Università di Salerno – Dipartimento di Ingegneria Civile
Rete dei Laboratori Universitari di Ingegneria Sismica

WORKSHOP
Materiali ed Approcci Innovativi per il Progetto in Zona Sismica e la Mitigazione della Vulnerabilità delle Strutture

Metodologie di progetto per strutture sismoresistenti dotate di dispositivi extrastrutturali di dissipazione energetica: *Il problema della disposizione in elevazione*

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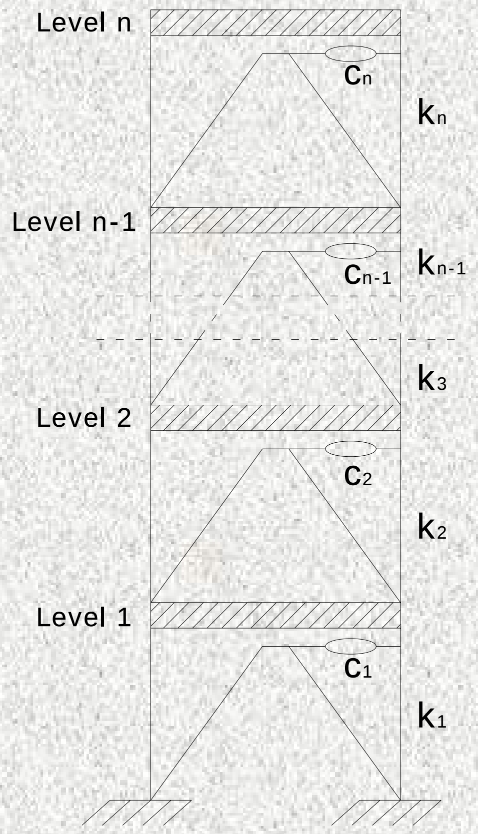
Design problem approach



MDOF system

System's motion equations in terms of interstory drifts:

$$
\begin{cases}
m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 - c_2\dot{x}_2 - k_2 x_2 = m_1\ddot{u}_g \\
\dots\dots\dots \\
m_{n-2}\ddot{x}_{n-2} + m_{n-2}\ddot{x}_{n-3} + m_{n-2}\ddot{x}_{n-4} + \dots + m_{n-2}\ddot{x}_i + \dots + m_{n-2}\ddot{x}_1 + \\
\qquad + c_{n-2}\dot{x}_{n-2} + k_{n-2}x_{n-2} - c_{n-1}\dot{x}_{n-1} - k_{n-1}x_{n-1} = -m_{n-2}\ddot{u}_g \\
m_{n-1}\ddot{x}_{n-1} + m_{n-1}\ddot{x}_{n-2} + m_{n-1}\ddot{x}_{n-3} + \dots + m_{n-1}\ddot{x}_i + \dots + m_{n-1}\ddot{x}_1 + \\
\qquad + c_{n-1}\dot{x}_{n-1} + k_{n-1}x_{n-1} - c_n\dot{x}_n - k_n x_n = -m_{n-1}\ddot{u}_g \\
m_n\ddot{x}_n + m_n\ddot{x}_{n-1} + m_n\ddot{x}_{n-2} + \dots + m_n\ddot{x}_i + \dots + m_n\ddot{x}_1 + c_n\dot{x}_n + k_n x_n = -m_n\ddot{u}_g
\end{cases}
$$

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Arranging the dynamic equations by writing down, for each level, the shear transmitted by the upper floor in terms of floor masses and accelerations

$$m_{n-1}\ddot{x}_{n-1} + m_{n-1}\ddot{x}_{n-2} + m_{n-1}\ddot{x}_{n-3} + \ldots + m_{n-1}\ddot{x}_i + \ldots + m_{n-1}\ddot{x}_1 + \\ + c_{n-1}\dot{x}_{n-1} + k_{n-1}x_{n-1} - c_n\dot{x}_n - k_n x_n = -m_{n-1}\ddot{u}_g$$

Level "n-1"

$$m_n\ddot{x}_n + m_n\ddot{x}_{n-1} + m_n\ddot{x}_{n-2} + \ldots + m_n\ddot{x}_i + \ldots + m_n\ddot{x}_1 + c_n\dot{x}_n + k_n x_n = -m_n\ddot{u}_g$$

Level "n"

$$c_n\dot{x}_n + k_n x_n = -m_n\ddot{u}_g - m_n\ddot{x}_n - m_n\ddot{x}_{n-1} - m_n\ddot{x}_{n-2} - \ldots - m_n\ddot{x}_i - \ldots - m_n\ddot{x}_1$$

Equation for level "n-1" can be rewritten as:

$$m_{n-1}\ddot{x}_{n-1} + c_{n-1}\dot{x}_{n-1} + k_{n-1}x_{n-1} + (m_n\ddot{x}_n + m_n\ddot{x}_{n-1} + m_n\ddot{x}_{n-2} + \ldots + m_n\ddot{x}_i + \ldots + m_n\ddot{x}_1 + m_n\ddot{u}_g) = \\ = -(m_{n-1}\ddot{x}_{n-2} + m_{n-1}\ddot{x}_{n-3} + \ldots + m_{n-1}\ddot{x}_i + \ldots + m_{n-1}\ddot{x}_1 + m_{n-1}\ddot{u}_g)$$

