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Recent developments in the risk-targeted assessment of existing structures

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ROSE
Centre for Training and Research on Reduction of Seismic Risk

Motivation

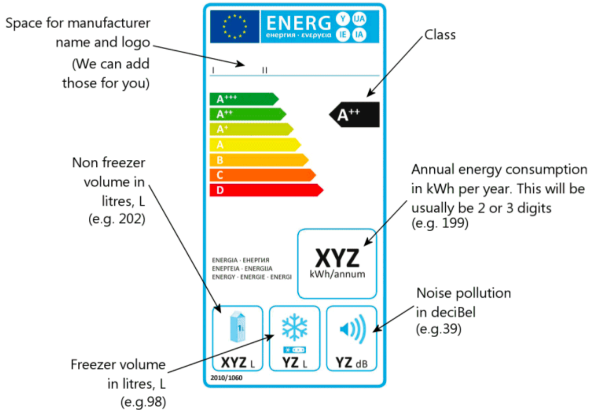
- When deciding on repairs and retrofitting, the accurate classification of seismic risk is important for decision-making
- Past earthquakes highlighted their increased vulnerability to ground-shaking



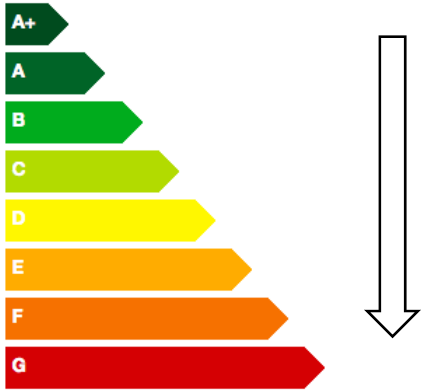



Italian Seismic Risk Classification Guidelines (*Sismabonus*)

- In 2017, the Italian Ministry of Infrastructure and Transportation issued the "*Guidelines for the Classification of Seismic Risk in Buildings*" – D.M. 58/2017
- Introduces expected annual loss (EAL) to classify the seismic risk of buildings
- Italian government offered tax rebates to incentivise owners to upgrade their buildings by a certain number of classes



Similar to energy rating system used in Europe



Increased seismic risk

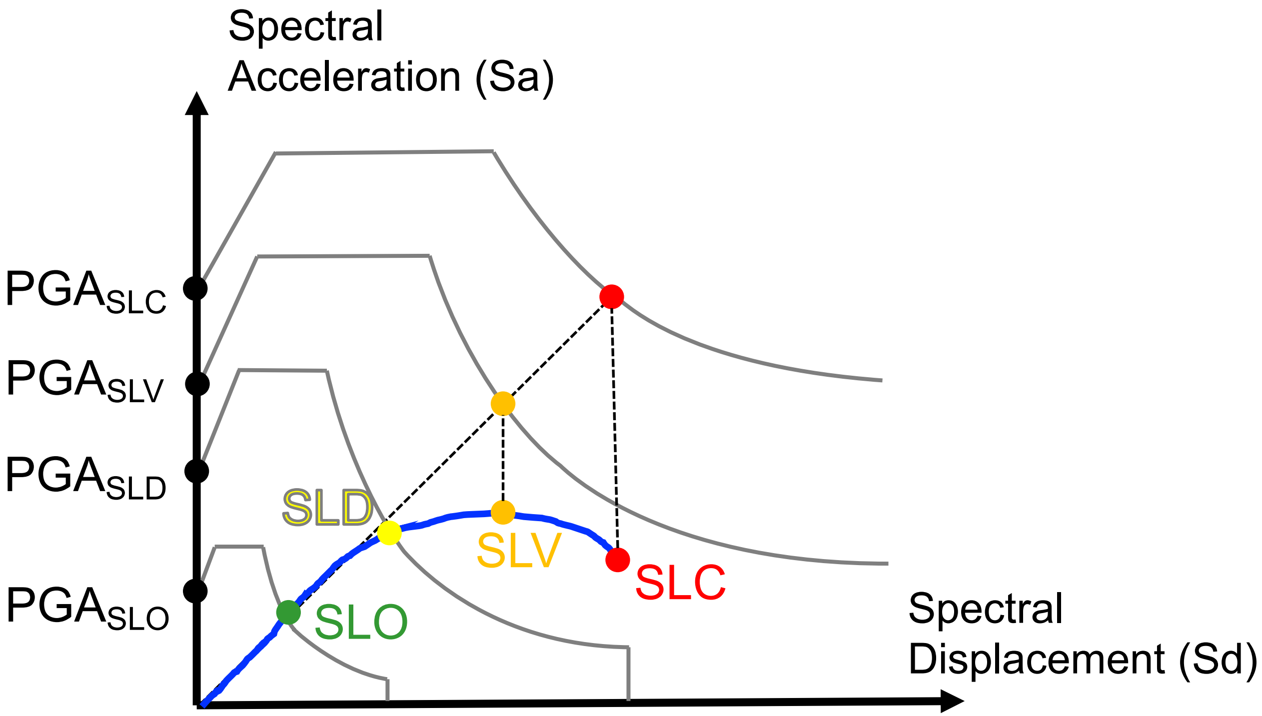
Decreto Ministeriale. [2017] Linee Guida per la Classificazione del Rischio Sismico delle Costruzioni - 58/2017, Il ministero delle infrastrutture e dei trasporti, Rome, Italy.
Decreto Legge [2020] Misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonche' di politiche sociali connesse all'emergenza epidemiologica da COVID-19 – 34/2020, Rome, Italy.

Italian Seismic Risk Classification Guidelines (Sismabonus)

- Perform a pushover analysis on the building and normalise to Sa-Sd
- Estimate the peak ground acceleration (PGA) of the design spectra needed to reach each limit state
- Additionally, estimate the ratio between $PGA_{C,SLV}$ capacity and the actual PGA you would use for a new design ($PGA_{D,SLV}$) to get ζ

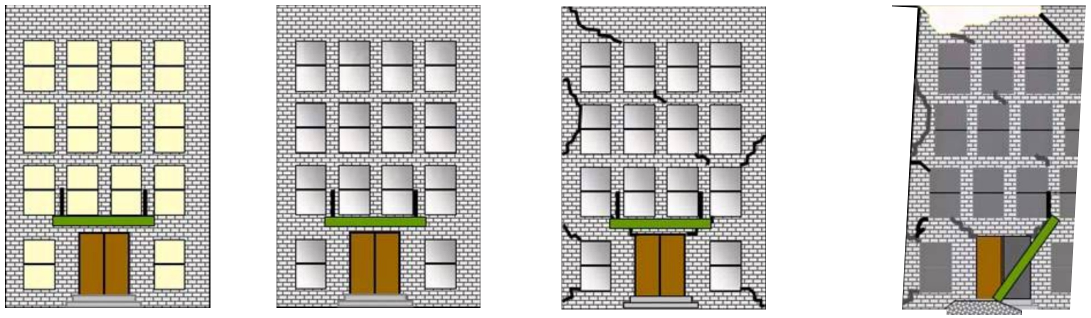
$$\zeta = \frac{PGA_{C,SLV}}{PGA_{D,SLV}} \approx \frac{\text{Capacity}}{\text{Demand}}$$

$PGA_{D,SLV}$ = PGA used for design
A new design should have $\zeta \geq 1.0$)

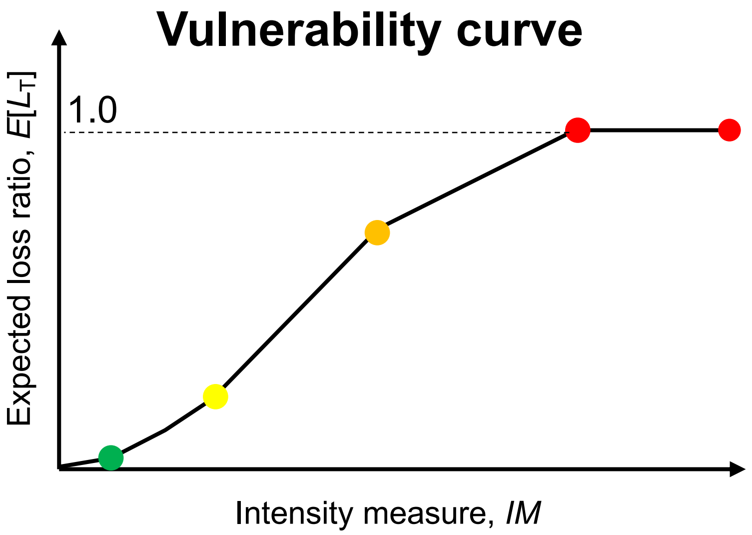


Italian Seismic Risk Classification Guidelines (Sismabonus)

- Expected loss ratios were assigned as fixed to each limit state
- This essentially gave a predefined vulnerability curve with only the intensities to be determined
- It removed the need for a component-based loss assessment

