BIM-based seismic vulnerability assessment using the Equivalent Frame Method

Expeditious modelling and analysis framework of existing URM-RC buildings

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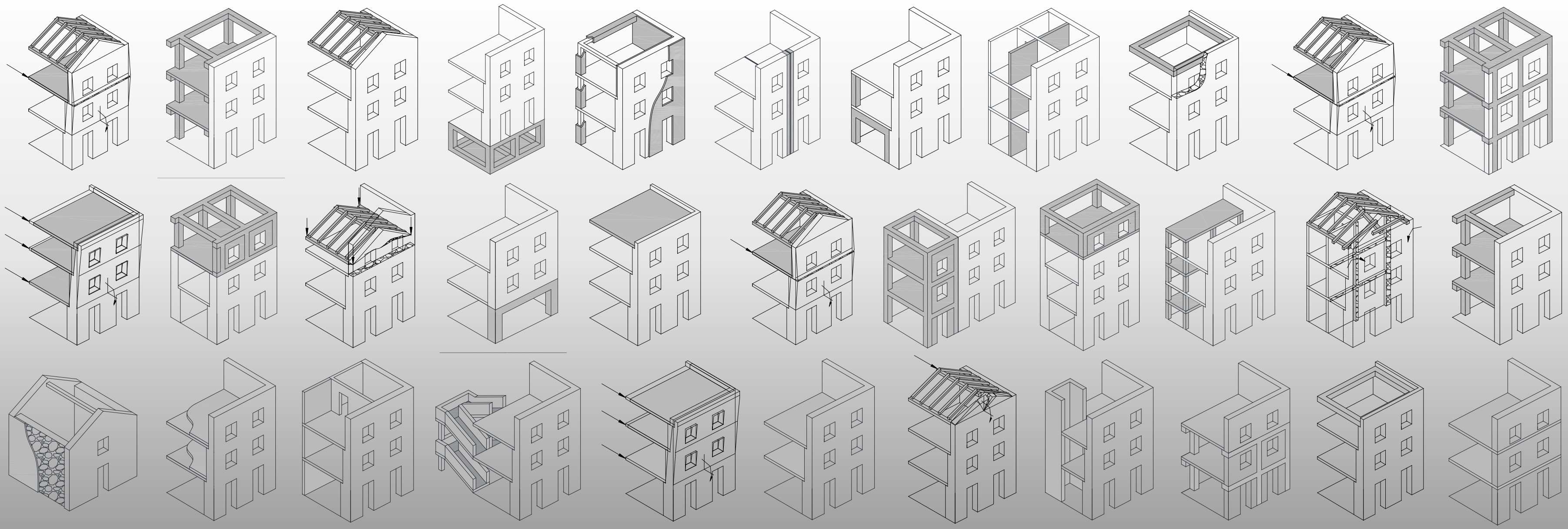


