Using targeted risk in seismic design codes:
A summary of the state of the art and outstanding issues

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Article in the conference proceedings

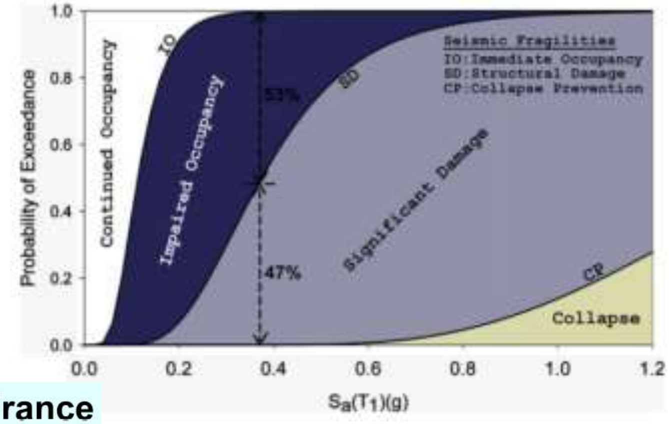
J. Douglas, T. Ulrich and C. Negulescu (2013), Risk-targeted seismic design maps for mainland France, *Natural Hazards,* **65**(3), 1999-2013, DOI: 10.1007/s11069-012-0460-6.

T. Ulrich, C. Negulescu and J. Douglas (2014a), Fragility curves for risk-targeted seismic hazard maps, *Bulletin of Earthquake Engineering*, **12**(4), 1479-1491, DOI: 10.1007/s10518-013-9572-y.

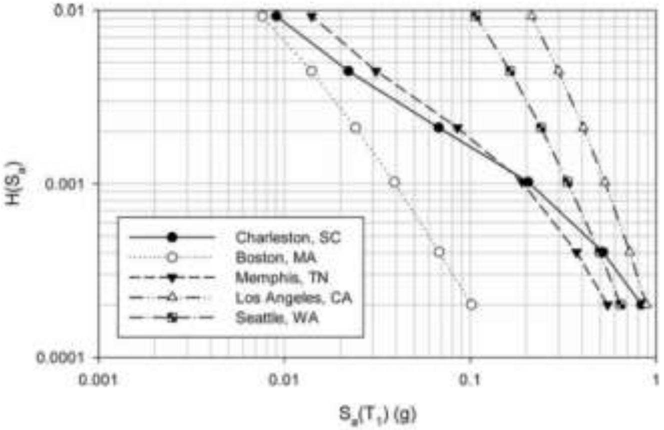
T. Ulrich, J. Douglas and C. Negulescu (2014b), Seismic risk maps for Eurocode-8 designed buildings, *2ECEES*, Istanbul, Turkey.

Calculation of risk

$$P(collapse) = \int P(collapse \mid a_g = x)\, P(a_g = x)\, dx$$

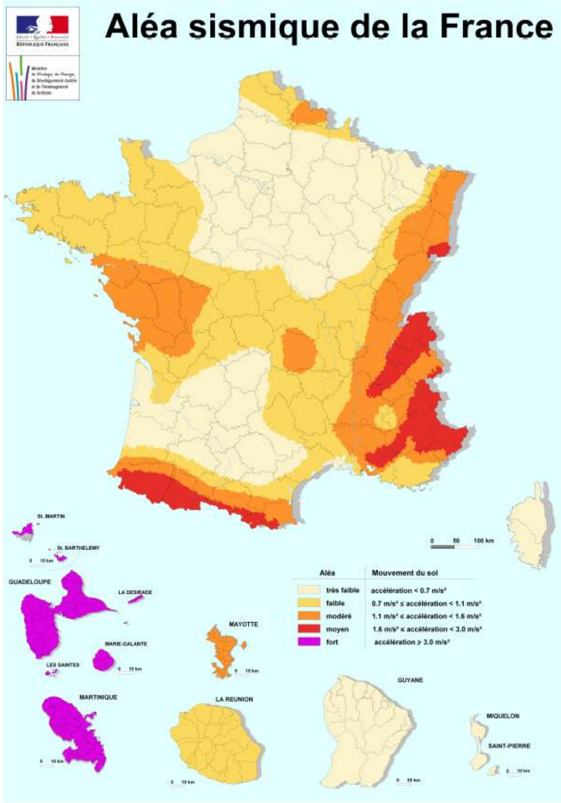


Fragility/vulnerability



Hazard

Seismic design map



Derived using PSHA for a return period of 475years that is uniform over country

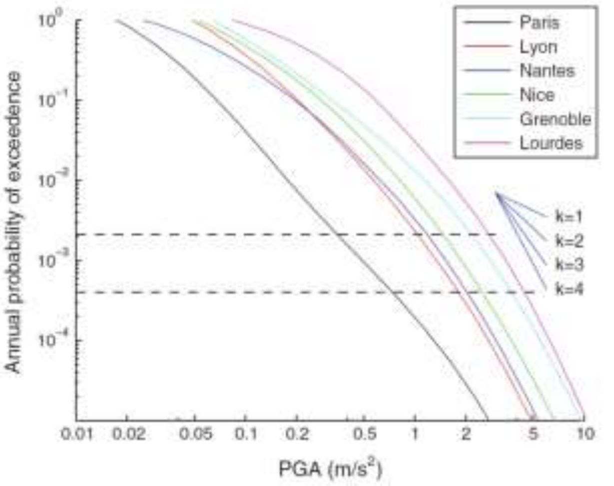
Use in conjunction with Eurocode 8 to design buildings

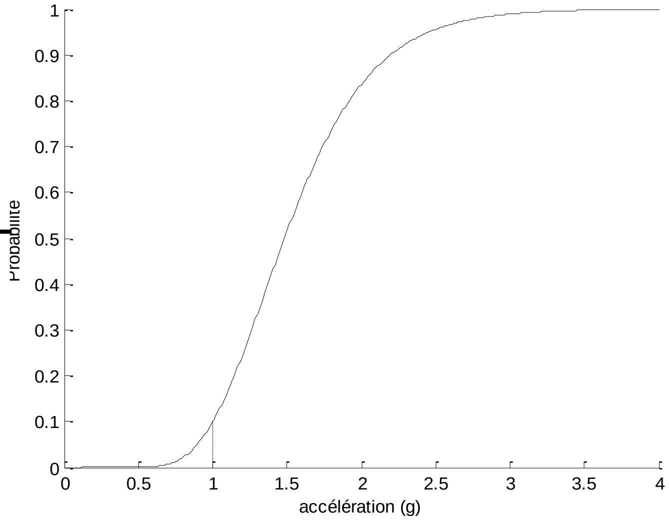
→ Seismic risk is not necessarily uniform over entire territory (e.g. Luco et al., 2007)

Risk-targeted seismic design maps

1. Choose the targeted acceptable risk (in the US, 0.02% of collapsed building every year) ← Y
2. Choose a fragility curve parameterization (in the US, log-normal curves, defined by: X → $p_{collapse}(a_g)$=10% and σ=0.6).
3. Choose a design acceleration a_g (ex: 1g)
4. Compute the fragility curve.
5. Calculate the risk by convolving the hazard curve and the fragility curve (ex. 0.04%)
6. Does the computed risk equal the targeted risk?

