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Risk and Uncertainty in Engineering Computations
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ESTIMATION OF FRAGILITIES BY THE MODIFIED INTENSITY MEASURES (IMS)

M. CIANO[1], M. GIOFFRÈ[1] AND M. GRIGORIU[2]

[1]Dept. of Civil and Environmental Engineering, University of Perugia, Italy
[2]Dept. of Civil and Environmental Engineering, Cornell University, USA

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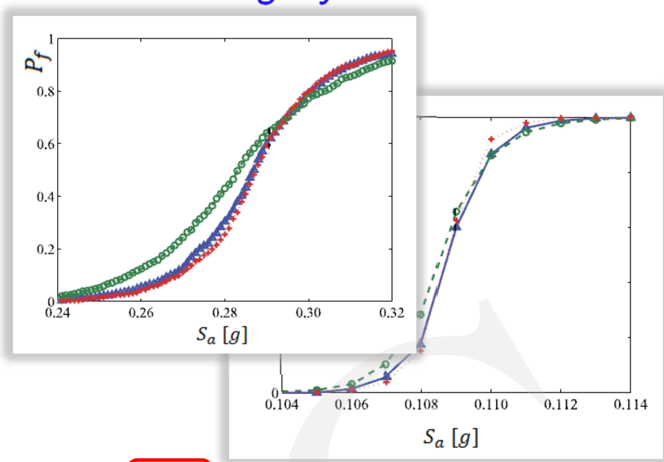
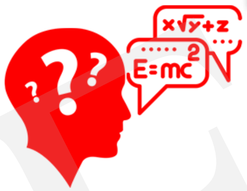
Motivation

Fragility curves





Is the fragility curve accurate or not?

How is possible to quantify the accuracy level?

Can this curve be improved?

Why the *probabilistic framework*:

Seismic events need a *not deterministic treatment*

Uncertainties consideration:
- *epistemic uncertainties (e.g. model parameters)*
- *aleatory uncertainties (e.g. seismic randomness)*

Rigorous and robust mathematical treatment by:
- *seismic intensity measure IM (e.g. PGA, Sa(T))*
- *system structural demand parameter D (e.g. maximum displacement)*

Development of synthetic results as *fragility curves*

PROBLEM DEFINITION

damage state defined by $\{D \in I \subset \mathbb{R}\}$

$$P_f(\xi) = P(D \in I|\mathrm{IM} = \xi) = E[1(D \in I|\mathrm{IM} = \xi)] = \int_I f_{D|\mathrm{IM}}(x|\xi)\,dx$$

- Dependence between *D* and IM is strong (limit, density became δ-function) → *D* | IM has small variance
- Dependence between *D* and IM is weak → *D* | IM has large variance
- Independence between *D* and IM (limit, *D* |IM and *D* are equal in distribution, fragility does not depend on ξ) → $P_f(\xi) = \int_I f_D(x)\,dx$

Dependence between D and IM can be investigated: e.g. correlation coefficients; copula models; multivariate extreme value theory

Grigoriu, M., 2016. Do seismic intensity measures (IMs) measure up? *Probabilistic Engineering Mechanics, 46, 80–93.*

FRAGILITIES BY SCALAR IMS

Fragility estimation:

1) selection of a finite set of intensity measures $\{\xi_k\}$ with $k = 1, \dots, N$

2) Generation of n_s seismic acceleration samples and for each value $\{\xi_k\}$ scale with reference IM_l $l = 1, \dots, 5$ in order to have intensity level $\mathrm{IM}_l = \xi_k,\ \xi_k > 0$

3) $\hat{P}_f(\xi_k) = \sum_{j=1}^{n_s} 1(d_{k,j} \in I)/n_s,\ \ j = 1, \dots, n_s$

FEMA P-58, 2012a. *Seismic Performance Assessment of Buildings: Vol. 1–Methodology. FEMA P-58.*

FRAGILITIES BY SCALAR IMs

Scalar intensity measures (IMs)

$\mathrm{IM}_1 = PGA$

$\mathrm{IM}_2 = S_a(T_1, \zeta_1)$

$\mathrm{IM}_3 = S_a(T_3, \zeta_3)$

$\mathrm{IM}_4 = I_h$

$\mathrm{IM}_5 = S^*(T_1, \zeta_1, C, \alpha)$

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FEMA P-58, 2012a. *Seismic Performance Assessment of Buildings: Vol. 1–Methodology. FEMA P-58.*

OVERVIEW ON ISSUE

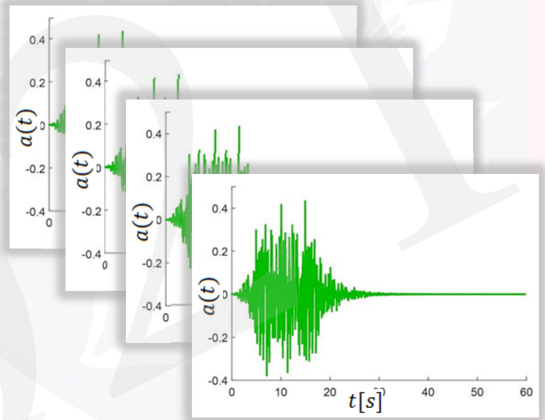
Stochastic equation of motion (Linear SDOF)

$$m\ddot{X}_{lsdof}(t) + c\dot{X}_{lsdof}(t) + kX_{lsdof}(t) = -mA(t)$$

$$\ddot{X}_{lsdof}(t) + 2\zeta\omega_0\dot{X}_{lsdof}(t) + \omega_0^2 X_{lsdof}(t) = -A(t)$$

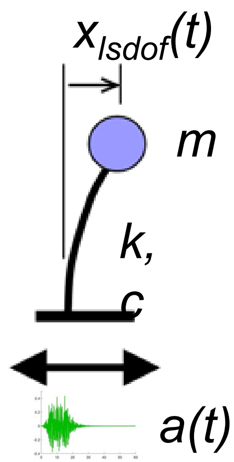
$$D_{lsdof} = \max_{0\leq t\leq\tau}|X_{lsdof}(t)|$$