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STEP 3

Equations can be arranged to represent equivalent SDOF systems by introducing the concept of coupling coefficient

$$
\begin{cases}
m_n\left(1+\frac{\ddot{x}_{n-1}}{\ddot{x}_n}+\ldots+\frac{\ddot{x}_i}{\ddot{x}_n}+\ldots+\frac{\ddot{x}_1}{\ddot{x}_n}\right)\ddot{x}_n+c_n\dot{x}_n+k_n x_n=-m_n\ddot{u}_g \\
(m_n+m_{n-1})\left(\frac{m_n}{m_n+m_{n-1}}\frac{\ddot{x}_n}{\ddot{x}_{n-1}}+1+\frac{\ddot{x}_{n-2}}{\ddot{x}_{n-1}}+\ldots+\frac{\ddot{x}_i}{\ddot{x}_{n-1}}+\ldots+\frac{\ddot{x}_1}{\ddot{x}_{n-1}}\right)\ddot{x}_{n-1}+c_{n-1}\dot{x}_{n-1}+k_{n-1}x_{n-1}=-(m_n+m_{n-1})\ddot{u}_g \\
(m_n+m_{n-1}+m_{n-2})\left(\frac{m_n}{m_n+m_{n-1}+m_{n-2}}\frac{\ddot{x}_n}{\ddot{x}_{n-2}}+\frac{m_n+m_{n-1}}{m_n+m_{n-1}+m_{n-2}}\frac{\ddot{x}_{n-1}}{\ddot{x}_{n-2}}+1+\frac{\ddot{x}_{n-3}}{\ddot{x}_{n-2}}+\ldots+\frac{\ddot{x}_i}{\ddot{x}_{n-2}}+\ldots+\frac{\ddot{x}_1}{\ddot{x}_{n-2}}\right)\ddot{x}_{n-2}+ \\
\quad +c_{n-2}\dot{x}_{n-2}+k_{n-2}x_{n-2}=-(m_n+m_{n-1}+m_{n-2})\ddot{u}_g \\
\ldots\ldots \\
(m_1+m_2+\ldots+m_n)\left(\frac{m_n}{m_n+m_{n-1}+\ldots+m_1}\frac{\ddot{x}_n}{\ddot{x}_1}+\frac{m_n+m_{n-1}}{m_n+m_{n-1}+\ldots+m_1}\frac{\ddot{x}_{n-1}}{\ddot{x}_1}+\frac{m_n+m_{n-1}+m_{n-2}}{m_n+m_{n-1}+\ldots+m_1}\frac{\ddot{x}_{n-2}}{\ddot{x}_1}+\ldots+1\right)\ddot{x}_1+ \\
\quad +c_1\dot{x}_1+k_1x_1=-(m_n+m_{n-1}+\ldots+m_1)\ddot{u}_g
\end{cases}
$$

Coupling "coefficients"

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By defining coupling coefficients as:

$$\chi_{M,n} = \left(1 + \frac{\ddot{x}_{n-1}}{\ddot{x}_n} + \ldots + \frac{\ddot{x}_i}{\ddot{x}_n} + \ldots + \frac{\ddot{x}_1}{\ddot{x}_n}\right)$$

$$\chi_{M,n-1} = \left(\frac{m_n}{m_n + m_{n-1}}\frac{\ddot{x}_n}{\ddot{x}_{n-1}} + 1 + \frac{\ddot{x}_{n-2}}{\ddot{x}_{n-1}} + \ldots + \frac{\ddot{x}_i}{\ddot{x}_{n-1}} + \ldots + \frac{\ddot{x}_1}{\ddot{x}_{n-1}}\right)$$

....

$$\chi_{M,1} = \left(\frac{m_n}{m_n + m_{n-1} + \ldots + m_1}\frac{\ddot{x}_n}{\ddot{x}_1} + \frac{m_n + m_{n-1}}{m_n + m_{n-1} + \ldots + m_1}\frac{\ddot{x}_{n-1}}{\ddot{x}_1} + \frac{m_n + m_{n-1} + m_{n-2}}{m_n + m_{n-1} + \ldots + m_1}\frac{\ddot{x}_{n-2}}{\ddot{x}_1} + \ldots + 1\right)$$

motion equations can be written as:

$$\begin{cases} m_n \chi_{M,n}\ddot{x}_n + c_n\dot{x}_n + k_n x_n = -m_n\ddot{u}_g \\ (m_n + m_{n-1})\chi_{M,n-1}\ddot{x}_{n-1} + c_{n-1}\dot{x}_{n-1} + k_{n-1}x_{n-1} = -(m_n + m_{n-1})\ddot{u}_g \\ (m_n + m_{n-1} + m_{n-2})\chi_{M,n-2}\ddot{x}_{n-2} + c_{n-2}\dot{x}_{n-2} + k_{n-2}x_{n-2} = -(m_n + m_{n-1} + m_{n-2})\ddot{u}_g \\ \ldots\ldots \\ (m_1 + m_2 + \ldots + m_n)\chi_{M,1}\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 = -(m_n + m_{n-1} + \ldots + m_1)\ddot{u}_g \end{cases}$$

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"EQUIVALENT" SDOF

In adimensional form, the dynamic of MDOF system can be represented as follow:

$$\begin{cases} \ddot{x}_n + 2\xi_n\omega_n\dot{x}_n + \omega_n^2 x_n = -\ddot{u}_g / \chi_{M,n} \\ \ddot{x}_{n-1} + 2\xi_{n-1}\omega_{n-1}\dot{x}_{n-1} + \omega_{n-1}^2 x_{n-1} = -\ddot{u}_g / \chi_{M,n-1} \\ \ddot{x}_{n-2} + 2\xi_{n-2}\omega_{n-2}\dot{x}_{n-2} + \omega_{n-2}^2 x_{n-2} = -\ddot{u}_g / \chi_{M,n-2} \\ \ldots\ldots \\ \ddot{x}_1 + 2\xi_1\omega_1\dot{x}_1 + \omega_1^2 x_1 = -\ddot{u}_g / \chi_{M,1} \end{cases}$$

where the circular frequency and the adimensional damping for every single degree of freedom are respectively defined as:

$$\omega_i = \sqrt{\frac{k_i}{(m_n + m_{n-1} + \ldots + m_i)\chi_{M,i}}} \qquad \xi_i = \frac{c_i}{2\sqrt{k_i(m_n + m_{n-1} + \ldots + m_i)\chi_{M,i}}}$$