Presentation summary

I. Motivation and Methodology

Mixed URM-RC building typologies

II. Expeditious modelling and analysis framework

Non-linear Static (Pushover) Analysis

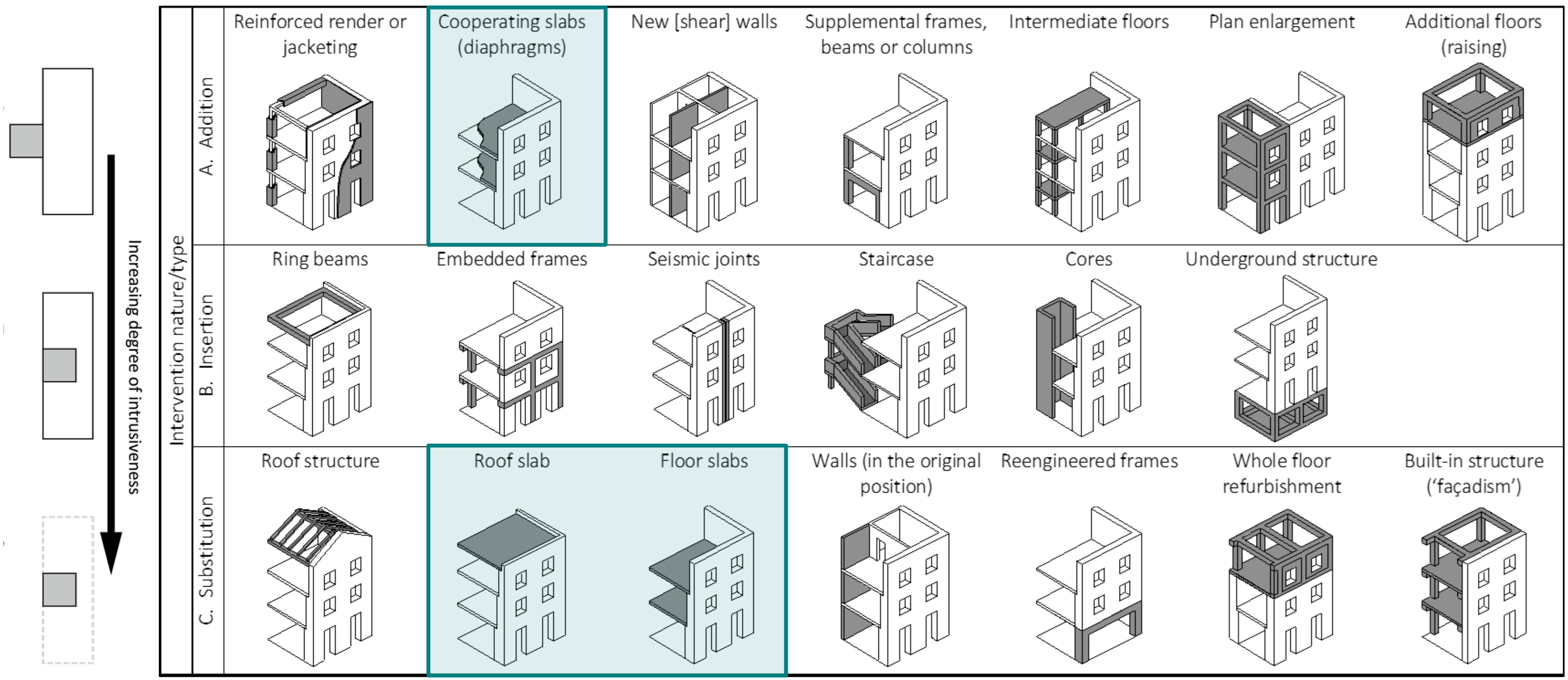
III. Case-study URM-RC buildings

Practical examples: From BIM to FEM/EFM

I. Motivation and Methodology

Mixed URM-RC building typologies

Mixed URM-RC building typologies



Goals

Faster numerical analysis

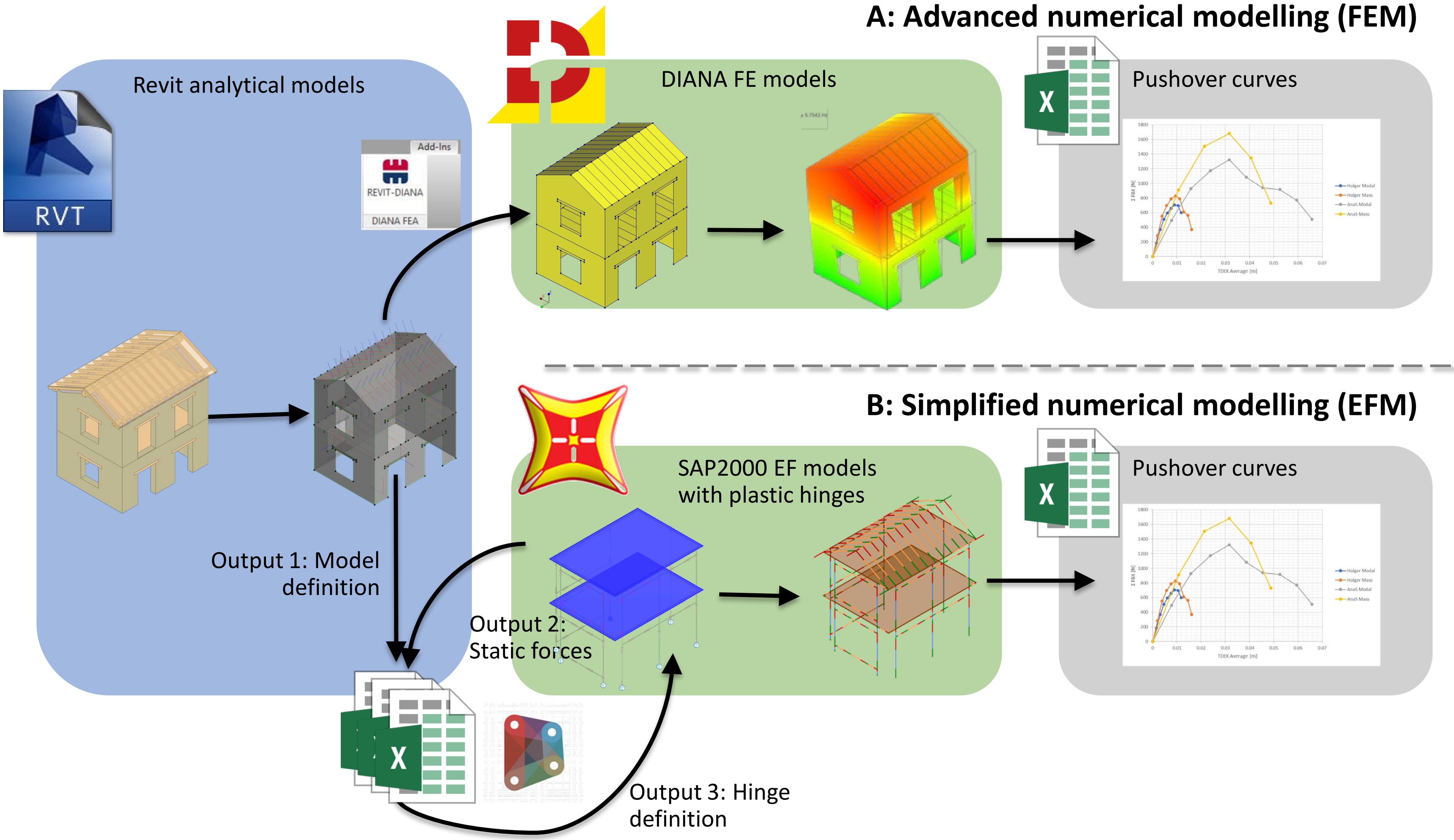
Robustness of the 3D models

Automation of processes

Convenience in engineering practice

Freedom of choice

Validation strategy of the seismic assessment methodology



Data iterative flow (Revit-Dynamo-Excel-SAP2000)