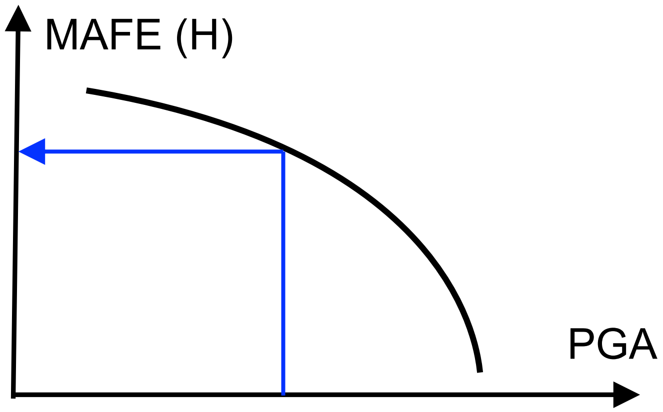


Limit state (LS):	Operational (SLO)	Damage limitation (SLD)	Life Safety (SLV)	Collapse Prevention (SLC)
Expected loss ratio:	7%	15%	80%	100%

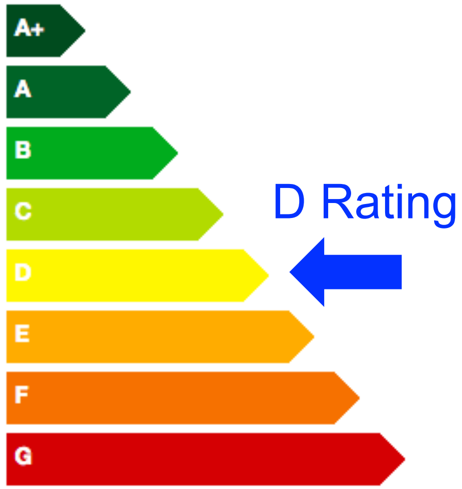


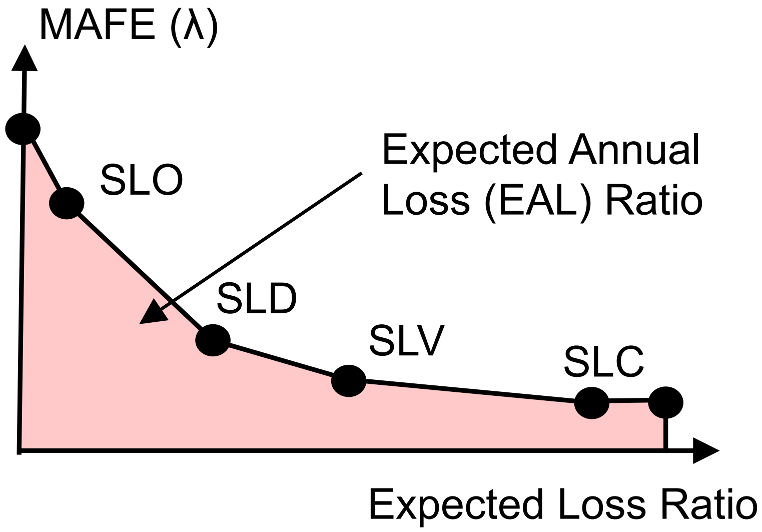
Italian Seismic Risk Classification Guidelines (Sismabonus)

- Knowing the PGA required to reach each limit state, the MAFE is computed from the hazard curve
- The limit state loss ratios are fixed values and the EAL is computed as the area under the loss curve
- Overall ranking is more critical of two



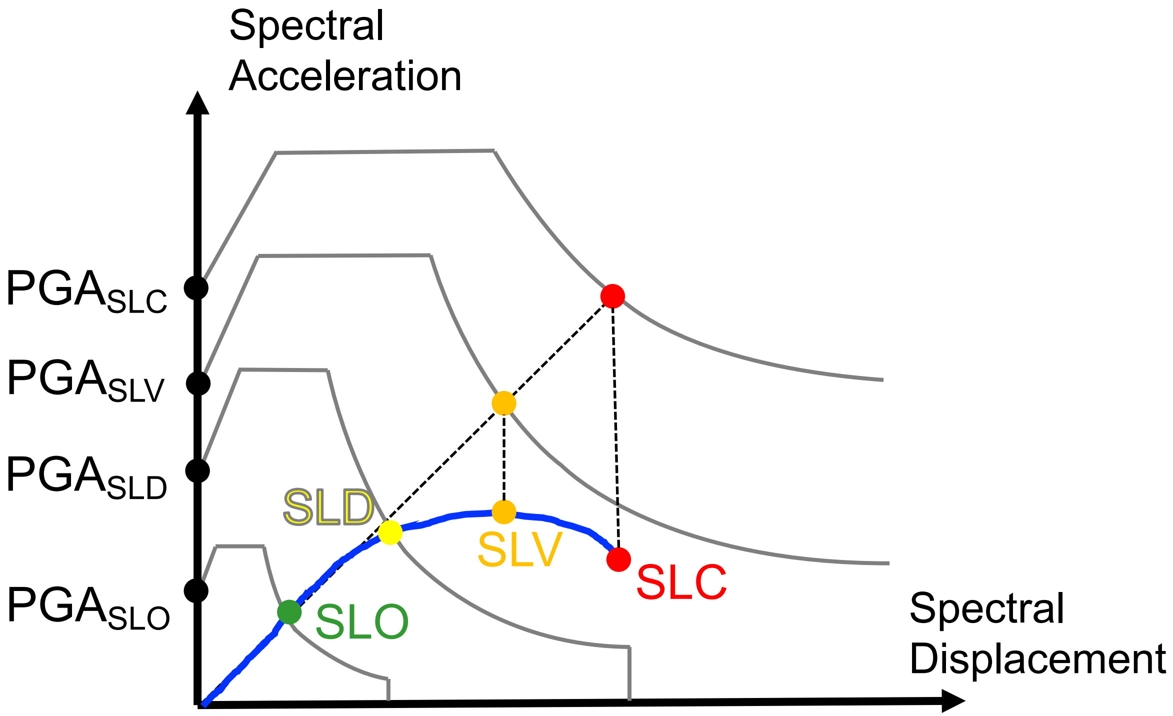
EAL Range	Life Safety Index (ζ)	
EAL ≤ 0.5%	100% < ζ	A+
0.5% < EAL ≤ 1.0%	80% ≤ ζ < 100%	A
1.0% < EAL ≤ 1.5%	60% ≤ ζ < 80%	B
1.5% < EAL ≤ 2.5%	45% ≤ ζ < 60%	C
2.5% < EAL ≤ 3.5%	30% ≤ ζ < 45%	D
3.5% < EAL ≤ 4.5%	15% ≤ ζ < 30%	E
4.5% < EAL ≤ 7.0%	ζ < 15%	F
EAL ≥ 7.0%		G





So what?

- This is not to question the goal or purpose of *Sismabonus*, but rather the robustness or appropriateness of its implementation
- *Sismabonus* is heavily integrated with the Italian National Building Code (NTC18)
- This means that the structural analysis remains largely the same for practitioners
- Some new add-ons open a door to enable the discussion of losses and risk

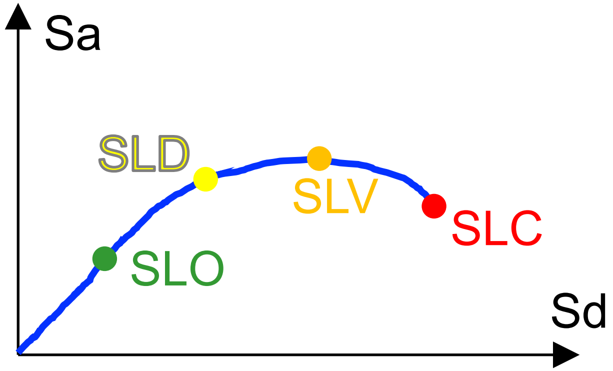


Connecting limit states and loss ratios

- The two issues that are worth scrutinising here are:
    1. How were the **loss ratios** used in building-specific loss assessment determined?
    2. How are these **limit states** identified in structures?
- Identifying the loss ratios to assign to each limit state is no easy task
- This was long discussed by the Italian Council for Public Works in the development of *Sismabonus*
- The decision was made to use repair cost data available from the L'Aquila 2009 earthquake
- There was a healthy amount of subjectivity in the choices made to do this and a feisty amount of uncertainty in the loss ratios proposed

Limit state	Loss
SLO	
SLD	
SLV	?
SLC	

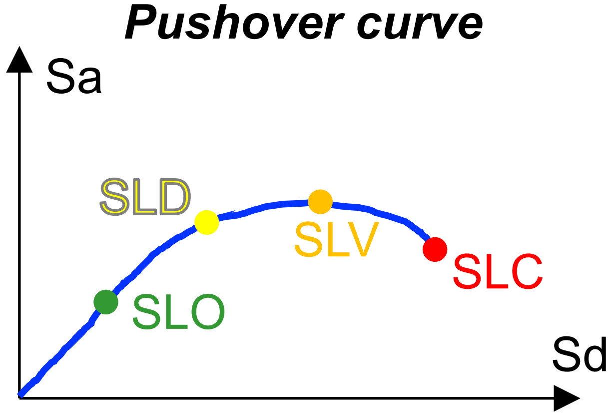
Pushover curve

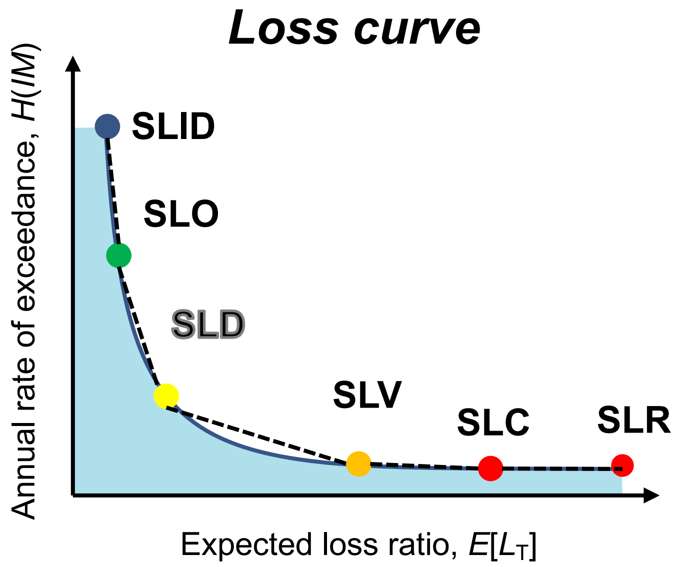


Cosenza, E., Prota, A., Di Ludovico, M., & Del Vecchio, C. (2017). Il metodo convenzionale per classificare il rischio sismico delle costruzioni. Costruire in Laterizio, 171, 70–77.

