Myths and Fallacies of Earthquake Engineering: Ode to Nigel

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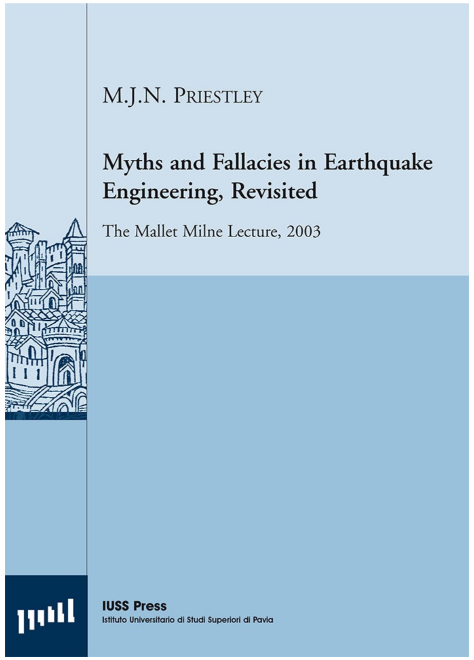
Myths and fallacies

- The original myths and fallacies in earthquake engineering series was put forth by Nigel Priestley
- This was first in 1993 and again in 2003
- These lectures and papers challenged existing ideas and put forth alternatives that helped shape modern earthquake engineering practice
- To quote the band Tenacious D:

  \- this is just a tribute…

M. J. Nigel Priestley
1943 - 2014

2003 Mallet Milne Lecture



1993 BNZSEE Paper

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MYTHS AND FALLACIES IN EARTHQUAKE ENGINEERING — CONFLICTS BETWEEN DESIGN AND REALITY

M.J. Nigel Priestley[1]

This paper was presented during the year as the 1993 NZNSEE Travelling Lecture

SUMMARY

Current practice in seismic analysis and design is examined, with particular reference to reinforced concrete structures. The attitude of the paper is deliberately iconoclastic, tilting at targets it is hoped will not be seen as windmills. It is suggested that our current emphasis on strength-based design and ductility leads us in directions that are not always rational. A pure displacement-based design approach is advanced as a viable alternative. Improvements resulting from increased sophistication of analyses are seen to be largely illusory. Energy absorption is shown to be a mixed blessing. Finally, accepted practices for flexural design, shear design, development of reinforcement, and the philosophic basis of capacity design are questioned.

1. **INTRODUCTION**

It has long been recognized that our codified approaches for seismic design bear a comparatively tenuous relationship to expected performance. Design is based on a static 'snapshot' simulation of the dynamic event, using methods extrapolated from approaches felt to be adequate and conservative for gravity load design. A major difference between gravity load effects and seismic response is that ultimate strength should never be developed under gravity load, while it is almost certain to be developed under seismic response, typically at a level of excitation which may be a fraction of the design level of seismic attack. Further, although ductile seismic response implies greater dependency on displacements than forces, we still, as a matter of convenience and tradition, design for specified force levels, and treat displacements in a comparatively cursory way.

When the design approach is based on carefully considered philosophy, as in the capacity design approach pioneered in New Zealand and gradually becoming accepted in many other seismic regions, excellent results are to be expected because the design structure is comparatively insensitive to the various assumptions made.

It appears, however, that the enormous approximations involved in seismic design are perhaps becoming less appreciated, rather than more, as sophisticated analytical techniques become specified by codes and accepted into common design practice, as a matter of routine. In the United States, and I suspect elsewhere, this has resulted in a tendency for the functions of analysis and design to be separated, and performed by different specialists. The analyst is responsible for modelling the structure and running the lateral force analysis - typically a 3-D modal analysis process. Results from the analysis are presented to the designer who determines member sizes, reinforcement quantities (if reinforced concrete construction) and detailing aspects. The analyst is typically more involved in the analytical process than the correct simulation of member characteristics, with potential dangers. The result of the separation of design and analysis tends to be that analysis drives the design process, rather than the reverse, which might seem to be more appropriate.

There is also room to examine current design and detailing practice, much of which is also extrapolated from gravity load considerations. Occasionally, this process can lead us in directions which are inappropriate for seismic behaviour. Even when tenets of structural performance are based on purely dynamic characteristics, such as energy absorption under cyclic response, the directions we are accustomed to taking are not necessarily the best for survival and damage control.

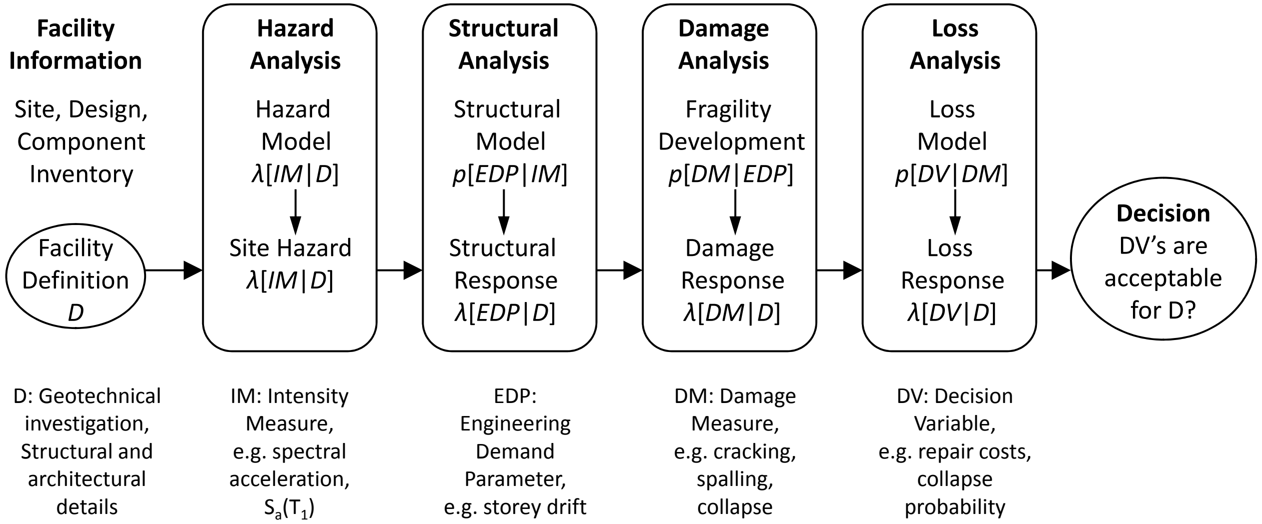
In this paper, some of the accepted seismic design and analysis procedures are identified as 'myths' or 'fallacies' - an overstatement perhaps, to make a rather dry topic seem more interesting. Nevertheless, a critical examination of the bases of our design processes is always appropriate, since the origin of these are often obscure, and lost in the history of design practice, or worse, in code committee minutes. Some of the points to be made are well known, others perhaps less so.

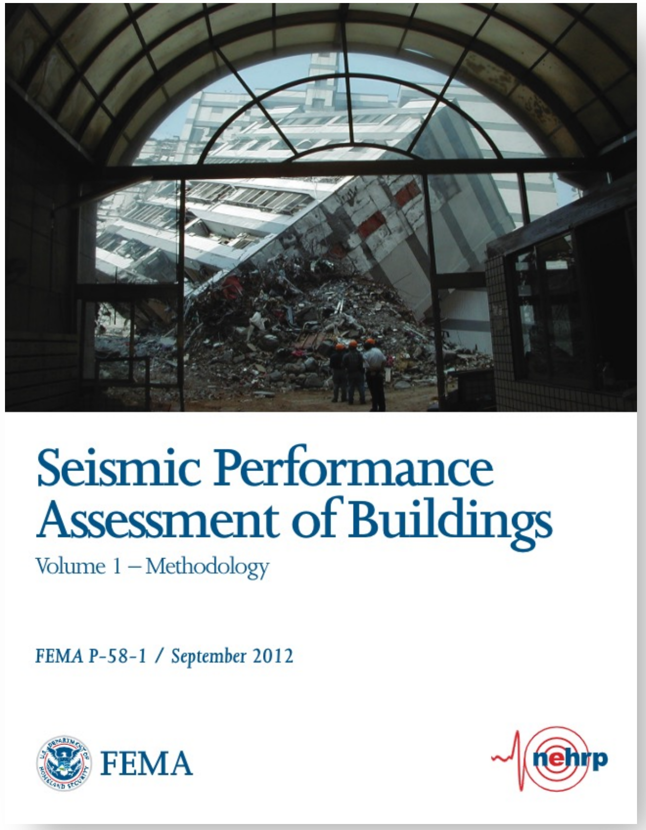
[1] *Professor of Structural Engineering, University of California, San Diego, U.S.A. (Fellow)*

BULLETIN OF THE NEW ZEALAND NATIONAL SOCIETY FOR EARTHQUAKE ENGINEERING, Vol. 26, No. 3, September 1993

Expected annual loss

- Expected (or average) annual loss (EAL) has become an established parameter in seismic loss assessment
- Initially rather conceptual requiring massive amounts of data, the work that went into developing FEMA P-58 and PACT made it accessible on a larger scale

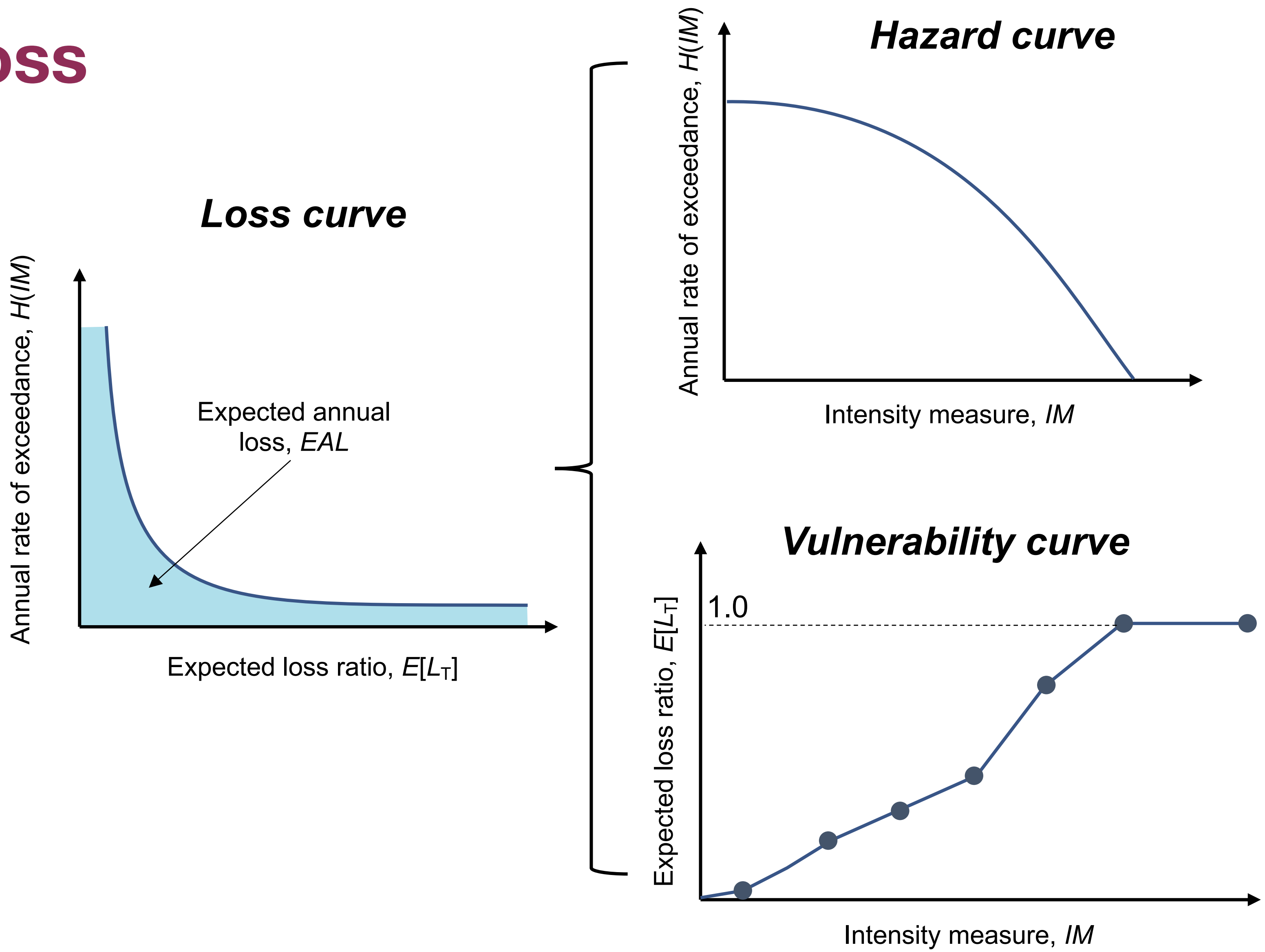




$$EAL = \int_{IM} E[L_T|IM] \left| \frac{dH(IM)}{dIM} \right| dIM$$

Expected annual loss

- The computation of EAL is conceptually simple: it integrates the vulnerability and hazard curves
- The computation of seismic hazard is (relatively) standardised, with many countries or regions possessing standardised hazard models (e.g., ESHM20)
- The computation of losses is less standardised
- FEMA P-58 and other work have formalised the procedure, but many components are still subject to large variations



Expected annual loss: only mildly subjective!

