Trento, 15 December 2021
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Fragility Analysis

Formulation and MatLab Computation

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https://github.com/CNardin/Lecture/tree/2021/ISPS

Fragility Analysis

VULNERABILITY

Vulnerability analysis

$p(EDP|IM)$

$\downarrow$

$p(EDP)$

engineering demand par.

VULNERABILITY

Damage analysis

$p(DM|EDP)$

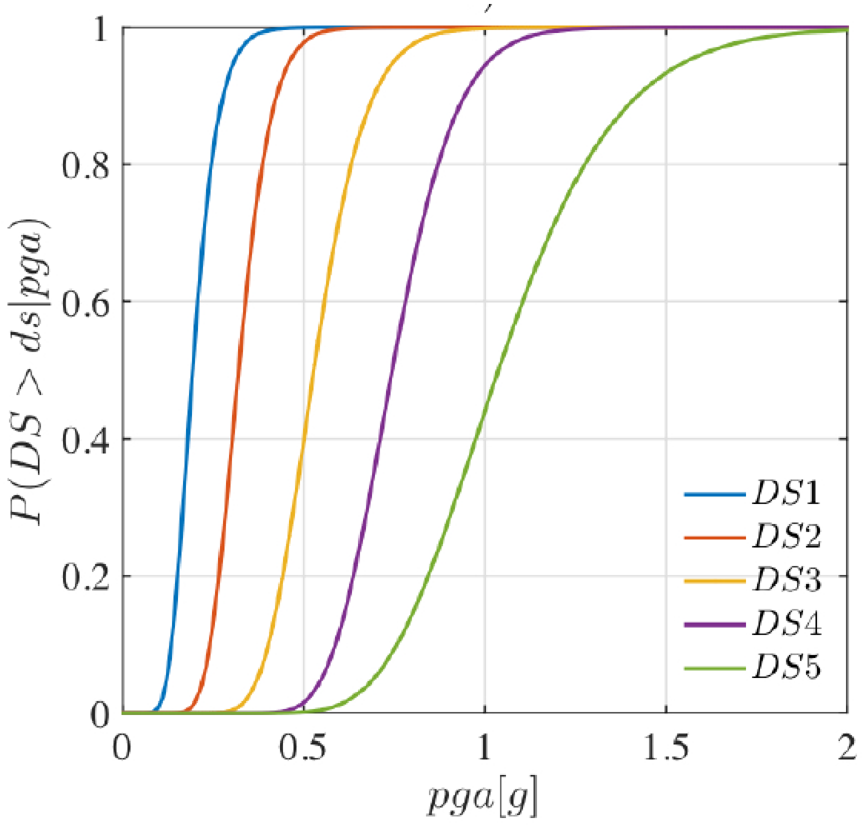
$\downarrow$

$p(DM)$

damage measure

$$P\ (D > d_{threshold}\ |\ IM = im)$$

Fragility curves for different damage limit states or thresholds.



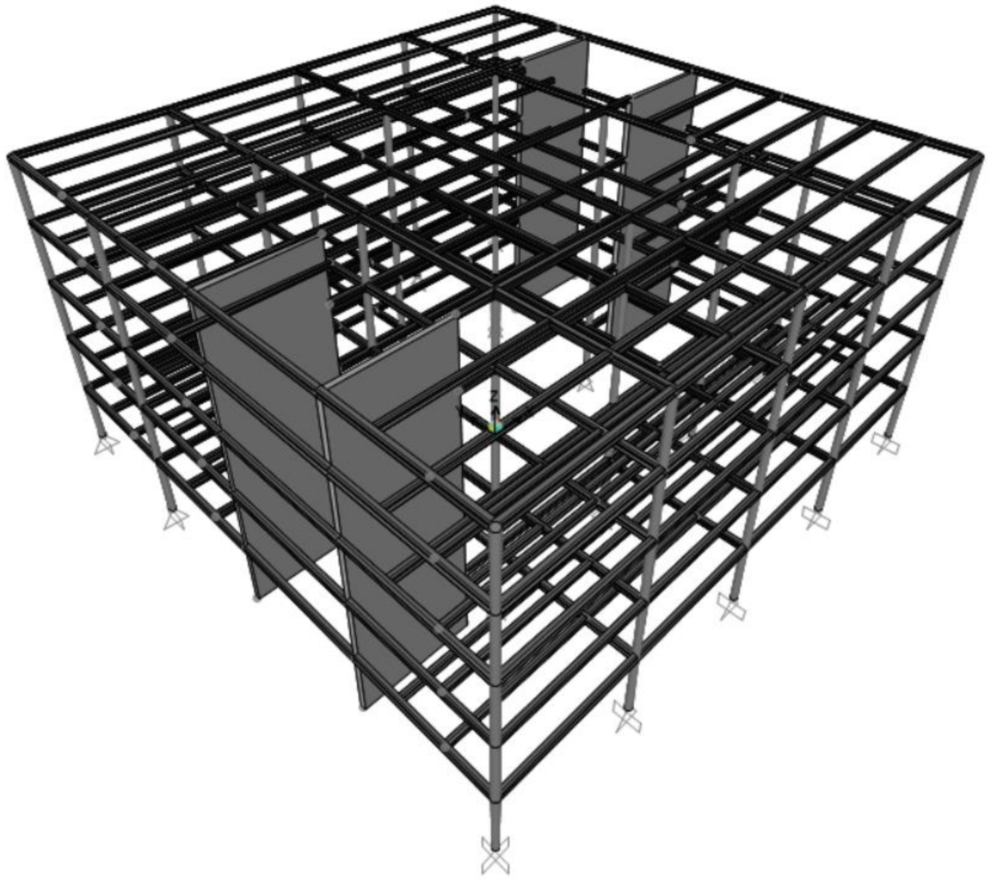
Goal: to perform fragility analysis

Given the provided set of ground motions, perform a classical and truncated incremental dynamic analysis (*IDA*) and determine fragility curves for:

- ATTEL – moment resistant frame (*MRF*);
- ATTEL – braced frame (*BF*)

by considering both

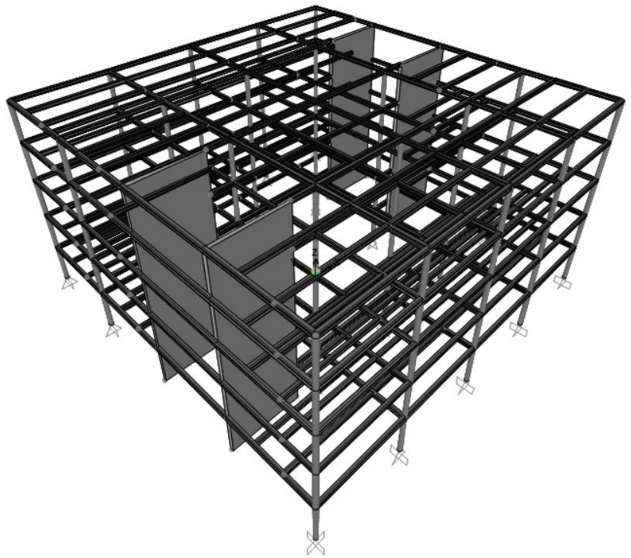
- Linear elastic behaviour
- Bouc – Wen model for hysteresis

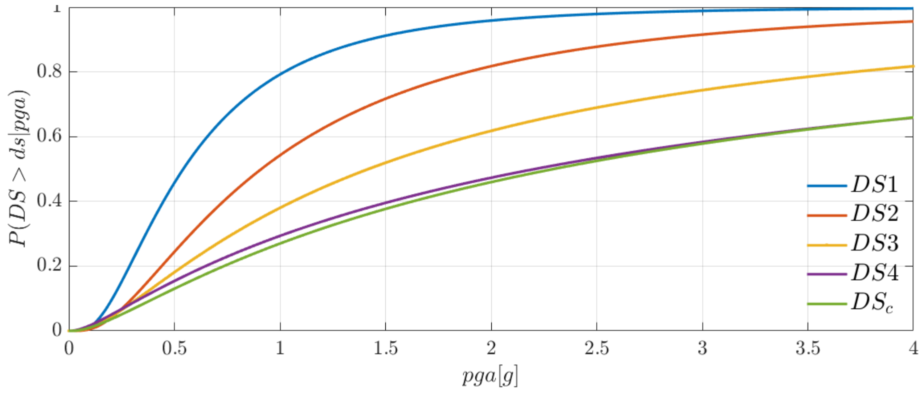


3D model of the case study ATTEL – SERA project.