Tables I: Model definition

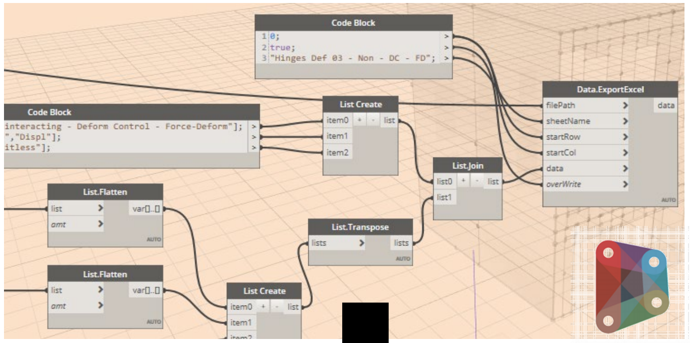
- Joint Coordinates
- Connectivity – Frame
- Frame Section Assignments
- Frame Props 01 - General
- Joint Restraint Assignments
- Connectivity – Area
- Frame Local Axes 1 – Typical
- Frame Offset (Length) Assigns
- Frame Insertion Point Assigns
- MatProp 01 - General
- MatProp 02 - Basic Mech Props
- Area Section Assignments
- Area Section Properties
- Area Section Property Layers
- Area Auto Mesh Assignments
- Load Case Definitions
- Load Pattern Definitions
- Auto Seismic - Eurocode8 2004
- Case - Modal 1 - General
- Case - Static 1 - Load Assigns
- Case - Static 2 - NL Load App
- Case - Static 4 - NL Parameters
- Case - Static 7 - Add Con Disps
- Program Control

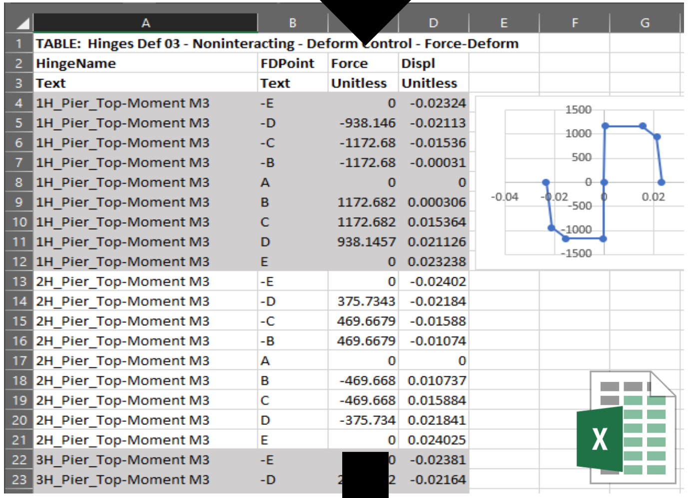
Tables II: Static forces

- Base Reactions
- Element Forces – Frames
- Program Control

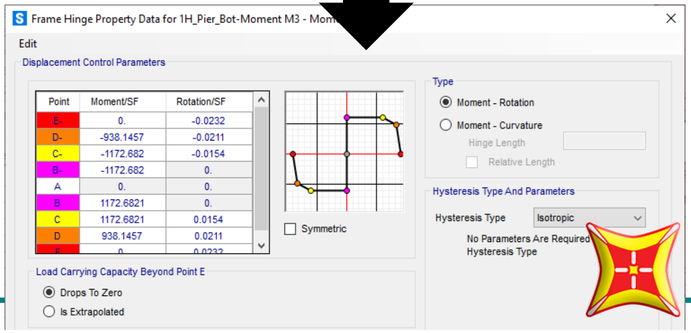
Tables III: Hinge definition

- Hinges Def 03 - Non - DC – FD
- Hinges Def 05 - Non – Fcontrol
- Hinges Def 02 - Non - DC – Gen
- Hinge Ass 02 - User Prop
- Hinge Ass 09 - Hinge Overwrites
- Program Control





	A	B	C	D
1	TABLE: Hinges Def 03 - Noninteracting - Deform Control - Force-Deform			
2	HingeName	FDPoint	Force	Displ
3	Text	Text	Unitless	Unitless
4	1H_Pier_Top-Moment M3	-E	0	-0.02324
5	1H_Pier_Top-Moment M3	-D	-938.146	-0.02113
6	1H_Pier_Top-Moment M3	-C	-1172.68	-0.01536
7	1H_Pier_Top-Moment M3	-B	-1172.68	-0.00031
8	1H_Pier_Top-Moment M3	A	0	0
9	1H_Pier_Top-Moment M3	B	1172.682	0.000306
10	1H_Pier_Top-Moment M3	C	1172.682	0.015364
11	1H_Pier_Top-Moment M3	D	938.1457	0.021126
12	1H_Pier_Top-Moment M3	E	0	0.023238
13	2H_Pier_Top-Moment M3	-E	0	-0.02402
14	2H_Pier_Top-Moment M3	-D	375.7343	-0.02184
15	2H_Pier_Top-Moment M3	-C	469.6679	-0.01588
16	2H_Pier_Top-Moment M3	-B	469.6679	-0.01074
17	2H_Pier_Top-Moment M3	A	0	0
18	2H_Pier_Top-Moment M3	B	-469.668	0.010737
19	2H_Pier_Top-Moment M3	C	-469.668	0.015884
20	2H_Pier_Top-Moment M3	D	-375.734	0.021841
21	2H_Pier_Top-Moment M3	E	0	0.024025
22	3H_Pier_Top-Moment M3	-E	0	-0.02381
23	3H_Pier_Top-Moment M3	-D	[illegible]	-0.02164