- EAL is attractive because of its meaning to stakeholders and insurance industries
- One of the earliest difficulties encountered was the robustness of this metric
- For example, an early study on the Van Nuys Hotel building by Krawinkler (2005) and Porter et al. (2004) gave vastly differing estimates of EAL for the same building (**2.2% vs 0.77%)**
- There were various reasons for this particular case, but scrutinising the loss estimation method reveals many potential sources of discrepancy

Porter, K. A., Beck, J. L., & Shaikhutdinov, R. (2004). Simplified Estimation of Economic Seismic Risk for Buildings. Earthquake Spectra, 20(4), 1239–1263. https://doi.org/10.1193/1.1809129
Krawinkler, H. (2005). Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment. PEER Report 2005/11.

Expected annual loss: many ingredients

- Consider the computation of total losses:

$$EAL = \int_{IM} E[L_T|IM] \left|\frac{dH(IM)}{dIM}\right| dIM$$

Total loss — Repair Cost for Estimated Damage — Probability of no collapse — Replacement Cost — Probability of collapse

$$E[L_T|IM] = E[L_T|NC, IM]P[NC|IM] + E[L_T|C]P[C|IM]$$

Non-collapse — Collapse

$$E[L_T|NC, IM] = \sum_{n=1}^{N_C} E[L_n|NC, IM]$$

Estimating damage state, repair costs, assumed damageable inventory

$$E[L_n|NC, IM] = \frac{1}{N_{gm}N_{sim}} \sum_{i}^{N_{gm}} \sum_{k}^{N_{sim}} L_{n,i,k}$$

$$L_{n,i,k} = N_n \sum_{j=1}^{N_{DS}} L_{n,k}[DS_j]P[DS_j|EDP_i]$$

So what?

- Computation of EAL using component-based methods depends on:
  - Replacement costs – this depends on who you ask…
  - Quantifying damage and repair costs – we are good at hazard and structural analysis!
  - Components to consider - What are our goals for recovery?
  - Impacts of residual drifts – Little data and studies
  - Quantifying the repairable damage threshold – Depends on many factors

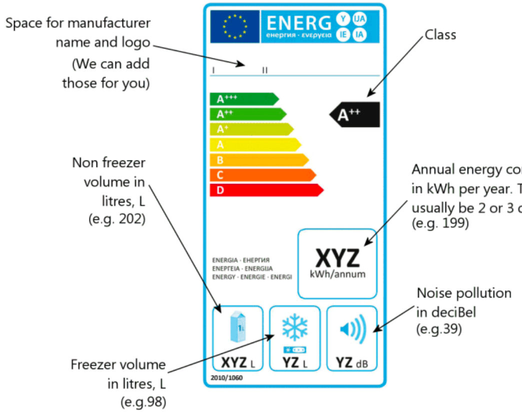
- Component-based EAL is subjective, as observed for the Van Nuys Hotel building

- Who cares? As long as we all follow the same approach and simplify some of the steps, it should be fine, right?

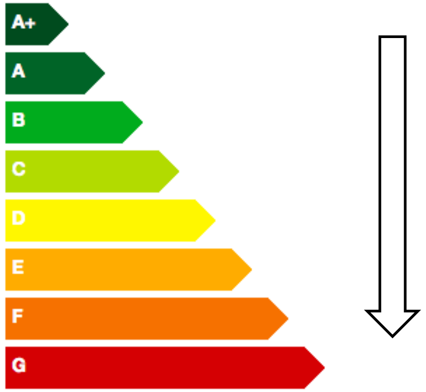
- In theory, yes, but in practice no….

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 EAL to classify the seismic risk of buildings
- Italian government offering tax rebates to incentivise owners to upgrade their buildings by a certain number of classes
- Following the COVID-19 pandemic, it was combined with other bonuses like energy efficiency improvement to help restart the economy
- They became collectively known as the *Superbonus* and gave tax rebates of up to 110%



Similar to energy rating system used in Europe

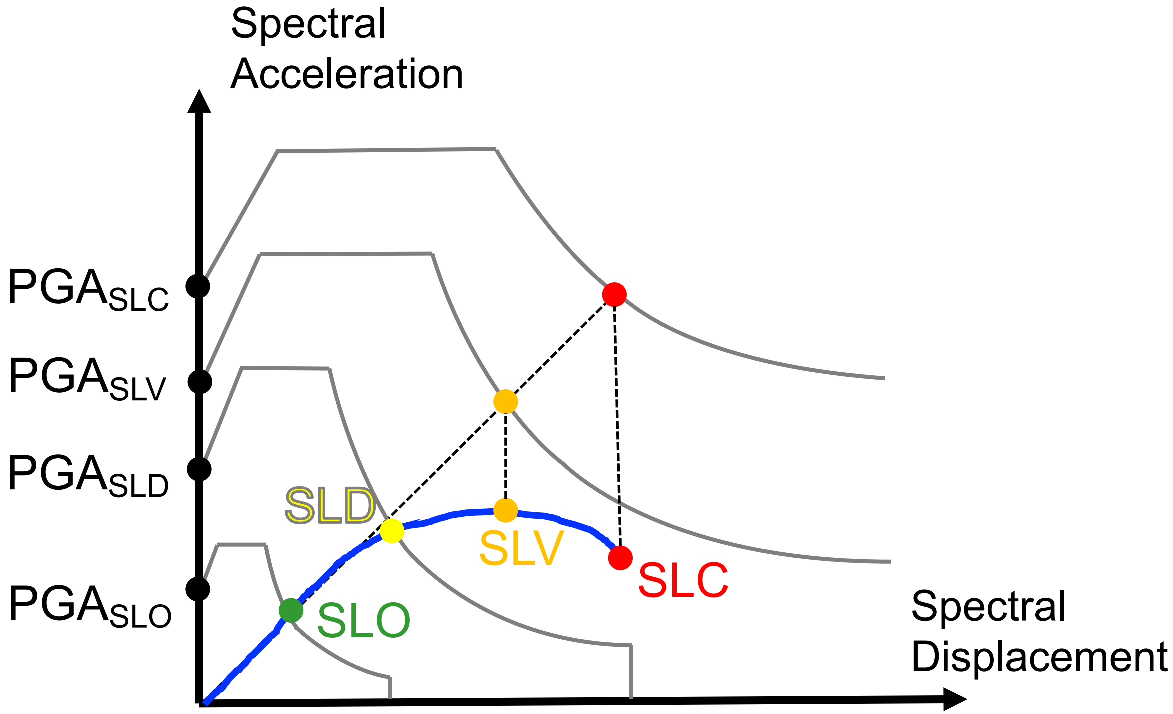


Increased seismic risk

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

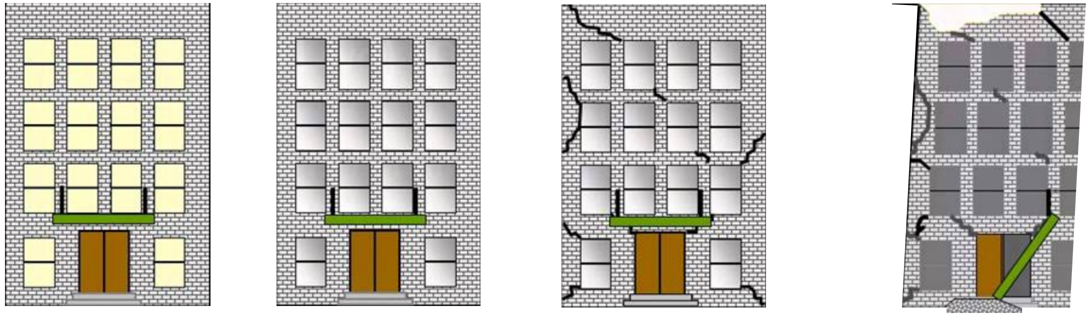


$$\zeta = \frac{PGA_{C,SLV}}{PGA_{D,SLV}}$$

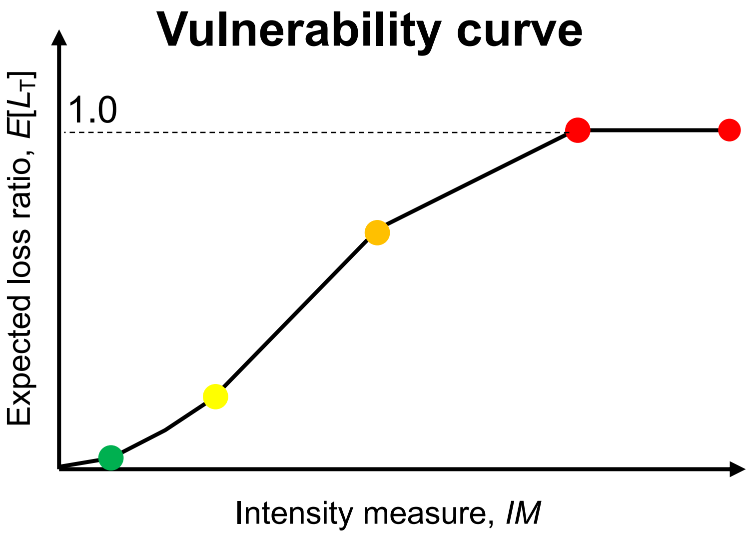
$PGA_{D,SLV}$ = PGA used for design
A new design should have ζ ≥ 1.0)

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
- Given what was seen in California for the Van Nuys hotel, this seems like a good thing

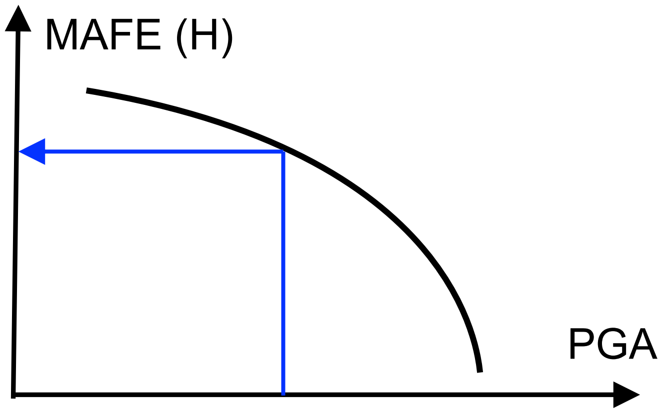


Limit state (LS):	Operational (SLO)	Damage limitation (SLD)	Life Safety (SLV)	Collapse Prevention (SLC)
Expected loss ratio:	7%	15%	80%	100%