Identifying loss ratios

Limit state	Loss Ratio	Justification
SLID		
SLO		
SLD	15%	Based on 2497 buildings (1598 RC and 899 masonry) classed as either B or C via AeDES These averaged a repair cost of €196/m^2, which considering €1200/m^2 as replacement cost, gives 16.3%
SLV	50%	Based on 760 buildings (447 RC and 313 masonry) classed as E via AeDES These averaged a repair cost of €498/m^2, which considering €1200/m^2 as replacement cost, gives 41.5%
SLC		
SLR		



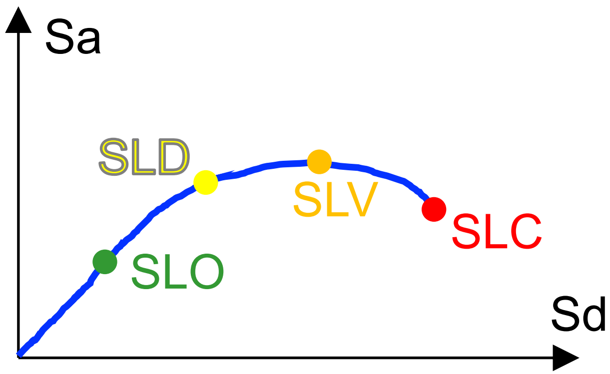


Cosenza, E., Del Vecchio, C., Di Ludovico, M., Dolce, M., Moroni, C., Prota, A., & Renzi, E. (2018). The Italian guidelines for seismic risk classification of constructions: technical principles and validation. Bulletin of Earthquake Engineering, 16(12), 5905–5935. https://doi.org/10.1007/s10518-018-0431-8
Taucer F, Pinto Vieira A, editors. Field Manual for Post-Earthquake Damage and Safety Assessment and Short Term Countermeasures (AeDES). EUR 22868 EN. 2007. JRC37914

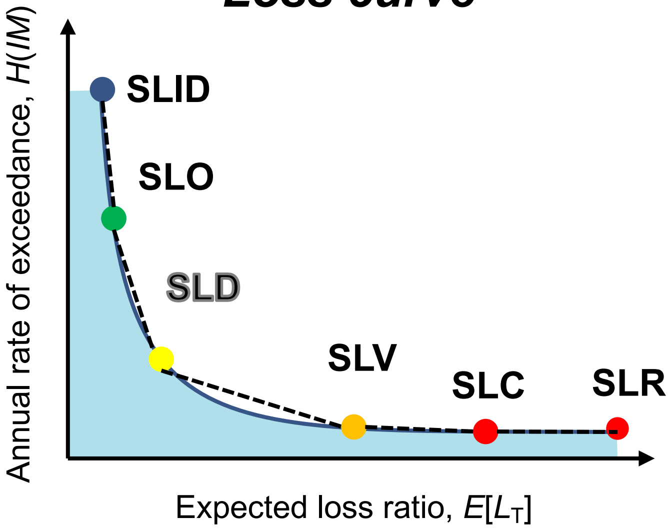
Identifying loss ratios

Limit state	Loss Ratio	Justification
SLID	0%	Assumption
SLO	7%	Approximately half of SLD
SLD	15%	Based on 2497 buildings (1598 RC and 899 masonry) classed as either B or C via AeDES These averaged a repair cost of €196/m^2, which considering €1200/m^2 as replacement cost, gives 16.3%
SLV	50%	Based on 760 buildings (447 RC and 313 masonry) classed as E via AeDES These averaged a repair cost of €498/m^2, which considering €1200/m^2 as replacement cost, gives 41.5%
SLC	80%	Judgement
SLR	100%	Assumption

Pushover curve



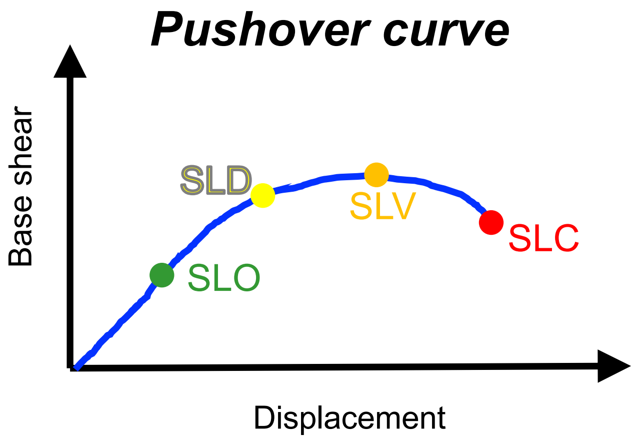
Loss curve



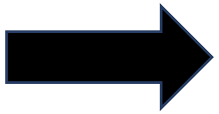
Cosenza, E., Del Vecchio, C., Di Ludovico, M., Dolce, M., Moroni, C., Prota, A., & Renzi, E. (2018). The Italian guidelines for seismic risk classification of constructions: technical principles and validation. Bulletin of Earthquake Engineering, 16(12), 5905–5935. https://doi.org/10.1007/s10518-018-0431-8
Taucer F, Pinto Vieira A, editors. Field Manual for Post-Earthquake Damage and Safety Assessment and Short Term Countermeasures (AeDES). EUR 22868 EN. 2007. JRC37914

Identifying limit states in theory

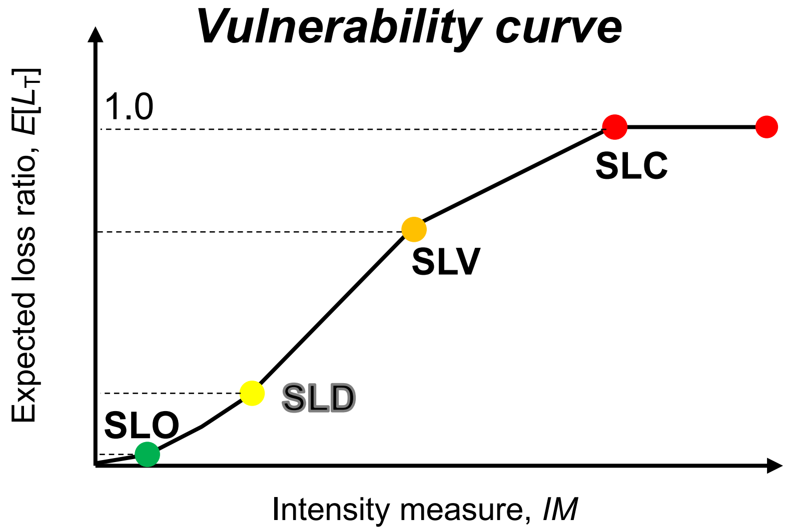
- It means that practitioners just need to do a pushover analysis and identify limit state intensities
- Loss ratios were assigned as ‘tags’ to each limit state



Limit state = loss ratio

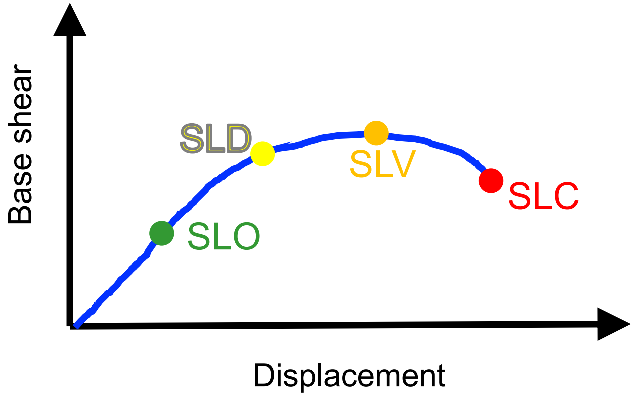


Non-linear static analysis

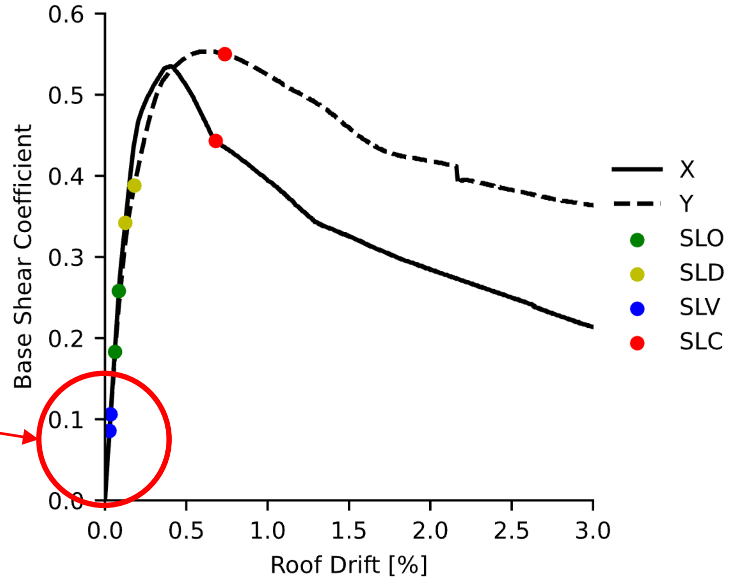


Identifying limit states in practice

- When we think of limit states in the sketch shown, it makes sense
- What do they look like in reality?
- Below is an existing school building in Italy analysed following the Italian building code procedures
- The limit states are triggered much earlier than the peak force and far from the lateral capacity
- Why?



