# Cost function for seismic risk mitigation

Sanam Moghimi

# Outline

- Thesis Review
- Accomplished Tasks
- Proposed Cost Function

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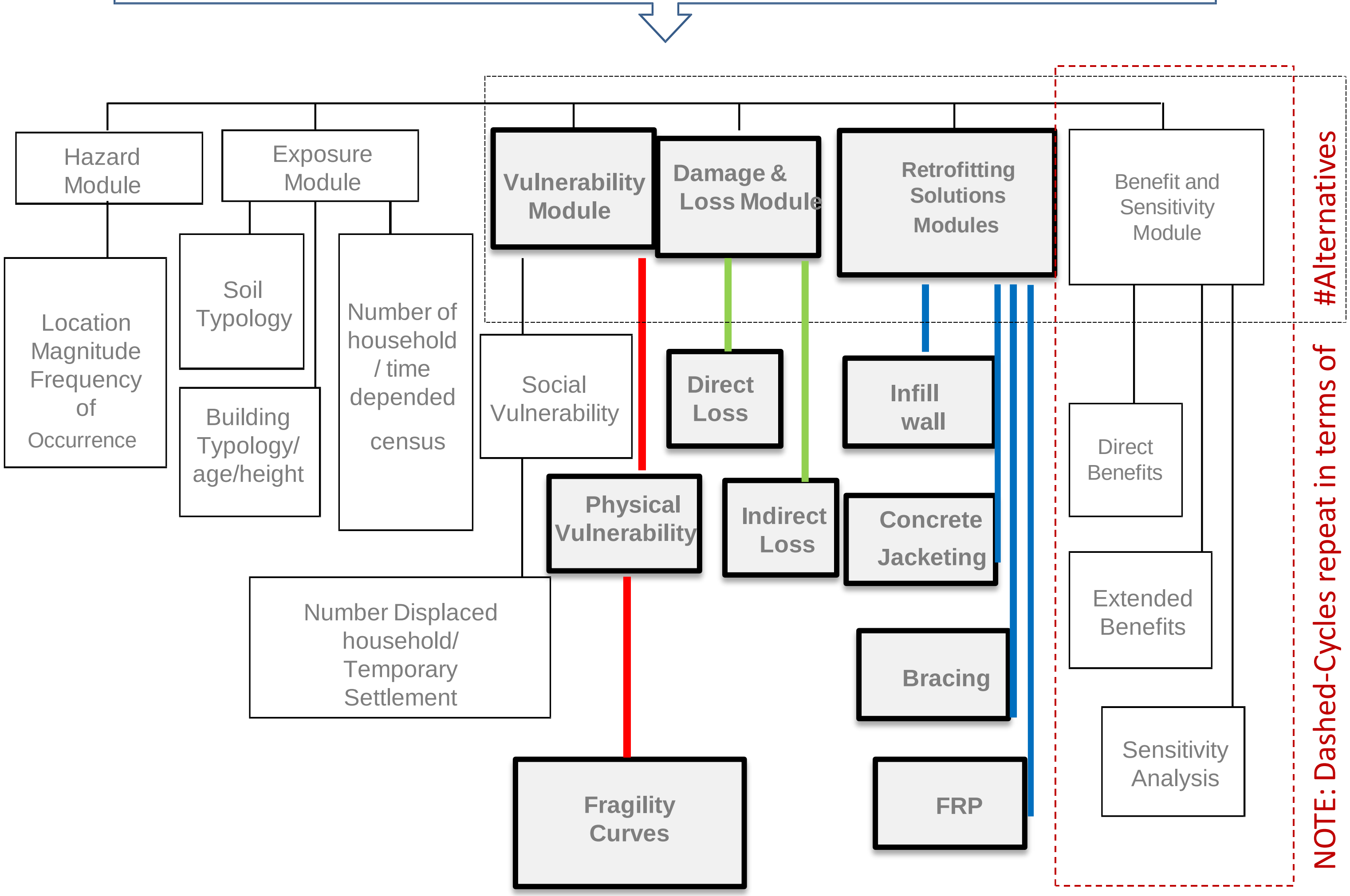
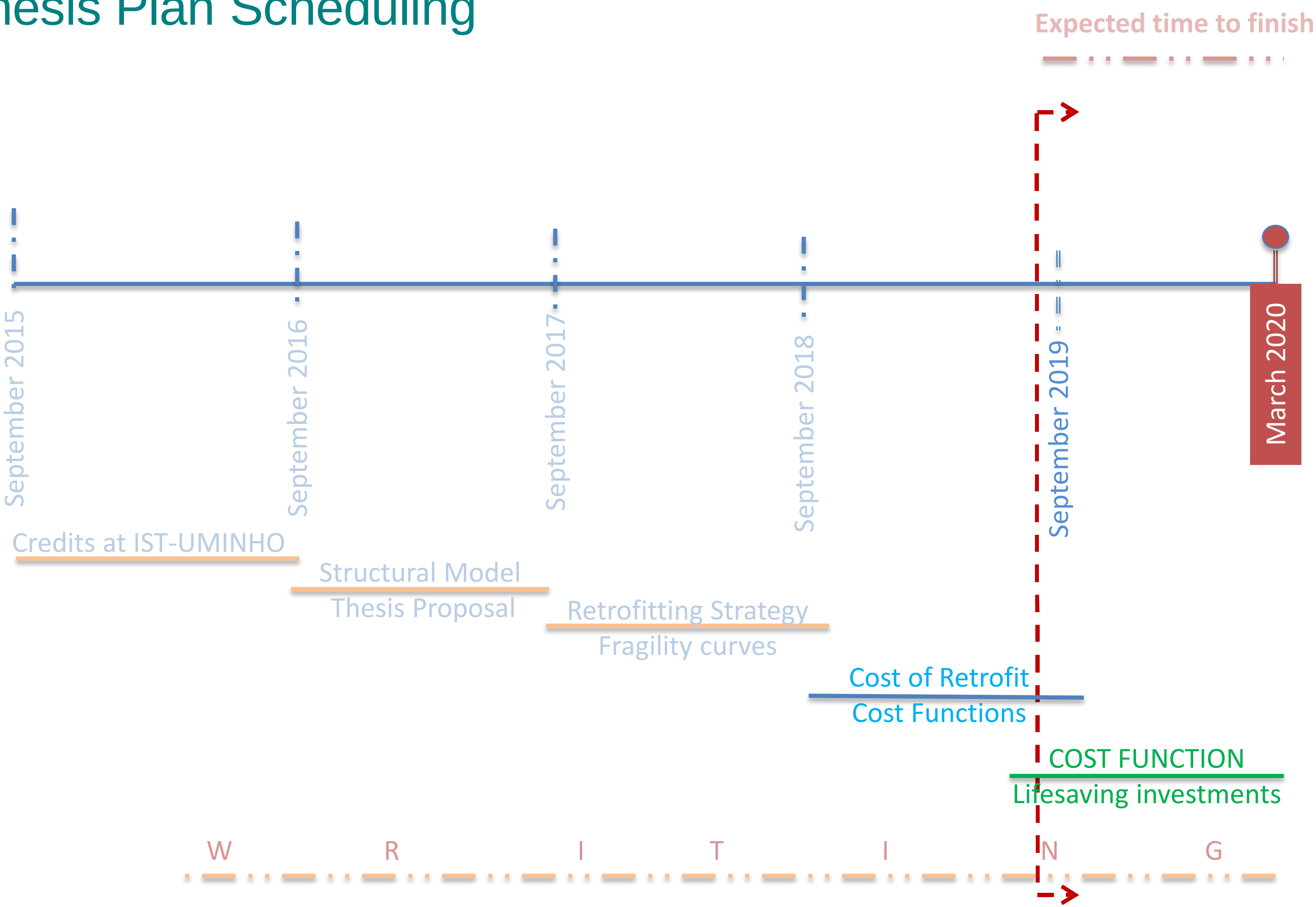
# Mitigation Framework; Cost Effectiveness Analysis



# Thesis Plan Scheduling



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- **Accomplished Tasks**
- Proposed Cost Function