II. Expeditious modelling and analysis framework

Non-linear Static (Pushover) Analysis

Purpose and necessary steps

Purpose:

- Determination of building capacity
- Description of building performance under horizontal actions

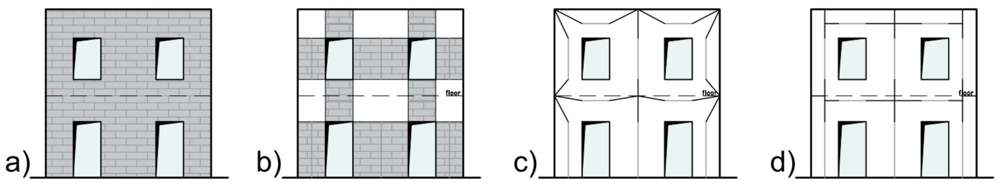
Steps:

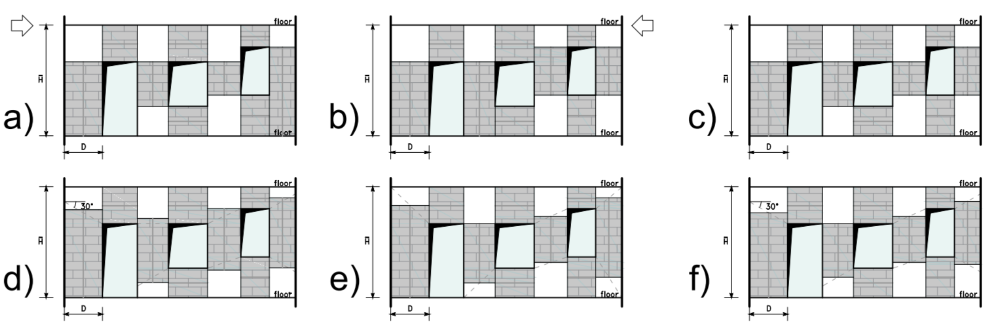
- Identification of structural components (piers, spandrels, rigid nodes)
- Creation of suitable structural model (incl. boundary conditions, gravity loads, etc.)
- Assignment of nonlinear behaviour properties/descriptions
- Definition of lateral load pattern or horizontal action (modal, uniform, EC8)

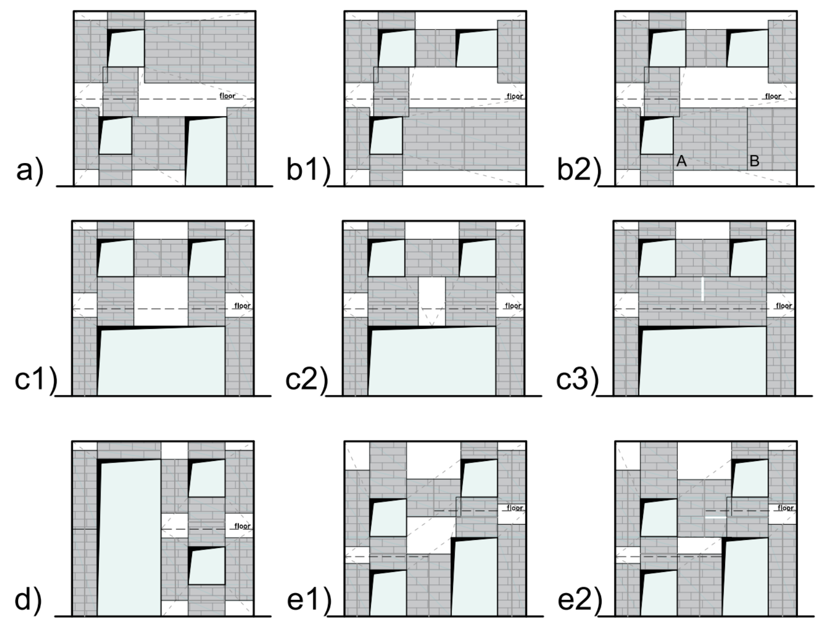
1. Definition of geometry

Multiple criteria for

- macroelements' discretisation
- calculating the deformable lengths of piers
- coping with irregular opening layouts





