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

Università degli Studi di Salerno – Consorzio ReLUIS,
12-13 Febbraio 2007

Force-based vs. displacement-based design of braced steel frames

G. Della Corte, M. D'Aniello, N. Calabrese and F.M. Mazzolani

Force-based Vs. Displacement-based design

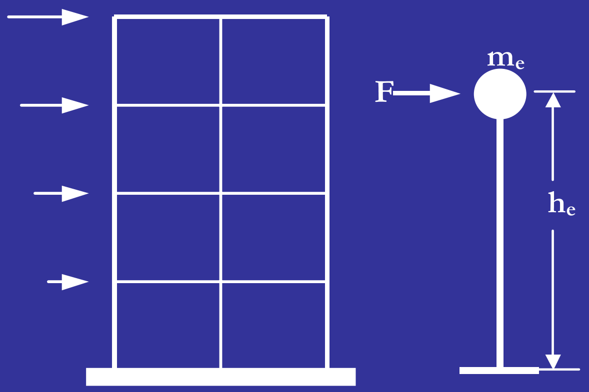
It is generally acknowledged that the structural damage due to seismic events is related to strains developed in members and, as a consequence, it is related to their displacements.

Hence, displacements and drifts are the best indicators of structural damage.

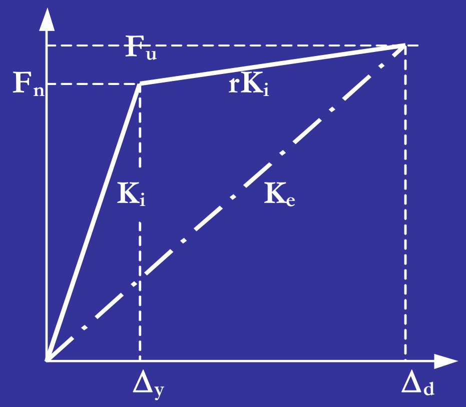
In codified force-based design procedures, displacements are considered only as an output of the design process

Contrary, in displacement-based design procedures, displacements are the input data of the design process.