The critical structural weaknesses at 'life safety' are the moment capacity of the beam column joints



Clemett, N., Carofilis Gallo, W. W., O'Reilly, G. J., Gabbianelli, G., & Monteiro, R. (2022). Optimal seismic retrofitting of existing buildings considering environmental impact. Engineering Structures, 250, 113391. https://doi.org/10.1016/j.engstruct.2021.113391

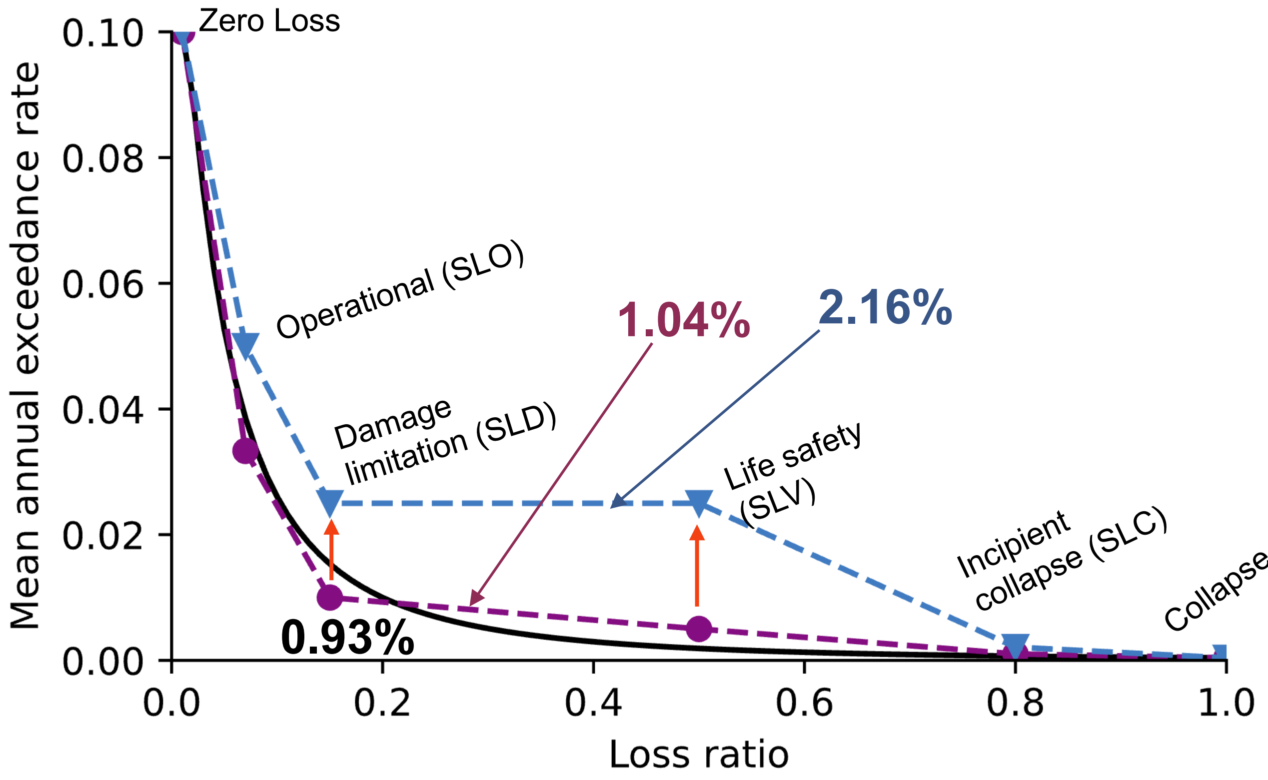
Identifying limit states in practice

- Limit states are triggered by several potential issues, both on a local and global level
- In particular, the life safety limit state (SLV) is triggered once one of the beam-column joint's moment demand exceeds its **<u>yield</u>** capacity
- The exceedance triggers a loss ratio of 80%

Criteria	Demand Parameter	SLO	SLD	SLV	SLC
Global Displacement-Based Criteria	Storey Drift	0.33%	0.5%		
Local Deformation-Based Criteria	Joint Rotation				> $\gamma_{ultimate}$
	Beam Rotation		> θ_{yield}	> $0.75x\theta_{ultimate}$	> $\theta_{ultimate}$
	Column Rotation				
Local Strength-Based Criteria	Beam Shear			> V_{yield}	
	Column Shear				
	Joint Moment			> M_{yield}	

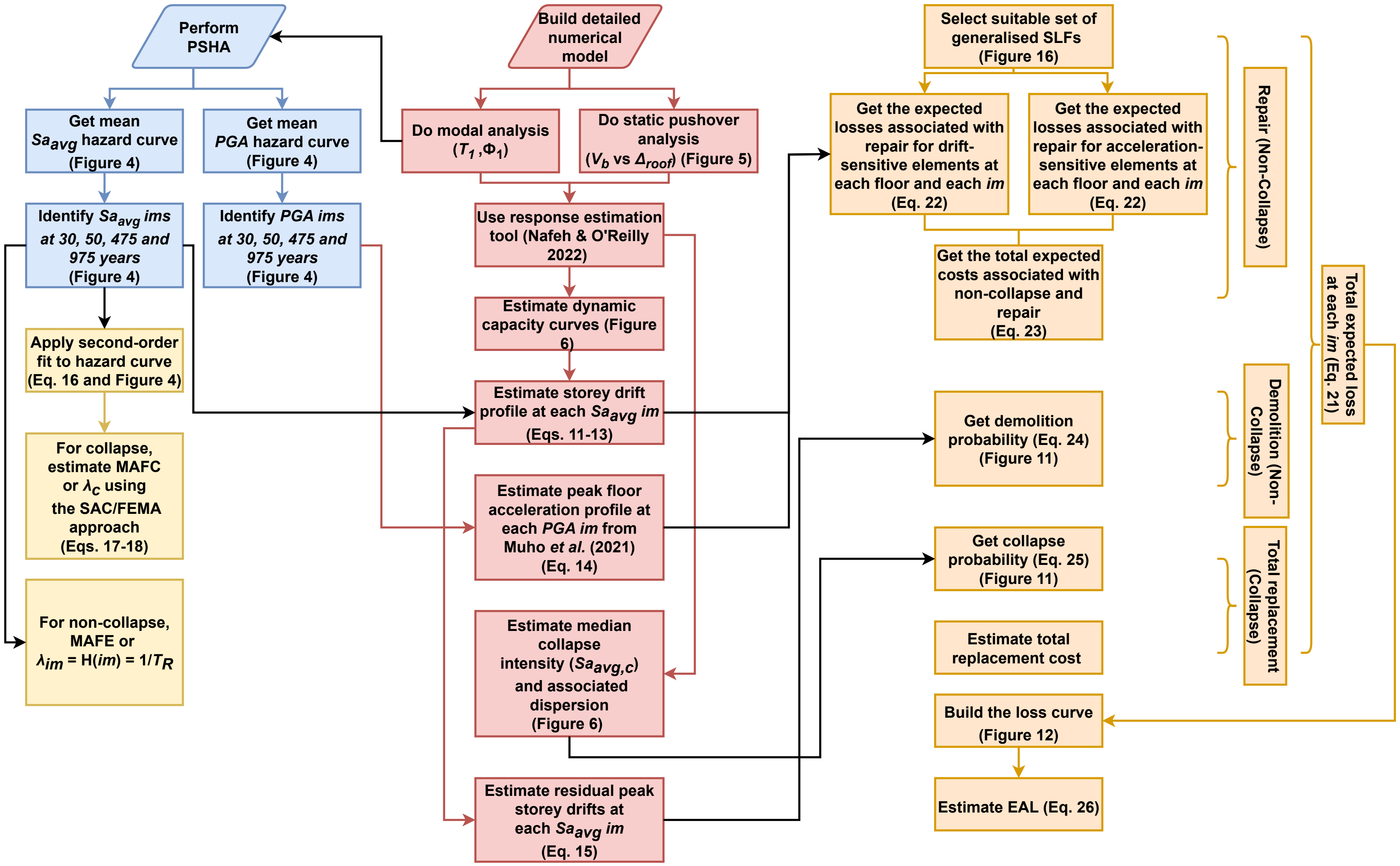
Impact on EAL evaluation

- Being overly sensitive to the declaration of SLV exceedance greatly impacts the loss curve
- Using the same example as before, declaring life safety because one single element has yielded, the EAL can be increased by **132%**
- This is not to discount the importance of life safety and the dangers of brittle elements
- But it is not what this EAL was intended for
- Any better solutions to identify losses for this kind of guideline?
- Yes….



