

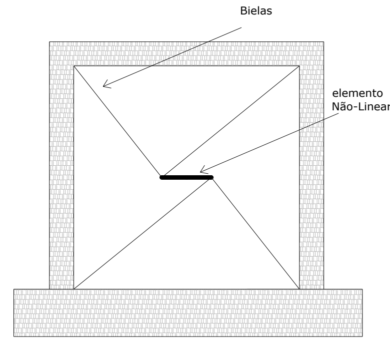





Lecciones aprendidas de terremotos recientes: Ideas para la evolución de los códigos de diseño sísmico

Lessons from recent earthquakes: thoughts for seismic design codes evolution

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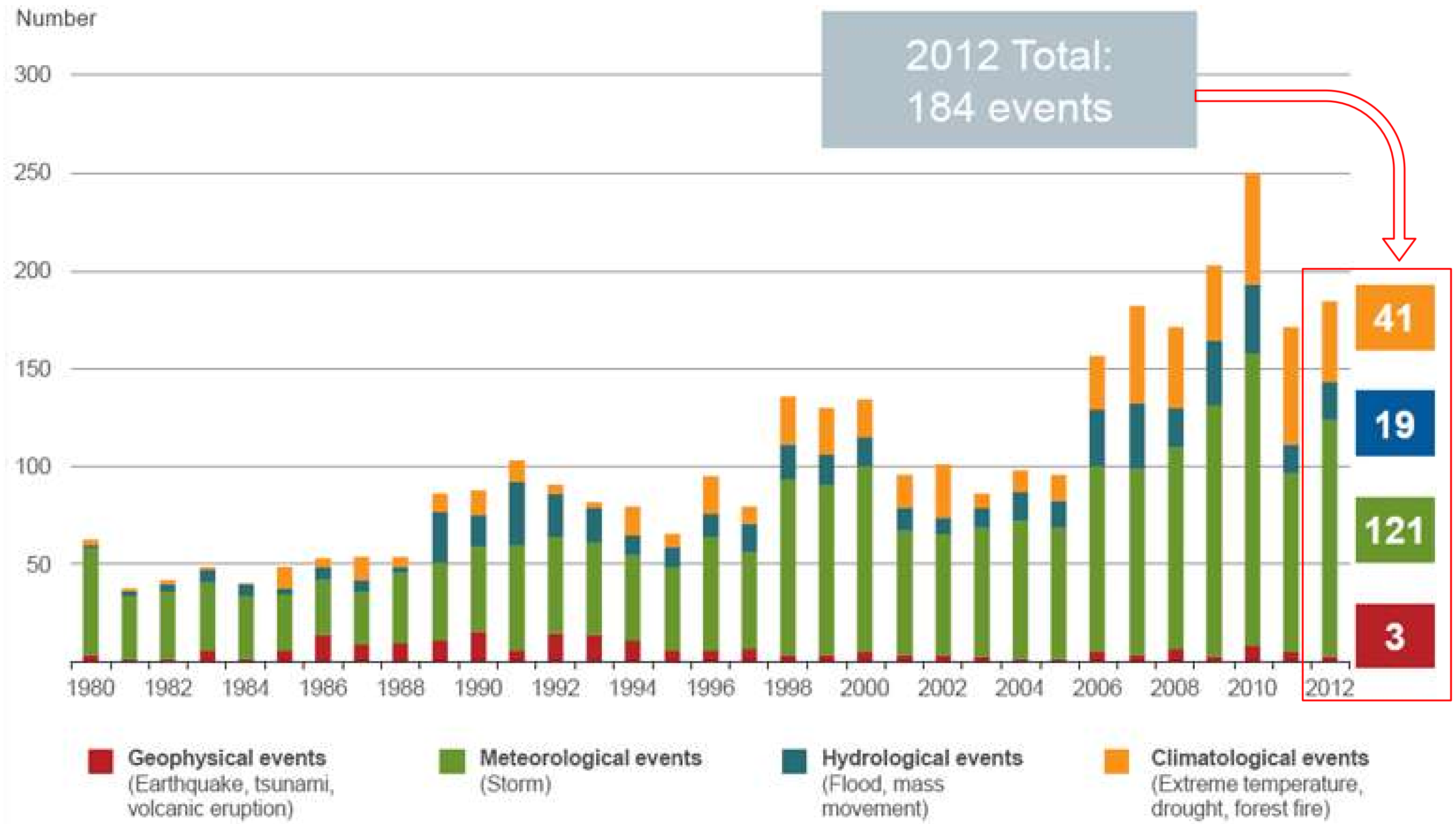
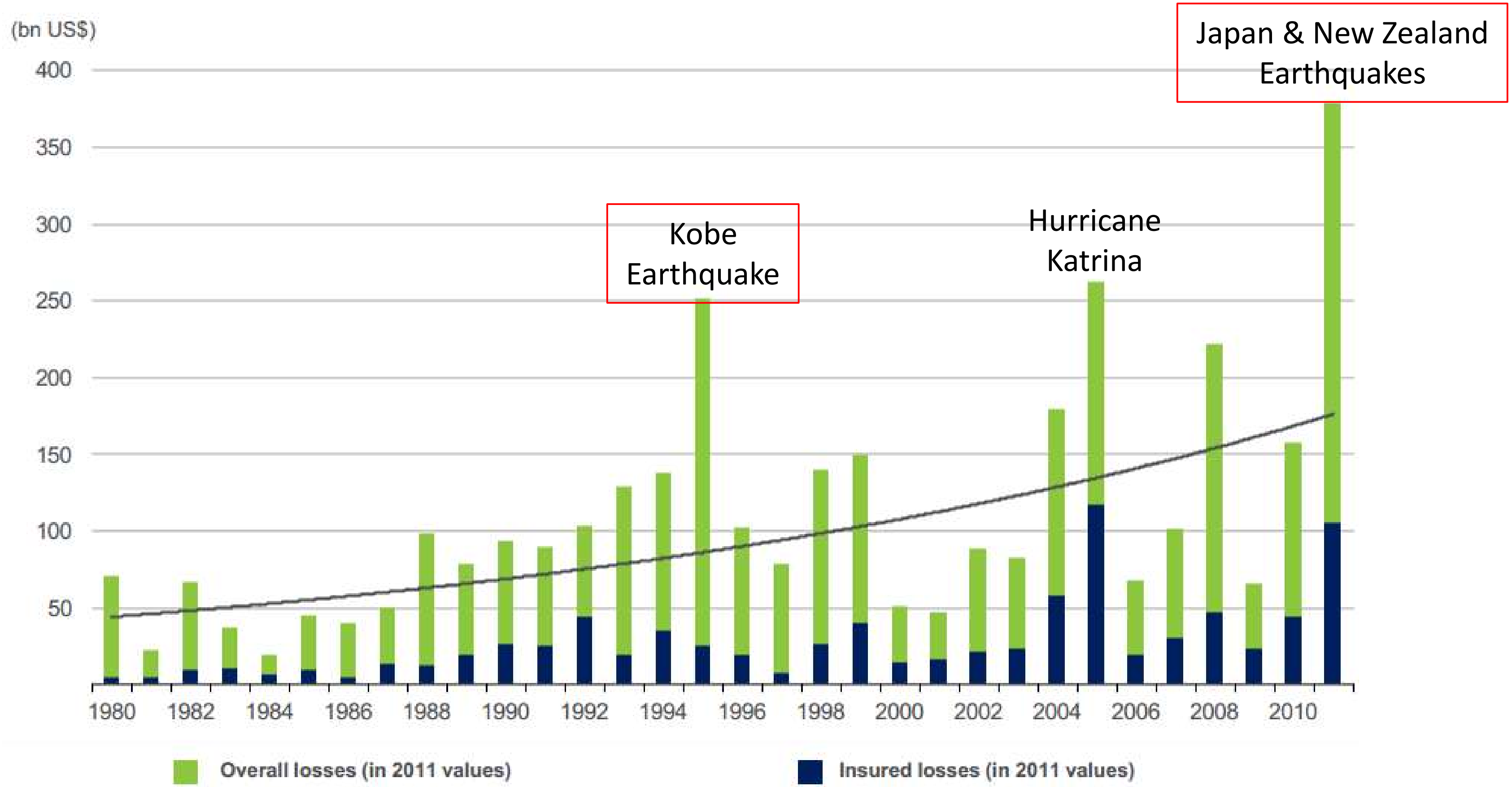


(Munich Re, 2012)

- Geophysical events (including earthquakes) are constant throughout the years
- Meteorological events have increased in the last years

Natural Disasters: Economical Losses



(Munich Re, 2012)

- Natural disasters are <u>more frequent</u> now than 30 years ago, <u>and are costing us much more</u>

Risk ?

Risk can be defined as the likelihood or probability of a given hazard of a given level causing a particular level of loss or damage. (Alexander, Confronting catastrophe, 2000)

Examples of Natural Disasters
affecting our society:

Avalanches
Earthquakes
Fires
Volcanic eruptions
Hydrological disasters (Floods, Tsunami)
Meteorological disasters (Blizzards, Tornados)
Wildfires
Health disasters (Epidemics)
Space disasters
…

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

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



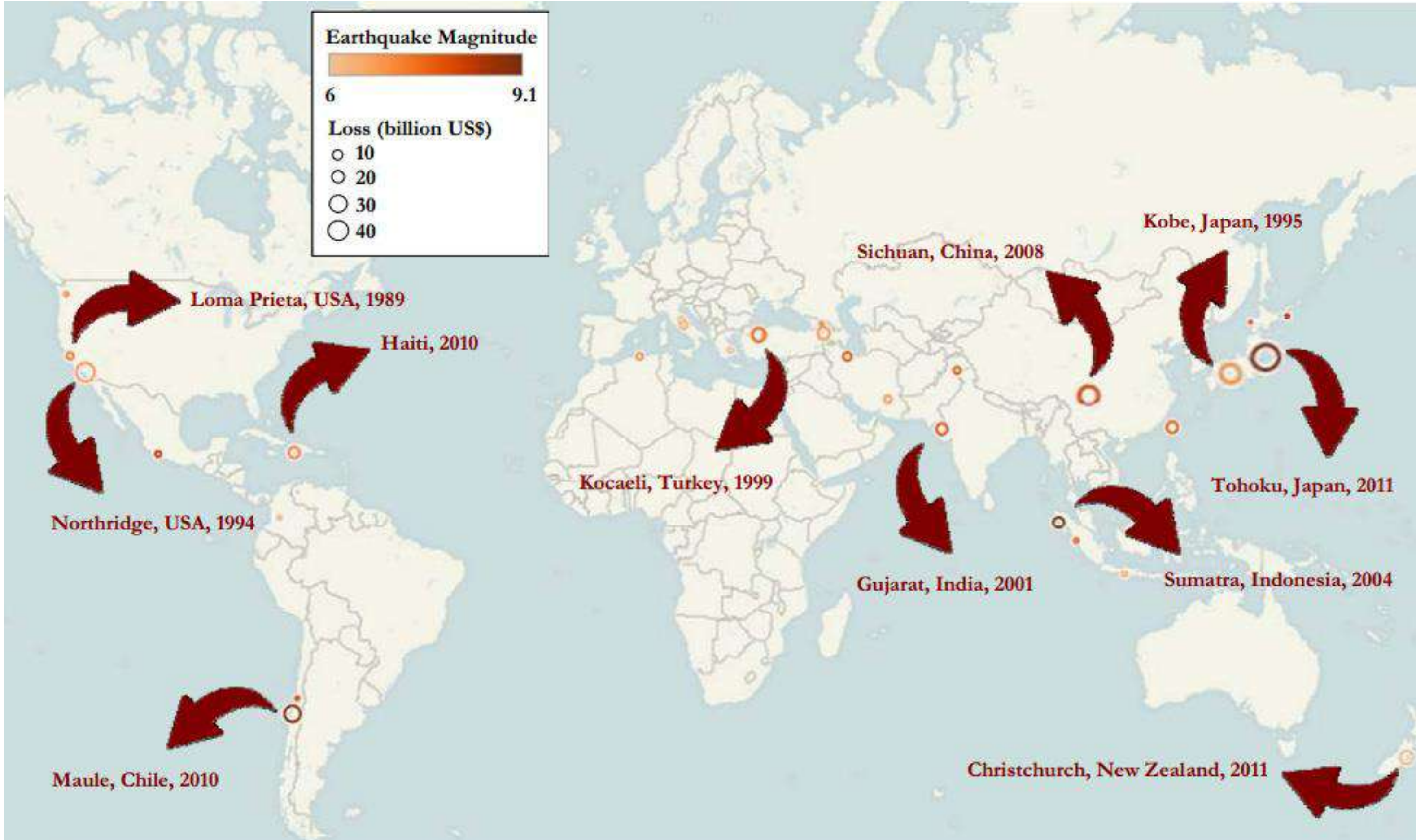
Lower Risk



Higher Risk

Solutions to mitigate the seismic 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 seismically active regions.

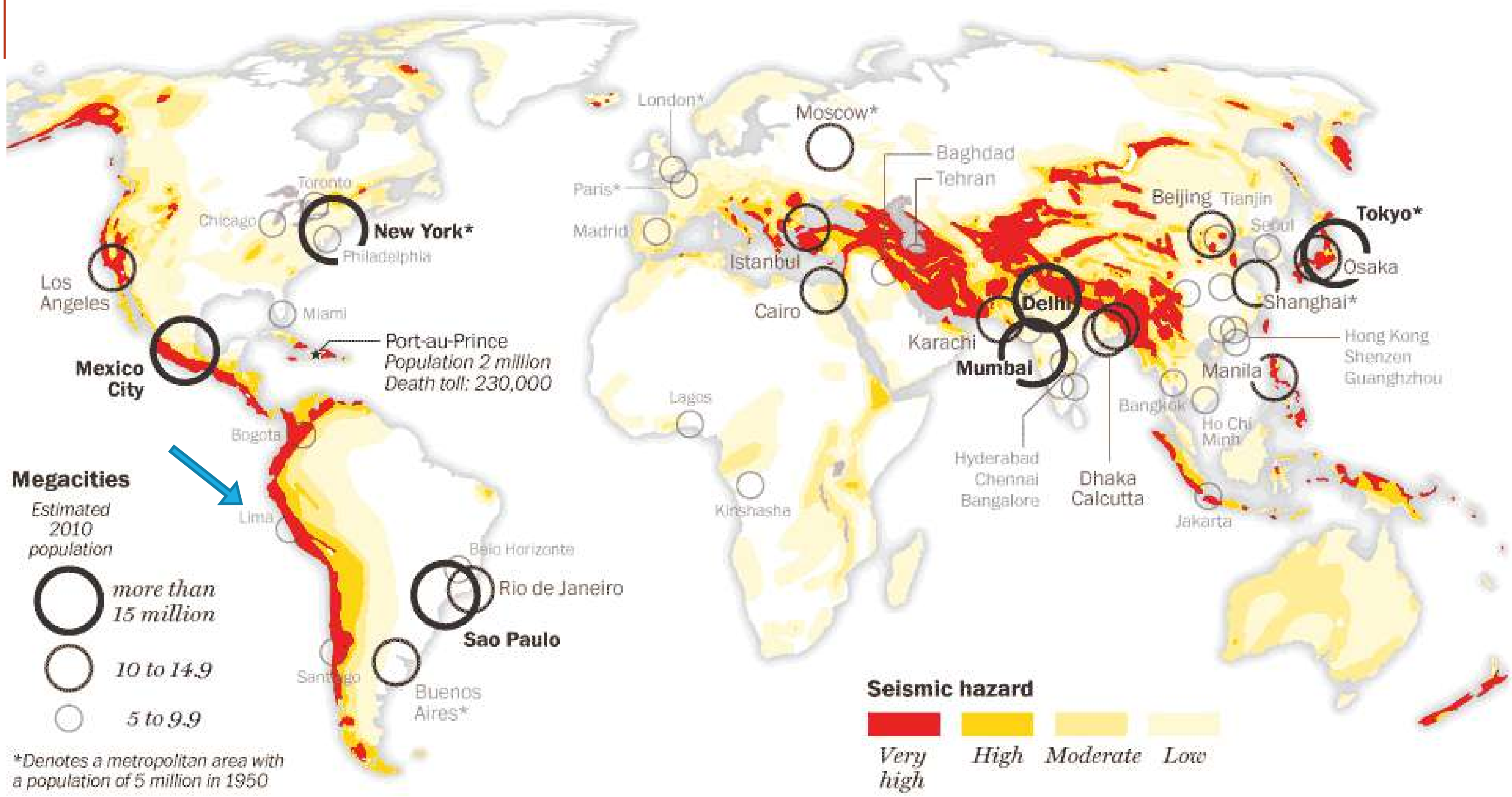
Earthquakes with M>6 and Losses>10,000M USD
between 1985 and 2011



Strong earthquakes with great economic impact happen in every continent. (Romão, 2012)

Seismic Hazard

Several <u>Megacities</u> are <u>located</u> in areas with <u>high seismic hazard</u>.



(Global Seismic Hazard Assessment Program, 2010)

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Initial considerations…

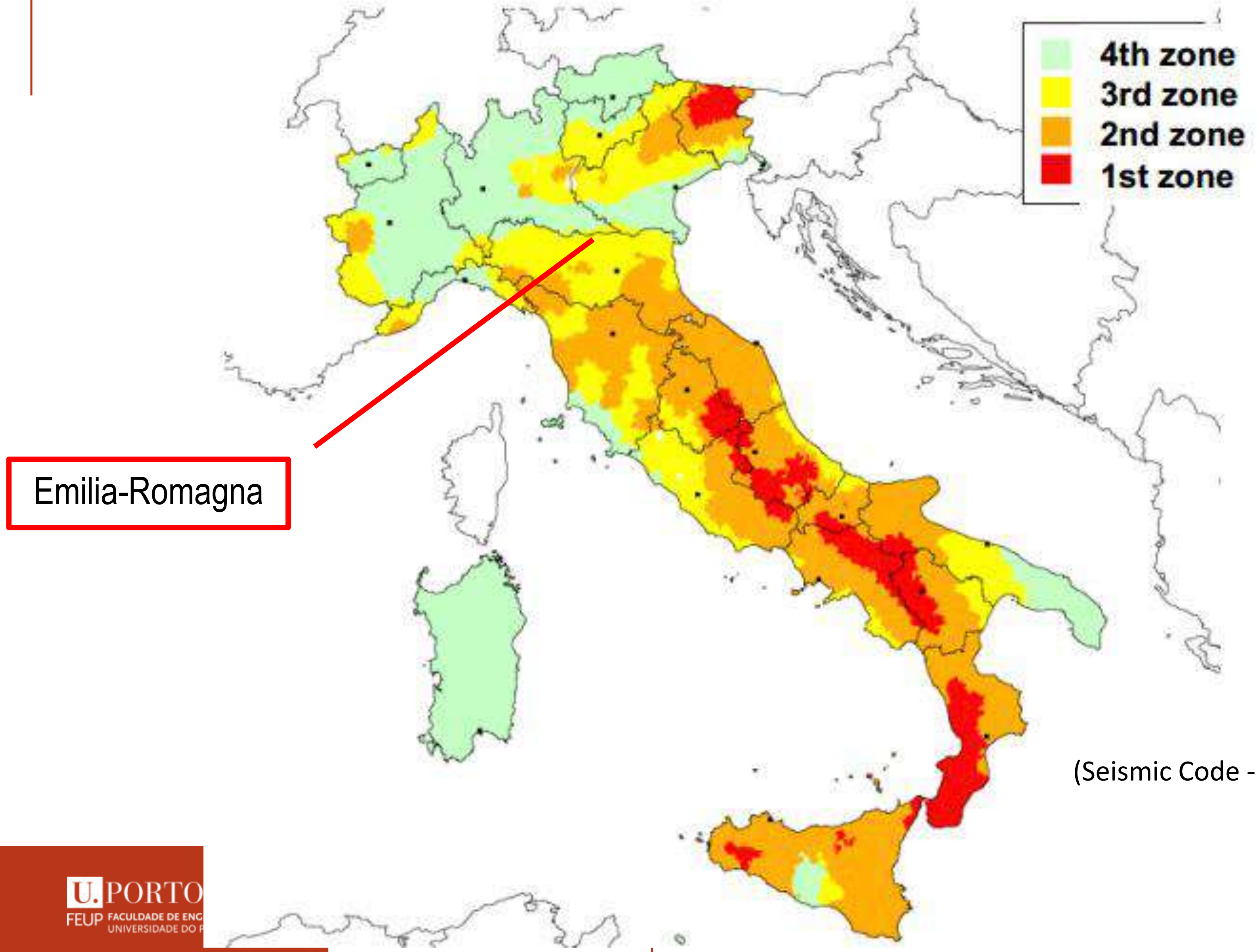
Do we know everything about the effect of earthquakes in the response of building structures, particularly regarding the influence of IM walls?