# Case study: RC Portuguese pre-seismic code building stock up to 4 storey

## Variables of material and geometry properties

Existing buildings

| Variáveis | Média | CV (%) | A | B | Referência |
|---|---|---|---|---|---|
| G (kN/m$^2$) | 8 | 12.5 | 6 | 10 | Sousa *et al.*, 2016 |
| Nº pisos | 1/2/3/4 | 28/42/15/15 | - | - | Censos, 2011 |
| $H_1$ | 3.2 | 10 | 2.5 | 5 | |
| $H_n$ | 2.8 | 6 | 2.5 | 4 | Silva *et al.*, 2014 |
| $L_{X/Y}$ (m) | 4.4 | 16 | 2.5 | 6.5 | Furtado *et al.*, 2015 |
| $h_{laje}$ (m) | 0.23 | 24 | 0.1 | 0.35 | |
| $f_{cm}$ (MPa) | 23.8 | 49 | 5.0 | 80.0 | Silva *et al.*, 2014 |
| $f_{yk}$ (MPa) | 235/400/500 | 25/50/25 | - | - | Silva *et al.*, 2014 |
| $\rho_l$ (%) | 1 | 40 | 0.3 | 3.5 | Furtado *et al.*, 2015<br>Sousa *et al.*, 2016 |

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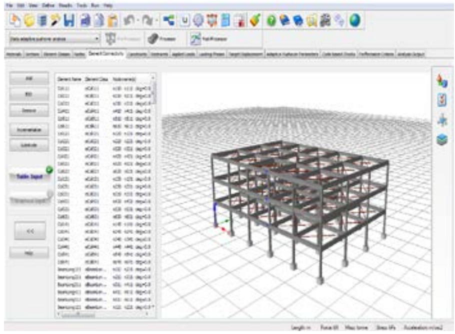
## Retrofitting Alternatives

- Concrete Jacketing : Shotcreet – Cast in Place
- Steel Jacketing
- FRP
- Bracing
- Infill Walls

# What I've done

- Seismostruct modeling 200 buildings in each direction of X and Y

- Pushover analysis and Fragility curves



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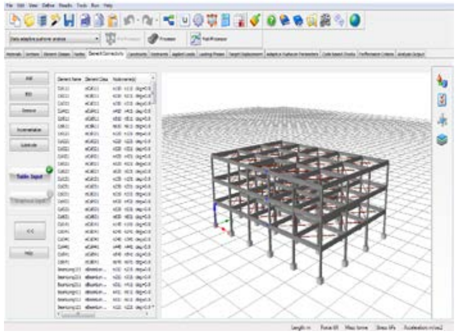

- Seismostruct modeling 200 buildings in each direction of X and Y
- Pushover analysis and Fragility curves
- Comparison of results with original LNECLOSS
  - Retrofitting solution :
    - ❑ RC Jacketing 2 level of reinforcement
    - ❑ Steel Jacketing 2 level of Confinement
    - ❑ FRP 2 level of reinforcement
    - ❑ Bracing 3 level of reinforcement
    - ❑ Infill Walls  with shotcreet

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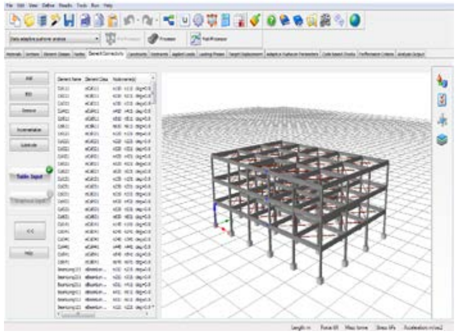

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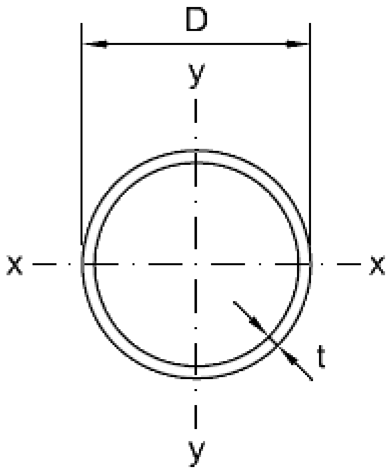
- Bracing retrofitting strategy
  - 3 different braces were considered
    - Steel members with circular hollow sections (CHS)
    - Steel S275



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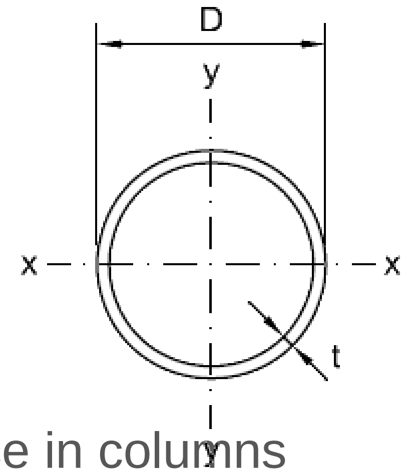


  - Bracing 3 : Designed so that the resulting axial force in columns equals the columns axial resistance
    - D = 76 mm ; t = 4 mm
  - Bracing 2 : Designed to a axial force value equal to 66% of Bracing 3 design force
    - D = 60 mm ; t = 3.2 mm
  - Bracing 1 : Designed to a axial force value equal to 33% of Bracing 3 design force
    - D = 34 mm ; t = 3.2 mm

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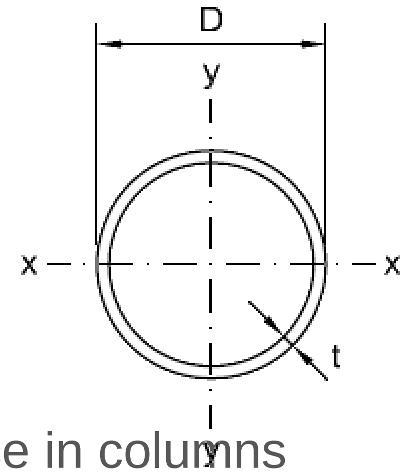