Fundamentals of Direct DBD



(a) SDOF Simulation



(b) Effective Stiffness K_e

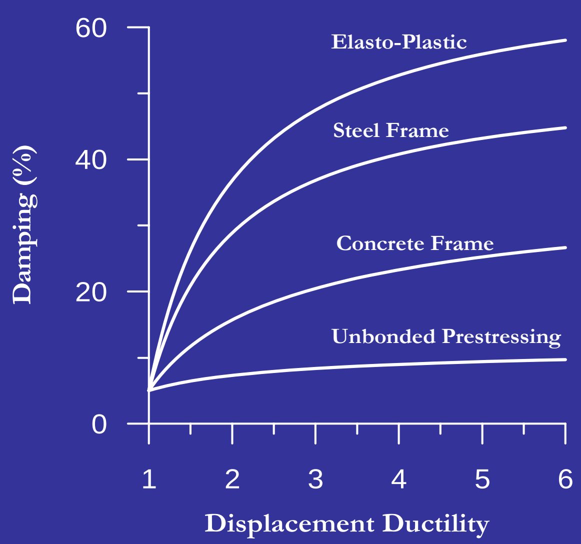
$$V_b = K_e \Delta_d$$

Set: Δ_d

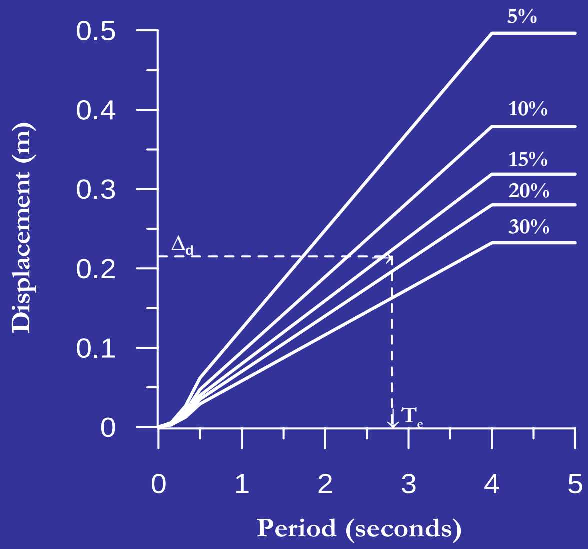
Get: μ

Use: μ

Get: ξ



(c) Equivalent damping vs. ductility



(d) Design Displacement Spectra

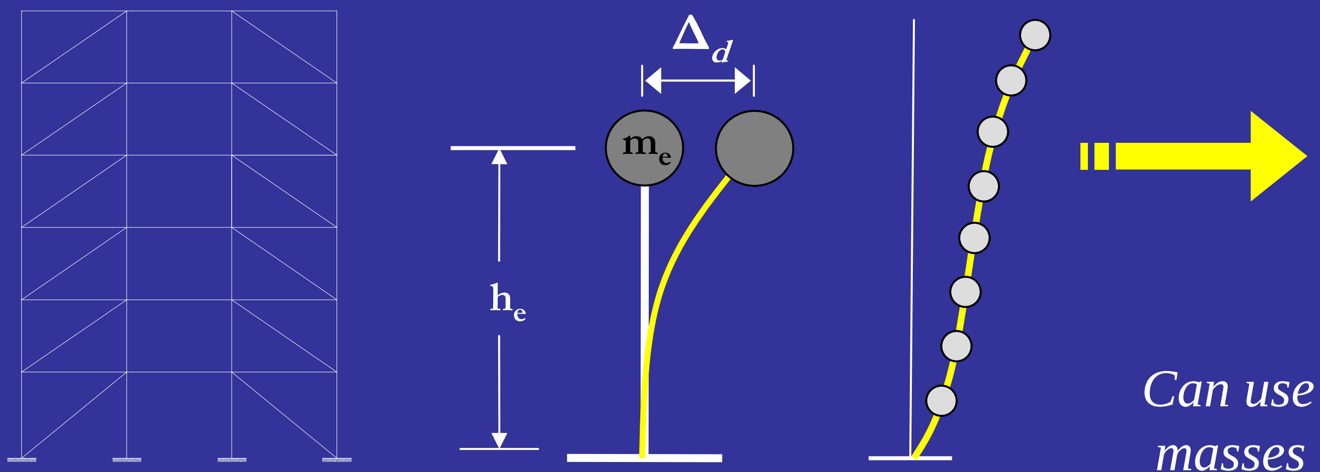
Use: Δ_d & ξ

Get: T_e

Use: T_e & m_e

Get: K_e

Setting the design displacement Δ_d

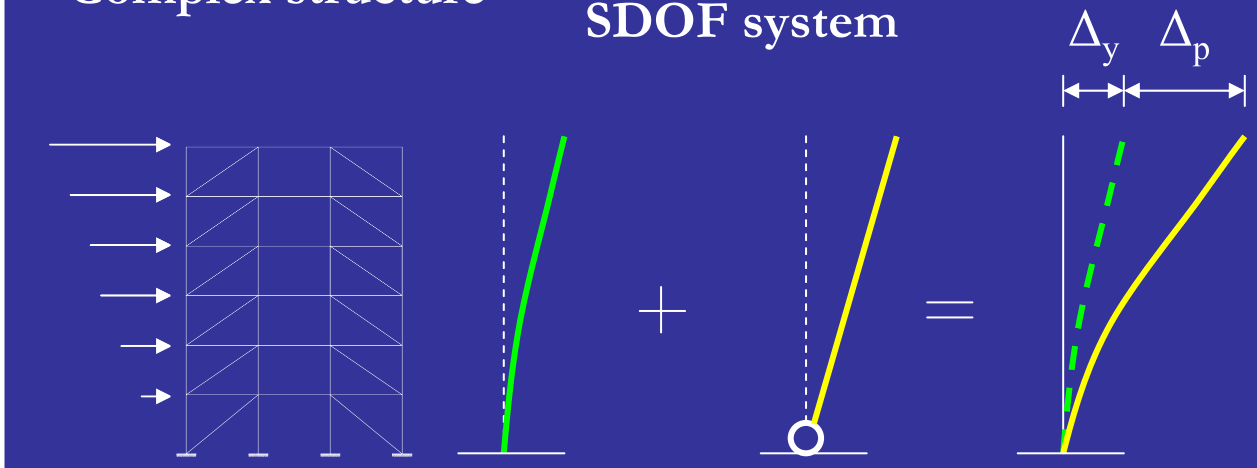


Complex structure

Equivalent SDOF system

$$\Delta_d = \frac{\sum_{i=1}^{n}\left(m_i \Delta_i^2\right)}{\sum_{i=1}^{n}\left(m_i \Delta_i\right)}$$

Can use displacements of masses (virtual work) to obtain design displacement.



Elastic deformations

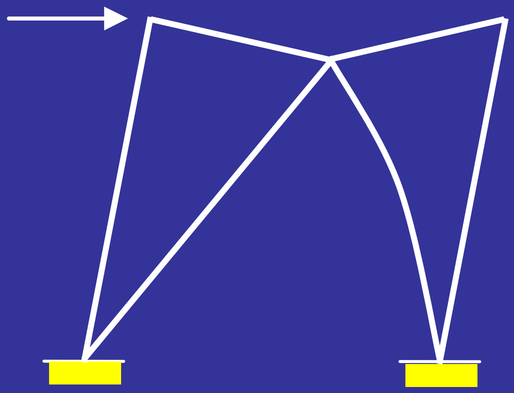
Plastic deformations

Final shape

To define $\boldsymbol{\Delta_d}$ will need to know displaced shape of structure *at yielding and at maximum response.*

Displacement shape of inverted V CB structures

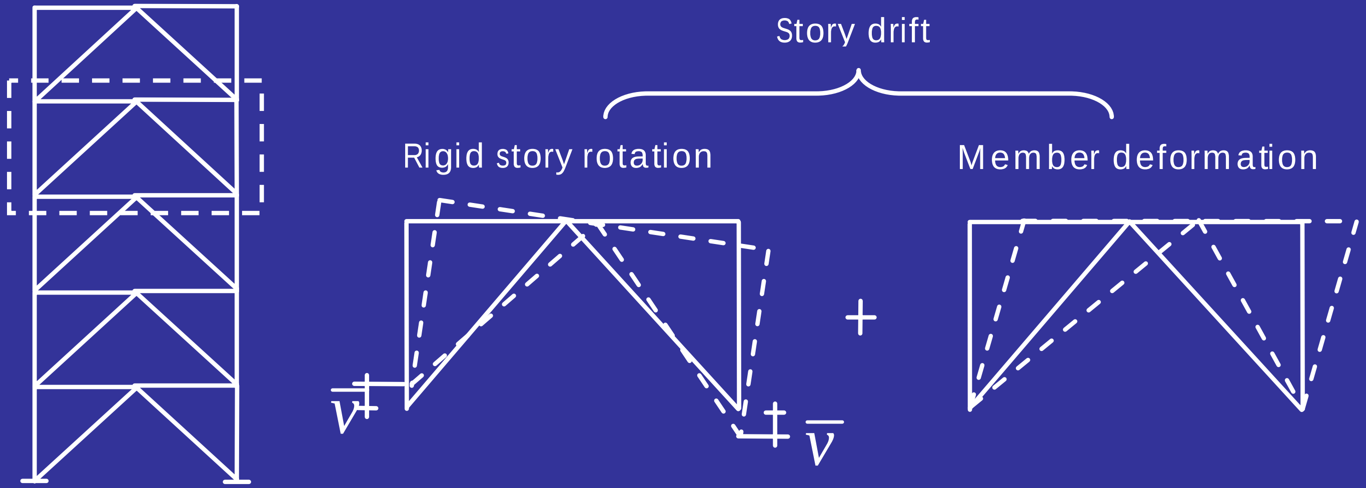
Concentrically braced structures are characterised by brace buckling, occurring with large strength degradation in the compression braces.



The pre-buckling response (elastic field) may be quite different from the post-buckling behaviour, in terms of height-wise distribution of story displacements.

Yield displacement shape of inverted V CB structures

Yield displacement correspond to the first non-linear event, i.e. the first brace buckling



$$\theta_{\mathrm{i,y}} = \frac{2\overline{v}_{\mathrm{i,y}}}{L} + \frac{2\varepsilon_{\mathrm{br,i}}}{sen2\alpha_{\mathrm{i}}} = \frac{2\overline{v}_{\mathrm{i,y}}}{L} + \frac{2\rho_{\mathrm{br,i}}\chi_{\mathrm{br,i}}\varepsilon_{\mathrm{y}}}{sen2\alpha_{\mathrm{i}}}$$

The coefficient $\rho_{\mathrm{br,i}}$ allows for selecting the floor at which braces must buckle first, where $\rho_{\mathrm{br}} = 1$ → $\rho_{\mathrm{br,i}} = \dfrac{\chi_{\mathrm{br,N}}}{\chi_{\mathrm{br,i}}}$

Yield displacement shape of inverted V CB structures

Yield displacement correspond to the first non-linear event, i.e. the first brace buckling

$$\overline{v}_{\mathrm{i,y}} = \sum_{j=1}^{i-1} \varepsilon_{\mathrm{br,j}} h_{\mathrm{j}} = \sum_{j=1}^{i-1} \rho_{\mathrm{c,j}} \chi_{\mathrm{c,j}} \varepsilon_{\mathrm{y}} h_{\mathrm{j}} \qquad \rho_{\mathrm{c,i}} = \frac{1}{\gamma_{\mathrm{ov}} h_{\mathrm{p}} h_{\mathrm{f}} \Omega \gamma_{\mathrm{G,i}} \gamma_{\mathrm{s}}}$$

The coefficient $\rho_{\mathrm{c,i}}$ takes into account the following phenomena:

(i) material yield stress (and strain) larger than nominal values;