Can we continue designing/assessing our structures ignoring the influence of IM walls (so-called "non-structural" elements)?

Even if we include in our next generation of design codes the most advanced and state-of-the-art knowledge, how can we deal with the seismic risk associated with the vast existing building stock?

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

Emilia Romagna, Italy, 2012



(Seismic Code - 2012)

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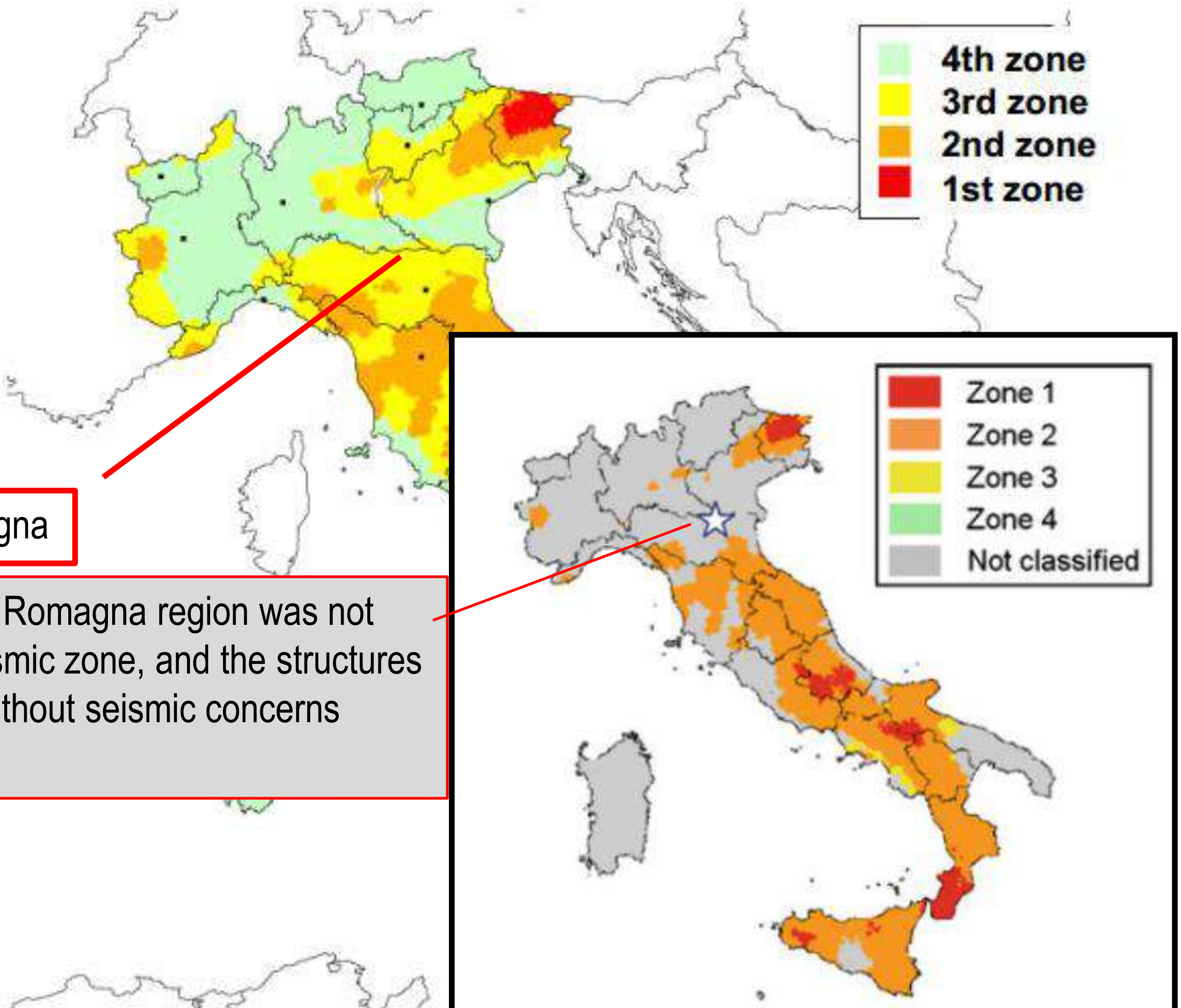
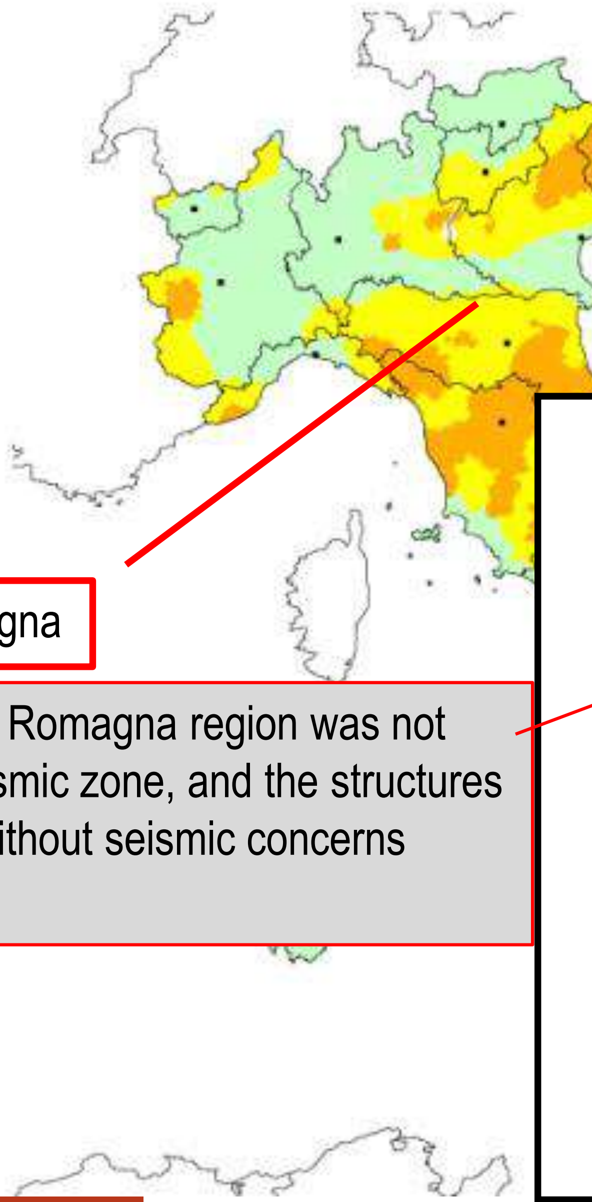
Emilia Romagna, Italy, 2012



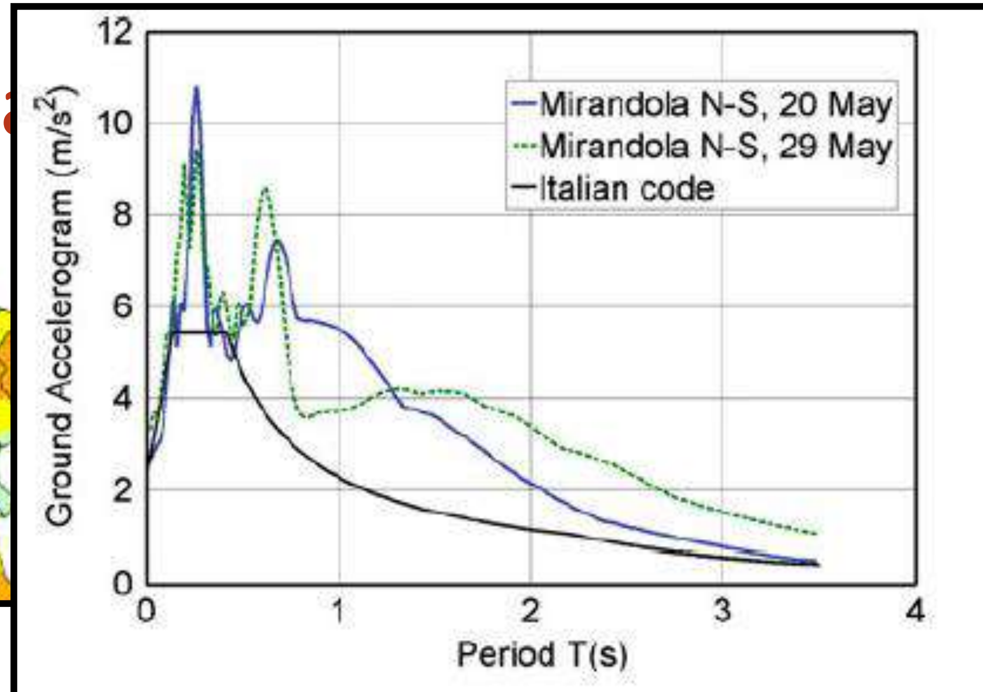
Emilia-Romagna

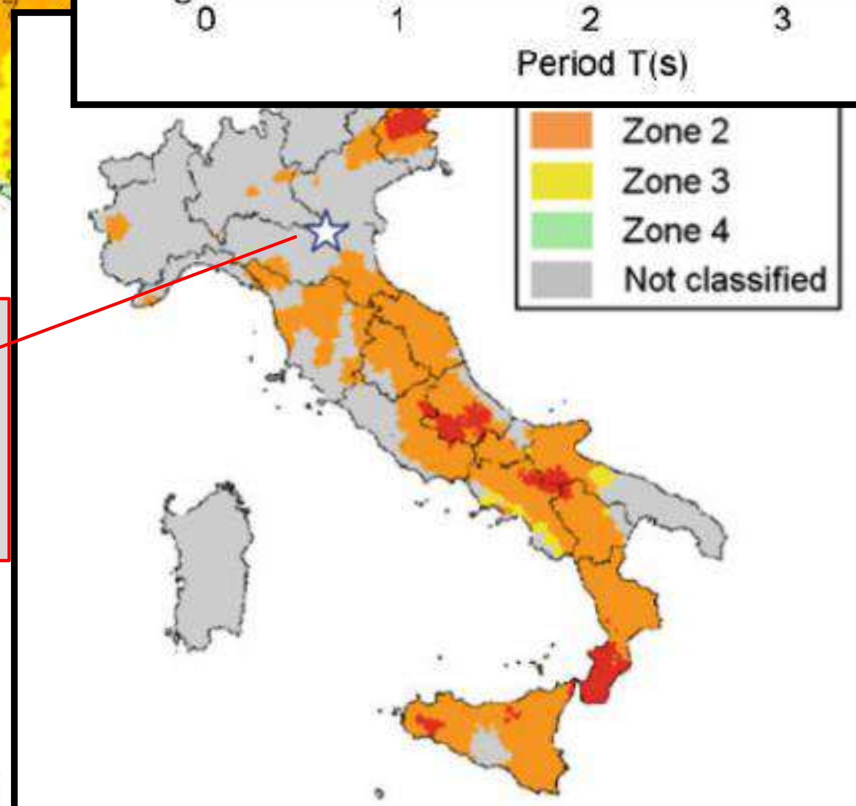
Until 2003 Emilia Romagna region was not considered a seismic zone, and the structures were designed without seismic concerns

Emilia Romagna, Ita

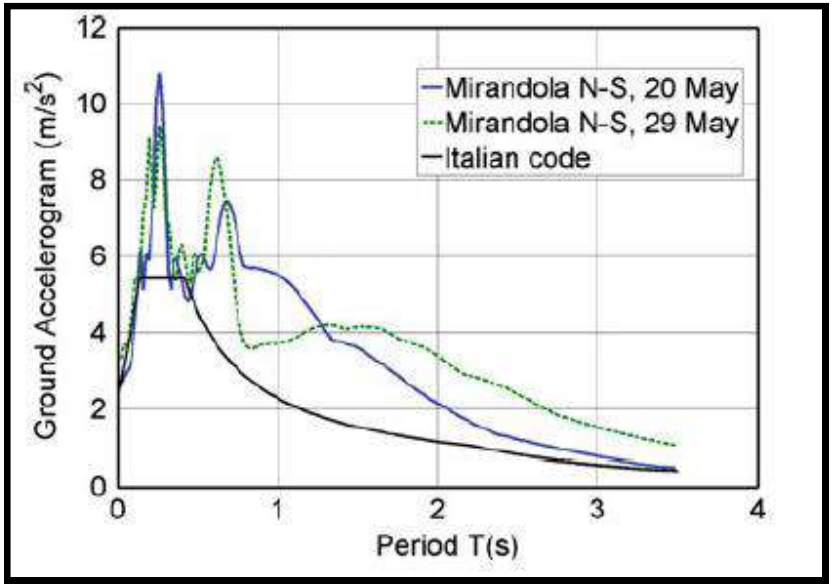


Until 2003 Emilia Romagna region was not considered a seismic zone, and the structures were designed without seismic concerns





Emilia Romagna, Italy, 2012



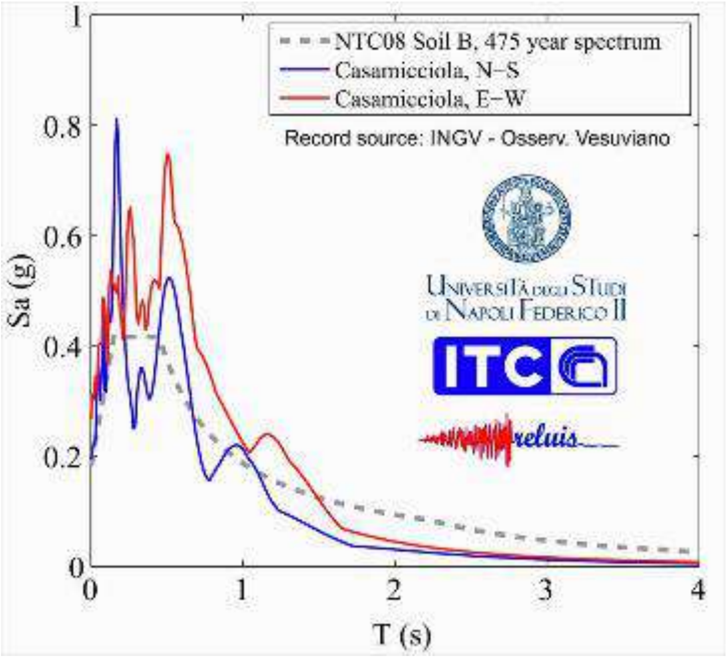
Bologna – May 20 and 29, 2012

Magnitude 6.1-5.8

26 deaths and 43,000 homeless

Economic loss of $13,000M US

Ischia, Italy, August 2017



Ischia – August 21, 2017

Magnitude 4.2

2 deaths, 42 Injured

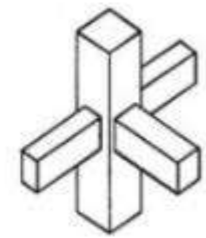
2,600 homeless

The Magnitude was relatively low, but the energy, hypocentric depth, propagation and soil response and the building vulnerability may justify the level of damage observed.

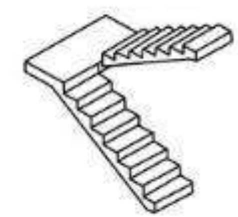
Damages in RC building structures

Eurocode 8 (EN 1998-1:2004) definitions

Structural elements

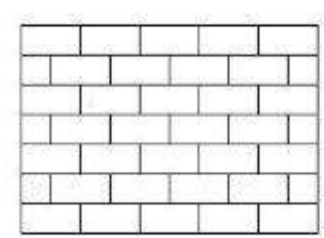


i) Primary members (SP): Members considered as part of the structural system that resist the seismic demands, modelled in the analysis for the seismic design situation and fully designed and detailed for earthquake resistance according to the specific rules of EN 1998.



ii) Secondary members (SS): Members which are not considered as part of the seismic action resisting system and whose strength and stiffness against seismic actions is neglected; they are not required to comply with all the rules of EN 1998, but are designed and detailed to maintain support of gravity loads when subjected to the displacements caused by the seismic design condition.

Non-structural elements (NS)



Architectural, mechanical or electrical element, system and component which, whether due to lack of strength or to the way it is connected to the structure, is not considered in the seismic design as load carrying element.

Damages in RC building structures

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

Non-Structural (NS)

Surroundings (foundations, soils, pounding,…)

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

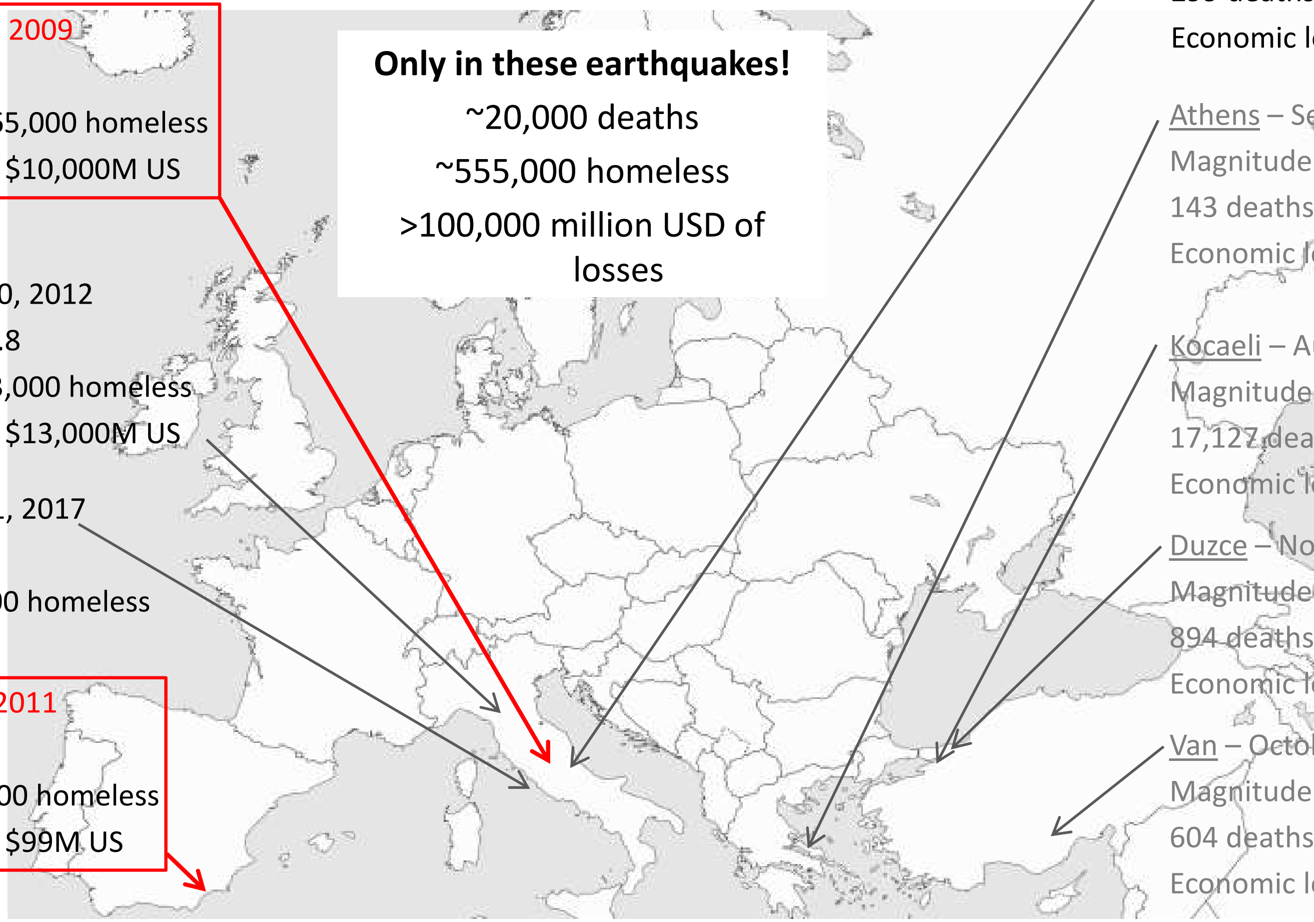
9. Damages in structural Secondary Elements (cantilivers, stairs,…)