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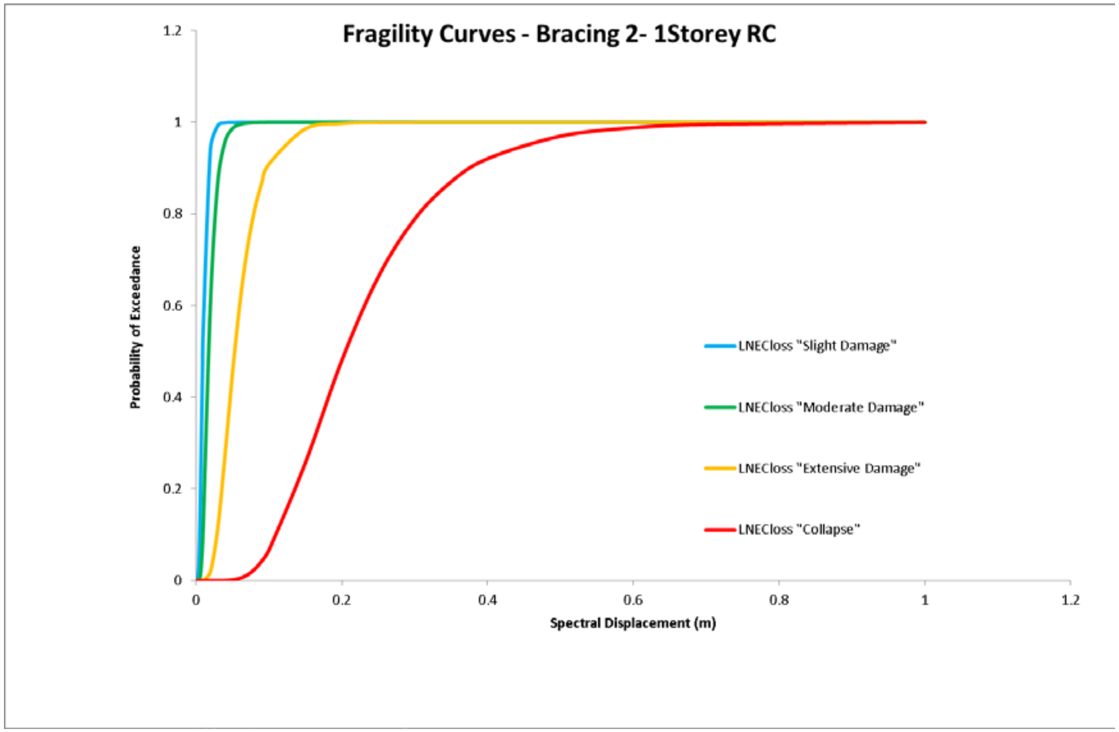
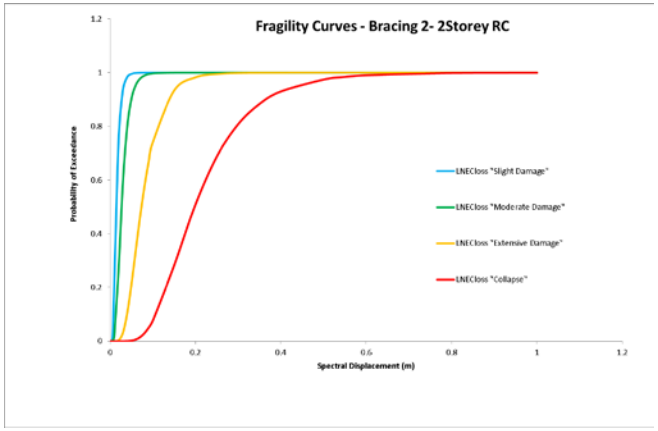
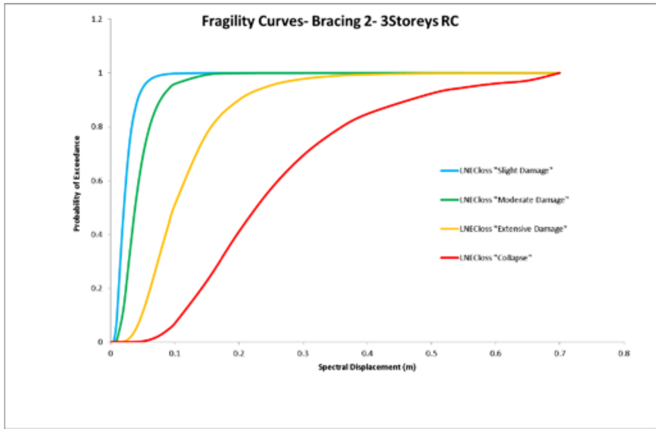
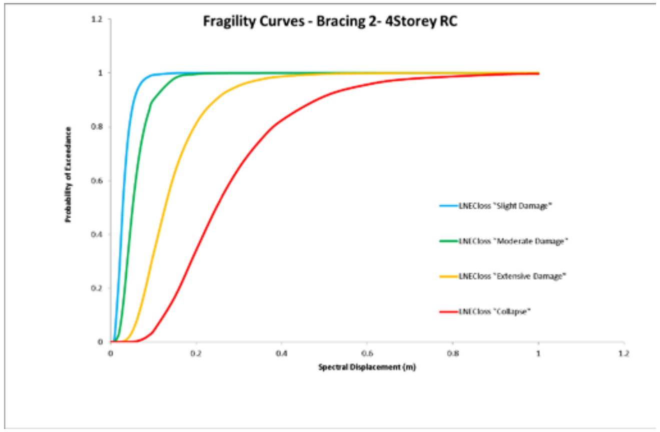
# What I’ve done

- Fragility curves for bracing strategy



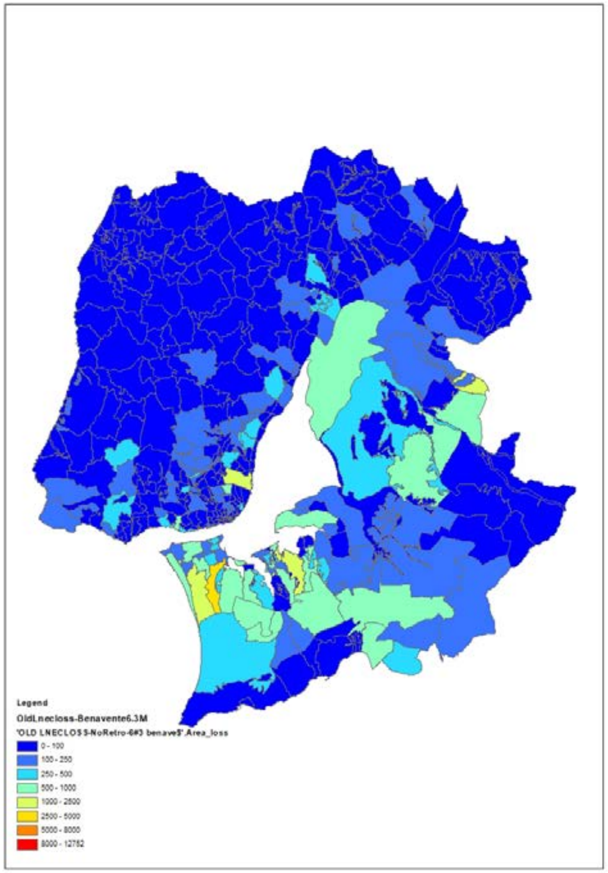



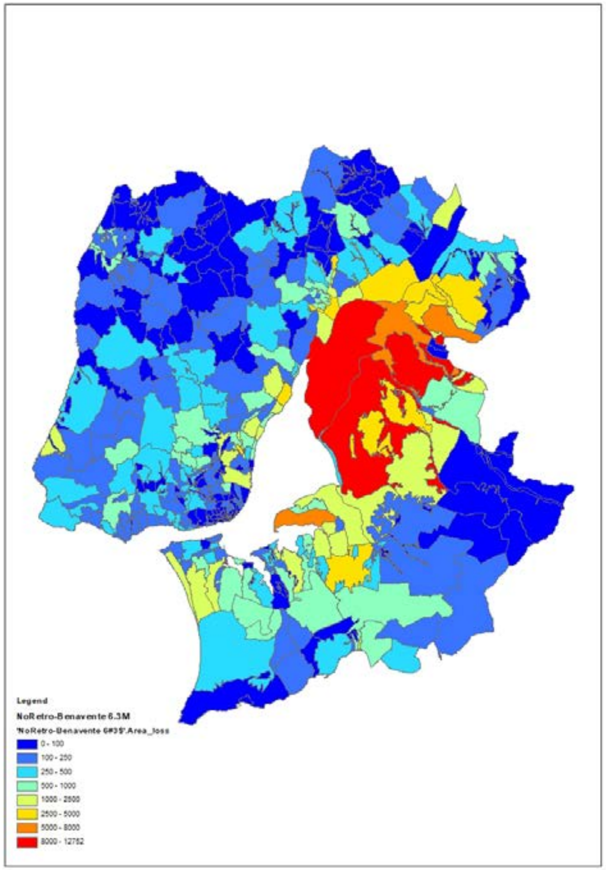



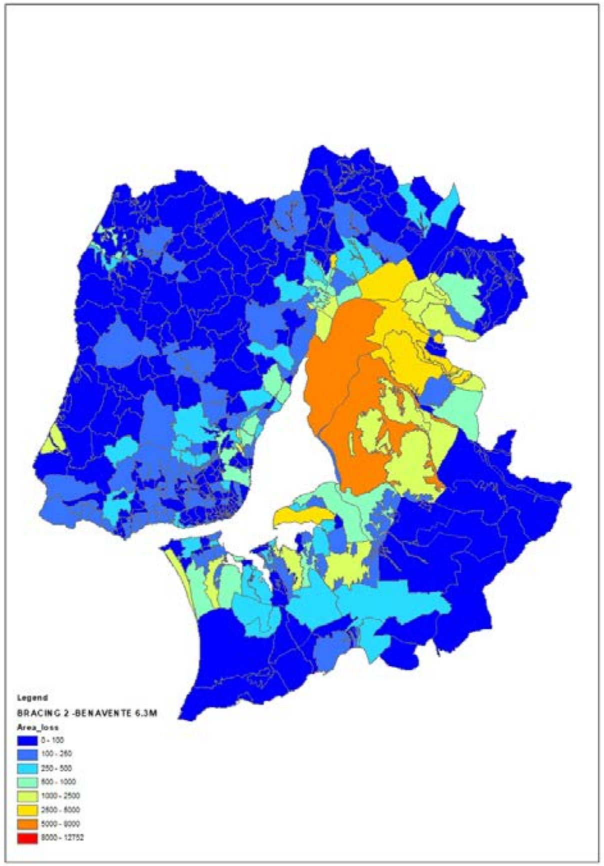

$$P_D\left(D \geq d \mid Sd\right) = \Phi\left[\frac{1}{\beta_d}\ln\left(\frac{Sd}{\langle Sd_d \rangle}\right)\right]$$