PB-Loss

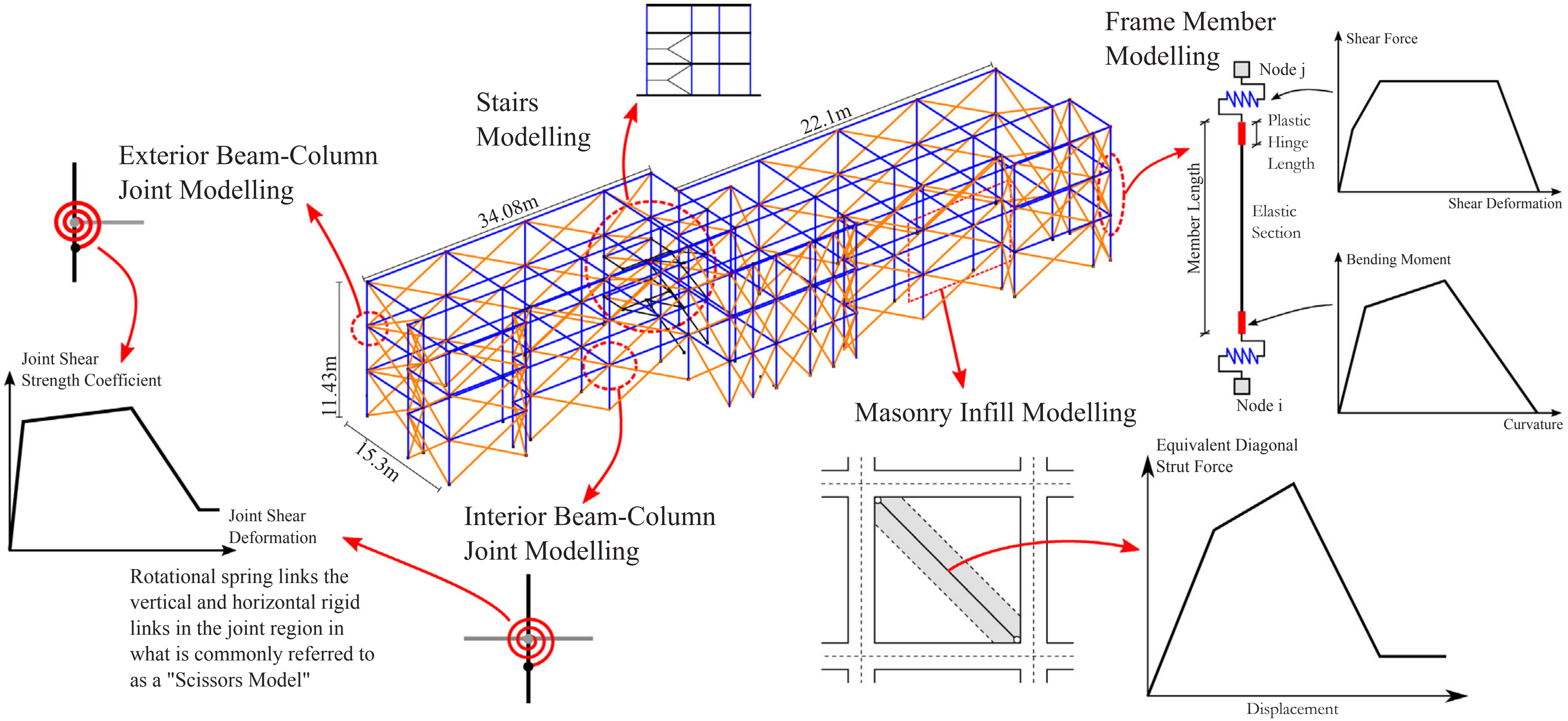
- A possible solution to many of these issues with Sismabonus has been proposed by Nafeh and O'Reilly (2023)
- It is termed PB-Loss since it is a loss assessment based on just a pushover analysis



Nafeh, A. M. B., & O'Reilly, G. J. (2023). Simplified pushover-based seismic loss assessment for existing infilled frame structures. Bulletin of Earthquake Engineering. https://doi.org/10.1007/s10518-023-01792-x

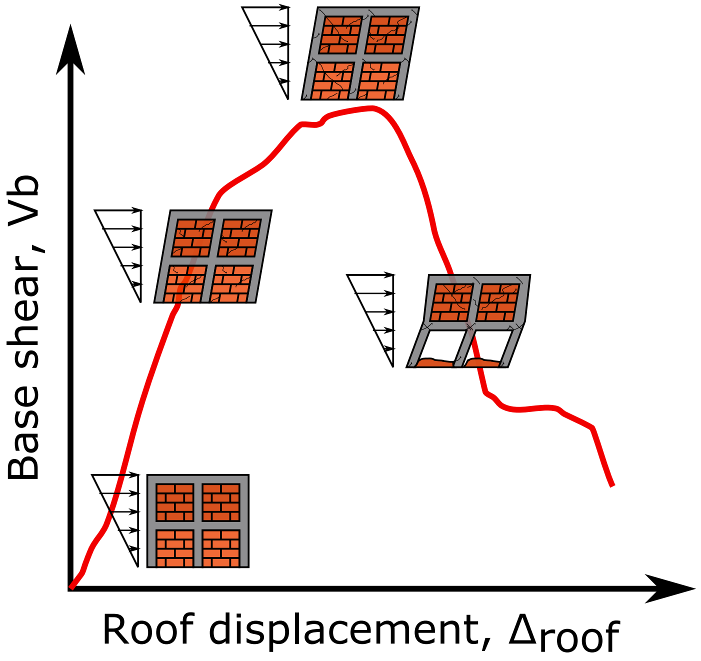
PB-Loss – numerical model and pushover

- It first starts with the user performing a static pushover analysis on their best numerical model



PB-Loss – simplify the pushover curve

- This static pushover curve is then linearised and normalised



We normalise the pushover curve:

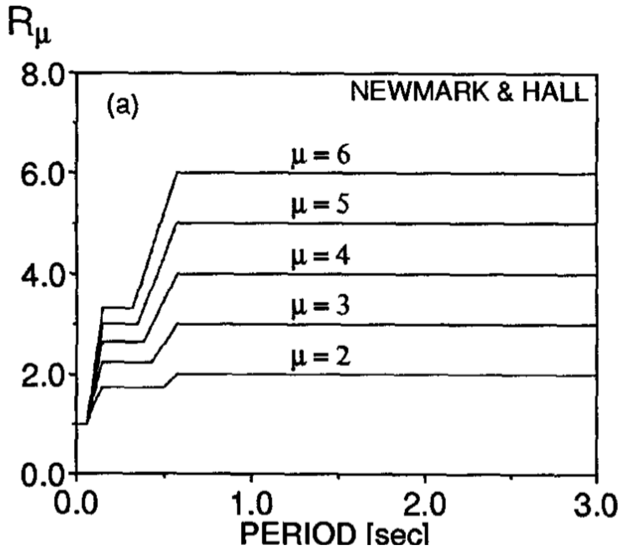
$$\mu = \frac{\Delta_{roof}}{\Delta_{roof,yield}}$$

Nafeh, A. M. B., & O'Reilly, G. J. (2022). Unbiased simplified seismic fragility estimation of non-ductile infilled RC structures. Soil Dynamics and Earthquake Engineering, 157, 107253. https://doi.org/10.1016/j.soildyn.2022.107253

R-μ-T Relationships

- Classic seismic analysis relies on *R-μ-T* relationships
- The basis stems from observations in 1960 by Veletsos and Newmark, formalised by Newmark and Hall in 1982

$$R = \frac{Sa(T_1)}{Sa_y}$$



It is of some interest to compare the maximum relative displacement of an elasto-plastic system, u_m, with the maximum relative displacement u_o of an elastic system having the same slope in the elastic part of its load deflection curve. Values of u_m/u_o are shown