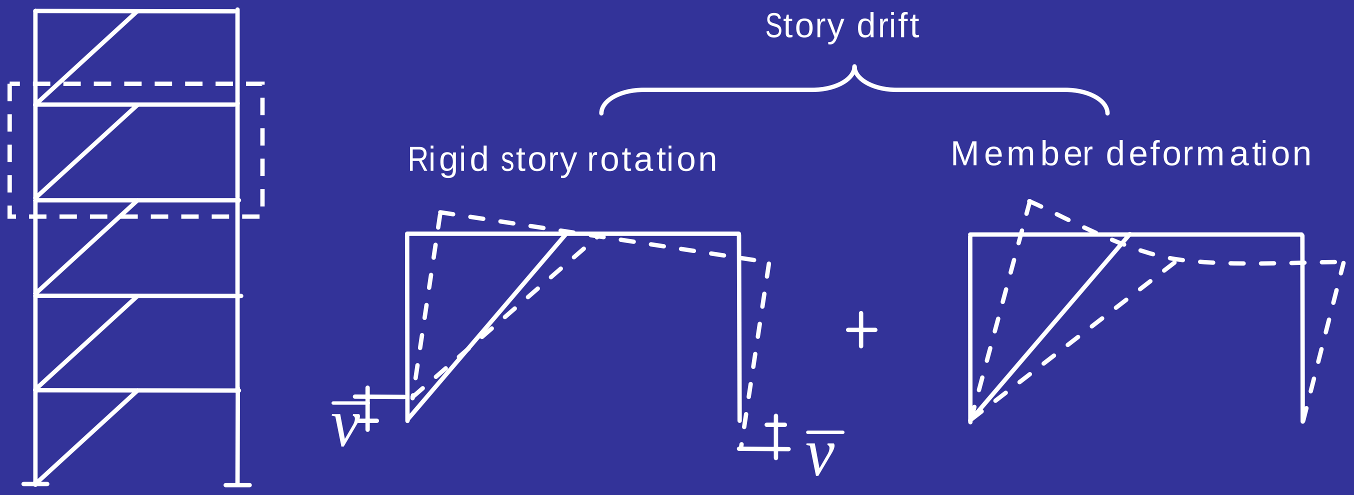
(ii) steel hardening due to plastic deformation;

(iii) plastic redistribution after first buckling (i.e. subsequent buckling of braces at different floors);

(iv) axial force in the brace due to gravity loads.

Target displacement shape of inverted V CB structures

It is assumed that braces have buckled and largely deformed into the post-buckling range



$$\theta_{i,t} = \frac{2\bar{v}_{i,t}}{L} + \frac{2\varepsilon_{br,i,t}}{sen2\alpha_i} + \frac{v_{b,i}}{h_i} tg\alpha_i + \frac{\varepsilon^{l}_{c,i,t} + \varepsilon^{r}_{c,i,t}}{2} tg\alpha_i$$

$\varepsilon_{br,t} = \gamma_{ov}\varepsilon_y$ $\varepsilon_{c,i,t} = \varepsilon_{c,i,y} / \rho_{c,i}$ $v_{b,i}$ **is the vertical beam deflection**