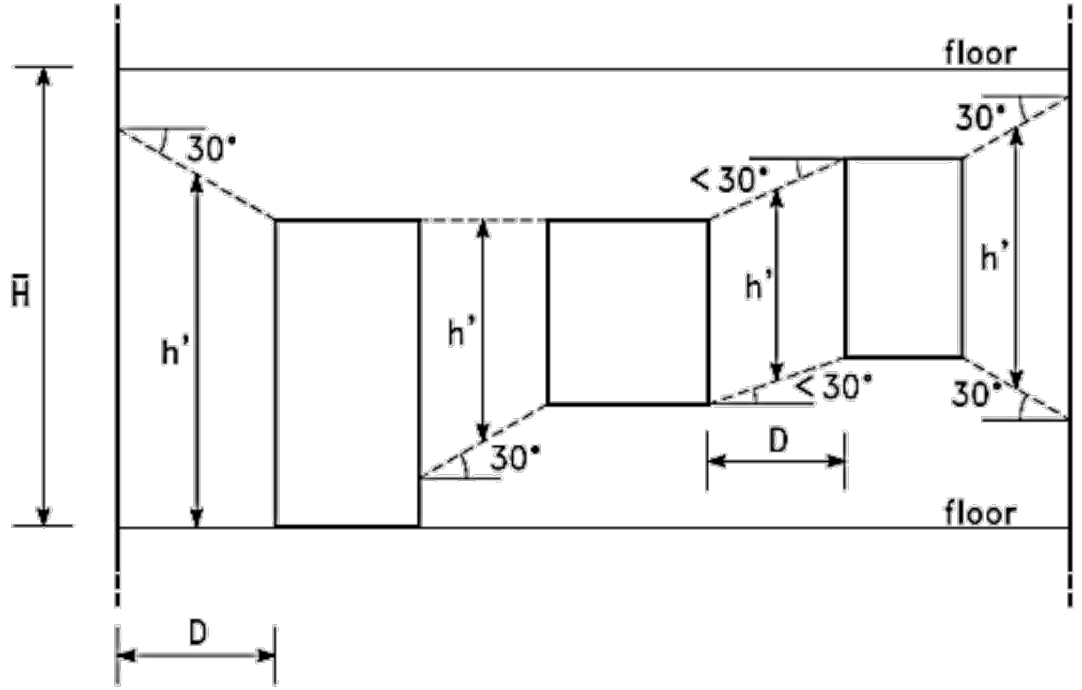


1. Definition of geometry

Piers' effective (deformable) height

$$H_{eff} = h' + \frac{1}{3} \cdot D \cdot \frac{\left(\overline{H} - h'\right)}{h'}$$

(Dolce, 1989)