No

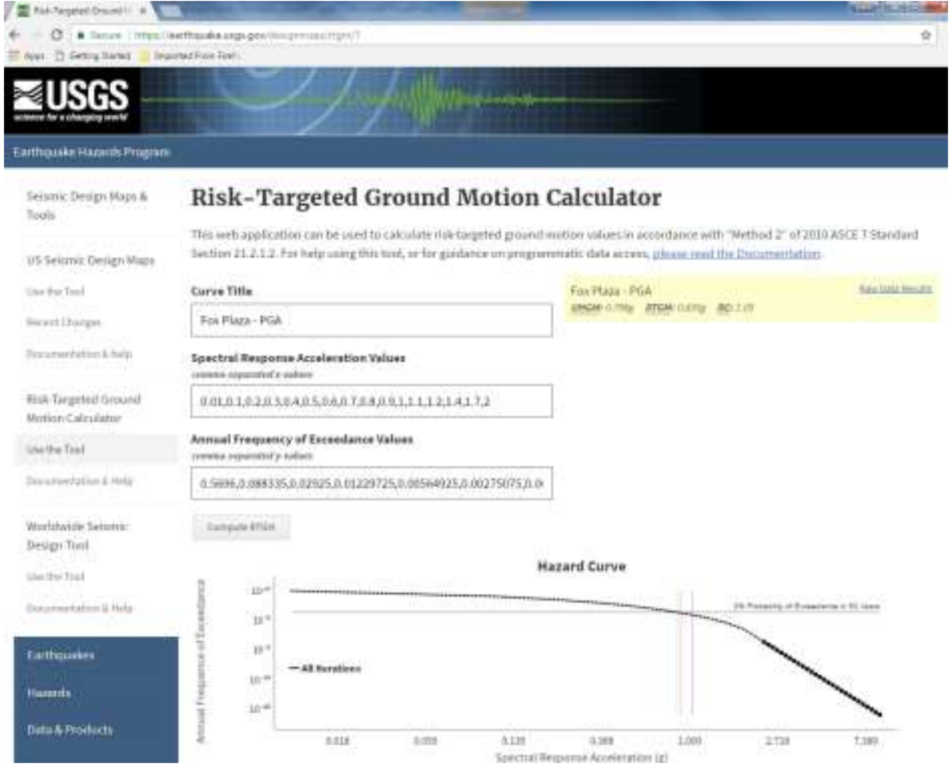




yes, a_g is the risk-targeted acceleration.

Previous studies and applications

- USA: Luco et al. (2007) and others (in code)



Risk-Targeted Ground Motion Calculator

This web application can be used to calculate risk-targeted ground motion values in accordance with "Method 2" of 2010 ASCE 7 Standard Section 21.2.1.2. For help using this tool, or for guidance on programmatic data access, please read the Documentation.

Curve Title: Fox Plaza - PGA

Spectral Response Acceleration Values: 0.01,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1,1.1,1.2,1.4,1.7,2

Annual Frequency of Exceedance Values: 0.5696,0.088335,0.02925,0.01229725,0.00564925,0.00275075,0.0

- Indonesia: SNI (2012)
- France: Douglas et al. (2013)
- Romania: Vacareanu et al. (submitted)
- Europe: Silva et al. (2016)

Acceptable risk (Y)

1. It falls below an arbitrarily-defined probability.
2. It falls below some level that is already tolerated.
3. It falls below an arbitrarily-defined fraction of the overall accident burden.
4. The cost of reducing the risk would exceed the costs saved.
5. The opportunity costs would be better spent on other public safety issues.
6. Health and Safety professionals say that it is acceptable.
7. The general public say that it is acceptable.
8. Politicians say that it is acceptable.

(Hunter and Fewtrell, 2001)

Of building collapse:

In USA practice (Luco et al., ASCE 7-10 and 2009 NEHRP, SNI 1726-2012): $2 \cdot 10^{-4}$

Fajfar & Dolsek (2011) and Goulet et al. (2007) (code-designed buildings): 10^{-4}

Appears high

Kennedy (2011) (nuclear practice): $3 \cdot 10^{-6}$

Labbé (2010) (historical observations): 10^{-6}

Duckett (2004) (accidental loading): 10^{-6}

Douglas et al. (2013) chose $Y=10^{-5}$

Empirical upper bound

$$Y \leq \frac{\text{Number of collapses per year}}{\text{Number of buildings in country}}$$

- For Italy:
  - 7 damaging earthquakes 1980-2009 (29 years)
  - 205 collapses of RC buildings
  - ~3 million buildings

$Y \leq 2 \cdot 10^{-6}$ to $1.3 \cdot 10^{-5}$

- For Greece:
  - 6 damaging earthquakes 1978-2003 (25 years)
  - 91 collapses of RC buildings
  - ~2.5 million buildings

$Y \leq 1.1 \cdot 10^{-6}$ to $1.9 \cdot 10^{-6}$

Note: Considerable uncertainties due to different references and assumptions of building populations

Also limited data for long geological recurrence intervals

Use yield rather than collapse

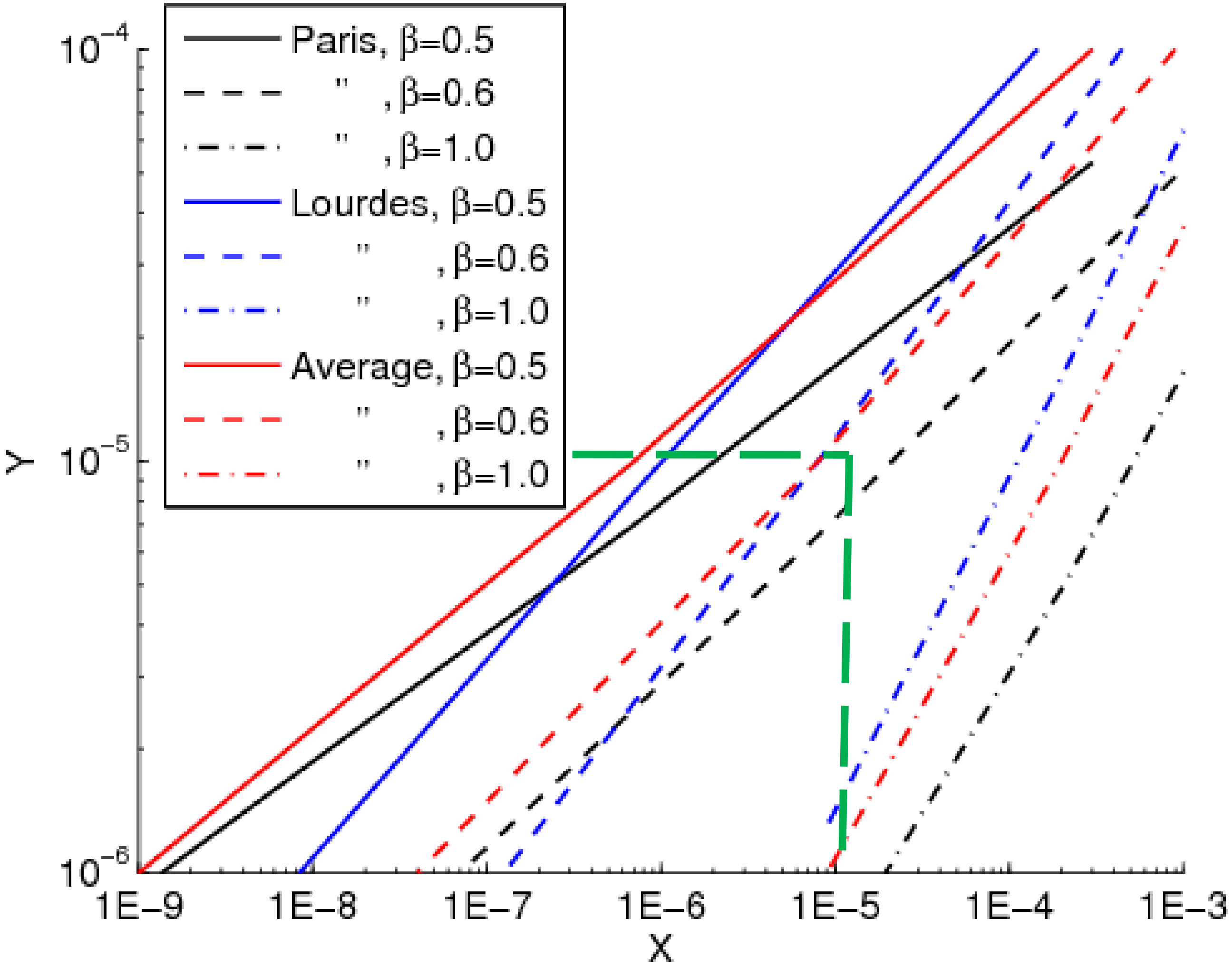
- Advantages over collapse:
  - Less controversial that yield is “acceptable”
  - Easier to determine yield numerically
  - Determine acceptability using cost-benefit?
- Empirical estimate:

$3 \cdot 10^{-5}$ for Italy (period of 29 years)

$1 \cdot 10^{-4}$ for Greece (only using 17-year period)

Relation between X et Y in order to find X

To obtain the same design accelerations

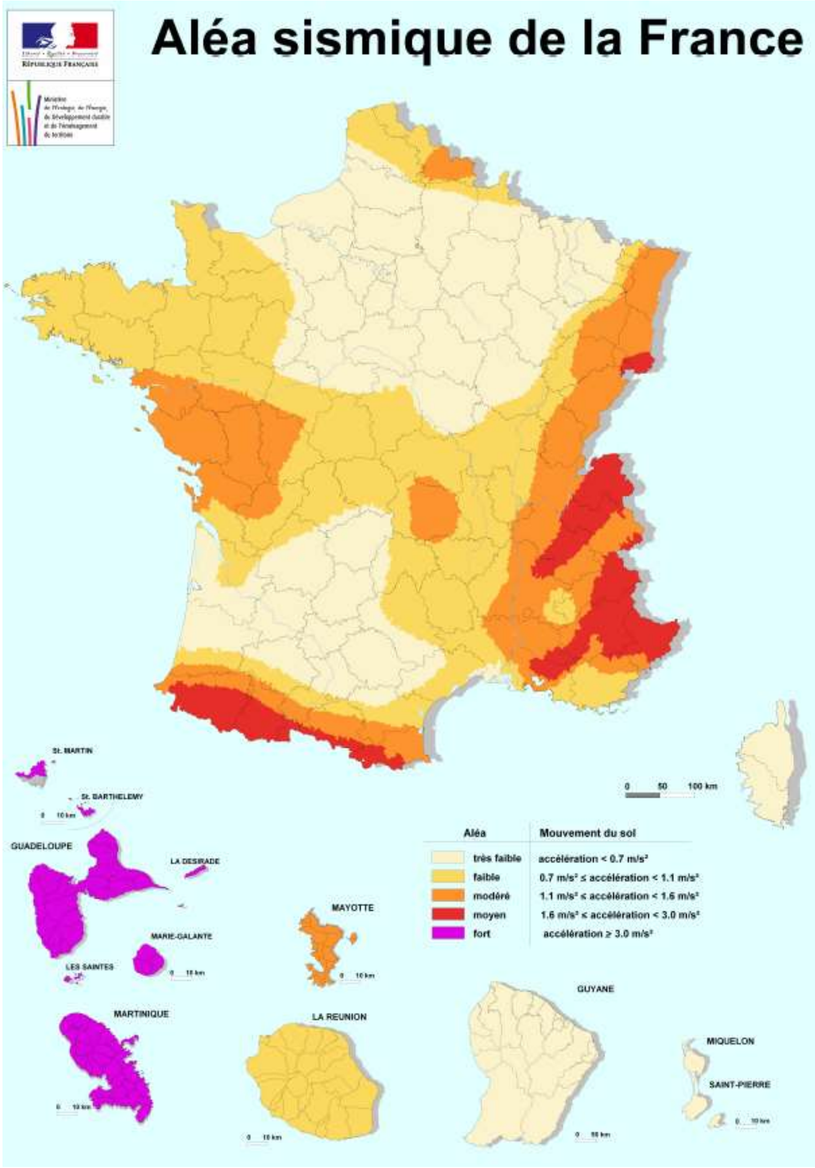


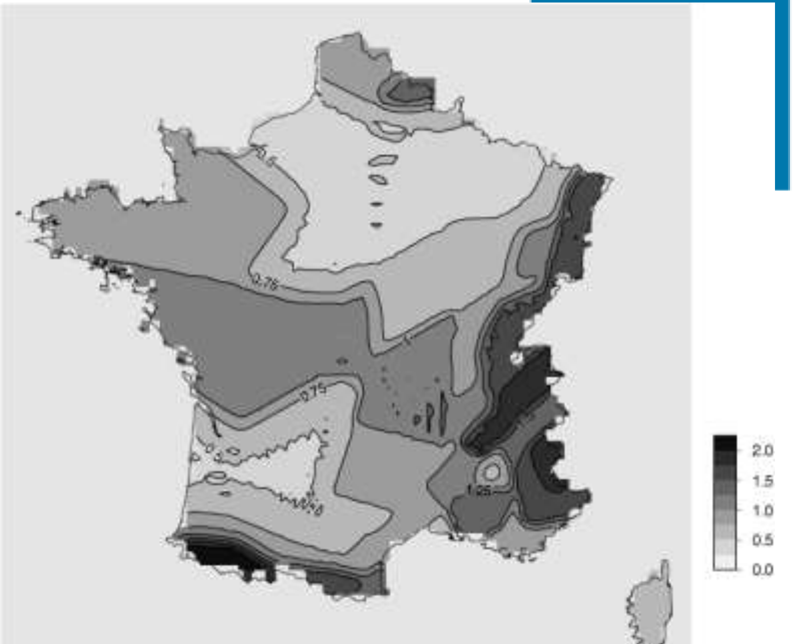
Trilemma: only 2 of X, Y and a_g can be chosen independently

Reason for high targeted risk in US practice?

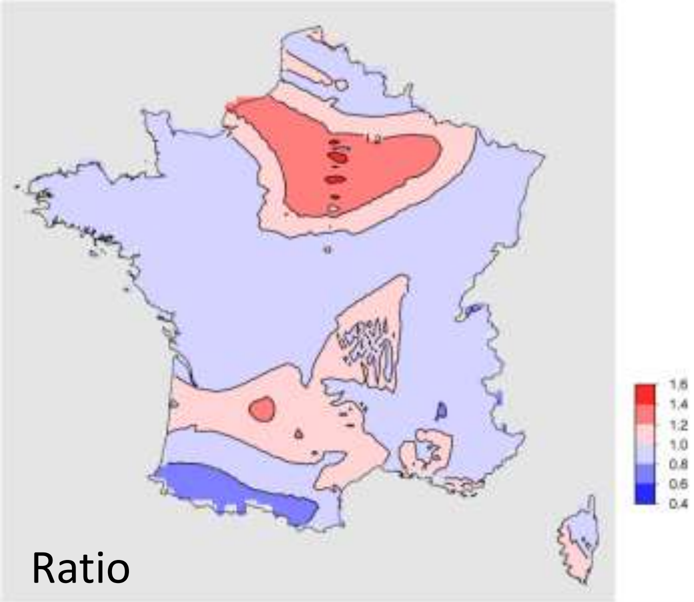
Douglas et al. (2013) chose $X=10^{-5}$

Results





Risk-targeted design map



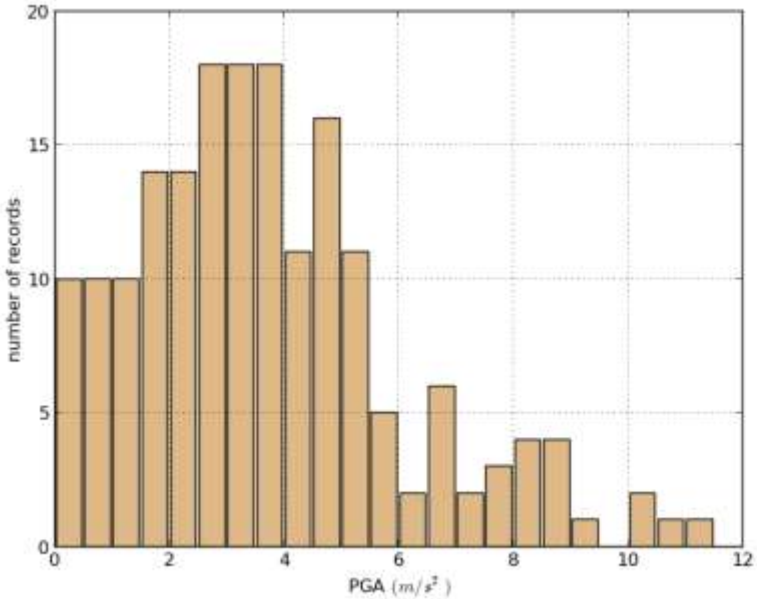
Ratio

Follow-up study (Ulrich et al., 2014a)