SS

10. Damages in Non-Structural Elements

NS

Observed damages in recent earthquakes: Field evidence



L'Aquila – April 6, 2009
Magnitude **6.3**
308 deaths and 65,000 homeless
Economic loss of $10,000M US

Bologna – May 20, 2012
Magnitude 6.1-5.8
26 deaths and 43,000 homeless
Economic loss of $13,000M US

Ischia – August 21, 2017
Magnitude 4,2
2 deaths and 2,600 homeless

Lorca – May 11, 2011
Magnitude **5.1**
9 deaths and 5,000 homeless
Economic loss of $99M US

Only in these earthquakes!
~20,000 deaths
~555,000 homeless
>100,000 million USD of losses

Central Italy – August 24, 2016
Magnitude 6,2
299 deaths and 4,500 homeless
Economic loss of $11,000M US

Athens – September 7, 1999
Magnitude 6.0
143 deaths and 50,000 homeless
Economic loss of $3,000M US

Kocaeli – August 17, 1999
Magnitude 7.5
17,127 deaths and 300,000 homeless
Economic loss of $23,000M US

Duzce – November 12, 1999
Magnitude 7.2
894 deaths and 24,000 homeless
Economic loss $40M US

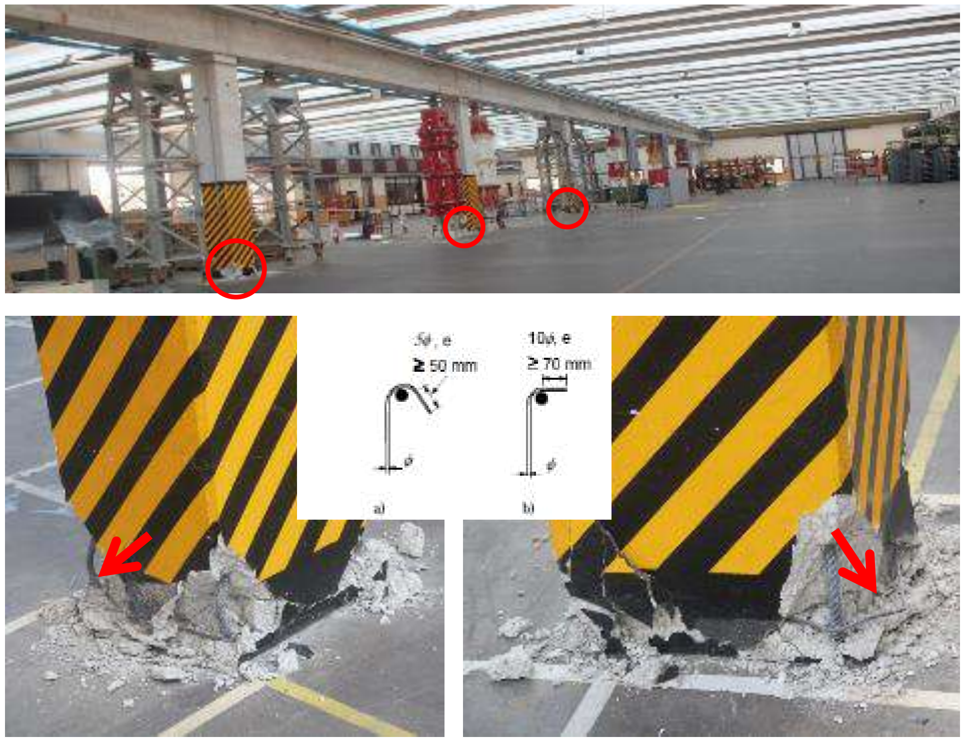
Van – October 23, 2011
Magnitude 7.1
604 deaths and 60,000 homeless
Economic loss of $2,000M US

Damages in RC building structures

1. Stirrups and hoops (inadequate quantity and/or detailing, regarding the required **ductility**)

Damages in RC building structures

1. Stirrups and hoops (inadequate quantity and/or detailing)



Detailing errors: hook bends at 90º

Emilia Romagna, 2012

Damages in RC building structures

2. Detailing (bond, anchorage and lap-splices)

Damages in RC building structures

2. Detailing (bond, anchorage and lap-splices)




Detailing errors: smooth plain bars, hook ends, lap-splices, hooks bends,…

2009 L'Aquila

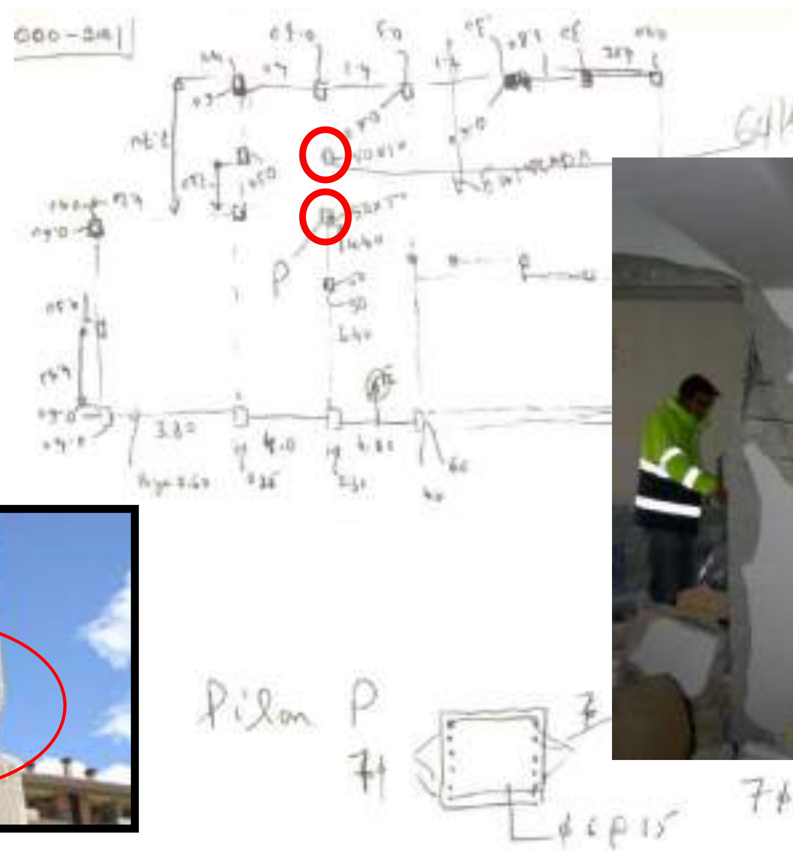
Damages in RC building structures

3. Inadequate capacity and failure (**shear**, flexural)

General data

- Location: Petino
- year of construction: 2000
- residential building
- 10 apartments
- isolated
- ground storey + 5 storeys
- without basement
- average storey height equal to 2.5m
- RC framed structure
- with masonry infill walls

<u>Shear failure</u> of interior columns at the ground storey level



2009 L'Aquila

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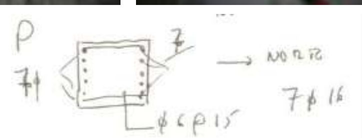
Damages in RC building structures

3. Inadequate capacity and failure (shear, flexural)



2009 L'Aquila

<u>Insufficient amount of transverse reinforcement</u>, and longitudinal reinforcement only in two column faces; excessive <u>distance</u> between *longitudinal bars* in two faces of the columns

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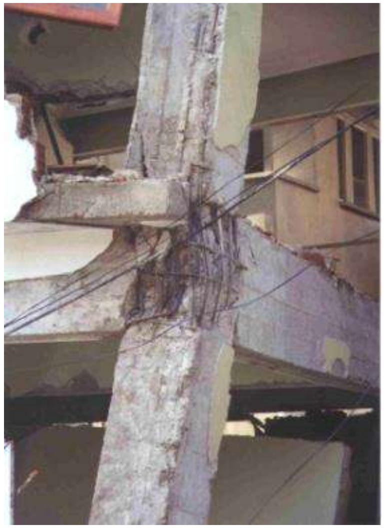
Damages in RC building structures

4. Inadequate shear capacity of the joints



Damages in RC building structures

4. Inadequate shear capacity of the joints

General data

- Location: Petino
- year of construction: 1982/83
- residential building
- isolated
- ground storey + 2 or 3 storeys
- without basement
- storey height: 2.4m (ground storey); 2.7m (other storeys)
- RC framed structure
- with masonry infill walls

Absence of hoops/stirrups in the joints; lap-splices of column reinforcing bars in the joint regions; inadequate bars anchorage

2009 L'Aquila

Damages in RC building structures

4. Inadequate shear capacity of the joints

<u>Deficiencies in the reinforcement detailing of beam-column joints</u>

Absence of joint transverse reinforcement; inadequate anchorage of the beam longitudinal bars; shear failure of joints

2009 L'Aquila

Damages in RC building structures

4. Inadequate shear capacity of the joints

RC building collapse a few hours after the earthquake: various deficiencies in the beam-column joints (absence of hoops/stirrups; lap-splices of column reinforcing bars in the joint region; poor anchorage of longitudinal bars)

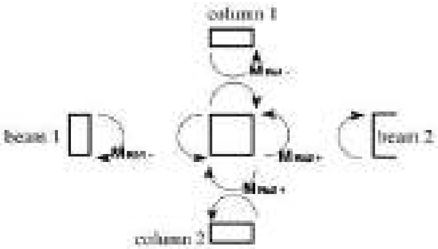
2011 Lorca

Damages in RC building structures

5. Strong-beam weak-column mechanism

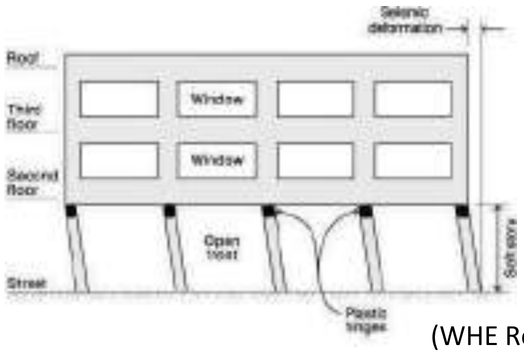
Damages in RC building structures

5. Strong-beam weak-column mechanism

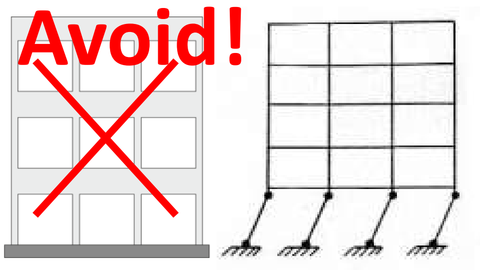


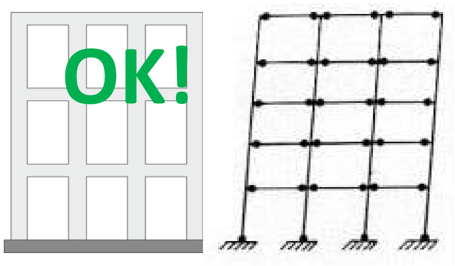
$$\sum M_{R,column} \geq \gamma_{R,d} \cdot \sum M_{R,beam}$$

Eurocode 8: $\gamma_{R,d} = 1.3$



(WHE Report)





Columns should have larger flexural capacity than beams at each joint.
Early design philosophies (pre-80s codes) did not have this mechanism hierarchy concern.

Damages in RC building structures

5. Strong-beam weak-column mechanism

General data
- Location: Petino
- year of construction: 1982/83
- residential building
- isolated
- ground storey + 2 or 3 storeys
- without basement
- storey height: 2.4m (ground storey); 2.7m (other storeys)
- RC framed structure
- with masonry infill walls

Inadequate plastic hinges hierarchy, with failures occurring first on columns

Damages in RC building structures

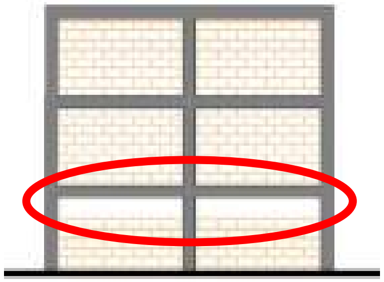
6. Short-column mechanism

Damages in RC building structures

6. Short-column mechanism

General data

- Location: Paganica
- year of construction: before 2000 ?
- residential building
- 8 apartments
- isolated
- ground storey + 2 storeys
- without basement
- ground storey height significantly lower than the height of the upper storeys
- RC framed structure with masonry infill walls



Openings interrupting the masonry infill walls, inducing a modification in the stress distribution along the structural elements

2009 L'Aquila

Damages in RC building structures

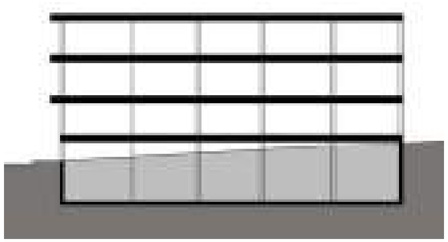
6. Short-column mechanism

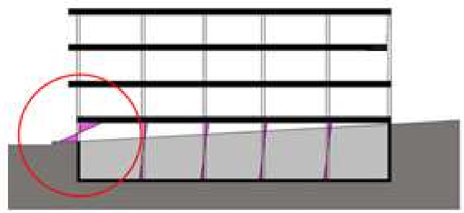
Short-columns' shear failure: due to openings, or in columns at ground storey levels where is observed a variable ground height, associated with insufficient amount of transverse reinforcement

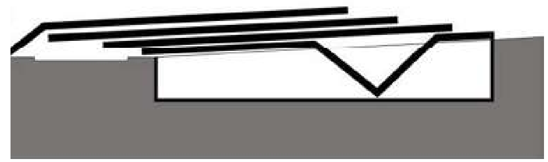
2011 Lorca

Damages in RC building structures

6. Short-column mechanism







<u>RC building collapse</u> (*pancake* type collapse) due to insufficient strength of the <u>short-columns</u> for the high shear force demands (due to the ground unevenness)

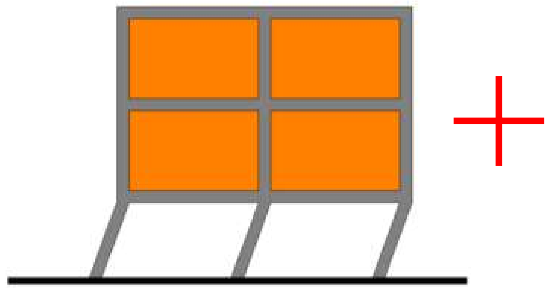
2011 Lorca

Damages in RC building structures

7. Structural irregularities (in plan or in elevation: torsion , “weak-storey”, “soft-storey”)

Damages in RC building structures

7. Structural irregularities (in plan or in elevation: torsion , “weak-storey”, “soft-storey”)



Structural scheme/plan (ground storey)

General data

- Location: Petino
- year of construction: 1982/83
- residential building
- isolated
- ground storey + 2 or 3 storeys
- without basement
- storey height: 2.4m (ground storey); 2.7m (other storeys)
- RC framed structure
- with masonry infill walls

Highly irregular (in terms of stiffness and strength), both in plan and in elevation:

+ Irregularities in elevation (ground storey with reduced number of walls - for garages) +

+ Irregularities in plan (torsion) +

+ Poor detailing of beam-column joints; absence of stirrups; poor concrete quality

2009 L’Aquila

Damages in RC building structures

7. Structural irregularities (in plan or in elevation: torsion , “weak-storey”, “soft-storey”)

Collapse due to soft-storey mechanism: reduced number of masonry infill walls in the ground storey, causing a significant variation of stiffness and strength in elevation, creating a “soft storey” and “weak storey” + irregularities in plan (torsion)

2009 L’Aquila

Damages in RC building structures

7. Structural irregularities (in plan or in elevation: torsion , “weak-storey”, “soft-storey”)

General data

- Several blocks built in different periods: The hospital’s construction began in 1972 / One of the most recent blocks was opened in 2000
- Main and larger medical centre (Central Hospital) in the affected region, serving a region with 1800 km^2
- The hospital complex has 13 independent wings, being composed by 20 buildings, including the Medical School
- Many buildings are irregular structures in plan and in elevation (3 to 5 storeys)
- RC structures (framed; some buildings have RC structural shear-walls with large dimensions)

Severe damages in the RC columns, due to pronounced irregularities in plan and in elevation

Building that gives access to the Emergency Ward - built in 2000 - 2 storeys

Damages in RC building structures

7. Structural irregularities (in plan or in elevation: torsion , “weak-storey”, “soft-storey”)

Severe damages in the RC columns, due to pronounced irregularities in plan and in elevation (induced by the structural itself + distribution of in fill masonry walls)

2009 L’Aquila

Damages in RC building structures

7. Structural irregularities (in plan or in elevation: torsion , “weak-storey”, “soft-storey”)

Flexible ground storey, convenient for commerce/services’ use, inducing a pronounced irregularity in elevation

Main characteristics:
(1) Height significantly greater than the upper storeys
(2) Absence of masonry infill walls
(3) Wall panels not developed along the total storey height

The walls at the ground storey often less resistant and stiff

Observed damages in recent earthquakes: Field evidence

Soft-storey mechanism (in-elevation irregularity)

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

(Patrick Corell, 2011)

Structural design:
- Without considering the masonry walls

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

But… infill masonry panels are usually considered in the design of new structures as non-structural elements, and its influence in the structural response is disregarded !