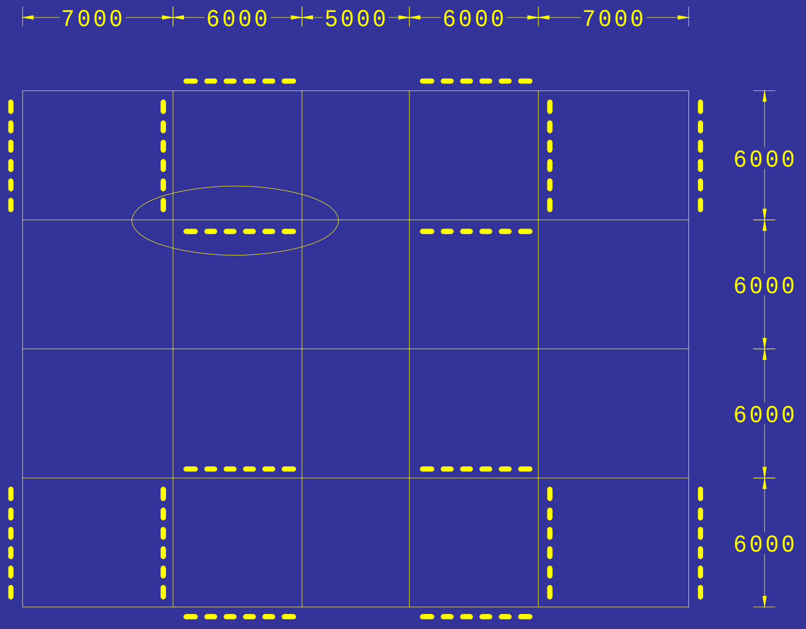
Applications: the study case

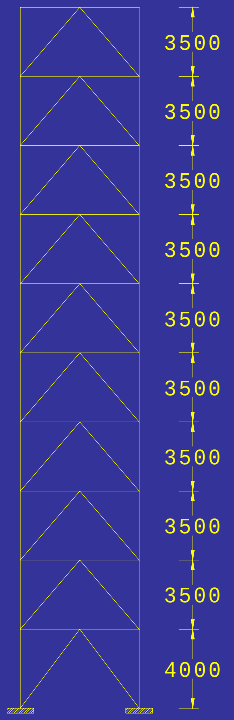
10 story building

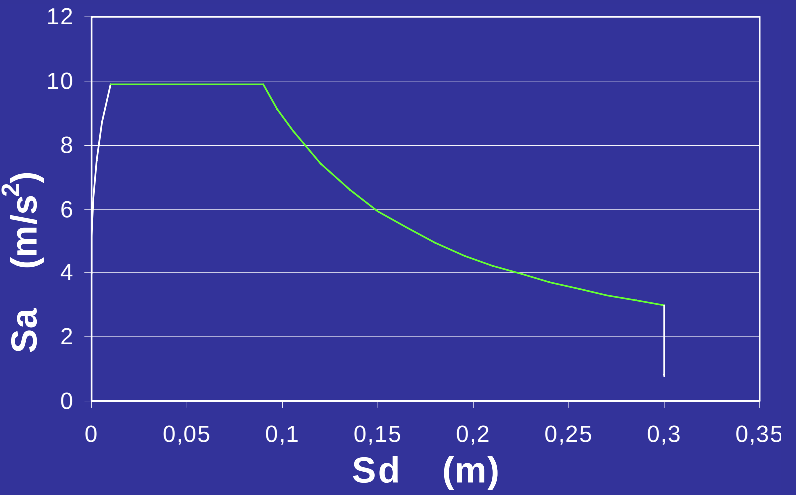
Roof mass: 55.11 kNs^2/m

1° floor mass: 51.11 kNs^2/m

ith floor mass: 51.19 kNs^2/m







Elastic design spectrum:
OPCM ground type C,
PGA on bedrock =0.35g

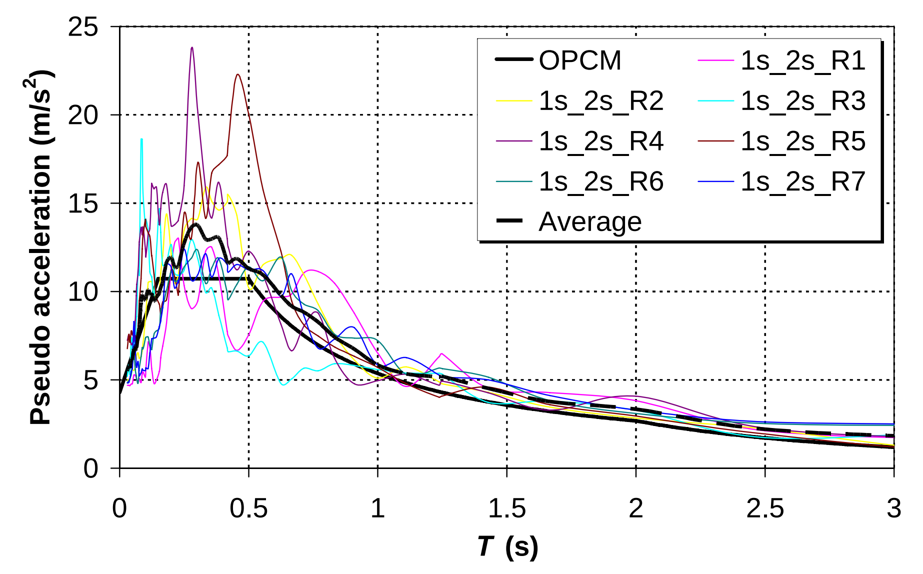
Member cross-sections: DDBD vs OPCM

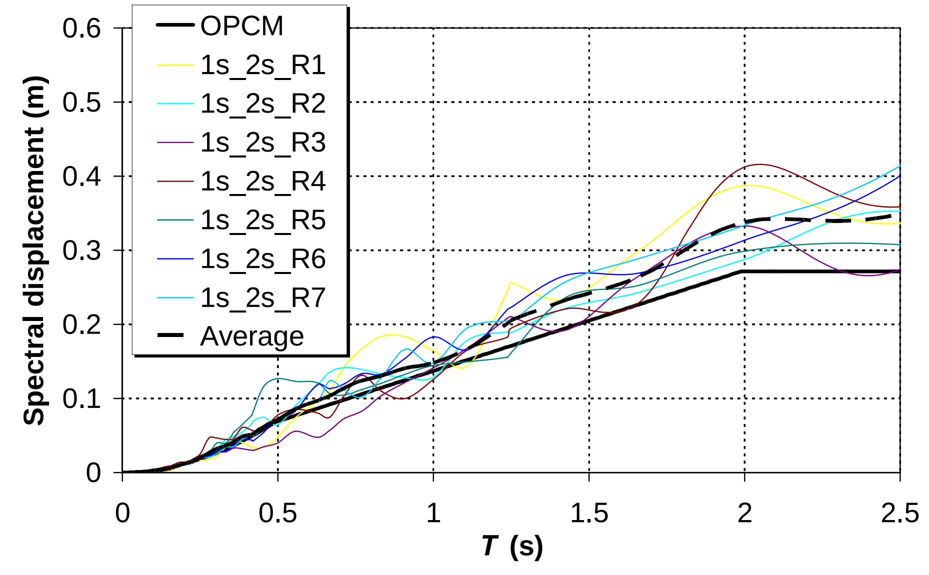
Floor level	Columns	Beams	Braces
	Wide flange double-T sections	Wide flange double-T sections	Circular hollow sections
10	HE 160 B	HE 340 B	88.9x5
9	HE 160 B	HE 360 B	88.9x7
8	HE 240 B	HE 400 B	101.6x7
7	HE 240 B	HE 450 B	101.6x8
6	HE 320 B	HE 450 B	114.3x7
5	HE 320 B	HE 450 B	114.3x8
4	HE 600 B	HE 500 B	114.3x10
3	HE 600 B	HE 500 B	127x8
2	HE 700 M	HE 500 B	127x9
1	HE 700 M	HE 550 B	159x7

Floor level	Columns	Beams	Braces
	Wide flange double-T sections simple or coupled (2⊥)	Wide flange double-T sections	Circular hollow sections
10	HE 160 B	HE 280 M	96x7
9	HE 160 B	HE 300 M	114.3x7
8	HE 260 B	HE 300 M	114.3x9
7	HE 260 B	HE 340 M	127x9
6	HE 260 M	HE 360 M	127x10
5	HE 260 M	HE 360 M	139.7x9
4	HE 300 M	HE 400 M	139.7x9
3	HE 300 M	HE 400 M	152.4x8
2	2⊥ HE 500 A	HE 400 M	152.4x8
1	2⊥ HE 500 A	HE 450 M	159x9

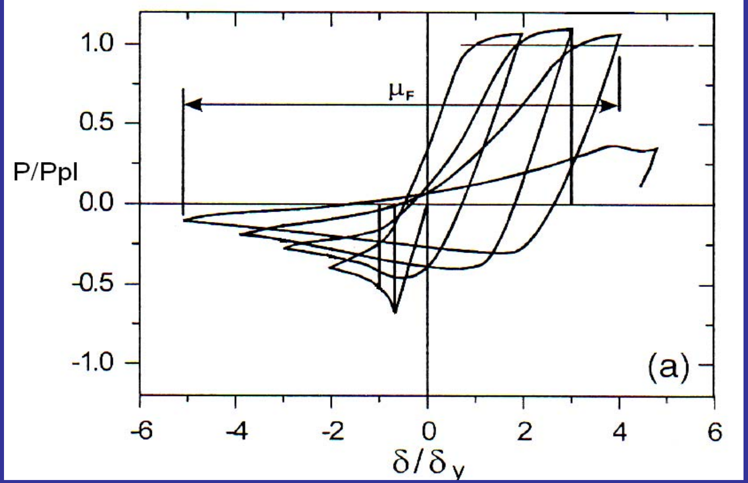
Numerical analyses: acceleration records

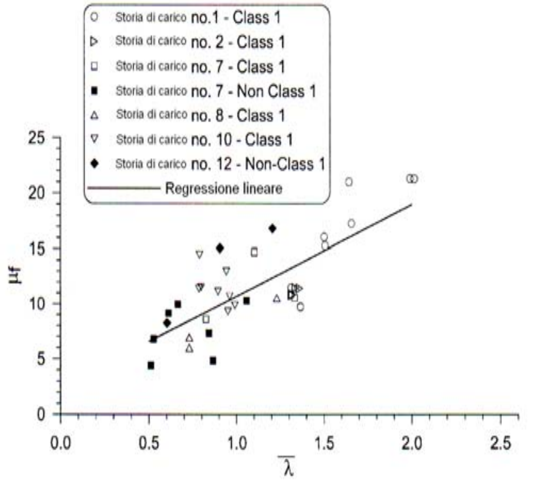
The set of acceleration records used for the analyses have been developed within the Reluis research project





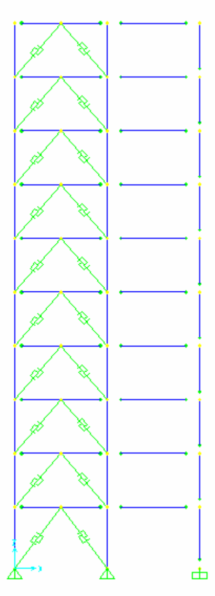
Numerical analyses: Diagonal brace modelling