$$t \in [0,\tau],\ \ T_0 = 2\pi/\omega_0$$

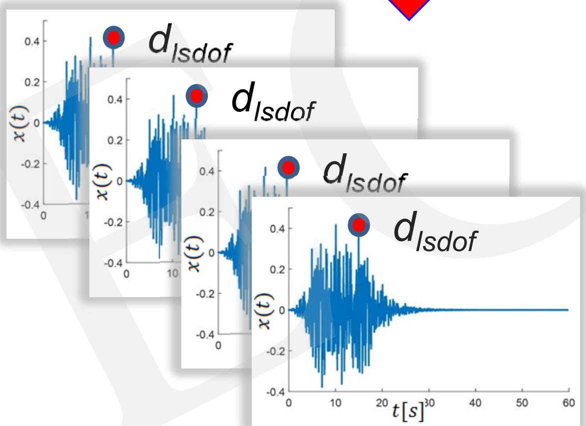


Stochastic
process A(t)
input

Idealization



output



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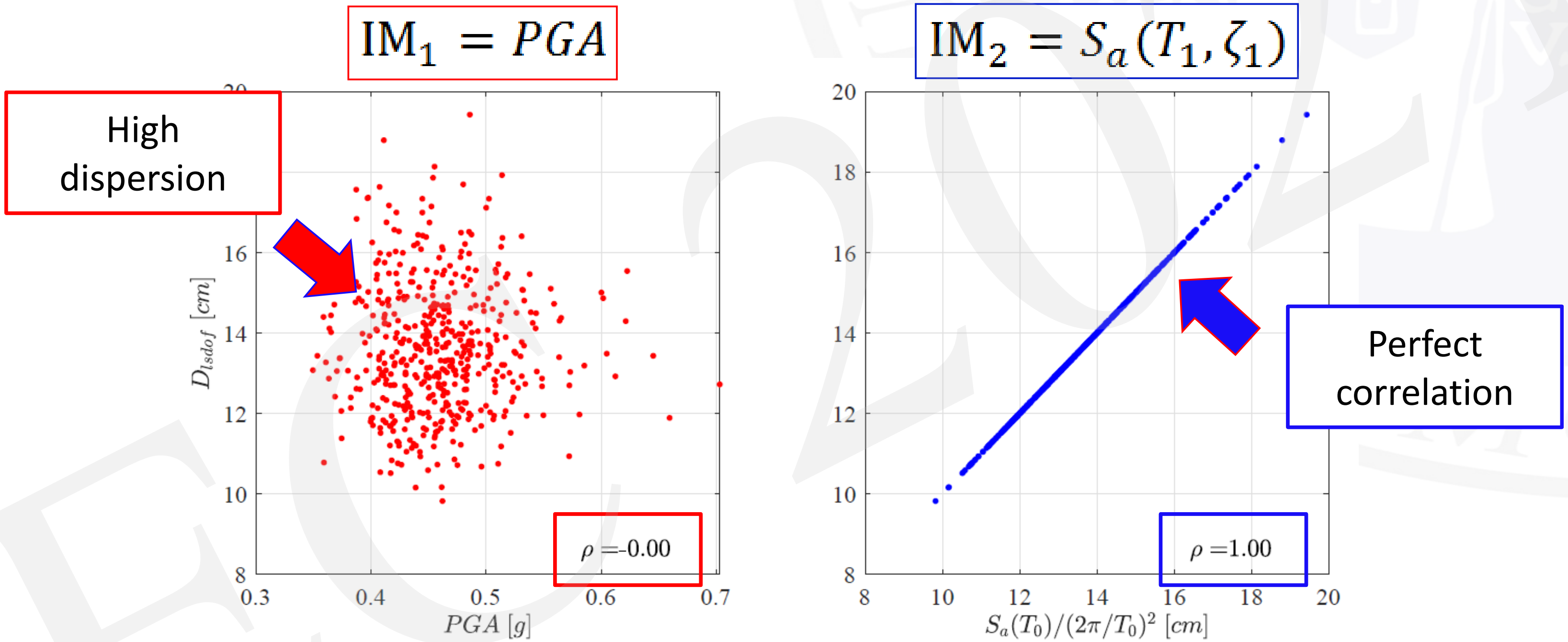
OVERVIEW ON ISSUE

Dependence between D_{lsdof} and common IMs

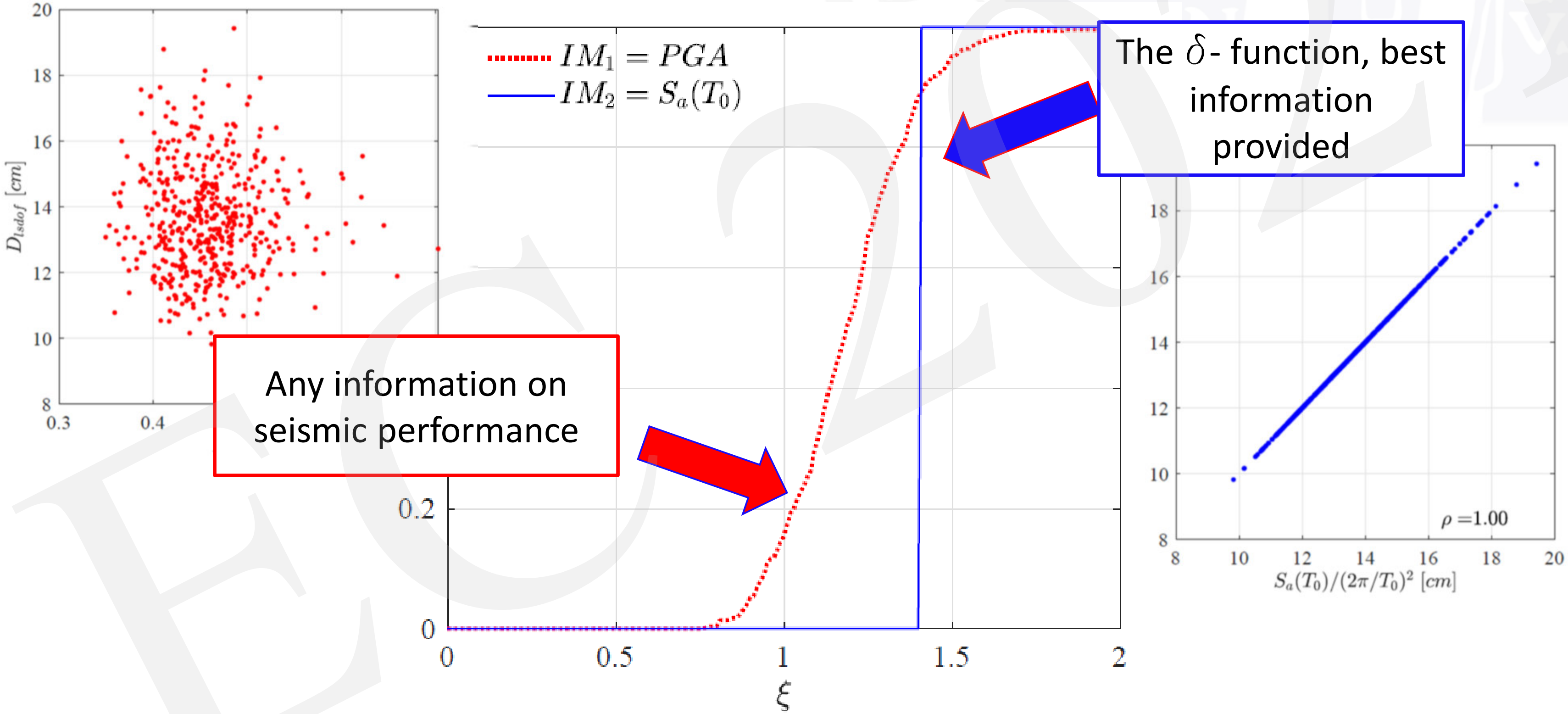


Scatter plots of n_s = 500 samples for linear SDOF system with $\omega_0 = 2\pi$ and ζ= 5%: (PGA, D_{lsdof}) (left panel); ($Sa(T0)/(2\pi/T1)^2$, D_{lsdof}) (right panel).

OVERVIEW ON ISSUE

Fragility analysis results

Critical assumption in Performance-Based Earthquake Engineering !!!



Fragilities against intensity level considering different definitions of IMs for linear SDOF system with $\omega_0 = 2\pi$ and ζ= 5%, limit state D_{lsdof} = 35 cm.

THE MODIFIED INTENSITY MEASURE mIM

Improving dependence:

1) given the stochastic process $A(t)$ compute the corresponding IM and $D^{(j)}$

2) evaluate the standardized random variables

$$Z(\mathrm{IM}) = \frac{\mathrm{IM} - E[\mathrm{IM}]}{\sigma_{\mathrm{IM}}} \qquad Z\left(D^{(j)}\right) = \frac{D^{(j)} - E[D^{(j)}]}{\sigma_{D^{(j)}}}, \qquad j = 1, \dots, m$$

3) for each n_s of the standardized variables compute the distance from perfect correlation

$$e_i^{(j)} = z\left(d_i^{(j)}\right) - z(im_i), \qquad i = 1, \dots, n_s, \qquad j = 1, \dots, m$$