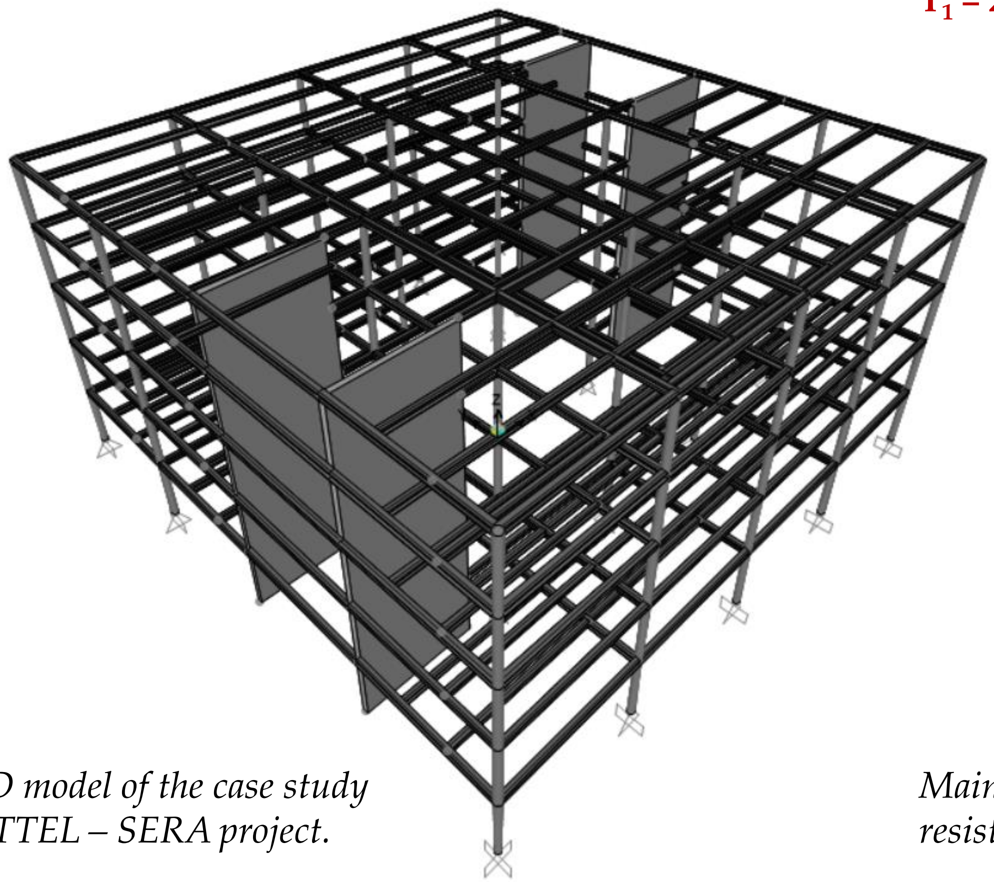
Main steps:

1) Definition of the numerical model
2) Input and *IM* selection
3) Definition of *damage limit states* and reference *EDP*
4) Performing non-linear time histories analysis (IDA, truncated IDA, cloud, MSA ...)
5) Collecting results pairs and computing fragility



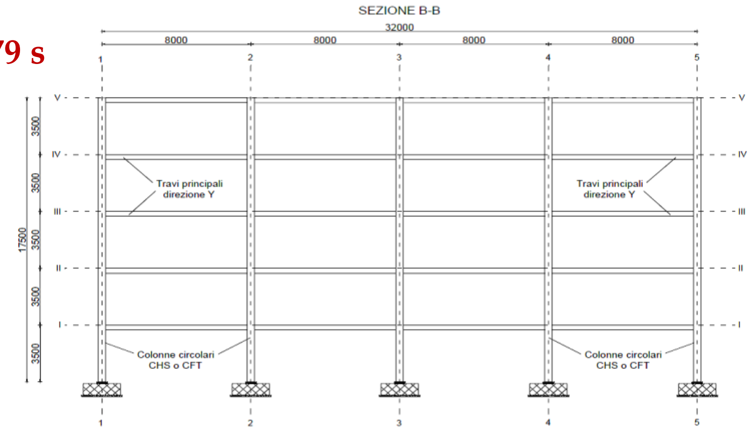


Step 1: the case study ATTEL[(1)]

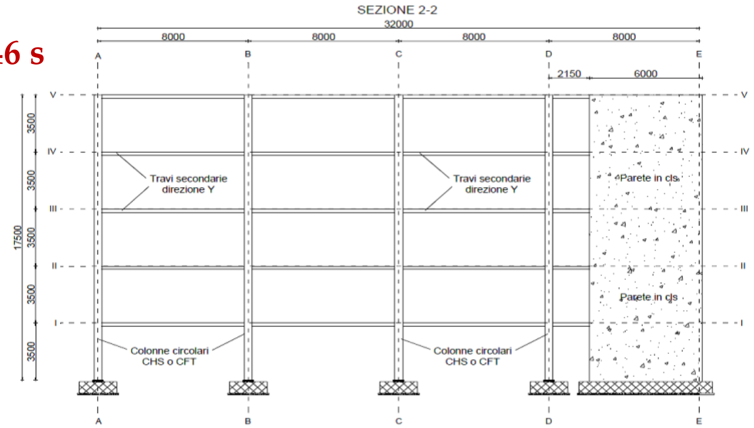


3D model of the case study ATTEL – SERA project.

