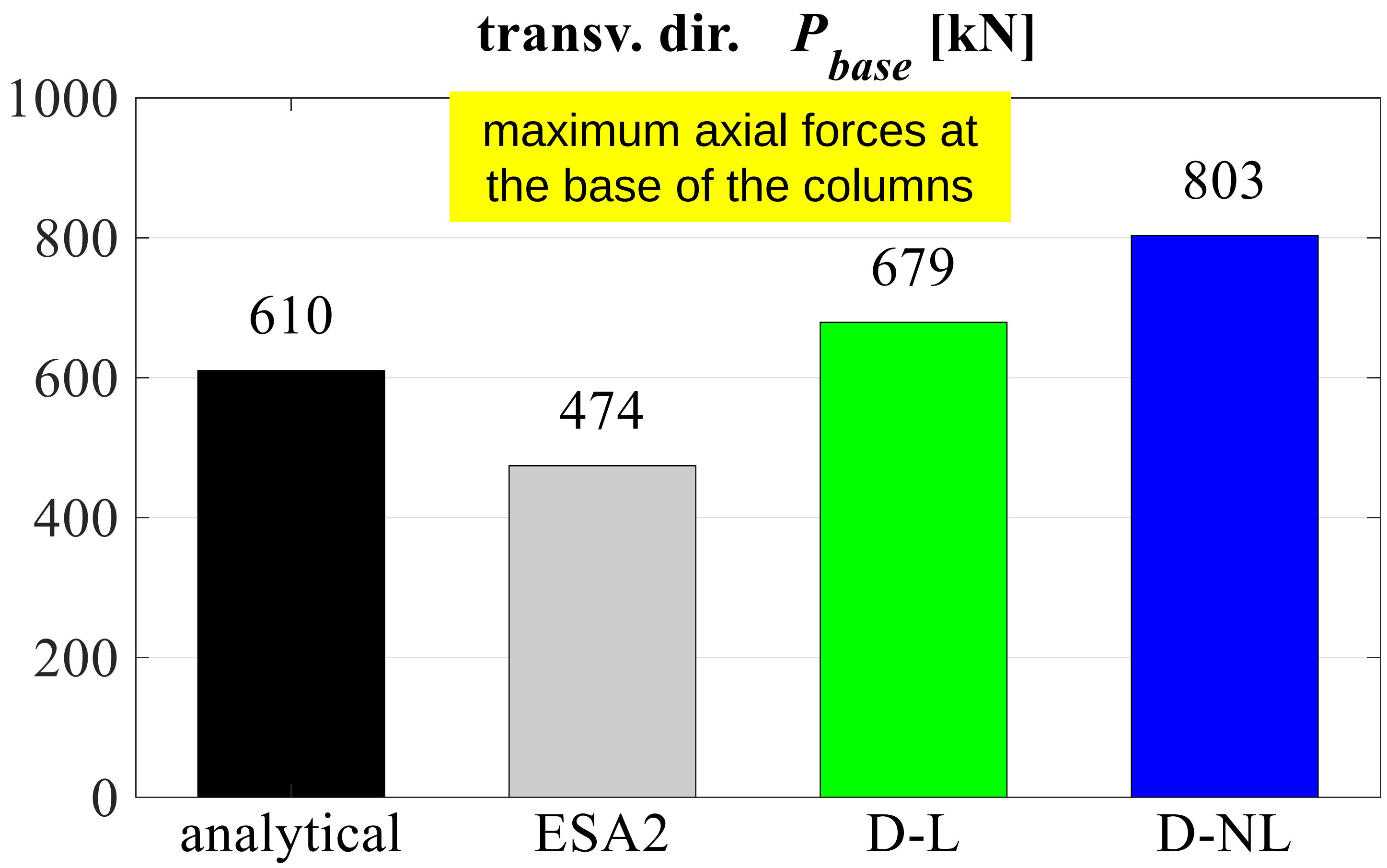
TH verification

axial forces in the columns



ESA2

TH verification



Conclusions

Conclusions

- A **<u>direct</u>** **(fully analtyical)** procedure for the seismic design of building structures with added viscous dampers is presented.

- It represents the **step forward** of the “five-step procedure” (2010).

- It aims at providing **practical tools** for a direct identification of the mechanical characteristics of the manufactured viscous dampers which allow **to achieve target levels of performances**.

- The procedure seems to be **conservative**.

- **In any case, a numerical verification of the final behaviour** of the system by means of non-linear time-history analyses **is recommended**.

Future developments

- In its current version, the procedure is applicable to **regular multi-storey frame structures** which are characterized by a period of vibration lower than 1.5 s.
- At this stage of the research, the procedure is suitable for the **preliminary design phase**, since **correction factors** for the higher modes contributions are necessary to improve its accuracy, especially for high-rise buildings.
- **Other applicative examples are currently under development** for the numerical validation and for the necessary adjustments.

Thank you for your kind attention!

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Questions?

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