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ISEP P.PORTO UNIVERSIDADE BEIRA INTERIOR UFRJ Politécnica UFRJ

PORTO, PORTUGAL

# ***Seismic behaviour of RC buildings:***
## *Lessons from recent earthquakes, standards and research needs*

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CONSTRUCT
Humberto Varum

2025

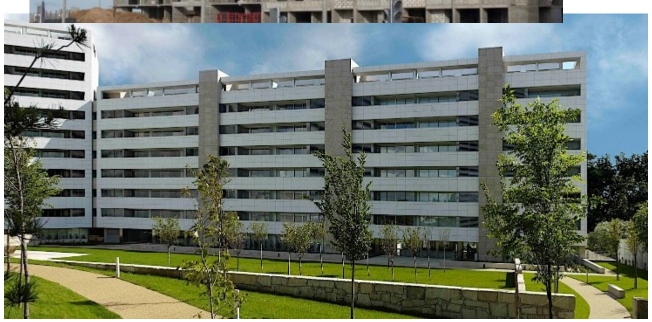
# Seismic design of **current RC buildings**





Current **use**
(Importance class II):
residential, offices, …

**Mid-rise**



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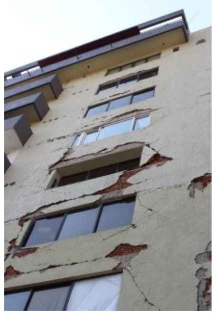
# Initial considerations…



Do we know everything about the seismic response of building structures?

Do we really have regular building structures?

Are the rules/procedures offered in codes adequate for the assessment and design of irregular building structures?

Can we design/assess structures ignoring the infill masonry walls ("non-structural" elements)?

Even if current design codes include the most advanced state-of-the-art knowledge, how can we deal with the seismic risk associated with the vast existing building stock (with emphasis on the irregular structures)?

In the last decades, a large number of new materials and solutions were introduced in the construction of buildings' envelopes. How will they behave in the future earthquakes?

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# Evolution of the seismic design codes

The **first codes**

The seismic provisions in building codes started as a **reaction to catastrophic events**, beginning after the **1755 Lisbon earthquake**.

Earthquakes in **Messina**, Italy (1908) and **Tokyo**, Japan (1923) resulted in suggesting design of buildings for lateral forces of about **10%** of their weight.

In **1909** the **first** seismic regulations for buildings started in **Italy**, with provisions for equivalent static analysis, where in the first storey, the horizontal force was equal to **1/12$^{th}$** of the weight above.

In **1924** emerged the first seismic code in **Japan** with a seismic coefficient equal to **10%**.

Holmes *et al.* (2021); Fajfar (2021)


Lisbon, Portugal (1755)

Messina, Italy (1908)

# Evolution of the seismic design codes

The **first codes**

In the **US**, the first code provisions appeared as a voluntary appendix in the **1927 Uniform Building Code** with a **seismic coefficient ranging between 7.5 and 10%** of the total <u>dead load plus the live load</u> of the building.

In **1978** come into force the **modern codes** with **ATC 3-06 guidelines** in **US** (probabilistic seismic maps, force reduction R-factors).

The **Standards and Regulations for Building in Seismic Regions**, adopted in the **USSR** in **1957**, included the **modal response spectrum method** as the <u>main analysis procedure</u>. This analysis procedure was later included in several European seismic codes and has remained the most popular procedure for seismic analysis in Europe, up until today.


BUILDING STANDARDS

UNIFORM
BUILDING CODE
1927 Edition

PREPARED BY

International Conference
of
Building Officials

COPYRIGHTED © 1928 and 1987
by
International Conference of Building Officials
19 Pine Avenue
LONG BEACH, CALIFORNIA

Fajfar (2021)

# Evolution of the seismic design codes

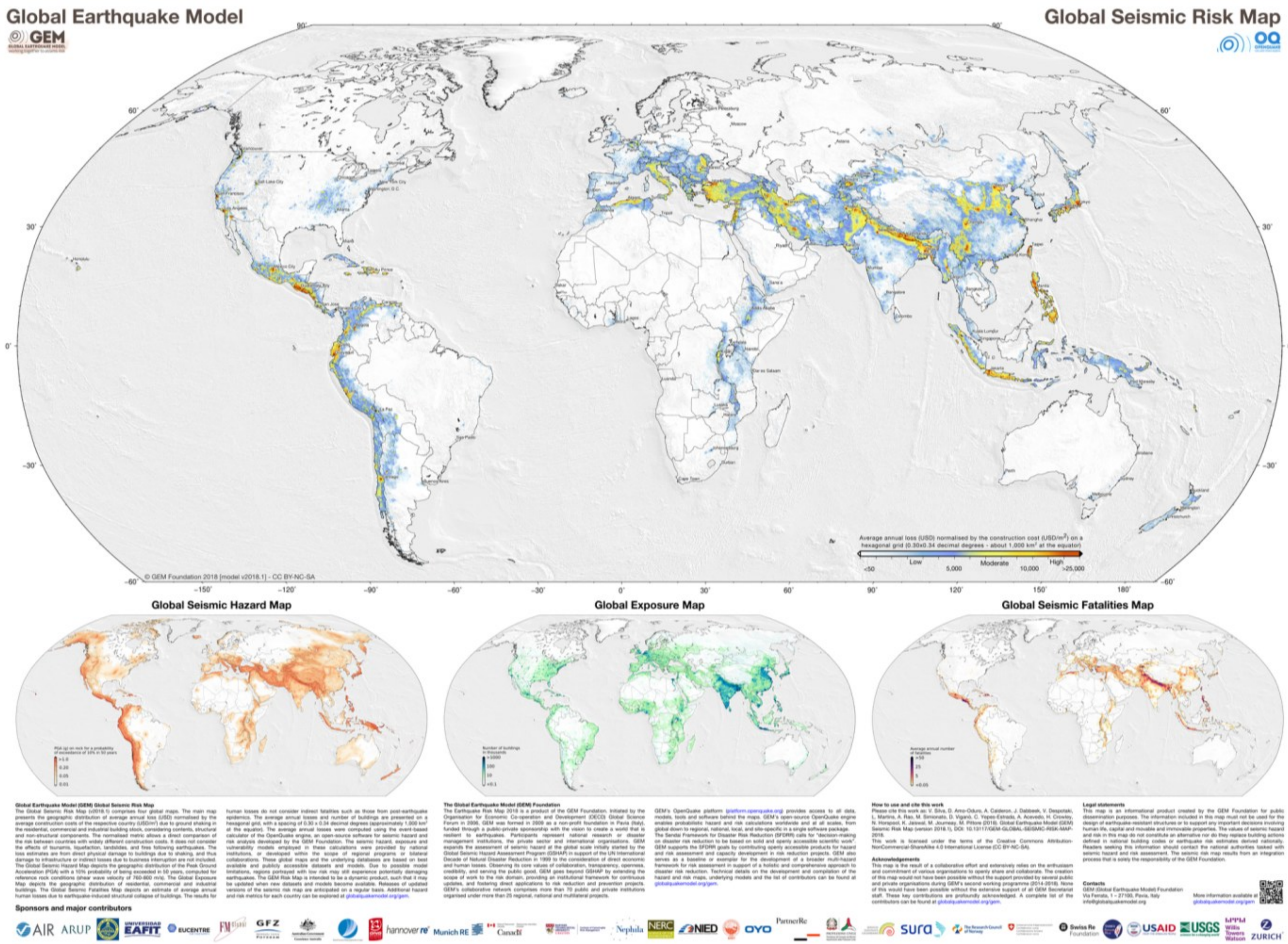
The Evolution of the seismic design codes is influenced by:

**Evolution of the seismic design codes**

- **More rigorous** characterization of the seismic **Hazard & Risk**
- **Knowledge development** based on **research outputs**
  - Laboratories with improved **testing capacity**
  - Large **European projects** financed (PREC8, ICONS, LESSLOSS, SAFER, SERA, RISE, …)
  - Great and fast evolution of the **tools for structural modelling**
  - **PhDs**, **publications** and other research outputs
- **Lessons learnt from Earthquakes** (with large economical and human losses)
- **Growing concerns** of the Society and Policy Makers

# Evolution of the seismic design codes

More rigorous **characterization of the seismic Hazard & Risk**




(Silva *et al*, 2020)

# Evolution of the seismic design codes

**Lessons learnt from Earthquakes**







# Evolution of the seismic design codes

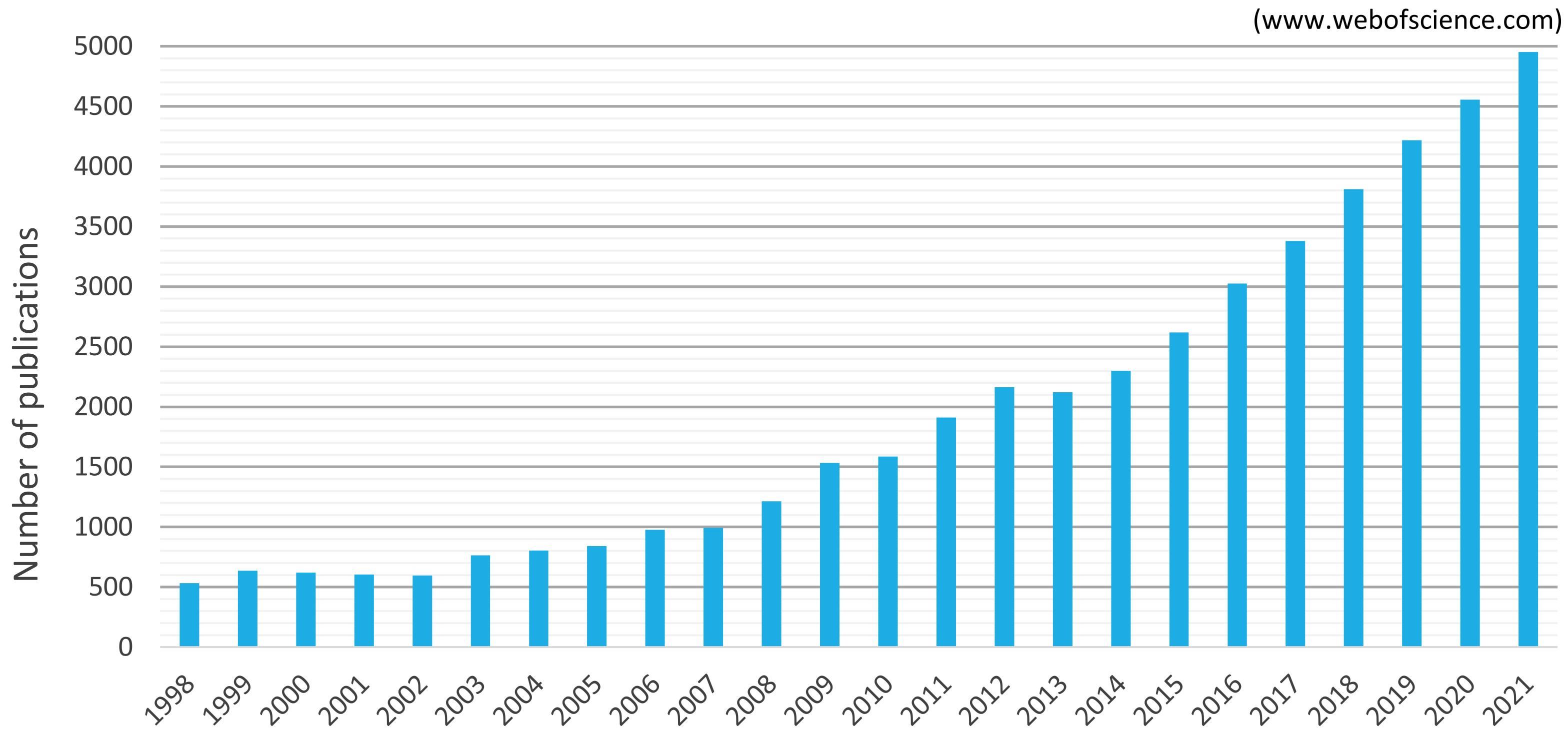
Knowledge development based on **research outputs**

**Improved and enhanced testing capacity of laboratories (Universities**, Research Centres, National Labs):

- Better **equipment** (control and data acquisition systems, actuators, load cells, transducers,…)
- **Monitoring** (DIC,…)
- Capacity to reproduce more realistic loading conditions (Dynamic, PsD, Sub-structuring,…)

# Evolution of the seismic design codes

Knowledge development based on **research outputs**



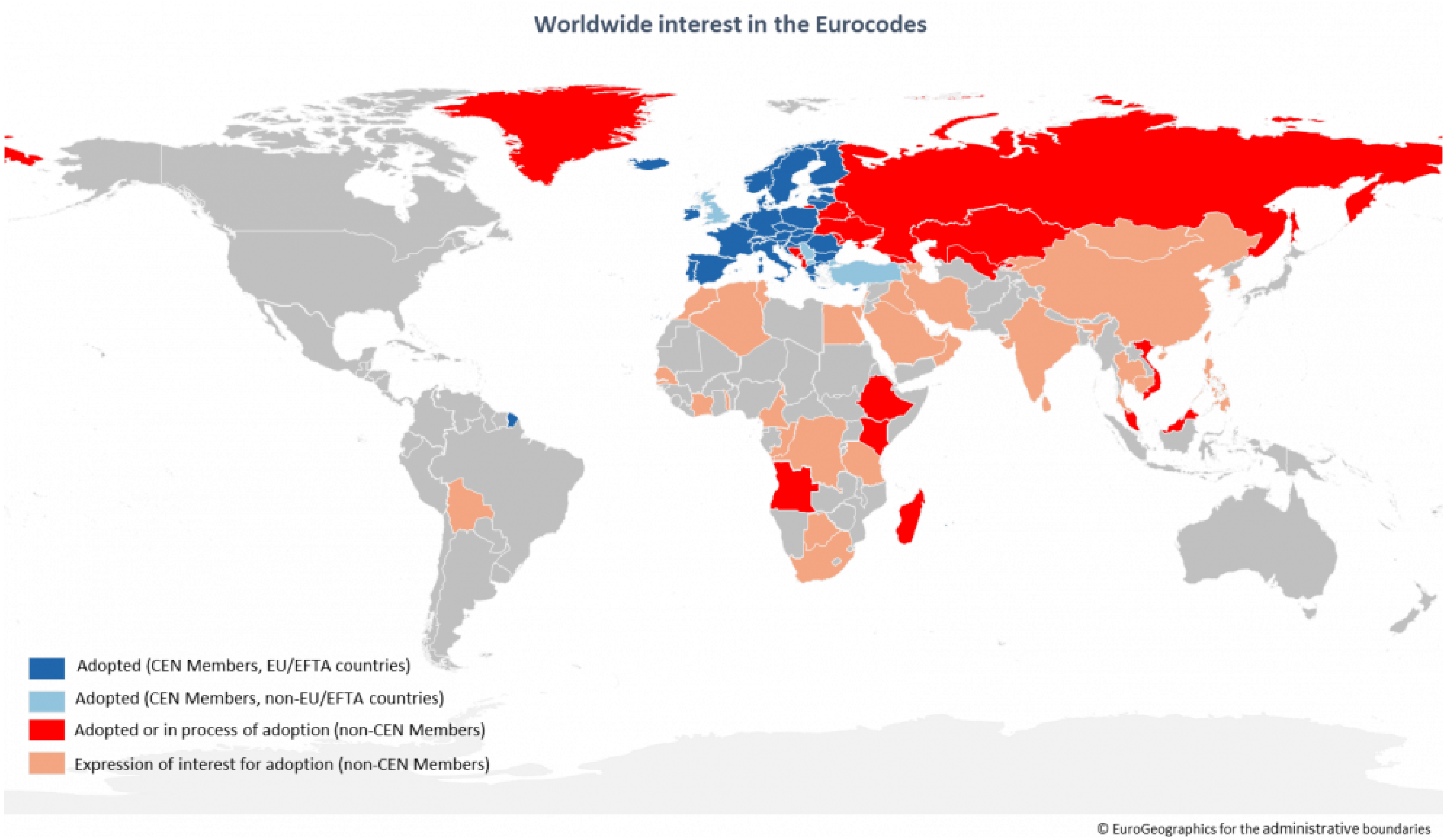

Number of **publications** per year from 1998 to 2021 listed on WoS within topics ‘seismic engineering’, ‘seismic design’, ‘seismic assessment’, ‘earthquake engineering’ or ‘Eurocode 8’

# Evolution of the seismic design codes

Growing **concerns** of the Society and Policy Makers

# Evolution of the seismic design codes

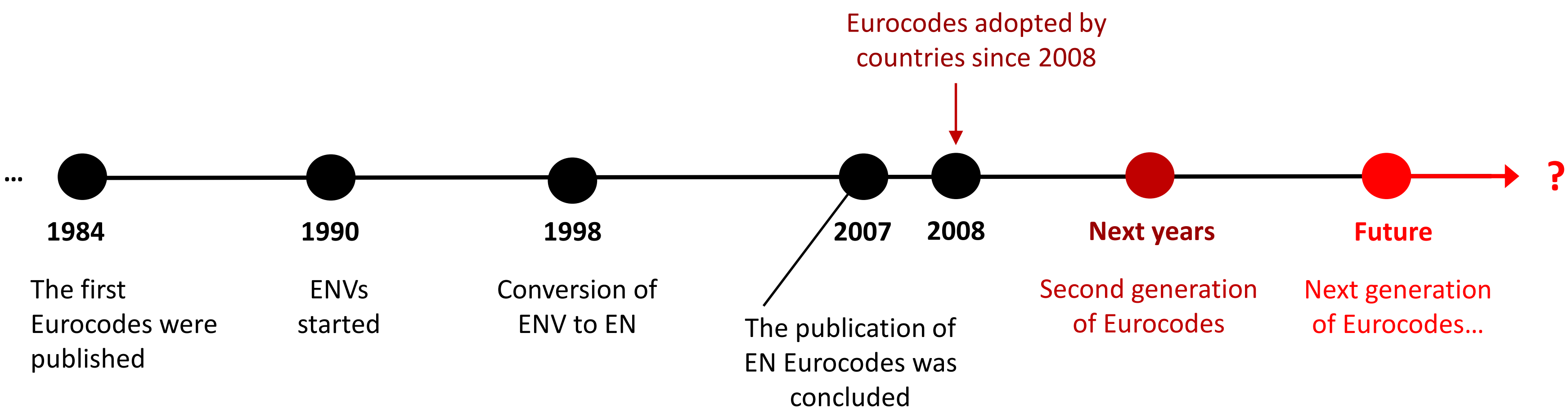
**Eurocodes** in the world




(https://eurocodes.jrc.ec.europa.eu)