T_1 = 2.79 s

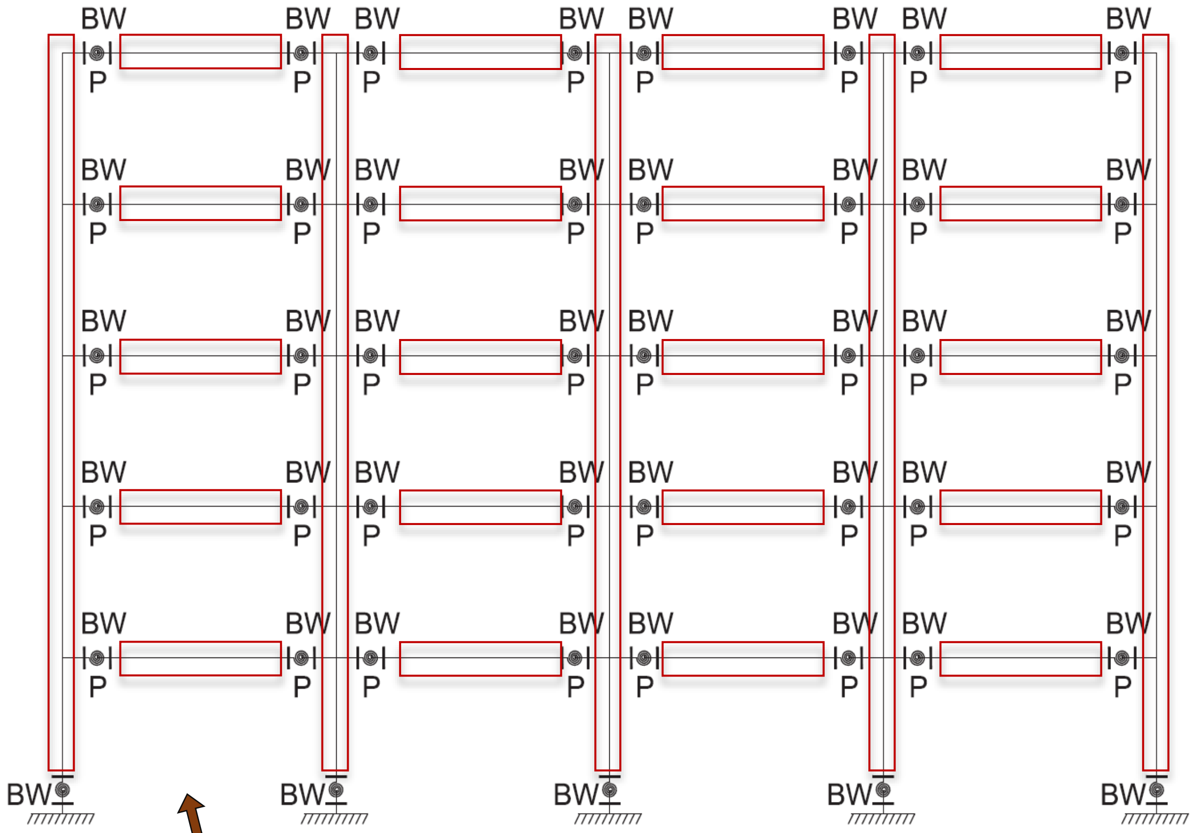


T_1 = 0.46 s



Main sections of the moment resistent frame and the braced one.

[1]BURSI, PUCINOTTI, TONDINI, ZANON, Tests and model calibration of high strength steel tubular beam-to-column and column-base composite joints for moment-resisting structures, Earthquake Engineering and Structural Dynamics, (2015).

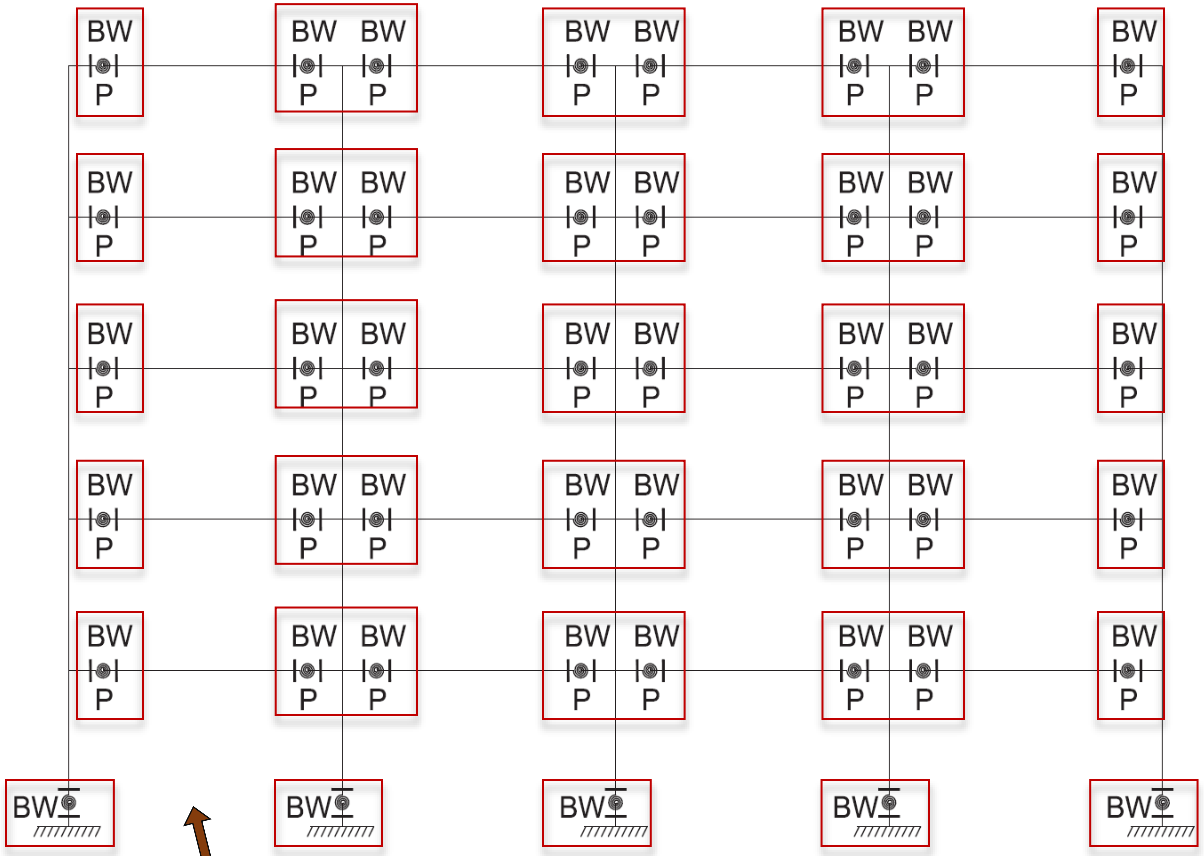


Designed according to EC8 and modelled in OS:

- beam and column elements with linear elastic behavior

`elasticBeamColumn`

```
element elasticBeamColumn $eleTag $iNode $jNode $A $E $Iz $transfTag
```



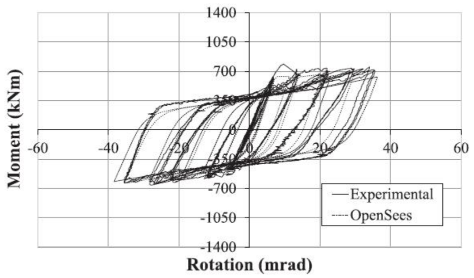
Designed according to EC8 and modelled in OS:

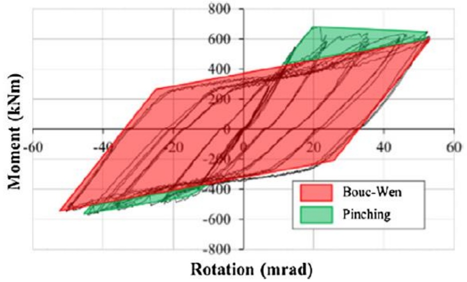
- beam and column elements with linear elastic behavior

```
elasticBeamColumn
```