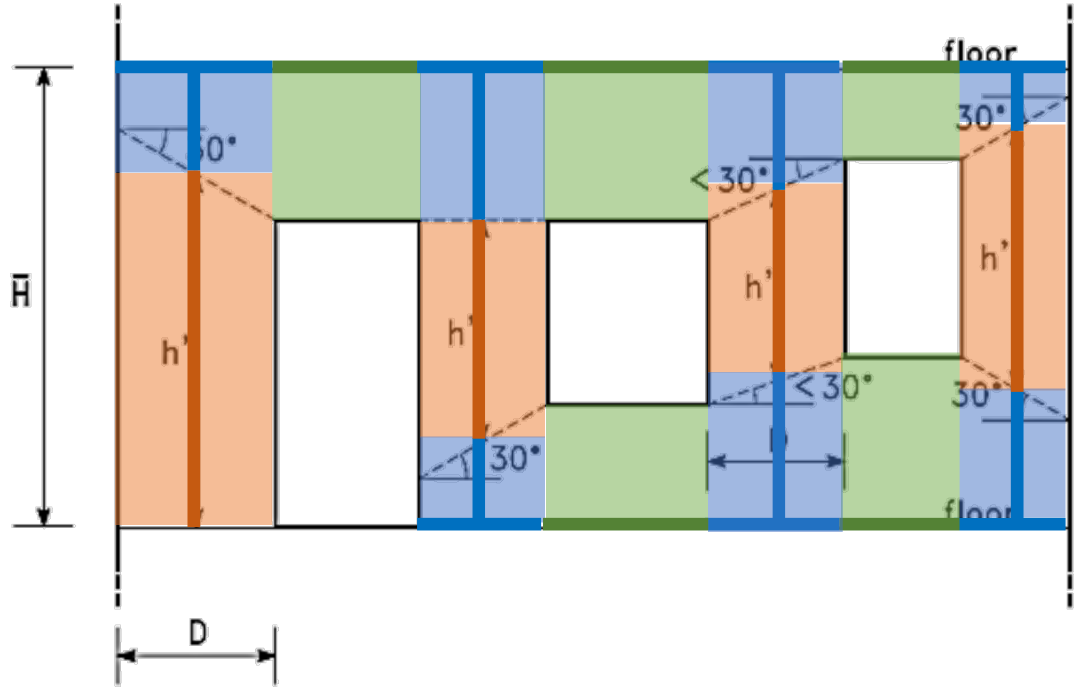
1. Definition of geometry

Macroelements

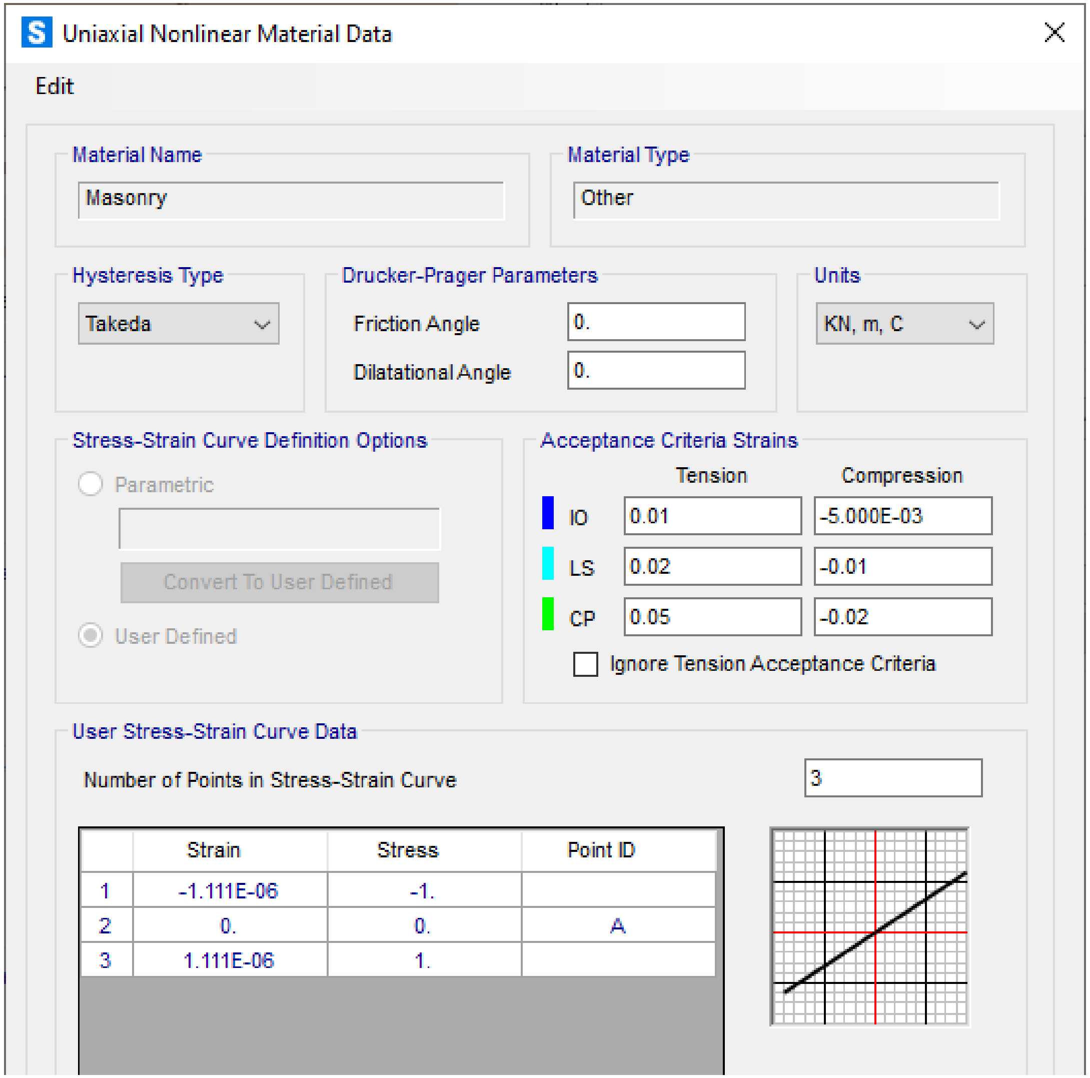
Rigid Nodes

Piers

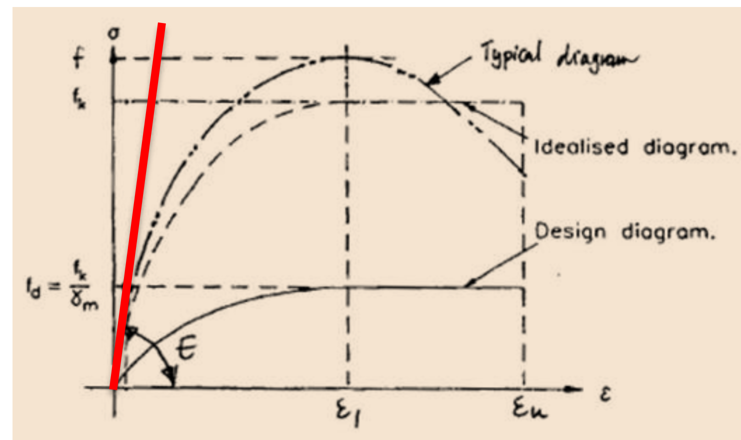
Spandrels



2. Definition of materials

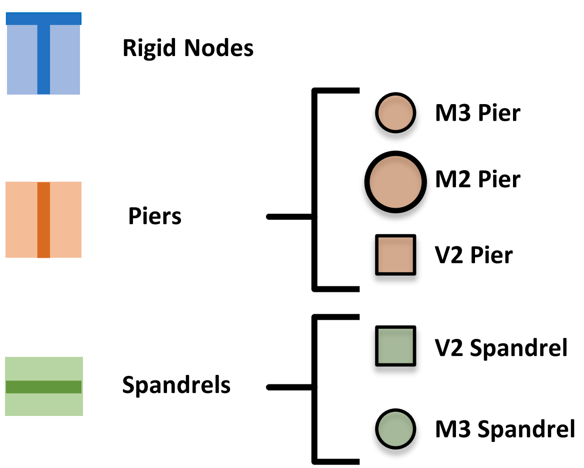


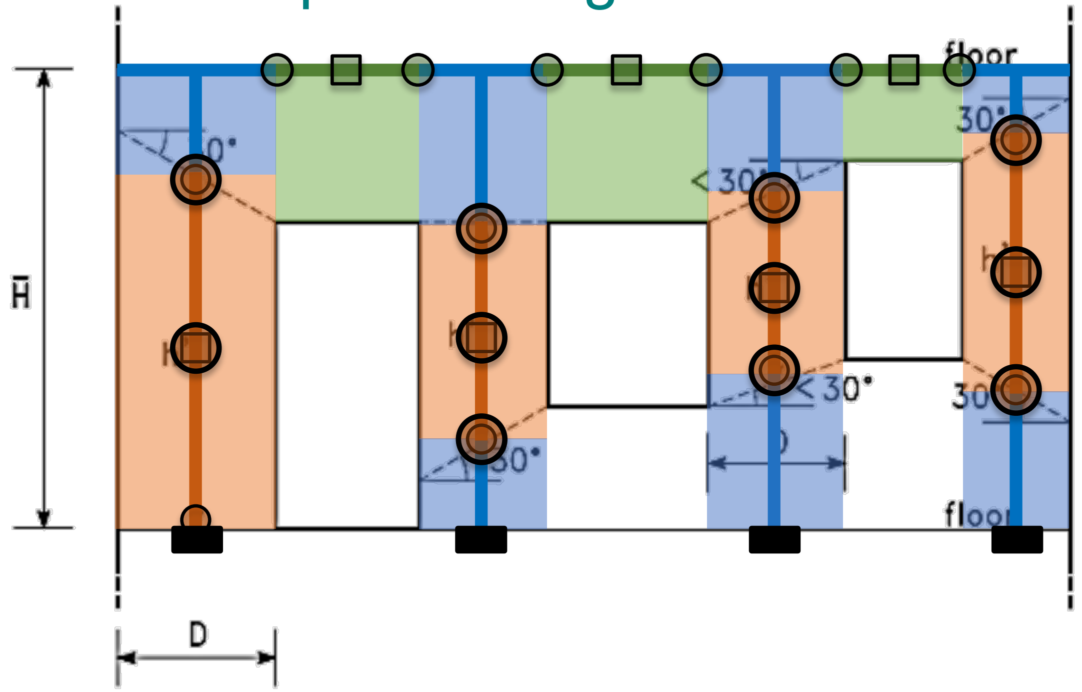
Each element can be modelled with **linear-elastic materials**, and the nonlinearity of the elements is translated through **concentrated / lumped inelasticity**



3. Definition of non-linear behaviour: plastic hinges

Macroelement's Plastic hinges



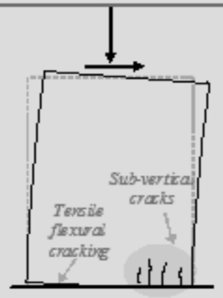