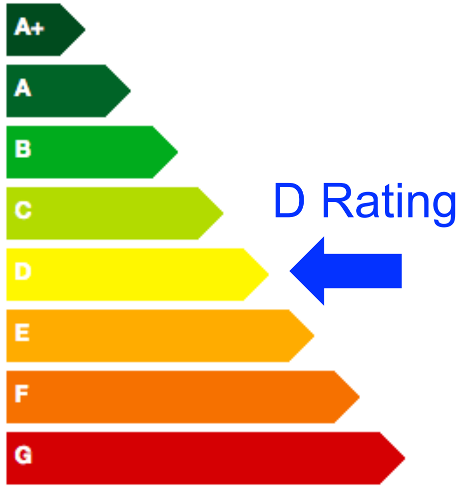


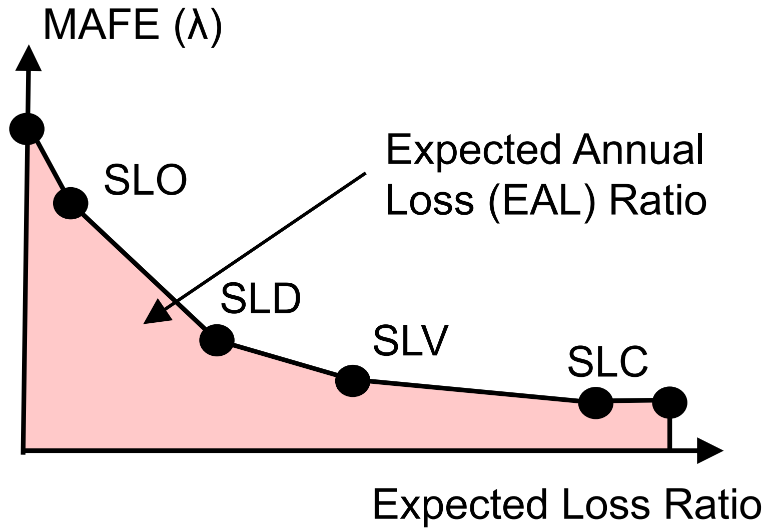
Italian Seismic Risk Classification Guidelines (Sismabonus)

- 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



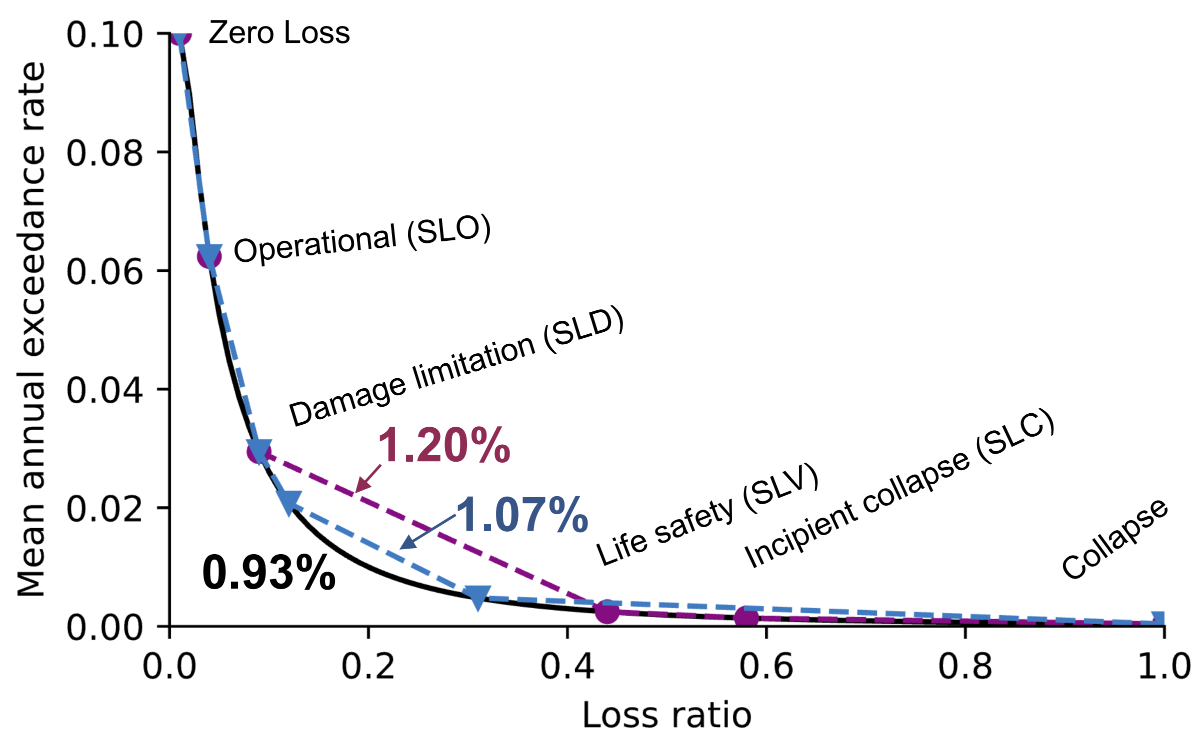
EAL Range	Life Safety Index (ζ)	
EAL ≤ 0.5%	100% < ζ	A+
0.5% < EAL ≤ 1.0%	80% ≤ ζ < 100%	A
1.0% < EAL ≤ 1.5%	60% ≤ ζ < 80%	B
1.5% < EAL ≤ 2.5%	45% ≤ ζ < 60%	C
2.5% < EAL ≤ 3.5%	30% ≤ ζ < 45%	D
3.5% < EAL ≤ 4.5%	15% ≤ ζ < 30%	E
4.5% < EAL ≤ 7.0%	ζ < 15%	F
EAL ≥ 7.0%		G





Senstivity of EAL to loss curve points

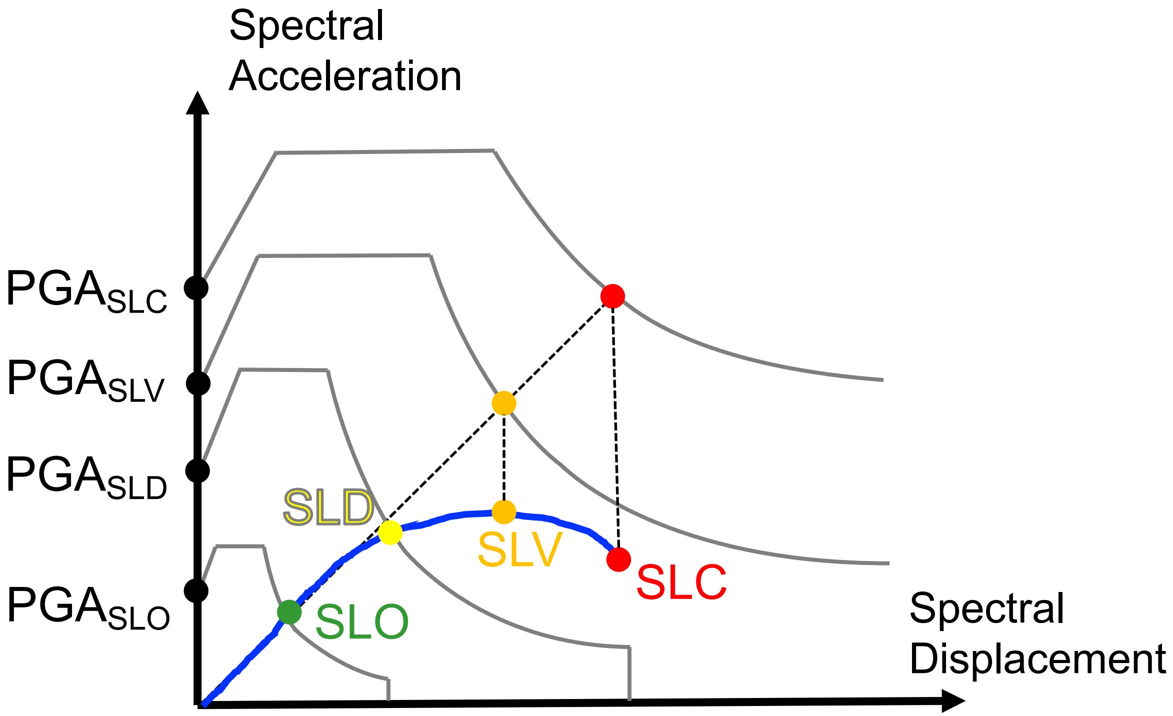
- One of the main results of using this limit state approach is the loss **curve** is a series of **lines**
- Integrating via the traprezoidal rule in logspace to compute EAL can give very different answers for nominally the same loss curve
- Consider the example curve shown, which is the hypothetically 'true' loss curve and has an EAL of 0.93%
- Depending on where the limit states fall, the EAL can reach up to 1.20%
- **This is a discretisation error of ~30%**
- This issue of discretisation isn't new, Section 9.4.3 of Baker, Bradley & Stafford (2021) has shown this



Baker, J., Bradley, B., & Stafford, P. (2021). *Seismic Hazard and Risk Analysis*. Cambridge University Press. https://doi.org/10.1017/9781108425056

Again, so what?

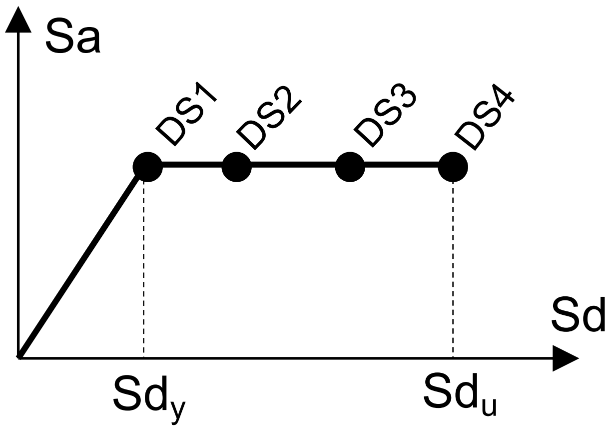
- Even without the discretisation errors, there are other issues
- This is not to question the goal or purpose of *Sismabonus*, but rather the robustness or appropriateness of its implementation
- *Sismabonus* is heavily integrated with the Italian National Building Code (NTC18)
- This means that the structural analysis remains largely the same for practitioners
- Some new add-ons open a door to enable the discussion of losses and risk



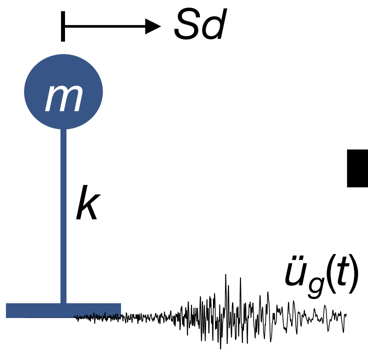
Connecting limit states and loss ratios

- Because of its integration with the building code, it leans heavily on the idea that each limit state can be assigned a loss ratio
- This makes conceptual sense and has been used with good success in the Global Earthquake Model's (GEM) global risk model to create risk maps and evaluate rupture scenarios, for example