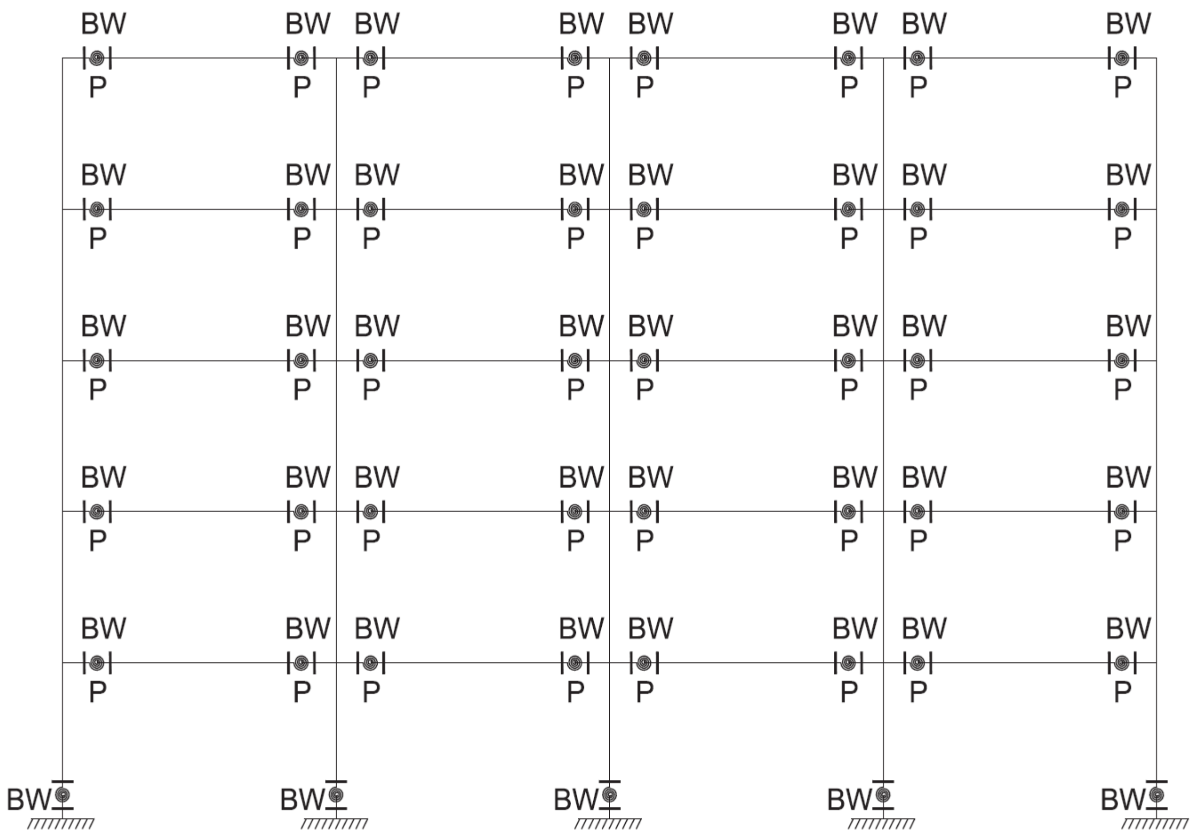
- mechanical nonlinearities

```
uniaxialMaterial BoucWen
uniaxialMaterial Pinching4
uniaxialMaterial Parallel
```






```
uniaxialMaterial Parallel $matBoucWen $matPinching
```



Model of the structure in OpenSees.

Designed according to EC8 and modelled in OS:

- beam and column elements with linear elastic behavior

```
elasticBeamColumn
```

- mechanical nonlinearities

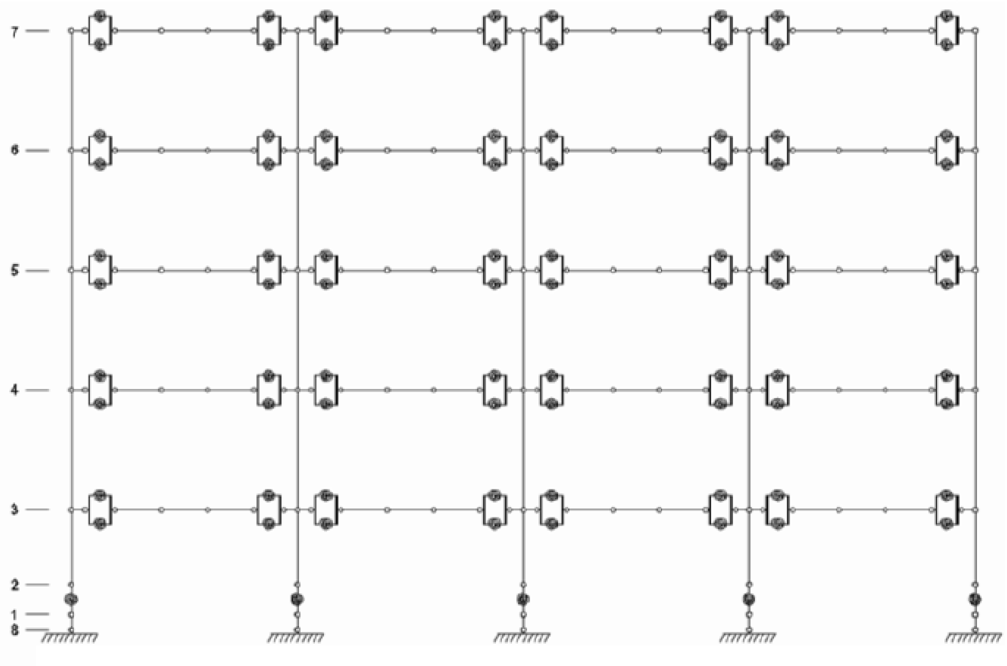
```
uniaxialMaterial BoucWen
uniaxialMaterial Pinching4
uniaxialMaterial Parallel
```

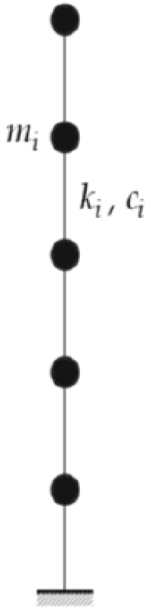
- geometric nonlinearities

```
geomTransf $tipoTrasf $PDelta
```

High number of analysis for seismic simulations

- to reduce computational burden
- to reduce required simulation times





Calibration oriented to correspondence of:

- main periods
- modes of vibrating
- dissipative behavior

high fidelity model in *OpenSees - OS* → simplified model MDOF in *MATLAB® - ML*

Trento, 02 December 2020
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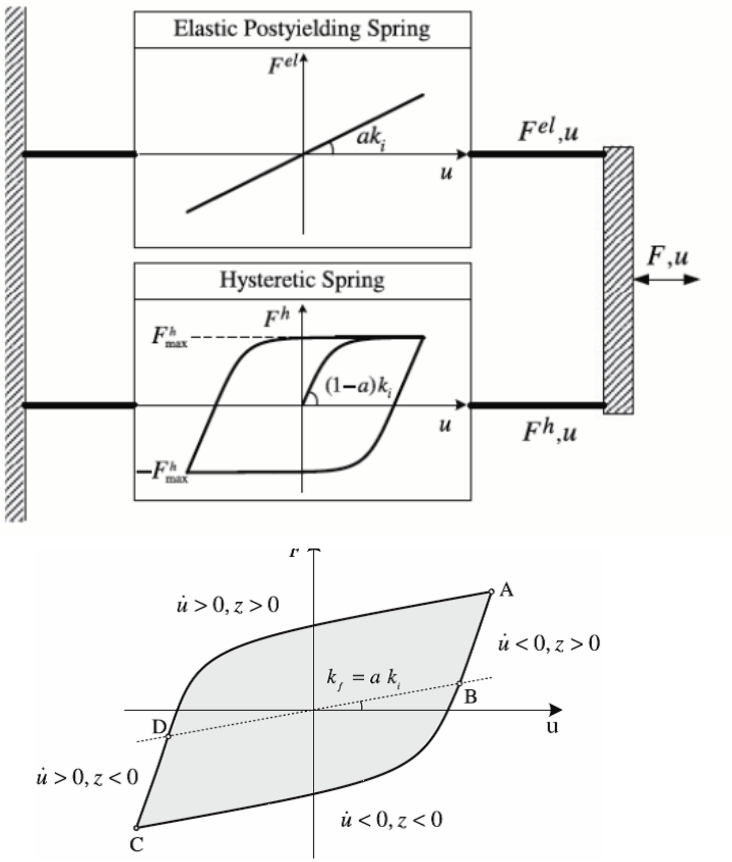