"EQUIVALENT" SDOF

In the case of adimensional damping smaller than 20-25%, the undamped modal forms can generally be considered a good approximation to describe the dynamicity of damped systems.
So the coupling coefficients can be estimated by using the modal parameters of undamped system:

$$\frac{\ddot{x}^{(i)}(t)}{\ddot{x}^{(j)}(t)} = \frac{x_1^{(i)}}{x_1^{(j)}}$$

when first modal form is considered

$$\frac{\ddot{x}^{(i)}(t)}{\ddot{x}^{(j)}(t)} = \frac{\sqrt{\sum_{k=1}^{n}\sum_{w=1}^{n}\rho_{kw} g_k g_w \omega_k^2 \omega_w^2 x_k^{(i)} x_w^{(i)}}}{\sqrt{\sum_{k=1}^{n}\sum_{w=1}^{n}\rho_{kw} g_k g_w \omega_k^2 \omega_w^2 x_k^{(j)} x_w^{(j)}}}$$

when multi-modal forms are considered

where $x_k^{(i)}$ is the i-th coordinate of the k-th modal form and ρ_{kw} is the correlation coefficient between "k" and "w" modal forms

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Benchmark structure

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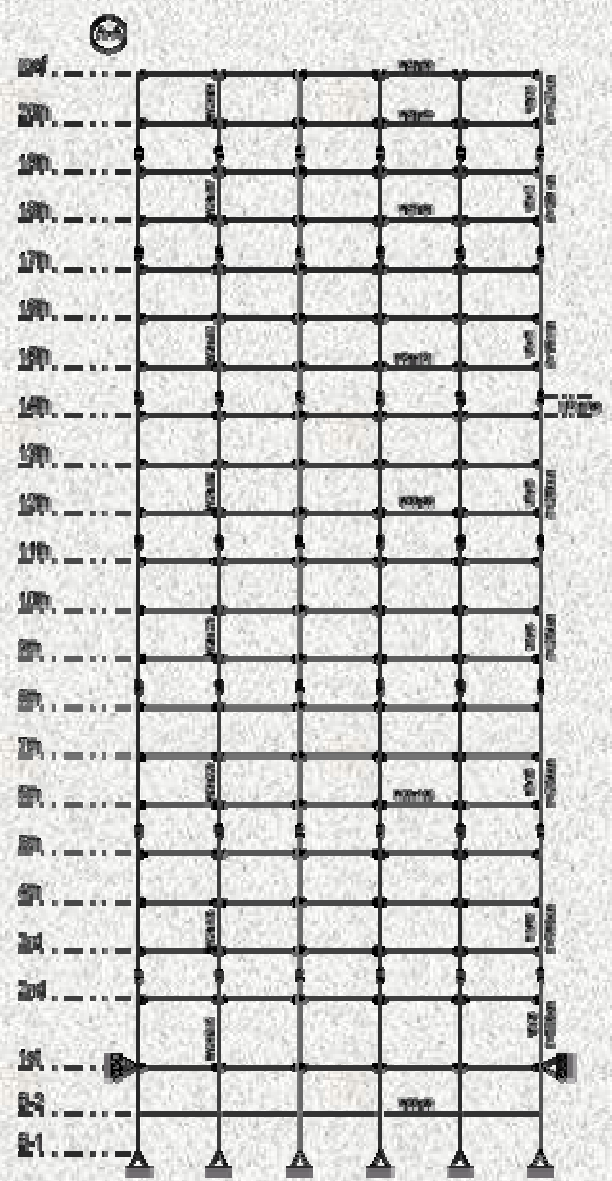
Elevation



NOTES

Beams (248 Mpa):
- B-2 – 8th level — W30x99;
- 9th – 11th level — W30x108;
- 12th – 16th level — W30x99;
- 18th – 19th level — W27x84;
- 20th level — W24x62;
- roof — W21x50.

Columns (345 Mpa):
- column sizes change at splices
- corner columns and interior columns the same, respectively, throughout elevation;
- box columns are ASTM A500 (15x15 indicates a 0.38 m (15 in) square box column with wall thickness of t).

Restraints:
- columns pinned at base;
- structure laterally restrained at 1st level.

Splices:
- denoted with ⧫;
- are at 1.83 m (6 ft) w.r.t. beam-to-column joint

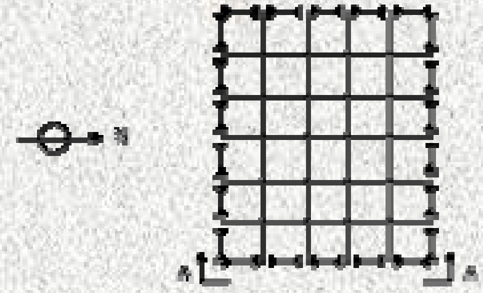
Connections:
- ⇥ ⇤ indicates a moment resisting connection.

Dimensions:
- all measurements are center line;
- basement level heights — 3.65 m (12'-0");
- 1st level height — 5.49 m (18'-0");
- 2nd – 20th level heights — 3.96 m (13'-0");
- bay widths (all) — 6.10 m (20'-0").

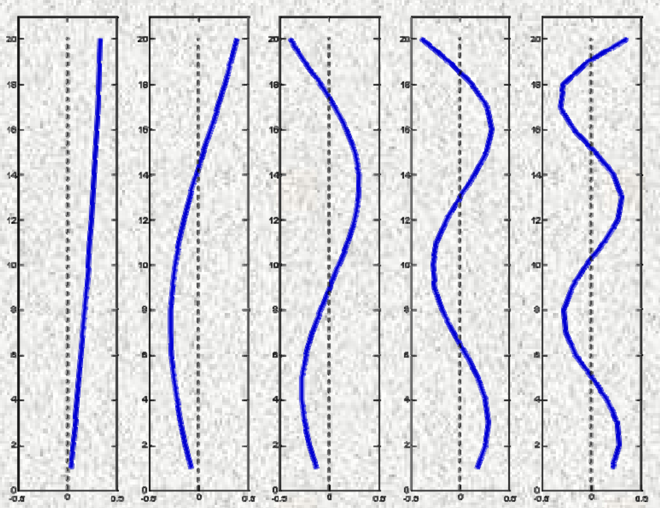
Seismic Mass:
- for single MRF in the N-S direction (including steel framing):
- 1st level — $2.66x10^5$ kg;
- 2nd level — $2.83x10^5$ kg;
- 3rd – 20th level — $2.76x10^5$ kg;
- roof — $2.92x10^5$ kg.