Simple backbone



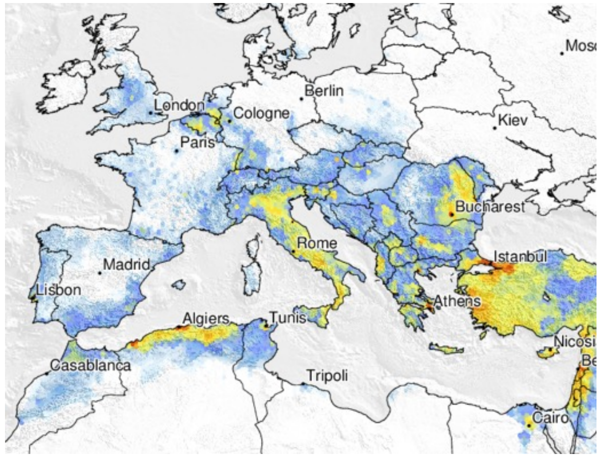
SDOF analysis



Damage-to-loss model

DS	Loss
DS1	
DS2	
DS3	
DS4	

Risk model



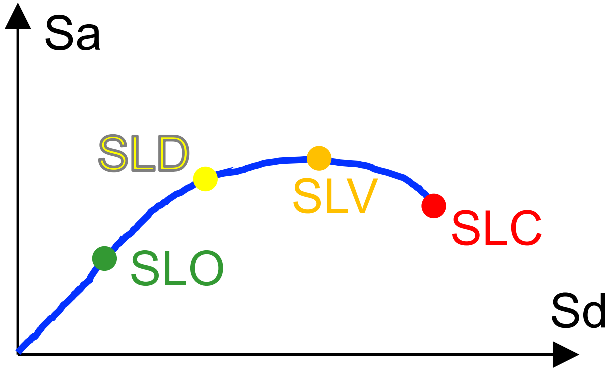
V. Silva, D. Amo-Oduro, A. Calderon, J. Dabbeek, V. Despotaki, L. Martins, A. Rao, M. Simionato, D. Viganò, C. Yepes-Estrada, A. Acevedo, H. Crowley, N. Horspool, K. Jaiswal, M. Journeay, M. Pittore (2018). Global Earthquake Model (GEM) Seismic Risk Map (version 2018.1), DOI: 10.13117/GEM-GLOBAL-SEISMIC-RISK-MAP- 2018.
Yepes-Estrada, C., Silva, V., Rossetto, T., D'Ayala, D., Ioannou, I., Meslem, A., & Crowley, H. (2016). The Global Earthquake Model Physical Vulnerability Database. Earthquake Spectra, 32(4), 2567–2585. https://doi.org/10.1193/011816EQS015DP

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

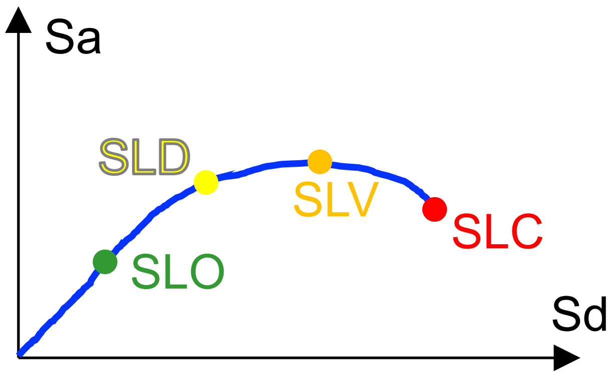


Cosenza, E., Prota, A., Di Ludovico, M., & Del Vecchio, C. (2017). Il metodo convenzionale per classificare il rischio sismico delle costruzioni. Costruire in Laterizio, 171, 70–77.

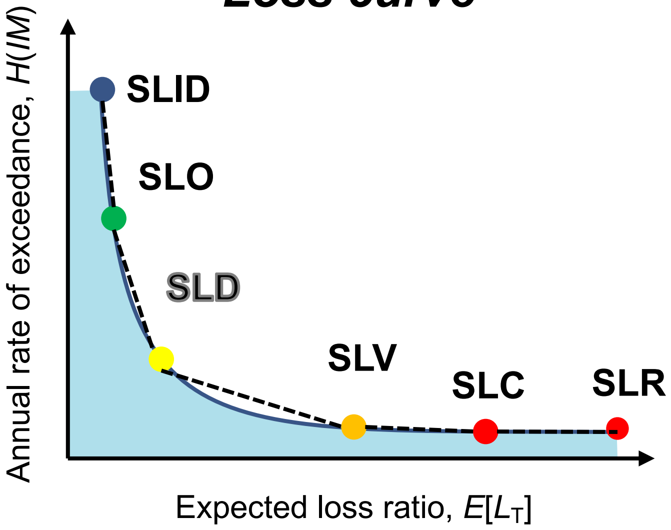
Identifying loss ratios

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		

Pushover curve



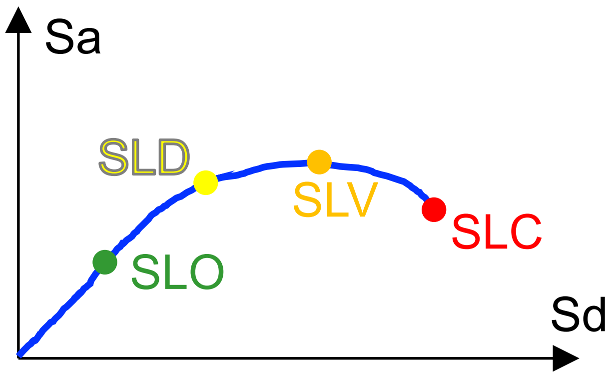
Loss curve

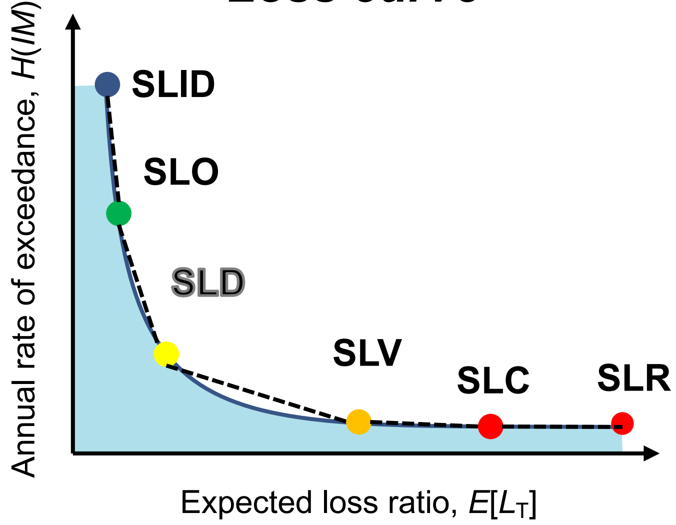


Cosenza, E., Del Vecchio, C., Di Ludovico, M., Dolce, M., Moroni, C., Prota, A., & Renzi, E. (2018). The Italian guidelines for seismic risk classification of constructions: technical principles and validation. Bulletin of Earthquake Engineering, 16(12), 5905–5935. https://doi.org/10.1007/s10518-018-0431-8
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 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

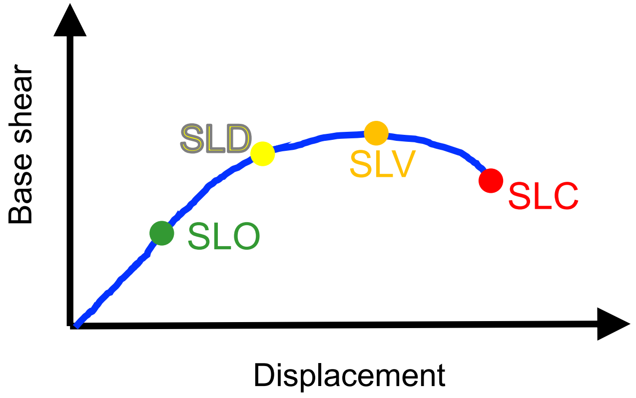


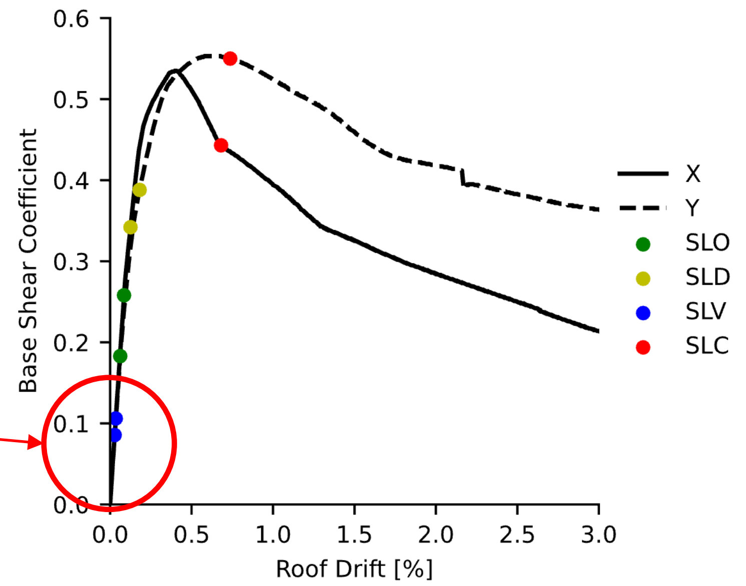


Cosenza, E., Del Vecchio, C., Di Ludovico, M., Dolce, M., Moroni, C., Prota, A., & Renzi, E. (2018). The Italian guidelines for seismic risk classification of constructions: technical principles and validation. Bulletin of Earthquake Engineering, 16(12), 5905–5935. https://doi.org/10.1007/s10518-018-0431-8
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 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