# What I’ve done

- Comparison of results with original LNECLOSS
  Lossed area : Graphical representation



# What I’ve done

| Not Retrofitted | | | | |
|---|---|---|---|---|
| Sum of Area_Loss(m^2) | Hard soil | Interm. soil | Soft soil | Grand Total |
| Masonry | 202878.1804 | 285693.9677 | 168025.4817 | 656597.6298 |
| RC Medium Ductility | 22236.99962 | 32795.56446 | 41564.55176 | 96597.11584 |
| RC Non ductil - low rise | 36584.40222 | 32218.4207 | 125798.3592 | 194601.1821 |
| RC Non ductil - med/high rise | 7631.965466 | 7691.427523 | 10111.55653 | 25434.94952 |
| Grand Total | 269331.5477 | 358399.3804 | 345499.9492 | 973230.8772 |

| Bracing 2 | | | | |
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Reduction achieved with mitigation

| Mitigation % of RC Non ductil - low rise | | | | |
|---|---|---|---|---|
| | Hard soil | Interm. soil | Soft soil | Grand Total |
| Bracing2/Not Retrofitted | 52.50% | 32.71% | 47.04% | 45.70% |

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# Seismic risk management strategies

- Mitigation
  - Temporary retrofit
  - Phased retrofit
  - Retrofit with occupancy
  - Retrofit vacant building
- Do nothing
- Demolition + reconstruction
- Occupancy profile change
- Insurance against losses

# Seismic risk management strategies

- **Mitigation**
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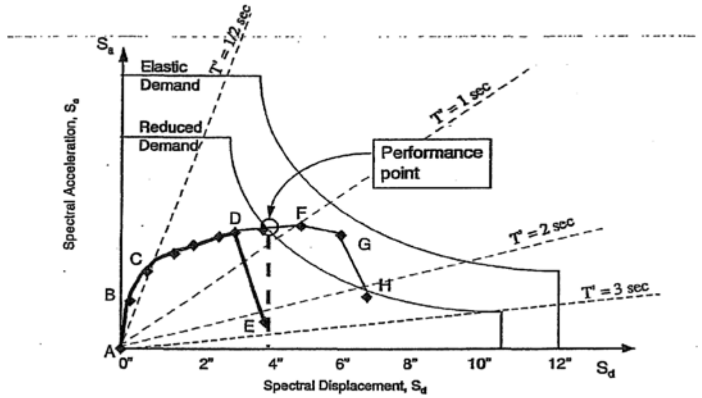
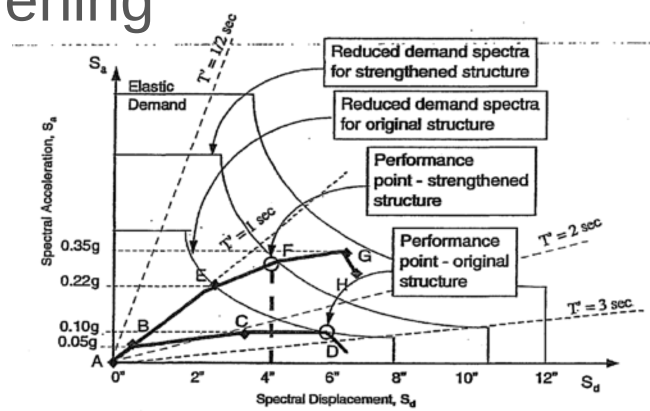
# Seismic risk mitigation strategies

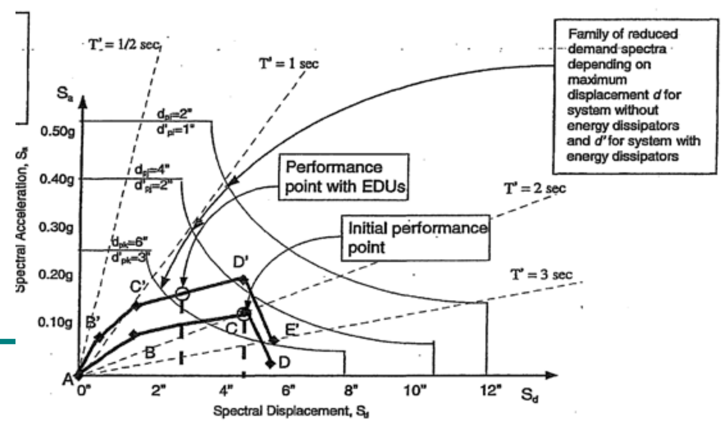
- Enhancing deformation capacity
  - FRP and steel jacketing




- System strengthening and stiffening
  - RC jacketing
  - Bracing
  - Reinforcing infill walls




- Reducing earthquake demand
  - Base isolation
  - Energy dissipation



# Seismic risk mitigation strategies

- **Enhancing deformation capacity**
  - FRP and steel jacketing
- **System strengthening and stiffening**
  - RC jacketing
  - Bracing
  - Reinforcing infill walls
- Reducing earthquake demand
  - Base isolation
  - Energy dissipation

# Enhancing deformation capacity strategy

- Steel plates

| Average height [m] | | Nº of strips | Column dimension [m] | | Plate dimension [m] | | | |
|---|---|---|---|---|---|---|---|---|
| | | | SH | SW | HP | SP | PT | |
| | | | | | | | Conf 1.5 | Conf 2.0 |
| **First Floor** | 3.2 | 22 | 0.20 | 0.25 | 0.05 | 0.1 | 0.003 | 0.006 |
| **Other Floor** | 2.8 | 19 | | | | | | |
| **First Floor** | 3.2 | 22 | 0.25 | 0.25 | 0.05 | 0.1 | 0.004 | 0.008 |
| **Other Floor** | 2.8 | 19 | | | | | | |
| **First Floor** | 3.2 | 22 | 0.30 | 0.25 | 0.05 | 0.1 | 0.004 | 0.01 |
| **Other Floor** | 2.8 | 19 | | | | | | |

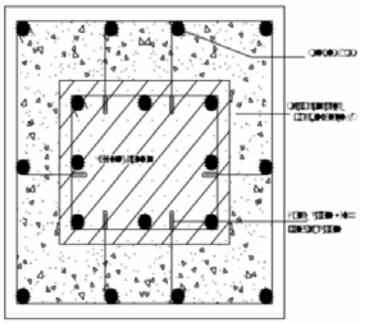
- FRP sheets

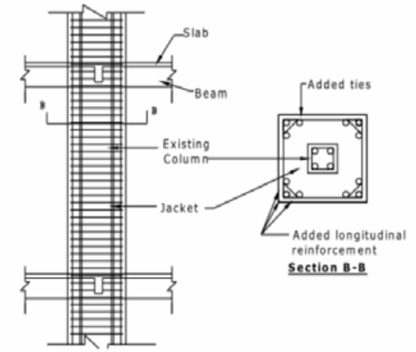
| | |
|---|---|
| External Height | EH |
| Internal Widht | IW |
| Section Height | SH |
| Section Widht | SW |
| Plate Thickness | PT |
| Plate Height | PH |
| Plate Space | SP |

| Average height [m] | | Nº of Strips | Column dimensions [m] | | Sheet dimensions [m] | | |
|---|---|---|---|---|---|---|---|
| | | | SH | SW | PH | | SP |
| | | | | | Conf.1.5 | Conf.2.0 | |
| **First Floor** | 3.2 | 30 | 0.20 | 0.25 | 0.04 | 0.07 | 0.20 |
| **Other Floor** | 2.8 | 24 | | | | | |
| **First Floor** | 3.2 | 27 | 0.25 | 0.25 | 0.04 | 0.08 | 0.20 |
| **Other Floor** | 2.8 | 24 | | | | | |
| **First Floor** | 3.2 | 22 | 0.30 | 0.25 | 0.05 | 0.10 | 0.20 |
| **Other Floor** | 2.8 | 19 | | | | | |

# System strengthening and stiffening : RC jacketing of columns

- Overview of strategy
  - New concrete
    - Additional 10 cm thickness
    - C25/30
    - 2,5 cm concrete cover