[B.F. Spencer Jr., R.E. Christenson and S.J. Dyke, 2000]

Building Plan



MODAL FORMS



T_1=3,58 sec | *T_2=1,38 sec* | *T_3=0,84 sec* | *T_4=0,57 sec* | *T_5=0,48 sec*

Coupling coefficients evaluation

"Coupling coefficients" for benchmark structure has been evaluated by considering the contribution of the first three modal forms:

Level	1	2	3	4	5	6	7	8	9	10
$\chi_{M,i}$	**3.5**	**16.6**	**36.2**	**88.4**	**25.2**	**15.1**	**12.0**	**11.0**	**11.3**	**12.8**
Level	11	12	13	14	15	16	17	18	19	20
$\chi_{M,i}$	**15.7**	**24.0**	**60.7**	**41.6**	**19.3**	**14.1**	**11.7**	**11.2**	**11.5**	**13.8**

Seismic Demand

In particular, response spectra representative of the "class A ground", defined according to EuroCode 8 (Eurocode 8 [ENV 1998-1-1], 2005) is considered in numerical experimentation.

The reduction factor to take into account the viscous dissipation of energy is evaluated according to the following equation (Eurocode 8 [ENV 1998-1-1], 2005):

$$q_\xi = \frac{1}{\eta} = \sqrt{\frac{5+\xi}{10}}$$

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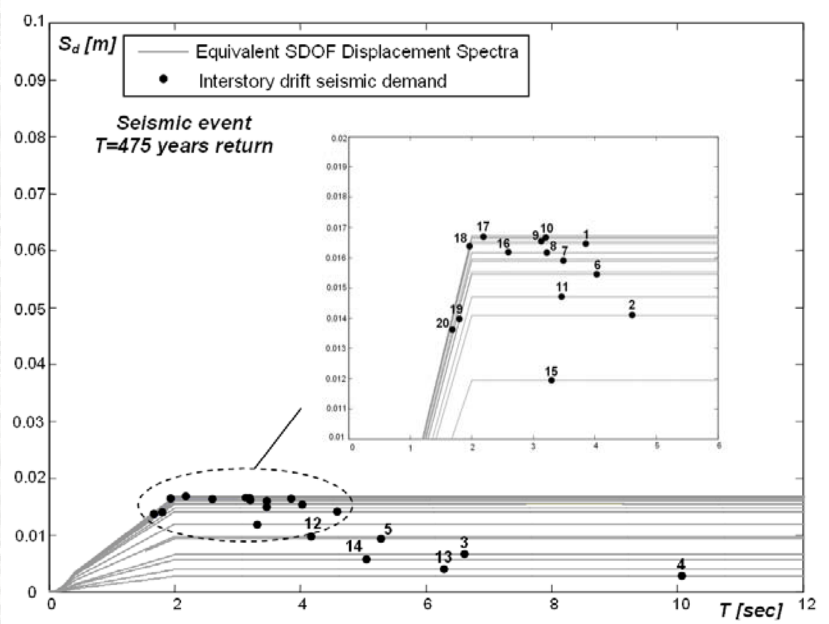
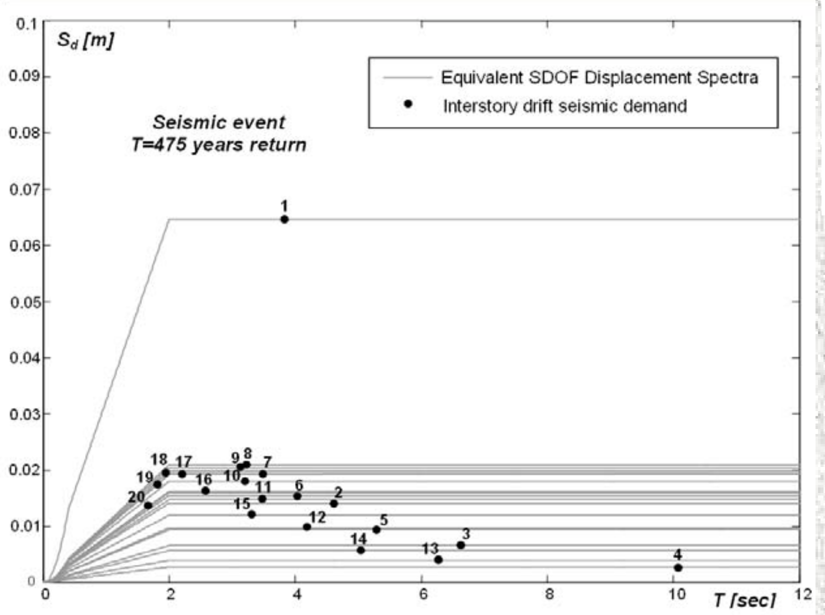
Analysis of Seismic demand