# Evolution of the seismic design codes

**Eurocodes** timeline



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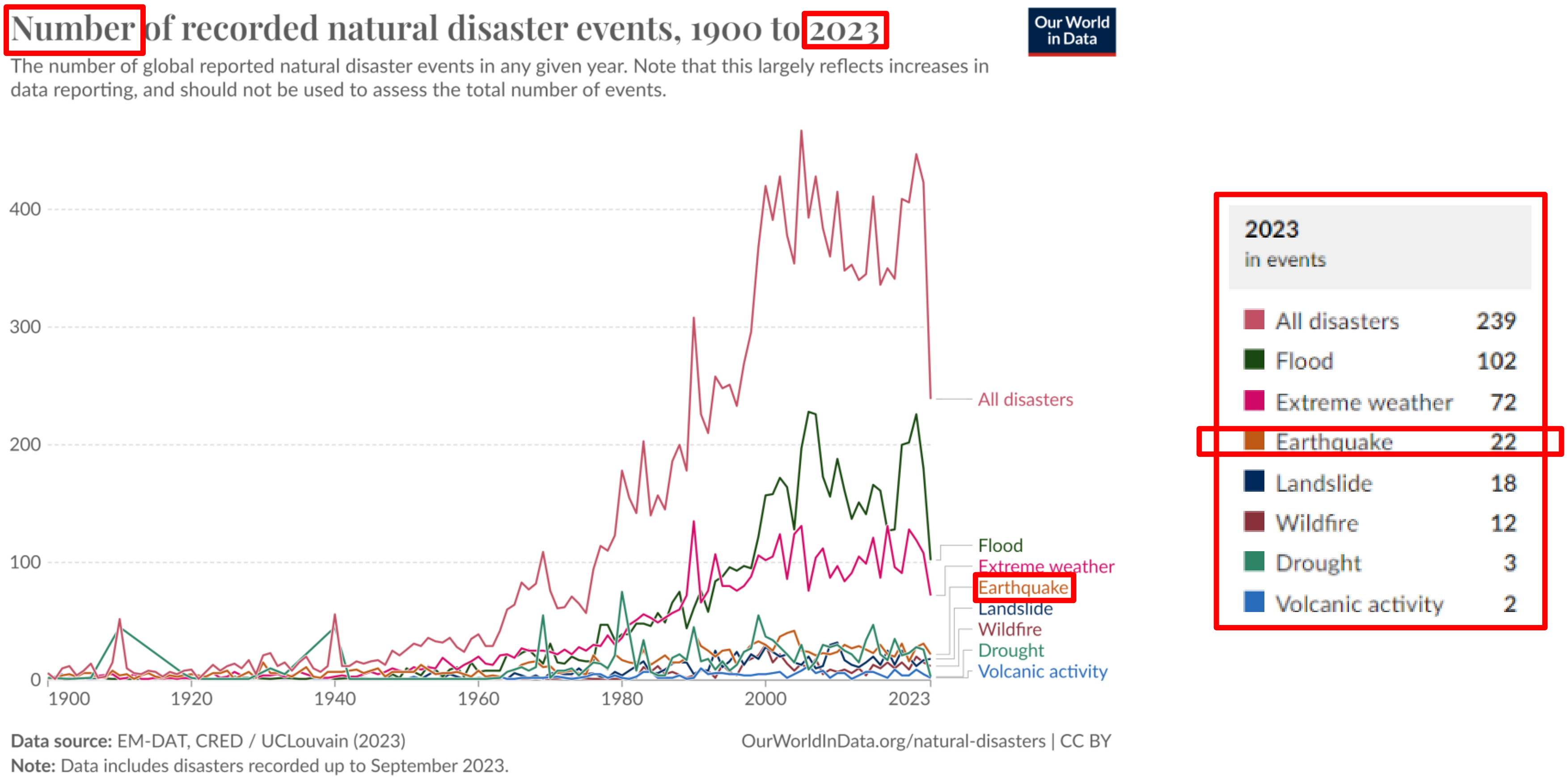
# Natural Disasters: Occurrences




- Geophysical events (including **earthquakes**) have increased since 1900's
- **Meteorological** events have largely increased in the last years

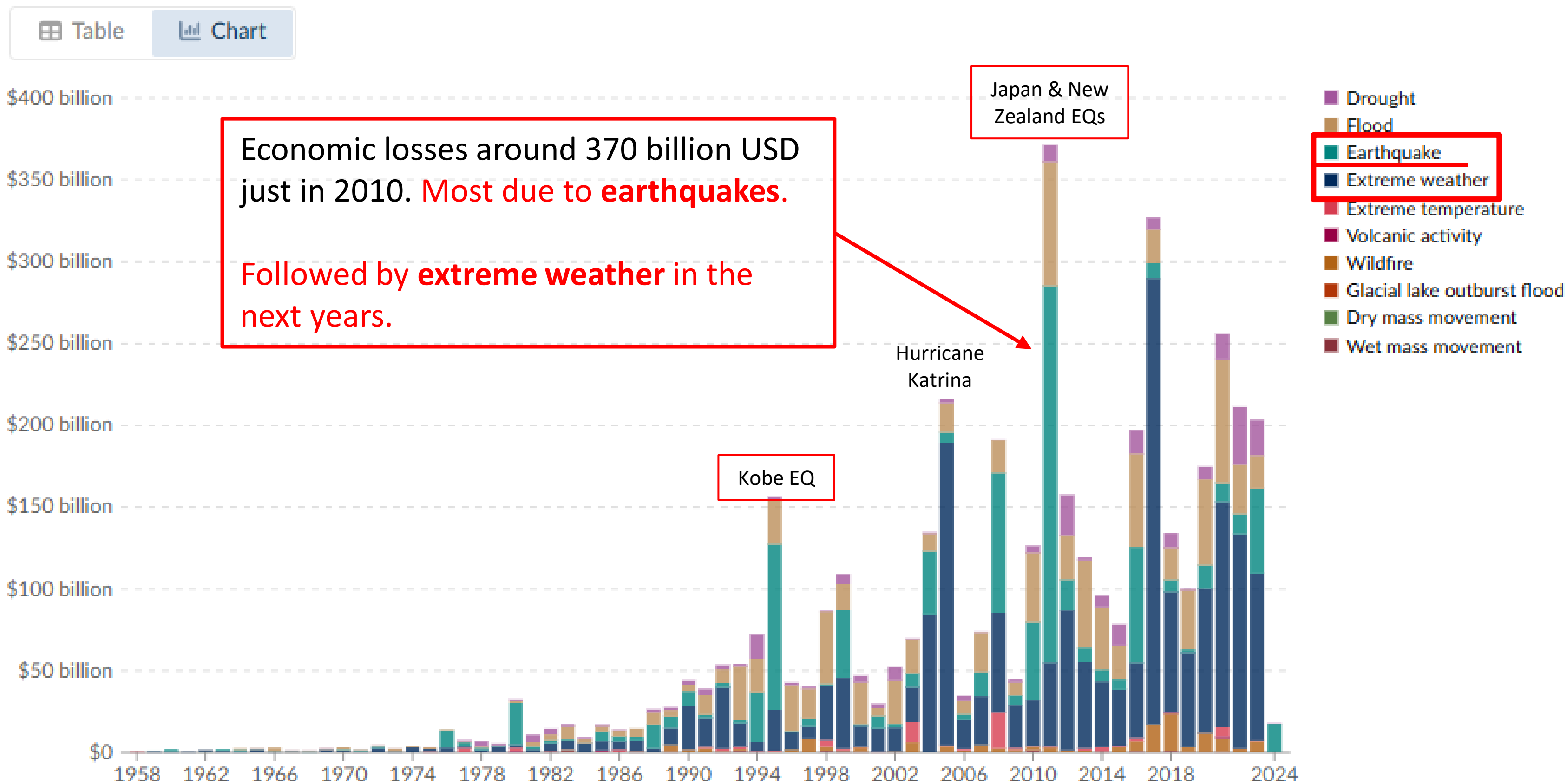


Data: https://ourworldindata.org/grapher/number-of-natural-disaster-events?country=All+disasters

# **Natural Disasters**: Economical Losses

**Economic damage by natural disaster type, 1958 to 2024**

Global economic damage from natural disasters, differentiated by disaster category and measured in US$ per year.




Natural disasters are **more frequent** now than 30 years ago, and are **costing** us **much more**!

https://ourworldindata.org/grapher/number-homeless-from-natural-disasters?time=1961..latest

# **Risk** (is the “product” of three vectors) “=“

| Hazard | “x” | Vulnerability | “x” | Exposure |
|---|---|---|---|---|
| Probability of… | | Engineering | | … of values |



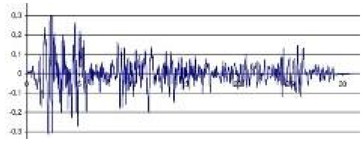
Lower Risk



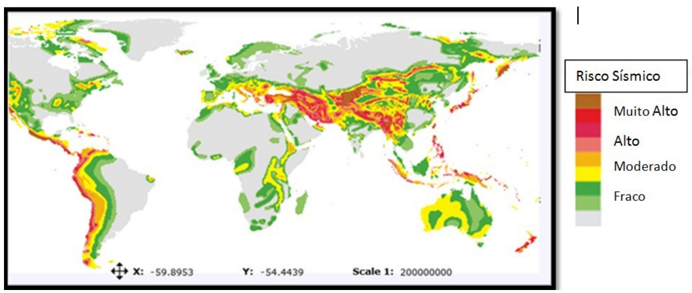
Higher Risk

Solutions to **mitigate the risk**: (1) Better characterization of hazard; (2) Reduce the vulnerability of the constructions through engineering; (3) Develop a land-use planning strategy, avoiding the development of big cities and important infrastructures in regions subjected to higher hazards.

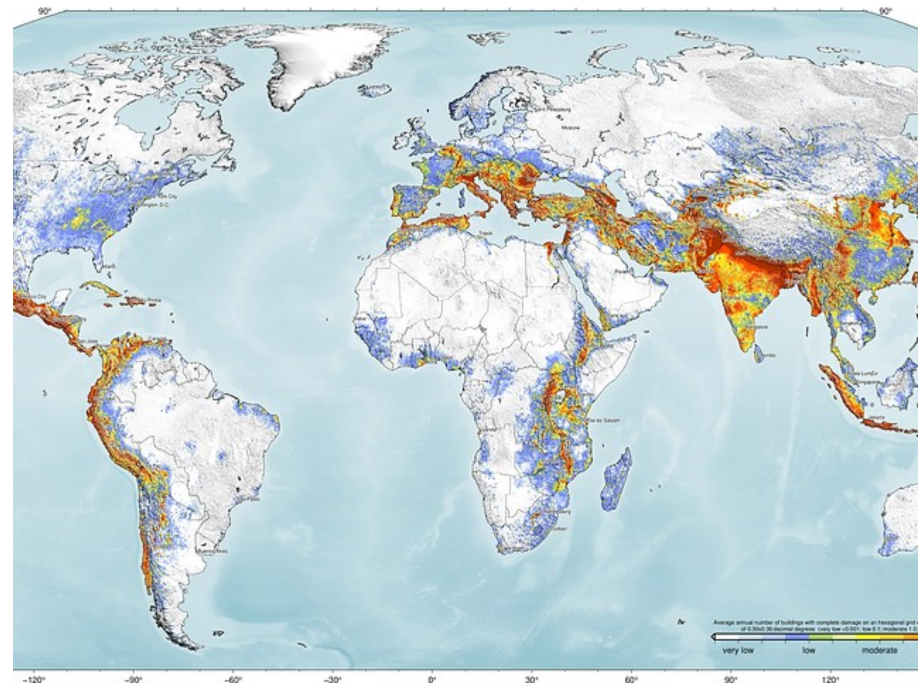
# **Seismic hazard** in the **World**



**Seismic Hazard** is defined as the probability of an earthquake occurring, with a given level of intensity, in a given time period (return period T) and in a specific location.




https://www.globalquakemodel.org/product/global-seismic-risk-map/




**Certainty:** We will have **several major earthquakes** in the **World** !

# Main Hazards in Portugal

European Commission

European Civil Protection and Humanitarian Aid Operations

According to the **National Risk Assessment (NRA)**, the risks of forest fires, heat waves, earthquakes, tsunamis, droughts, windstorms, dam break, radiological emergencies and floods are key risks in Portuguese mainland.

## Earthquakes

https://www.nytimes.com/interactive/2023/02/10/world/middleeast/kahramanmaras-turkey-earthquake-damage.html

## Storms

https://www.lisbob.net/en/blog/hurricane-leslie-lisbon-portugal-alert

## Tsunamis

https://www.angloinfo.com/blogs/portugal/lisbon/whatever-tickles-manuelas-fancy/when-the-earth-moves-in-cascais/

## Fires

https://www.euronews.com/green/2020/02/17/facing-the-flames-how-portugal-is-preparing-for-increased-fire-risk

## Coastal erosion

https://www.portugalresident.com/coastal-erosion-serious-and-effects-will-only-get-worse-say-experts/

## Floods

https://www.lisbob.net/en/blog/red-alert-portugal-flood-storm-december

https://civil-protection-humanitarian-aid.ec.europa.eu/what/civil-protection/national-disaster-management-system/portugal_en

# Seismic hazard in Portugal

## *November 1st, 1755*

**Lisbon Earthquake, Magnitude > 7.7 (?)**

- Epicenter: is believed to be on the Azores-Gibraltar Transform Fault (Atlantic Ocean west of Portugal)

**Impact:**

- Widespread destruction in Lisbon, demolishing buildings and public structures. Many churches collapsed during mass services, leading to a high number of casualties (**estimates around 85% of the whole city – over 12 thousand dwellings**)
- A powerful tsunami followed the earthquake, generating waves up to 20 meters high that flooded the city and caused further destruction
- Fires erupted throughout Lisbon, fueled by overturned candles and broken stoves, and raged for days
- **Between 12,000 and 50,000 people in Lisbon alone died** (plus casualties in Spain and North Africa)
- Considered to be one of the most destructive natural disaster in European History


https://www.britannica.com/event/Lisbon-earthquake-of-1755
https://www.nature.com/articles/s43247-021-00216-5

# **Seismic** hazard in Portugal

**Certainty:**

…In the future, **we will have earthquakes in Portugal**, possibly "similar" to that of 1755, or even "stronger"…

# Vulnerability

**Vulnerability** represents the degree of damage, or potential loss, to an element, or set of elements, as a consequence of the occurrence of an extreme event of a certain intensity.







# Exposure

**Exposure** is related to **goods** that are **exposed** to the effect of extreme actions, as well as **users**.







In **summary**: **Risk** depends on the level of **hazard** expected at the **location** of the structure, on the **options** and **attention** taken in the **structural** design/**assessment** and construction of the structure, but also on the **type of use** and **assets** (heritage, cultural,...) associated with the structure of infrastructure.

# **Risk** (is the “product” of three vectors) “=“

Hazard “x” Vulnerability “x” Exposure

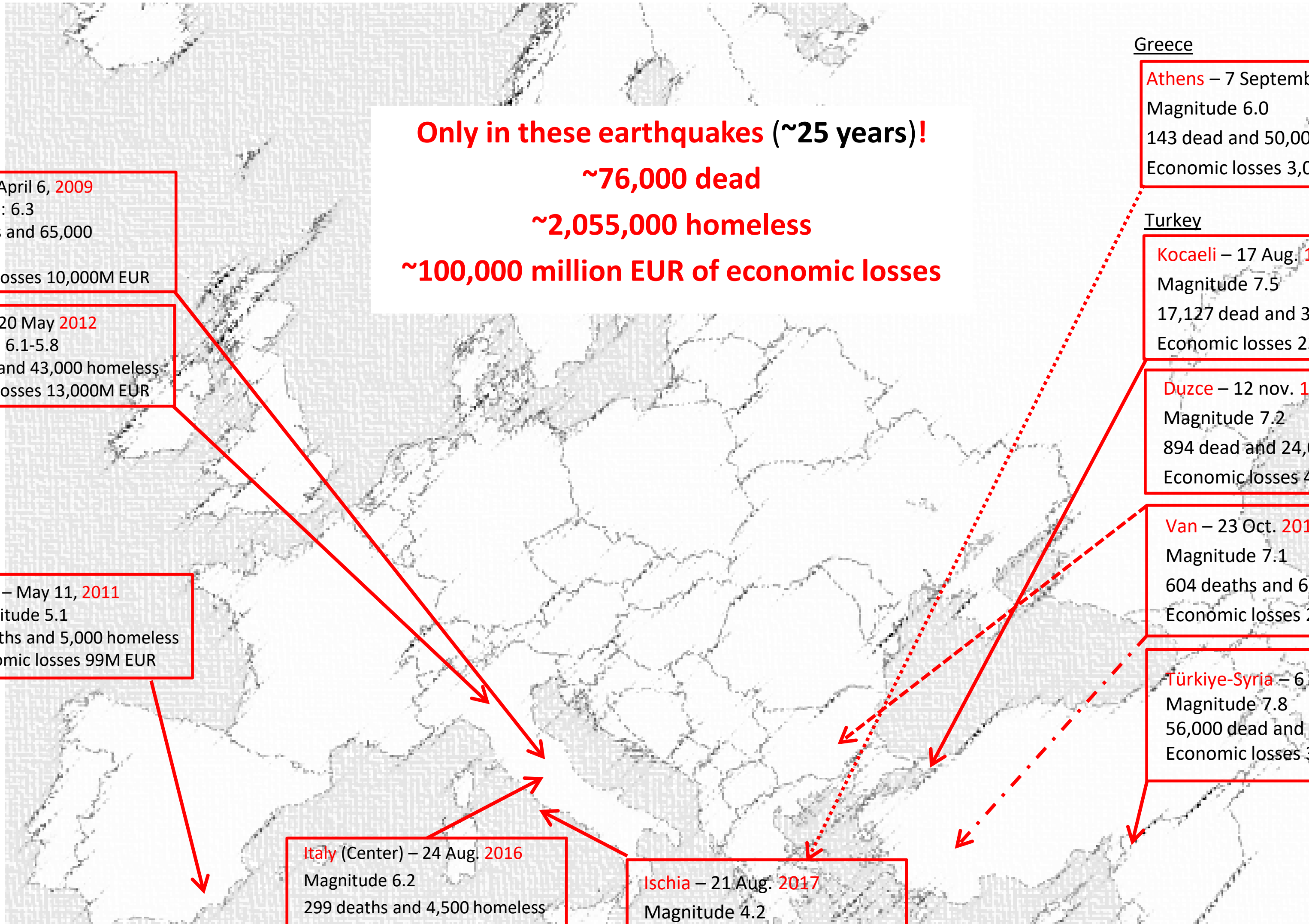
Probability of… | Engineering | … of values

Lower Risk

Higher Risk

Solutions to **mitigate the risk**: (1) Better characterization of hazard; (2) Reduce the vulnerability of the constructions through engineering; (3) Develop a land-use planning strategy, avoiding the development of big cities and important infrastructures in regions subjected to higher hazards.