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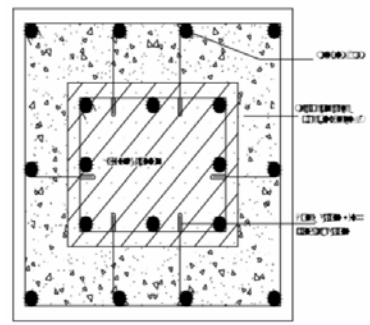

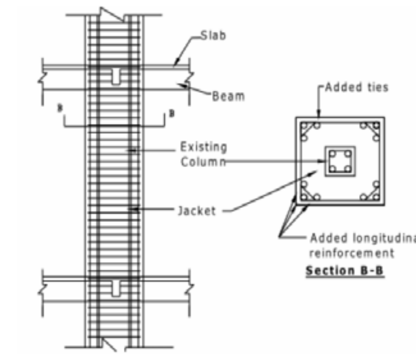


  - 2 different RC jacketing solutions
    - Jacketing 2 : 2% ratio of reinforcement area (wrt new Ac)
    - Jacketing 3 : 3% ratio of reinforcement area (wrt new Ac)

    - Applied by shotcreet or cast in place

# Cost-Benefit analysis

- Benefits
  - Increased value of the building due to its improved seismic performance (B)
- Costs
  - Costs of implementing mitigation strategy ($C_{MS}$)
  - Damage repair costs ($C_{RP}$)
  - Demolition and reconstruction costs ($C_D$ + $C_{RC}$)
  - Costs of relocation of users ($C_{RU}$)
  - Costs of loss revenue ($C_{LR}$)
  - Costs of fatalities/injuries compensations ($C_{FIC}$)
  - ...

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  - Costs of fatalities/injuries compensations ($C_{FIC}$)
  - .....

# Cost-Benefit analysis

- Cost function

$$C_{TOT} = C_{MS} + C_{RP} + (C_D + C_{RC}) + C_{RU} + C_{LR} + C_{FIC}$$

- In order to compare costs at different times, all values must be adjusted to a reference year prices, multiplying the costs by

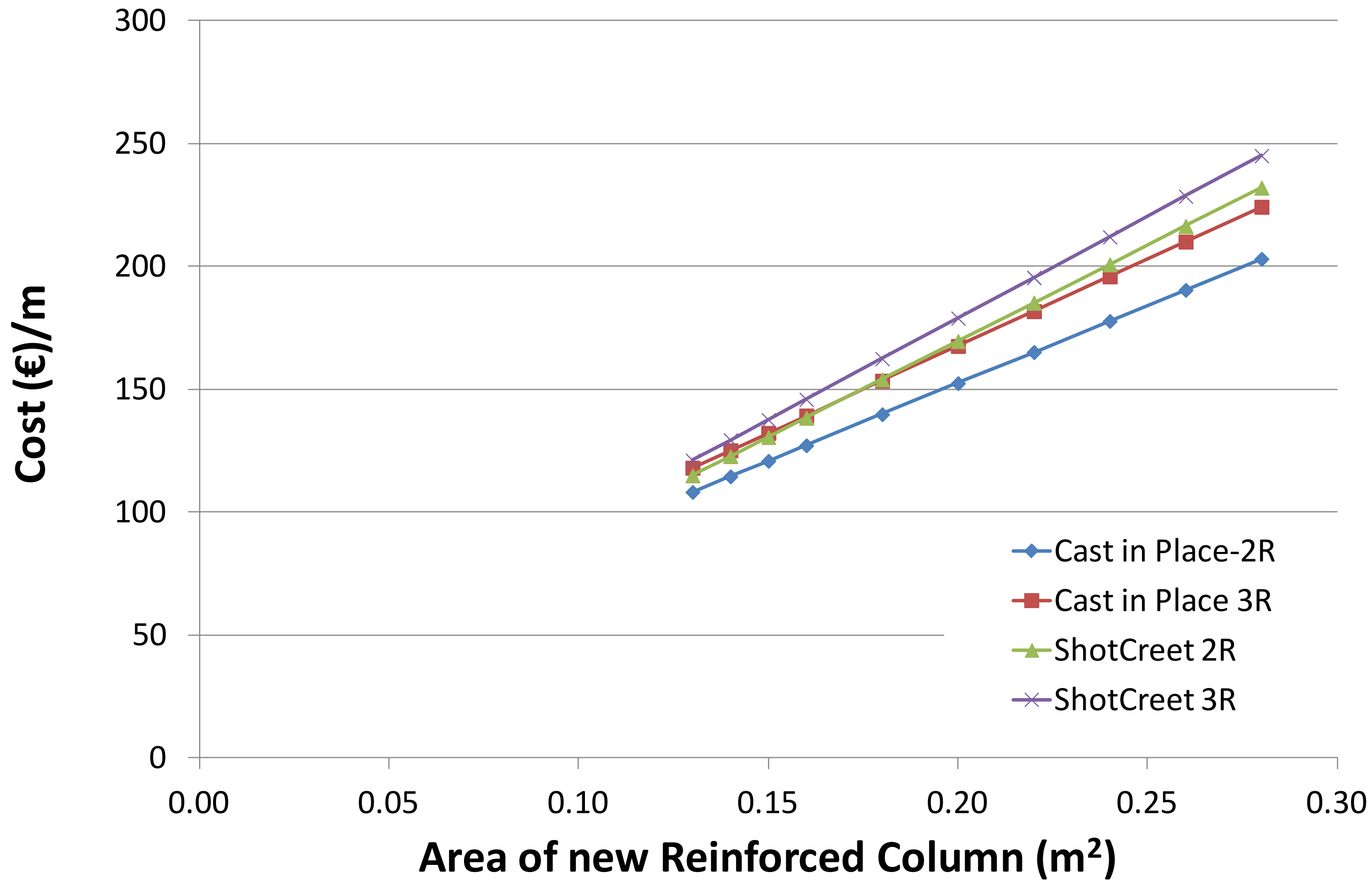
$$\frac{1}{(1+r)^{\Delta T}}$$

  - *r* represents the discount rate [2% to 4%]
  - $\Delta T$ is given by $T_i - T_r$, where $T_i$ represents the year of cost *i* and $T_r$ represents the reference year