"optimal" distribution of 50 viscous dampers with c=15000 Nsec/m



Benchmark structure equipped with 50 dampers



Benchmark structure with no dampers

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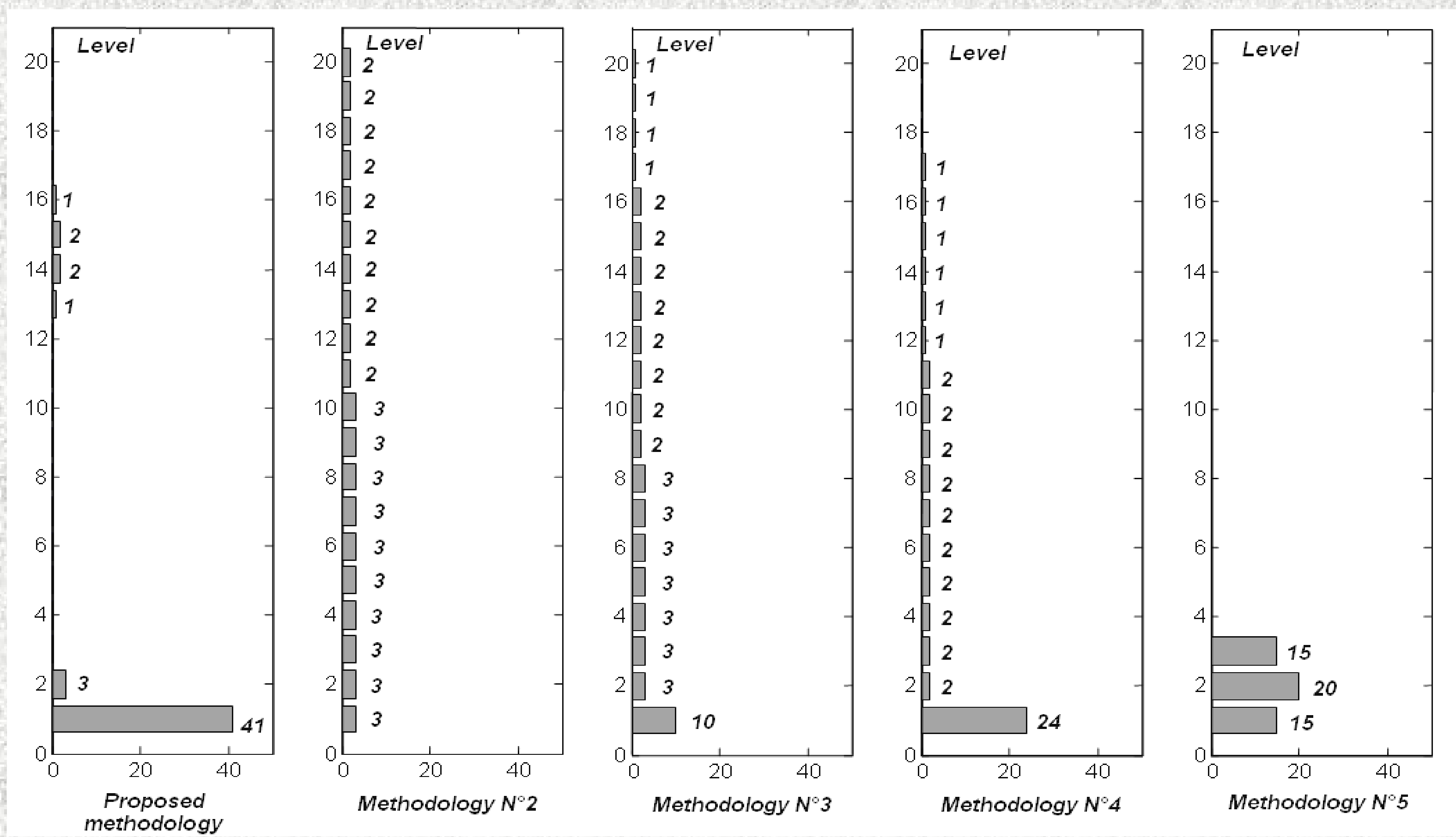
Design methodology results



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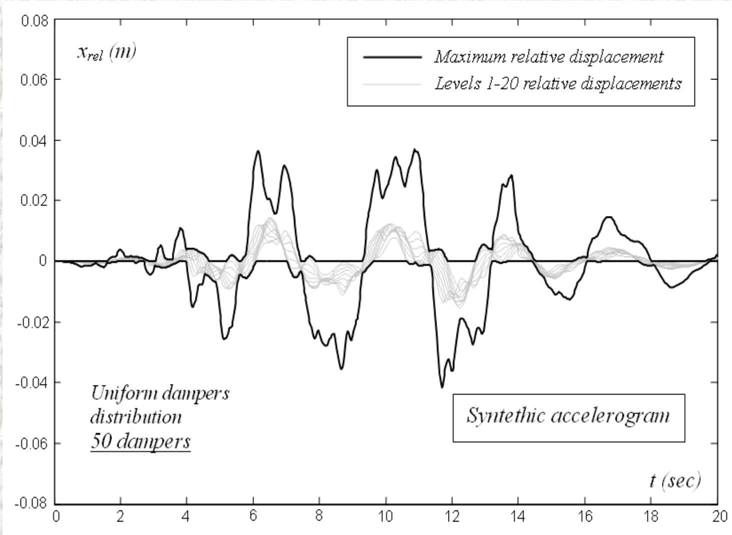
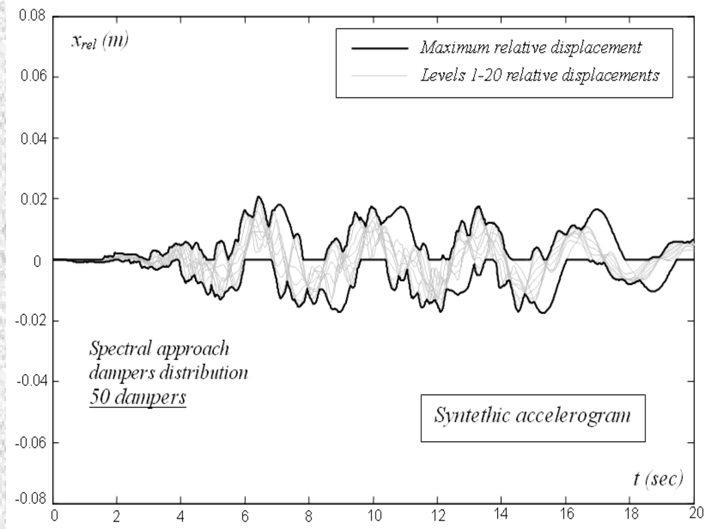
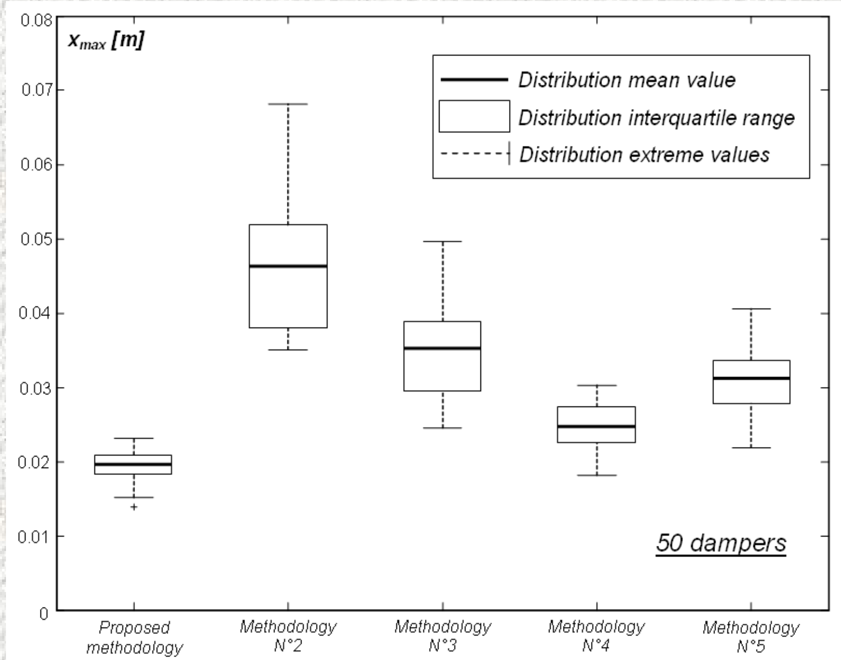
- *proposed methodology*
- *uniformly allocated (methodology N°2)*
- *proportionally distributed to the first modal form component (methodology N°3)*
- *proportionally to the square of the first modal form component (methodology N°4)*
- *viscous devices allocated to maximize a performance index representing instantaneous power dissipation (Petti and De Iuliis, 2003) (methodology N°5)*