# Impact of recent earthquakes: **Numbers**!



**Only in these earthquakes (~25 years)!**
**~76,000 dead**
**~2,055,000 homeless**
**~100,000 million EUR of economic losses**

Italy

L'Aquila – April 6, 2009
Magnitude: 6.3
308 deaths and 65,000 homeless
Economic losses 10,000M EUR

Bologna – 20 May 2012
Magnitude 6.1-5.8
26 deaths and 43,000 homeless
Economic losses 13,000M EUR

Italy (Center) – 24 Aug. 2016
Magnitude 6.2
299 deaths and 4,500 homeless
Economic losses 11,000M EUR

Ischia – 21 Aug. 2017
Magnitude 4.2
2 deaths and 2,600 homeless

Spain

Lorca – May 11, 2011
Magnitude 5.1
9 deaths and 5,000 homeless
Economic losses 99M EUR

Greece

Athens – 7 September. 1999
Magnitude 6.0
143 dead and 50,000 homeless
Economic losses 3,000M EUR

Turkey

Kocaeli – 17 Aug. 1999
Magnitude 7.5
17,127 dead and 300,000 homeless
Economic losses 23,000M EUR

Duzce – 12 nov. 1999
Magnitude 7.2
894 dead and 24,000 homeless
Economic losses 40M EUR

Van – 23 Oct. 2011
Magnitude 7.1
604 deaths and 60,000 homeless
Economic losses 2,000M EUR

Türkiye-Syria – 6 Feb. 2023
Magnitude 7.8
56,000 dead and 1,500,000 homeless
Economic losses 34,000M EUR

# Common damages in RC buildings

1. Stirrups and hoops (inadequate quantity and detailing, regarding the required ductility)
2. Detailing (bond, anchorage and lap-splices)
3. Inadequate capacity and failure (shear, flexural)
4. Inadequate shear capacity of the joints
5. Strong-beam weak-column mechanism
6. *Short-column* mechanism
7. Structural irregularities (in plan or in elevation: torsion , "weak-storey", "soft-storey")
8. Pounding

SP

9. Damages in structural Secondary Elements (cantilivers, staircases,...)

SS

10. Damages in Non-Structural Elements

NS

# Common damages in RC buildings

**Stirrups** and hoops


Bond, **anchorage**, splices

Inadequate **capacity** and failure (M,V)

Inadequate shear capacity of the **joints**

# Common damages in RC buildings

**Strong-beam weak-column** mechanism

**Short-column** mechanism

Structural **irregularities**

Pounding

# Common damages in RC buildings

The **structural damages**/problems previously shown are **more common** in **existing/old buildings** (non-code compliant or designed to former codes/procedures).

**New buildings**, **designed** with **modern codes** (benefiting from the **actual knowledge**, from the available powerful **numerical tools**, using **new materials** and **building technology**):

- tends to have **a better structural behaviour and performance**; but,

- **non-structural elements** may continue generating problems…

# Observed damages in recent earthquakes: Field evidence

Damage to masonry enclosure walls

- in plane diagonal cracking / detachment from the surrounding frame


(L'Áquila, Italy, 2009)


# Observed damages in recent earthquakes: Field evidence

Damage to masonry enclosure walls

- in plane (detachment between infills and surrounding RC structure, diagonal cracking)
- **Out-of-plane collapse**

(L'Áquila, Italy, 2009)

Possible causes: improper outer masonry leaf support conditions; poor connection conditions of the external leaf; no ties or anchoring systems either between internal and external leaf and/or between infill walls and the frame

# Observed damages in recent earthquakes: Field evidence

Damage to masonry enclosure walls

- in plane damage (interface separation between infill walls and the surrounding RC structure, diagonal cracking, corner crushing)
- Out-of-plane collapse
- in plane (IP) and out-of-plane (OOP) **interaction** **(OOP instability after IP damage) ?**

(L'Áquila, Italy, 2009)

# Observed damages in recent earthquakes: Field evidence

Out-of-plane collapse of masonry enclosure walls

(Lorca, Spain, 2011)

(L'Áquila, Italy, 2009)

- Inadequate connection between the masonry infill and the surrounding RC frame
- No wall ties in **double leaf** or **veneer walls**
- Inadequate wall support conditions of the exterior panel (correction of the thermal bridges purposes)
- OOP instability (after IP damage)

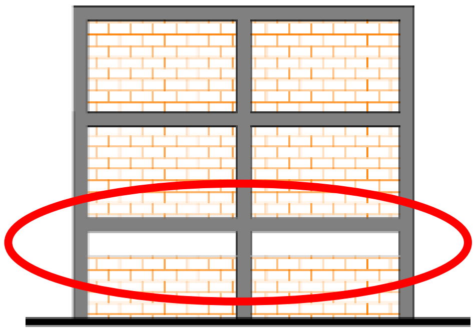
# Observed damages in recent earthquakes: Field evidence

<u>Out-of-plane collapse</u> of masonry enclosure walls

(L’Áquila, Italy, 2009)

# Observed damages in recent earthquakes: Field evidence

Short-column mechanism



(L’Áquila, Italy, 2009)

Causes: wall openings (dimensions and location) in masonry enclosure walls

# Observed damages in recent earthquakes: Field evidence

Soft-storey mechanism (irregularity in elevation)

(2011 Lorca)

*Flexible* ground storey, convenient for commerce/services' use, inducing a pronounced irregularity in elevation, in buildings with 3 to 5 storeys

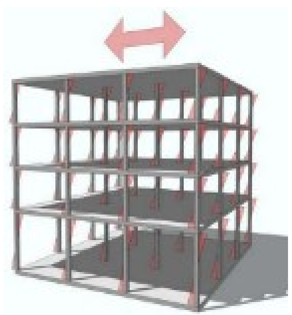
Common characteristics of **Ground Storey**:
(1) larger inter-storey height than the upper storeys, for commercial/services
(2) absence of masonry infill walls, or wall panels not developed along the total storey height, or weaker walls (stiffness and strength)

**Infill** non-structural elements with poor performance, causing major economic and human losses

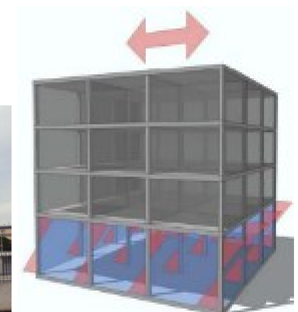
# Observed damages in recent earthquakes: Field evidence

Soft-storey mechanism (irregularity in elevation)

- Common infill masonry walls can modify drastically the global structural behaviour, attracting forces/deformations to parts of the structure that were not designed to support them, eventually leading to unexpected behaviour/response and collapse mechanisms



Structural design:
- Without considering the masonry walls



(Patrick Corell, 2011)

Real behaviour:
- Concentration of demands at the ground storey level

But… the influence of infill masonry walls in the structural response is frequently disregarded !

# 2017 Central Mexico earthquake (19th Sep.)

RC building structures – Observed damages

Poor material properties and detailing
Weak columns (section size, insufficient transversal reinforcement, poor detailing)
Pounding
Short-column mechanisms
**Flat slab**
…

The *Denver Post* news:
"The suspect building technique called **flat slab** — in which floors are supported only by concrete columns — **caused 61 percent of the building collapses** in last month's magnitude 7.1 quake, which killed 369 people and blanketed tree-lined avenues in rubble."

Engineers: Lives lost in Mexico quake could have been saved – The Denver Post

# 2017 Central Mexico earthquake (19th Sep.)

RC building structures – Observed damages

But …

**Irregularities** (in elevation and in plan) in terms of stiffness/strength due to drastic changes in the structural and/or IM walls configuration (number and layout/arrangement of infill walls):

- **Soft/Weak-storey** mechanism
- **Torsion**

# 2017 Central Mexico earthquake (19th Sep.)

## RC building structures – Observed damages

Structural configuration problems were a major cause of failure, or severe damage. Most configuration problems were associated with the contribution of non-structural elements to the building response, especially in **corner buildings in urban blocks**, where two perpendicular facades are fully infilled with masonry walls, and in the facades facing the street present the concentration of openings.

# Damages in RC building structures

Common damages in RC buildings

1. Stirrups and hoops (inadequate quantity and detailing, regarding the required ductility)
2. Detailing (bond, anchorage and lap-splices)
3. Inadequate capacity and failure (shear, flexural)
4. Inadequate shear capacity of the joints
5. Strong-beam weak-column mechanism
6. *Short-column* mechanism
7. **Structural irregularities** (in plan or in elevation: torsion , “weak-storey”, “soft-storey”)
8. Interaction and Pounding

SP

← INT

9. Damages in structural Secondary Elements (cantilivers, staircases,…) SS

10. Damages in Non-Structural Elements NS

# Damages in RC building structures

Structural: Primary (SP) and Secondary (SS) elements

INTERACTION (INT)

Non-Structural (NS)

Surroundings (foundations, soils, pounding,…)

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# Structural irregularities

**Codes/recommendations** of the second-half of the past century **take into account concerns** and **simplified approaches** relatively to the **irregularities**.

Examples:

- Canada (NBCC, 1960) – the first Canadian code refer the need to consider torsional effects, but no specific guidance was given.
- USA (UBC, 1976) – contains the first explicit treatment of structural "irregularities" in a U.S. building code.
- Portugal (RSA, 1983) – accidental eccentricities are included.
- …

# Observed damages in recent earthquakes: Field evidence

Damage/Collapse due to structural irregularities

Torsional irregularity


Irregularity in plan and in elevation


(FEMA P-2012 -  Kobe, 1995)

# Structural irregularities

**Field evidences** reports recognize the important influence of the **irregularities**, both in plan and in elevation, in the **seismic vulnerability and performance** of RC buildings.

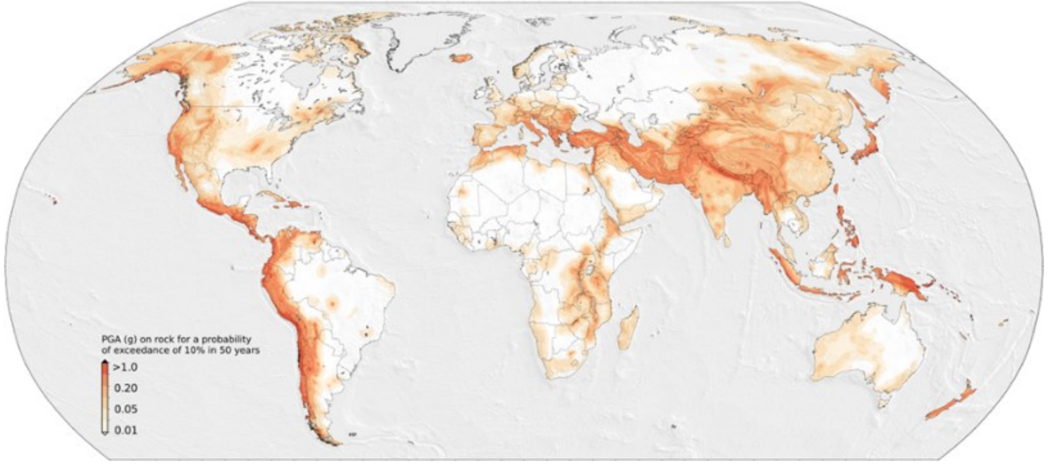
(Mexico, 1985)


(Mexico, 1985/2017)

# Structural irregularities

<u>International codes</u> approach relatively to the consideration of <u>structural irregularities</u>:

- **Europe** (CEN, 2004)
- Turkey (AFAD, 2018)
- Mexico (CFE, 2015)
- India (BIS, 2002)
- USA (ASCE, 2016)
- New Zealand (CSNZ, 2004)
- Canada (NRC, 2015)




(Silva *et al.*, 2020)

# Criteria to evaluate the irregularities

**In plan**

| Criteria | **Eurocode** | Turkey | Mexico | India | USA | New Zealand | Canada |
|---|---|---|---|---|---|---|---|
| Mass distribution | + | | + | + | | | |
| Lateral stiffness | + | | + | + | | | |
| Symmetry of resistant elements | + | | + | + | | | |
| Rigid diaphragm | + | | | | | | |
| Alignment structural elements in orthogonal axes | | | | | | | |
| Oper… | | | | | | | |
| Geom… config… ratio, F… eccentr… | | | | | | | |
| Relation… and plan… | | | | | | | |
| Torsional … torsional ra… gyration,…) | ++ | ++ | | ++ | ++ | ++ | ++ |
| Out-of-plane discontinuity | | | | + | + | | + |
| Lateral irregularity due to gravity | | | | | | | ++ |

**in elevation**

| Criteria | **…rocode** | …key | …co | | | New Zealand | Canada |
|---|---|---|---|---|---|---|---|
| Vertica… | | | | | | | + |
| | | | | | | | ++ |
| | | | | | | | ++ |
| | | | | | | ++ | ++ |
| … | ++ | | ++ | ++ | ++ | ++ | ++ |
| Weak-storey | | ++ | ++ | ++ | ++ | ++ | ++ |
| Floor area variation | | | ++ | | | | |
| Relationship between height and lower plan dimension | | | ++ | | | | |

\+ Qualitative ++ Quantitative

**The criteria adopted in the majority of the codes for the evaluation of the irregularities (in plan and in elevation) are, generally, based on simple qualitative and quantitative rules.**

# Seismic analysis and design

Implications of structural regularity on the seismic analysis/design method allowed/recommended

| | | | |
|---|---|---|---|
| **Regular in plan** | ✓ | ✓ | X |
| **Regular in elevation** | ✓ | X | |
| **Eurocode 8** | **Lateral force** | | |
| Tu… | | | |
| | | …ce<br>Modal | |
| | | Modal<br>Time-history analysis | |
| | Lateral force | Modal<br>Time-history analysis | |
| Canada | Lateral force | Modal | |

**In the majority of the codes, the irregularity of buildings restrict the methods and models allowed in design.**

# Behaviour factor reduction

Behaviour factor ($q$) reduction due to the irregularities

| Region/Country | Code | Behaviour factor or equivalent |
|---|---|---|
| **Eurocode 8** | EN 1998-1:2004 | **Torsionally flexible** systems with fixed valu… If the building is **non-re**… For b… |
| **Turke**… | | |
| **Me**… | | |
| **USA** | | …**educes directly the Modification Coefficient** (R), but …egory; (ii) the method of analysis (analytical procedures); and (iii) the … |

**For force-based design approaches, the generality of the codes recommend a reduction of the q-factor (ranging between 10% and 30%), depending on the irregularity (in plan, in elevation, both).**

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# EC8 evolution – new generation

A new generation of the Eurocodes is under development.

The new Eurocode 8, **prEN 1998-1-2:2022 (*draft*)**, establishes **new ductility classes** and the approach for the evaluation and consideration of the **irregularities** presents some differences.

# prEN 1998-1-2:2022 (*draft*)

**Ductility classes**

**prEN 1998-1-2:2022 (*draft*)** – **Concrete** buildings

**DC1:** the overstrength capacity is taken into account, while the deformation capacity and energy dissipation capacity are disregarded.

**DC2:** the local overstrength capacity, the local deformation capacity and the local energy dissipation capacity are taken into account. Global plastic mechanisms are controlled.