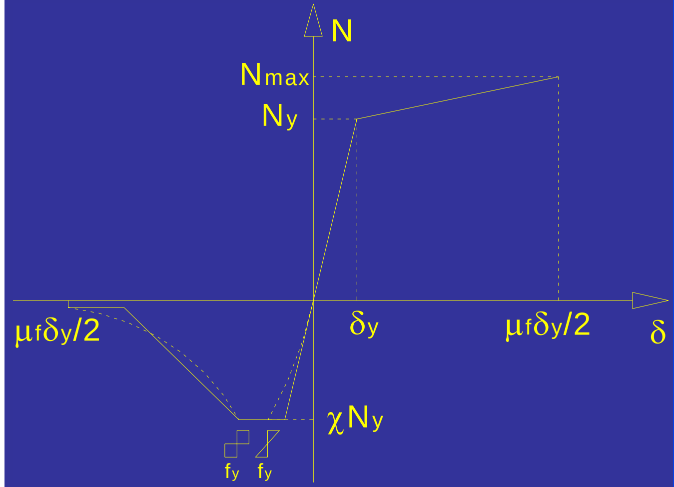


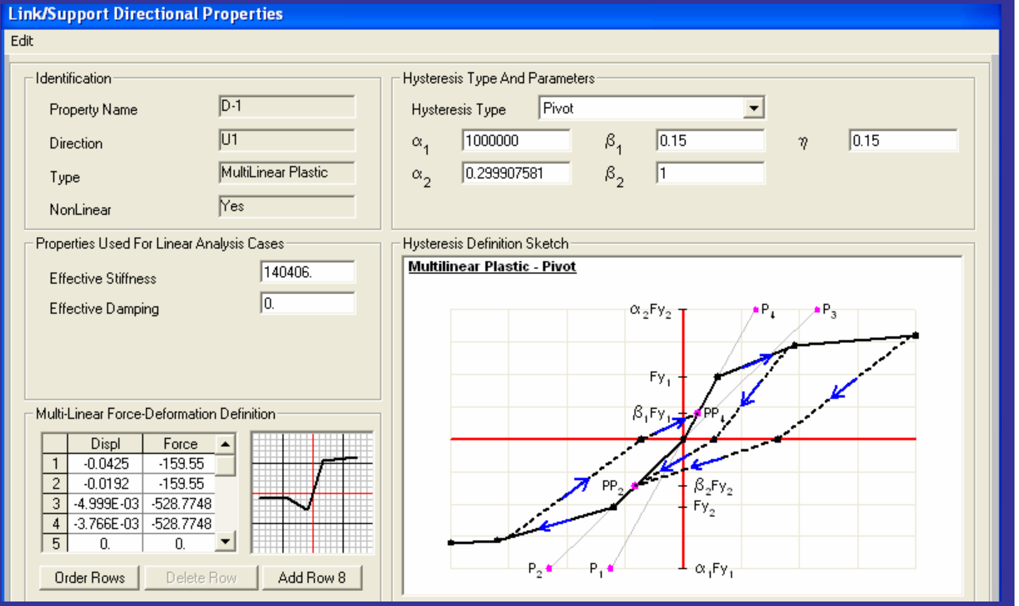


$$\mu_f = 2,4 + 8,3\overline{\lambda}$$

Tremblay (2001)







Link/Support Directional Properties

Edit

Identification

Property Name: D-1
Direction: U1
Type: MultiLinear Plastic
NonLinear: Yes

Hysteresis Type And Parameters

Hysteresis Type: Pivot
α_1: 1000000
β_1: 0.15
η: 0.15
α_2: 0.299907581
β_2: 1

Properties Used For Linear Analysis Cases

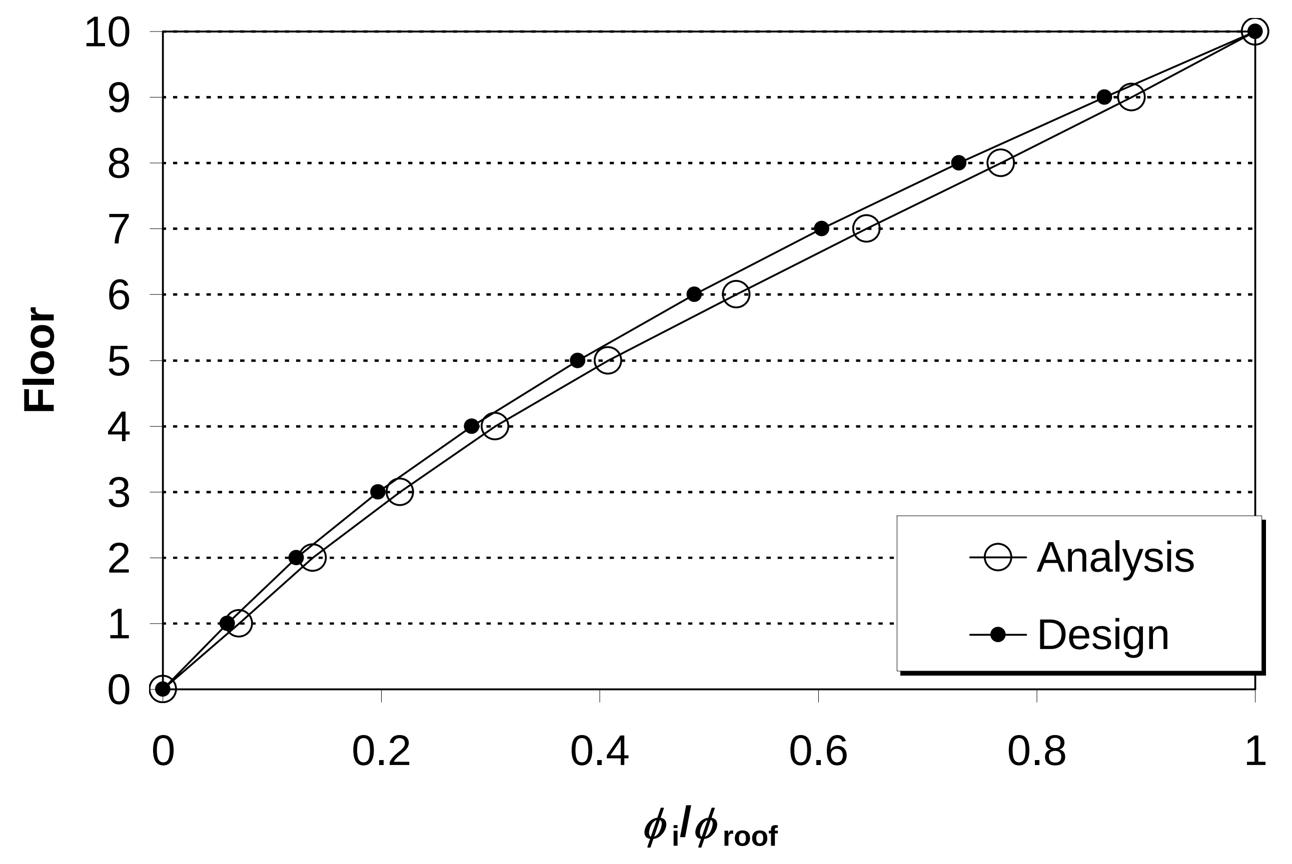
Effective Stiffness: 140406.
Effective Damping: 0.