Effectiveness analysis

Time-history seismic response of the benchmark structure to 20 synthetic excitations







Seismic response to synthetic excitations
<u>Box plot representation</u>

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Spectral Method vs complex approaches

System *A* [Levy & Lavan, 2006]

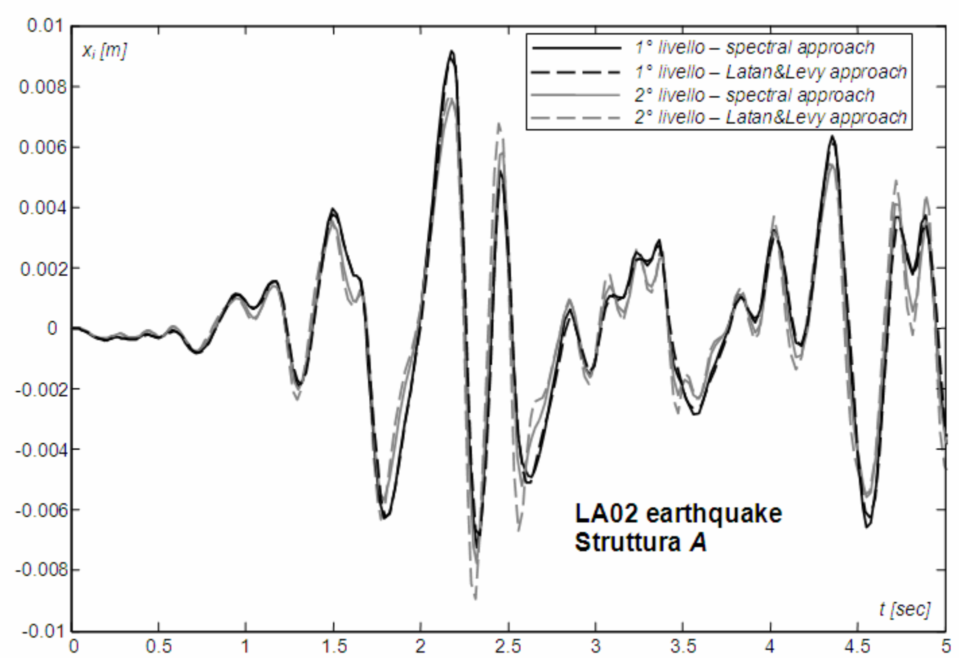
Two levels share-type frame with a 5% Rayleigh modal damping on both forms. The two fundamental periods are equal to 0.281 sec and 0.115 sec

Levy & Lavan methodology

Recursive approach of the "**fully stressed design**" optimization technique. **Seismic dynamic analysis of controlled structures needed.**

Extra-structural damping configuration

Level	1	2
Design methodology		
Lavan & Levy	1300.4	181.4
Spectral approach	**1067.0**	**414.8**



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Spectral Method vs complex approaches

System *B* [Takewaki, 1997]