- Douglas et al (2013) used:
  - X [i.e. $p_{collapse}(a_g)$]=10^{-5}
  - σ= 0.5,0.6,1.0 tested, final choice 0.5.
- Noted considerable uncertainty in X (and Y)
- Aim of follow-up study:
  - Design a representative building for several design accelerations: a_g = 0, 0.7, 1.1, 1.7, 2.3, 3 m/s² with EC8.
  - Compute fragility curves
  - Ascertain if the hypotheses for $p_{collapse}(a_g)$ and σ made in the risk-targeted approach are valid
  - RC Building : 3 storeys – 3 bays – 3 frames

Modelling choices

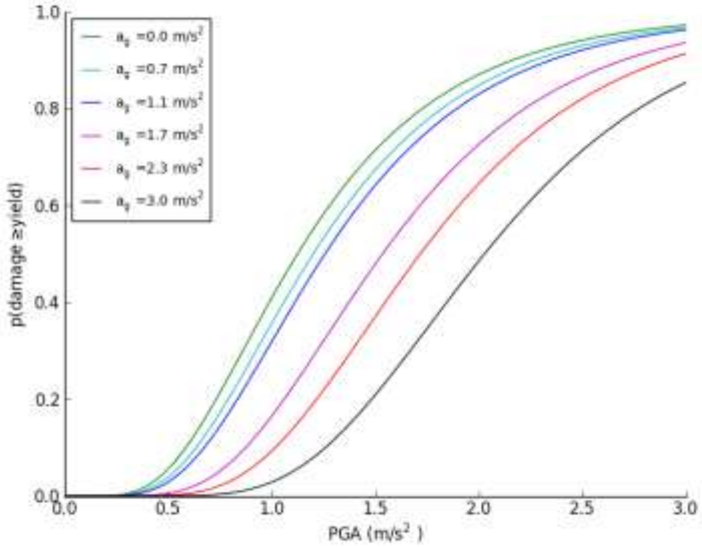
- Choice of the input records
  - Selected from the European Strong-Motion Database (Ambraseys et al. 2004)
  - Mw 4.5 – 6.5, R_{epi}<100 km, shallow crustal earthquakes
  - Dataset of 183 records



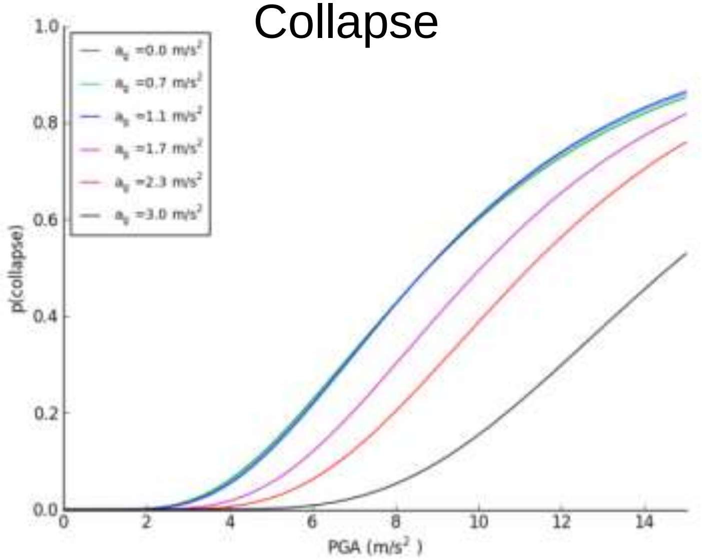
- Nonlinear dynamic analyses
  - Via the finite element software Opensees
  - Each structural element discretized by 4 *Force-Based Beam-Column Elements*
  - Corrotational transformation (P-Delta) considered