Multi-Linear Force-Deformation Definition

	Displ	Force
1	-0.0425	-159.55
2	-0.0192	-159.55
3	-4.999E-03	-528.7748
4	-3.766E-03	-528.7748
5	0.	0.

The brace was modelled in SAP2000 with a non-linear MultiLinear plastic link

Results of static and dynamic analyses: DDBD vs OPCM



The vibration mode assumed at the design stage is very close to the one predicted by back-analysis of the final design solution.

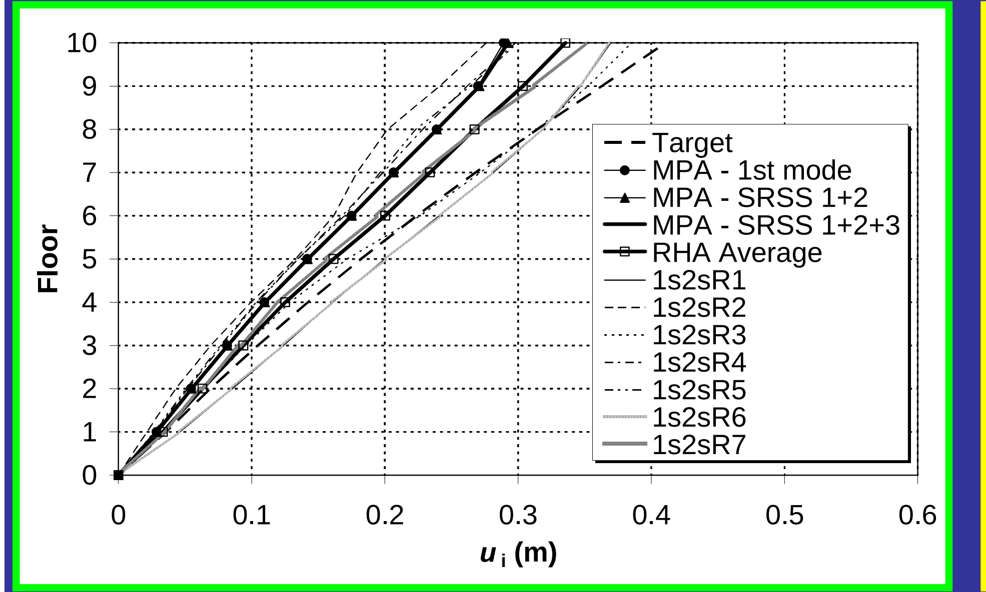
Results of static and dynamic analyses: DDBD vs OPCM

Lateral displacements
under 1s_2s_7R accelerogram
(DBD structure)

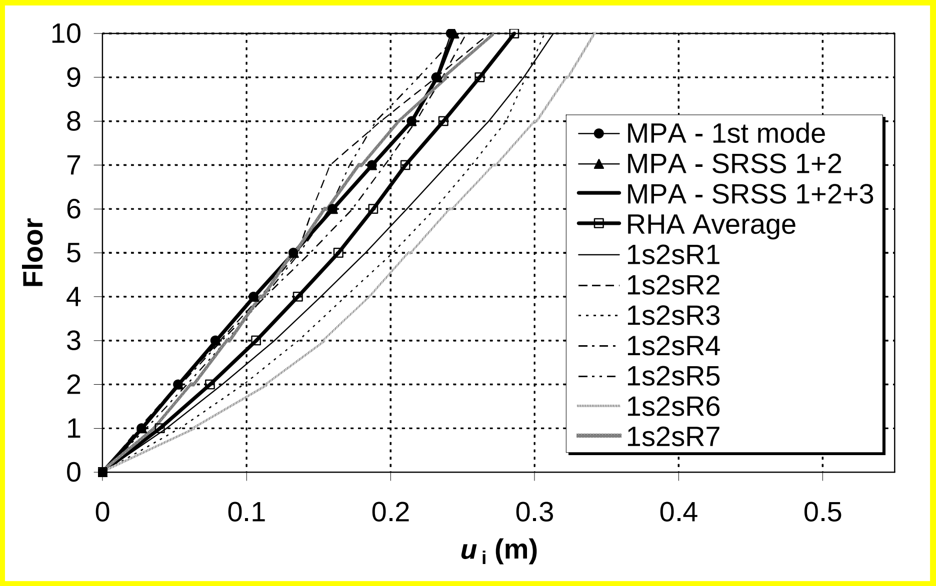
Lateral displacements
under 1s_2s_7R accelerogram
(OPCM structure)

Results of static and dynamic analyses: DDBD vs OPCM

The average response over accelerograms (RHA) is also shown and compared with both the results of multi-modal pushover analysis (MPA, Chopra, 2004) and the target displacements



displacement profiles (DDBD)