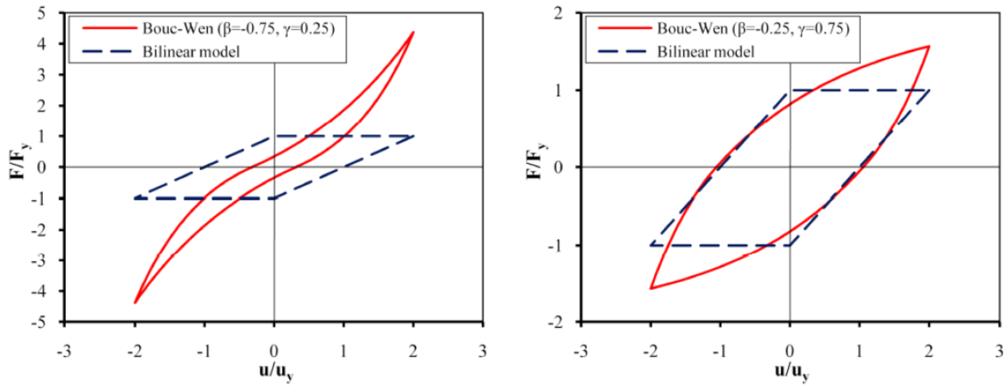
Hysteretic model of Bouc Wen.

Hysteretic model of Bouc Wen

$$m\ddot{u}(t) + c\dot{u}(t) + F_s(t) = F(t)$$

$$F_s(u(t),\dot{u}(t),z(t)) = F_{el}(t) + F_h(t) = \alpha\, k_i\, u(t) + (1-\alpha)\, k_i\, z(t)$$

$$\dot{z} = \frac{A\dot{u} - \{\beta\,|\,\dot{x}\,|\,z\,|\,z\,|^{n-1} + \gamma\dot{u}\,|\,z\,|^{n}\}\,\nu}{\eta}$$



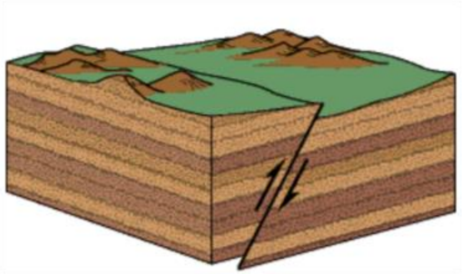
Formulation of the problem and examples of hysteretic cycles.

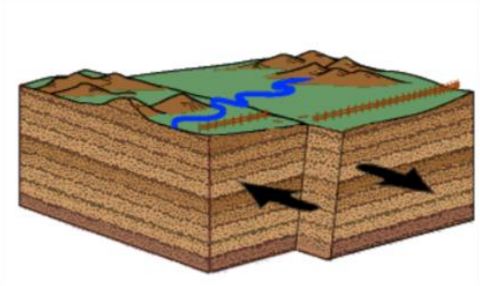
Step 2: input and *IM* selection

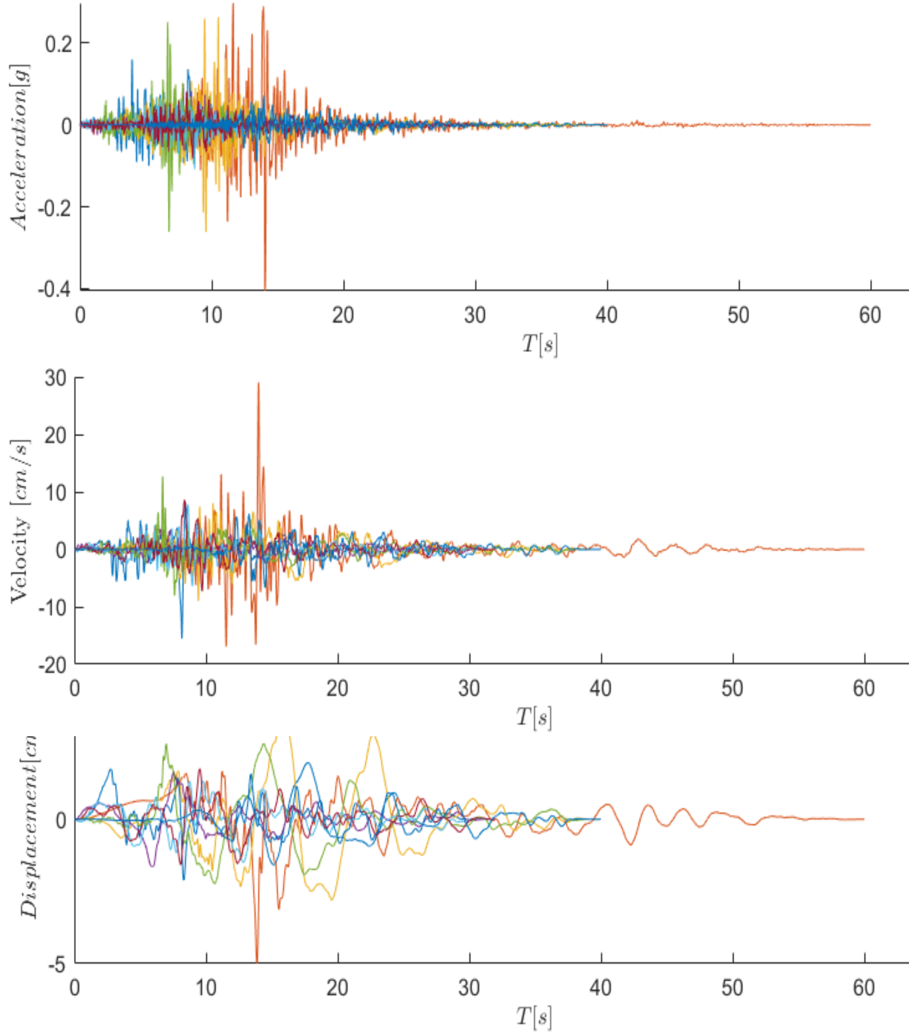
Dataset NGA-WEST 2 → *206 ground motions*

main features
- crustal earthquakes
- $M_w > 6$
- $R_{rup} > 10$ km
- $V_{s30} > 600$ m/s