**DC3:** the ability of the structure to form a global plastic mechanism at SD limit state and its local overstrength capacity, local deformation capacity and local energy dissipation capacity are taken into account.

| **EN 1998-1:2004** | **prEN 1998-1-2:2022 (*draft*)** |
|---|---|
| DCL (Low) | DC1 (Ductility Class 1) |
| DCM (Medium) | DC2 (Ductility Class 2) |
| | DC3 (Ductility Class 3) |
| DCH (High) | |

# prEN 1998-1-2:2022 (*draft*)

**Structural types** – Concrete buildings

| **EN 1998-1:2004** | **prEN 1998-1-2:2022 (*draft*)** |
|---|---|
| Frame system | Moment resisting frame (MRF) structure |
| Wall system | Ductile wall structure (coupled or uncoupled) |
| Dual system<br>Frame-equivalent dual system<br>Wall-equivalent dual system | Dual structure<br>Moment resisting frame-equivalent dual structure<br>Wall-equivalent dual structure |
| Large lightly reinforced walls system | Large walls structure |
| Torsionally flexible system | --- |
| Inverted pendulum system | Inverted pendulum structure |
| --- | Flat slab structure |

# prEN 1998-1-2:2022 (*draft*)

**Behaviour factor, *q***

| EN 1998-1:2004 | prEN 1998-1-2:2022 (*draft*) |
|---|---|
| $q = q_0 \cdot k_W \geq 1{,}5$ | $q = q_R \cdot q_S \cdot q_D \geq 1{,}5$ |
| $q_0$ is the **basic value** of the behaviour factor, dependent on the type of the structural system and on its regularity in elevation<br><br>$k_w$ is the factor reflecting the prevailing failure mode in structural systems with walls | $q_R$ behaviour factor component accounting for **overstrength** due to the **redistribution of seismic action effects in redundant structures**<br><br>$q_S$ behaviour factor component accounting for **overstrength** due to **all other sources**<br><br>$q_D$ behaviour factor component accounting for the **deformation capacity and energy dissipation capacity** |

# prEN 1998-1-2:2022 (*draft*)

**Torsionally flexible systems**: definition/verification

| | EN 1998-1:2004 | prEN 1998-1-2:2022 (*draft*) |
|---|---|---|
| Criteria to **classify/verify** if the building is a **torsionally flexible system** | $r_i \geq l_{s,i}$ | $r_i \geq l_{s,i}$<br>Clarification: when the first mode in one horizontal direction is substantially influenced by torsion |

=

# prEN 1998-1-2:2022 (*draft*)

**Regularity in plan**: criteria

| Criteria for regularity | EN 1998-1:2004 | prEN 1998-1-2:2022 (*draft*) - (Annex A.8) | |
|---|---|---|---|
| Lateral stiffness and mass distribution approximately symmetric in plan with respect to two orthogonal axes | | | = |
| The plan configuration is compact. For each set-back, the **area between the outline of the floor and a convex polygonal** line enveloping the floor does not exceed | 5% of the floor area | **15%** of the floor area | ≠ |
| The in plan stiffness of the floors is sufficiently large in comparison with the lateral stiffness of the vertical structural elements | | | = |
| The slenderness $\lambda = L_{max}/L_{min}$ of the building in plan dimensions is not higher than 4 | | *(this rule is exempted for particular configurations)* | ≈ |
| At each level *i* and for each direction of analysis *x* or *y*, the structural eccentricity $e_o$ and the torsional radius *r* satisfy two conditions | | | = |

In **prEN 1998-1-2:2022 (*draft*)** guidance rules for **in plan regularity** are included in Annex A.8, concerning a good practice for the design of earthquake resistant buildings.

# prEN 1998-1-2:2022 (*draft*)

**Regularity in elevation**: criteria

| Criteria for regularity | **EN 1998-1:2004** | **prEN 1998-1-2:2022 (*draft*)** | |
|---|---|---|---|
| All primary elements (cores, structural walls, frames and diaphragms) provide a continuous resisting system without interruption from the top of the foundation or the top of a rigid basement to the top of the building | | | = |
| Lateral stiffness and the mass of the individual storeys variations | Constant or reduce gradually. | **No more than 20%** relative to the storey below, without abrupt changes, from the base to at least one storey below the top storey | ≠ |
| Ratio of the actual storey resistance to the resistance required by the analysis | In framed buildings the ratio of the actual storey resistance to the resistance required by the analysis should not vary disproportionately between adjacent storeys. Special aspects of masonry infilled frames are specified | The ratio of the actual storey resistance to the resistance required by the analysis **does not vary by more than 30%** between adjacent storeys. Special aspects of masonry infilled frames are specified | ≠ |
| Setbacks | 3 geometrical conditions | *It was eliminated* | ≠ |

# prEN 1998-1-2:2022 (*draft*)

***q*-factor reduction** for torsional flexible systems and irregular structures (in plan and in elevation)

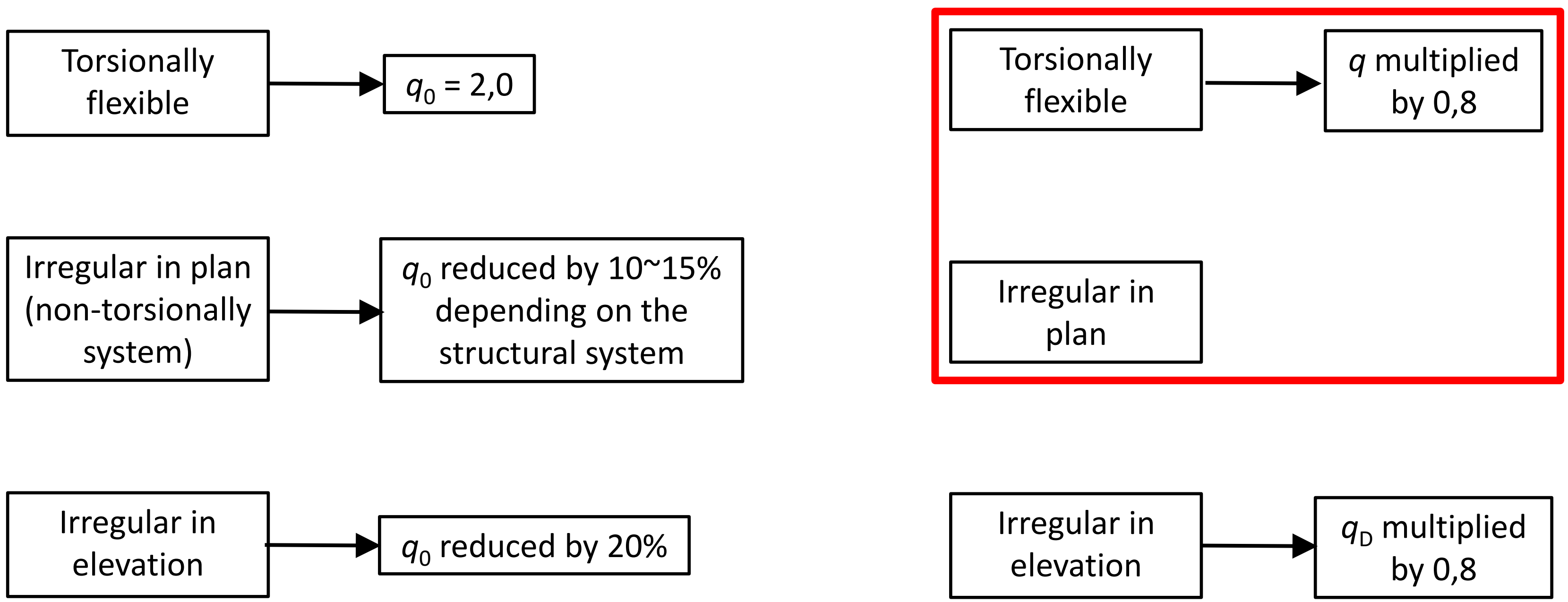
| | EN 1998-1:2004 | prEN 1998-1-2:2022 | |
|---|---|---|---|
| Torsionally flexible systems | The **system** is classified explicitly as "**torsionally flexible**" with f... maxim... | *q* defined bas... | ≠ |
| Irre... plan... | ... g on the ... (by **10~15%**) | *It is not proposed a reduction of the q-factor* | ≠ |
| Irregu... elevati... | $q_0$ should be **reduced** by **20%** | $q_D$ should be **multiplied by 0,8** | = |

**Lower penalties of q-factors for the in plan irregular structures !**

# prEN 1998-1-2:2022 (*draft*)

***q*-factor reduction** - Summary

**EN 1998-1:2004** | **prEN 1998-1-2:2022 (*draft*)**



# prEN 1998-1-2:2022 (*draft*)

**Minimum design eccentricity** in buildings

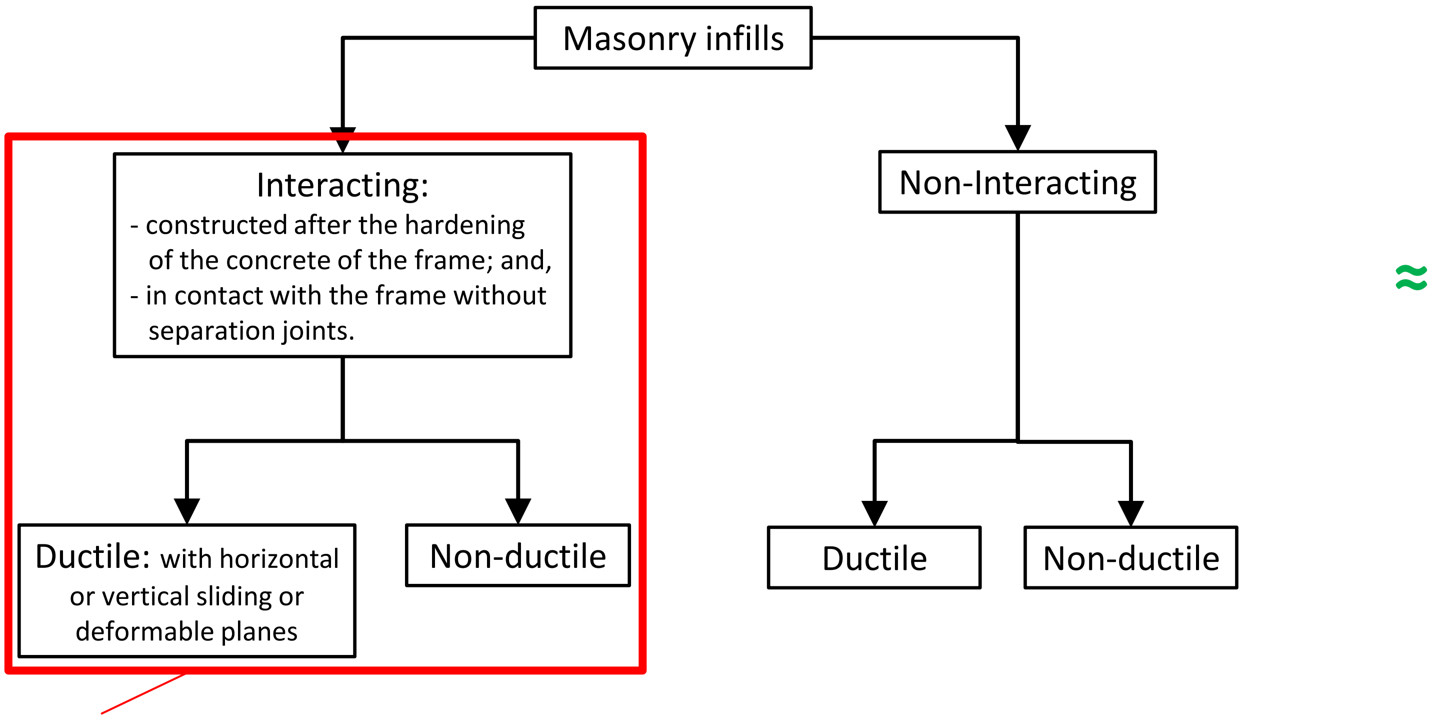
| EN 1998-1:2004 | prEN 1998-1-2:2022 (*draft*) |
|---|---|
| The calculated **centre of mass** at each floor *i* shall be considered as being **displaced** from its nominal location in each direction by an **accidental eccentricity**: $$e_{ai} = \pm 0{,}05 \cdot L_i$$ $e_{ai}$ is the accidental eccentricity of storey mass *i* from its nominal location, applied in the same direction at all floors. $L_i$ is the floor-dimension perpendicular to the direction of the seismic action. | A **minimal eccentricity**, measured perpendicularly to the considered direction *i* of the seismic action, should be calculated at every storey *j* and should be **taken into account if it exceeds the natural eccentricity** $e_{0,i,j}$. $$e_{min,i,j} = 0{,}05 \cdot L_{i,j}$$ $L_{i,j}$ is the width of the floors at the considered level *j*, measured perpendicularly to the direction *i* of the seismic action considered. |

≠

Annex B of **prEN 1998-1-2:2022 (*draft*)** gives procedures for the calculation of the natural eccentricity.

# prEN 1998-1-2:2022 (*draft*)

**Aspects regarding irregularities in frames with infills**




The effects of interacting infills on the building response should be taken into account, due to their influence in the regularity (in plan and in elevation)

# prEN 1998-1-2:2022 (*draft*)

**Aspects regarding irregularities in frames with Interacting Infills**

**Interacting infills** may be considered:
- a) with a model of the bare frame only (w/o modelling the infills)
- b) with a model of the interaction between frame and infills

Infills with **unsymmetrical arrangeme**…
spatial models).

The … considering the effect of

… of a structure of irregularity in elevation due to **interacting**
… into account.

W… **reduction** of more than **30%** of infills in a **storey**, the design should take into account the **increase of the seismic action effects in the structure**, adopting a magnification factor.

…

**The requirements for consideration of infills are strongly related with the concerns on the eventual irregular response of the building.**

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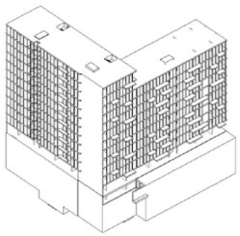
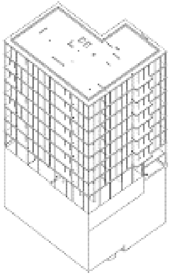
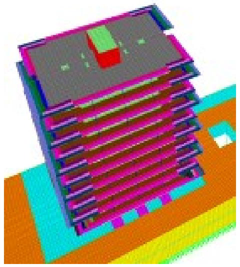
# Case studies: irregularity assessment



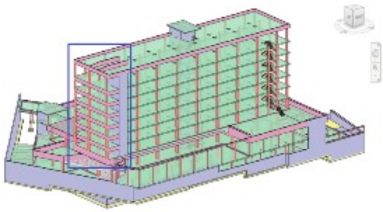
Building E01



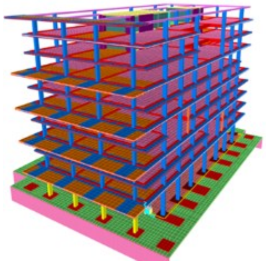
Building E02



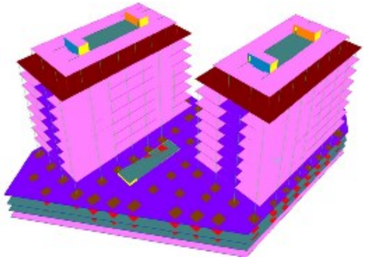
Building E03



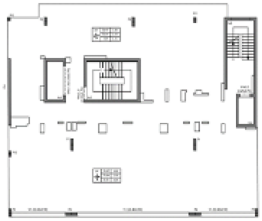
Building E04



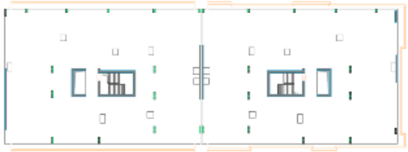
Building E05



Building E06



Building E07



Building E08

# Case studies: irregularity assessment

**8 buildings** recently designed (between 2018 and 2020);

All buildings located in Portugal;

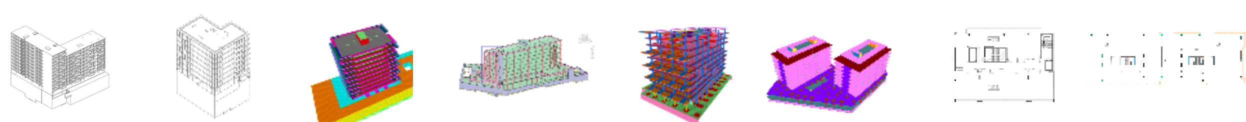
buildings with **8 to 12 storeys**;

4 residential buildings with services in the ground-storey, 2 office buildings and 2 hotels;

**only 2 buildings** have **constant inter-storey height**;

all buildings with structural systems composed by **RC columns and walls**, with **flat slabs**;

**5 designed** according to **EN 1998-1 (2004)** and **3** according to the **Portuguese national code** (RSA – application accepted until November 2022).

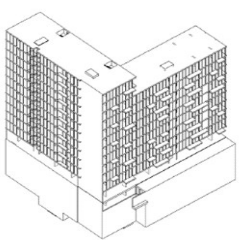
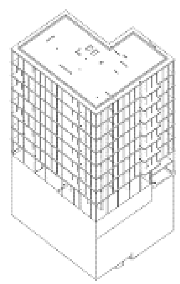
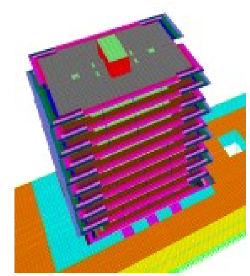
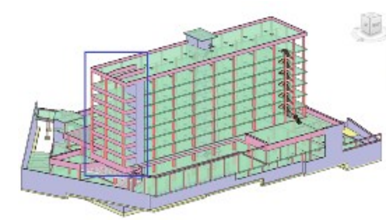
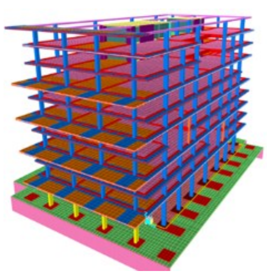
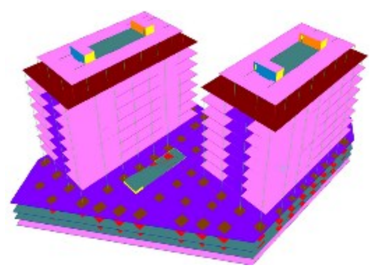
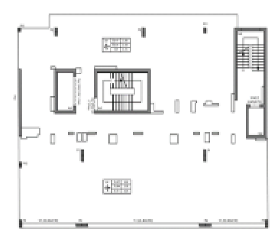


# Case studies: irregularity assessment

**Systems classification**

The **8** buildings are classified as **wall systems**, in both directions, with a **frame/total stiffness ratio** lower than 5,7%.