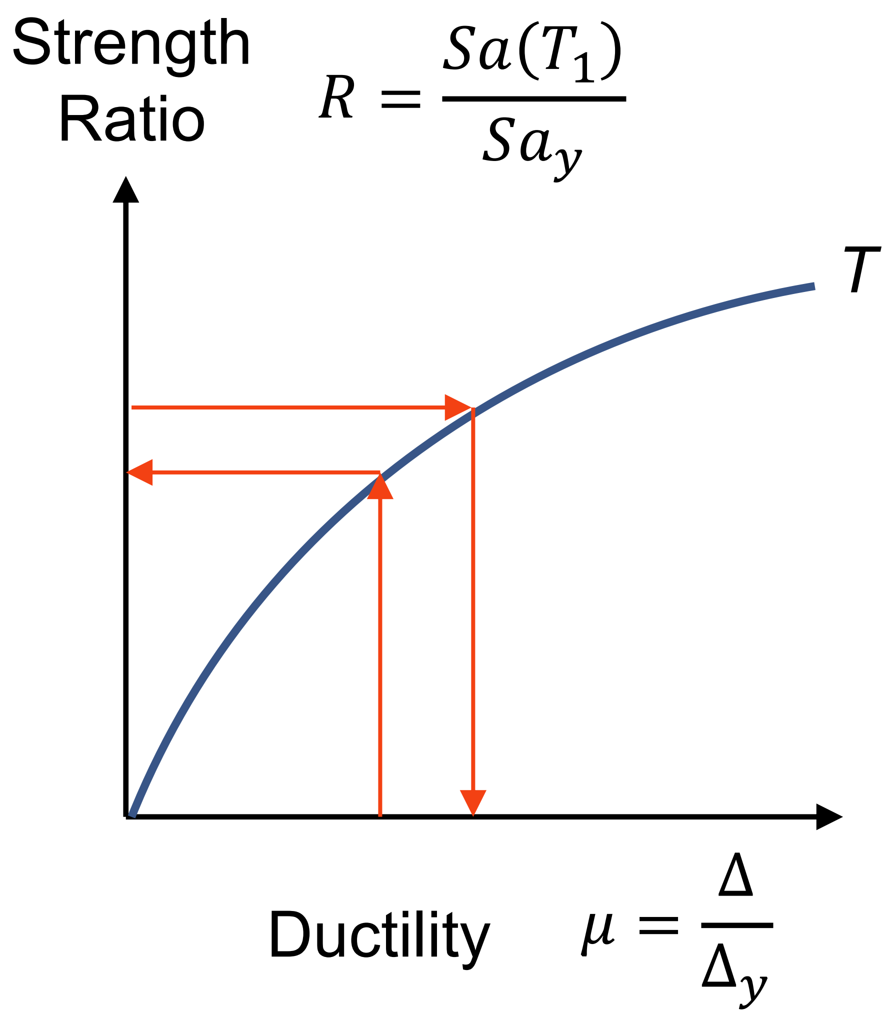
$$R_y = \begin{cases} 1 & T_n < T_a \\ (2\mu-1)^{\beta/2} & T_a < T_n < T_b \\ \sqrt{2\mu-1} & T_b < T_n < T_{c'} \\ \frac{T_n}{T_c}\mu & T_{c'} < T_n < T_c \\ \mu & T_n > T_c \end{cases}$$

- These form a crucial part of methods like the N2 method implemented in Eurocode 8

Veletsos, A. S., and Newmark, N. M., 1960, Effects of inelastic behavior on the response of simple system to earthquake motions, Proceedings of the 2nd World Conference on Earthquake Engineering, Japan, Vol. 2, pp. 895-912
Newmark, N. M., and Hall, W. J., 1982, Earthquake Spectra and Design, Earthquake Engineering Research Institute, Berkeley, CA

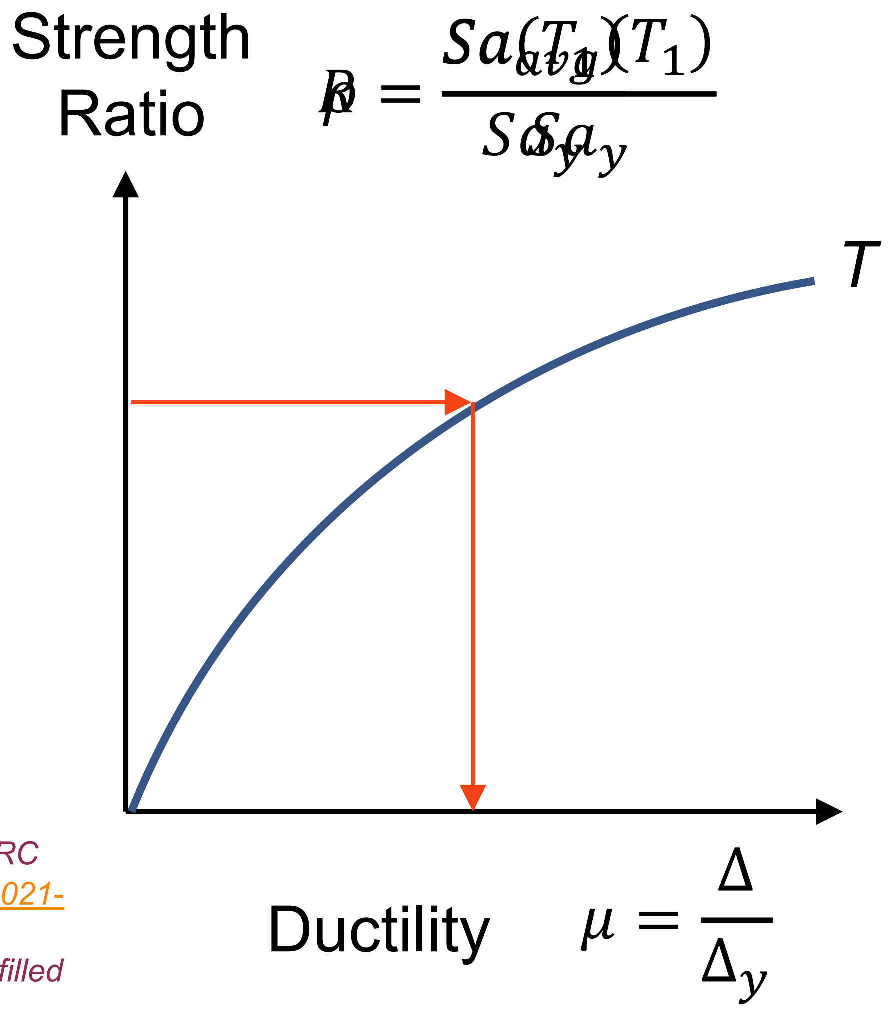
R-*μ*-*T* Relationships

- If you know the strength ratio *R* and period *T*, you can estimate the ductility demand *μ*
- Likewise, for a given ductility demand *μ* and period *T*, you can estimate the required strength ratio *R*



ρ-μ-T (or *fancy R-μ-T*) relationships

- *R-μ-T* relationships implicitly use $Sa(T_1)$ as the intensity measure
- Several works show that $Sa(T_1)$ is not a very good predictor of response (i.e., efficient, sufficient etc.) and that average spectral acceleration $Sa_{avg}(T)$ is much more accurate
- Like Newmark and Hall (1982), Nafeh and O'Reilly (2022) formalised these as *ρ-μ-T* relationships
- As before, for a given strength ratio *ρ* and period *T*, you can estimate the ductility demand *μ*
- These provide fragility functions for a given ductility in terms of average spectral acceleration



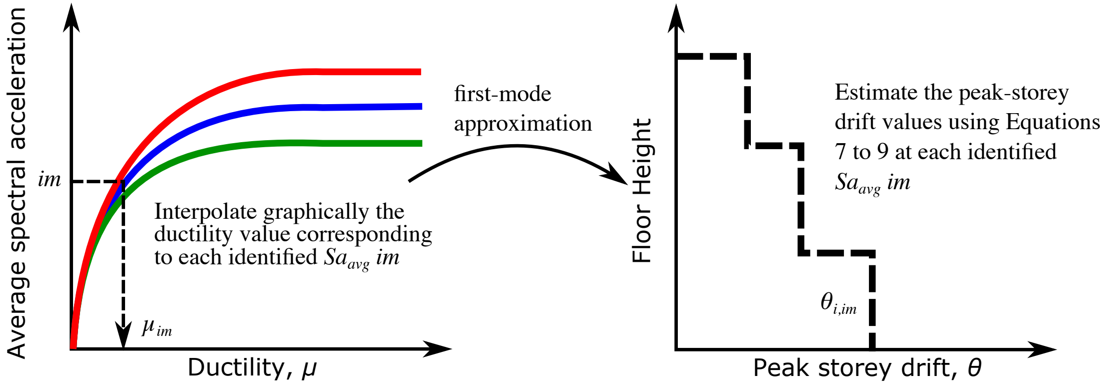
O'Reilly, G. J. (2021). Limitations of Sa(T1) as an intensity measure when assessing non-ductile infilled RC frame structures. Bulletin of Earthquake Engineering, 19(6), 2389–2417. https://doi.org/10.1007/s10518-021-01071-7

Nafeh, A. M. B., & O'Reilly, G. J. (2022). Unbiased simplified seismic fragility estimation of non-ductile infilled RC structures. Soil Dynamics and Earthquake Engineering, 157, 107253. https://doi.org/10.1016/j.soildyn.2022.107253

PB-Loss – estimate drift and acceleration profiles

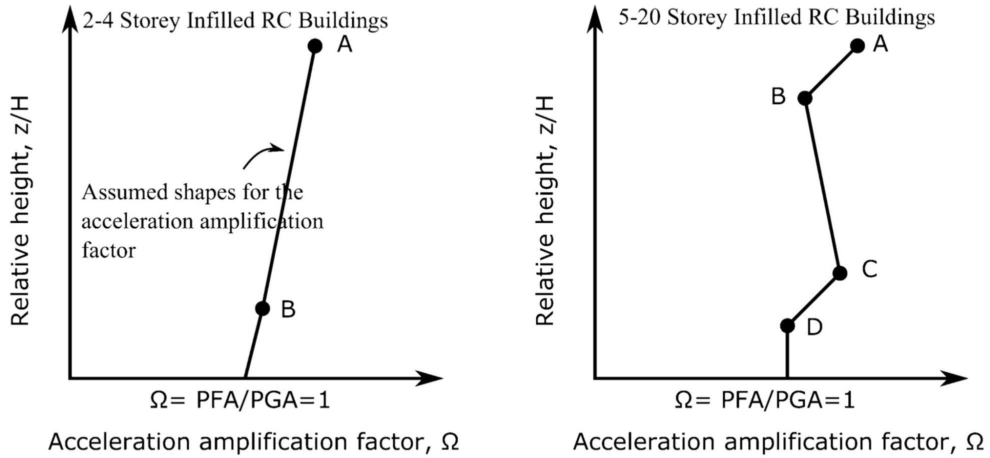
- With knowledge of the expected ductility at a given IM level, a first-mode drift profile is assumed and the demands are estimated

$$\rho = \frac{Sa_{avg}(T^*)}{Sa_y} \qquad \rho = \mathrm{f}(\mu, T^*) \qquad Sa_y = \frac{V_b}{m}$$