3. Definition of non-linear behaviour: plastic hinges

Piers' in plane mechanisms

Flexural failure

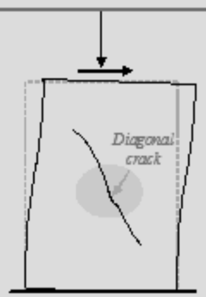
Rocking



$$M_u = \frac{\sigma_o D^2 t}{2}\left(1 - \frac{\sigma_o}{k f_d}\right)$$

Shear failure

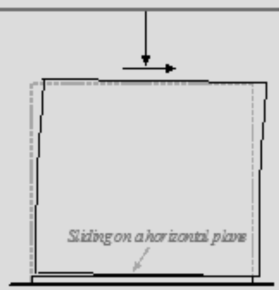
Diagonal cracking



$$V_{u,f\_diag} = \frac{1.5\tau_o D t}{b}\sqrt{1 + \frac{\sigma_o}{1.5\tau_o}}$$

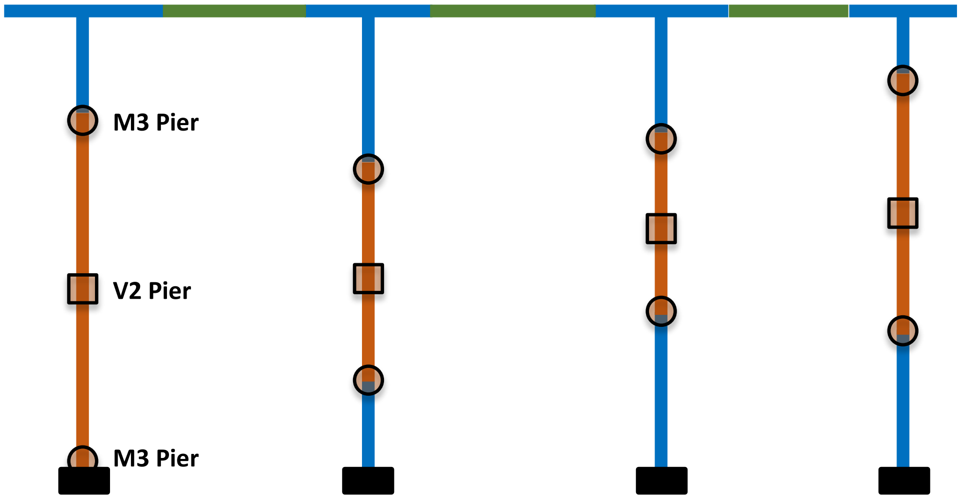
Teoria de Turnsek & Cacovic

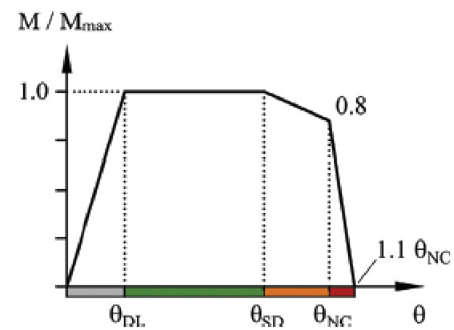
Shear sliding



$$V_{u,desliz} = \frac{1{,}5 c_u + \sigma_o \mu}{1 + \frac{3H'}{\sigma_o D}} Dt$$