Damages in RC building structures

8. Interaction and Pounding

<u>Interaction between buildings</u>: adjacent buildings with different heights, or with different structural and/or constructive or material solutions, in the urban centre, leading to different dynamic responses, hence boosting <u>pounding</u>, as well as to stress and strain <u>demands concentration</u> in certain points

2011 Lorca

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Damages in RC building structures

9. Damages in Structural Secondary Elements

(ARTI, 2011)

(AFP, 2014)

(USGS, 1989)

Damages in RC building structures

9. Damages in Structural Secondary Elements: Stairs





Damages associated with the stairs' elements, mainly in the lower storeys. Lack of specific design of these secondary structural elements, and/or reinforcement detailing errors (design?/construction?), and/or non specific connection to the main structural system

2011 Lorca

Damages in RC building structures

10. Damages in Non-Structural Elements: infill masonry (in-plane)

Damages in masonry exterior panels

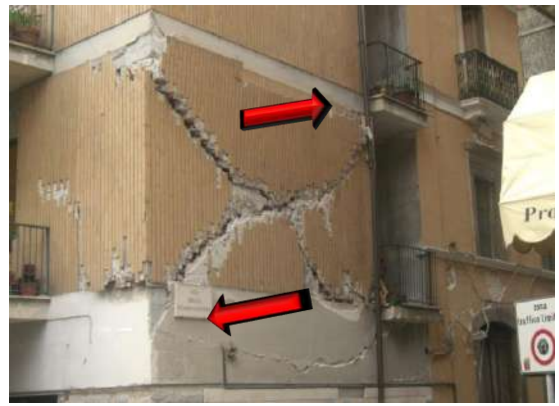



In-plane response (interface separation between infills and resistant structure, diagonal cracking, corner crushing)

2009 L'Aquila

Damages in RC building structures

10. Damages in Non-Structural Elements: infill masonry (in-plane response: diagonal cracking)



2009 L'Aquila

Damages in RC building structures

10. Damages in Non-Structural Elements: infill masonry (in-plane response)

Widespread damages in the masonry infill walls in all building of Aquila Hospital

- Significant structural damages; complete buildings' collapse did not occur
- A few hours after the earthquake, the Hospital was declared inoperative in 90% of its functions

2009 L'Aquila

Damages in RC building structures

10. Damages in Non-Structural Elements: infill masonry (out-of-plane response)

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

2009 L'Aquila

Damages in RC building structures

10. Damages in Non-Structural Elements: Parapets

Elements not adequately connected to the structure may fall over the street

2009 L'Aquila

Damages in RC building structures

10. Damages in Non-Structural Elements: Parapets

OOP collapse of masonry enclosure walls

(L'Áquila, Italy, 2009)

Damages in RC building structures

10. Damages in Non-Structural Elements: collapse of exterior panels in double-leaf walls

Damages in masonry exterior panels

Excessive deflection in cantilevers; large dimensions of the masonry panels; exterior panels non confined; with poor connection (to the structure and to the interior panel)

2009 L'Aquila

Damages in RC building structures

10. Damages in Non-Structural Elements: collapse of exterior panels in double-leaf walls

Damages in masonry exterior panels – Inadequate support

Possible causes: Poor connection between the exterior and interior panels (in double leaf walls), and between the exterior panel and the structural elements. Exterior panels supported on the beams/slabs, approximately, in only half panel thickness

2009 L'Aquila

Damages in RC building structures

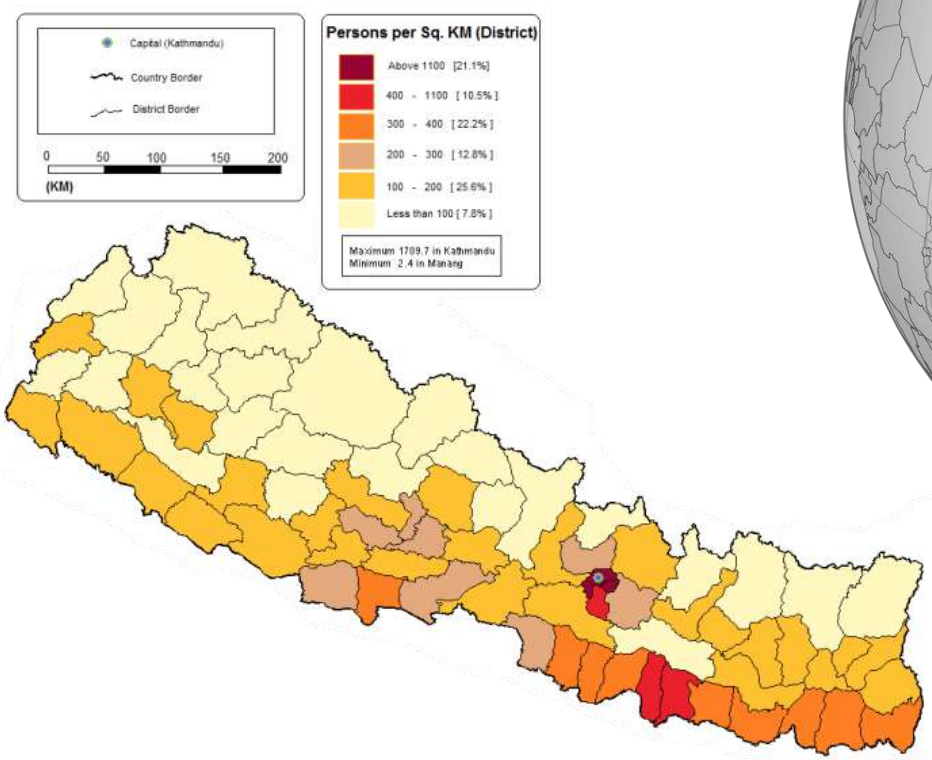
10. Damages in Non-Structural Elements: Coatings

<u>Poor connection</u> of <u>finishing/coverings</u> (heavy pieces) glued in singular points with “cement glue”, without any mechanical fixing system

2011 Lorca

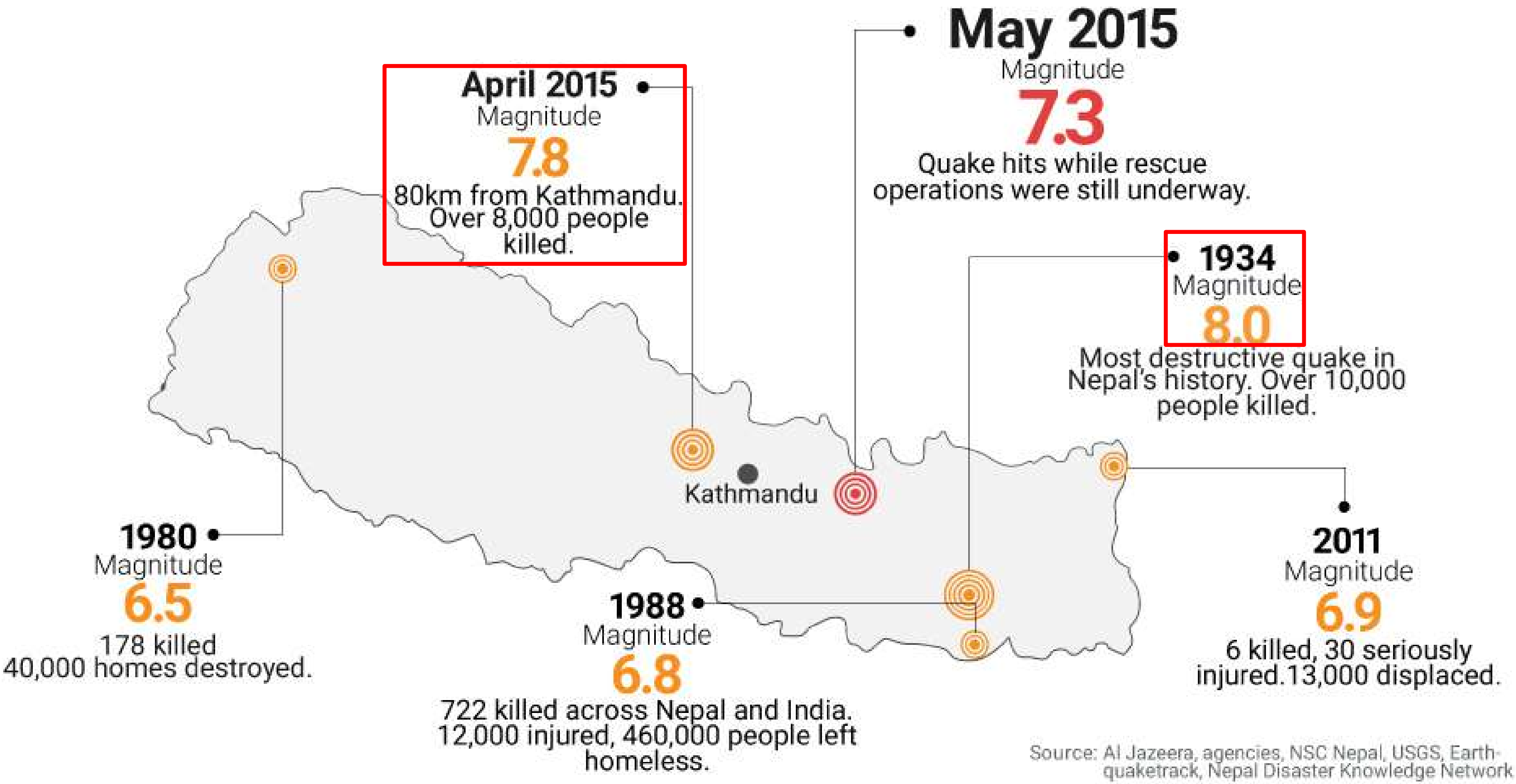
Nepal: 2015 EQs

Capital Kathmandu (largest city)
Total Area 147,181 km^2 (1,6x PT)
Population 28,120,000 (2,7x PT)
Density 180 /km^2
GDP 19.77 USD Billion (8% PT)



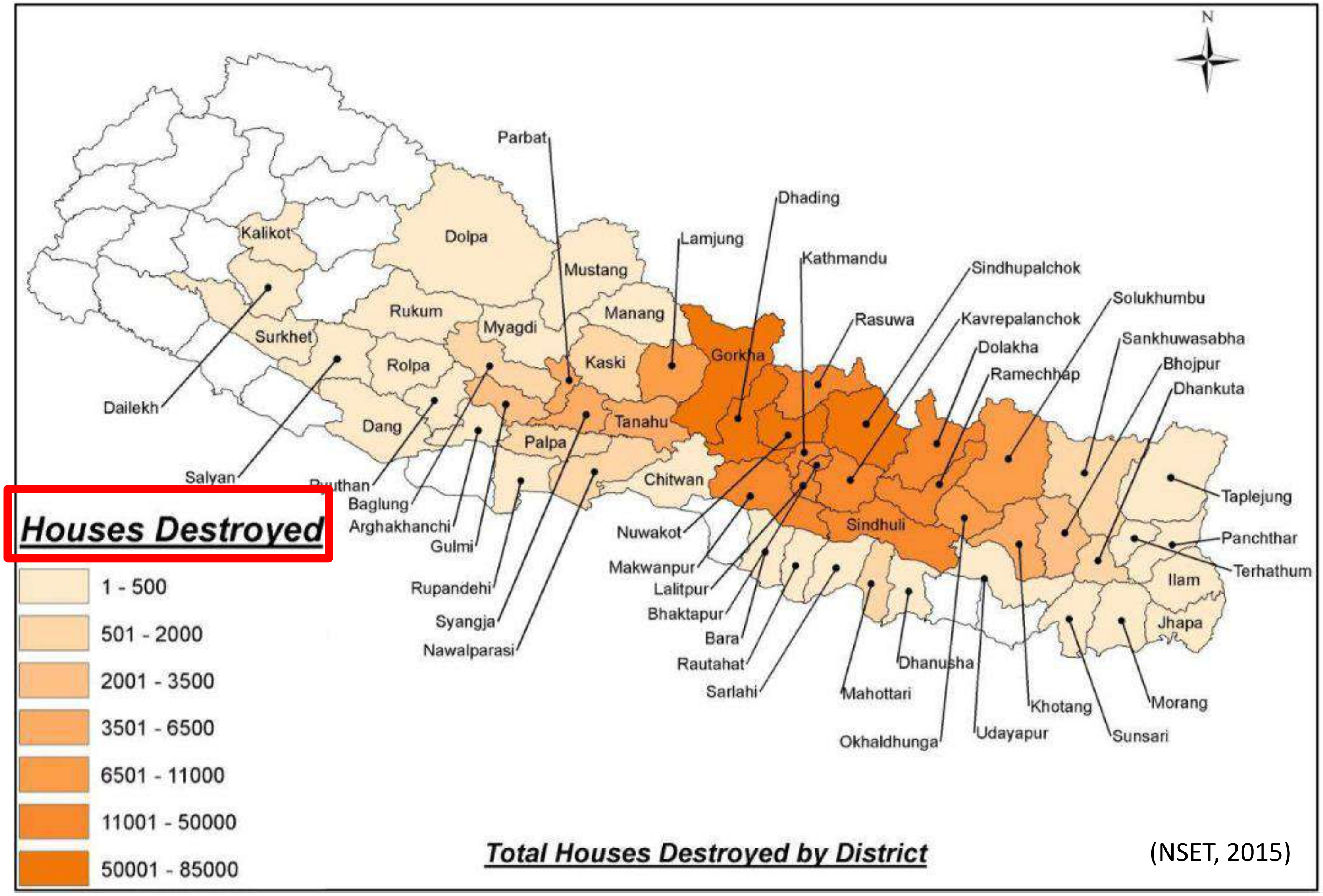
Sources:
wikimedia.org
tradingeconomics.com

Nepal: Past strong Earthquakes (since 20th century…)



NEPAL: 2015 EQs

Distribution of the collapsed and damaged buildings

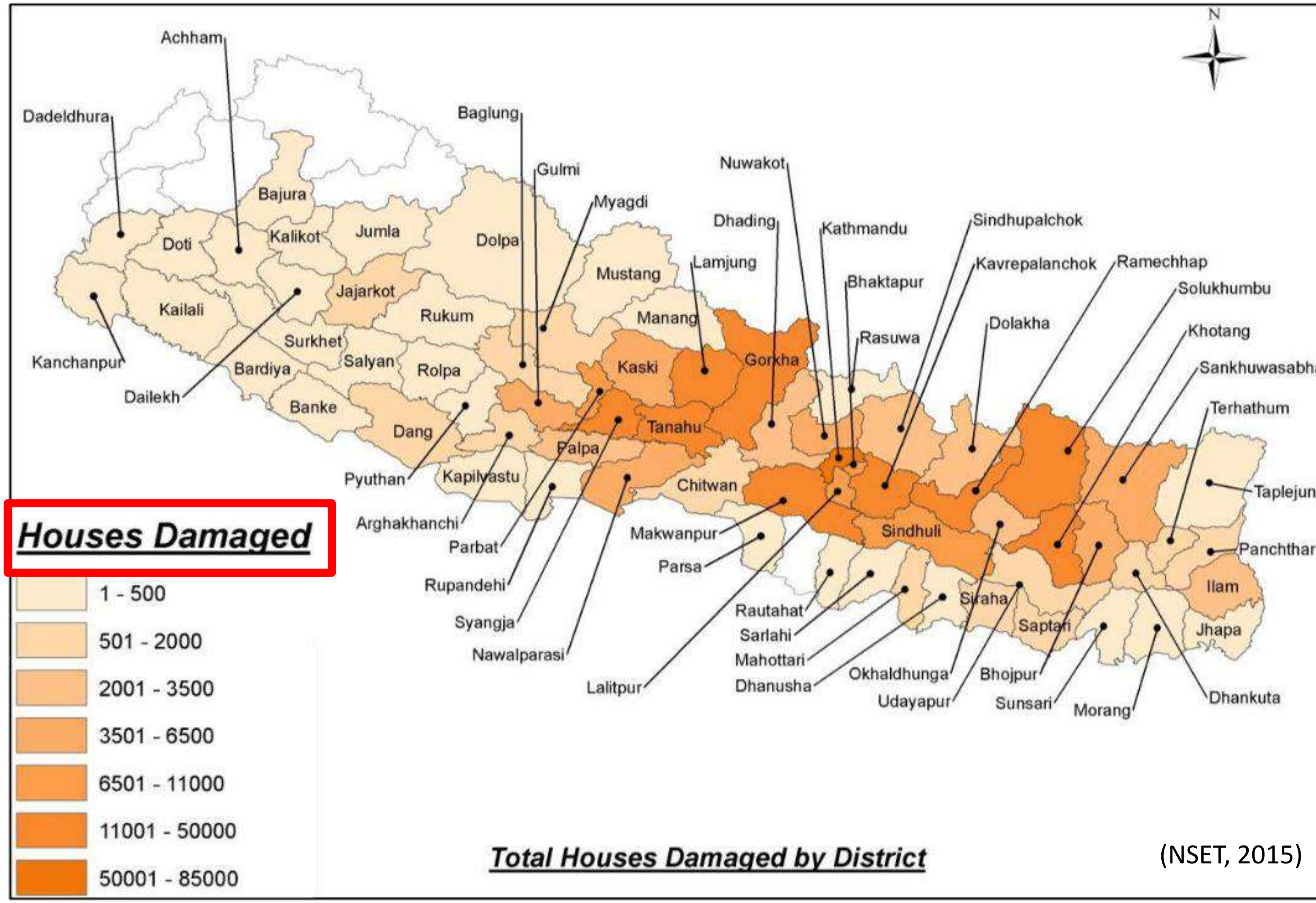


(NSET, 2015)

EXTENSIVE CATASTROPHIC DAMAGE TO PROPERTY WAS REPORTED THROUGHOUT CENTRAL NEPAL, INCLUDING KATHMANDU

NEPAL: 2015 EQs

Distribution of the collapsed and damaged buildings



EXTENSIVE CATASTROPHIC DAMAGE TO PROPERTY WAS REPORTED THROUGHOUT CENTRAL NEPAL, INCLUDING KATHMANDU

***Adobe** buildings:* sun-dried bricks with mud mortar

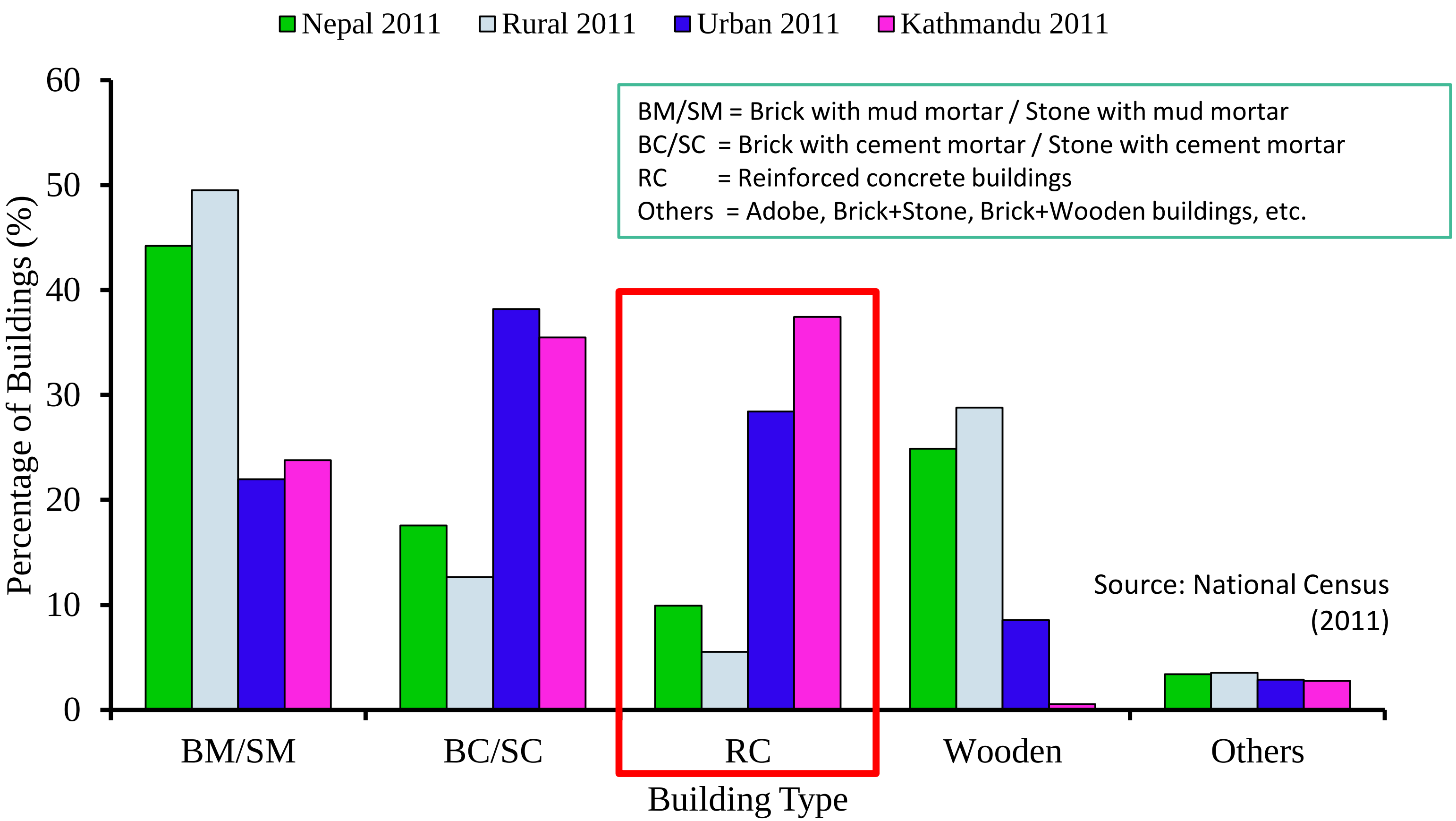
***Stone** masonry with mud mortar:* plastered or non-plastered

***Brick** masonry with mud mortar:* fired bricks

Stone masonry with cement mortar:
plastered or non-plastered

Brick masonry with cement mortar:
fired bricks

NEPAL
Buildings typologies



The 2011 census data shows that mud-bonded brick and stone (BM&SM) buildings were more popular in Nepal (~45%), followed by wooden constructions, and by cement-bonded brick and stone buildings (BC&SC).

In urban areas, cement-bonded brick and stone (BC&SC) buildings represents ~35%. About 29% of the buildings in urban areas are reinforced concrete structures.

In Kathmandu valley, 38% of the buildings were constructed with RC framed structures, followed by BC&SC and BM&SM.

Over the last few decades (1991-2001), RC building construction has rapidly increased, replacing other construction materials and solutions, like adobe, stone and brick masonry, in Kathmandu Valley.