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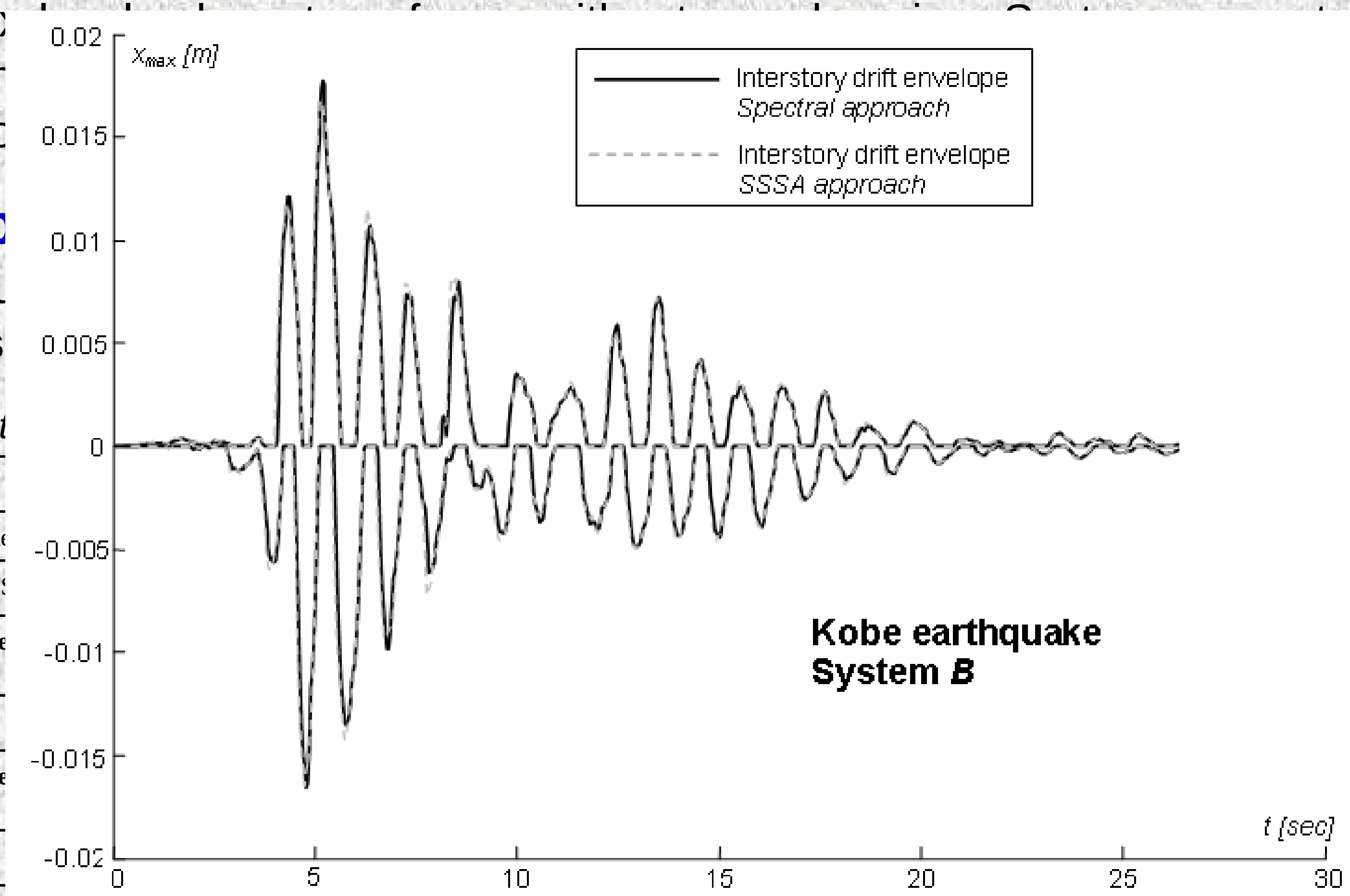

Strate...						
SS...						
Spe...						
Spe...						
Spectral approach Taft	***3***	***1***	***1***	***1***	***1***	***1***
SSSA/Rinaldi	*2*	*2*	*1*	*1*	*1*	*1*
Spectral approach Rinaldi	***2***	***2***	***1***	***1***	***1***	***1***

...y drift

...Rinaldi
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Spectral Method vs complex approaches

System *C* [Gluck et al., 1996]

S … st

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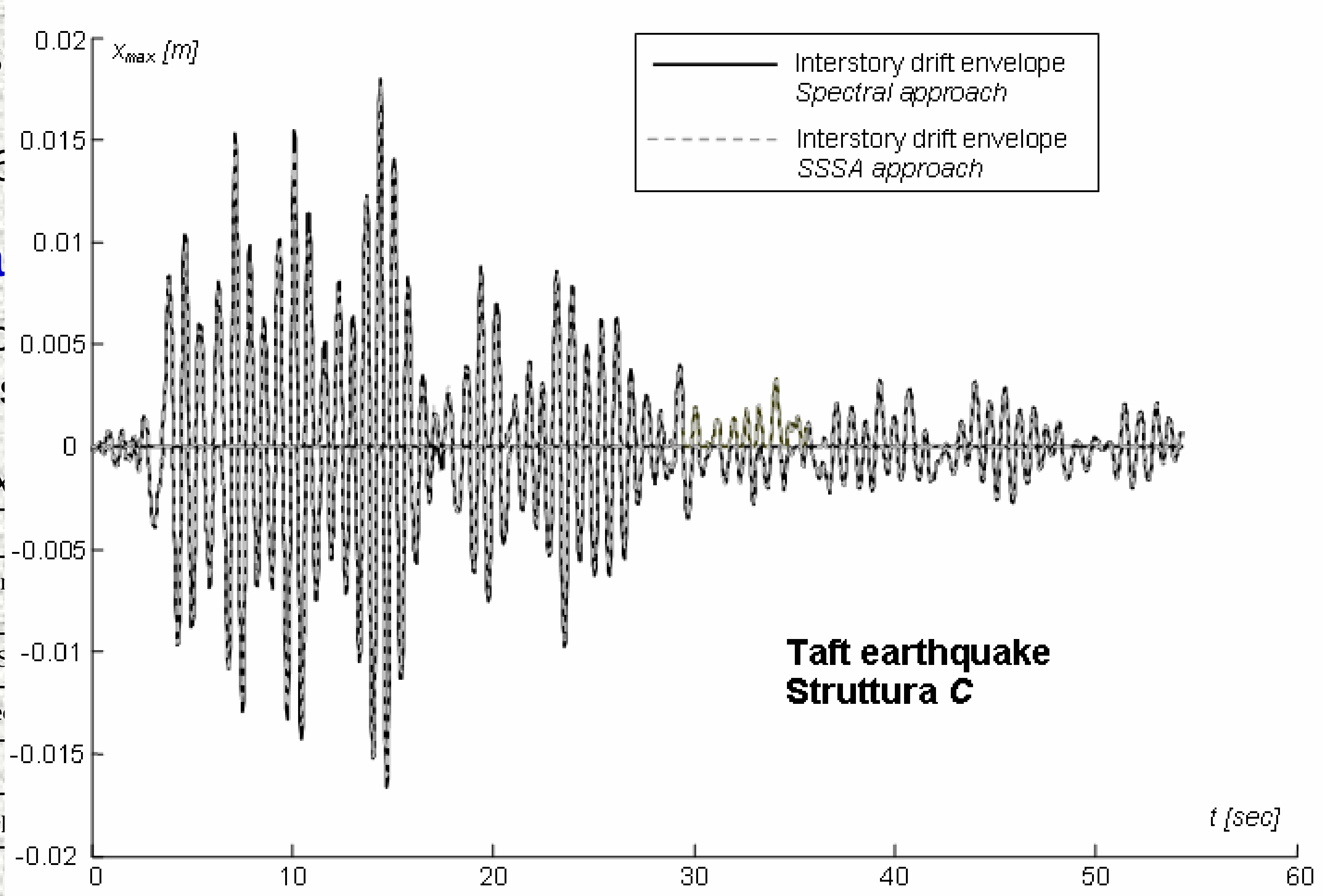