4) the average distance of the $j \geq 1$ demand parameters $\bar{e}_i = \frac{1}{m}\sum_{j=1}^{m} e_i^{(j)}, \qquad i = 1, \dots, n_s$

and the results are collected in the vector $\bar{E}$

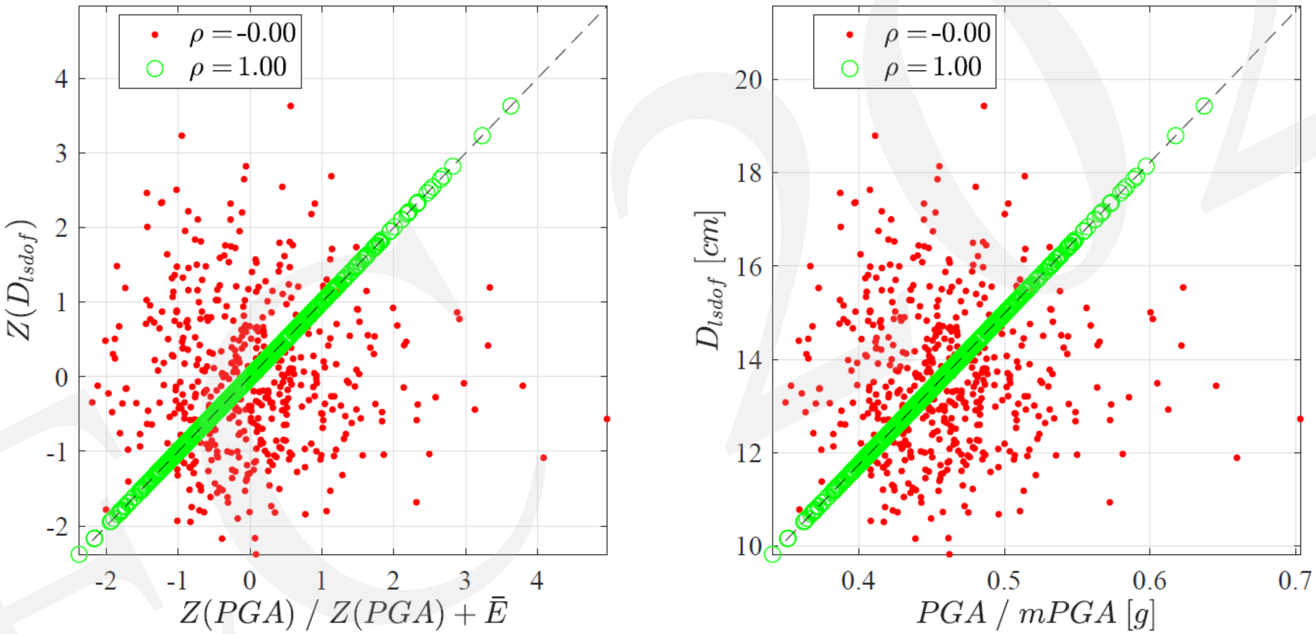
5) define n_s samples of the new modified intensity measure version $m\mathrm{IM}$ by the linear transformation

$$mim_i = [z(im_i) + \bar{e}_i]\sigma_{\mathrm{IM}} + E[\mathrm{IM}], \qquad i = 1, \dots, n_s$$

IMPROVING DEPENDENCE BY mIM

Dependence between D_{lsdof} and common PGA

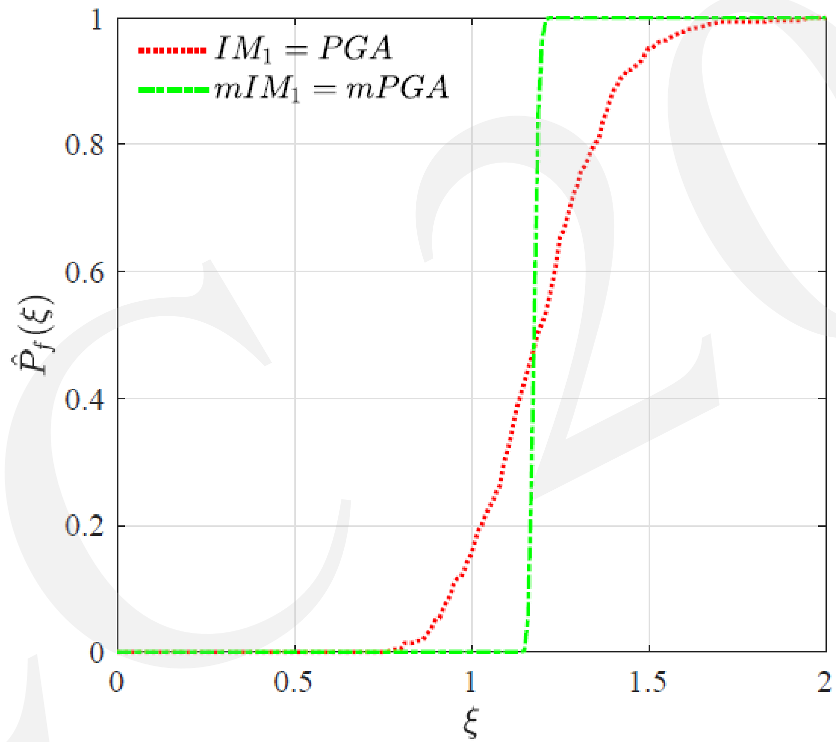
$\mathrm{IM}_1 = PGA$



Scatter plots of n_s = 500 samples for linear SDOF system with $\omega_0 = 2\pi$ and ζ= 5%:
($Z(PGA)$, $Z(D_{lsdof})$) red dots, ($Z(PGA)$ +E , $Z(D_{lsdof})$) green circles (left panel);
(PGA, D_{lsdof}) red dots, (mPGA, D_{lsdof}) green circles (right panel).

IMPROVING DEPENDENCE BY mIM

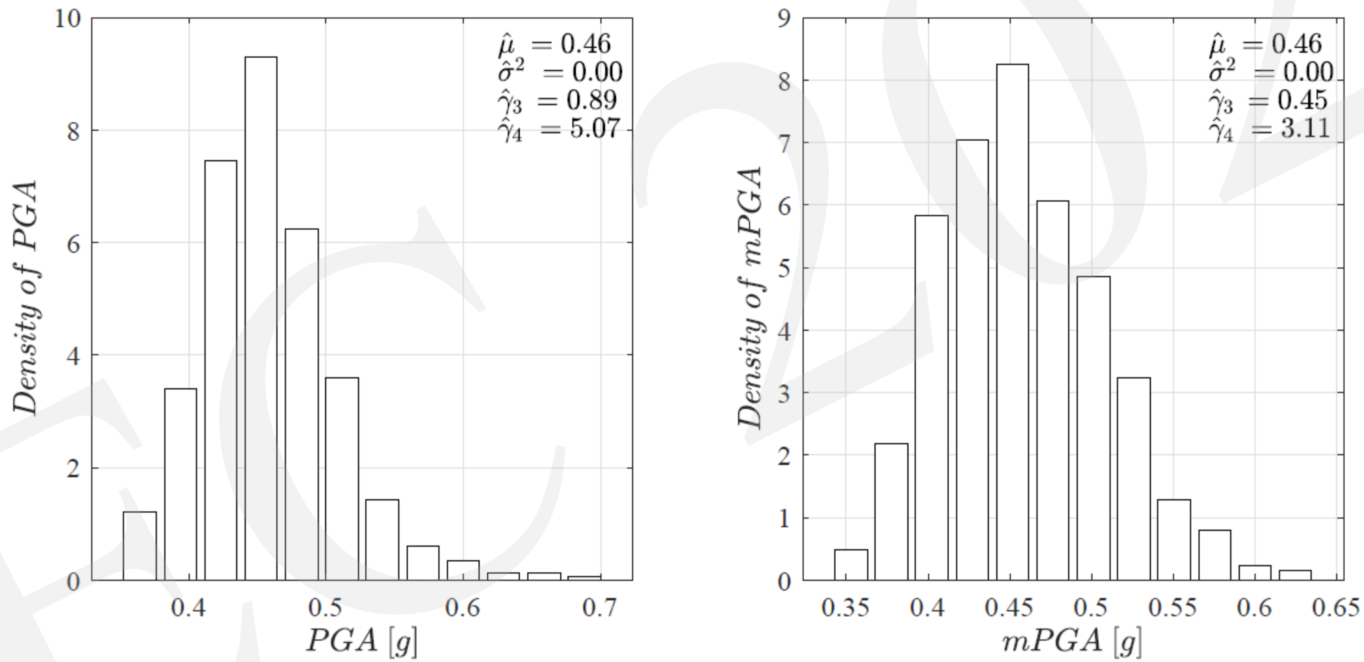
Fragility analysis results



Fragilities against intensity level considering the intensity measure PGA and its modified version mPGA for linear SDOF system with $\omega_0 = 2\pi$ and $\zeta = 5\%$, limit state $\bar{D}_{lsdof} = 35$ cm.