# Costs of implementing one RC jacketing mitigation strategy

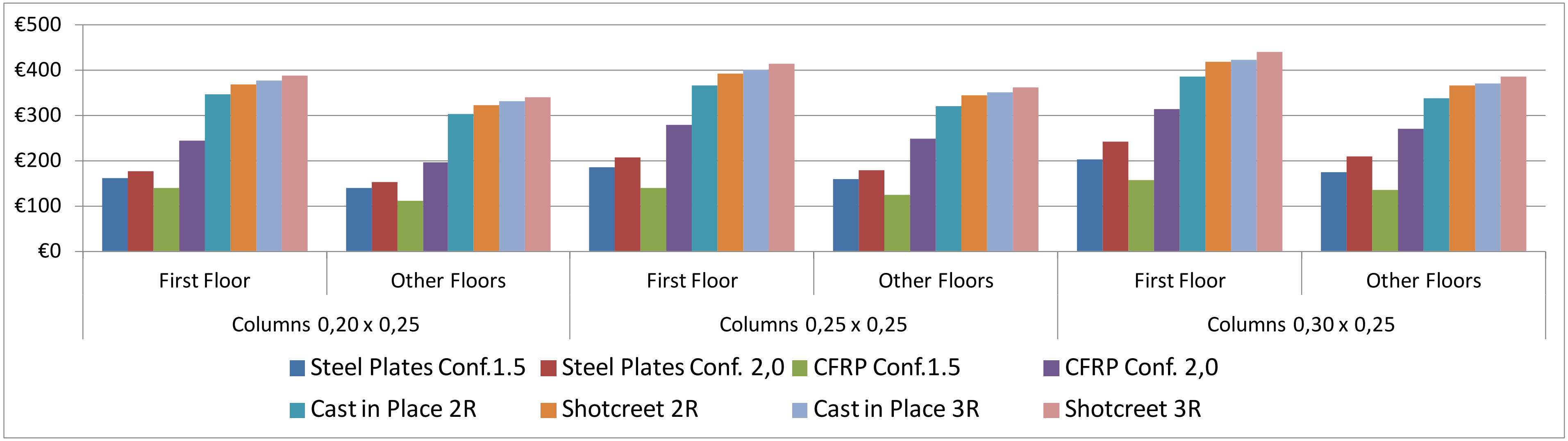
| Description of activity | | | | | | | Sheet n.º |
|---|---|---|---|---|---|---|---|
| Reinforcement of reinforced concrete pillar of 20x25cm, by means of filling of 10 cm of thickness in all its faces, with reinforced concrete, realized with concrete C25 / 30 (XC1 (P); D12; S3; Cl 0,4) manufactured in central, and concrete with crane, and steel A400 NR, with an amount of 157 kg / m³, direct bond through adhesive; discharge with manual means from the slab of the upper plant by holes previously executed; prior application of a continuous layer of epoxy resin based two-component thixotropic adhesive on the surface of the cured concrete. The price includes the assembly and dismantling of the formwork system and the preparation and assembly of the reinforcement at the definitive place of its installation. | | | | | | | |
| Resources | | Unit | Quant. | Nuit cost (€) | Cost (€) | Sub-total (€) | % of direct cost (%) |
| Mat | Two-component thixotropic adhesive based on epoxy resin for the correct connection between fresh concrete and hardened concrete or to improve the adhesion of hardened concrete and steel according to NP EN 1504-7. | kg/m | 1.35 | 10.85 | 14.65 | 37.88 | 35.02 |
| | Concrete C25 / 30 (XC1 (P) D12; S3; Cl 0,4), manufactured in plant according to NP EN 206-1. | m3/m | 0.13 | 83.08 | 10.58 | | |
| | Steel in ribbed bars, A 400NR, supplied in unworked work of various diameters | kg/m | 20.82 | 0.60 | 12.49 | | |
| | Galvanized binding wire, 1,30mm in diameter | kg/m | 0.14 | 1.10 | 0.16 | | |
| Eqp | Electric hammer | hr/m | 0.70 | 2.80 | 1.96 | 6.30 | 5.83 |
| | Electric battery | hr/m | 0.70 | 4.81 | 3.38 | | |
| | Metal sheet 50x50 cm, for formwork of reinforced concrete pillars of rectangular or square section, up to 3 m in height, including fittings | m2/m | 0.02 | 48.00 | 0.96 | | |
| Labour | Officer of 1st shipowner of iron | hr/m | 0.18 | 19.31 | 3.50 | 63.98 | 59.15 |
| | Iron Helper Assistant | hr/m | 0.20 | 18.78 | 3.77 | | |
| | Non specialised construction workers | hr/m | 0.74 | 17.39 | 12.85 | | |
| | Specialised construction workers | hr/m | 0.74 | 17.84 | 13.18 | | |
| | Officer of 1st structurer, in concrete works | hr/m | 0.94 | 19.31 | 18.07 | | |
| | Structuralist assistant in concrete works | hr/m | 0.67 | 18.78 | 12.60 | | |
| Direct cost (CD) | | | | | Total (€) | 108.16 | |
| Cost of operation S / profit, 10% Indirect costs | | | | | Total (€) | 118.98 | |
| Total Cost Operation 8% Profits | | | | | Total (€) | 128.50 | |

# Costs of implementing one RC jacketing mitigation strategy



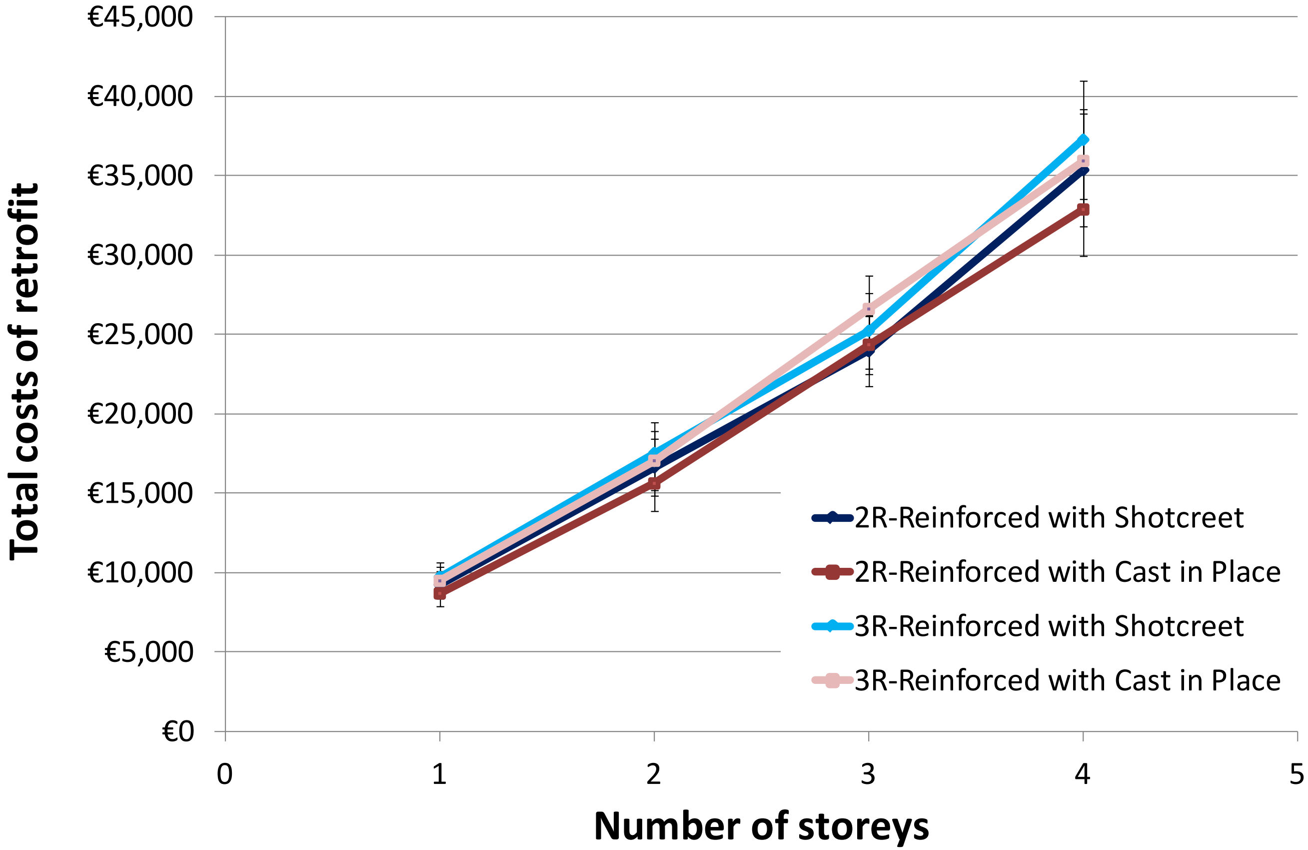
# Costs of implementing mitigation strategies

- Other strategies



# Costs of implementing mitigation strategy

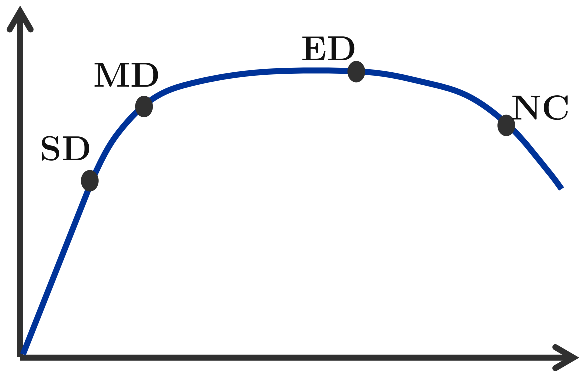
- RC jacketing : All building typologies




| Mean - 2R | Shotcreet | Cast in place |
|---|---|---|
| 1 Storey | € 9,227.93 | € 8,681.28 |
| 2 Storeys | € 16,631.75 | € 15,607.92 |
| 3 Storeys | € 23,944.50 | € 24,342.89 |
| 4 Storeys | € 35,346.46 | € 32,856.05 |
| STDV - 2R | Shotcreet | Cast in place |
| 1 Storey | € 877.62 | € 823.70 |
| 2 Storeys | € 1,821.06 | € 1,711.33 |
| 3 Storeys | € 2,216.75 | € 1,877.61 |
| 4 Storeys | € 3,534.10 | € 2,921.25 |

| Mean - 3R | Shotcreet | Cast in place |
|---|---|---|
| 1 Storey | € 7,150.19 | € 7,843.58 |
| 2 Storeys | € 12,765.32 | € 13,971.72 |
| 3 Storeys | € 18,104.17 | € 21,427.43 |
| 4 Storeys | € 26,174.22 | € 28,459.18 |
| STDV - 3R | Shotcreet | Cast in place |
| 1 Storey | € 676.10 | € 739.35 |
| 2 Storeys | € 1,428.41 | € 1,566.73 |
| 3 Storeys | € 1,454.01 | € 1,182.95 |
| 4 Storeys | € 1,640.82 | € 1,633.37 |