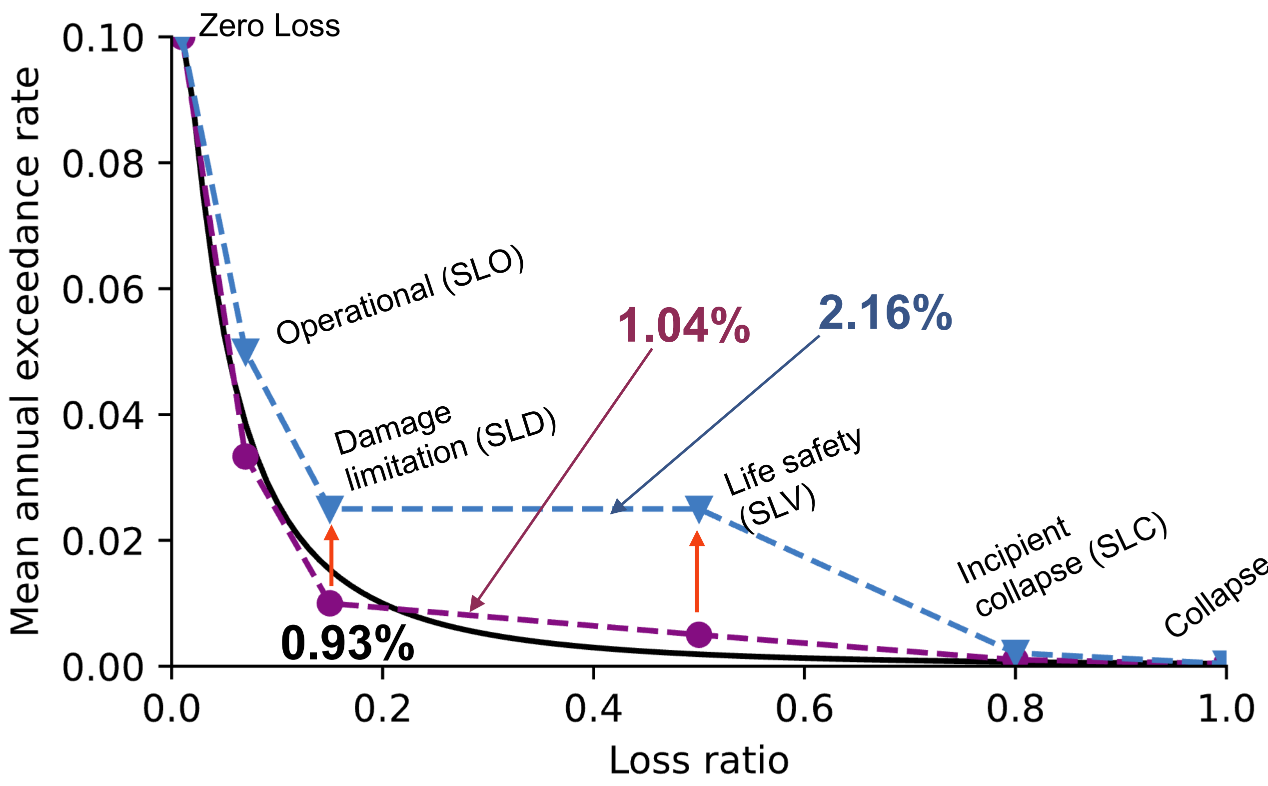
Identifying limit states in practice

- 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 50%

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

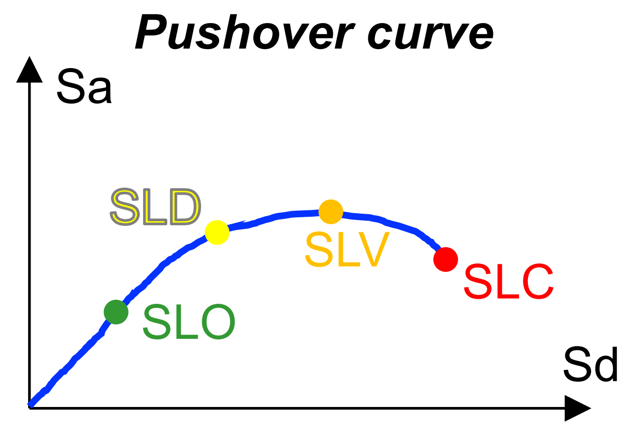
- Being overly sensitive to the declaration of SLV exceedance greatly impacts the loss curve
- Using the same example as before, declaring life safety because one single element has yielded, the EAL can be increased by <u>**132%**</u>
- This is not to discount the importance of life safety and the dangers of brittle elements
- But it is not what this EAL was intended for

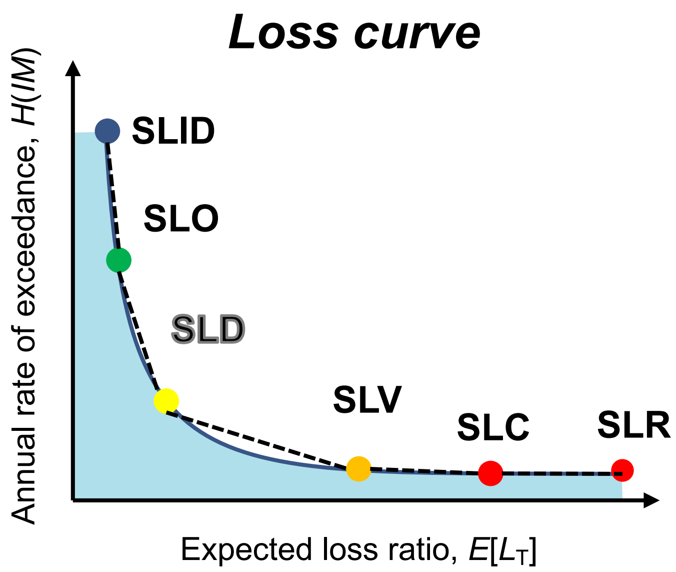


Impact on EAL evaluation

- Mixing concepts like loss ratios where they were never intended to be used is fudging things
- More ‘danger’ should imply more ‘loss’, which is true, but the EAL computed is essentially meaningless
- It is already a very sensitive parameter
- Better leave safety issues to indices like annual probability of collapse etc.
- Any better solutions to identify losses for this kind of guideline?
- Yes, but not today…

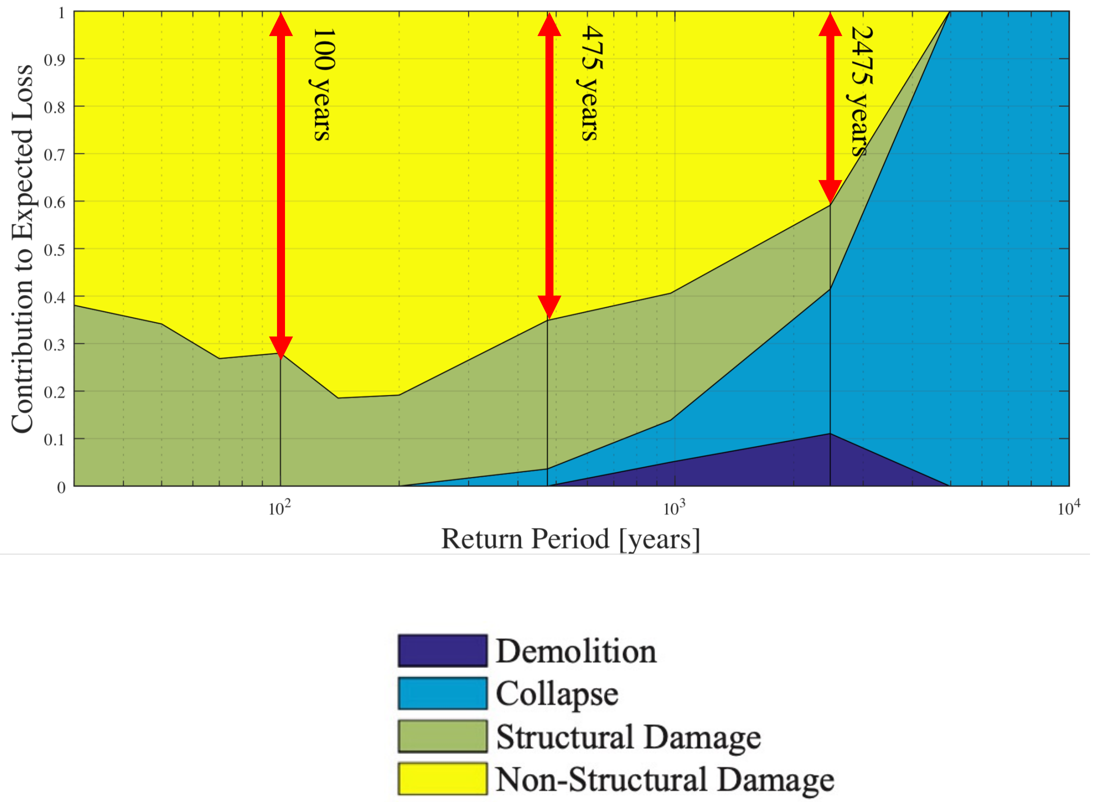
Limit state	Loss
SLID	0%
SLO	7%
SLD	15%
SLV	50%
SLC	80%
SLR	100%





Relative importance of component groups

- There is also the issue that when the EAL is identified, how does one go about actually reducing it?
- One would expect that you would improve the components that contribute the most to the losses
- It is widely accepted that non-structural elements (NSEs) are a major contributor
- There has been increased interest in NSE research
- Likely due to historically being overlooked and regular observations of damage during frequent events
- But do we really care that much about **all** NSEs?



Relative importance of NSEs

- Recent experiences in Japan confirm that much damage is indeed sustained by NSEs
- Interviews with building managers indicate that as long as this NSE damage was minor and does not impact building <u>functionality</u>, it was not of much concern
- Structural damage was a primary concern followed by functionality

- For instance, cracks in partition walls were considered damage right after the earthquake but became ‘a picture on the wall’ afterwards
- In many cases, minor damage to NSEs was just accepted as a consequence of the recent earthquake that would be either left as-is or just addressed during the next building renovation and redecoration cycle

Relative importance of NSEs

- The key deciding factor for many building managers was whether the functionality of the building was interrupted or not
- For example, if a pipe bursts causing flooding, this was an issue
- This is essentially field evidence of functional recovery that has gained much attention recently
- Guidelines such a REDi have developed such concepts
- Recent work Molina Hutt et al. (2022) have also made notable developments
- It centres around the idea that the building doesn't need to be repaired perfectly, some functional or other level will oftentimes do just fine

Recovery state	FEMA P-58	REDi	Molina Hutt et al. (2022)
Full recovery	●	●	●
Functional recovery		●	●
Reoccupancy		●	●
Shelter-in-place			●
Stability			●

Arup. (2013). The resilience-based earthquake design initiative (REDi^{TM}) rating system. URL: https://www.arup.com/perspectives/publications/research/section/redi-rating-system (Issue October). https://www.arup.com/perspectives/publications/research/section/redi-rating-system?query=redi
Molina Hutt, C., Vahanvaty, T., & Kourehpaz, P. (2022). An analytical framework to assess earthquake-induced downtime and model recovery of buildings. Earthquake Spectra, 38(2), 1283–1320. https://doi.org/10.1177/87552930211060856

Implications of recovery states

- It can be used to identify the relative importance of NSEs
- Taking a simple example of a building and performing a loss assessment
- The components considered were based on their ability to impede a recovery state
- Neglecting components that are not needed for functional recovery, the EAL reduces by 40%

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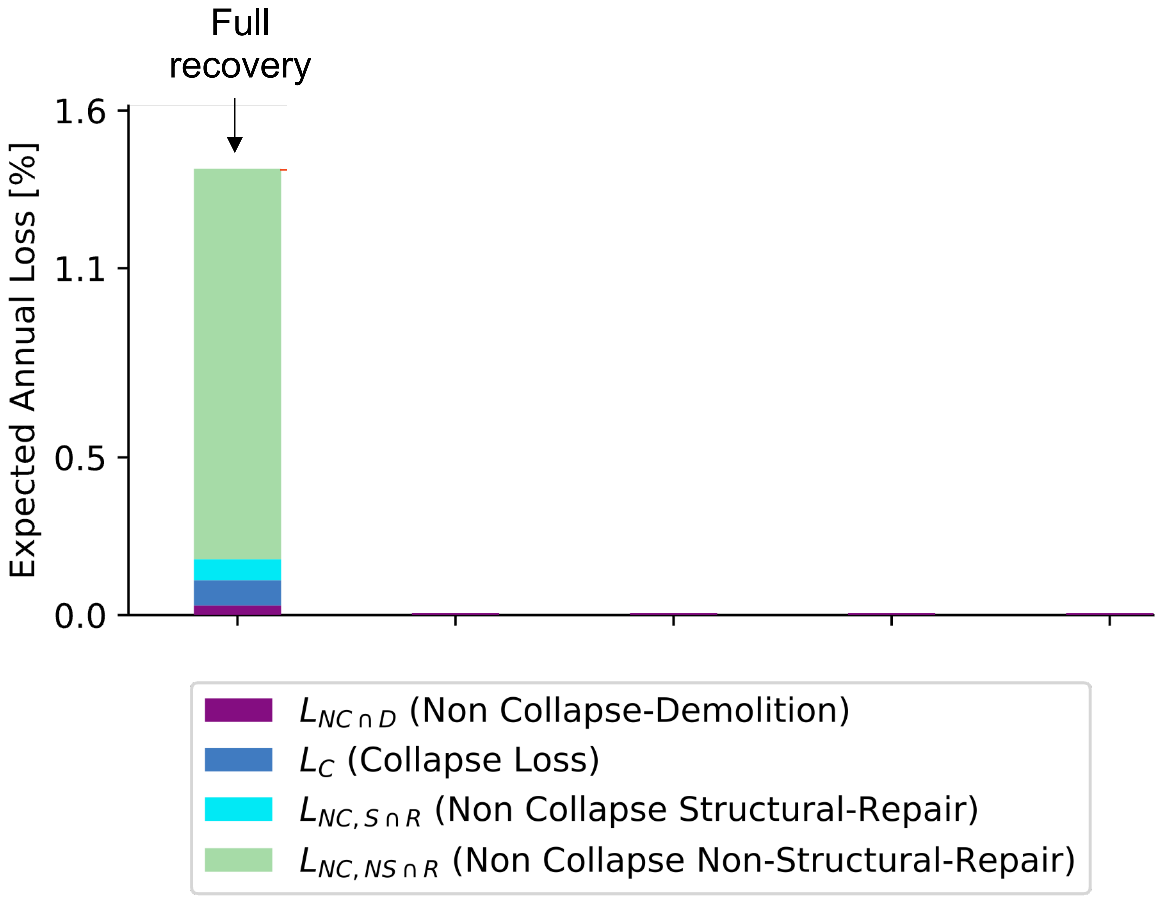
Stability			●