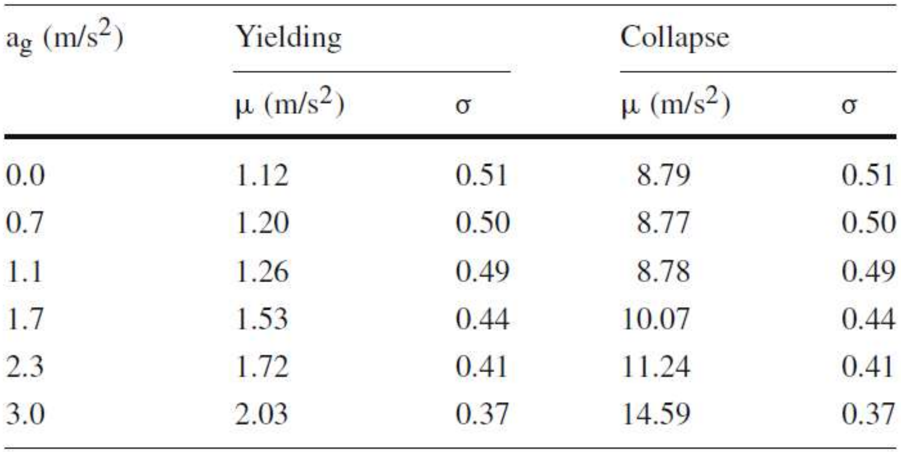
Fragility curves

Yield



Collapse



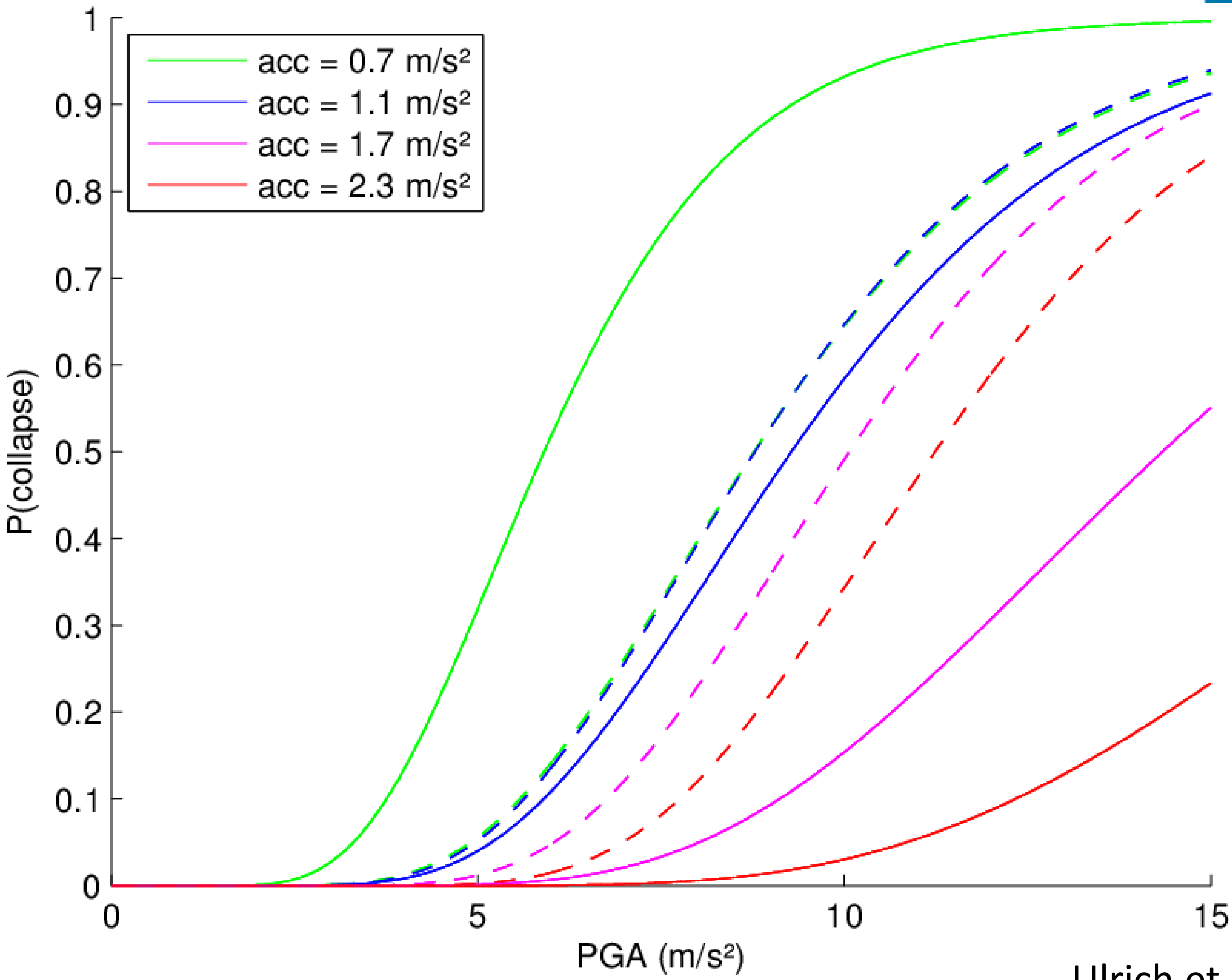


a_g (m/s^2)	Yielding		Collapse	
	μ (m/s^2)	σ	μ (m/s^2)	σ
0.0	1.12	0.51	8.79	0.51
0.7	1.20	0.50	8.77	0.50
1.1	1.26	0.49	8.78	0.49
1.7	1.53	0.44	10.07	0.44
2.3	1.72	0.41	11.24	0.41
3.0	2.03	0.37	14.59	0.37

a_g (m/s^2)	yield	collapse
0.7	0.139	1.73×10^{-7}
1.1	0.392	9.80×10^{-6}
1.7	0.592	2.58×10^{-5}
2.3	0.763	5.23×10^{-5}
3.0	0.854	1.04×10^{-5}

➡ Use as X in risk-targeting procedure

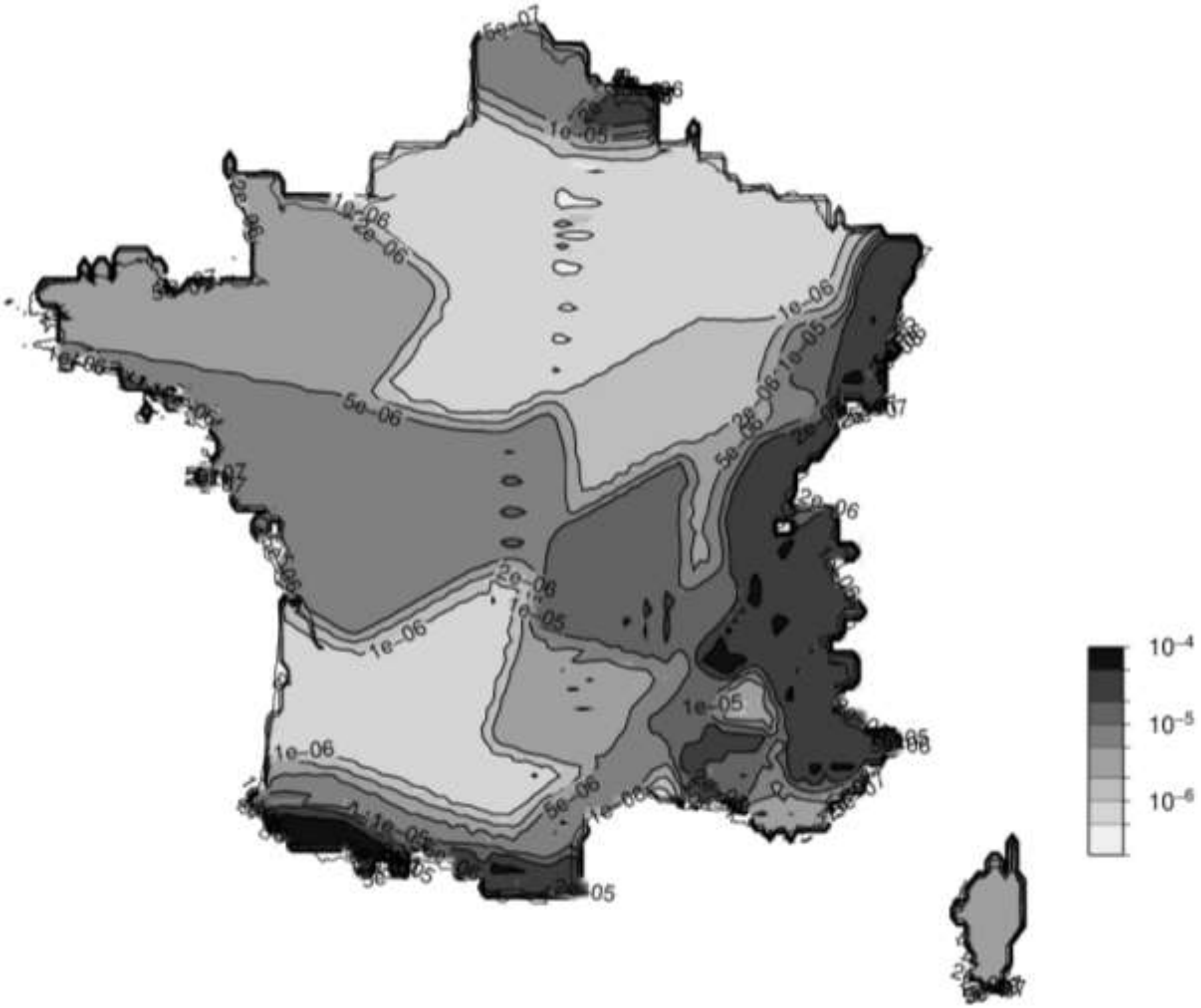
Comparison to curves assumed by Douglas et al.



Ulrich et al. (2014b)

Seismic design for PGA<1m/s^2 not required (for regular structures)

What is the current annual probability of collapse?



Average: 9×10^{-6}

Minimum: 3×10^{-7} (e.g. Paris)

Maximum: 8×10^{-5} (e.g. the Pyrenees).

Ulrich et al. (2014b)