IMPROVING DEPENDENCE BY mIM

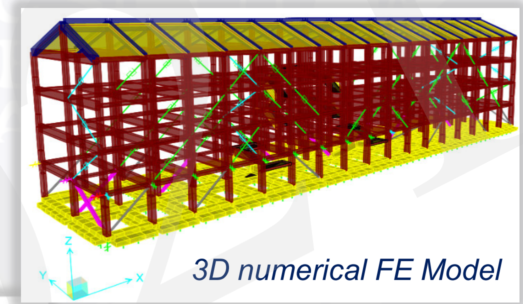
Probability density function estimates

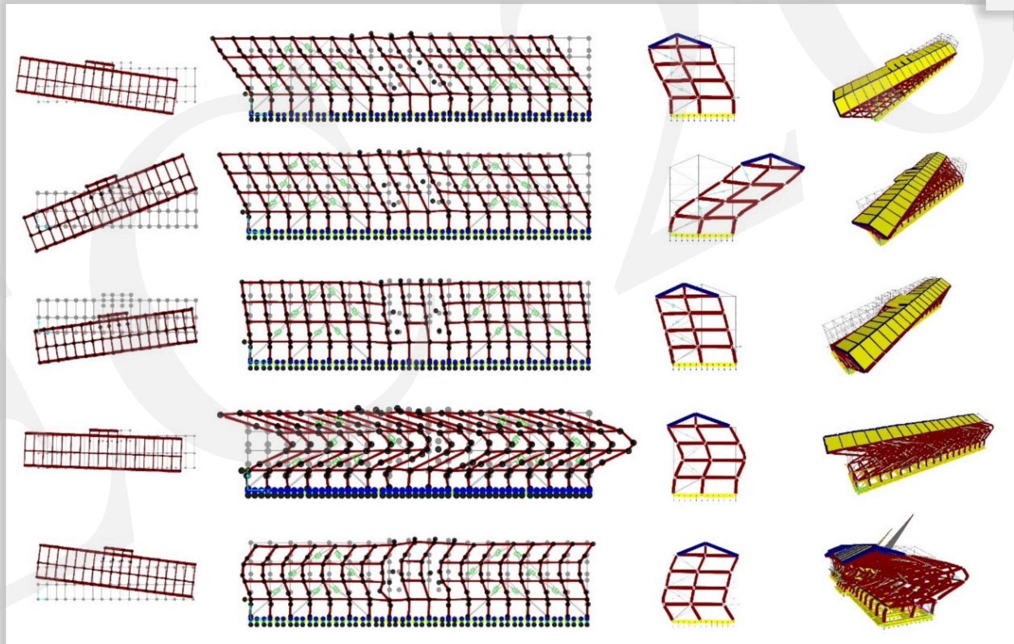


Estimated PDF for n_s = 500 samples of PGA (left panel) and mPGA (right panel).

COMPLEX LINEAR/NONLINEAR MDOF SYSTEM: NORCIA SCHOOL MODEL

Calibrated model


3D numerical FE Model



1st modal shape — T_1 = 0,34 s, f_1 = 2,86 Hz

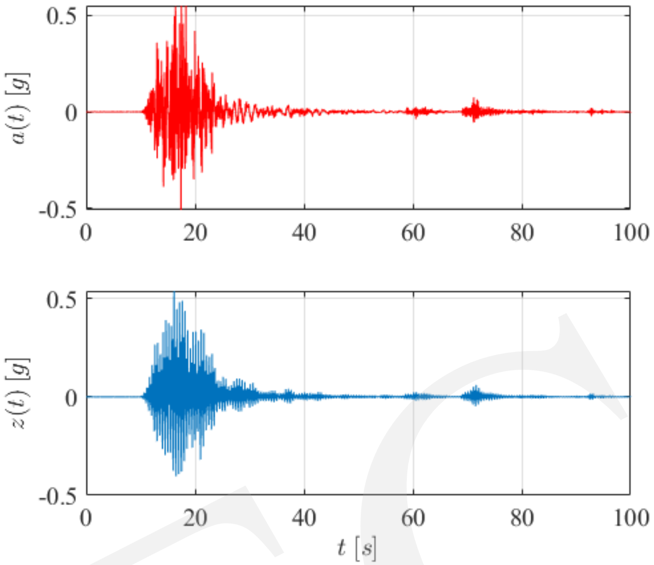
2nd modal shape — T_2 = 0,28 s, f_2 = 3,46 Hz

3rd modal shape — T_3 = 0,26 s, f_3 = 3,74 Hz

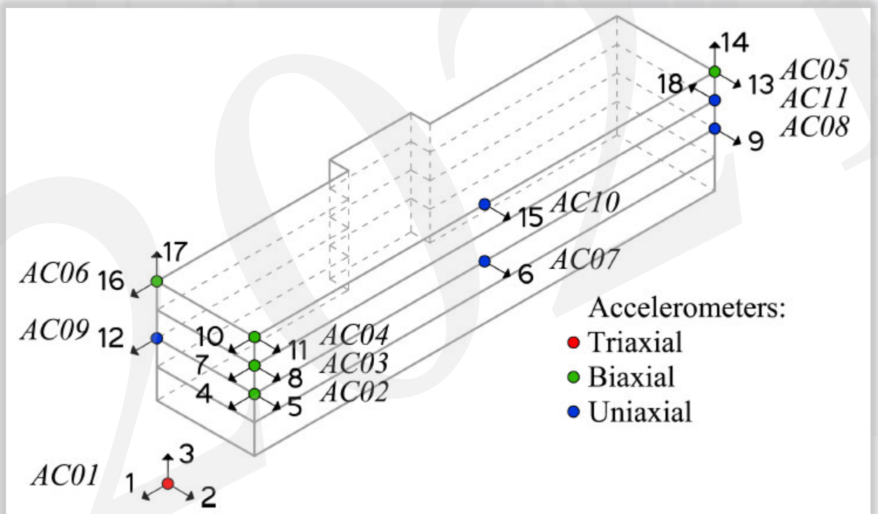
4th modal shape — T_4 = 0,11 s, f_4 = 8,43 Hz

8th modal shape — T_8 = 0,09 s, f_8 = 11,09 Hz

NON-STATIONARY SIMULATION: MODEL FOR STOCHASTIC PROCESS



Acceleration time history AC01-1 recorder in Norcia on October 30th, 2016 (m=6.5 and r=5 km) (top); simulated sample of the non-stationary process Z(t) (bottom)



Scheme of the monitoring system of Norcia school building (Italian National Seismic Observatory)

Non-stationary uniformly modulated stochastic process

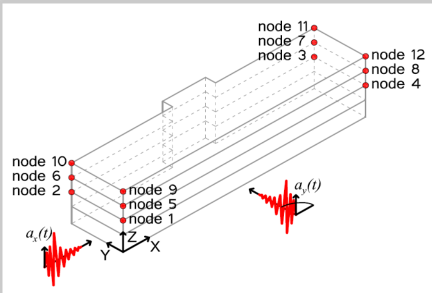
$$Z(t) = c(t)Y(\varphi(t)) \qquad \sigma_Z^2 = c^2(t)\sigma_Y^2$$

$$G_Z(t,\omega) = c^2(t)G_Y(\omega)$$

Grigoriu, M., Ruiz, S. E., Rosenblueth, E., 1988. The Mexico earthquake of September 19, 1985—Nonstationary models of seismic ground acceleration.*Earthquake Spectra, 4(3), 551–568.*