- For the case of floor accelerations, the method of Muho et al. (2021) is used for infilled RC frames
- The parameters a_1, a_2, a_3, a_4, a_5 are calibrated based on building height

$$\frac{PFA_{i,im}}{PGA_{im}} = \Omega_{i,im} = a_1 \theta_{i,im}^{a_2} T^{a_3} \left(\frac{E_2}{E_1}\right)^{a_4} t^{a_5}$$



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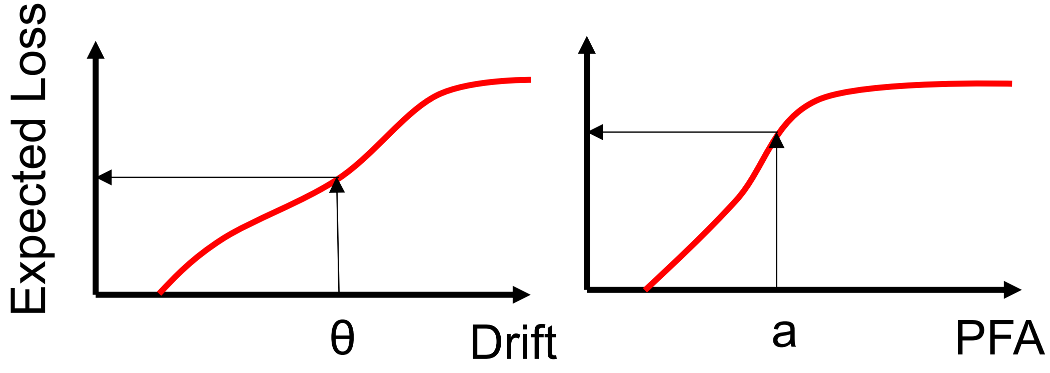
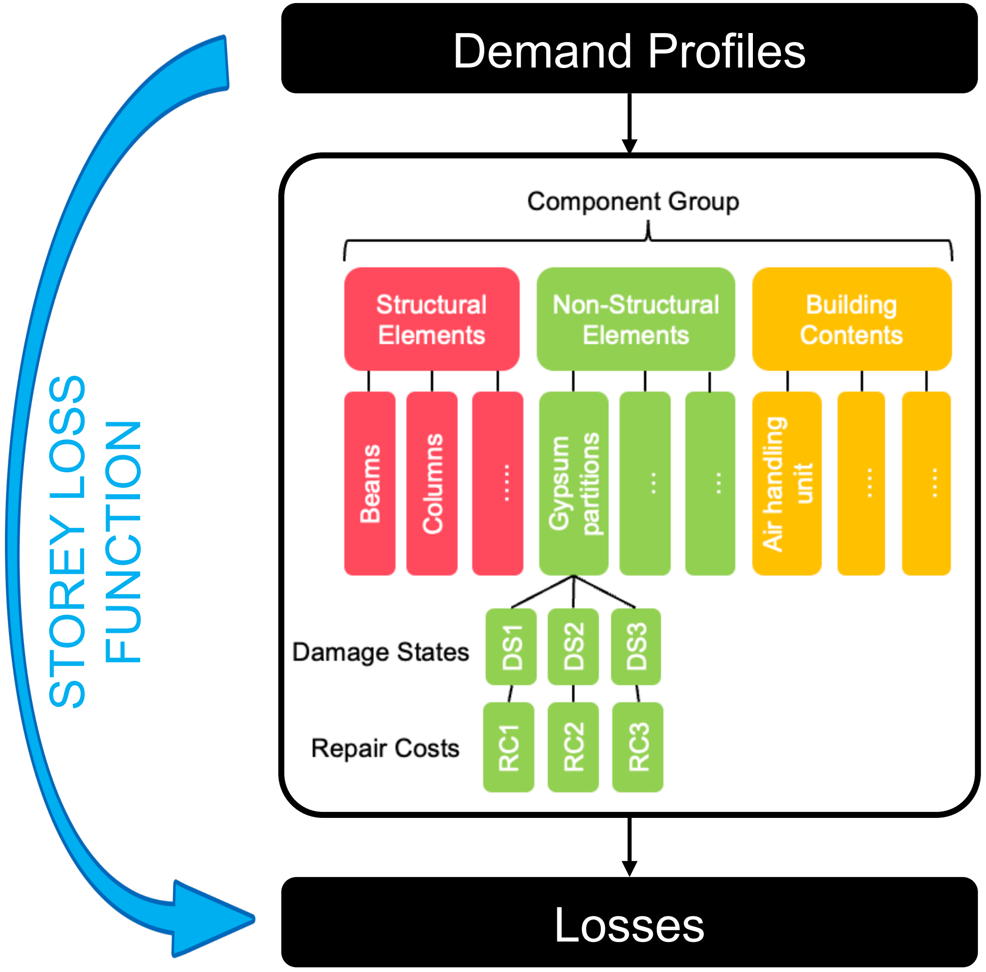
Muho EV, Pian C, Qian J, Shadabfar M, Beskos DE (2021) Deformation-dependent peak floor accelera- tion for the performance-based design of nonstructural elements attached to R/C structures. Earthq Spectra 37(2):1035–1055. https://doi.org/10.1177/8755293020988015

Storey loss functions

- In many situations, the damageable inventory, fragility functions and repair cost functions are known for a given building typology
- The process follows the same steps every time
- Ramirez and Miranda (2009) proposed condensing these steps down to a few functions
- We call these **storey loss functions** that link EDP directly to the expected economic loss

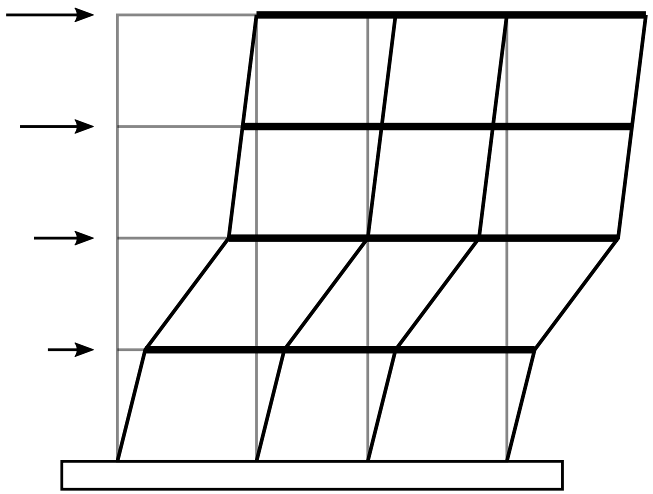




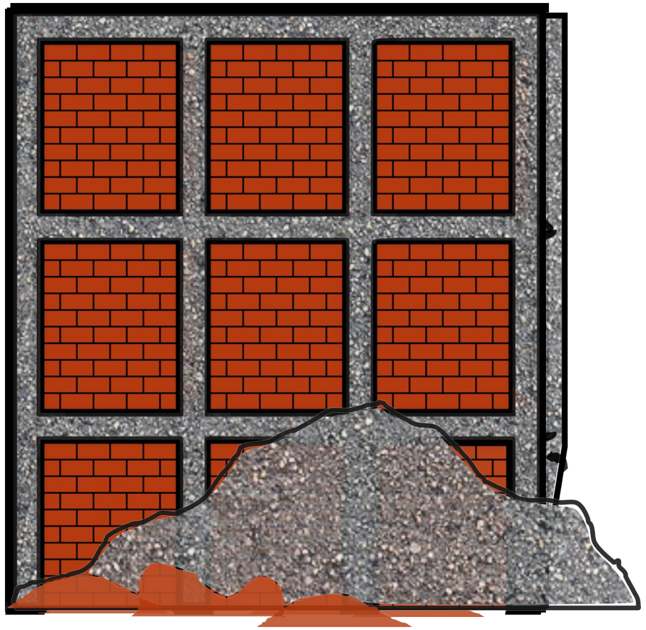
Ramirez, C. M., & Miranda, E. (2009). Building Specific Loss Estimation Methods & Tools for Simplified Performance Based Earthquake Engineering. Blume Report No. 171.