Conclusions

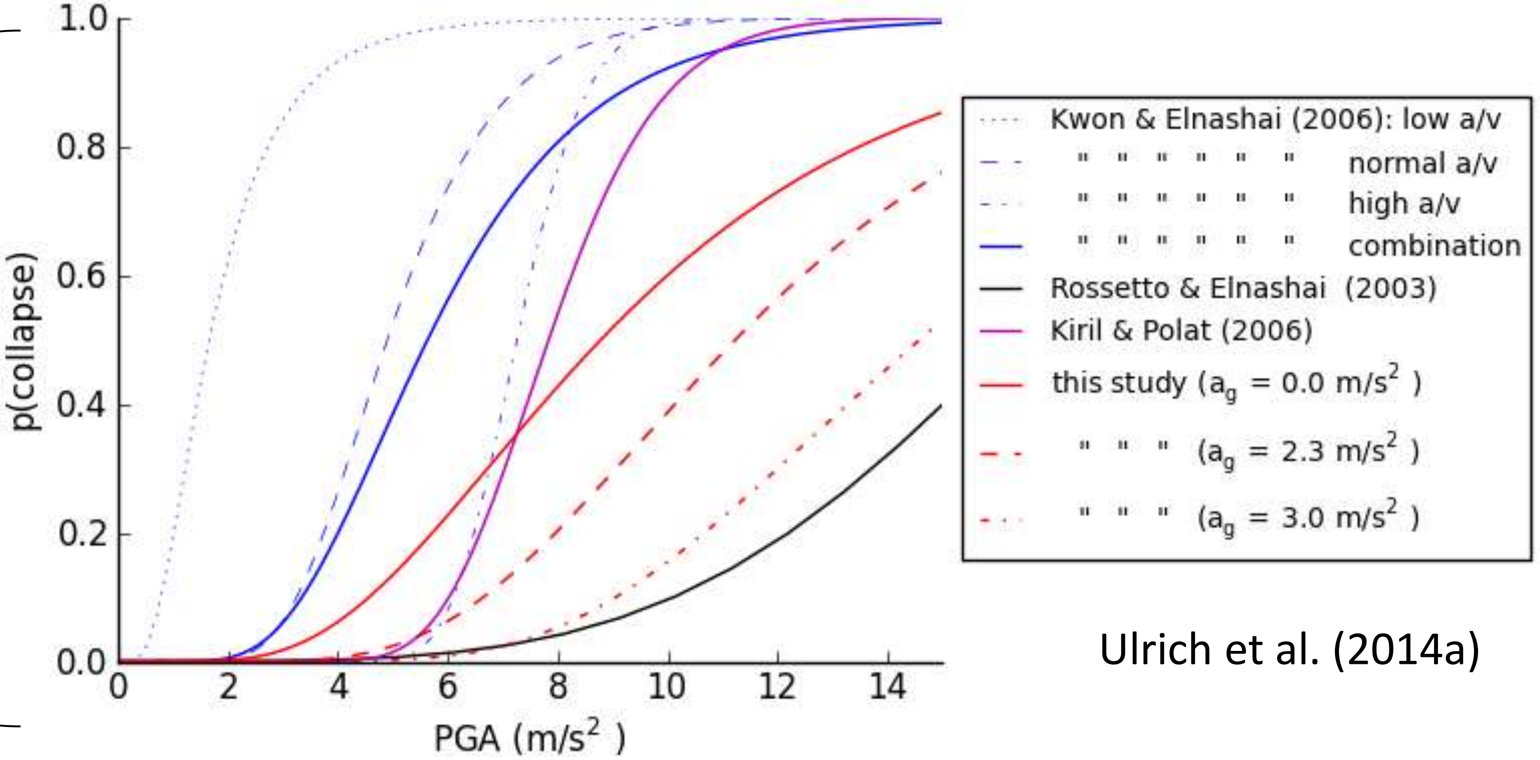
- Risk-targeting has three main advantages:
  - Transparency
  - Uniform risk across a territory
  - Ability to compare risk for different hazards
- Disadvantage: Decisions now explicit
- Many studies have been made (see paper)
- Online tool and code use in the US
- Some outstanding issues

Outstanding issues

- What level of risk should be targeted (Y)?
- What is the probability of collapse at design acceleration (X)?
- Is a lognormal distribution for fragility curves correct?
- What β should be used to capture all possible buildings?

Wide dispersion → use high β?

Does it seem reasonable that collapse is possible at low PGAs but some structures survive until high PGAs?



Ulrich et al. (2014a)

Also see Table 1 of Douglas et al. (2013)

Ways forward

- Develop a suite of fragility curves for different a_g and geometries (and materials)
  - Otherwise β is inflated
- Do not scale fragility uniformly with a_g
- Move away from a single design map to many

- We are currently working on these issues
- Potentially for future version of Eurocode 8

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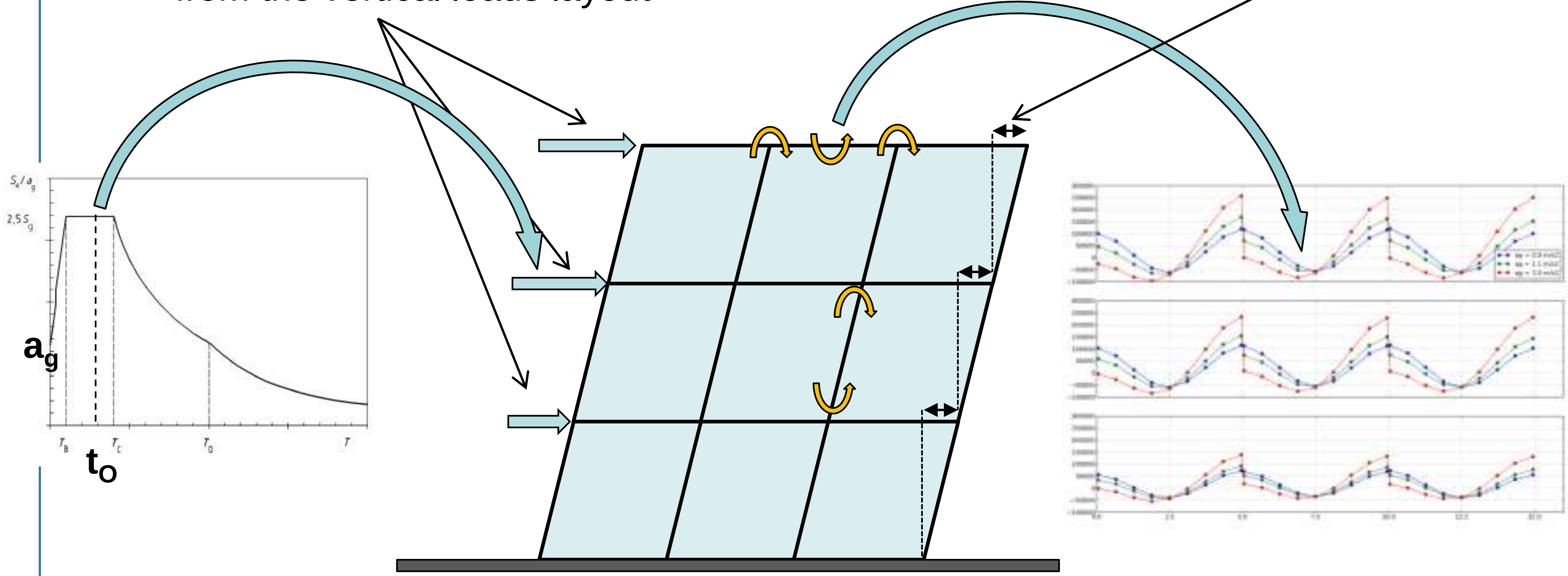
Design procedure



Horizontal load pattern inferred from a_g, from the building geometry and from the vertical loads layout

Design checks at the building scale: drift ratios

Elastic Response spectra

Static Linear “Push Over” Analysis

Local checks (moments, deflection, etc.) in the structural elements

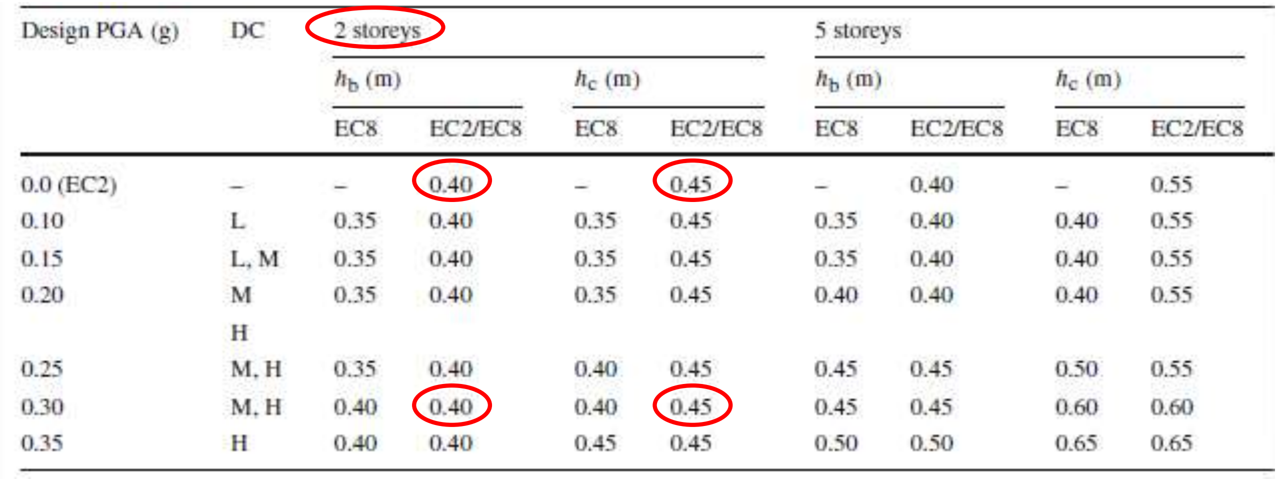
Designed structures

- **Considered RC Building : 3 storeys – 3 bays – 3 frames, C25/30**
- **Obtained dimensions**