FRAGILITIES WITH IMs

Analysis scheme

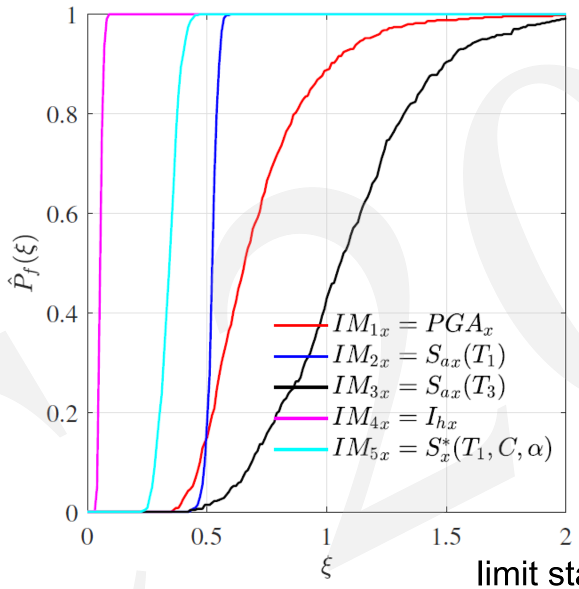


- Fragility curves

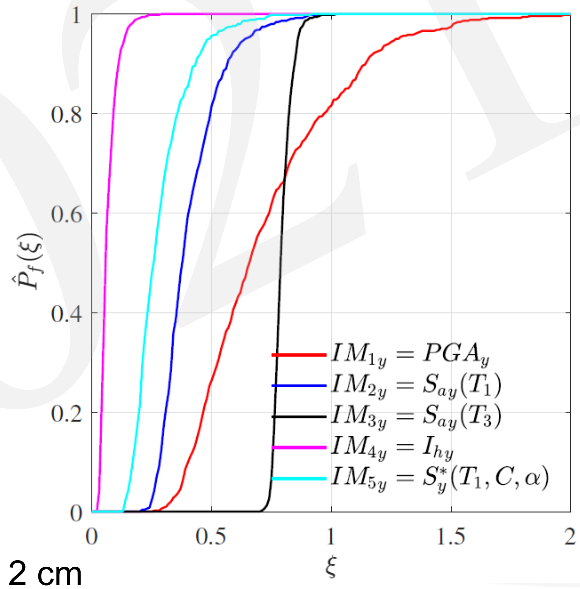
- n_s=500 independent samples of stochastic processes

- Displacement response in x and y-direction by *linear analysis*

Node 9 - *D_{dx}*



Node 9 - *D_{dy}*



limit state 2 cm

$\boxed{\mathrm{IM}_1 = PGA}$ $\boxed{\mathrm{IM}_2 = S_a(T_1, \zeta_1)}$ $\boxed{\mathrm{IM}_3 = S_a(T_3, \zeta_3)}$

$\boxed{\mathrm{IM}_4 = I_h}$ $\boxed{\mathrm{IM}_5 = S^*(T_1, \zeta_1, C, \alpha)}$

$$\hat{P}_f(\xi_k) = \sum_{j=1}^{n_s} 1(d_{k,j} \in I)/n_s, \quad j = 1, \dots, n_s$$

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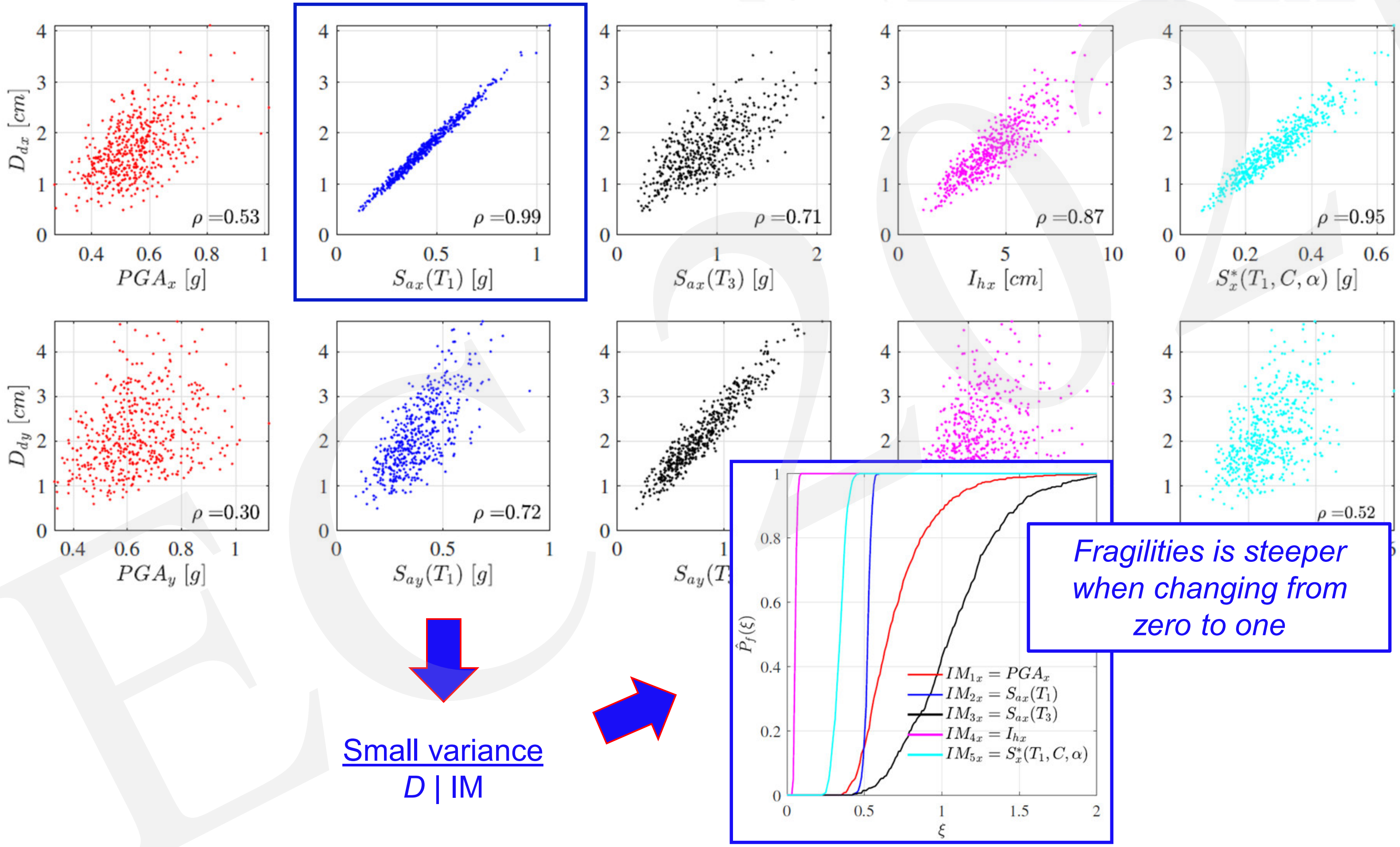
Dependence with IMs