Most RC buildings in Nepal were constructed with framed structures with infill masonry panels. These buildings offered insufficient capacity, lacked ductile detailing and were poorly constructed and may have limited durability.

Chaulagain, Rodrigues, Varum (2014)

RC Buildings

WDS
(Well Designed Structure)

WDS building structures designed based on the International standards/codes (e.g. Indian Standard code), considering seismic design with ductile detailing

NBC (MRT)
(Nepal Building Code)

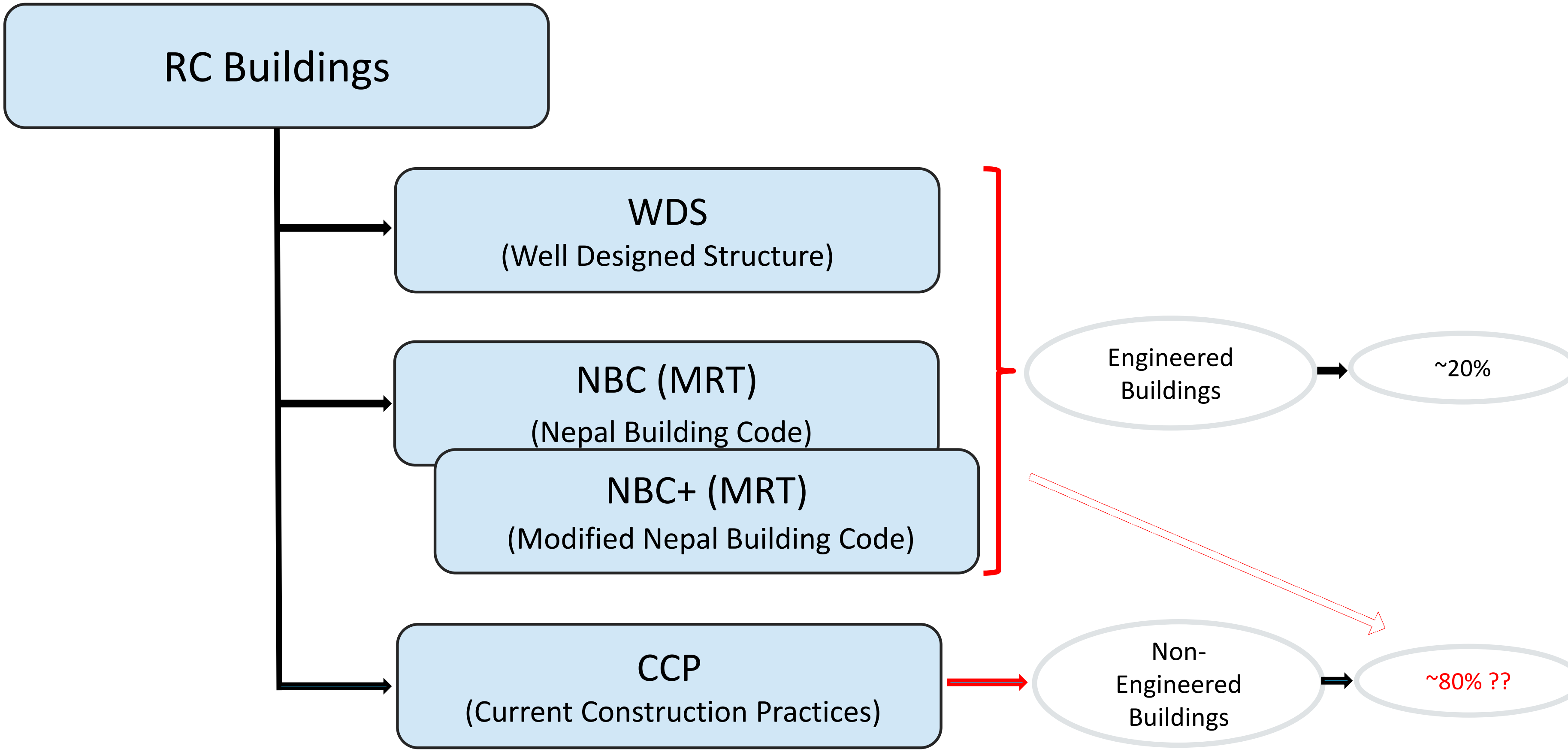
NBC+ (MRT)
(Modified Nepal Building Code)

NBC structures are designed with mandatory rules of thumb (MRT), which provides some ready-to-use provisions in terms of dimensions and details for structural and non-structural elements for up to 3 storeys in RC framed, ordinary residential buildings in Nepal

NBC+ is an improvement of the recommendations for the minimum size and reinforcement detailing in columns, relatively to the NBC

CCP
(Current Construction Practices)

Buildings group that represent the current construction practices (CPP) in Nepal. CCP structures in many urban areas of Nepal represent the largest group.


RC Buildings
WDS
(Well Designed Structure)
NBC (MRT)
(Nepal Building Code)
NBC+ (MRT)
(Modified Nepal Building Code)
CCP
(Current Construction Practices)
Engineered Buildings
~20%
Non-Engineered Buildings
~80% ??

NEPAL

RC buildings

Non-Engineered Reinforced Concrete Moment-Resisting-Frame buildings

These are the buildings with RC elements and unreinforced brick masonry walls with cement mortar joints. The prevalent practice in most urban areas of Nepal for the construction of residential and commercial complexes generally falls under this category. These buildings are not structurally designed and supervised during construction by engineers.

<u>Engineered</u> Reinforced Concrete Moment-Resisting-Frame buildings

These buildings consist of a frame assembly of cast-in-situ concrete beams and columns. Floor and roof elements consist of cast-in-situ concrete slabs. Lateral forces are resisted by RC moment frames that develop their stiffness through monolithic beam-column connections. For these engineered buildings, the structural design and construction supervision is <u>made by engineers</u>.

DEFICIENT RC STRUCTURAL SYSTEMS | SOLID BRICKS INFILL WALLS WITH POOR MORTAR JOINTS

NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

RC structures with infill walls

SOFT-STOREY MECHANISMS | IN-ELEVATION IRREGULARITY | FAILURE OF COLUMNS

NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

RC structures with infill walls

SOFT-STOREY MECHANISMS | IN-ELEVATION IRREGULARITIES | 3+ ADDED STOREYS

NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

RC structures with infill walls

COLUMNS/JOINTS SHEAR FAILURE | POOR DETAILING | INADEQUATE BARS' ANCHORAGE AND INSUFFICIENT STIRRUPS | POOR MATERIALS QUALITY

MEDIUM-RISE BUILDING | SEVERE DAMAGES CONCENTRATED IN SOME COLUMNS AT GROUND LEVEL | IN-PLAN IRREGULARITY (ONLY-ONE FULL INFILLED FAÇADE)

MEDIUM-RISE BUILDING | SEVERE DAMAGES CONCENTRATED IN SOME COLUMNS AT GROUND LEVEL | IN-PLAN IRREGULARITY (ONLY-ONE FULL INFILLED FAÇADE)

NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

RC structures with infill walls

MEDIUM-RISE BUILDINGS | STRONG INFILL WALLS | SHEAR SLIDING MECHANISM AND DAMAGE IN ADJACENT COLUMNS (SHEAR-OUT)

MEDIUM-RISE BUILDINGS | POOR QUALITY OF CONCRETE | SHEAR-OUT

NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

RC structures with infill walls

POOR QUALITY OF MATERIALS AND CONSTRUCTION DETAILING

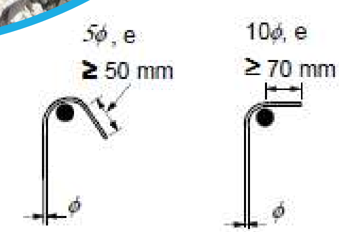
NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

RC structures with infill walls

INADEQUATE CAPACITY OF COLUMNS | DIMENSIONS AND DETAILING | SOFT-STOREY

NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

RC structures with infill walls



INSUFFICIENT CAPACITY OF RC ELEMENTS | DIMENSIONS AND DETAILING | SOFT-STOREY | STIRRUPS FAILURE

HIGH-RISE WDS BUILDINGS

DAMAGES ESSENTIALLY AT NON-STRUCTURAL ELEMENTS

NEPAL 2015 EQs - SURVEY DAMAGE ASSESSMENT

High-Rise RC structures with infill walls

PRONOUNCED IN-PLANE CRACKING | OUT-OF-PLANE COLLAPSE OF WALLS

FINAL REMARKS

RC building structures

- **Non EQ-designed** structures suffered extensive damage and partial or full collapses, mostly due to vertical irregularities
- **Well-designed** RC buildings demonstrated significant non-structural damage
- Insufficient control by Nepalese entities (design and construction)

URM buildings

- Extensive damage and collapses are attributed to poor materials and inadequate construction detailing/practices
- Weak connections between the walls and floors/roof, which do not guarantee a proper demand distribution/transfer and stability

Historical buildings

- Slender monumental structures, such as towers and temples, presented higher level of damage

Reuters and ABC

2017 Central Mexico earthquake (19th Sep.)

RC building structures – Observed damages

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

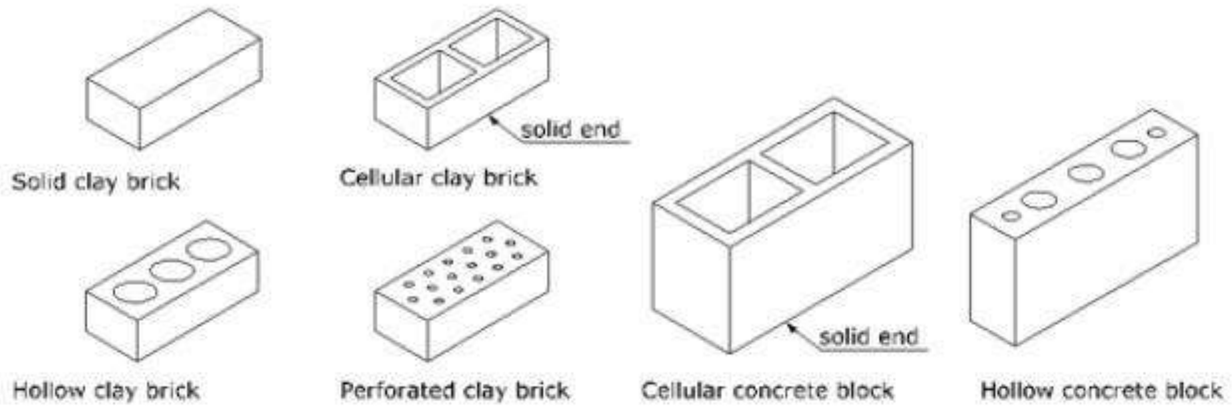
But …
Irregularities (in-elevation and in-plan) in terms of stiffness/strength due to drastic changes in the structural and/or IM walls configuration (location and number of infill walls):

Soft/Weak-storey mechanism
Torsion

IM walls in Mexico

Masonry units

Different masonry units are used to construct IM walls: solid, perforated unit, hollow unit, cellular unit and horizontally perforated



Rivero, J. (2002), "Manual técnico de construcción"

IM walls in Mexico

Confined masonry walls and IM walls



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 where two perpendicular facades were fully infilled with masonry walls, and the facades facing the street were left open.


2017 Central Mexico earthquake (19th Sep.)

RC building structures – Observed damages

IM walls

Jean Ingenieros (2017)

IP damages:
- diagonal cracking;
- detachment from the surrounding frame

OOP collapse:
- IP-OOP interaction

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, stairs,...)

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,…)

Damages in RC building structures

Main conclusions and lessons from the recent earthquakes

(1) **Structural damage** are mainly present in **columns** and beam-column **joints**, due to the **design philosophy** and **poor** reinforcement **detailing**, according to old design codes

(2) **Many buildings were severely damaged or collapsed due to the irregularities**, in plan or in elevation (ground storey used for commerce), induced by both structural and/or non-structural elements

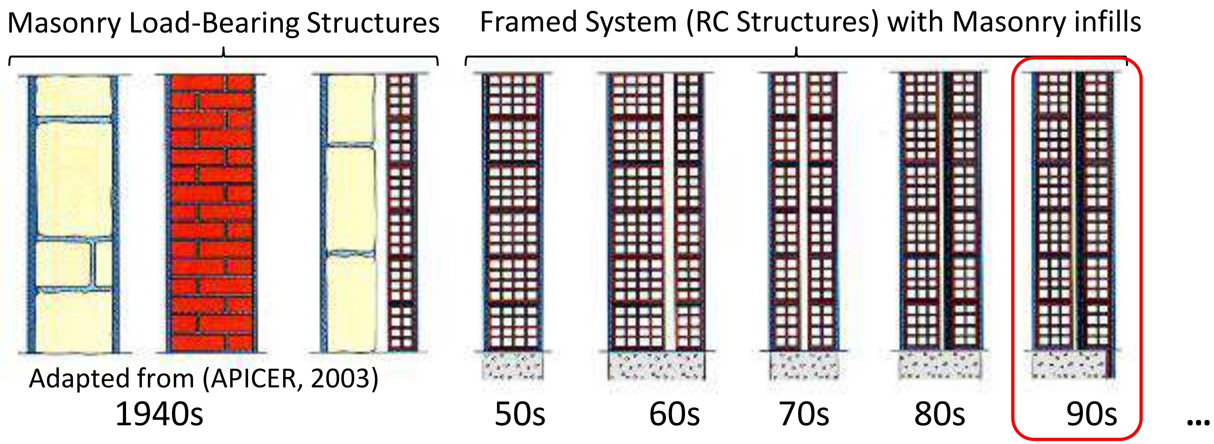
(3) **Most damages** in buildings **comes from non-structural elements**, such as infill walls

(4) **Non-structural elements** with very **poor performance**, causing **major economic losses** and some **deaths** (detachment and collapse of exterior panels in façade masonry walls)

This evidences the influence of the "non-structural" elements, like masonry infill walls, in the structural behaviour and performance of RC buildings

Contents

Evolution of exterior Masonry walls in Southern Europe (Portugal, …)



- 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 behavior 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 (Portugal,…)

Horizontal hollow clay bricks
with different dimensions (thickness)

Vertical hollow clay bricks

Vertical hollow concrete blocks

… 1950 — 1990 — 2000 — 2018 → ?

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 these buildings will perform in the next earthquakes?

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Current construction practice

IN masonry walls with horizontal hollow clay bricks:

How these buildings will perform in the next earthquakes?

Current construction practice

IN masonry walls with different types of units:

Bare Frame RC structure – Stage 1

RC structure with different types of IM walls – Stage 2

How these buildings will perform in the next earthquakes?

Current construction practice

IN masonry walls with vertical hollow concrete blocks:

How these buildings will perform in the next earthquakes?

Contents

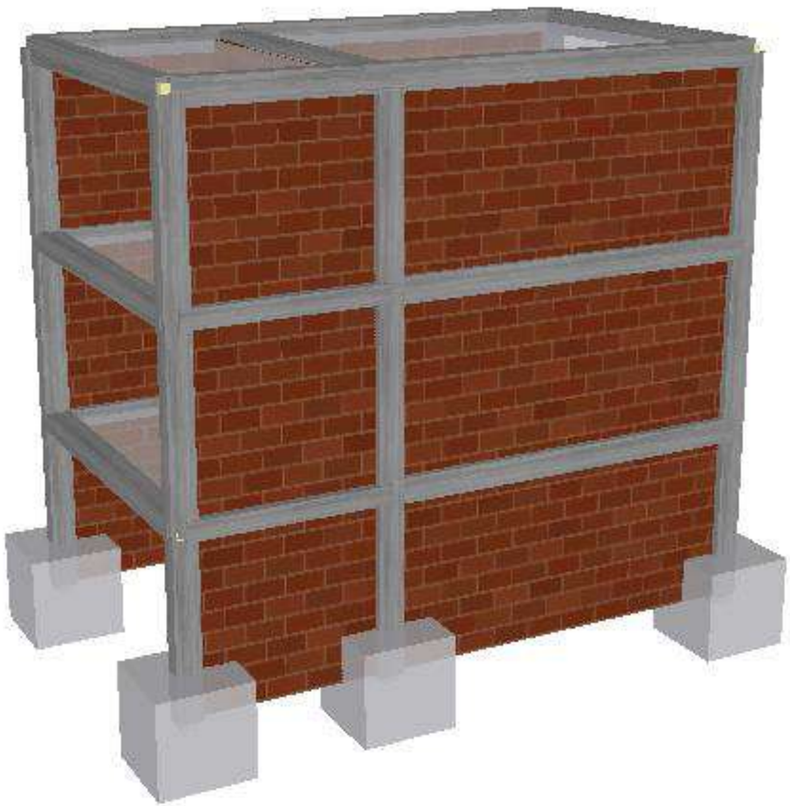
Seismic assessment of RC structures

Existing buildings (1950s, 1960s, …) and New construction

1983 – RSA/REBAP // Eurocodes (EC8)

Seismic assessment of RC structures

LESE activities



- **RC structural System**
  - RC columns (biaxial tests with a w/o retrofit)
  - RC Beam-column joints (tests with and w/o retrofit)
  - Numerical modelling
- **Infill Masonry Walls**
  - Geometric characterization
  - Mechanical characterization tests
  - Ambient vibration tests
  - Cyclic OOP tests with and without previous damage
  - Numerical modelling

Seismic assessment of RC structures

LESE activities

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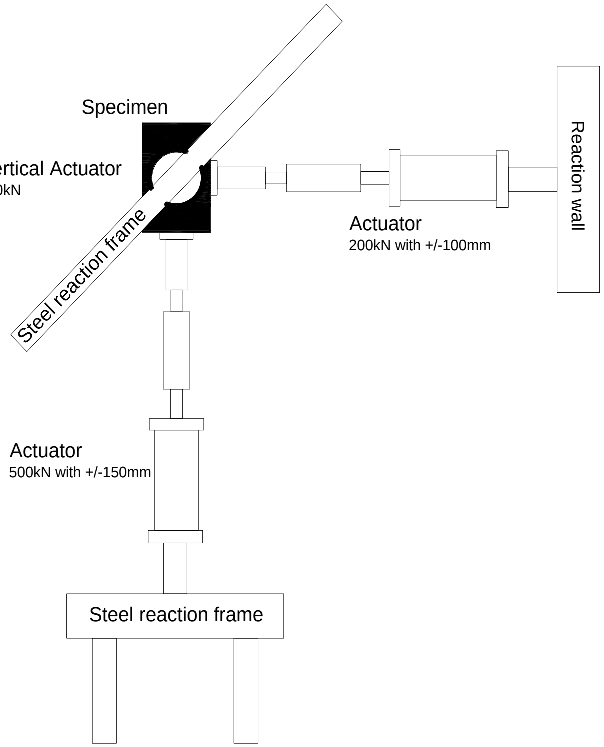
Seismic assessment of RC columns

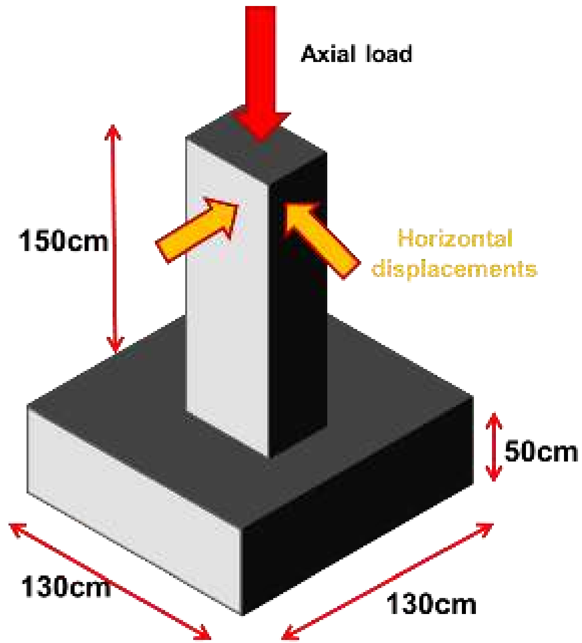
In the last years, the LESE group have carried out a large number of uniaxial and biaxial experimental tests on as-built and retrofitted RC columns