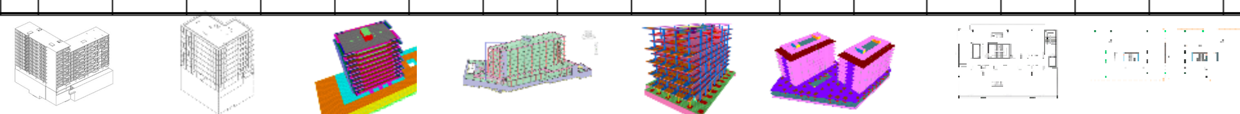
**7** structures are classified as **torsionally flexible** buildings, based on the disposition and stiffness of the vertical elements.


# Case studies: irregularity assessment

## Regularity criteria in plan - Results

| Criteria | | E01 | | E02 | | E03 | | E04 | | E05 | | E06 | | E07 | | E08 | | EC8 2004 | | *draft* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | EC8 2004 | *draft* | EC8 2004 | *draft* | EC8 2004 | *draft* | EC8 2004 | *draft* | EC8 2004 | *draft* | EC8 2004 | *draft* | EC8 2004 | *draft* | EC8 2004 | *draft* | X % | ✓ % | X % | ✓ % |
| Lateral stiffness ~ symmetric | x | X | X | X | X | ✓ | ✓ | X | X | ✓ | ✓ | X | X | X | X | X | X | 75 | 25 | 75 | 25 |
| | y | X | X | X | X | ✓ | ✓ | X | X | ✓ | ✓ | ✓ | ✓ | X | X | ✓ | ✓ | 50 | [illegible] | [illegible] | 50 |
| Mass distribution ~ symmetric | x | X | X | X | X | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [illegible] | [illegible] | [illegible] | [illegible] | 75 |
| | y | X | X | ✓ | ✓ | ✓ | ✓ | X | X | ✓ | ✓ | ✓ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 62,5 |
| Plan configuration compact | | X | X | X | ✓ | ✓ | ✓ | X | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 75 |
| | | X | X | X | X | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | |
| Rigid diaphragm condition | x | ✓ | ✓ | X | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12,5 | 87,5 | 12,5 | 87,5 |
| | y | X | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ✓ | ✓ | ✓ | 37,5 | 62,5 | 37,5 | 62,5 |
| Slenderness λ... *L*max/*L*... | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 12,5 | 87,5 | 0 | 100 |
| Eccentric... and the t... radius *r* | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | X | X | X | X | X | X | X | X | X | X | 100 | 0 | 100 | 0 |
| | | [illegible] | [illegible] | X | X | X | X | ✓ | ✓ | X | X | X | X | ✓ | ✓ | ✓ | ✓ | 62,5 | 37,5 | 62,5 | 37,5 |
| Masonry infills | x | X | X | X | X | ✓ | ✓ | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | 66,6 | 33,3 | 66,6 | 33,3 |
| | y | X | X | X | ✓ | ✓ | ✓ | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | 66,6 | 33,3 | 33,3 | 66,6 |



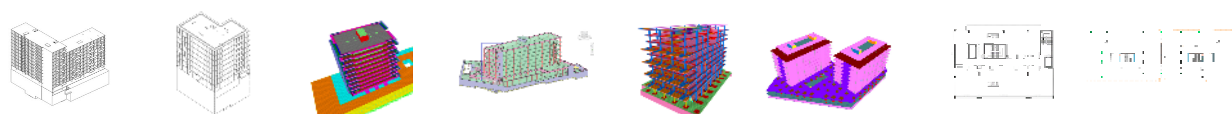
**All buildings studied are classified as irregular in plan, both according to EN 1998-1:2004 and to prEN 1998-1-2:2022 (draft) !**

# Case studies: irregularity assessment

**Regularity criteria in elevation - Results**

| Criteria | | E01 EC8 2004 | E01 *draft* | E02 EC8 2004 | E02 *draft* | E03 EC8 2004 | E03 *draft* | E04 EC8 2004 | E04 *draft* | E05 EC8 2004 | E05 *draft* | E06 EC8 2004 | E06 *draft* | E07 EC8 2004 | E07 *draft* | E08 EC8 2004 | E08 *draft* | EC8 2004 X % | EC8 2004 ✓ % | *draft* X % | *draft* ✓ % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vertical elements continuous up to the top | | X | X | X | X | ✓ | ✓ | X | X | ✓ | ✓ | X | X | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 75 | 25 |
| Lateral stiffness or gradual decrease | x | X | X | ✓ | ✓ | ✓ | ✓ | X | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 25 |
| | y | X | X | X | X | ✓ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 87,5 | 12,5 | 87,5 | 12,5 |
| | (x, y) | X | X | X | X | ✓ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | |
| Constant mass or gradual decrease | | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ✓ | ✓ | ✓ | ✓ | 37,5 | 62,5 | 25 | 75 |
| Setbacks | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | ✓ | - | X | - | X | - | X | - | 62,5 | 37,5 | - | |
| Masonry infills | | [illegible] | [illegible] | [illegible] | [illegible] | ✓ | X | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | 0 | 100 | 33,3 | 66,6 |
| | | [illegible] | X | ✓ | ✓ | ✓ | X | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | 0 | 100 | 33,3 | 66,6 |

**7 (out of 8) buildings studied are classified as irregular in elevation, both according to EN 1998-1:2004 and to prEN 1998-1-2:2022 (draft) !**



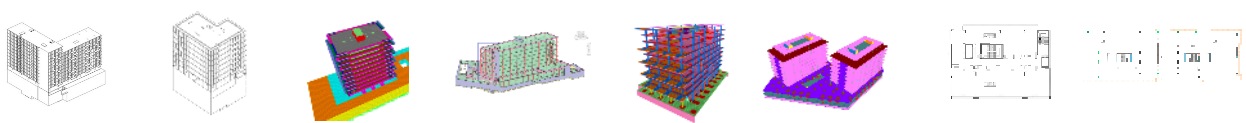
# Irregularities

**Open research questions?**

Considering that the **regular structures are "uncommon"**:

In design, the **rigour** of criteria adopted in the **regularity classification** of the structures (regular/irregular), as well as in the quantification of the consequent penalties (*q*-factor reduction), is **not in line** with the **degree of rigour adopted in other design phases** (e.g. design verifications and detailing….)?

**Is it adequate** to keep in codes a **binary classification of the regularity** (in plan and in elevation): (regular/irregular)?
Or, should we have different **levels of irregularity** (**at least two**) for the classification of the regularity (regular/irregular/strongly irregular)?
Such strategy could eventually impact different issues of design (*q*-factor, design rules, detailing…).



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# Influence of infill masonry walls in buildings' response

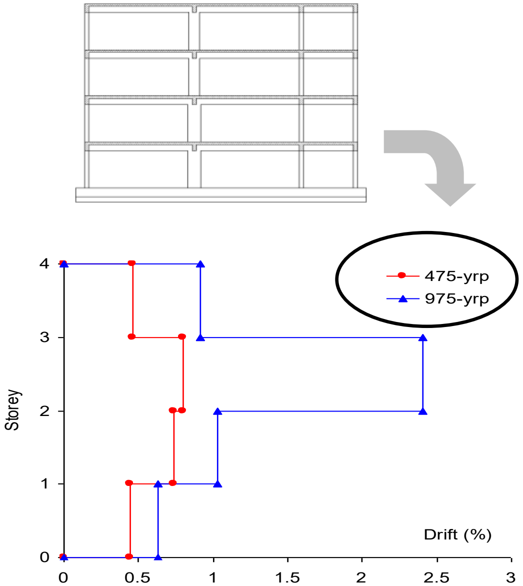
- **Infill masonry (IM) panels** are usually considered in the new RC building structures design, as well as in the assessment of existing ones, as non-structural elements

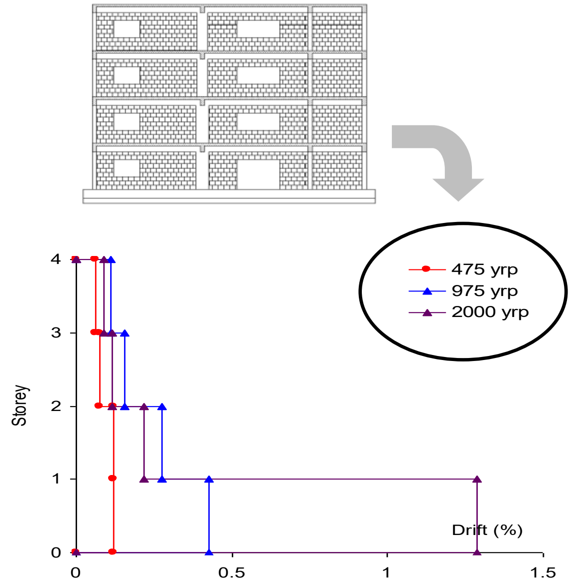
- Infill masonry panels may change considerably:
  - the global lateral stiffness and strength of building structures
  - their natural frequencies and vibration modes
  - the energy dissipation capacity
  - a brittle behaviour and failure mechanism

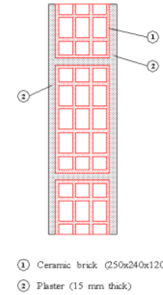
- Common infill masonry panels can modify drastically the global structural behaviour

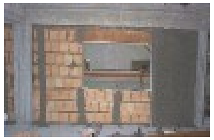



# ICONS Project: Infilled Frame response



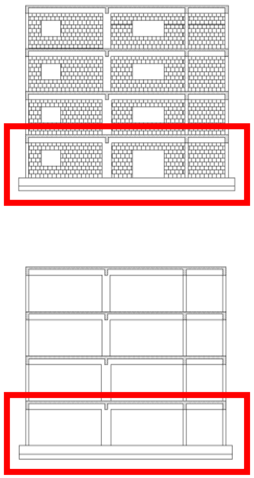
Bare Frame (BF) *vs* Infilled Frame (IN): Important changes of structural response

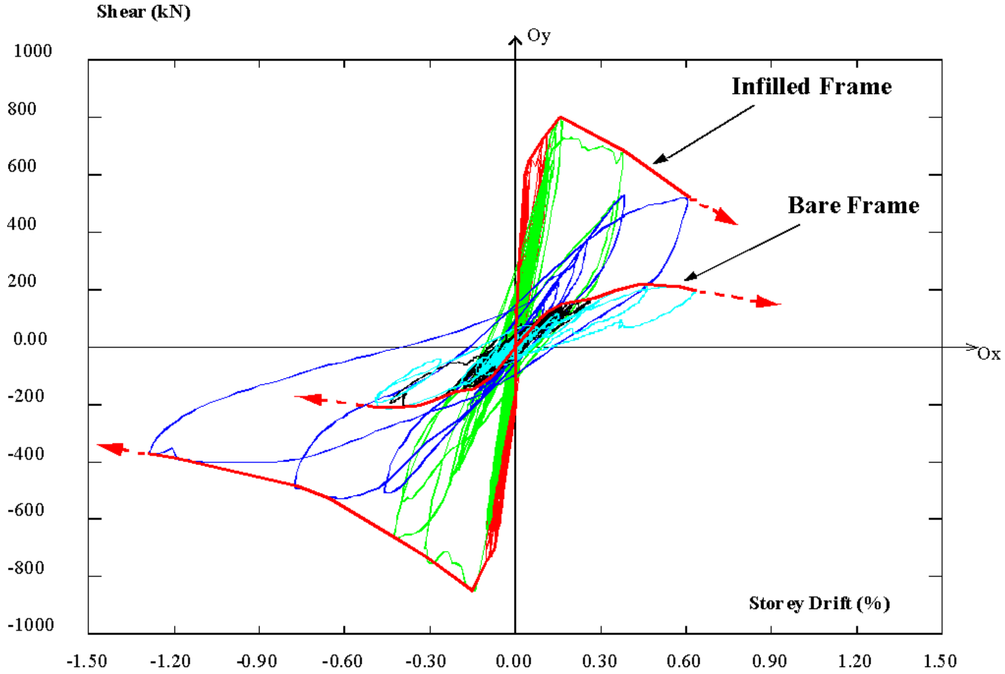
Infilled Frame (IN): → For low/medium seismic loadings masonry protects the structure

→ For medium/high levels tend to induce undesired mechanisms

(Pinto *et al.*, 2000)

# ICONS Project: Infilled Frame response






- Infilled frame (IN) showed higher storey shear capacity than bare frame (BF)
- Brittle behaviour may occurs in the infills, and the load distribution on the frame may be changed, eventually increasing the vulnerability of the frame/infills system

(Pinto *et al.*, 2000)

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# Numerical studies: influence of infills (IP)

*Costa-Cabral*, 1953

- Rectangular geometry in plan (37.2 x 16.4 $m^2$)
- 8 storeys
- 4 longitudinal frames (X)
- 10 transverse frames (Y)
- Technical storey between the ground storey and the 1st storey

*Parnaso*, 1955

- Rectangular in plan geometry (26.2 x 9.9 $m^2$)
- 6 storeys
- 3 longitudinal frames (X)
- Staircases isolated from the housing block by an expansion joint

*Infante Santo*, 1954

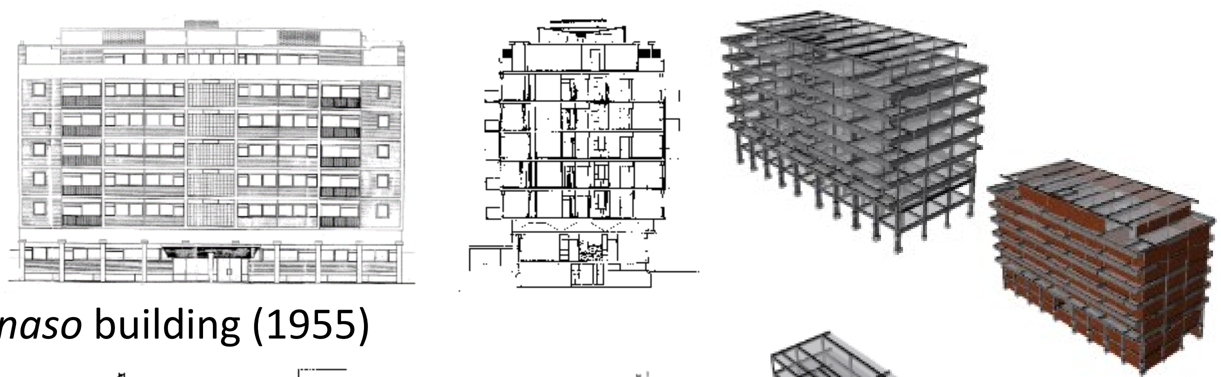
- Rectangular in plan geometry (46.1 x 11.1 $m^2$)
- 9 storeys
- 12 transverse frames (Y)
- Non-infilled ground-story

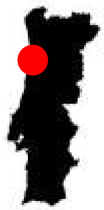
Location

# Numerical studies: influence of infills (IP)

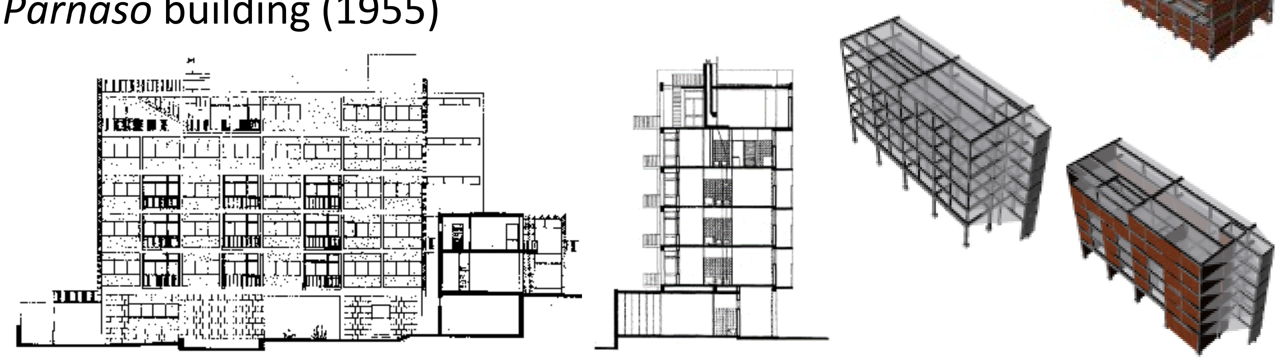
Information from blueprints (structure and infills), checked (*in loco* inspections)
Calibration of the models with *in-situ* dynamic measurements
Non-linear dynamic time-history analysis with *SeismoStruct* software

*Costa Cabral* building (1953)