drift

…naldi

…197

…204

Spectral/Taft	***5***	***2***	***1***	***1***	***0***	***0***	***0***
SSSA/Rinaldi	*4*	*3*	*0*	*2*	*0*	*0*	*0*
Spectral/Rinaldi	***3***	***3***	***2***	***1***	***0***	***0***	***0***

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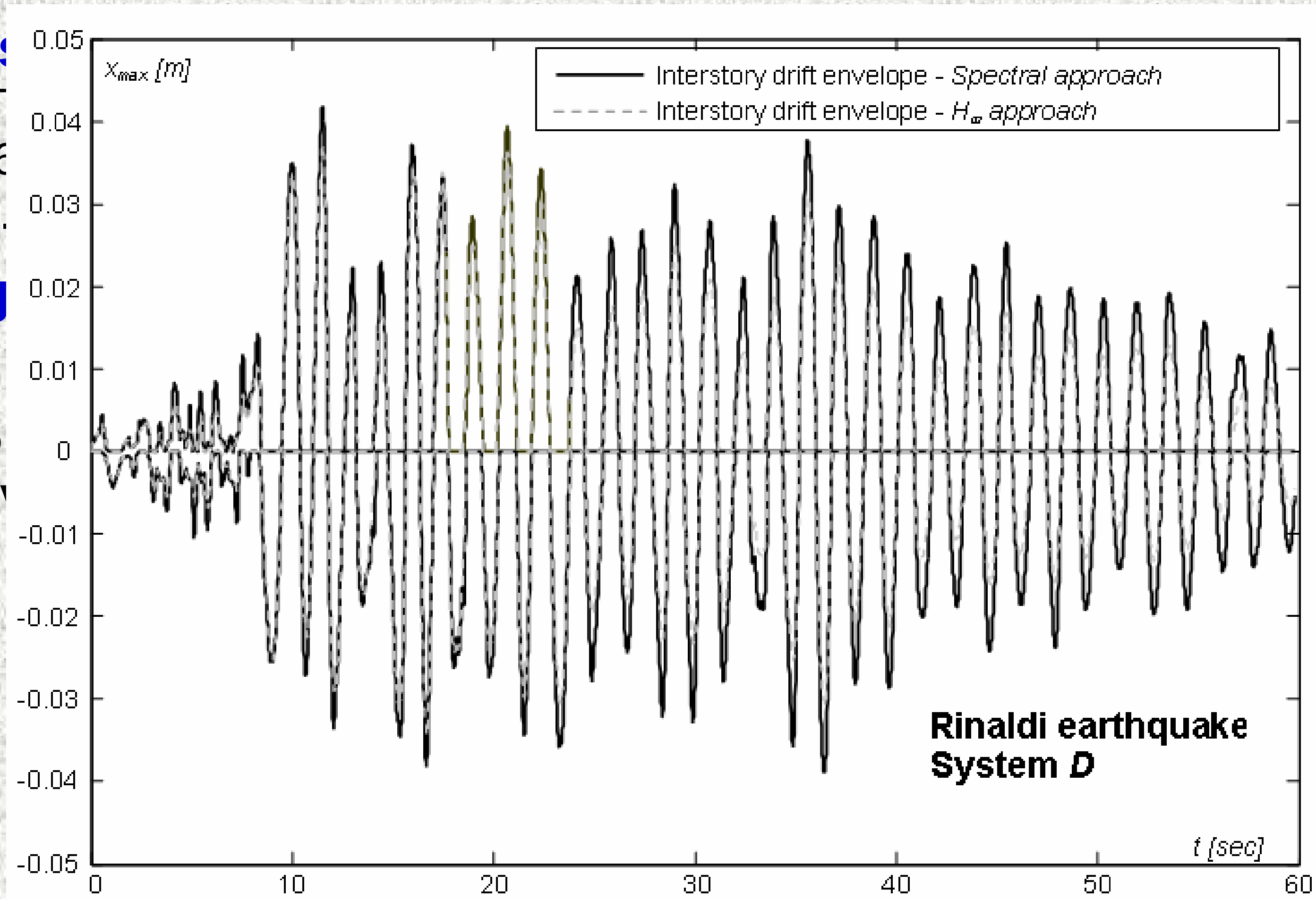

H_∞	[illegible]	[illegible]	[illegible]	[illegible]
Spectral	***0.0170***	***0.0094***	***0.0175***	***0.0418***

Concluding remarks

A new design methodology for the optimal allocation of viscous damping devices has been proposed. It only needs a linear modal analysis to be performed, its effectiveness has been compared with other simple design strategy. Results allow for the following considerations:

- **The proposed methodology is effective with a 250% reduction in maximum average seismic response when compared to the uniform distribution (methodology 2) and a 30% reduction when compared to the distribution obtained according to other simple approach**
- **It allows for a structure presenting uniform inter-storey drift seismic demand. Moreover, maximum inter-storey drift presents a numerical value close to that estimated during the design process.**
- **Within the literature methods, the proposed strategy uses spectral representation to describe seismic demand. It is able to evaluate interstory drift seismic demand in a simple and reliable way for practical values of available extra-structural dissipation resource**
- **The proposed approach, despite its conceptual and computational simplicity, allow for seismic performance close to the ones obtained by adopting complex strategy generally based on multiple dynamic analysis**

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