- More than 45 biaxial tests under constant or variable axial load and different lateral displacement paths
- More than 100 uniaxial tests under constant or variable axial load

Seismic assessment of RC columns

Test Setup





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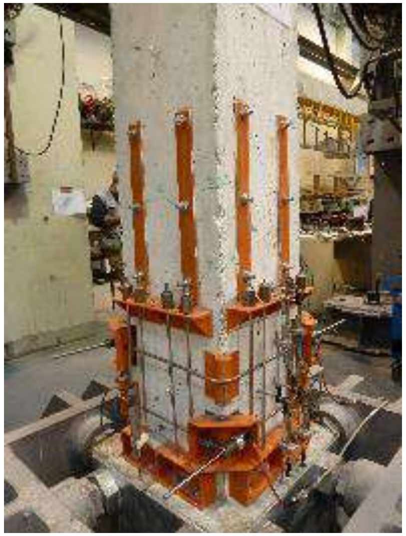
Seismic assessment of RC columns
Retrofitting solutions

Retrofitting solutions

Realistic repair and retrofitting solutions were developed and tested

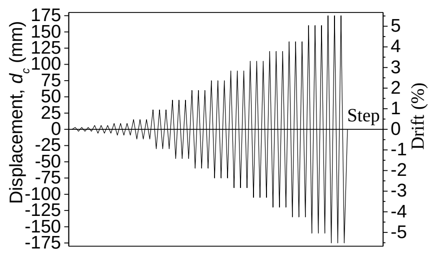
- Steel plates wrapping
- CFRP wrapping
- Concrete jacketing
- External longitudinal reinforcement

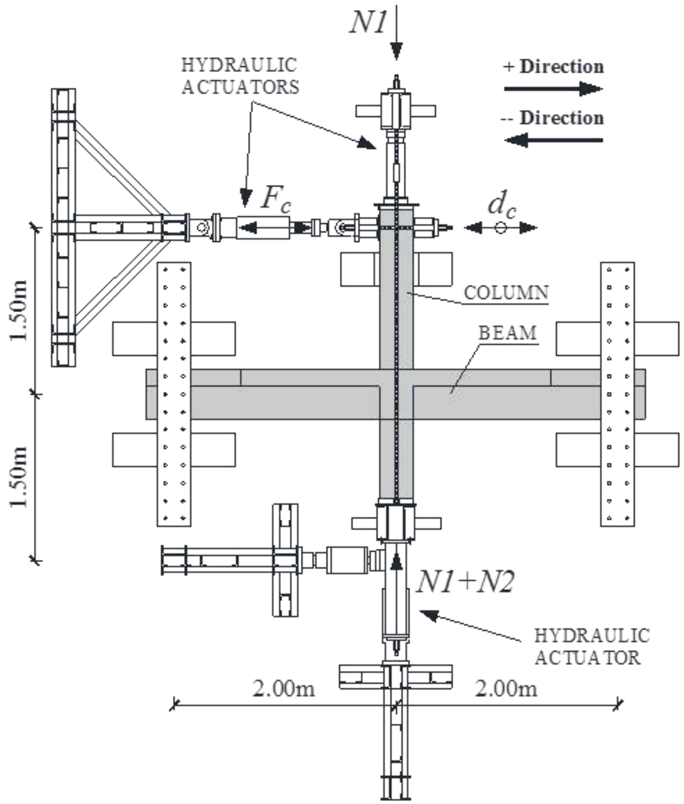


Seismic assessment of RC beam-column joints

Test Setup

- The specimens are tested in the horizontal position
- Sliding devices at the beam extremities were used to simulate the beams support conditions
- Two hydraulic actuators for the axial load and one servo-actuator to impose the lateral displacements at the top of the column





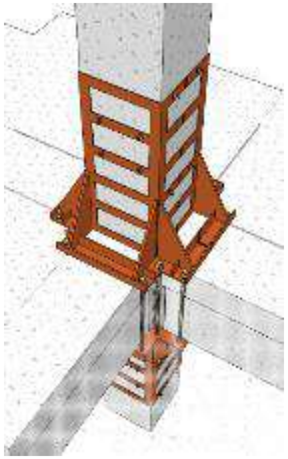
Seismic assessment of RC beam-column joints

Retrofitting solutions

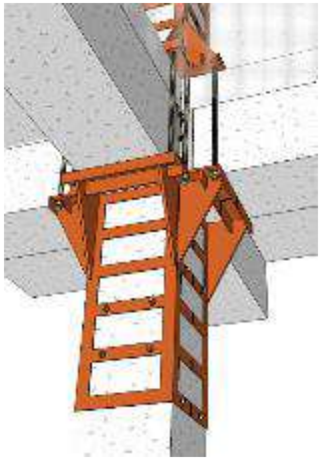
Realistic retrofitting solutions were developed and tested for RC beam-column joints with transversal beams and slab

- Steel plates wrapping
- CFRP wrapping
- Concrete jacketing

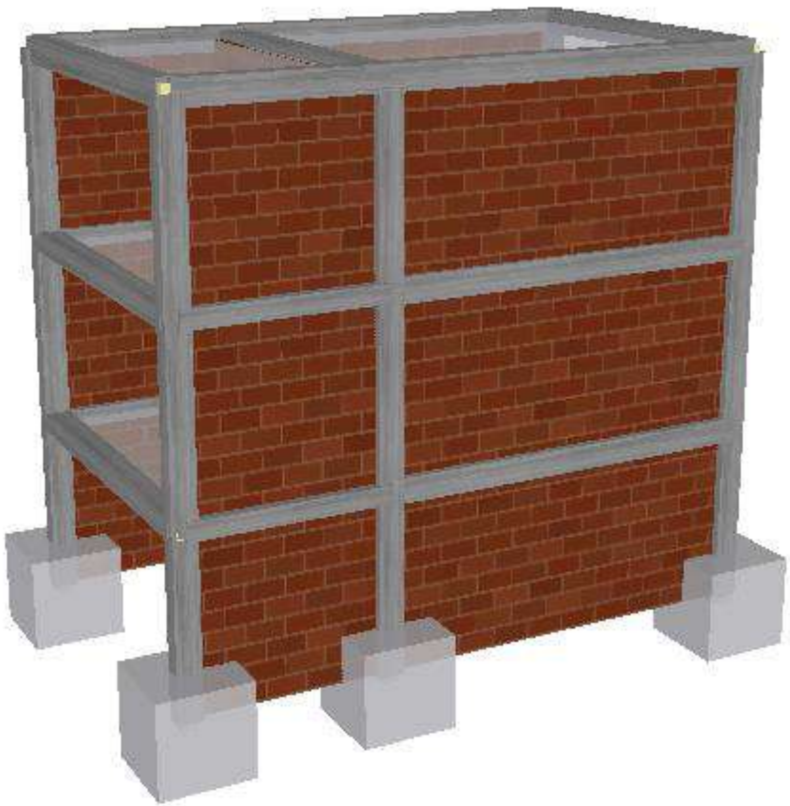
Top column



Bottom column



Activities of LESE



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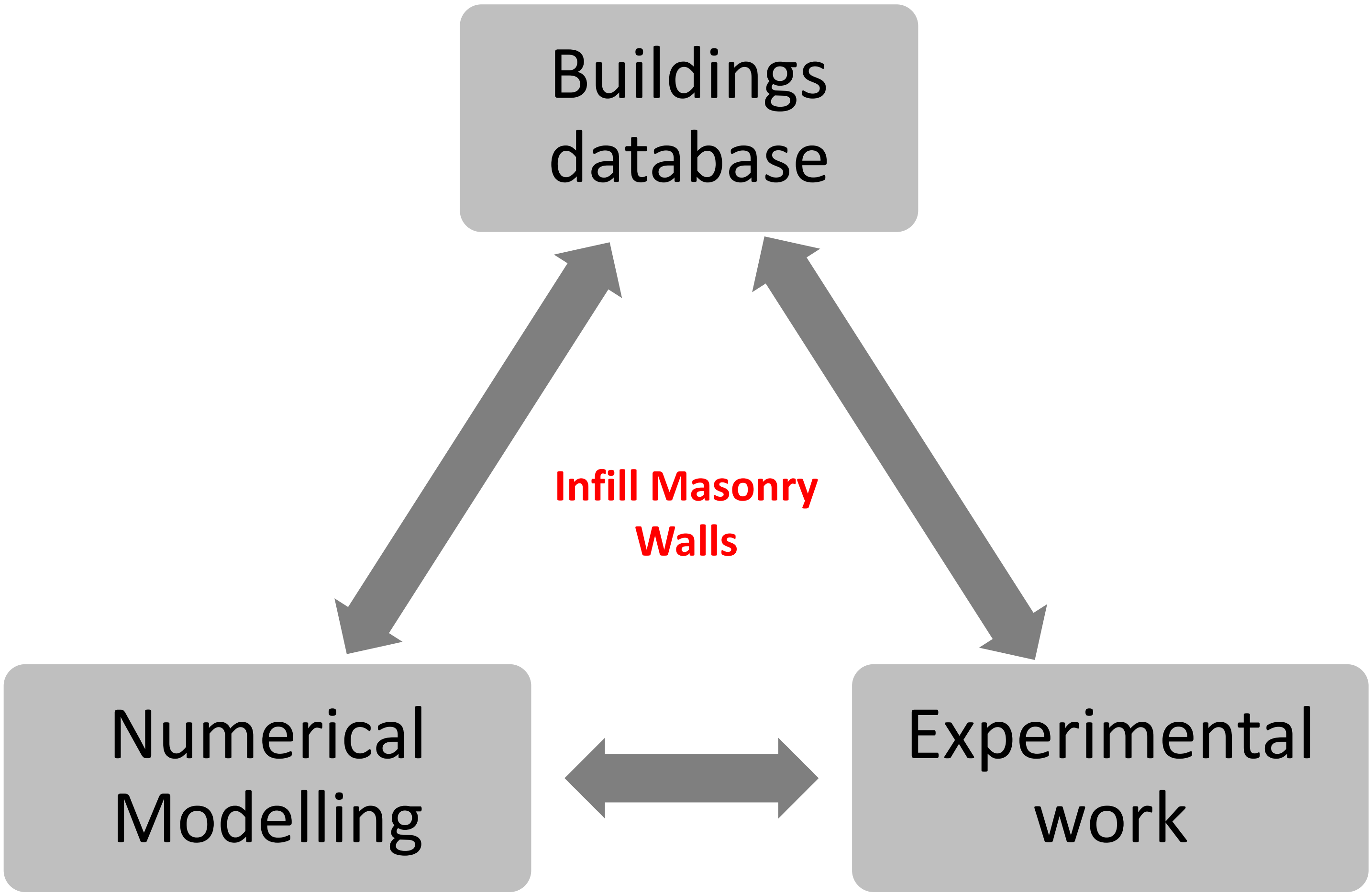
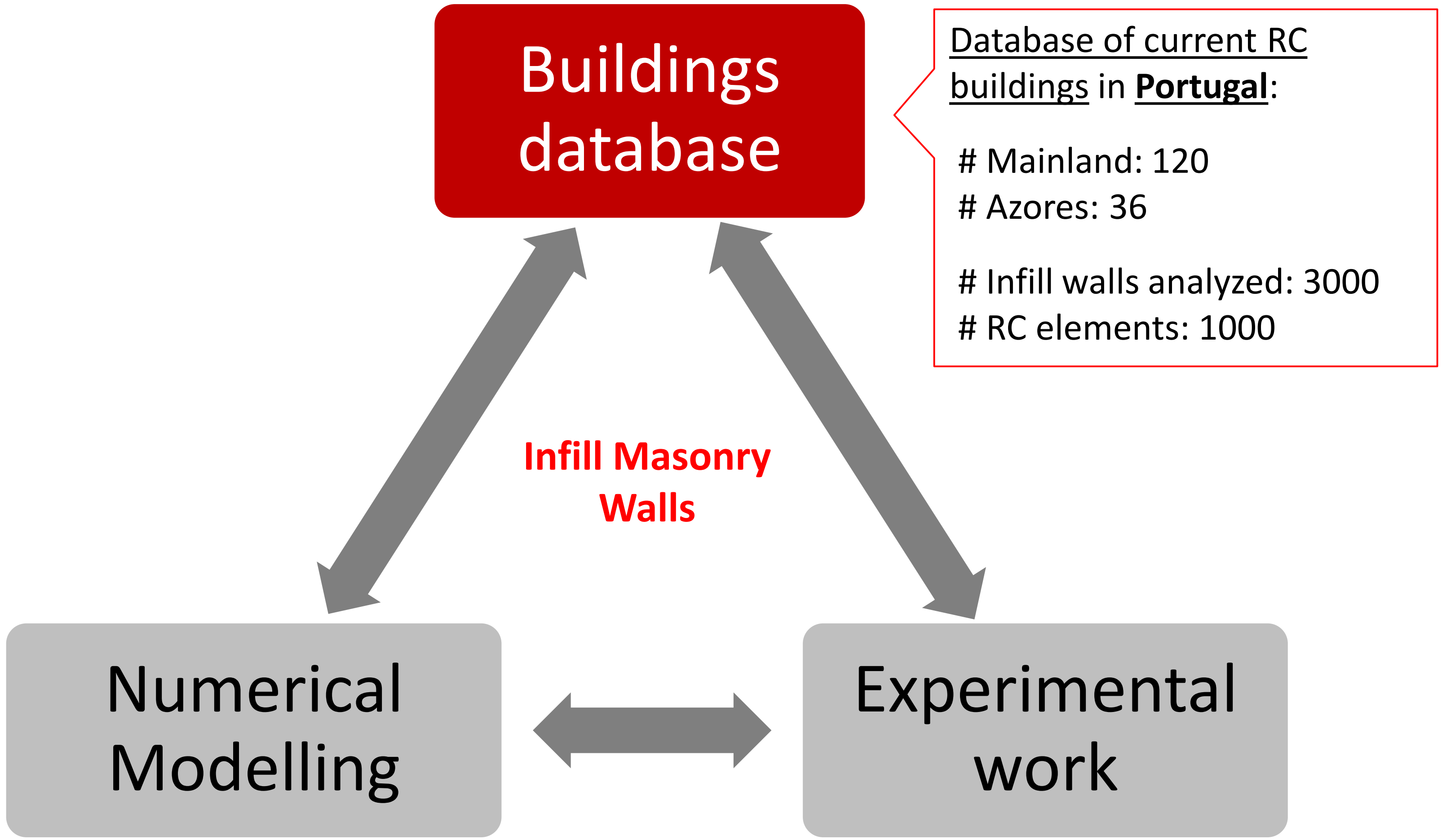
Activities of LESE



Geometric characterization of the masonry infill walls

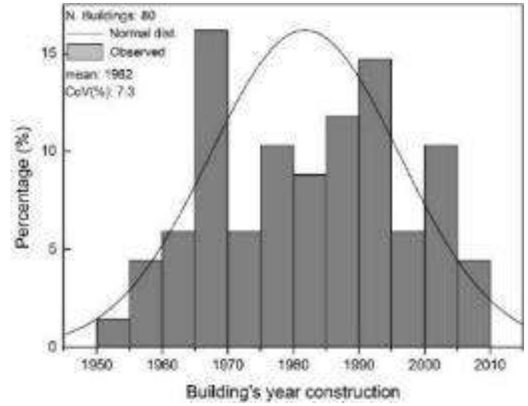


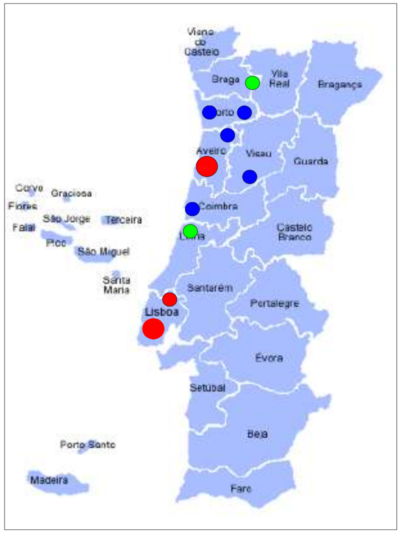
Geometric characterization of the masonry infill walls

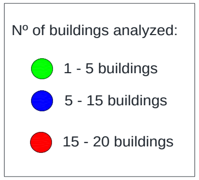
Main results:

- Majority of existing RC buildings were constructed between 1965 and 1995

- 40% of the buildings were designed without seismic concerns or for low seismic demands



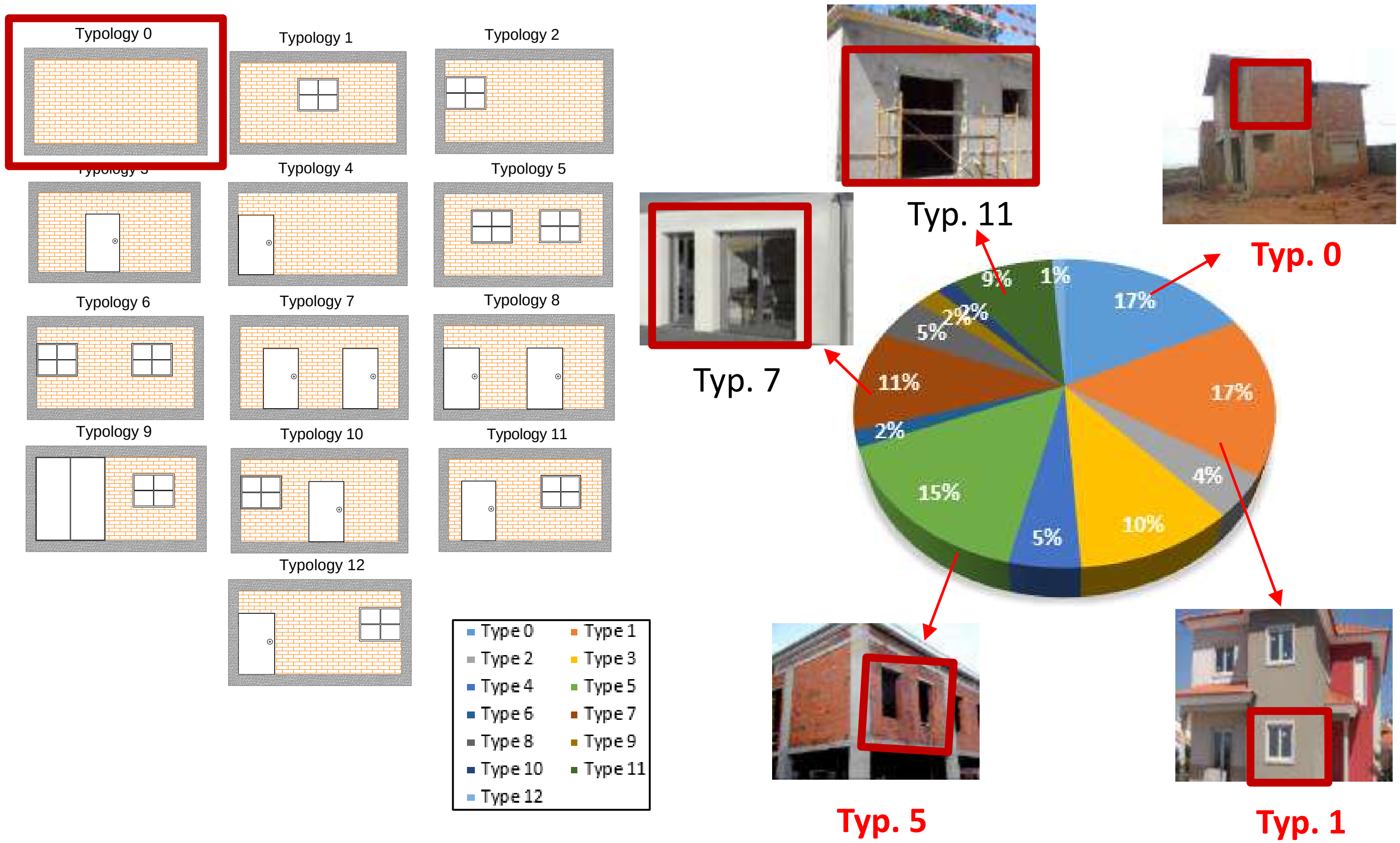




- 73% of the buildings analyzed have a residential use-only, and the others have multiple use (residential, offices and/or commercial stores).