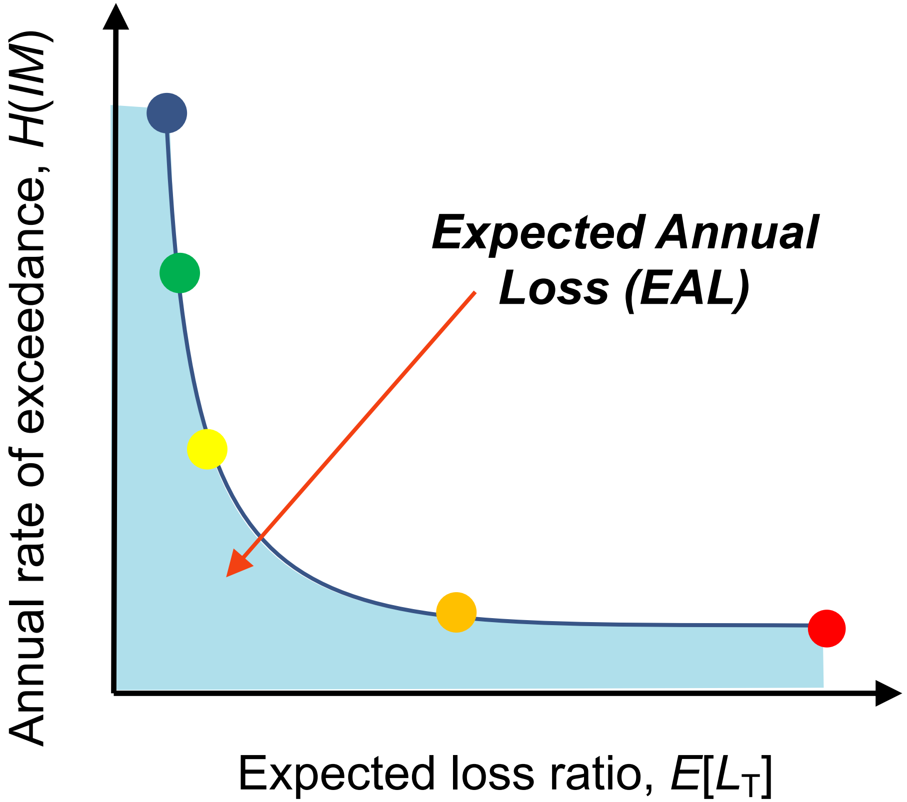
PB-Loss – assembling the vulnerability function

- Once the structural demands are estimated at each IM level
- The losses are computed using the SLFs



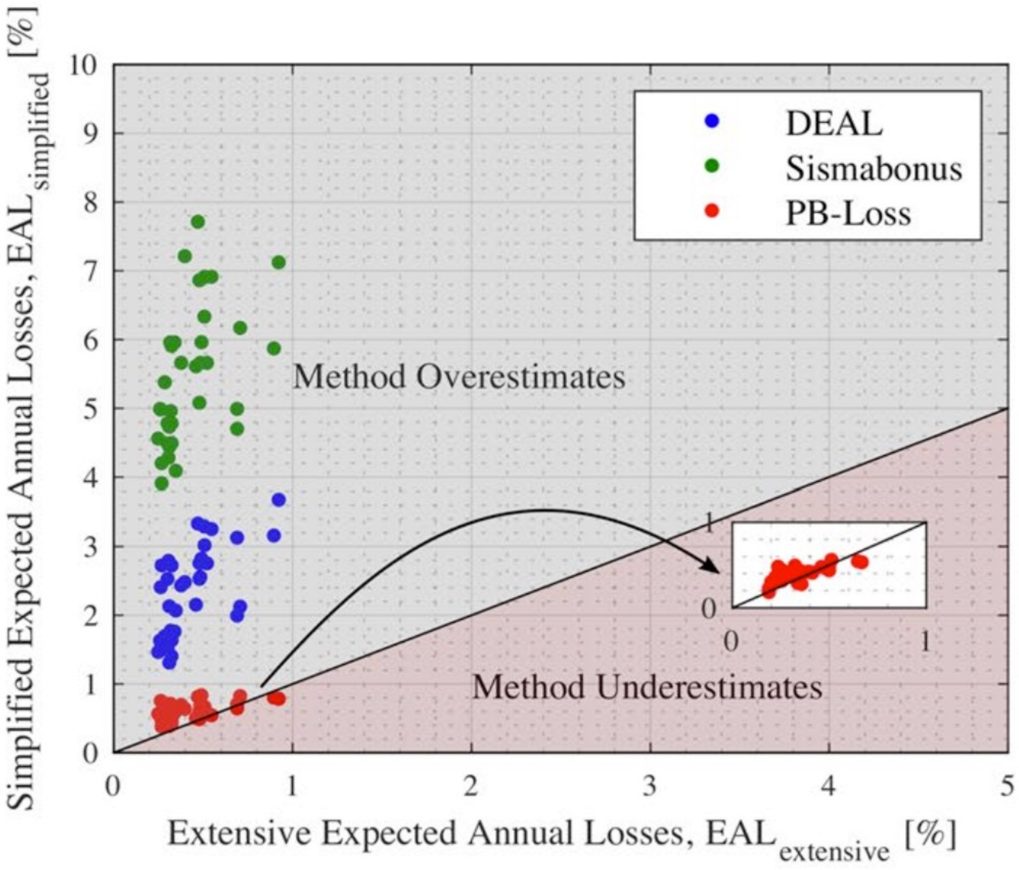
PB-Loss – assembling the loss curve





PB-Loss - evaluation

- Several case study comparisons were performed to evaluate the PB-Loss methods accuracy
- When compared to benchmark component-based loss assessment, it is the most accurate of all available simplified loss assessment methods
- It is a risk-consistent and far more accurate means to classify buildings



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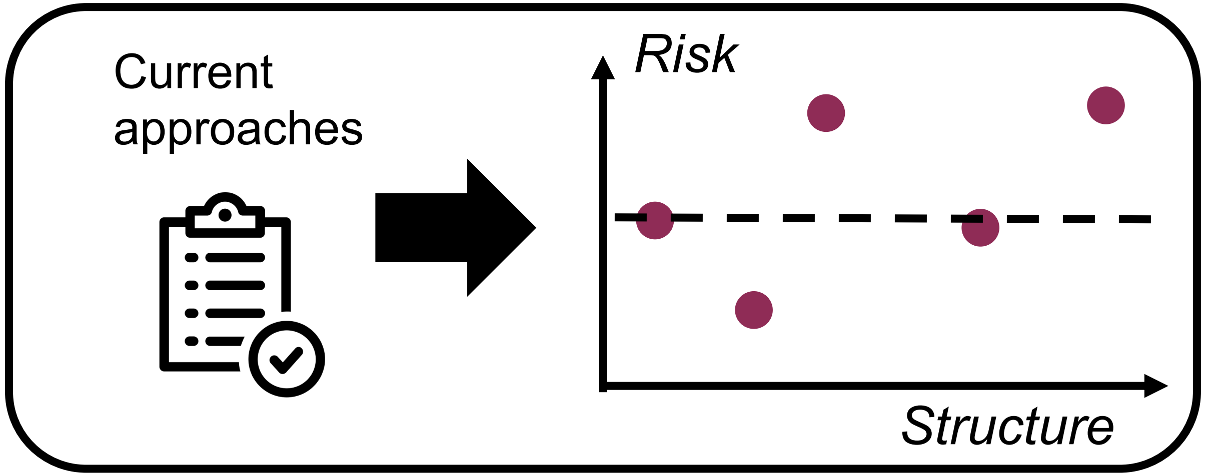
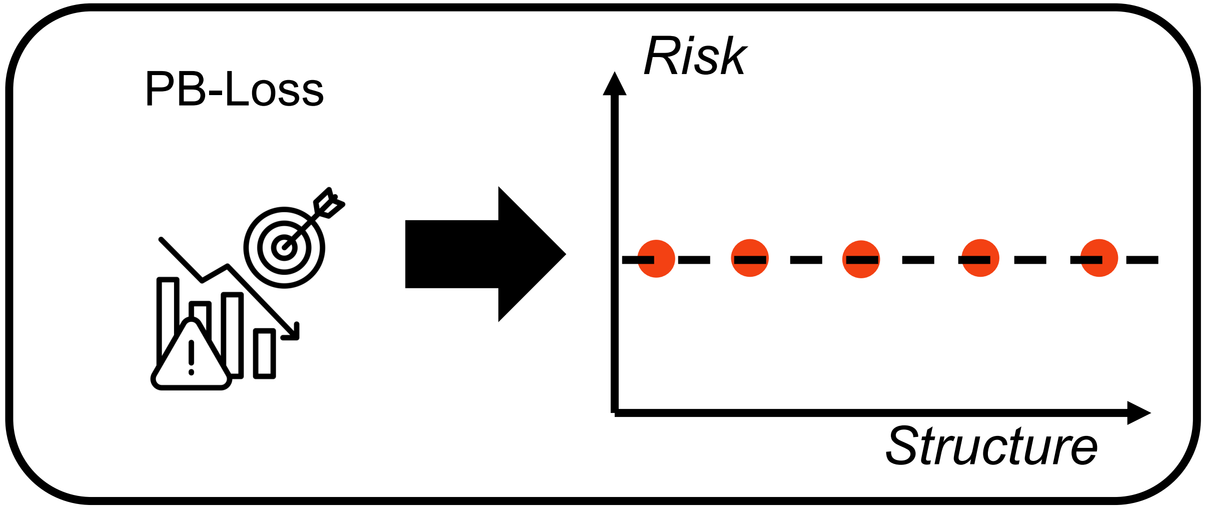
Conclusions

- When deciding on repairs and retrofitting, the accurate classification of seismic risk is important for decision-making
- A means to do this has been introduced in Italy, but has several shortcomings
- An alternative method termed ***PB-Loss*** was introduced
- It requires practitioners to do just a pushover analysis, the rest is data that can be provided in guidelines
- Results were much more accurate when compared to benchmark studies





Special thanks to Al Mouayed Bellah Nafeh (ex-PhD student, now GEM Foundation) who developed large part of this work for his thesis

Questions?

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