# Damage repair costs



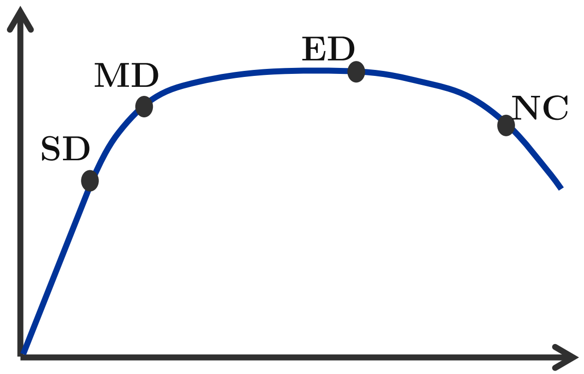

- Depend on Limit States definition

  – **Slight Damage (SD)**

  o The structure is only slightly damaged and economic to repair

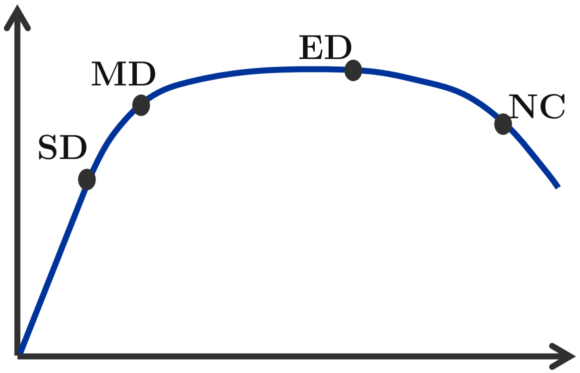
  o 50% of Maximum Base Shear is achieved

# Damage repair costs




- Depend on Limit States definition
  - **Slight Damage (SD)**
    - The structure is only slightly damaged and economic to repair
    - 50% of Maximum Base Shear is achieved
  - **Moderate Damage (MD)**
    - The structure is moderately damaged
    - 75% of Maximum Base Shear is achieved

# Damage repair costs




- Depend on Limit States definition

– **Slight Damage (SD)**

o The structure is only slightly damaged and economic to repair

o 50% of Maximum Base Shear is achieved

– **Moderate Damage (MD)**

o The structure is moderately damaged

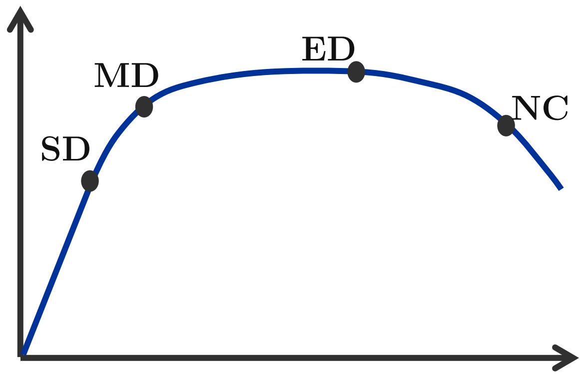
o 75% of Maximum Base Shear is achieved

– **Extensive Damage (ED)**

o The structure is significantly damaged

o 100% (Maximum) Base Shear is achieved

# Damage repair costs




- Depend on Limit States definition

– **Slight Damage (SD)**

o The structure is only slightly damaged and economic to repair

o 50% of Maximum Base Shear is achieved

– **Moderate Damage (MD)**

o The structure is moderately damaged

o 75% of Maximum Base Shear is achieved

– **Extensive Damage (ED)**

o The structure is significantly damaged

o 100% (Maximum) Base Shear is achieved

– **Near Collapse (NC)**

o The structure is completely damaged

o 80% of Max Base Shear is achieved

# Damage repair costs

- Depend on Limit States definition
  [Damage to non-structural elements is not yet taken into account]

# Damage repair costs

- Depend on Limit States definition
  [Damage to non-structural elements is not yet taken into account]

  – Slight damage : Mortar injection repair

# Damage repair costs

- Depend on Limit States definition
  [Damage to non-structural elements is not yet taken into account]

  - Slight damage : Mortar injection repair

  - Moderate damage : RC jacketing

# Damage repair costs

- Depend on Limit States definition
  [Damage to non-structural elements is not yet taken into account]

  - Slight damage : Mortar injection repair

  - Moderate damage : RC jacketing

  - Extensive damage and Near collapse : Demolition + reconstruction

# Costs for mortar injection repair

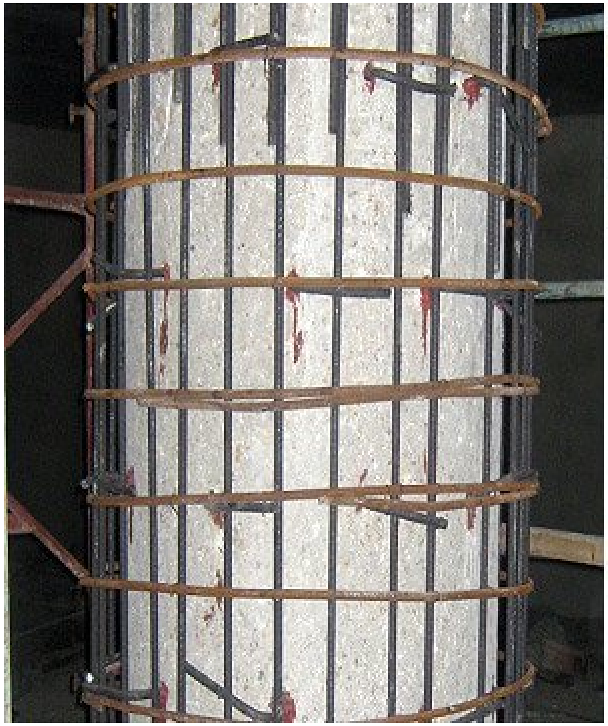
- Injection of mortar
  - Suited for repair of stabilised fissures and cracks
    - Epoxy based : crack width > 0.2 to 0.3 mm < 5 to 6 mm
    - Cement based : crack width > 6 mm

# Costs for mortar injection repair

- Injection of mortar
  - Suited for repair of stabilised fissures and cracks
    - Epoxy based : crack width > 0.2 to 0.3 mm < 5 to 6 mm
    - Cement based : crack width > 6 mm
  - 50€ per m of crack [*e.g. 1 m every element*]
  - 700€ for injection equipment

# Costs for RC jacketing

- Costs are considered the same as for the mitigation strategy




# Demolition costs and reconstruction costs

- Cost of demolition of an existing building

  [400 m$^2$/floor, Demolition by manual equipment and heavy machinery]

  – Normal condition of the building

    - 4 storeys (11,6 m tall) :  75,000.00€
    - 3 storeys (8,8 m tall) :  55,000.00€
    - 2 storeys (6,0 m tall) :  36,000.00€
    - 1 storey (3,2 m tall) :  18,000.00€

# Demolition costs and reconstruction costs

- Cost of demolition of an existing building

  [400 m$^2$/floor, Demolition by manual equipment and heavy machinery]

  - Normal condition of the building
    - 4 storeys (11,6 m tall) : 75,000.00€
    - 3 storeys (8,8 m tall) : 55,000.00€
    - 2 storeys (6,0 m tall) : 36,000.00€
    - 1 storey (3,2 m tall) : 18,000.00€
  - Poor condition of the building [e.g. after an earthquake]
    - 4 storeys (11,6 m tall) : 90,000.00€
    - 3 storeys (8,8 m tall) : 65,000.00€
    - 2 storeys (6,0 m tall) : 44,000.00€
    - 1 storey (3,2 m tall) : 22,500.00€