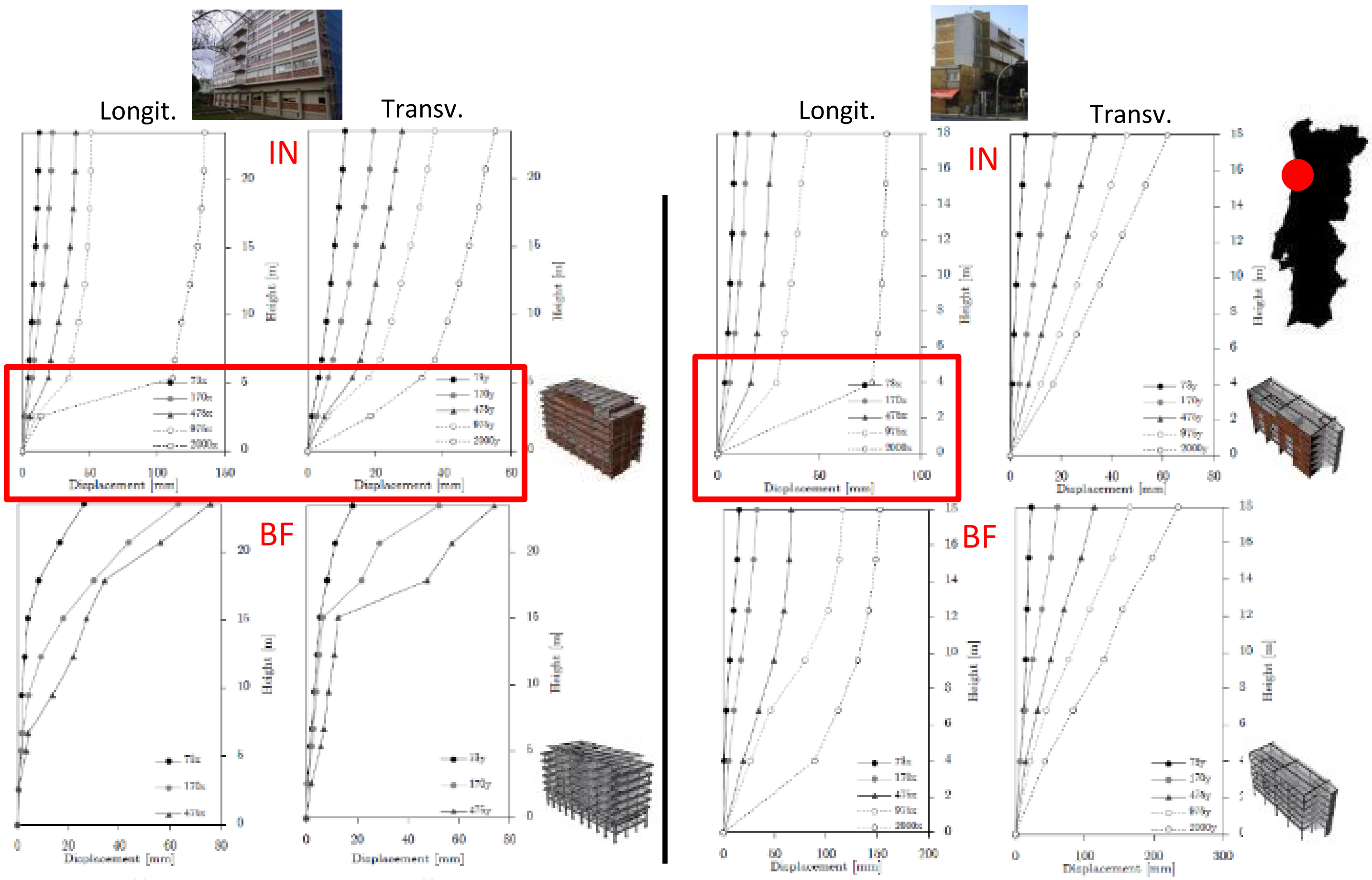


*Parnaso* building (1955)



# Numerical studies: influence of infills (IP)

**Regular structures with regular distribution of infills**



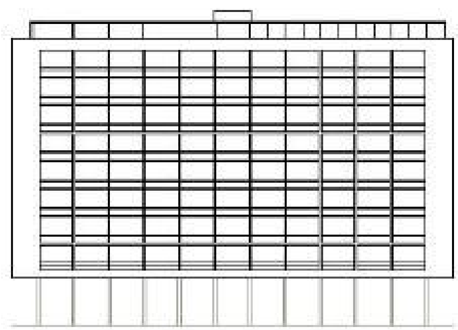

Concentration of deformations demands in the first storeys after failure of infills.

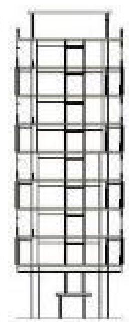
# Numerical studies: influence of infills (IP)

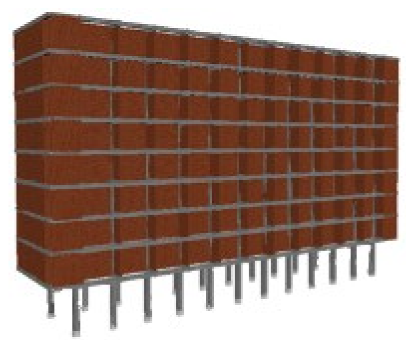
Regular structure with **irregular** distribution of infills

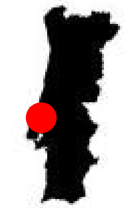
Information from blueprints (structure and infills), checked (*in loco* inspections)
Calibration of the models with *in-situ* dynamic measurements
Non-linear dynamic time-history analysis with *SeismoStruct* software

*Infante Santo* building (1954)





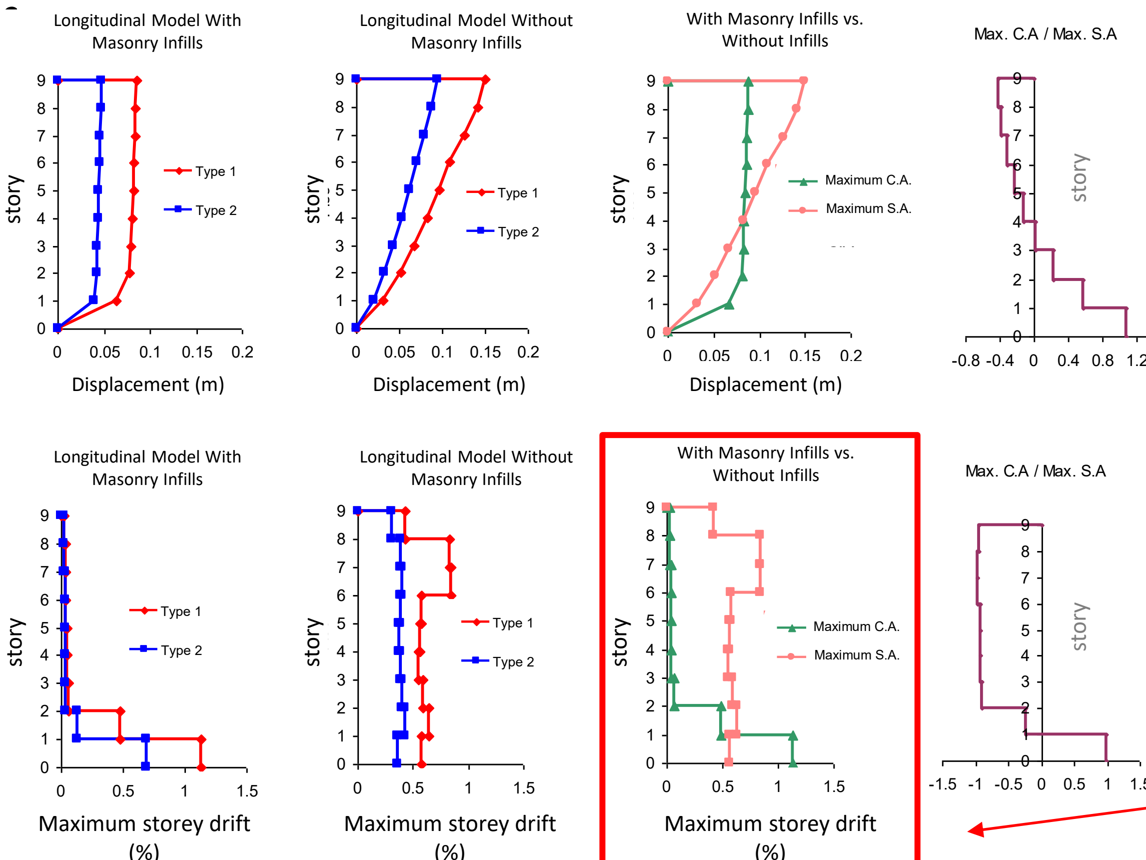


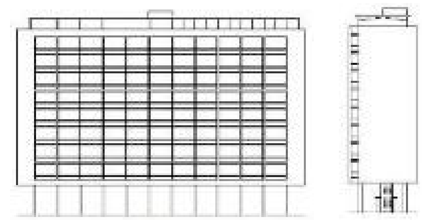


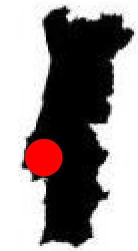
# Numerical studies: influence of infills (IP)

<u>Regular structure with **irregular** distribution of infills</u>

*Infante Santo* building, Longitudinal





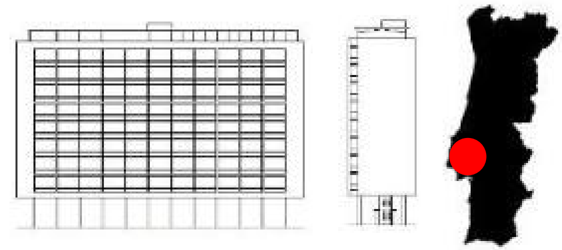
Pronounced irregular behaviour induced by the infill walls

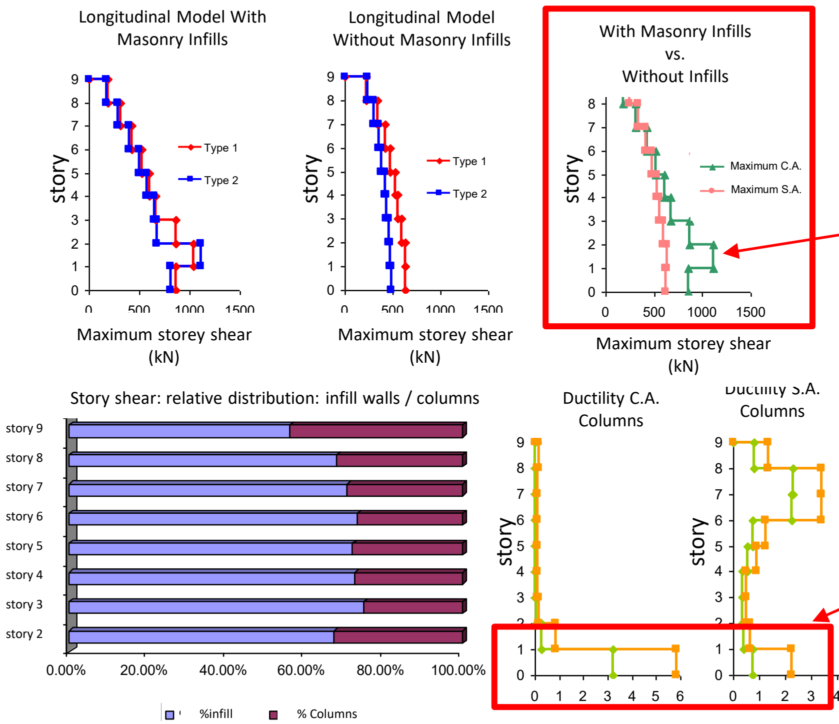
2x max. IS-Drift demand at 1$^{st}$ storey

# Numerical studies: influence of infills (IP)

<u>Regular structure with **irregular** distribution of infills</u>

*Infante Santo* building, Longitudinal direction






~2x max. storey shear

~3x max. ductility demand in columns

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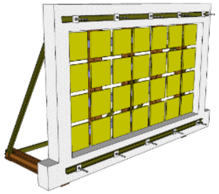
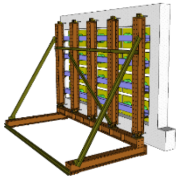
# OOP behaviour

## Why?

(L'Áquila, Italy, 2009)


(LESE Laboratory, FEUP, 2018)

- Inadequate connection between the masonry infill and the surrounding RC frame
- Inadequate wall support conditions of the exterior panel (correction of the thermal bridges purposes)
- High panel' slenderness
- Poor workmanship quality (can influence the panel boundary conditions)
- No wall ties in double leaf or veneer walls
- OOP instability (after IP damage)


# OOP behaviour

Laboratory tests on **as-built specimens**

### Reduction of the panel or brick breadth support conditions over the beam/slab

Reduced deformation capacity | **Reduction** of **strength** and **energy dissipation** of about **~60%**

### Influence of workmanship quality

Variation of the **maximum strength ~50%** | **Collapse displacement** varies **~20%**

### Different masonry units

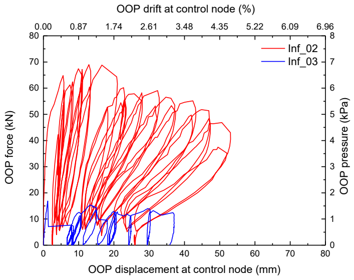
Panels made with **large masonry units** (i.e. strong infills) presented a **low collapse vulnerability**. However, these units can play an important role in the IP behaviour of frames…

### Influence of previous IP damage (IP+OOP)

Medium IP drift (0.3%): Maximum strength reduced of ~35%

High **IP drift (0.5%)**: **Maximum strength reduced ~70%**

Energy dissipation reduced **~90%**

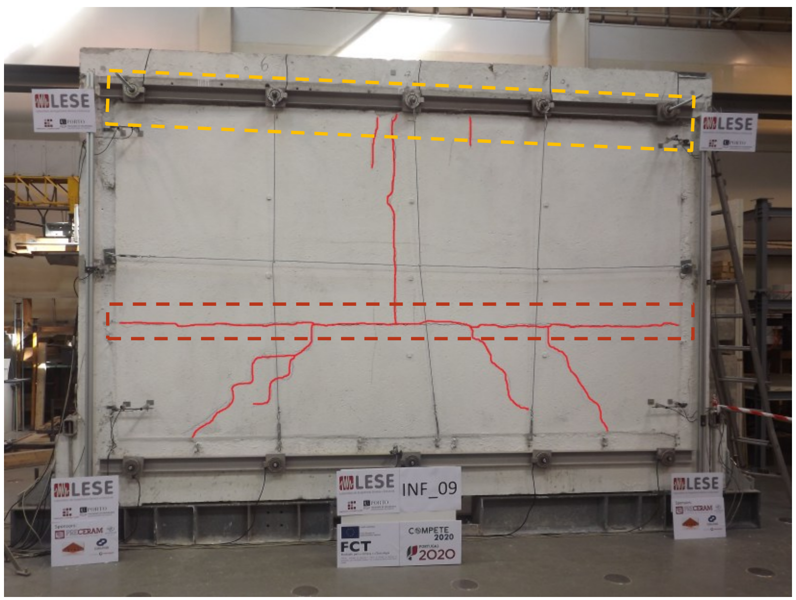



# Retrofitting of IM walls to prevent the OOP collapse

**Retrofitting** technique: Textile-Reinforced Mortar (TRM)

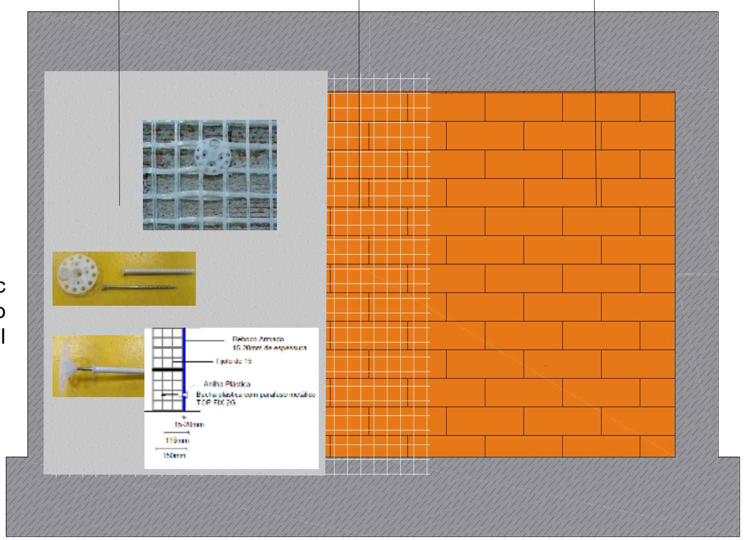
Traditional mortar (M5)

## Reference panel (as-built)




Same geometry, materials and loading protocol

## Retrofitted panel (TRM)




Steel connectors - connecting the reinforcement to the RC elements

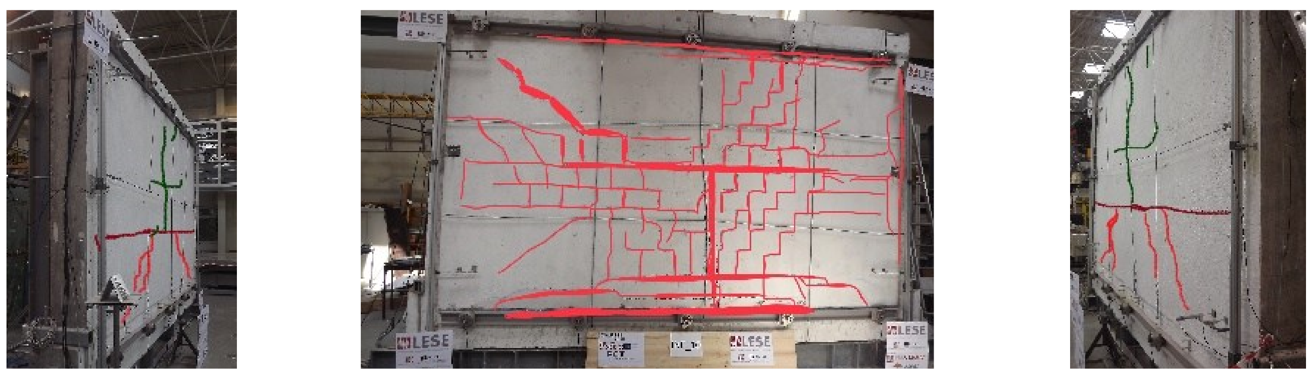
# Retrofitting of IM walls to prevent the OOP collapse

Out-of-plane tests of masonry infill walls (as-built and retrofitted)

Final Damage state

Reference panel (as-built)
(max OOP disp. 30mm)

Retrofitted panel (TRM)
(max OOP disp. 70mm)



# Retrofitting of IM walls to prevent the OOP collapse

**Retrofitting** technique: Textile-Reinforced Mortar (TRM)

**Reference panel (as-built)**


**Retrofitted panel (TRM)**


**$F_{max}$ +30%** | **$d_{max}$** +240% (**collapse prevented**) | $E_{dissipation}$ +60%

# Retrofitting of IM walls to prevent the OOP collapse

Combined **Seismic + Energy** retrofitting solutions (**SpE**)

**In Portugal**, **RC buildings**:

represents about **60%** of the **building stock** | **house** approximately **65%** of its **population**

**Half** of these buildings were **not designed** according to **modern seismic codes**

**70%** were **not designed** according to any **energy or thermal regulation** (first Portuguese thermal code: 1990)

Also, **Energy poverty: 20% !**

There is a strong need of SpE retrofitting solutions.