Small variance
D | IM

Fragilities is steeper when changing from zero to one

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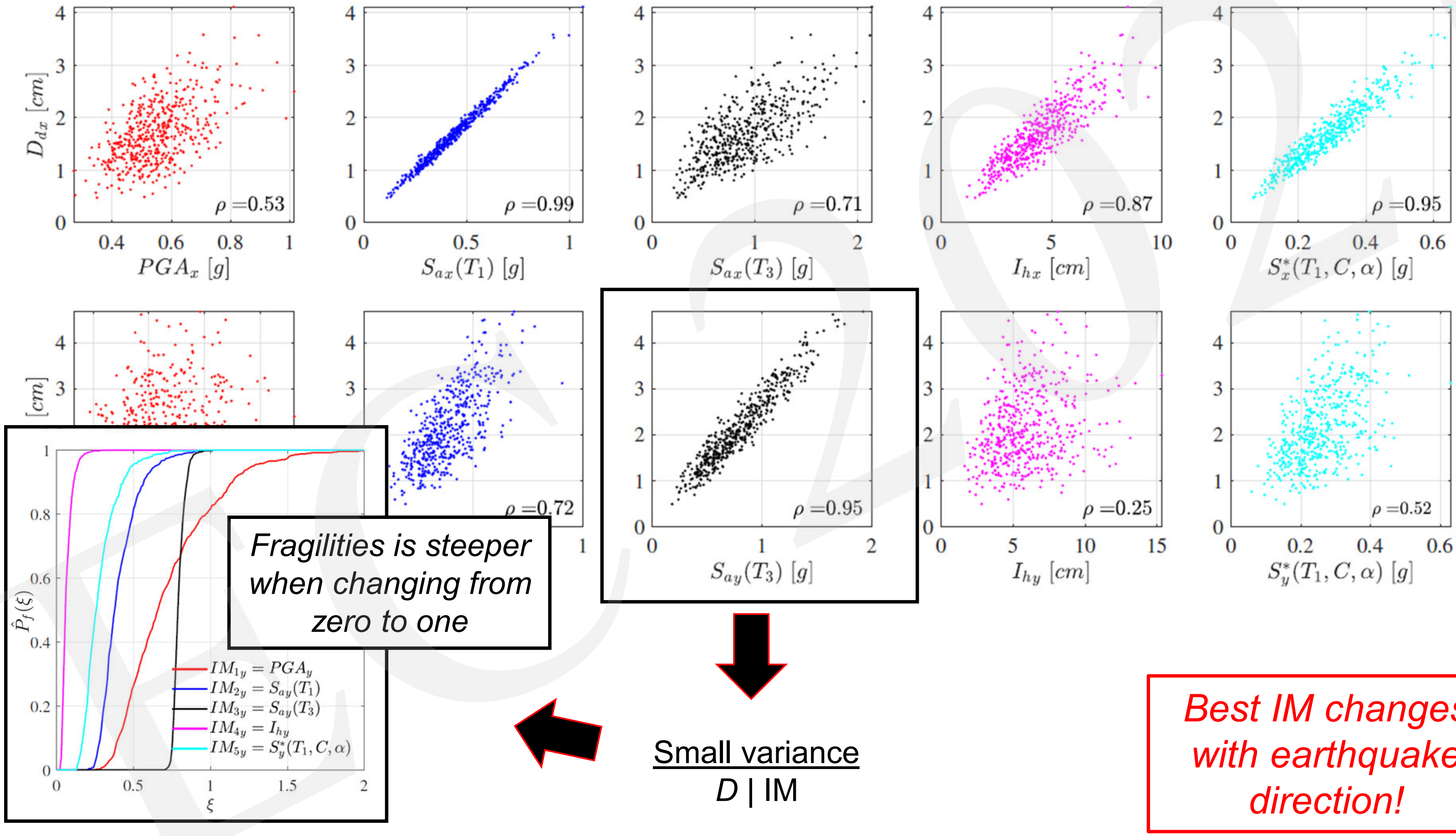
DEPENDENCE WITH IMS



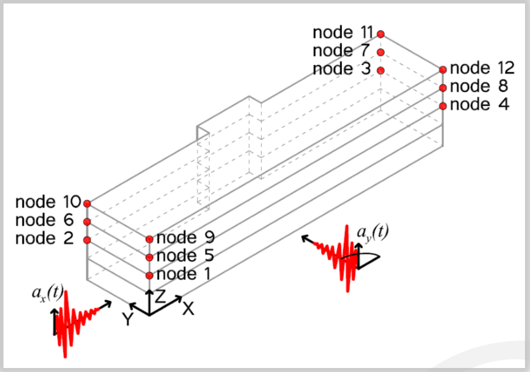
Fragilities is steeper when changing from zero to one

Small variance
D | IM

Best IM changes with earthquake direction!

DEPENDENCE WITH mIMs

Analysis scheme



- considering the most widespread IMs in PBEE, i.e. PGA and $S_a(T_1)$

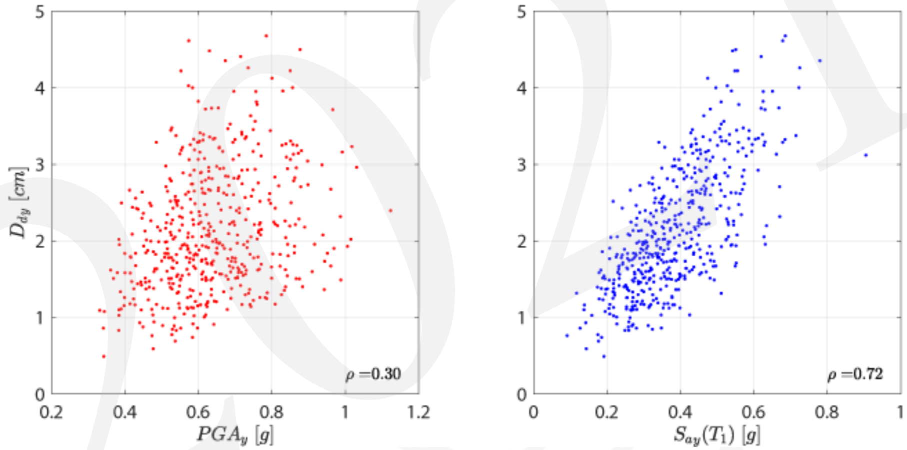
- Improving dependence with the definition of the mPGA and $mS_a(T_1)$

- m=12 demand parameters of interest in fragility analysis in both x e y-directions