fault mechanism
- *reverse REV*
- *strike slip SS*







Step 2: input and *IM* selection

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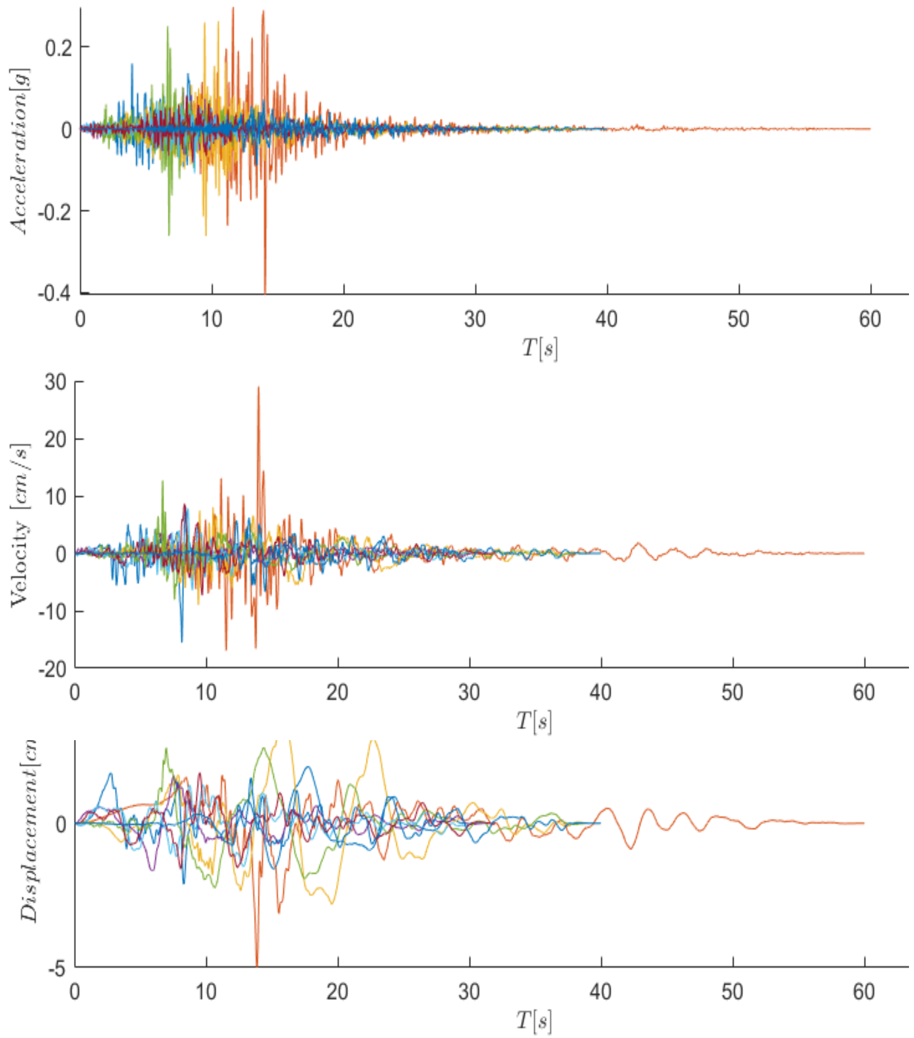
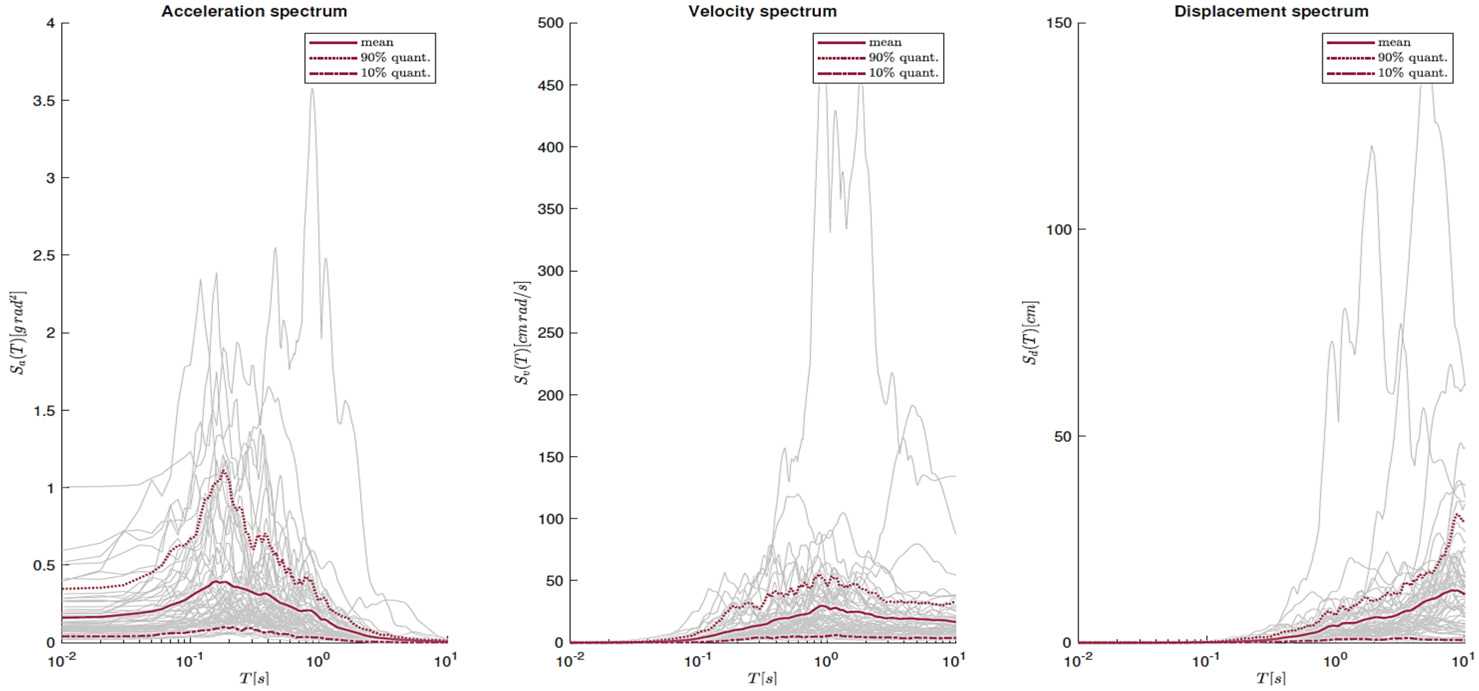
IMs investigated

- PGA [*g*]
- PGV [*cm/s*]
- PGD [*cm*]
- Sa (T_1) [*g rad*^{2}]
- Sv (T_1) [*cm rad/s*]
- Sd (T_1) [*cm*]
- PSa (T_1) [*g rad*^{2}]
- PSv (T_1) [*cm rad/s*]

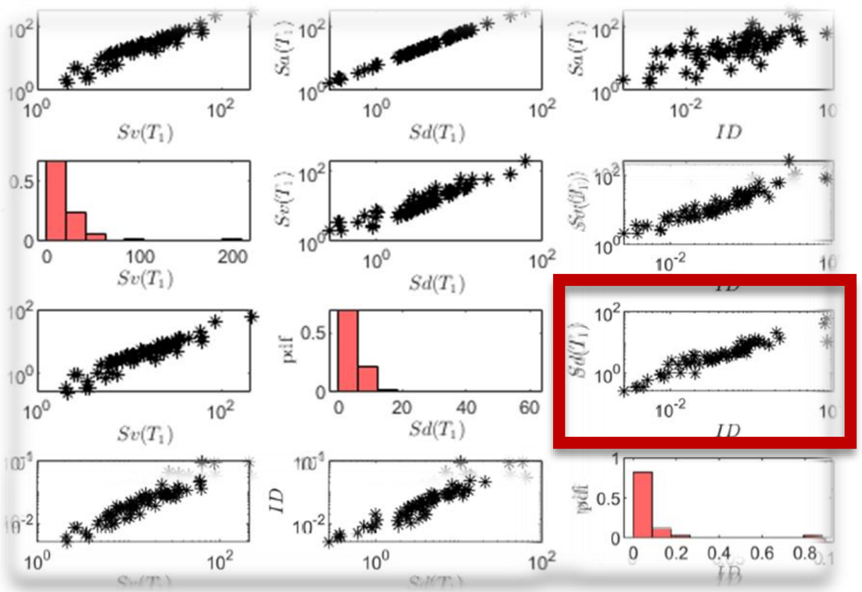


Step 2: input and *IM* selection

1) Data exploration of recorded gms
2) Scatter plot and statistic tools to evaluate proper *IM*



Acceleration, velocity and displacement response spectra with mean value, 10-th and 90-th quantile.