Geometric characterization of the masonry infill walls

<u>Main results:</u>



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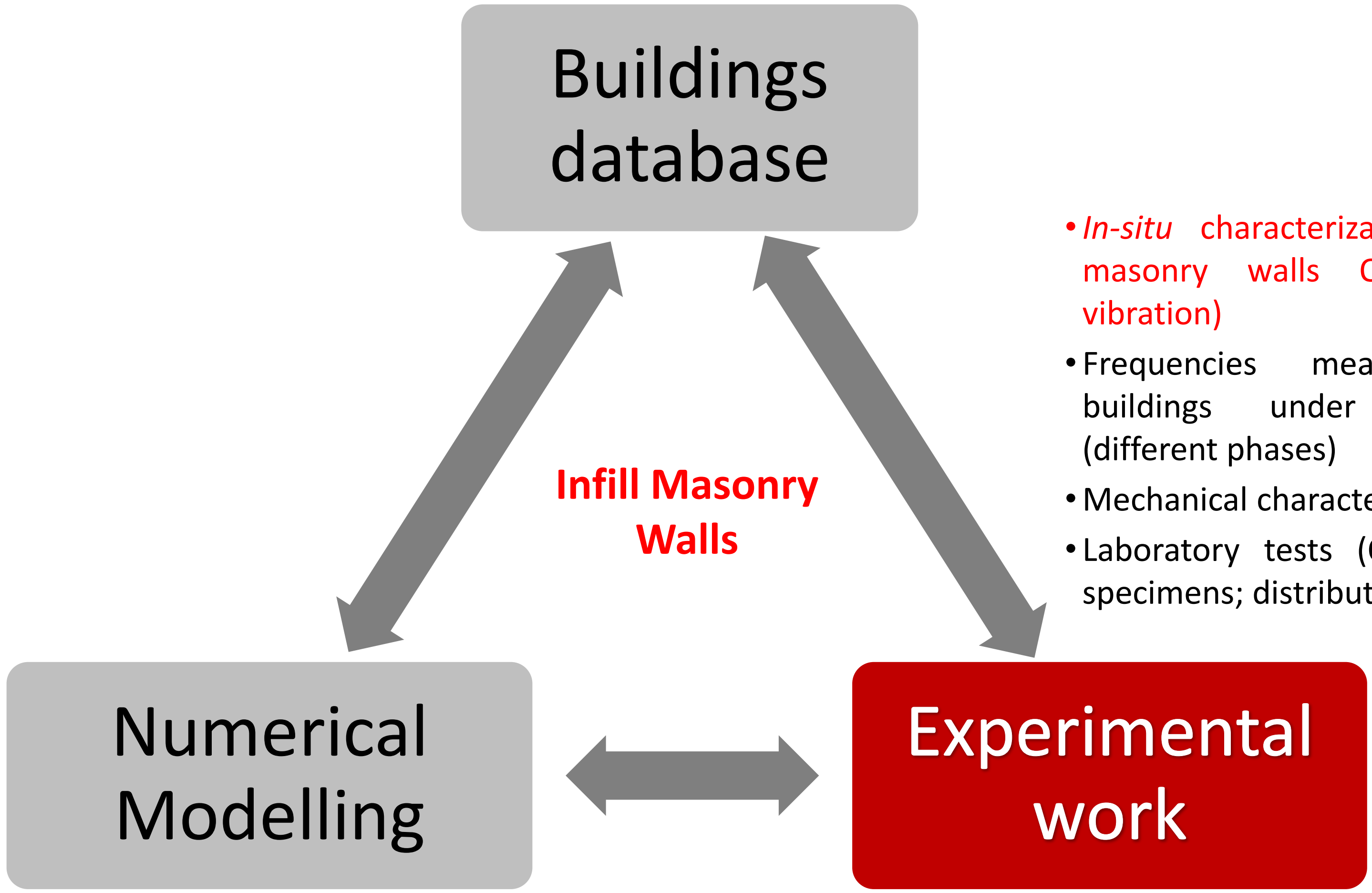
Activities of LESE

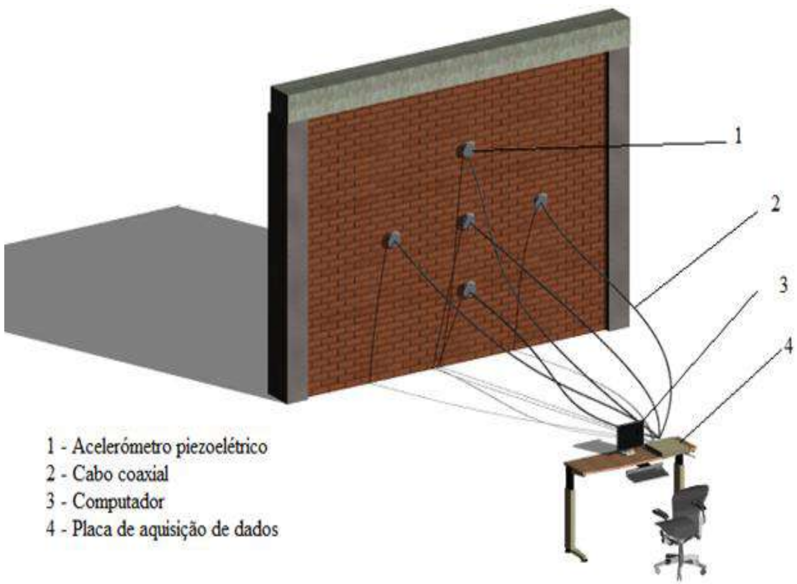


- *In-situ* characterization tests on masonry walls OOP (ambient vibration)
- Frequencies measurement in buildings under construction (different phases)
- Mechanical characterization tests
- Laboratory tests (OOP; full-scale specimens; distributed loading)

In-situ characterization on masonry walls

<u>Main Goals</u>

- Calibration of numerical models
- Damage detection for post-earthquake rehabilitations
- In-situ and laboratory testing



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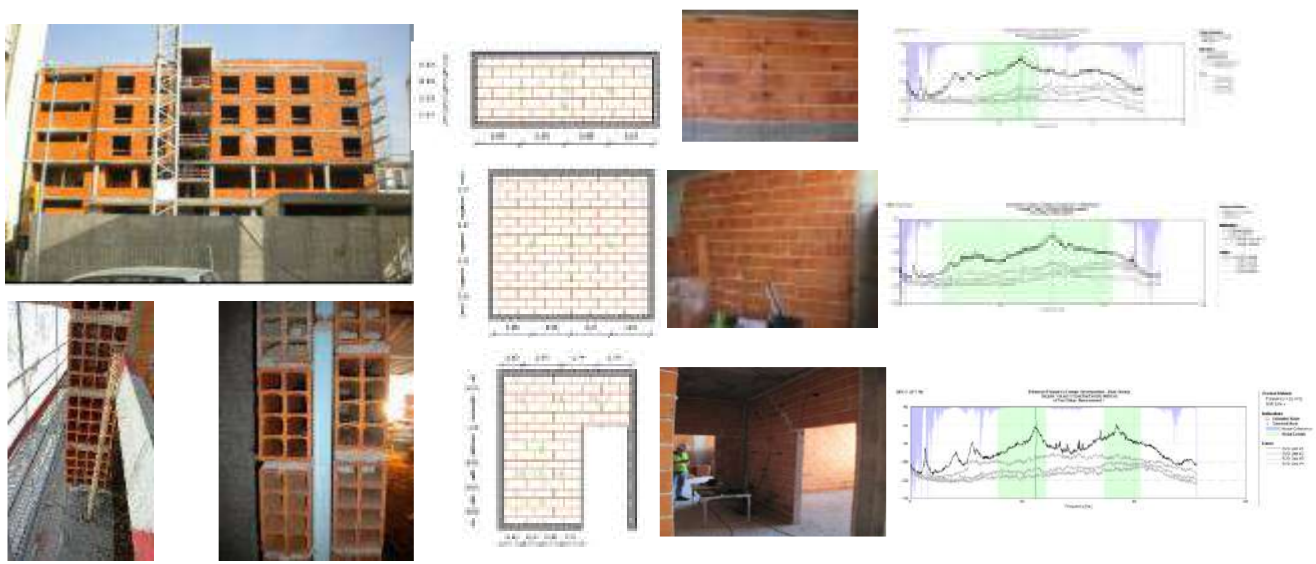
In-situ characterization on masonry walls

<u>Main Goals</u>

- <u>Existing</u> buildings, but also in buildings <u>under construction</u>
- different: typologies; <u>panel dimensions</u>; <u>openings</u> dimensions and locations; <u>border support</u> conditions; …



Furtado A., Rodrigues H., Arêde A., Varum H. (2017) – Modal identification of infill masonry walls with different characteristics, *Engineering Structures*, Vol. 145, PP. 118-134

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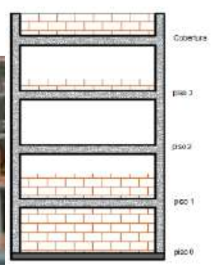
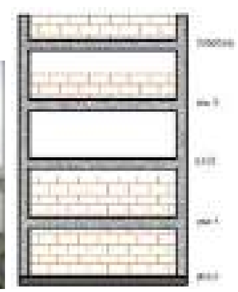
In-situ characterization on masonry walls

Evolution of building natural frequencies: Building B

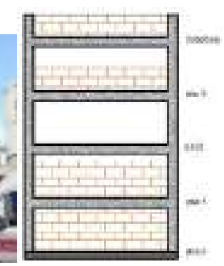
- 4 storeys building
- Horizontal hollow clay bricks



f_x=2.93Hz f_y=2.93Hz



f_x=3.42Hz f_y=3.42Hz



f_x=3.91Hz f_y=3.42Hz

Activities of LESE

Buildings database

Infill Masonry Walls

Numerical Modelling

Experimental work

- In-situ characterization tests on masonry walls OOP (ambient vibration)
- Frequencies measurement in buildings under construction (different phases)
- Mechanical characterization tests
- Laboratory tests (OOP; full-scale specimens; distributed loading)

Experimental characterization of masonry walls mechanical properties

Different types of masonry units were developed and introduced in the construction, throughout the last decades, pushed by the architectural requirements, comfort and energy efficiency concerns/requirements, or aiming at the use of innovative green materials and solutions.

Mechanical characterization tests

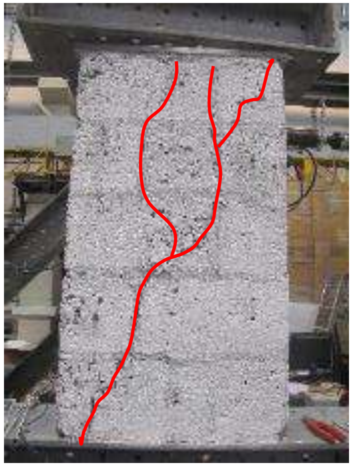
Compression strength tests: main results

$F_{m,brick11}$=0.7MPa
SD:0.1MPa COV 18,8%
$E_{m,brick11}$=855MPa
SD:332MPa COV:39%

$F_{m,brick15}$=1.1MPa
SD:0.1MPa COV:11,3%
$E_{m,brick15}$=942MPa
SD:233MPa COV:24,8%

Hollow clay brick

- Fragile behaviour
- Larger dispersion



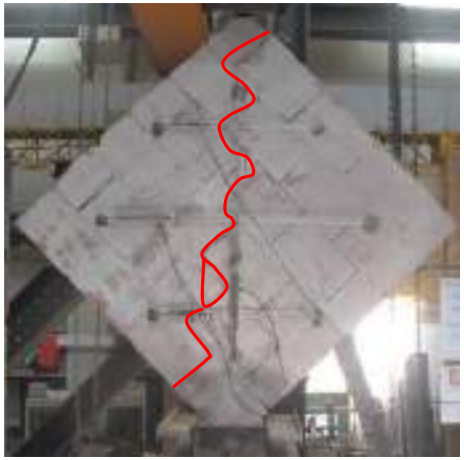
$F_{m,concrete31.5}$=1.9MPa
SD:0.1MPa COV:5,1%
$E_{m,concrete31.5}$=2304MPa
SD:115MPa COV:5.1%

$F_{m,concreteAzores}$=2.4MPa
SD:0.1MPa COV:3,8%
$E_{m,concreteAzores}$=3855MPa
SD:165MPa COV:4,8%

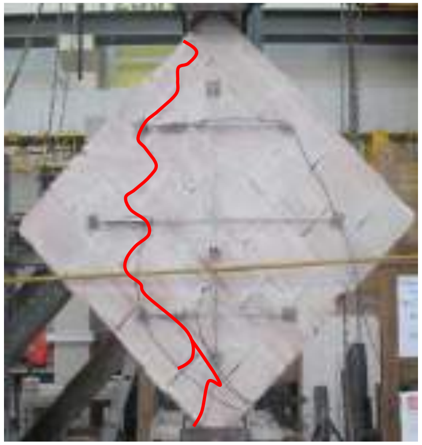
Concrete block

Mechanical characterization tests

Diagonal compression strength tests: main results



$F_{m,brick11}$=0.5MPa
SD:0.2MPa COV:34,7%
$G_{,brick11}$=1068MPa
SD:76.6MPa COV:7,2%



Fm,brick15=0.6MPa
SD:0.1MPa COV:20,1%
G,brick15=925.5MPa
SD:36.6MPa COV:4,1%

$F_{m,concrete31.5}$=0.3MPa
SD:0.1MPa COV:21,7%
$G_{,concrete31.5}$=1472MPa
SD:630MPa COV:42,9%

$F_{m,concreteAzores}$=0.4MPa
SD:0.1MPa COV:33,3%
$G_{,concreteAzores}$=1867MPa
SD:402MPa COV:16%

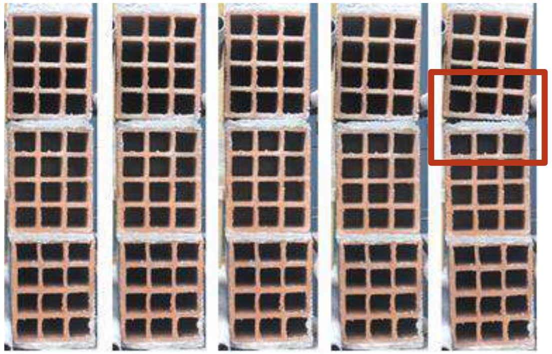
<u>Concrete block wallets</u>

- Similar failure pattern
- High dependence of the mortar-block interface

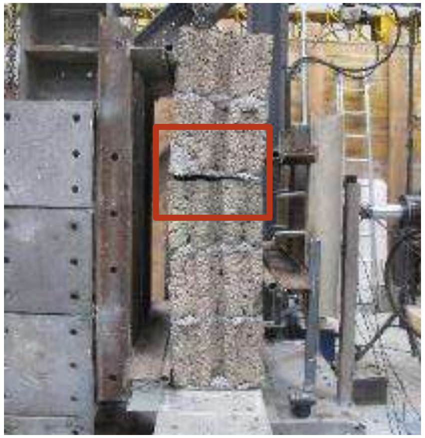
Mechanical characterization tests

Flexural tests (parallel to bed-joints joints): main results

$F_{xi,brick11}$=0.12MPa
SD:0.005MPa COV:3,9%



$F_{xi,brick15}$=0.11MPa
SD:0.047MPa COV:4.3%



$F_{xi,concrete31.5}$=0.10MPa
SD:0.019MPa COV:18,8%
$F_{xi,concreteAzores}$=0.25MPa
SD:0.09MPa COV:33,8%

- Similar failure pattern (detachment between block and joint)
- High dependence of the brick/block-joint interface

Mechanical characterization tests

Flexural tests (perpendicular to bed-joints joints): main results

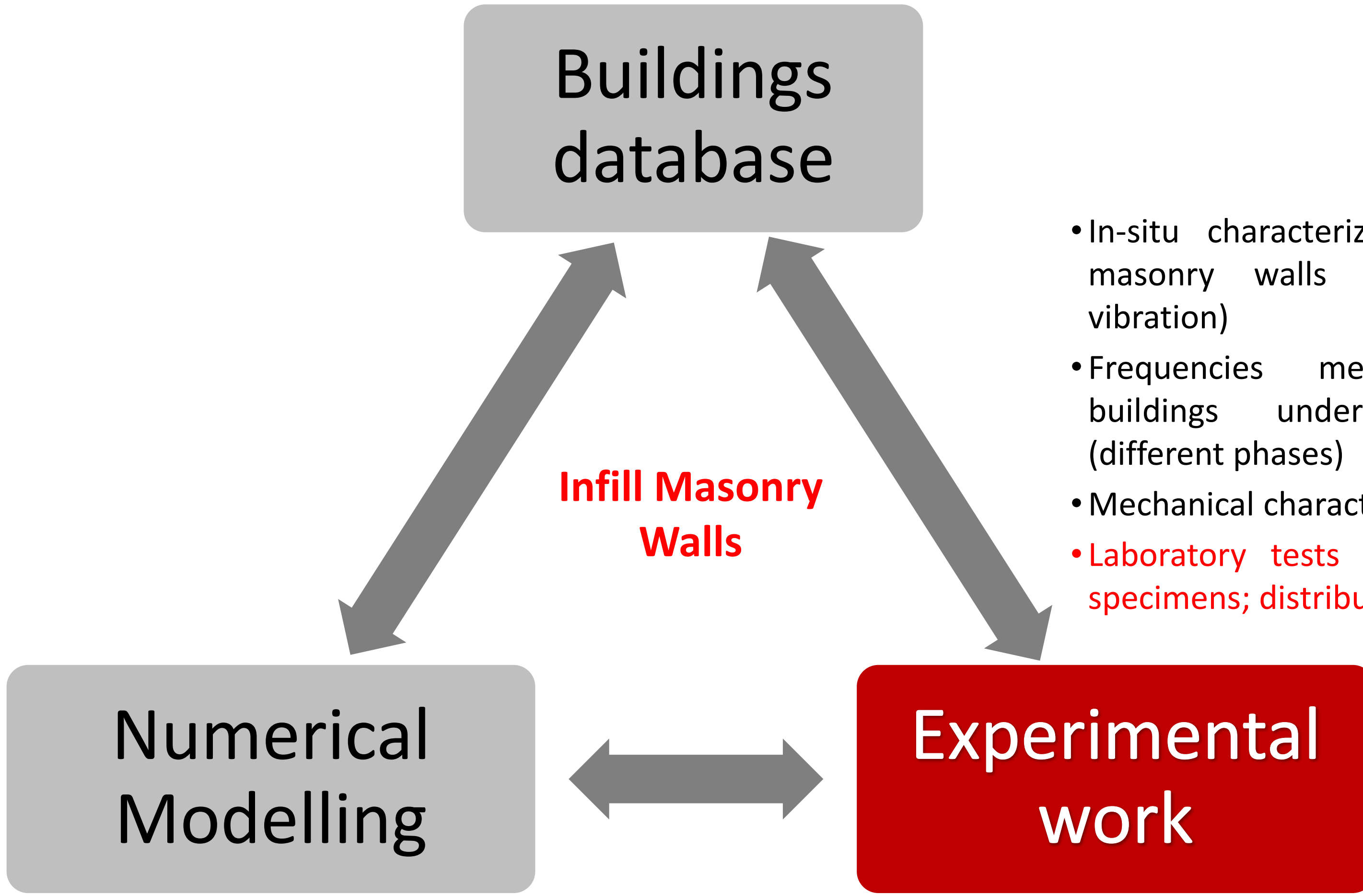
$F_{xii,brick11}$=0.32MPa
SD:0.061MPa COV:19,9%

$F_{xii,brick15}$=0.38MPa
SD:0.036MPa COV:9,9%

$F_{xi,concrete31.5}$=0.12MPa
SD:0.03MPa COV:24.7%
$F_{xi,concreteAzores}$=0.32MPa
SD:0.05MPa COV:14,1%

- Similar failure pattern
- Dependence of the masonry unit holes direction

Activities of LESE



- In-situ characterization tests on masonry walls OOP (ambient vibration)
- Frequencies measurement in buildings under construction (different phases)
- Mechanical characterization tests
- Laboratory tests (OOP; full-scale specimens; distributed loading)