	Beams			Columns	
ag	**dim (HxB)**	**upper reinf.**	**lower reinf.**	**dim (HxB)**	**reinf.**
m/s²	**m x m**	**nb x mm (mm²)**		**m x m**	**nb x mm (mm²)**
0.0	0.35 x 0.30	6 x 16 (1206)	3 x 12 (339)	0.35 x 0.35	5 x 20 (1571)
0.7	0.35 x 0.30	3 x 25 (1473)	5 x 12 (565)	0.35 x 0.35	4 x 25 (1963)
1.1	0.35 x 0.30	5 x 20 (1571)	5 x 12 (565)	0.35 x 0.35	4 x 25 (1963)
1.7	0.35 x 0.30	6 x 20 (1885)	4 x 16 (804)	0.40 x 0.40	4 x 25 (1963)
3.0	0.40 x 0.35	3 x 32 (2413)	4 x 16 (804)	0.45 x 0.45	6 x 25 (2945)

Margins			
drift	**beams up**	**beams dn**	**columns**
	9%	0%	6%
56%	3%	19%	8%
29%	-1%	5%	0%
12%	5%	12%	0%
4%	12%	8%	7%

- **Comparison with Fardis et al (2012)**

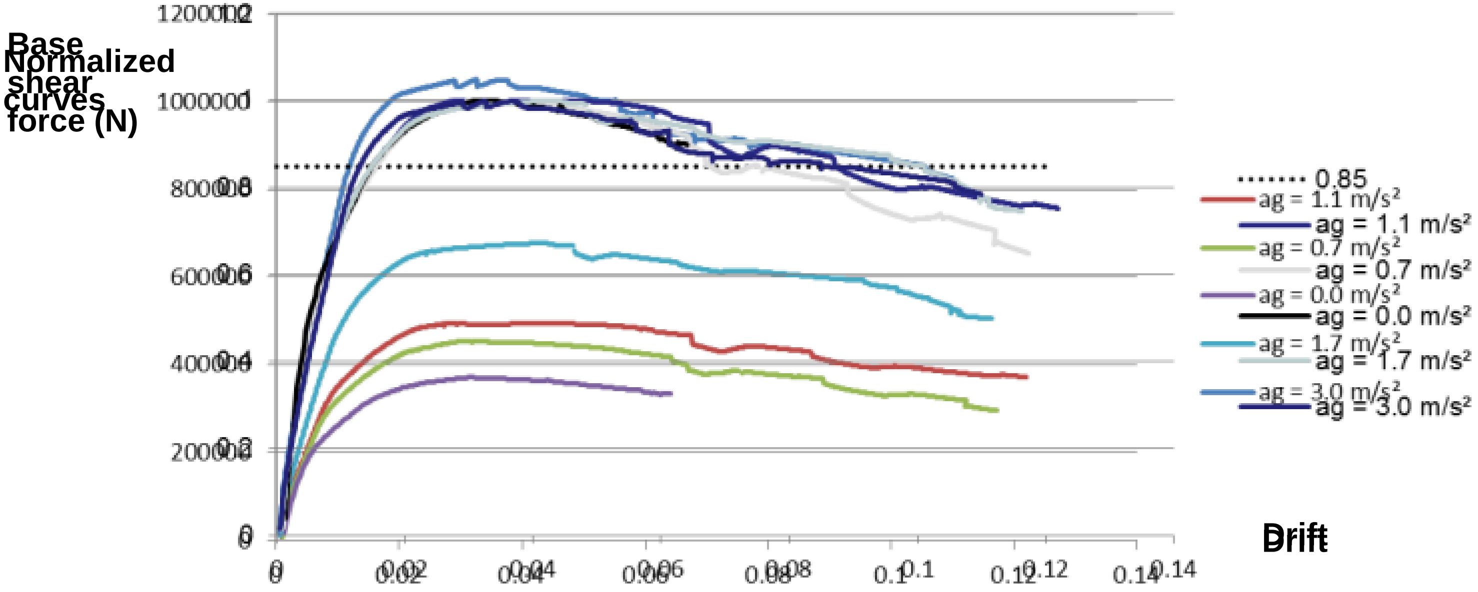


Design PGA (g)	DC	2 storeys				5 storeys			
		h_b (m)		h_c (m)		h_b (m)		h_c (m)	
		EC8	EC2/EC8	EC8	EC2/EC8	EC8	EC2/EC8	EC8	EC2/EC8
0.0 (EC2)	–	–	0.40	–	0.45	–	0.40	–	0.55
0.10	L	0.35	0.40	0.35	0.45	0.35	0.40	0.40	0.55
0.15	L, M	0.35	0.40	0.35	0.45	0.35	0.40	0.40	0.55
0.20	M H	0.35	0.40	0.35	0.45	0.40	0.40	0.40	0.55
0.25	M, H	0.35	0.40	0.40	0.45	0.45	0.45	0.50	0.55
0.30	M, H	0.40	0.40	0.40	0.45	0.45	0.45	0.60	0.60
0.35	H	0.40	0.40	0.45	0.45	0.50	0.50	0.65	0.65

Choice of the drift thresholds

> Risk-UE – AUTH method (PO based)

- PO: Same normalized shape

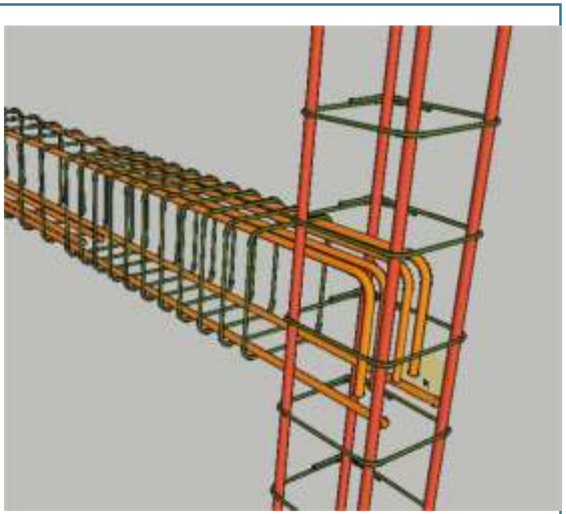


- Ultimate drift too high

> Gobarah (2004): ductile moment-resisting frames

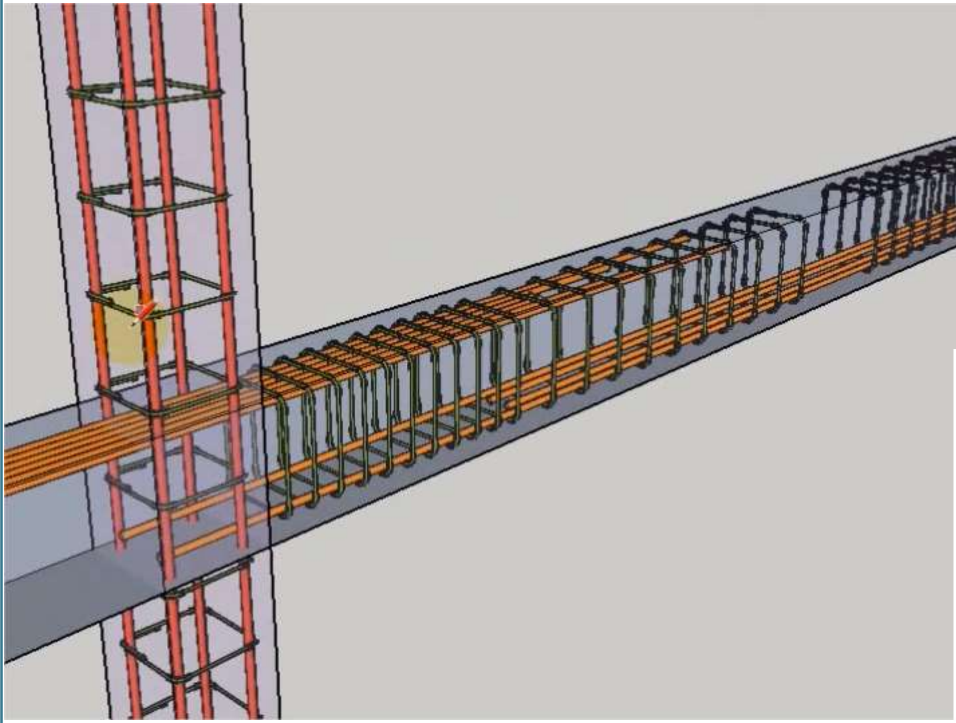
	Light	Moderate	Irreparable	Severe	Collapse
Risk-UE AUTH drifts	0.6%	0.9%	2.1%	4.3%	8.1%
Gobarah (2004)	0.2%	0.4%	1.0%	1.8%	3.0%