# Retrofitting of IM walls to prevent the OOP collapse

**Combined Seismic + Energy** retrofitting solutions (**SpE**)

Solutions tested (LESE Laboratory):

1 – Traditional ETIC system (E_0)

2 – Improved ETIC system (ES_1)

3 – TRM + ETIC system (ES_2)

4 – Reinforced Thermal plaster (ES_3)

ETICS - External Thermal Insulation Composite Systems

With the technical support of: FASSA BORTOLO

# Strengthening of IM walls to prevent the OOP collapse

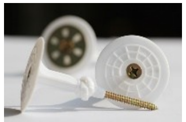
Combined **Seismic + Energy** retrofitting solutions (**SpE**)

Performance of **Improved ETIC** system (ES_1)

Improved External Thermal Insulation Composite System:

- **EPS** (Expanded Polystyrene) **plate** (thickness: 6cm)
- **GFRP structural mesh**
- **Plastic connectors w/ steel bolts** (6 per m$^2$)
- The last layer is made of the non-structural GFRP mesh





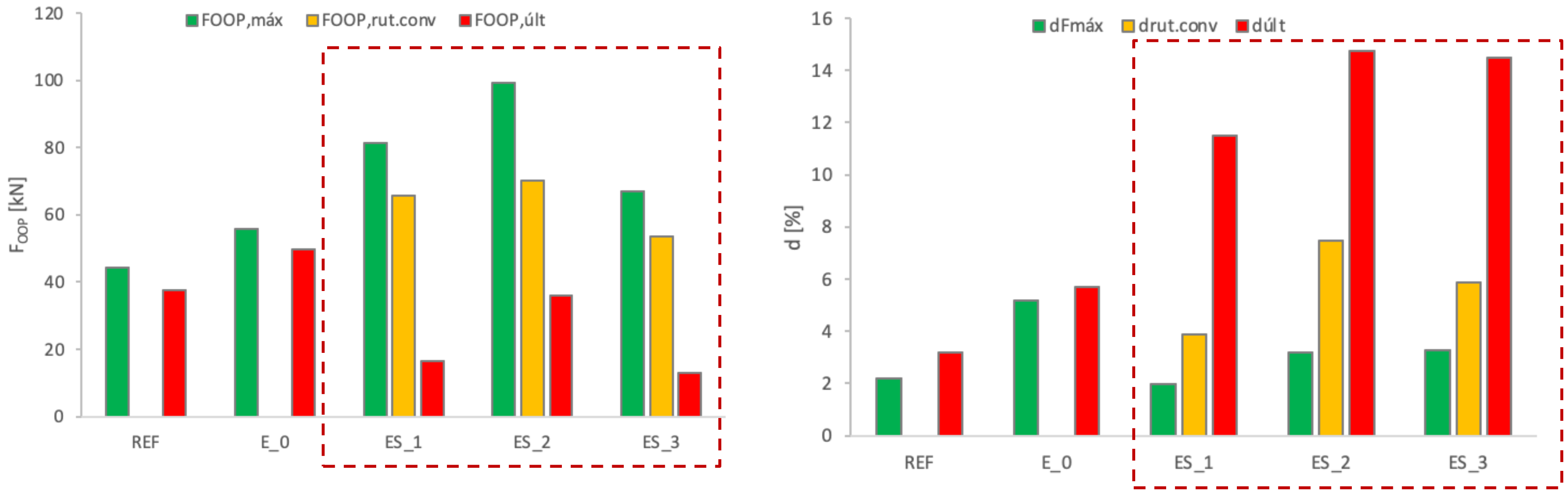





With the technical support of: FASSA BORTOLO

# Comparison between SpE retrofitting solutions

## Maximum Strength and Deformation Capacity




**Results from the tested SpE retrofitting solutions:**

Increased the load capacity (between **1,5x to 2,25x**)

Larger maximum displacements imposed (**preventing the collapse**) ($d_{ult}$) (between **3,5x to 4,6x**)

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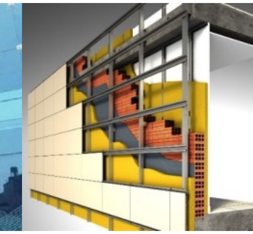
# Current construction practice



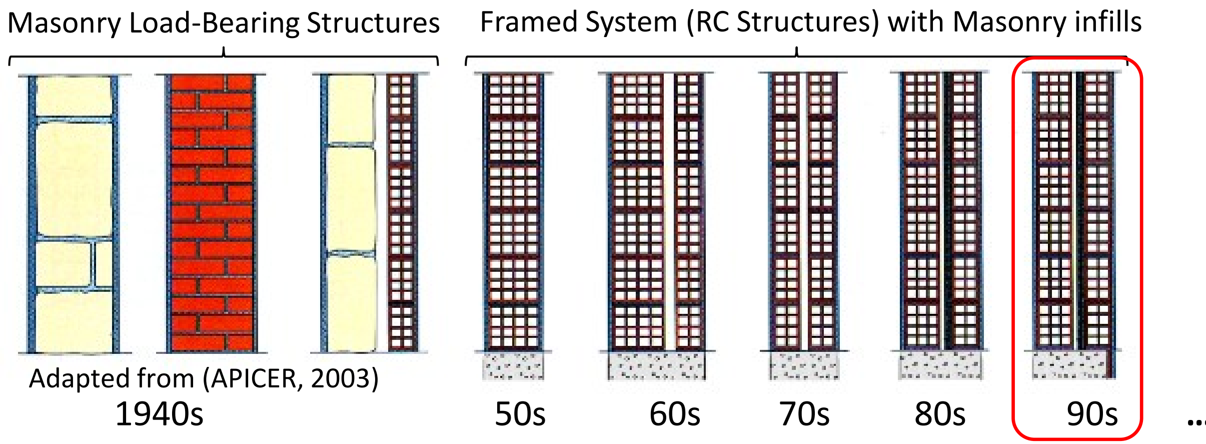
# Evolution of the structural systems

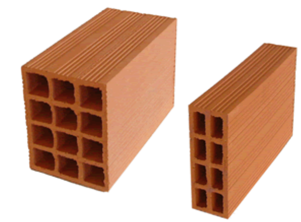
RC building structures:
Common solutions adopted

Frame Structures; Ductile walls

Flat slabs;
Precast elements (Structural and in the facades)

# Evolution of exterior Masonry walls in Southern Europe regions

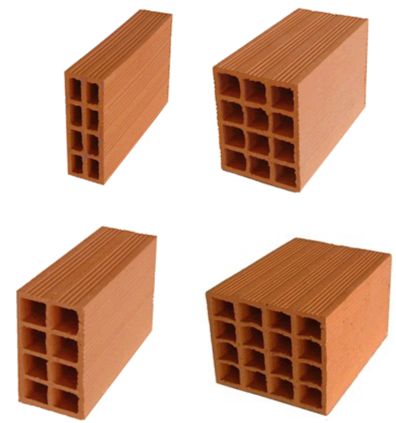


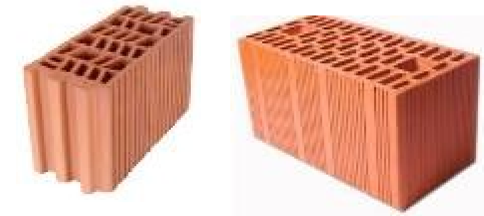
- The type of units and the dimensions and detailing of infill walls have been influenced by the emerging requirements in terms of thermal and acoustical performance
- Associated to these new requirements, new solutions and materials were also introduced: perforated clay bricks, isolating layers, air gaps, "*thermal*" blocks, etc.
- The connection of the infill walls with the main structural system and between internal and external layers was progressively improved
- In any case, up to a recent past, these "non-structural" elements where generally disregarded in the structural design and analysis of buildings. Their behaviour and influence in the seismic structural response was considered negligible or, wrongly, it was commonly assumed that if ***"…they influence the structural response and safety, it is in its benefit!"***

# Masonry units of common use

Construction practice in Southern European regions

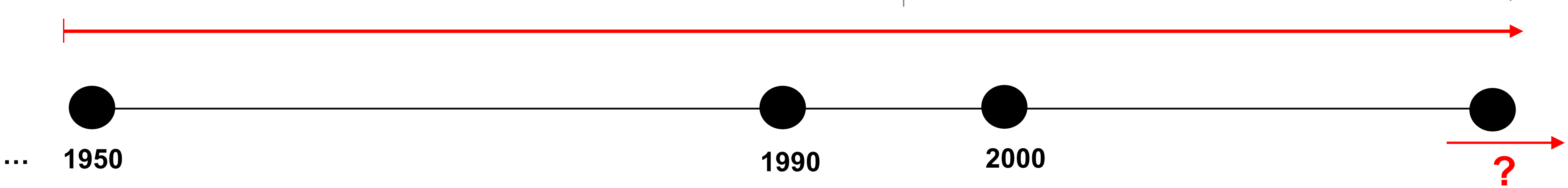


Horizontal hollow clay bricks
with different dimensions (thickness)



Vertical hollow clay bricks

Vertical hollow concrete blocks



# Current design and construction practice

In some Southern European regions, the following solutions are nowadays commonly adopted in façade walls:

- horizontal-hole bricks (with more than 60% of voids)
- double or single masonry panels, confined by the RC structural elements
- without connection to the main structure
- absence of connectors between panels
- correction of thermal bridges with mechanically unstable solutions




Even when the constructive details for the walls construction are provided, they basically consist of typified solutions for common situations, without giving particular attention to the singular points

# Current construction practice

IN masonry walls with horizontal hollow clay bricks:

How will these buildings perform in the next earthquakes?

# Current construction practice

IN masonry walls with horizontal hollow clay bricks:

How will these buildings perform in the next earthquakes?

# Current construction practice

IN masonry walls with different types of units:

Bare Frame/Wall RC structure – Stage 1

RC structure with different types of IM walls – Stage 2

How will these buildings perform in the next earthquakes?

Lisbon (Portugal)

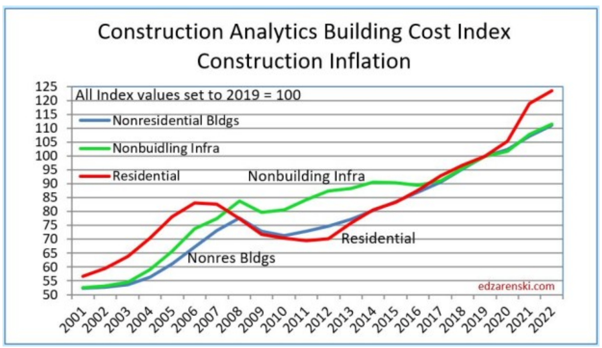
# Current construction practice

IN masonry walls with vertical hollow concrete blocks:

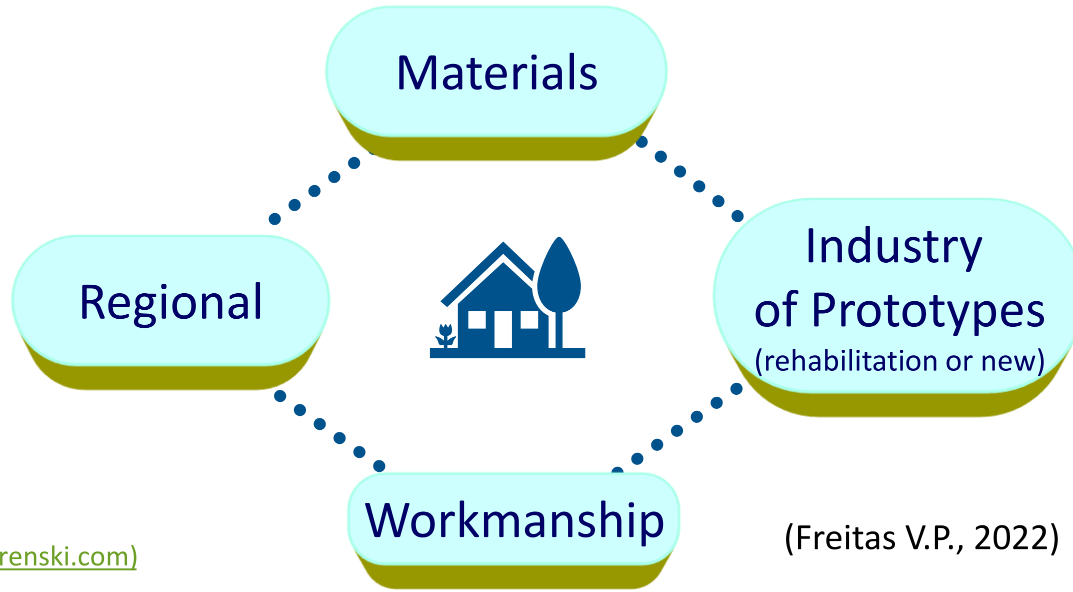
How will these buildings perform in the next earthquakes?

# The Future…

Construction **costs**?




Construction Inflation 2021 « Construction Analytics (edzarenski.com)



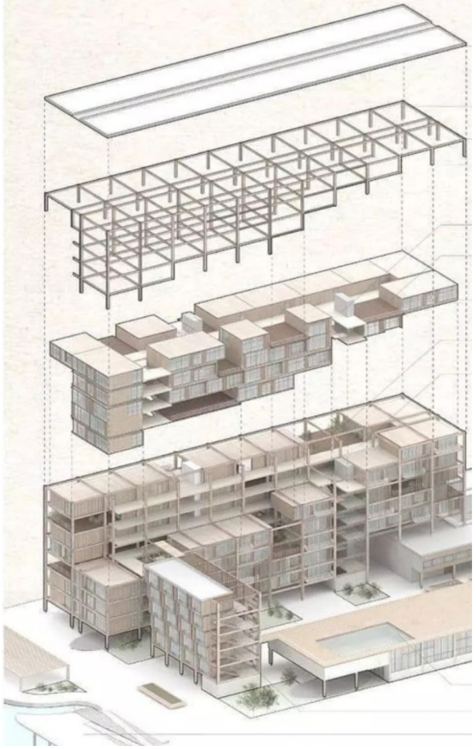

(Freitas V.P., 2022)

# The Future…

Construction **costs**?

**<u>Construction costs</u>** (current buildings):

- General costs (Construction site, Demolitions, Earthworks, Soil decontamination, Exterior arrangements, Archaeology…)
- **Structure** (foundations, superstructure)
- Envelope (system, insolation, covering,…)
- Interior (non structural) – (Interior walls, Coatings, Doors, Sanitary equipment, Kitchen equipment,…)
- Instalations (Electrical, Telecommunications, Security and Fire Safety, Gas, Water drainage, Water supply, HVAC, Renewable energies, Elevators,…)

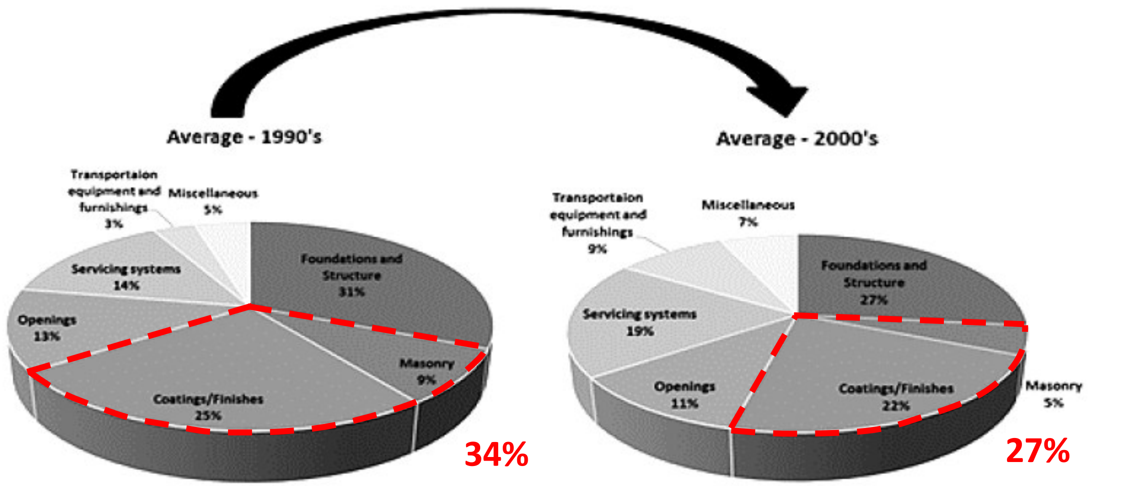


(Freitas V.P., 2022)

# Costs in current buildings…

## Current buildings in Southern European regions

Distribution of the economic weight of the different building elements



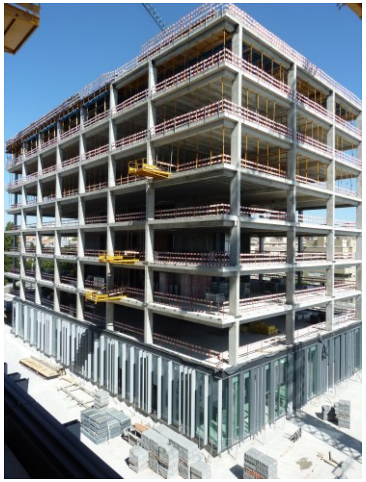

Exemplo da distribuição do peso económico dos diferentes elementos dos edifícios entre os anos 90 e início do século XXI [7].