# Demolition costs and reconstruction costs

- Cost of construction of a new building
  - Flat rate of 1000€/$m^2$ is considered at this phase

    [Portaria n.º 65/2019 : governs the construction of residential buildings with controlled costs]

# Demolition costs and reconstruction costs

- Cost of construction of a new building
  - Flat rate of 1000€/m$^2$ is considered at this phase

    [Portaria n.º 65/2019 : governs the construction of residential buildings with controlled costs]

$$C_{RC} = C_S \cdot 1.30 \cdot C_R \cdot C_O$$

  - $C_S$ : reference cost of construction per m$^2$ = 710 €/m$^2$ [2019 value]
  - $C_R$ : regional coeficient
    - 1,0 for the Portuguese mainland
    - 1.2 for Azores and Madeira
  - $C_O$ : operational coeficient
    - Between 1.00 and 1.12,. taken as ≈ 1.08

# Cost-Benefit analysis

- Assuming B = cte $\rightarrow$ minimize Cost function
  - Annual expected costs given seismic action ($a_{gR}$)

$$
\begin{aligned}
E[C_{TOT} \mid a_{gR}] = {} & E[C_{MS}] + \\
& + E[C_{RP,mortar} \cdot P(S_{d,SD} \leq S_d < S_{d,MD}) \mid a_{gR}] + \\
& + E[C_{RP,jacket} \cdot P(S_{d,MD} \leq S_d < S_{d,ED}) \mid a_{gR}] + \\
& + E[(C_D + C_{RC}) \cdot P(S_{d,ED} \leq S_d) \mid a_{gR}]
\end{aligned}
$$

# Cost-Benefit analysis

- Assuming B = cte → minimize Cost function
  - Annual expected costs considering all seismic actions, $a_{gR,i}$

    = *integral of* $E[C|a_{gR,i}]$ *over* $P(a_g > a_{gR,i})$ :

$$= E[C_{MS}] + \int E[C_{TOT} - C_{MS} \mid a_{gR,i}]\, dP(a_g > a_{gR,i})$$

$$\approx E[C_{MS}] + \sum_{i=1}^{\infty} E[C_{TOT} - C_{MS} \mid a_{gR,i}] \cdot \left| \frac{dP(a_g > a_{gR,i})}{da_g} \right| \cdot \Delta a_g$$

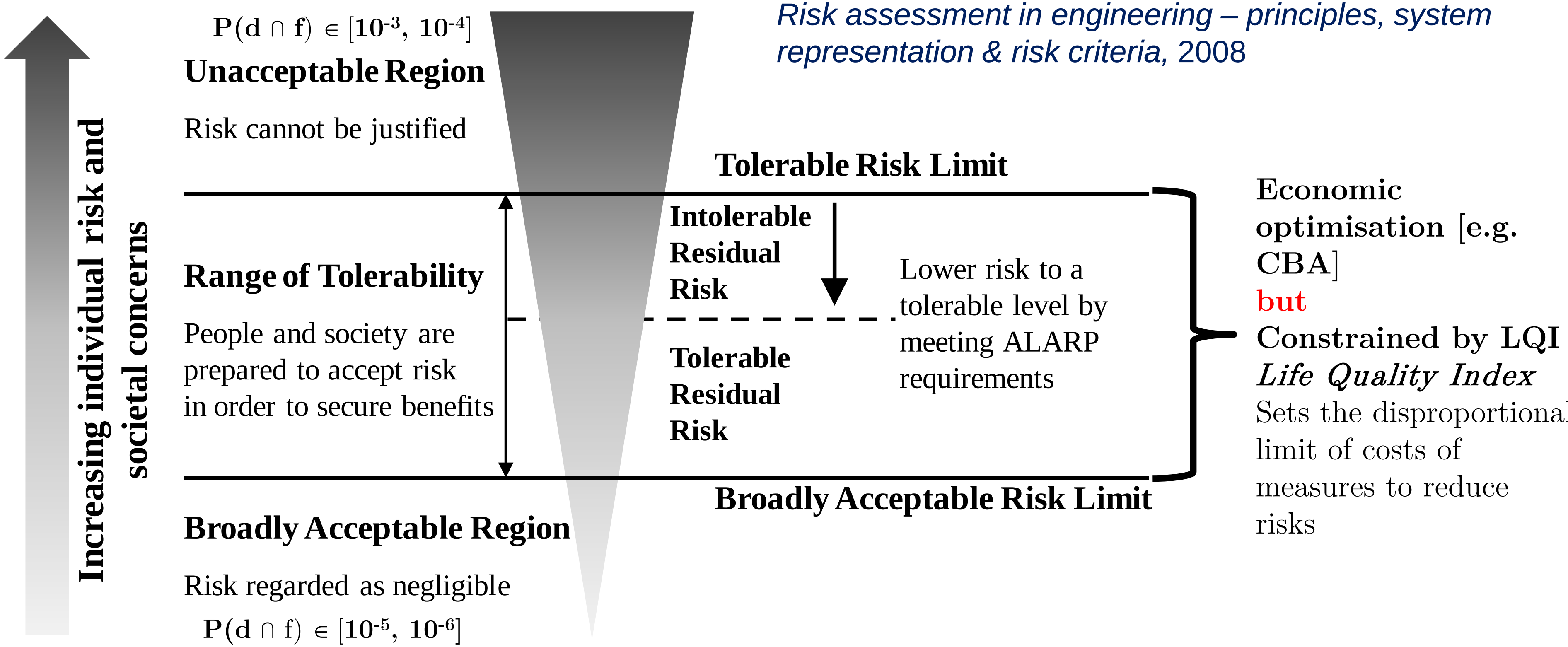
  - $P(a_g > a_{gR,i})$ : Mean annual probability of exceedance of the seismic action *i*

Eads L. et al
*An efficient method for estimating the collapse risk of structures in seismic regions*.
Earthquake Engng Struct. Dyn. 42:1, 25-41, 2013

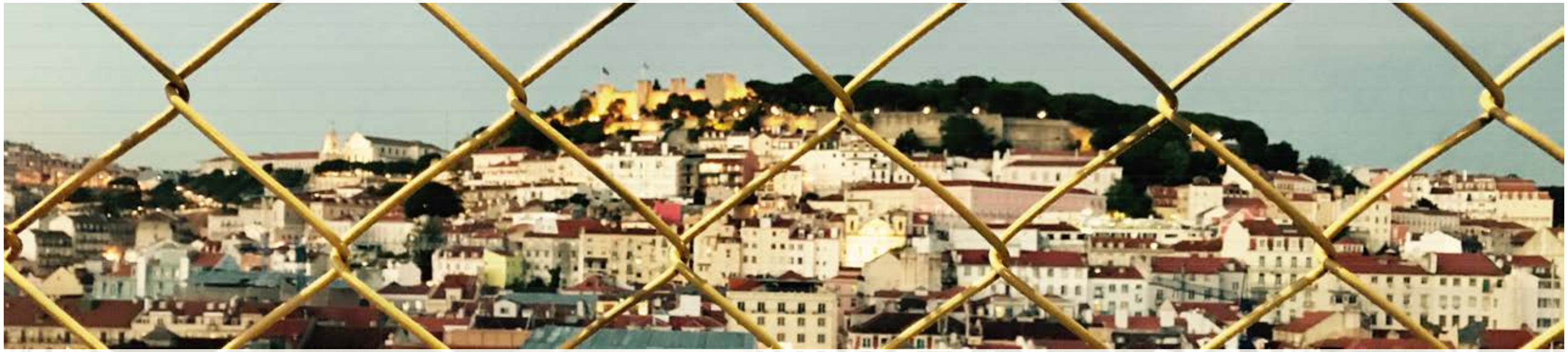
# Risk management

- **Next step**
  Evaluating if these investments are justifiable in terms of life safety improvements

JCSS – Joint Committee for Structural Safety
*Risk assessment in engineering – principles, system representation & risk criteria,* 2008




$\mathbf{P(d \cap f)}$ : Probability of human fatality as a result of a structural failure



Thank You for Your Attention

smoghimi@lnec.pt