Design of the buildings (reality)

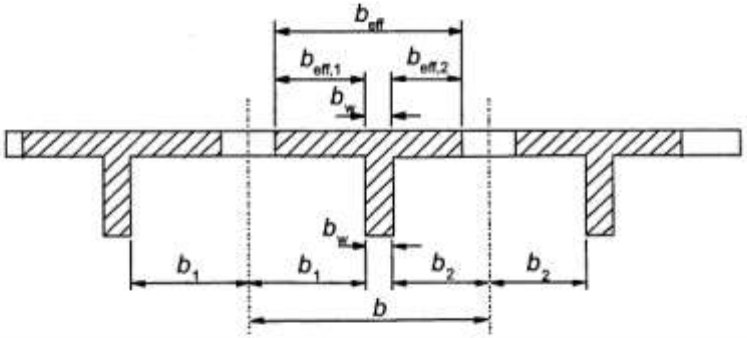


> **Complexity of the reinforcement layout**

- Densification of stirrups near the columns
- Evolution of the density of longitudinal reinforcement in the beam
- Complex beam-column joint area



- Participation of the slab in the structural behaviour



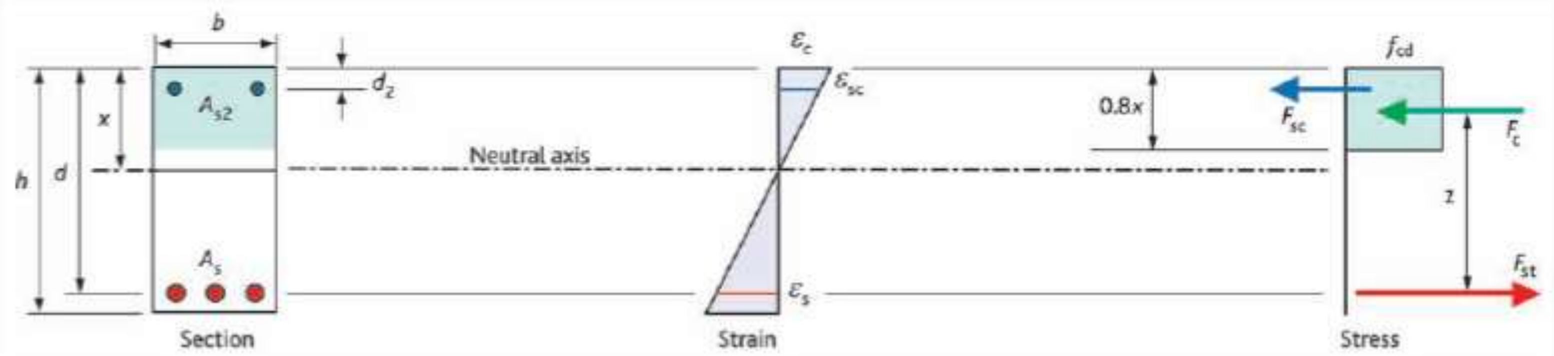
Design of the buildings (model)

> Model simplifications

- No longitudinal variation in the reinforcement area along the beam (e.g. the top reinforcement at mid-span is the same as at member ends)
- The structural effect of the slab is not considered
- The reinforcement layout is the same for all the beams (idem columns) → non-optimal design

> Simplifications in the design procedure

- “Rectangular stress block” approximation for the concrete



Detailed design procedure (1)

- **Sections design: geometrical constrains**
  - Spacing between longitudinal bars (EC 8.2)
  - Bars anchoring (EC8 5.6.2.2)
- **Beam design**
  - Bending resistance (at mid-span and at member ends, EC2 9.2.1.1)
  - Deflection
  - Vertical shear reinforcement (not computed → only impacts stirrup spacing)

How to Design Concrete Structures using Eurocode 2

(critical underlined)

Detailed design procedure (2)

Column design

- Bending Resistance
- Biaxial bending
- Plastic hinges in beams and not in columns (EC8 4.4.2.3)

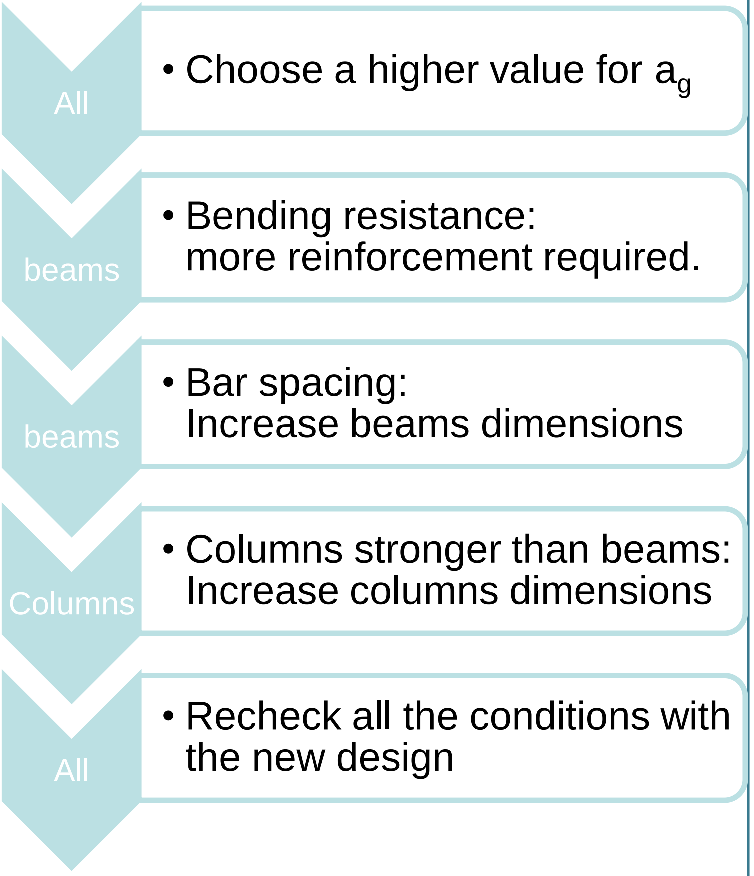
$$\sum M_{\mathrm{Rc}} \geq 1{,}3 \sum M_{\mathrm{Rb}}$$

Overall design

- Drift limitation: $d_{\mathrm{r}} \nu \leq 0{,}0075\, h$
  (EC8 4.4.3.2)
  → Critical for ~ ag > 2 m/s²
- P-Delta effects: $\theta = \frac{P_{\mathrm{tot}} \cdot d_{\mathrm{r}}}{V_{\mathrm{tot}} \cdot h} \leq 0{,}10$
  (EC8 4.4.2.2)

(critical underlined)

Example when increasing the seismic design of a building



- Choose a higher value for a_g
- Bending resistance:
  more reinforcement required.
- Bar spacing:
  Increase beams dimensions
- Columns stronger than beams:
  Increase columns dimensions
- Recheck all the conditions with the new design