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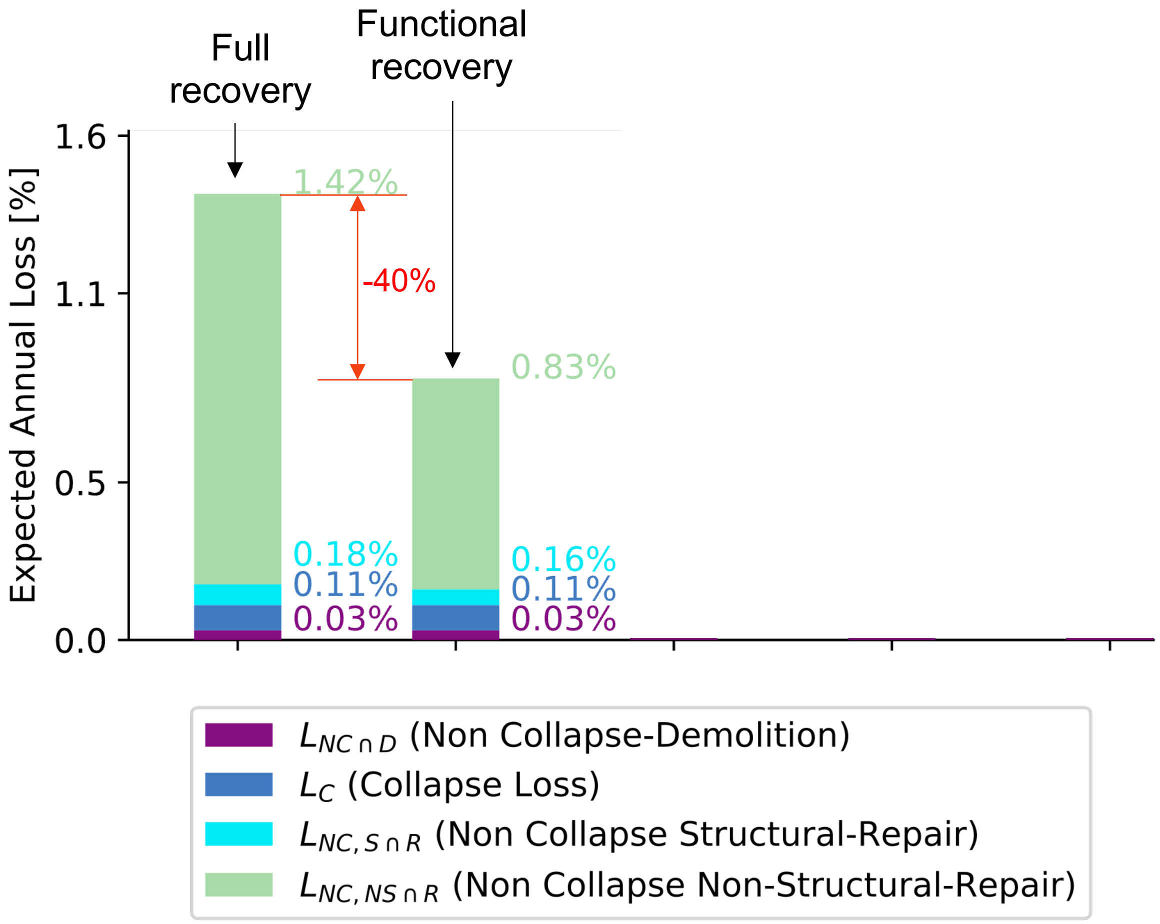

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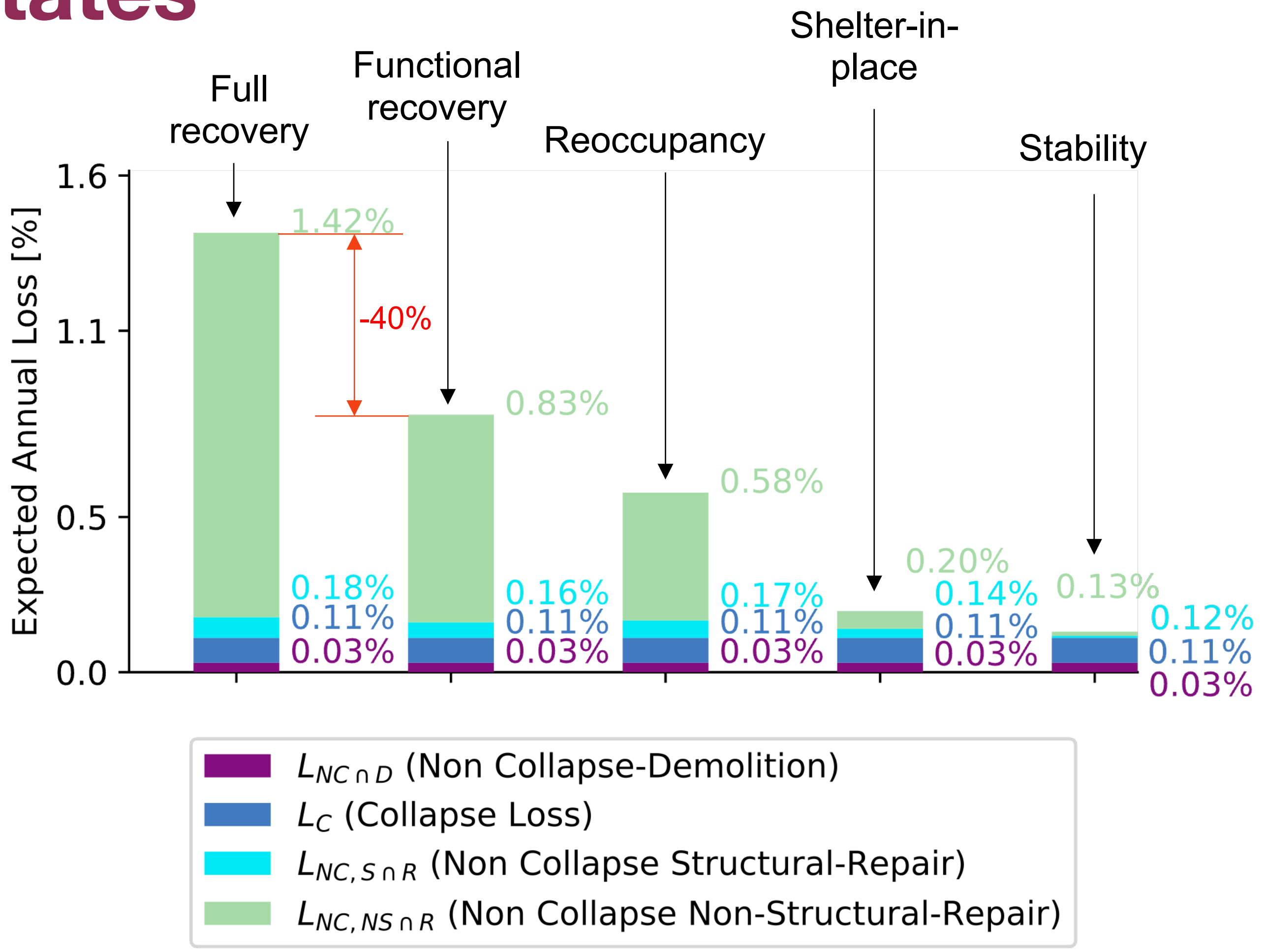
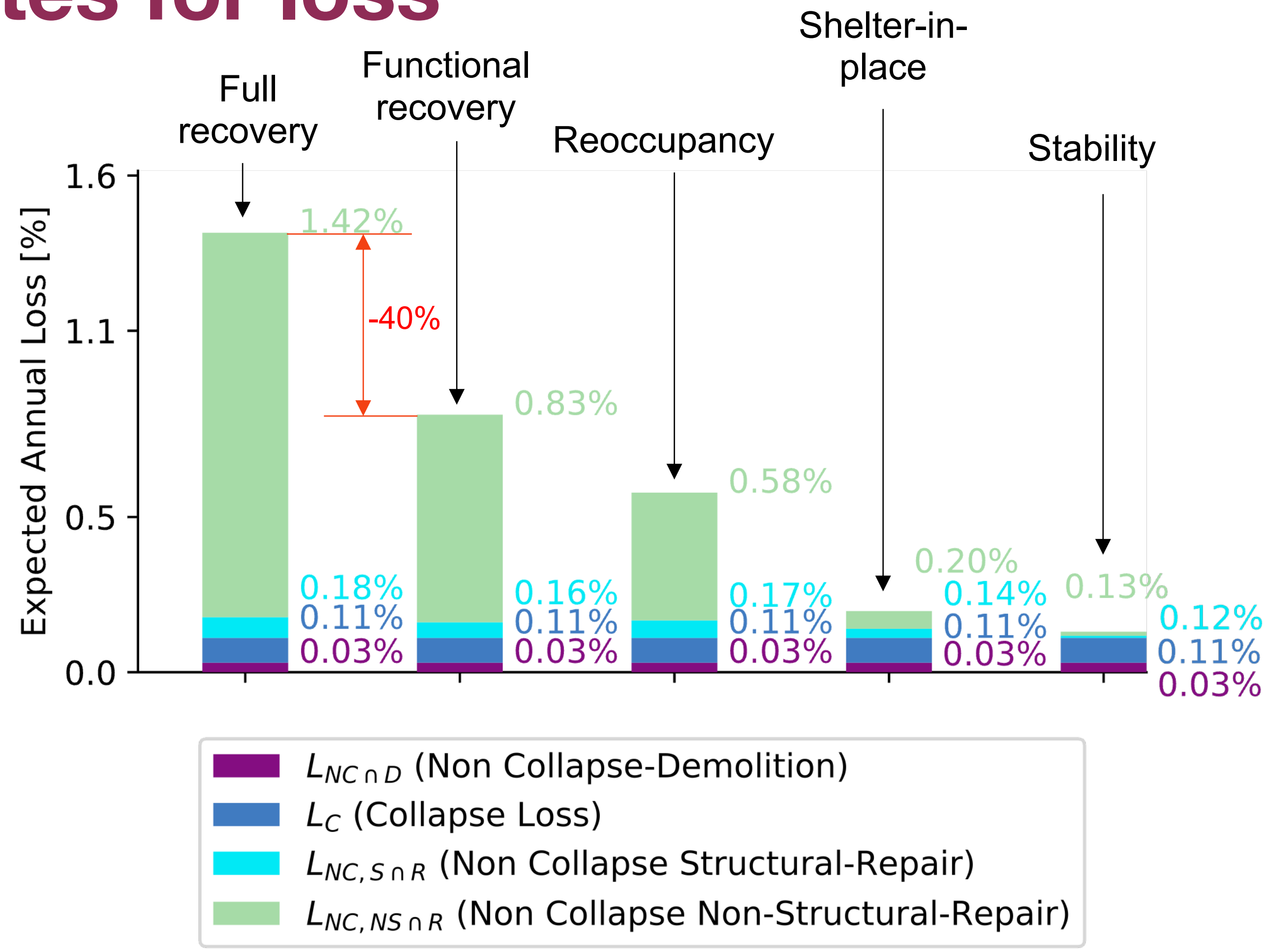