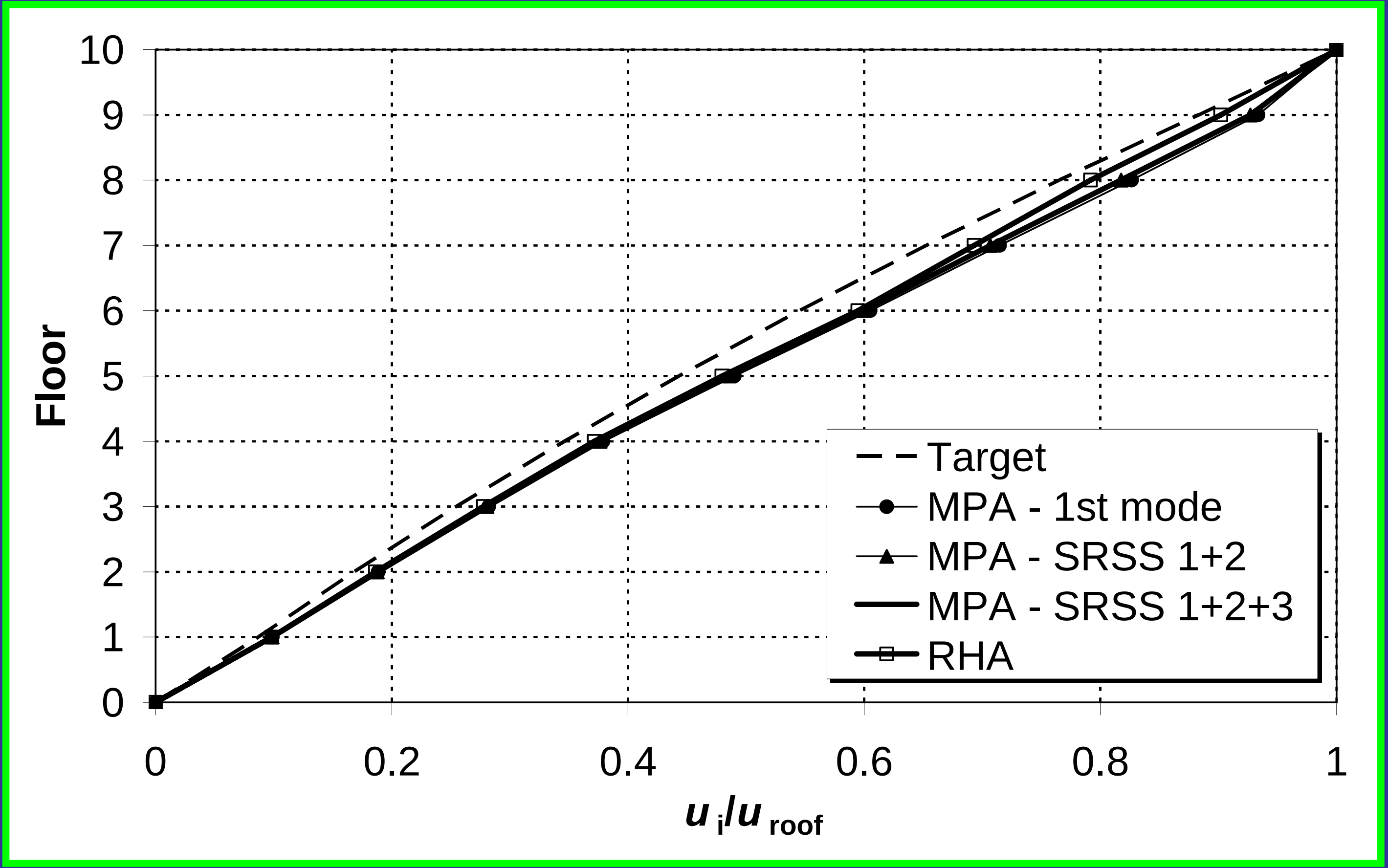


displacement profiles (OPCM)

The average displacement of OPCM structure tends to a parabolic shape, while the one of DBD is linear. This implies that in case of DBD there is a more uniform plastic engagement

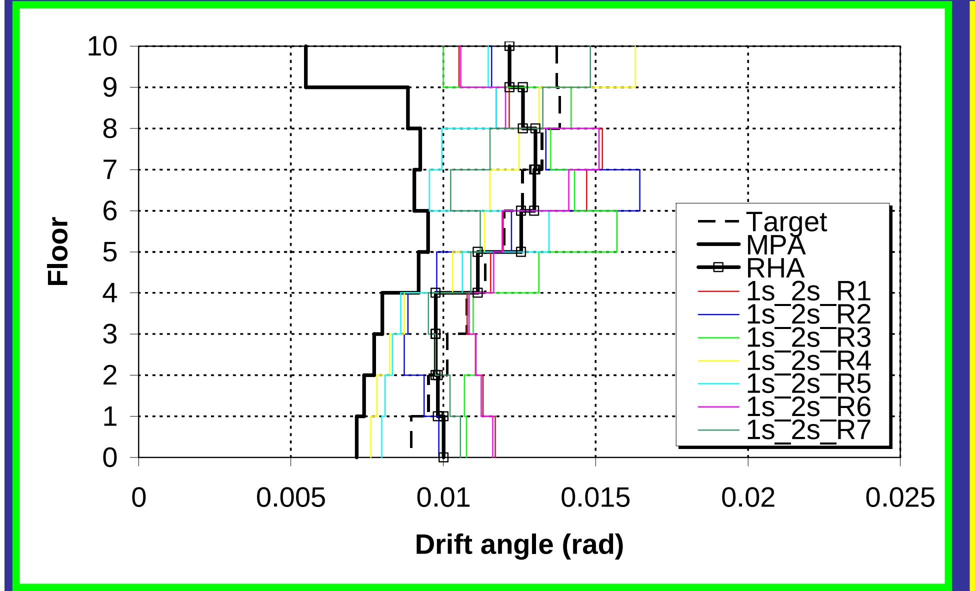
Results of static and dynamic analyses: DDBD vs OPCM

normalised displacement profiles (DBD structure)

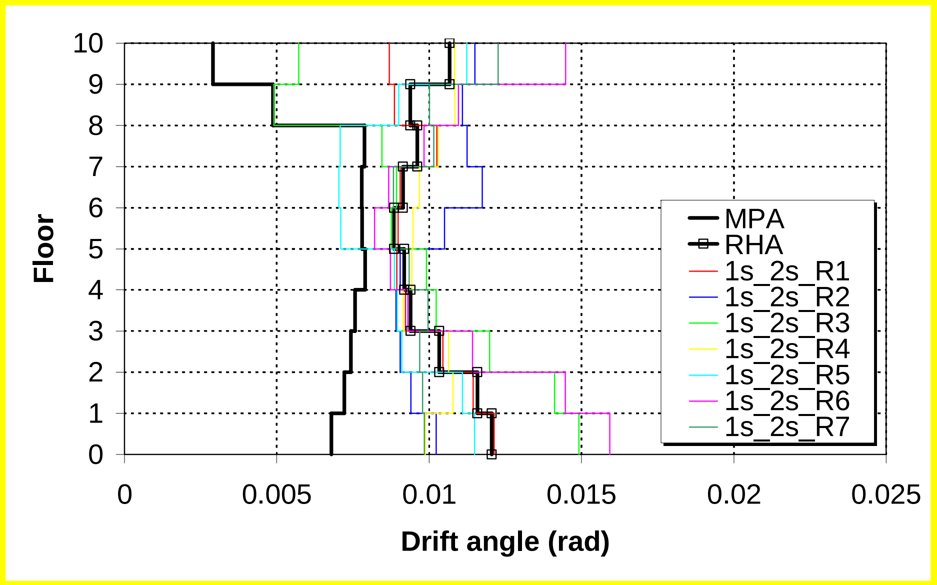


The average response over accelerograms (RHA) is well matched by MPA in case of DBD.

Results of static and dynamic analyses: DDBD vs OPCM



Inter-story drift angles
(DBD structure)

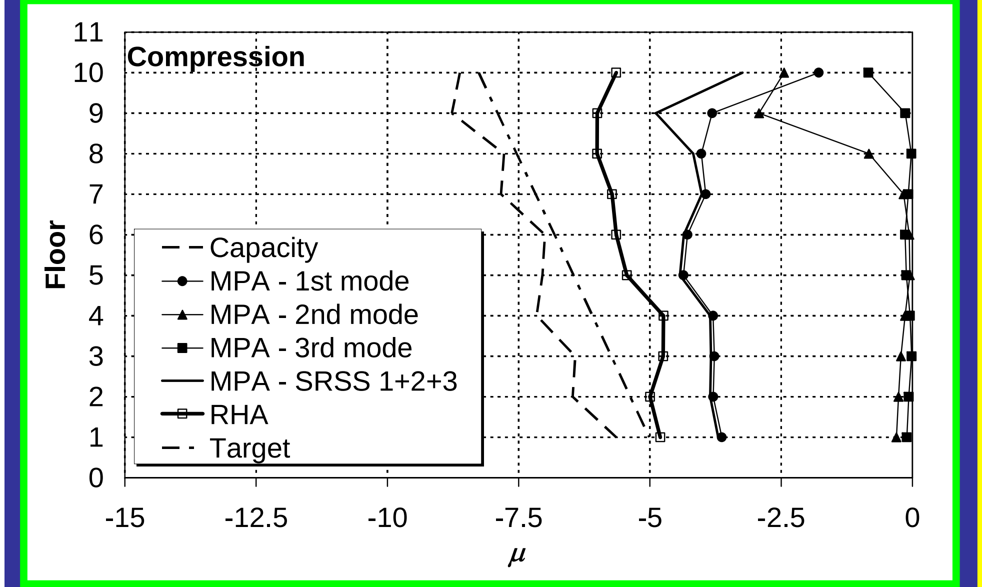


Inter-story drift angles
(OPCM structure)