- *linear behaviour* for FEM analysis

Node 9 - D_{dy}

$\mathrm{IM}_1 = PGA$ $\mathrm{IM}_2 = S_a(T_1, \zeta_1)$

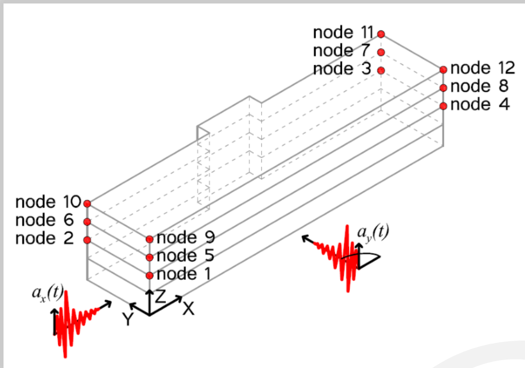


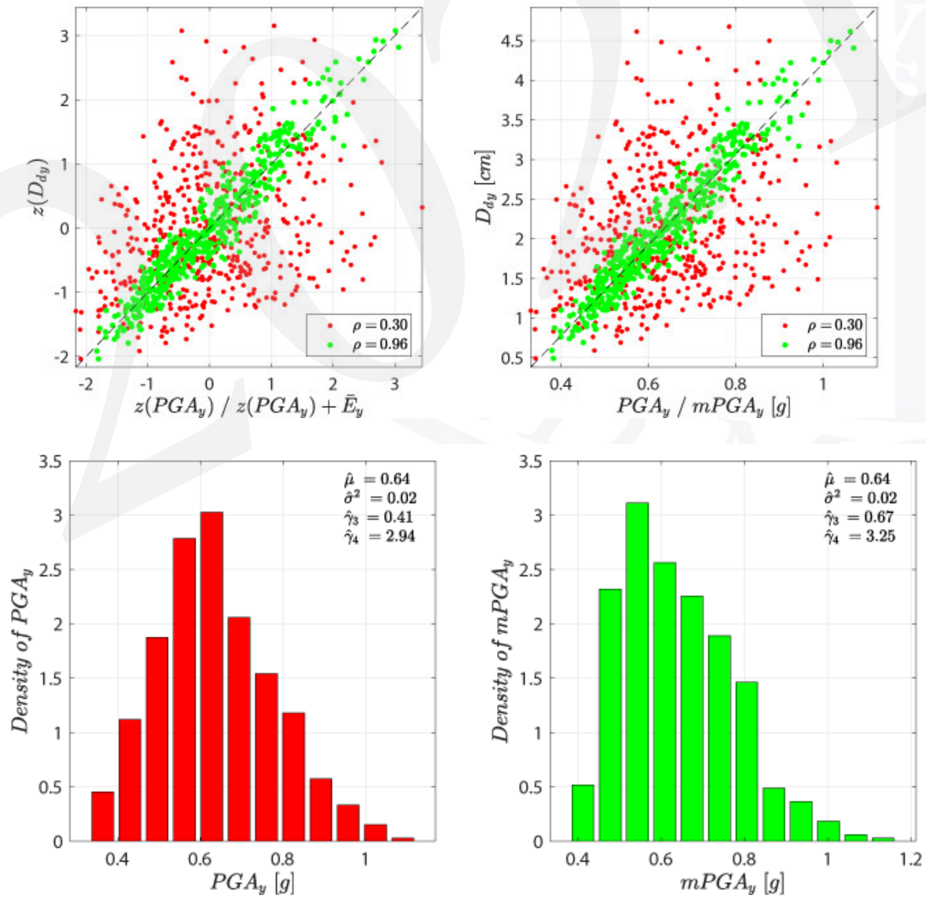
DEPENDENCE WITH mIMs

Node 9 - D_{dy}

$\boxed{\mathrm{IM}_1 = PGA}$

Analysis scheme





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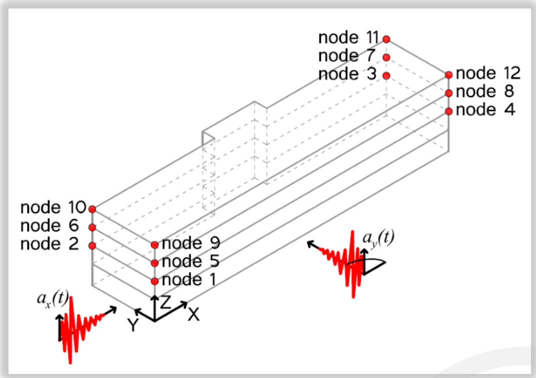
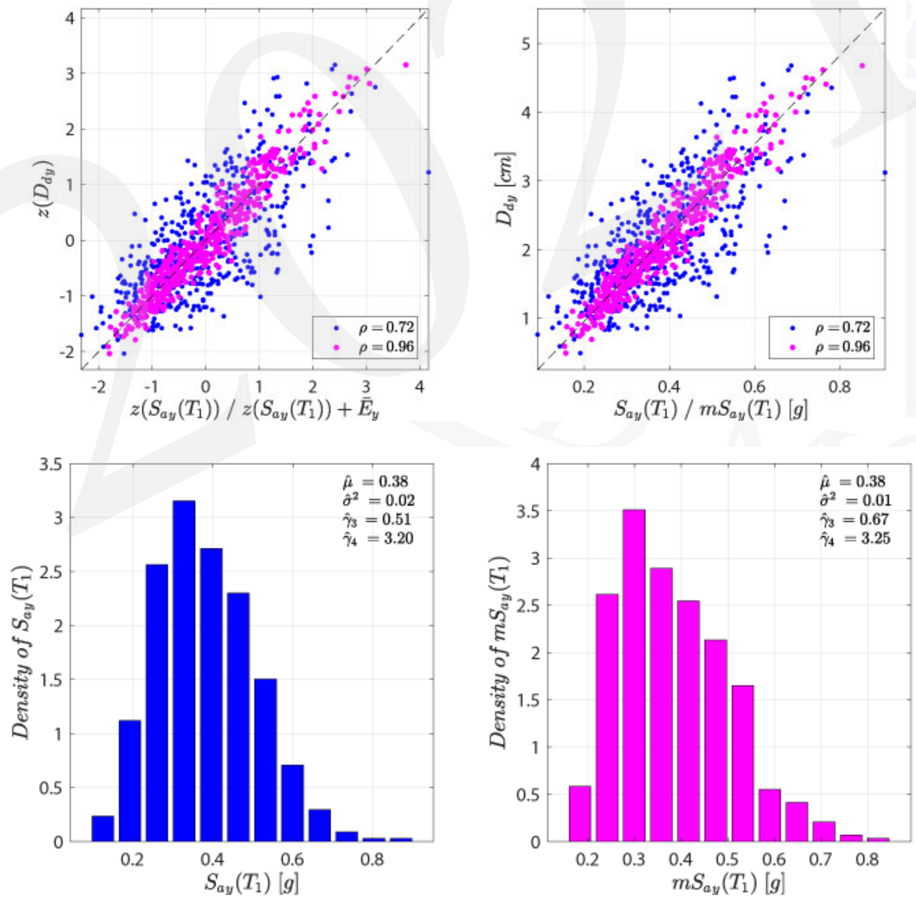
DEPENDENCE WITH mIMs