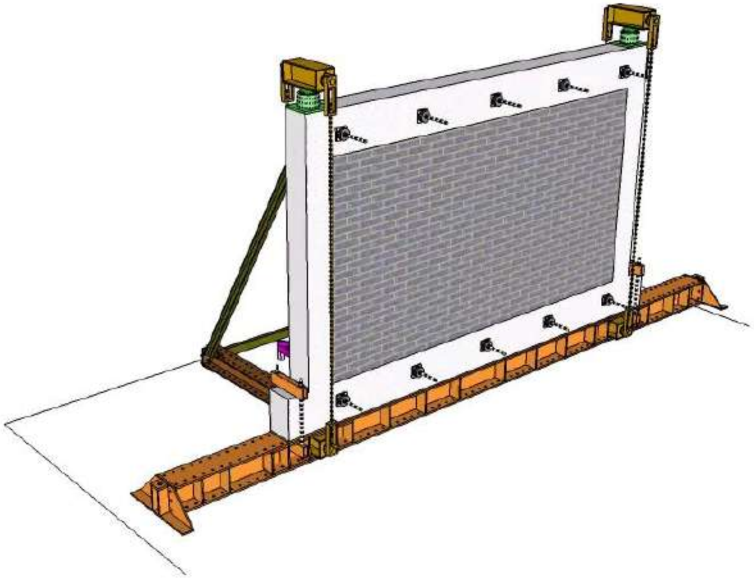
Full-scale OOP tests of IM walls

Objectives of the OOP testing campaign on full-scale IM specimens

- Characterization of the out-of-plane behaviour of full-scale IM walls (with and without previous in-plane damage)
- Development of an innovative out-of-plane experimental test setup
- Development, study and validation of retrofitting solutions

Full-scale OOP tests of IM walls

Testing platform: 2nd phase (pneumatic actuators) – General views



→ Project ASPASSI, reference PTDC/ECM-EST/3790/2014, FCT (2016-2018); Partners: FEUP (Leader), UM and LNEC.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Full-scale OOP tests of IM walls

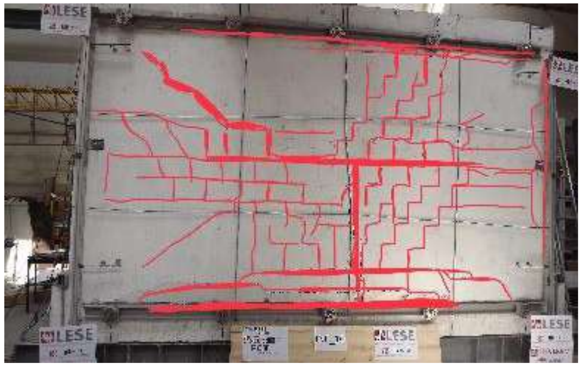
Influence of retrofitting (GFRP mesh with connectors)

Inf_07	Cyclic	As-built
Inf_08	Cyclic	Retrofitted

Final Damage state

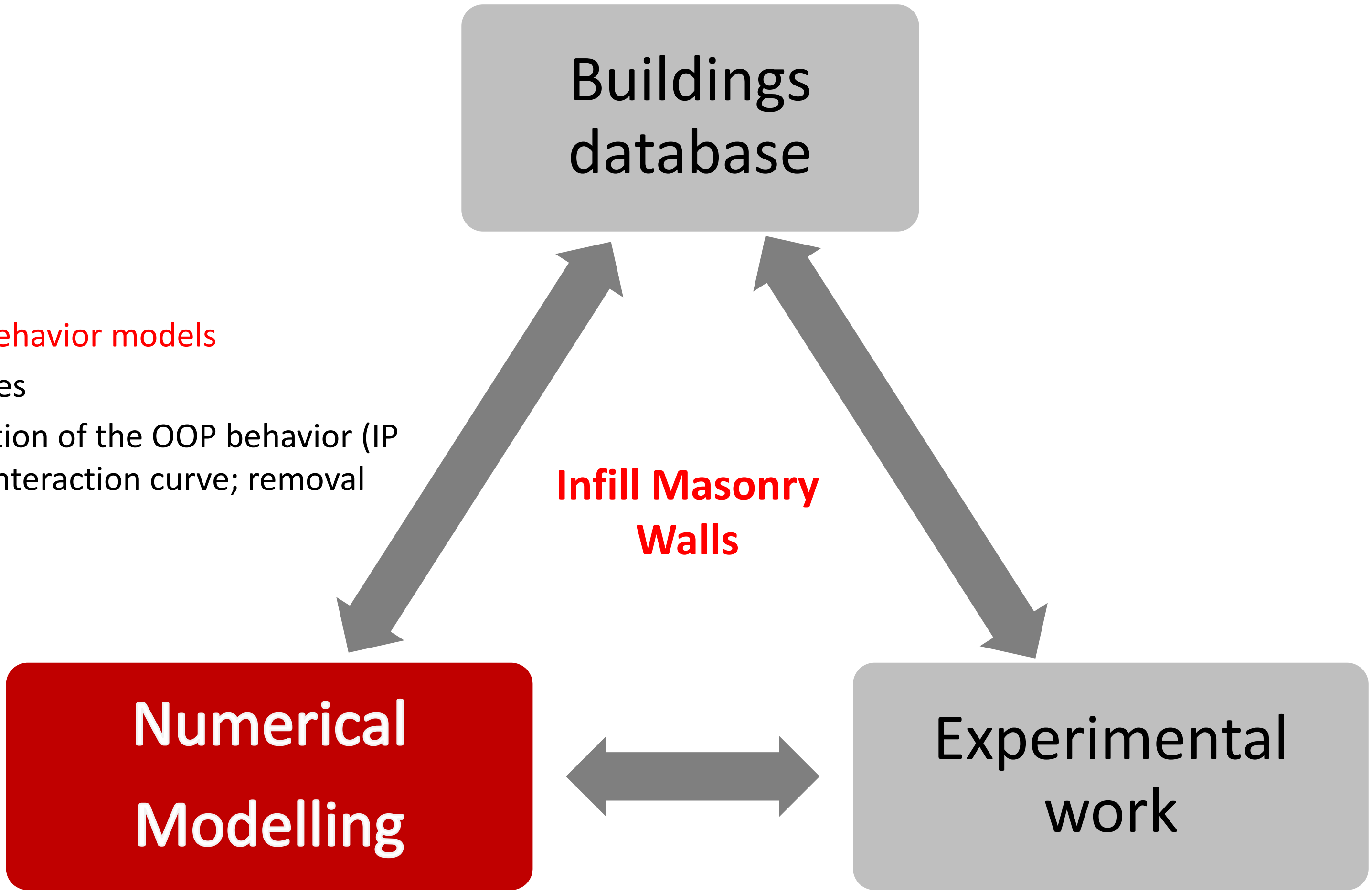
As-built
(max OOP disp. 30mm)

Retrofitted
(max OOP disp. 70mm)



Activities of LESE

- In-plane behavior models
- Case studies
- Consideration of the OOP behavior (IP and OOP interaction curve; removal algorithm)



Case studies: modelling the in-plane behavior of infills


Costa-Cabral, 1953

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


Parnaso, 1955

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


Infante Santo, 1954

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

Location

Contents

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) recommendations/requirements

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 s[...] 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)

} <u>should not have any type of brittle failure</u> in any element

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	-	$b_w \leq \min(b_c + h_w; 2b_c)$	$b_w \leq \min(b_c + h_w; 2b_c)$ $b \geqslant 20cm$ $b/h \geqslant 0.25$
Design forces	Structural Analysis	V_{Sd} with extreme moments $\gamma_{Rd} = 1.0$	V_{Sd} with extreme moments $\gamma_{Rd} = 1.2$
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.	-	$A_{inf} \geqslant 0.5 A_{sup}$	$A_{min,inf} = A_{max,inf}/4$ $A_{inf} \geqslant 0.5 A_{sup}$ $A_{min,sup} = A_{min,inf} = 2\phi 14$
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	$s_w \leqslant 0.75$ $\rho_w 0.08\sqrt{f_{ck}/f_{yk}}$	$s_w \leqslant 0.75$ $\rho_w 0.08\sqrt{f_{ck}/f_{yk}}$	$s_w \leqslant 0.75$ $\rho_w 0.08\sqrt{f_{ck}/f_{yk}}$
In CR	$d_{bw} \geqslant 6mm$	$d_{bw} \geqslant 6mm$ $s_w \leqslant \min(h_w/4; 24d_{bw}; 225mm; 8d_{bL})$	$d_{bw} \geqslant 6mm$ $s_w \leqslant \min(h_w/4; 24d_{bw}; 175mm; 6d_{bL})$
Column	**DCL**	**DCM**	**DCH**
Dimensions	-	$b_c \geqslant h_v/10$ if $\theta (= P\delta/Vh) > 0.1$	$b_c \geqslant 25cm$ $b_c \geqslant h_v/10$ if $\theta (= P\delta/Vh) > 0.1$
Forces	Structural Analysis	$\gamma_{Rd}=1.3$, M_{Sd} from beams' M_{Rd} $\gamma_{Rd}=1.1$, V_{Sd} from column extremities' M_{Rd}	$\gamma_{Rd}=1.3$, M_{Sd} from beams' M_{Rd} $\gamma_{Rd}=1.3$, V_{Sd} from column extremities' M_{Rd}
Ultimate strength	EC2	EC2 $(\nu_d \leqslant 0.65)$	EC2 $(\nu_d \leqslant 0.55)$
Biaxial bending	EC2	Biaxial bending or simplified uniaxial bending with M_{Rdz} e $_{Rdy}$ reduced in 30%	Biaxial bending or simplified uniaxial bending with M_{Rdz} 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	-	$d_{bw} \geqslant 6mm$ $s_w \leqslant \min(b_0/2; 175mm; 8d_{bL})$	$d_{bw} \geqslant 0.4 d_{bL,max}\sqrt{f_{yd}/f_{ywd}}$ $s_w \leqslant \min(b_0/3; 125mm; 6d_{bL})$
Transv. reinf. out of CR	$d_{bw} \geqslant \max(d_{bL}/4; 6mm)$ $s_w \leqslant \min(20d_{bL}; 40cm; \min(h_c; b_c))$	$d_{bw} \geqslant \max(d_{bL}/4; 6mm)$ $s_w \leqslant \min(20d_{bL}; 40cm; \min(h_c; b_c))$	$d_{bw} \geqslant \max(d_{bL}/4; 6mm)$ $s_w \leqslant \min(20d_{bL}; 40cm; \min(h_c; b_c))$
Confinement in CR	-	$d_{bw} \geqslant 6mm$ $s_w \leqslant \min(b_0/2; 175mm; 8d_{bL})$	$\alpha\omega_{wd} \geqslant 30\mu_\phi \nu_d \varepsilon_{sy,d}(b_c/b_0) - 0.035$ $\omega_{wd} \geqslant 0.08$
Confin. bottom of columns	-	$\alpha\omega_{wd} \geqslant 30\mu_\phi(\nu_d + \omega_\nu)\varepsilon_{sy,d}(b_c/b_0) - 0.035$ $\omega_{wd} \geqslant 0.08$	$\alpha\omega_{wd} \geqslant 30\mu_\phi(\nu_d + \omega_\nu)\varepsilon_{sy,d}(b_c/b_0) - 0.035$ $\omega_{wd} \geqslant 0.12$

Code requirements

Requirements for design of building 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	Infill σ_I	K_I	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	$*ray \vee T_a = C_t h^{0.75}$ $C_t = \frac{.075}{\sqrt{A_c}}$ $A_c = \sum A_i \left(0.2 + \min\left\{\frac{l_{wi}}{h}; 0.9\right\}\right)^2$ (m)	28 / 25	100	N	[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]	-	-	-	-	-	-	Y	Y	-	Y
[illegible]	[illegible]	[illegible]	25	N	Y	Y	2	Y	Y	N	Y	Y
[illegible]	[illegible]	[illegible]	-	-	-	-	N	-	-	-	-	-
[illegible]	[illegible]	$*ray \vee T_a = C_t h^{0.75}$ $C_t = \frac{0.05048}{\sqrt{A_c}}$ $A_c = \sum A_i \left(0.2 + \min\left\{\left(\frac{l_{wi}}{h}\right)^2; 0.9\right\}\right)$ (m)	N	N	N	N	1.5	N	N	N	N	N
[illegible] 7-81, 1996]	-	-	-	-	-	-	-	-	-	-	-	-
Venezuela [COVENIN-2002, 1988]	Y	Rayleigh formula ($*ray$) $T_a = 2\pi\sqrt{\left(\sum_{i=1}^{N} W_i\delta_{ei}^2\right) / \left(g\sum_{i=1}^{N} F_i\delta_{ei}\right)}$	25	N	N	N	X	N	N	N	N	N
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), σ_I (strength of infill), K_I (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 !

Timeline of Eurocodes

1984 - The first Eurocodes were published by the Commission

1990 - ENVs started, following a Mandate issued in 1989 by the EC and the MS. The preparation and publication of the Eurocodes was transferred to CEN. The Eurocodes were intended to become European Standards

1992 - Publication of ENV Eurocodes by CEN begun

1998 - Conversion of ENV to EN was initiated following the Commission Mandate to CEN

2004 - The Directive on Public Works contracts, Public Supply contracts and Public Service contracts was issued

2007 - The Publication of EN Eurocodes was **concluded**

…….. - on-going a new revision of the Eurocodes …

Final comments

In the assessment of existing buildings, and in the design of new buildings…

- consideration of the IM walls in the structural design (based on simple checking rules/procedures after the structural design) should be enforced

- particular attention should be given to:
  - irregularities in-elevation (as in the stiffness differences between the 1st and the upper storeys: storey height, dimensions and position of openings, distribution of IM walls)
  - irregularities in-plan: torsion
  - influence of plain reinforcing bars
  - reinforcement detailing (beam-column joints, transverse reinforcement in the columns, and anchorage of the longitudinal reinforcing bars of the columns and beams)

- The OOP collapse of infills can result in serious human and material consequences, as observed in recent earthquakes. So, there is a need to consider the OOP behavior of IM walls in the seismic safety assessment of existing RC structures.

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Lesson…

“Earthquakes don't kill, buildings do…”

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MASTER IN CIVIL ENGINEERING

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1st Year, 1st Semester	Credits	1st Year, 2nd Semester	Credits
Mathematical Analysis I	7,0	Mathematical Analysis II	7,0
Algebra	7,0	Numerical Analysis	6,0
Technical Drawing	6,5	Topography	6,0
Computation	6,0	Mechanics 1	7,0
History of Civil Engineering	2,0	Economics and Management	4,0
Project FEUP	1,5		
Total	30	Total	30

2nd Year, 1st Semester	Credits	2nd Year, 2nd Semester	Credits
Mathematical Analysis III	5,5	Statistics	6,5
Environmental and Social Assessment	4,5	Architecture	5,5
Mechanics 2	6,0	Physics	5,0
Engineering Geology	6,0	General Hydraulics I	5,0
Strength of Materials I	8,0	Strength of Materials II	8,0
Total	30,0	Total	30,0

3rd Year, 1st Semester	Credits	3rd Year, 2nd Semester	Credits
Construction Materials I	5,5	Construction Materials II	5,5
Structural Analysis I	7,0	Structural Analysis II	7,0
General Hydraulics II	6,5	Hydrology and Water Resources	6,5
Physic of Constructions	6,0	Technology of Construction	5,5
Operational Research	5,0	Territorial Planning	5,5
Total	30,0	Total	30,0

4th Year, 1st Semester	Credits	4th Year, 2nd Semester	Credits
Structural Concrete I	8,0	Structural Concrete II	8,0
Soil Mechanics I	7,0	Soil Mechanics II	6,0
Environmental and Urban Hydraulics	6,5	Urban Environment and Transport Planning	5,0
Roads I	5,5	Roads II	6,5
Project Management	3,0	Construction Management and Safety	4,5
Total	30,0	Total	30,0

MASTER IN CIVIL ENGINEERING

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Materials and Construction Processes

5th Year, 1st Semester	Credits	5th Year, 2nd Semester	Credits
Materials Pathologies	5,0	Thesis in Materials and Construction Processes	30,0
Application Geosynthetics in Civil Engineering	5,0		
Construction with New Materials	5,0		
Construction Processes	5,0		
Prefabrication	5,0		
Construction Monitoring and Observation	5,0		

Structures

5th Year, 1st Semester	Credits	5th Year, 2nd Semester	Credits
Advanced Structural Analysis	5,0	Thesis in Structures	30,0
Structural Dynamics and Earthquake Engineering	5,0		
Prestressed Structures	5,0		
Steel and Composite Structures	5,0		
Bridges	5,0		
Foundations and Retaining Structures	5,0		

Geotechnics

5th Year, 1st Semester	Credits	5th Year, 2nd Semester	Credits
Foundations	5,0	Thesis in Geotechnics	30,0
Models and Safety in Geotechnics	5,0		
Numerical Methods in Geotechnics	5,0		
Earth Retaining Structures	5,0		
Embankment Works	5,0		
Underground Works	5,0		

Territory Planning and Environment

5th Year, 1st Semester	Credits	5th Year, 2nd Semester	Credits
Planning and Environmental Quality	5,0	Thesis in Territory Planning and Environment	30,0
Urban Planning	5,0		
Planning and Mobility Management	5,0		
Regional Planning	5,0		
Urban Management	5,0		
Transport Systems	5,0		

MASTER IN CIVIL ENGINEERING STRUCTURES

U.PORTO

1st Year, 1st Semester	Study hours	Contact contact/week	Credits
Numerical Methods in Structural Analysis	162	56[TP]	6
Structural Safety and Risk Analysis	162	56[TP]	6
Design of Concrete Structures	162	56[TP]	6
Soil and Structural Dynamics	162	56[TP]	6
Foundations	162	56[TP]	6
1st Year, 2nd Semester			
Project 1	162	56[TP]	6
Steel and Composite Structures	162	56[TP]	6
Non-Linear Structural Analysis (optional)	162	56[TP]	6
Seismic Engineering & Wind Engineering (optional)	162	56[TP]	6
Prestressed Structures (optional)	162	56[TP]	6
Masonry and Timber Structures (optional)	162	56[TP]	6
Earth Support Structures (optional)	162	56[TP]	6
Underground Works (optional)	162	56[TP]	6
2nd Year, 1st Semester			
Project 2	162	56[TP]	6
Recycled Materials in Structures and Geotechnics	162	56[TP]	6
Advanced Structural Materials (optional)	162	56[TP]	6
Bridges (opcional)	162	56[TP]	6
Pre Fabricated Structures (optional)	162	56[TP]	6
Rehabilitation of Structures & Foundations (optional)	162	56[TP]	6
Landfill Works (optional)	162	56[TP]	6
Instrumentation & Monitoring of Works (optional)	162	56[TP]	6
Any UPorto 2nd Cycle Course Unit (optional)	162	-	6
2nd Year, 2nd Semester			
Dissertation	810	14[OT]	30

DOCTORAL PROGRAMME IN CIVIL ENGINEERING

U.PORTO

Course unit	Study hours	Contact contact/week	Credits
Civil Engineering Course Units - Branch	540(d)	T/TG: 180 (d)	10 a 30
Civil Engineering Course Units	135 (e)	T/OT/PL: 45 (e)	0 a 10
Non-Civil Engineering Course Units	135 (f)	T/OT: 45 (f)	0 a 10
Research Thesis Project	810	OT: 80	30
Original Thesis	3240	OT: 320	120

Notes

(a) – To choose from the range of course units included in the table below, in the Civil Engineering scientific area - Specialism chosen;

(b) – To choose from the range of course units included in the table below, in the different Civil Engineering scientific sub-areas and any other course units taught in other civil engineering doctoral programmes at any other Portuguese or foreign university, on approval by the Programme Scientific Committee;

(c) – To choose from any course units taught at the UP outside the scope of the Civil Engineering Doctoral Programme (including those offered in the table below as OUT), and any other course units taught in other doctoral programmes at any other Portuguese or foreign university, on approval by the Programme Scientific Committee;

(d) – Calculation for 20 ECTS;

(e) – Calculation for 5 ECTS;

(f) – Calculation for 5 ECTS.

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INSTITUTO DA CONSTRUÇÃO

Gracias por
Vuestra atención!

Humberto Varum

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