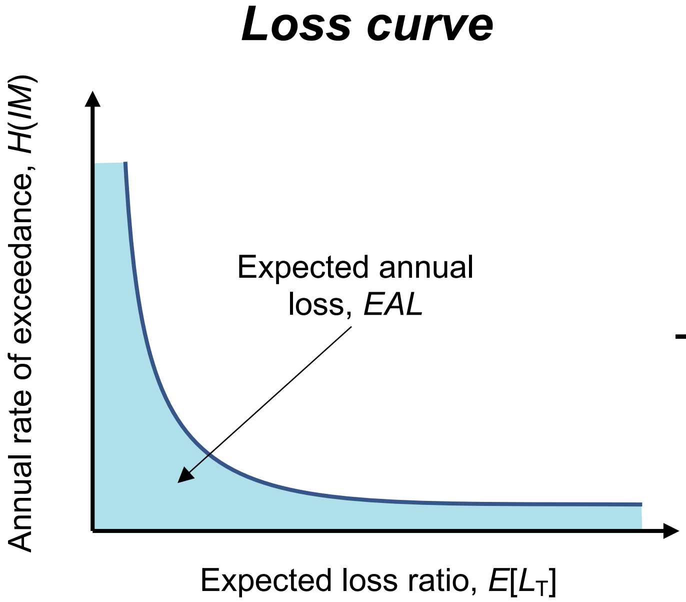
Utilisation of recovery states for loss

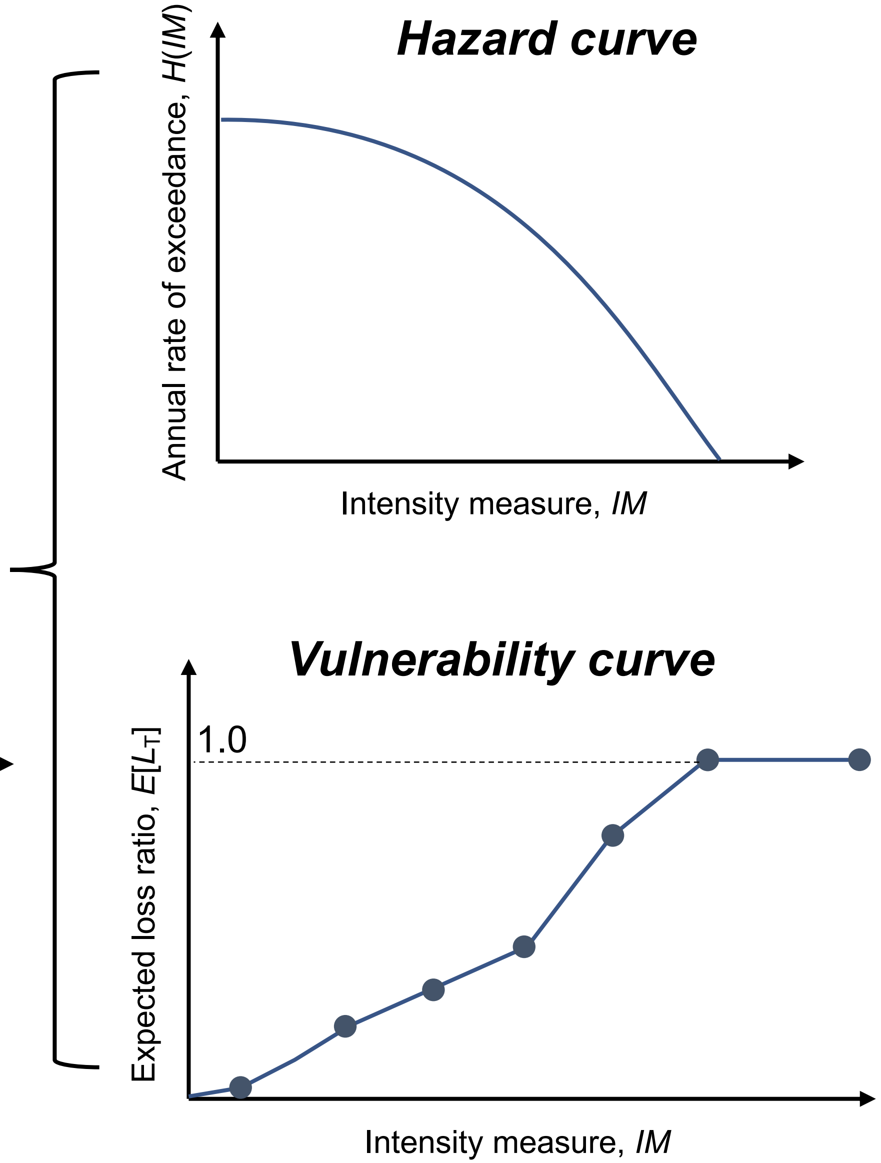
- This idea of recovery state could be used to set bounds on the damageable inventory to consider in component-based loss assessment
- This would help given the previous discussion on the subjectivity of EAL
- By opting for a more reasonble state of recovery (functional or reoccupancy) is that the eventual cost of repairs would not be impacted by post-event price and demand surge
- Many non-essential repairs could be carried out when society has returned back to a relatively normal state post-disaster



Computing EAL

- Coming back to the definition of EAL
- It is the integration of the building's vulnerability with the seismic hazard
- It is the annualised loss one would expect due to repairs of damage or replacement if <u>that building</u> was eternally exposed to that seismic hazard

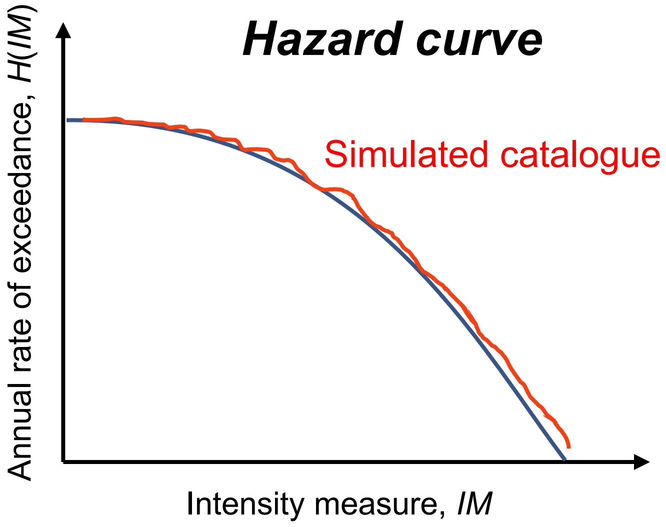


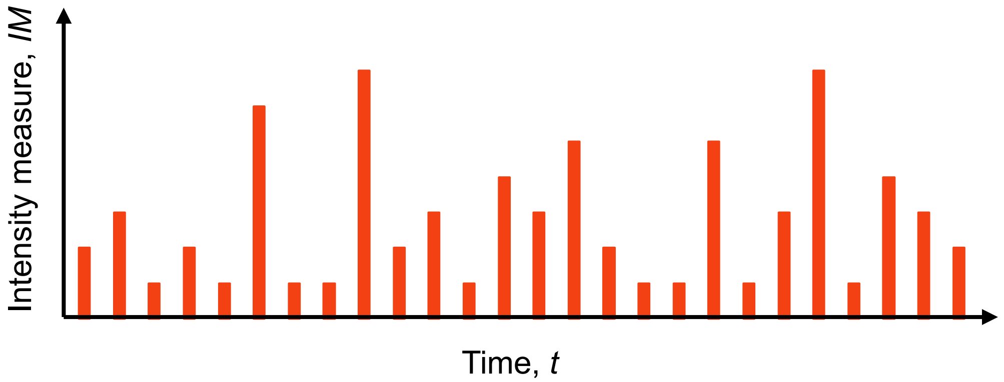


$$EAL = \int_{IM} E[L_T|IM] \left| \frac{dH(IM)}{dIM} \right| dIM$$

Computing EAL – an alternative angle

- Let's look at this another way
- Imagine a building is situated at a site where we have a catalogue of rupture events over a given time period
- This catalogue of rupture events' exceedance curve is the same as the hazard curve



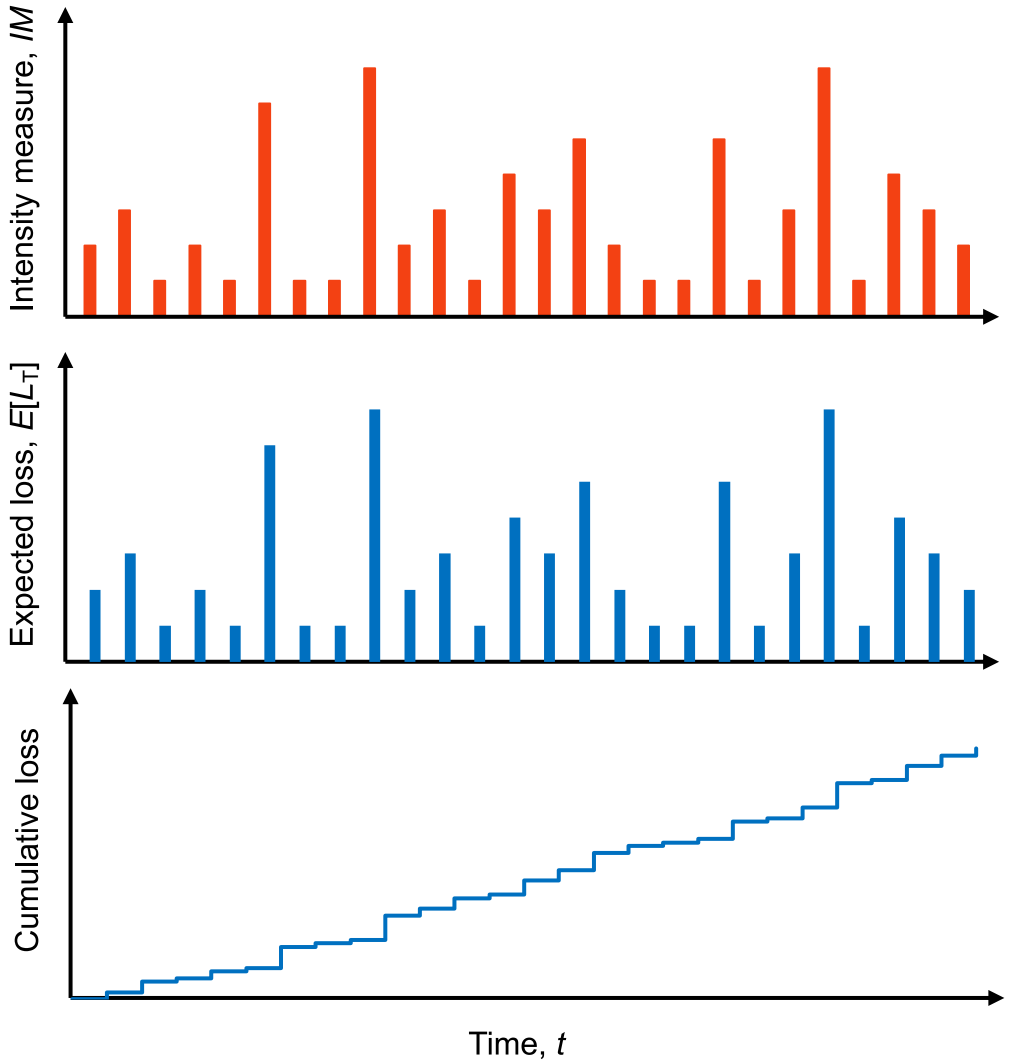


Computing EAL – an alternative angle

- For a building exposed to this catalogue of events, we could do a scenario-based loss assessment for each rupture event *rup* in the catalogue
- To get the EAL, we would essentially compute the average value over the duration of the catalogue of events, t_{cat}

$$EAL = \frac{1}{t_{cat} n_{rup}} \sum_{i=1}^{n_{rup}} L_T | rup_i$$

- This assumes that the building is repaired to the pre-event conditions each time
- It does not consider the possibility that the repaired structure has been <u>improved</u>