Node 9 - D_{dy}

$$\mathrm{IM}_2 = S_a(T_1, \zeta_1)$$

Analysis scheme





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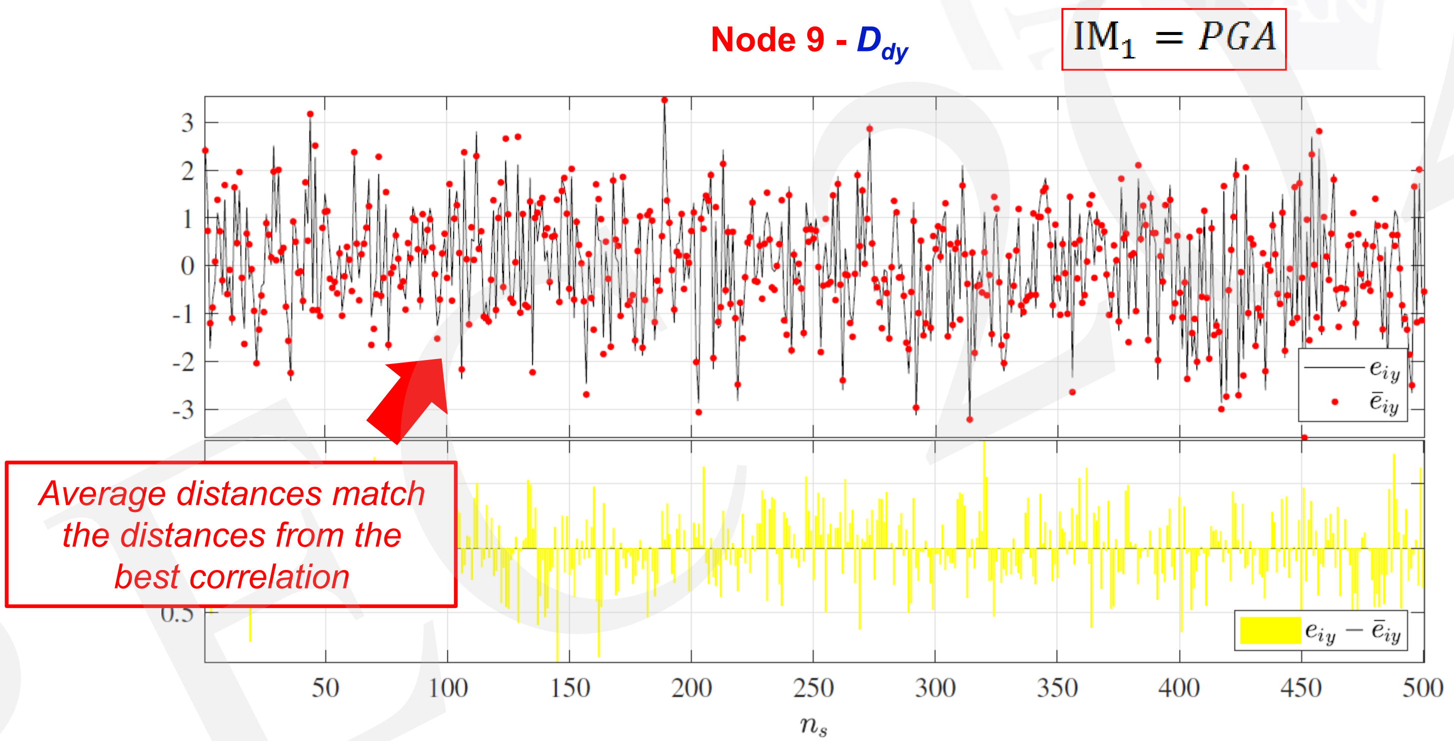
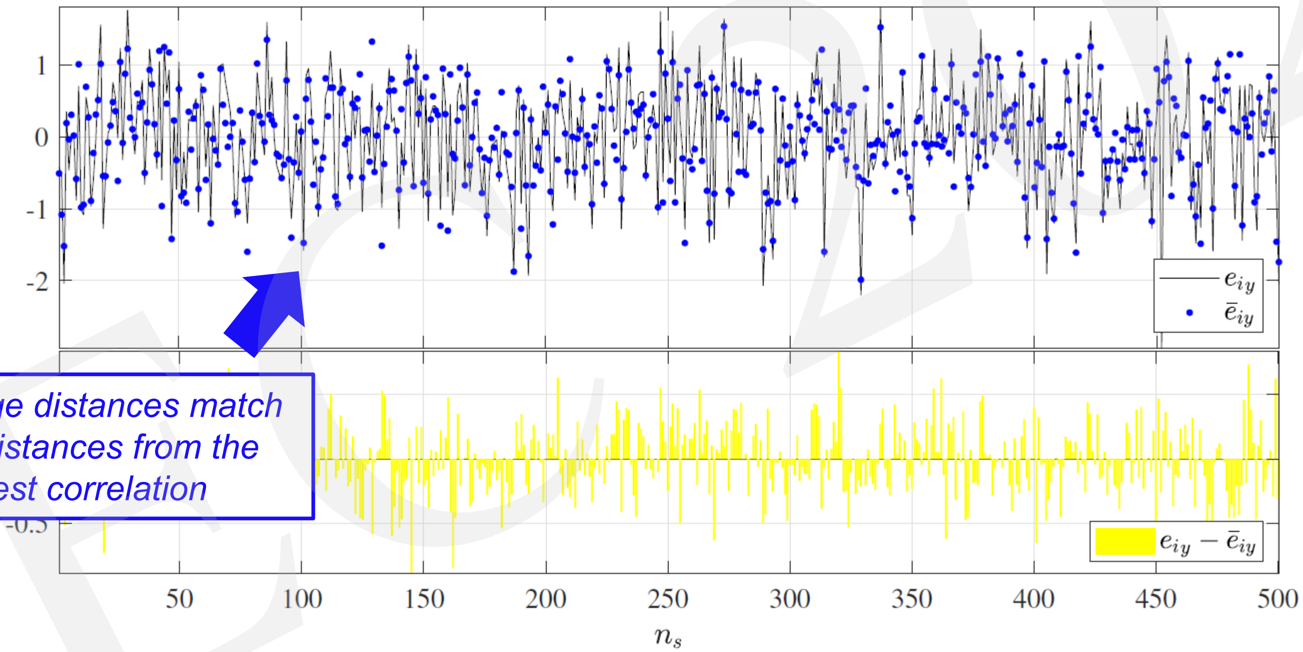
DISTANCE FROM BEST CORRELATION VERSUS AVERAGE DISTANCE



DISTANCE FROM BEST CORRELATION VERSUS AVERAGE DISTANCE

Node 9 - D_{dy}

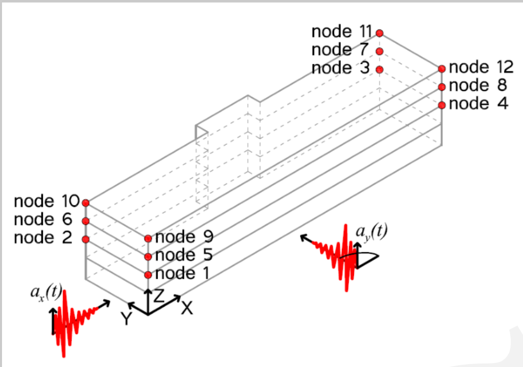
$$\mathrm{IM}_2 = S_a(T_1, \zeta_1)$$



Average distances match the distances from the best correlation

FRAGILITIES WITH mIMs

Analysis scheme



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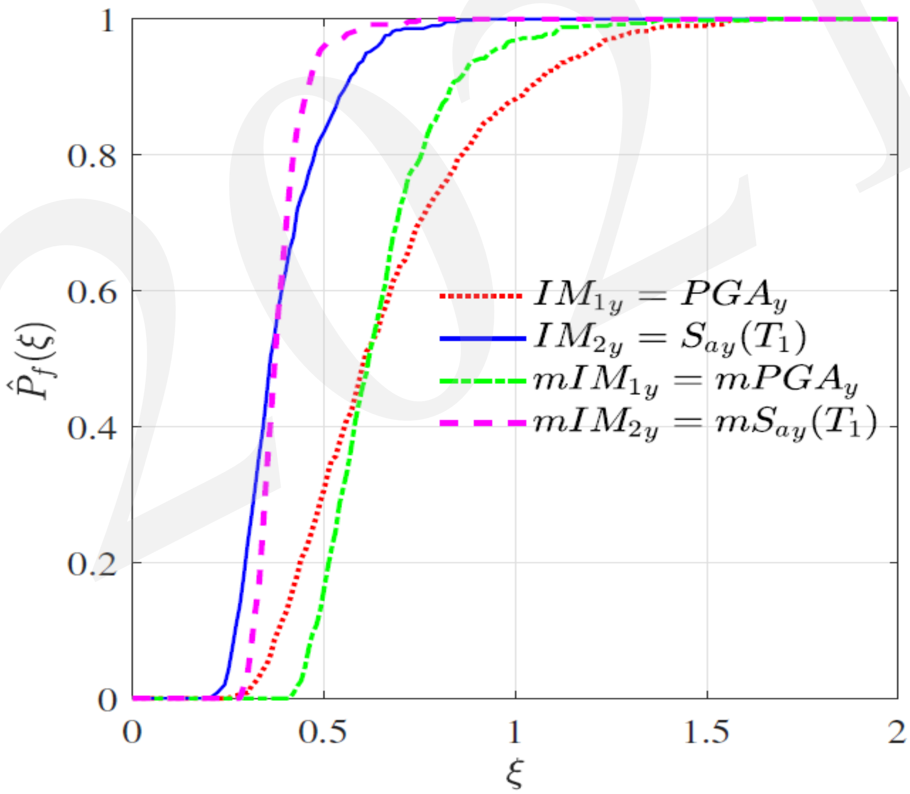

limit state 2 cm

Conclusion

In Performance-Based Earthquake Engineering the seismic fragilities are commonly estimated by using widespread *IMs*, i.e. *PGA* and $S_a(T_1)$, and scaling the seismic accelerograms.

Strong dependence is required between the system demand parameter *D* and *IM* used in fragility analysis.

The substantial and unstated assumption is that it is possible to accurately predict the response of complex nonlinear structural systems using the results of linear SDOF systems, e.g. $S_a(T)$, or the specific characteristic of the input ground motion acceleration, e.g. *PGA*.

Proposed approach is based on a linear transformation of samples of a chosen standard *IM*, which improves the correlation with a set of demand parameters. This transformation provides the definition of the modified version *mIM* of the current intensity measure approach.

Applicability to all *IMs* used in PBEE in order to construct fragilities that promise more accurate information than those obtained from standard *IMs*.

Work is in progress to investigate the novel approach in the nonlinear field.

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THANK YOU!

matteo.ciano@unipg.it
matteo.c@w1s3.com