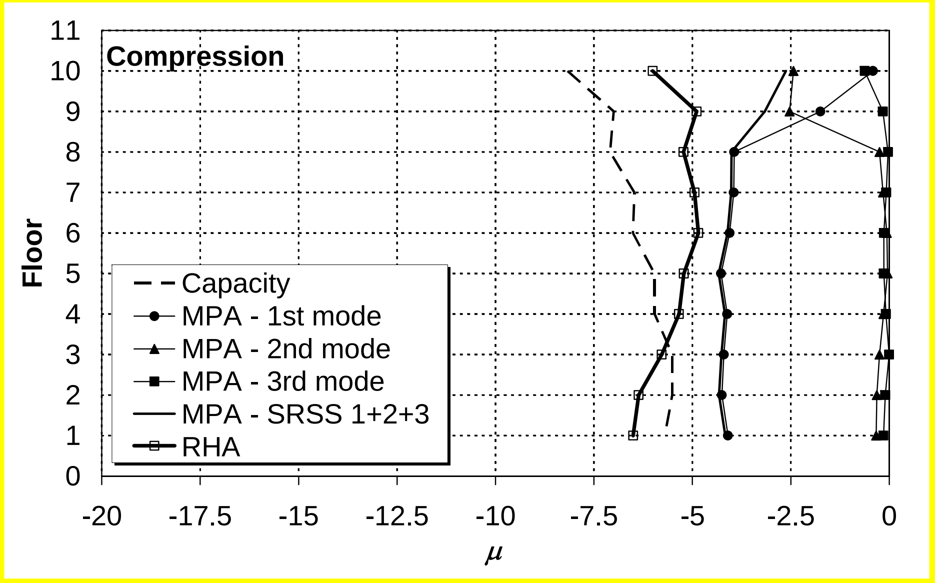
Results of static and dynamic analyses: DDBD vs OPCM

The peak ductility demand in the braces is compared with both the ductility capacity (Tremblay, 2002) and the target ductility.

In case of OPCM, the ductility capacity has been exceeded at lower floors. In fact, because of the structure parabolic displacement shape the displacement demand is greater at lower floor.



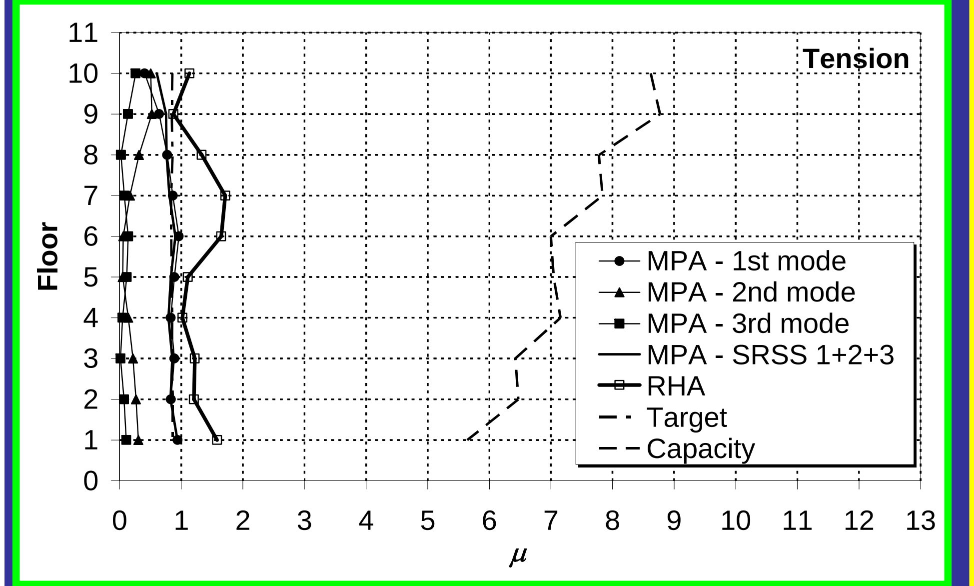
ductility demand to compression braces (DBD structure)



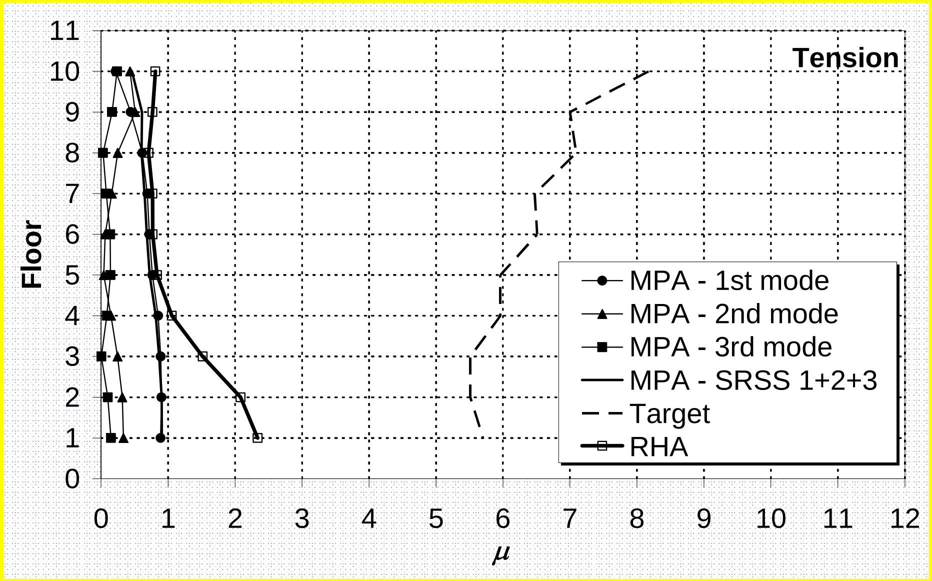
ductility demand to compression braces (OPCM structure)

Results of static and dynamic analyses: DDBD vs OPCM

In case of DBD, the ductility demand is uniform and involves all braces. While, in case of OPCM, the damage is only concentrated at lower floors. This is mainly due to the different displacement shape of the structure under examination.



ductility demand to tension braces (DBD structure)



ductility demand to tension braces (OPCM structure)

Conclusions

- The non-linear response of the DBD structure was satisfactory, matching quite well the design target.
- The OPCM structure exhibited ductility demand exceeding the capacity at the lowest stories.
- The better behaviour of DBD structure is due to the fact that the lateral displacement shape of structure has been imposed to the structure a–priori in such a way to avoid an exceeding ductility demand in brace members. The correct choice of displacement shape implies a more uniform engagement in dissipative members.
- The main advantage of DBD is the fact that the strength demand depends on the required performance, as a consequence the strength reduction factor depends on the performance. In case of Force-based approaches (as in OPCM) the reduction factor is a-prori fixed, hence the performance is implicitly imposed a-priori.