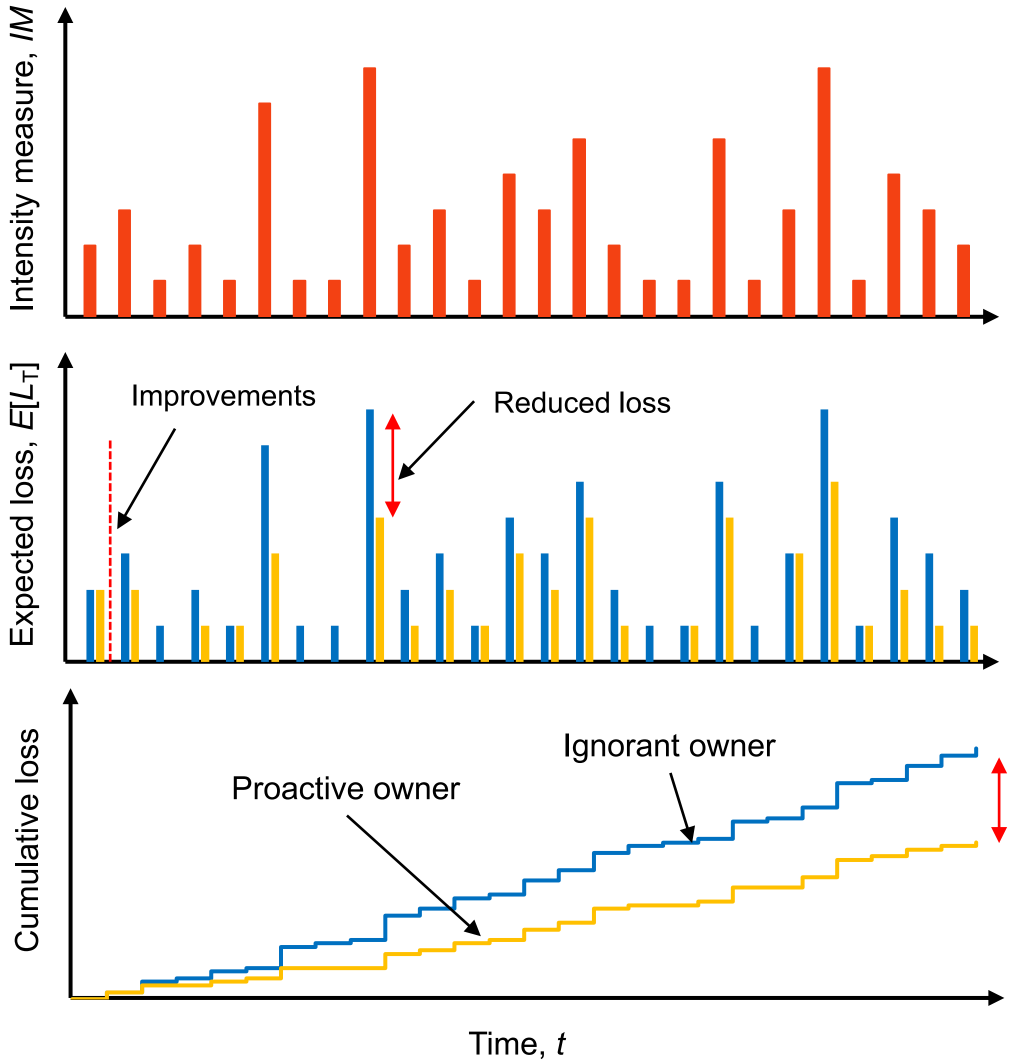


Computing EAL – an alternative angle

- If instead we have a more proactive building owner who implements retrofitting measures and improves the building during the repair
- The cumulative loss over time will be lower

$$EAL = \frac{1}{t_{cat} n_{rup}} \sum_{i=1}^{n_{rup}} L_T | rup_i$$

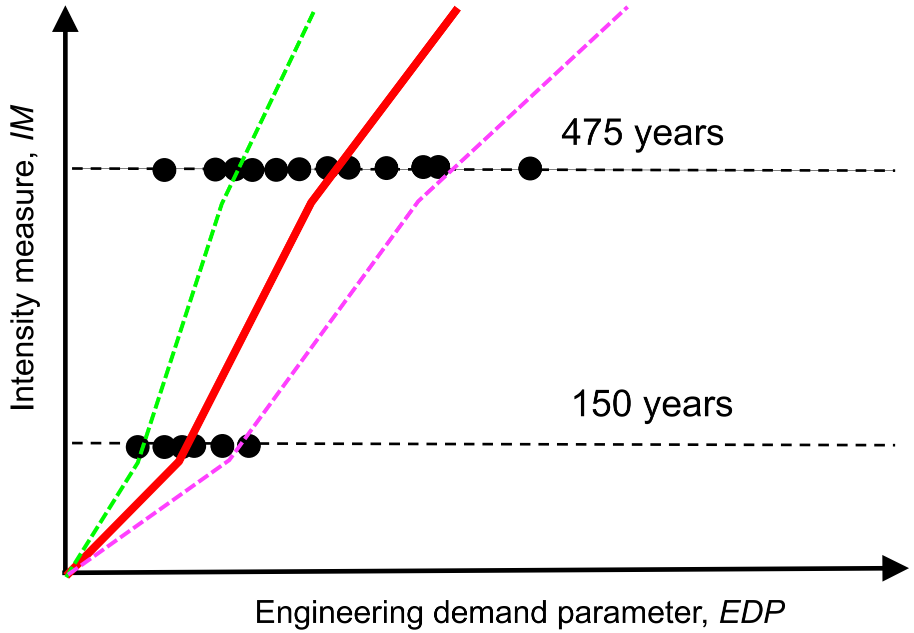
- This is a consequence of the stationarity assumption in the EAL's integration
- It is a more fair reflection of what would occur in reality



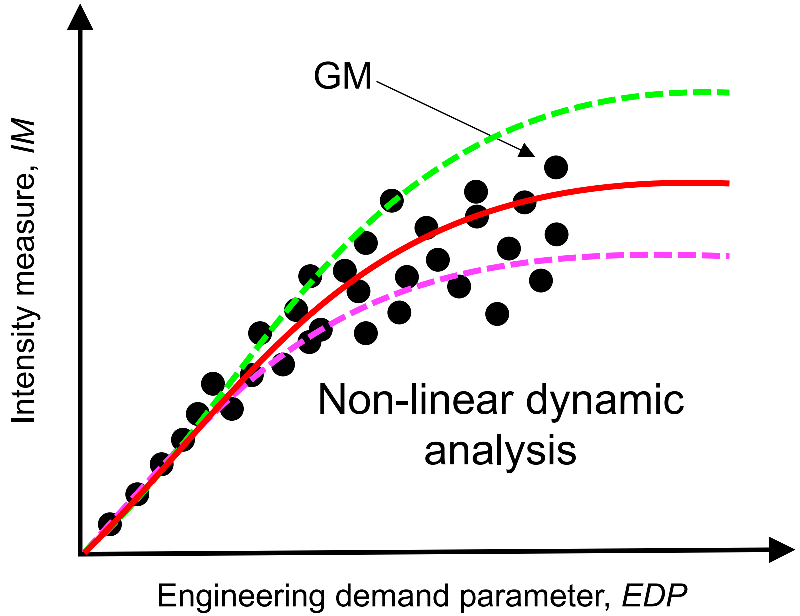
Implementation in practice

- There is a practical issue with the format of the results obtained from the structural response:
  - $E[L_T|IM]$ is computed at stripes using carefully selected ground motions (e.g., conditional spectrum)
  - $L_T|rup_i$ could be done using a cloud analysis with ground motions of IM in the catalogue

Multiple stripe analysis

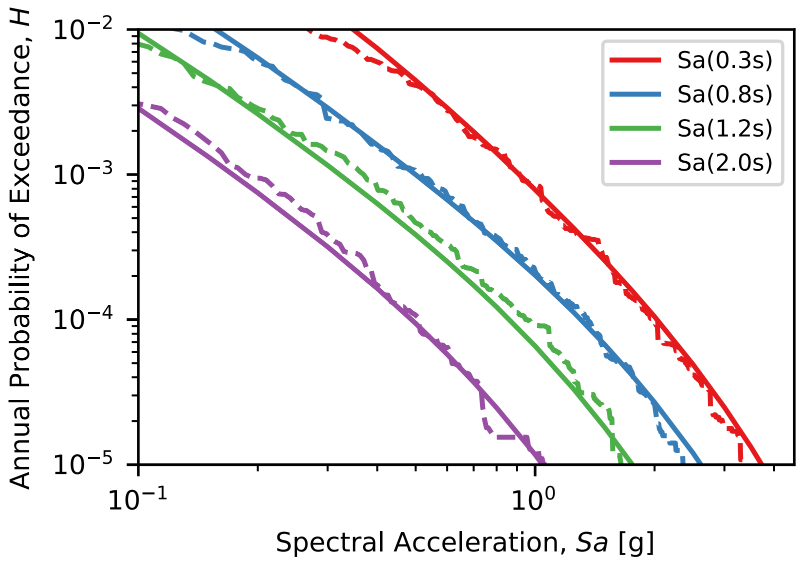


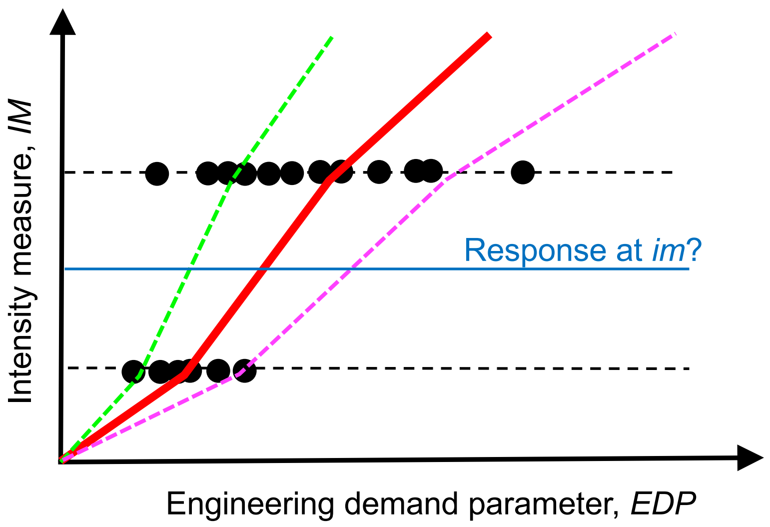
Cloud analysis



Implementation in practice

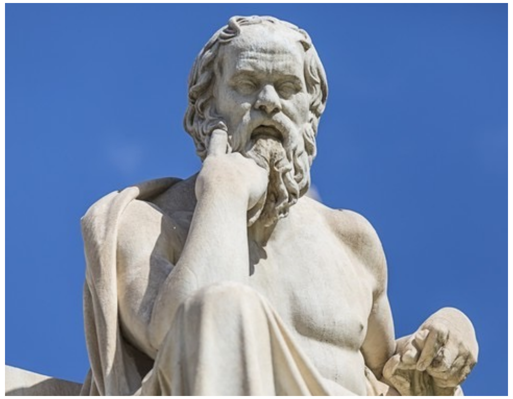
- The issue then becomes how to obtain those ground motions?
- One could simply do a traditional cloud analysis but would lose any guarantee of hazard consistency that conditional spectrum matching gives
- Another approach would be to interpolate between the results of MSA
- This would be a multi-dimensional interpolation because:
  - The illustration shows a simple demand-intensity model representing $IM\ vs.EDP$
  - We would require $IM\ vs.\boldsymbol{EDP} = \{EDP_1, EDP_2, \ldots, EDP_n\}$





Summary

- Talked about expected annual loss (EAL) within assessment and classification
- The point here was not to critice anything in particular, but point out some misconceptions that may not make a lot of sense
- The points raised were just illustrations, without much hard data to support them
- The idea is to point out the problems, hear some of your feedback and possible work to proposing some kind of solution



Questions?

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