(Mêda, Sousa and Ferreira; 2016)

- **Foundations + Structure** parcial costs tends to reduce: **31% → 27% ↘?**
- **Partition and envelope walls** represent an important share of the total construction costs (masonry + finishings): **~30%**
- Damages in walls may have associated high repair/reconstruction costs…

# Precast RC structures and elements…

In many regions, it is noticed in the design and construction of current buildings (structures and façade elements) a **sudden growth** of the interest/adoption of **precast systems**, **components** and **solutions** (due to the recognised **advantages**: speed of construction, lower costs, products quality and performance checks, material durability,…).



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# Code requirements

## Eurocode 8 (2004) recommendations/requirements

**EC8** highlight the following **principles** regarding the structural conception/design:

- Structural simplicity
- Uniformity, symmetry and redundancy
- Bi-directional strength and stiffness
- Torsional resistance and stiffness
- Rigid diaphragm at storey level
- Adequate foundations

**IM walls with high potential influence**

Those principles should influence the structural system configuration definition. If they are followed associated with the remaining code dispositions and requirements, **structures** will tend to **perform better** for the expected earthquake **demands**.

# Code requirements

Eurocode 8 (2004)

## Ductility classes

- Low ductility (DCL): only recommended for regions with low ... ying almost only provisions from Eurocode 2. This type of stru... sustain seismic action within elastic range. In se... nded a design for other DCs, with provisions a... ic capacity to dissipate energy at specific building criti...

**IM walls with high potential influence**

- Medium ductility (DCM)
- High ductility (DCH)

→ should not have any type of brittle failure in any element

# Open research questions

Should the codes allow the **design of building** structures for **high levels of ductility** when they have **interacting non-ductile infills**?

# Code requirements

## Requirements for design and detailing of RC elements

Table 2.5: General performance recommendations according to the different ductility classes by Eurocode 8 [CEN, 2003; Fardis, 2009].

| General | DCL | DCM | DCH |
|---|---|---|---|
| Concrete | none | $> C16/20$ | $> C20/25$ |
| Steel | Ductility class B or C | Class B or C | Class C |
| Steel conditions | EC2 | Ribbed bars (except closed stirrups and cross-ties) | Ribbed bars (except closed stirrups and cross-ties) |
| Steel overstrength | none | none | $f_{yk,0.95} \leqslant 1.25 f_{yk}$ |
| **Beams** | **DCL** | **DCM** | **DCH** |
| Dimensions | - | $b_w \leqslant \min(b_c + h_w; 2b_c)$ | $b_w \leqslant \min(b_c + h_w; 2b_c)$<br>$b \geqslant 20cm$<br>$b/h \geqslant 0.25$ |
| Design forces | Structural Analysis | $V_{Sd}$ with extreme moments<br>$\gamma_{Rd} = 1.0$ | $V_{Sd}$ with extreme moments<br>$\gamma_{Rd} = 1.2$ |
| Strength | EC2 ($1 \leqslant \cot\theta \leqslant 2.5$) | EC2 ($1 \leqslant \cot\theta \leqslant 2.5$) | EC2 ($1 \leqslant \cot\theta \leqslant 2.5$) (*) |
| Critical region (CR) | $h_w$ | $h_w$ | $1.5h_w$ |
| Min. long. reinf. | $\rho_{min} = 0.26 f_{ctm}/f_{yk} \geqslant 0.13\%$ | $\rho_{min} = 0.5 f_{ctm}/f_{yk}$ | $\rho_{min} = 0.5 f_{ctm}/f_{yk}$ |
| Min. long. reinf. | - | $A_{inf} \geqslant 0.5 A_{sup}$ | $A_{min,inf} = A_{max,inf}/4$<br>$A_{inf} \geqslant 0.5 A_{sup}$<br>$A_{min,sup} = A_{min,inf} = 2\phi 14$ |
| Max. long. reinf. | $\rho_{max} = 4\%$ | $\rho_{max} = \rho' + 0.0018 f_{cd}/(\mu_\phi \varepsilon_{Sy,d} f_{yd})$ | $\rho_{max} = \rho' + 0.0018 f_{cd}/(\mu_\phi \varepsilon_{Sy,d} f_{yd})$ |
| Interior joints | - | $d_{bl}/h_c \leqslant 7.5 f_{ctm}(1 + 0.8\nu_d)/(f_{yd}(1 + 0.5\rho'/\rho_{max}))$ | $d_{bl}/h_c \leqslant 6.25 f_{ctm}(1 + 0.8\nu_d)/(f_{yd}(1 + 0.75\rho'/\rho_{max}))$ |
| Exterior joints | - | $d_{bl}/h_c \leqslant 7.5 f_{ctm}(1 + 0.8\nu_d)/f_{yd}$ | $d_{bl}/h_c \leqslant 6.25 f_{ctm}(1 + 0.8\nu_d)/f_{yd}$ |
| Out of CR | $s_w \leqslant 0.75$<br>$\rho_w 0.08\sqrt{f_{ck}/f_{yk}}$ | $s_w \leqslant 0.75$<br>$\rho_w 0.08\sqrt{f_{ck}/f_{yk}}$ | $s_w \leqslant 0.75$<br>$\rho_w 0.08\sqrt{f_{ck}/f_{yk}}$ |
| In CR | $d_{bw} \geqslant 6mm$ | $d_{bw} \geqslant 6mm$<br>$s_w \leqslant \min(h_w/4; 24d_{bw}; 225mm; 8d_{bL})$ | $d_{bw} \geqslant 6mm$<br>$s_w \leqslant \min(h_w/4; 24d_{bw}; 175mm; 6d_{bL})$ |
| **Column** | **DCL** | **DCM** | **DCH** |
| Dimensions | - | $b_c \geqslant h_v/10$ if $\theta (= P\delta/Vh) > 0.1$ | $b_c \geqslant 25cm$<br>$b_c \geqslant h_v/10$ if $\theta (= P\delta/Vh) > 0.1$ |
| Forces | Structural Analysis | $\gamma_{Rd}$=1.3, $M_{Sd}$ from beams' $M_{Rd}$<br>$\gamma_{Rd}$=1.1, $V_{Sd}$ from column extremities' $M_{Rd}$ | $\gamma_{Rd}$=1.3, $M_{Sd}$ from beams' $M_{Rd}$<br>$\gamma_{Rd}$=1.3, $V_{Sd}$ from column extremities' $M_{Rd}$ |
| Ultimate strength | EC2 | EC2 ($\vartheta_d \leqslant 0.65$) | EC2 ($\vartheta_d \leqslant 0.55$) |
| Biaxial bending | EC2 | Biaxial bending or simplified uniaxial bending with $M_{Rdx}$ e $_{Rdy}$ reduced in 30% | Biaxial bending or simplified uniaxial bending with $M_{Rdx}$ e $M_{Rdy}$ reduced in 30% |
| Critical region | $l_{cr} = \max(h_c; b_c)$ | $l_{cr} = \max(h_c; b_c; l_c/6; 45cm)$ | $l_{cr} = \max(1.5h_c; 1.5b_c; l_c/6; 60cm)$ |
| Min. long. reinf. (longitudinal) | $\rho_{min} = 0.01 N_d/A_c f_{yd} \geqslant 0.2\%$ | $\rho_{min} = 1.0\%$ - symmetric | $\rho_{min} = 1.0\%$ - symmetric |
| Long. bars per side | $\geqslant 2$ | $\geqslant 3$ | $\geqslant 3$ |
| Spacing between restrained bars | - | $\leqslant 200mm$ | $\leqslant 150mm$ |
| Distance of unrestrained bar from | - | $\leqslant 150mm$ | $\leqslant 150mm$ |
| Max. long. reinf. | $\rho_{max} = 4\%$ | $\rho_{max} = 4\%$ | $\rho_{max} = 4\%$ |
| Longitudinal bar diameter | $d_{bL} \geqslant 8mm$ | $d_{bL} \geqslant 8mm$ | $d_{bL} \geqslant 8mm$ |
| Transv. reinf. in CR | - | $d_{bw} \geqslant 6mm$<br>$s_w \leqslant \min(b_0/2; 175mm; 8d_{bL})$ | $d_{bw} \geqslant 0.4 d_{bL,max}\sqrt{f_{yd}/f_{ywd}}$<br>$s_w \leqslant \min(b_0/3; 125mm; 6d_{bL})$ |
| Transv. reinf. out of CR | $d_{bw} \geqslant \max(d_{bL}/4; 6mm)$<br>$s_w \leqslant \min(20d_{bL} 40cm; \min(h_c; b_c))$ | $d_{bw} \geqslant \max(d_{bL}/4; 6mm)$<br>$s_w \leqslant \min(20d_{bL} 40cm; \min(h_c; b_c))$ | $d_{bw} \geqslant \max(d_{bL}/4; 6mm)$<br>$s_w \leqslant \min(20d_{bL} 40cm; \min(h_c; b_c))$ |
| Confinement in CR | - | $d_{bw} \geqslant 6mm$<br>$s_w \leqslant \min(b_0/2; 175mm; 8d_{bL})$ | $\alpha\omega_{wd} \geqslant 30\mu_\phi \vartheta_d \varepsilon_{sy,d}(b_c/b_0) - 0.035$<br>$\omega_{wd} \geqslant 0.08$ |
| Confin. bottom of columns | - | $\alpha\omega_{wd} \geqslant 30\mu\varphi(\vartheta_d + \omega_v)\varepsilon_{sy,d}(b_c/b_0) - 0.035$<br>$\omega_{wd} \geqslant 0.08$ | $\alpha\omega_{wd} \geqslant 30\mu\varphi(\vartheta_d + \omega_v)\varepsilon_{sy,d}(b_c/b_0) - 0.035$<br>$\omega_{wd} \geqslant 0.12$ |

# Code requirements

Requirements for design of buildings considering the IM walls' influence

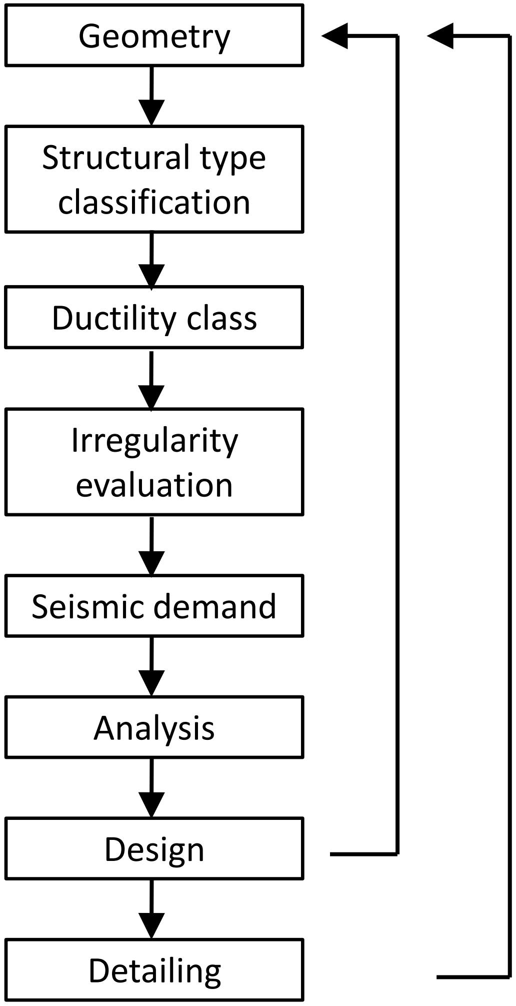
Table 2.7: Seismic standards on masonry infilled RC frames (adapted from [Kaushik *et al.*, 2006] and [Nazief, 2014]).

| Country & Reference | D | Natural period | Min. force (%) Frame | Inf | Irregularity Plan | Elev. | K | Drift | $\sigma_t$ | Infill $K_t$ | O | OOP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Albania [KTP-N2-89, 1989] | Y | | N | N | N | N | 1.2-1.5 | N | N | N | N | N |
| Algeria [RPA, 1988] | Y | $*_{ray} \vee T_a = \min\left\{0.09\frac{h}{\sqrt{d}}; 0.05h^{0.75}\right\}$ | 25 | N | N | N | 1.42 | N | N | N | N | N |
| Bulgaria [BCSC, 1987] | Y | X | N | N | N | Y | 1.5-3.0 | N | N | N | [illegible] | [illegible] |
| Canada [CSA-S304.1, 2004] | - | - | - | - | - | - | Y | - | [illegible] | [illegible] | [illegible] | [illegible] |
| China [GBJ-11, 1989] | Y | X | N | N | N | N | X | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Colombia [NSR, 1998] | Y | $*_{ray} \vee T_a = C_t h^{0.75}$ $C_t = \frac{.075}{\sqrt{A_c}}$ | 28 | 100 | N | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | $A_c = \sum A_i \left(0.2 + \min\left\{\frac{l_{wi}}{h}; 0.9\right\}\right)^2$ (m) | 25 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Costa Rica [CFIA, 1986] | Y | $T_a = 0.08N$ (infilled) \| $T_a = 0.1N$ (bare) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Egypt [ECP, 1988] | Y | $T_a = 0.09\frac{h}{\sqrt{d}}$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Ethiopia [ESCP-1, 1983] | Y | $T_a = 0.09\frac{h}{[illegible]}$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Europe [CEN, 2003] | Y | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| France [AFPS [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | N | N | N |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | Y | Y | Y | Y |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | X | N | N | N | N | N |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | Y | Y | 1.15 | N | Y | N | N | N |
| [illegible] | [illegible] | [illegible] | [illegible] | - | - | - | - | - | - | - | - | - |
| [illegible] | [illegible] | [illegible] | - | - | - | - | - | - | Y | Y | - | Y |
| [illegible] | [illegible] | [illegible] | 25 | N | Y | Y | 2 | Y | Y | N | Y | Y |
| [illegible] | [illegible] | [illegible] | - | - | - | - | N | - | - | - | - | - |
| [illegible] | [illegible] | $*_{ray} \vee T_a = C_t h^{0.75}$ $C_t = \frac{0.05048}{\sqrt{A_c}}$ | N | N | N | N | 1.5 | N | N | N | N | N |
| | | $A_c = \sum A_i \left(0.2 + \min\left\{\left(\frac{l_{wi}}{h}\right)^2; 0.9\right\}\right)$ (m) | | | | | | | | | | |
| [illegible]-II-7-81, 1996] | - | - | - | - | - | - | - | - | - | - | - | - |
| [illegible]enezuela [COVENIN-2002, 1988] | Y | Rayleigh formula ($*_{ray}$) | 25 | N | N | N | X | N | N | N | N | N |
| | | $T_a = 2\pi\sqrt{\left(\sum_{i=1}^{N} W_i \delta_{ei}^2\right) / \left(g \sum_{i=1}^{N} F_i \delta_{ei}\right)}$ | | | | | | | | | | |
| Only standard [FEMA, 1998] | Y | X | N | N | N | N | X | Y | Y | Y | Y | Y |

D (dynamic analysis for irregular buildings), $K$ (ratio for design forces MI-RC), $\sigma_t$ (strength of infill), $K_t$ (stiffness of infill), O (consider openings of infill)
$C_t$ (correction factor for masonry infill), $l_{wi}$ (length of the wall i in the first storey), $A_i$ (cross-section area of the wall),
$A_c$ (combined effective area of masonry infill in the first storey), h (height of the building), - (no information yet).

**In many codes coexist: a rigorous set of rules and requirements for the design and detailing of RC structures, and their elements, with simplified, or even totally absence, of rules taking into account the influence of IN in the response of the building structures, and to their detailing !**

# Seismic design procedure (*Force-based*)



# Design requirements

Partial factors
Steel
SLS
Costs
Beams
Bends
Maximum diameter
Ductility claas
Confinement
Ductility
IRREGULARITIES
....
Capacity design
Joints
2nd order effects
Chord rotation
Resistance
Structural type
Concrete grade
Safety factors
Drift limit
Strength
Walls
Redistribution
....
Anchorage length
M-N, V
Slenderness
Ductility class
INFILLS
Stiffness
....
Concrete-steel bond
Stirrups spacing
Energy dissipation
Lap length
Minumum dimensions
Columns
Damage limitation
....

# Provisions for Irregular structures

- The rules for the **regularity classification**, the **behaviour factors penalties**, the **design verifications** and **detailing rules** could be re-checked for structures **irregular in elevation and/or in plan**
- Influence of **infill walls in the regularity classification**, as well as in the analysis, should be further studied

# Buildings external envelope

Innovative **solutions** for the **buildings' envelope** (new or in renovations) **should be developed**, and they should combine the following requirements/criteria:

- Aesthetics / Architecture
- Gravity loads / Wind
- Guaranty thermal insolation
- Energy efficiency / Energy performance
- LCA ($CO_2$ emissions, …), Environment concerns,…
- Acoustical comfort
- Moisture
- Fire safety
- Easy installation (and rapid for existing buildings)
- Durable


but… **they should be earthquake-safe** !
(light, connections, accommodate the deformations imposed by the support,…)

# Conclusions

- **Recent earthquakes** keep proving that several existing buildings may induce serious **human** and **economic consequences** in future events.
- The large **majority** of buildings are **irregular**. In the assessment of existing RC buildings, and in the design of new buildings, particular attention should be given to:
  - irregularities in elevation (as in the stiffness difference between the 1st and the upper storeys: storey height, dimensions and position of openings, distribution of IM walls)
  - irregularities in plan: torsion
- **IM walls** can change drastically the seismic behaviour/response of the buildings. They should be considered in the **structural design**, particularly for irregular distribution of infills (based on simple design rules/procedures)
- **Currently**, we are designing **more ductile** structures, exploring the ductility and deformation capacity of the structural elements. Having infills, can the structures explore this ductility?
- The **OOP collapse** of infills may result in serious human and material consequences, as observed in **recent earthquakes**. So, there is a need to develop retrofitting solutions.

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# Thank you for your attention!

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