Scatter plot for correlation.

Step 2: input and *IM* selection

Codes:

```
%% Ground motions
Ground_motions = load('accelrot_cellarray.mat');
%
NN = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 19, 21, 23, 24,...
    25, 26, 28, 29, 30, 31, 32, 33, 34, 36, 37]; % number ID of the SS ground motions
DT = [0.01 , 0.01 , 0.005, 0.005, 0.005, 0.005, 0.02 , 0.02, 0.02, 0.01,...
    0.01 , 0.01 , 0.02 , 0.02 , 0.02 , 0.02 , 0.02 , 0.02, 0.01, 0.01,...
    0.005, 0.005, 0.005, 0.005, 0.02 , 0.005, 0.005, 0.01, 0.01, 0.01,...
    0.01 , 0.005, 0.005, 0.02 , 0.005, 0.01 , 0.01]; % integration time step
```

Step 3: Definition of *damage limit states* and reference *EDP*

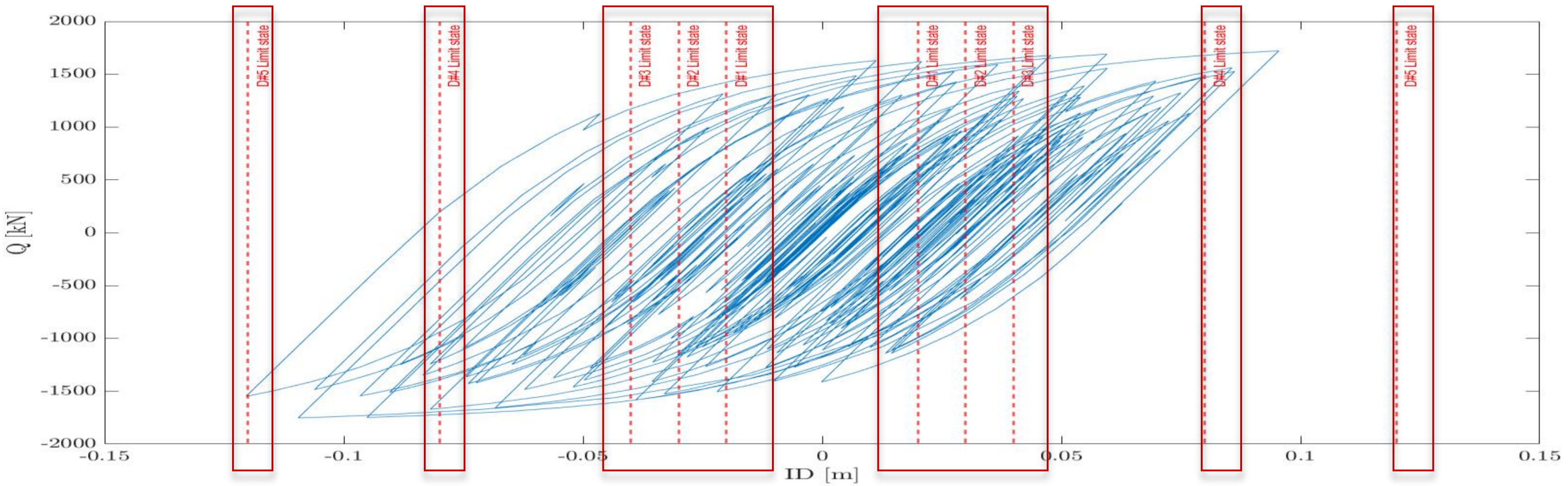
MRF

		Structural Performance Levels			
		Collapse Prevention	**Life Safety**	**Service**	**Immediate Occupancy**
Drift	[%]	5%	2,50%	1%	0,70%
	[m]	0,175	0,088	0,035	0,025

BF

		Structural Performance Levels			
		Collapse Prevention	**Life Safety**	**Service**	**Immediate Occupancy**
Drift	[%]	2,00%	1,00%	0,50%	0,30%
	[m]	0,07	0,035	0,0175	0,0105

Document *FEMA 356 - Prestandard and Commentary for the Seismic Rehabilitation of Buildings; Table C1-3 - Structural Performance Levels and Damage.*



Step 3: Definition of *damage limit states* and reference *EDP*

Codes:

```
%% MDOF Properties
% Choose between the structural system
MDOF_properties_BW_MRF
MDOF_properties_BW_BF
% and  between linear or hysteretic behaviour
%% Structural behaviour
System_type = 'le'; % 'bw'
% bw = bouc-wen
% le = linear elastic
```

```
…
%% Limit States
LS = [0.50 0.75 1 2 3]*4/100;
for ls_i = 1:numel(LS)
ls_val = LS(ls_i)
Main_IDA_o_t
ls_i = ls_i + 1;
end
```

Step 4: Performing non-linear time histories analysis

Codes:

```
 %% Initial condition
Mat.dFe=zeros(Mat.NDOF,numel(a_g_norm));    % Preallocation for the load for the time series
a_g = a_g_norm*scale;                         % Scaled ground motion
Mat.Fe=Mat.M*Mat.r'*a_g'*g;
%% Computation response
[HistVarBw]=ResponceMDF_Bw(Mat);
edp = max(abs(HistVarBw.eps(1,:)));
EDP(i) = edp; %store the EDP for each time history analysis
SCALE(i) = scale; %store the scale factor for each time history analysis…
```

Step 5: Computing fragilities

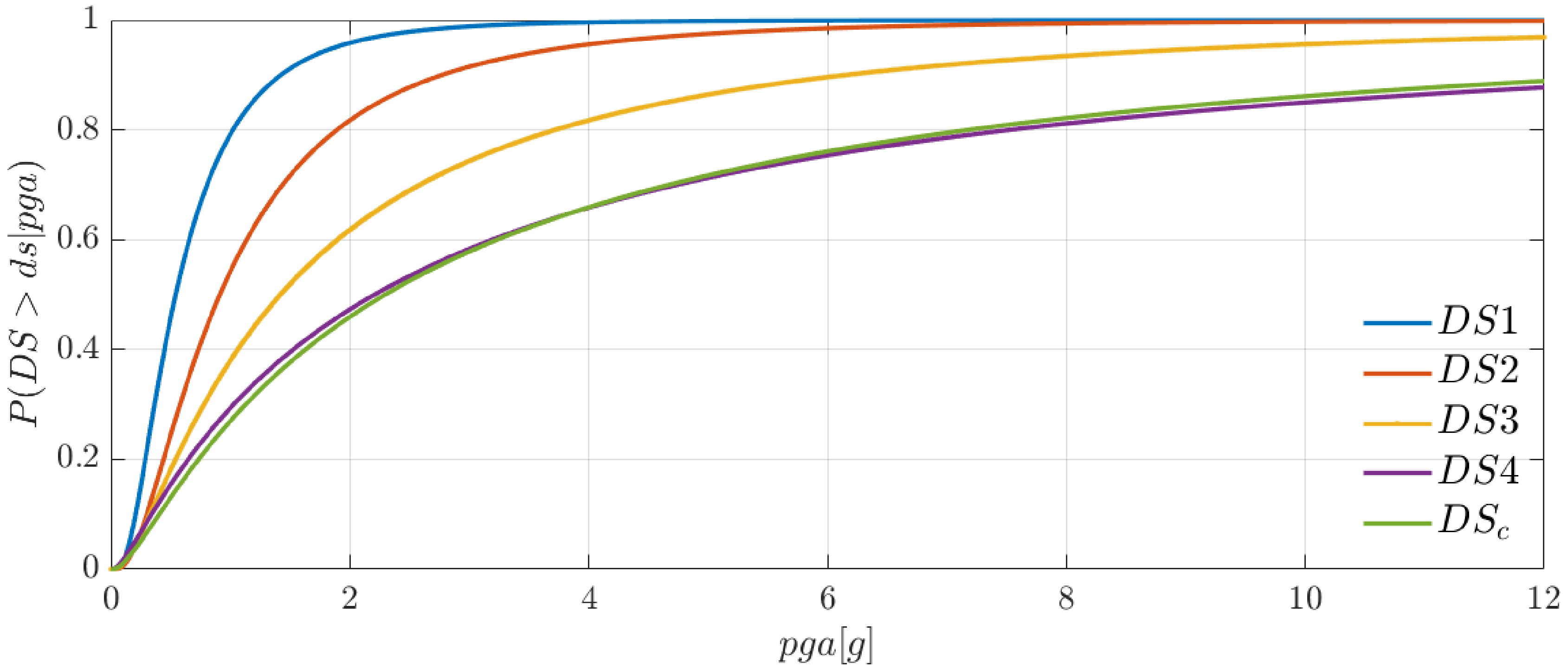
$$\mathcal{L}(\mu,\sigma) = \underline{\mathcal{L}}(\mu,\sigma)\overline{\mathcal{L}}(\mu,\sigma) = \prod_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n)-\mu}{\sigma}\right)\left[1-\Phi\left(\frac{\ln(\overline{IM})-\mu}{\sigma}\right)\right]^{N-\bar{N}} \quad (1)$$

$$\ln\mathcal{L}(\mu,\sigma) = \sum_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n)-\mu}{\sigma}\right) + (N-\bar{N})\left[1-\Phi\left(\frac{\ln(\overline{IM})-\mu}{\sigma}\right)\right] \quad (2)$$

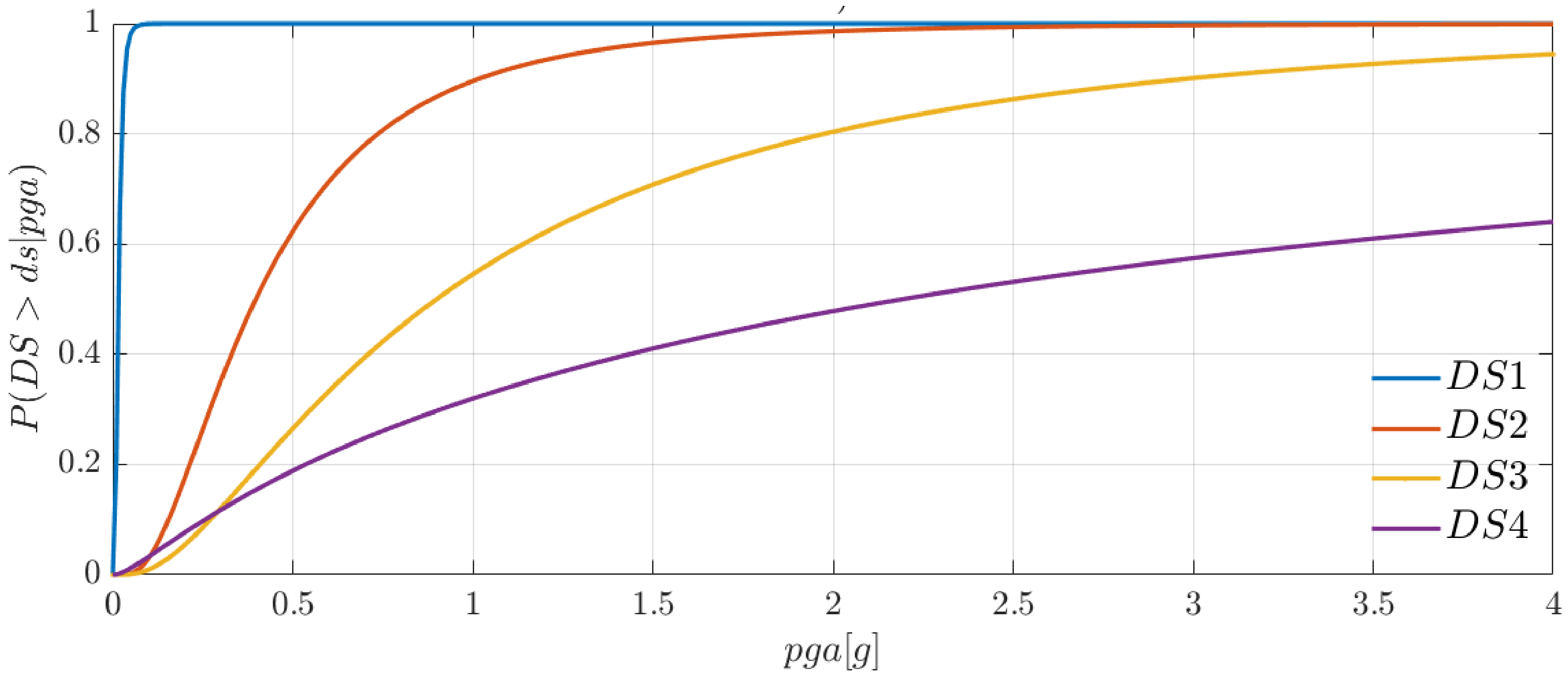
<u>Codes:</u>

```
%% Untruncated IDA
[parmhat,parmci] = lognfit(IM_t_c ,0.01);
mu_IDA = parmhat(1);
sigma_IDA = parmhat(2);
%% Truncated IDA
IM_max = 2.2;
IM_trunc = IM_t_c(IM_t_c < IM_max); % take only the results with IM < IM_max
eq_over = sum(IM_t_c >= IM_max);    % number of analyses reached IM_max without collapsing
% Maximum likelihood fit, using equation (1) and (2) of previously slides
[mu_IDA_t, sigma_IDA_t ] = truncated_ida(IM_trunc, IM_max, eq_over);
```

Step 5: Computing fragilities - Results



Step 5: Computing fragilities - Results



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- http://zonesismiche.mi.ingv.it/ → Italian database

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- Broccardo, M. (2018) *Probabilistic seismic risk analysis for civil systems*, Lecture Notes
- Charalampakis, A. & Koumousis,V. (2010). *Parameters of Bouc–Wen Model Revisited*, Applied Mechanics.
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Thanks for the attention!

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