Teoria de Mohr-Coulomb



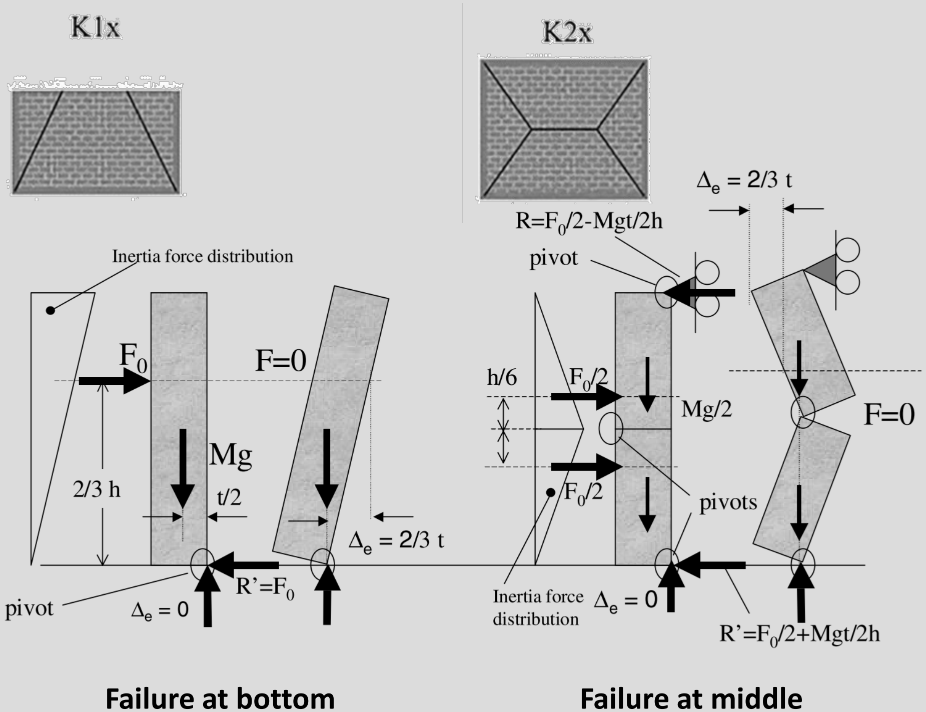


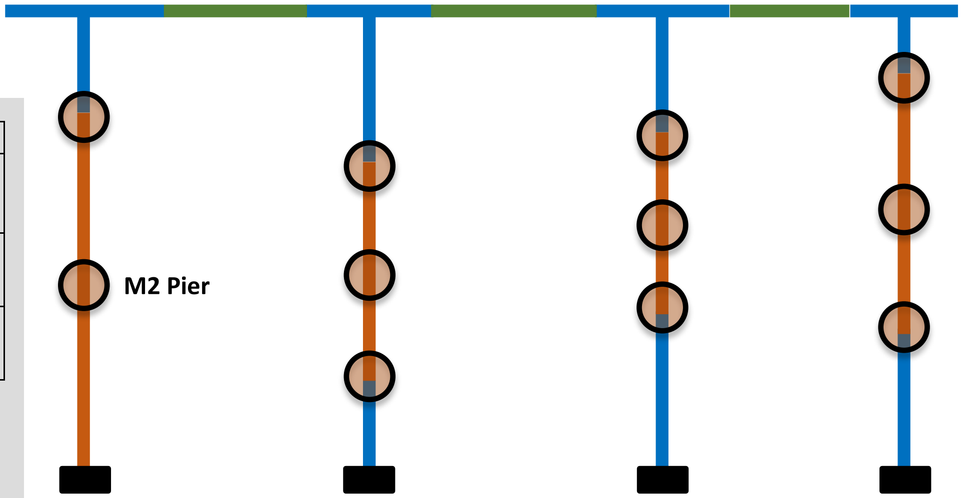
Failure mode	Pier (in-plane)		
	θ_{DL}	θ_{SD}	θ_{NC}
Rocking	θ_{cr}	$0.008\alpha_V$	$0.011\alpha_V$
Shear[a]	θ_{cr}	0.004	0.005

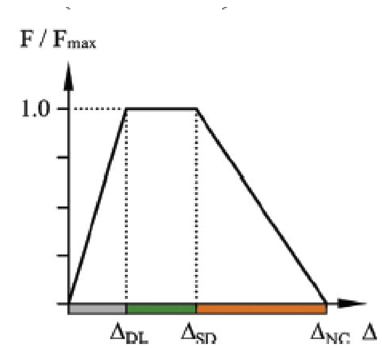
3. Definition of non-linear behaviour: plastic hinges

Piers' out-of-plane mechanisms

	Uniform	Triangular
K1x top hinge	$\frac{3[illegible]\dot{B}[illegible] - \Delta_N' + [illegible]\frac{[illegible]}{2} - \Delta_N\, b}{3[illegible] - 2[illegible] \cdot \tan[illegible]}$	$\frac{[illegible]\dot{B}[illegible] - \Delta_N' + [illegible]\frac{[illegible]}{2} - \Delta_N\, b}{[illegible] - [illegible] \cdot \tan[illegible]}$
K1x bottom hinge	$\frac{3[illegible] - \Delta_N' + [illegible]\frac{[illegible]}{2}}{3[illegible] - 4[illegible] \cdot \tan[illegible]}$	$\frac{[illegible]2[illegible] - \Delta_N' + [illegible]}{2[illegible] - 3[illegible] \cdot \tan[illegible]}$
K2x middle hinge	$\frac{3[illegible] - \Delta_N' + [illegible]\frac{[illegible]}{4}}{3[illegible] - [illegible] \cdot \tan[illegible]}$	$\frac{[illegible]4[illegible] - \Delta_N' + [illegible]}{2[illegible]2[illegible] - [illegible] \cdot \tan[illegible]'}$



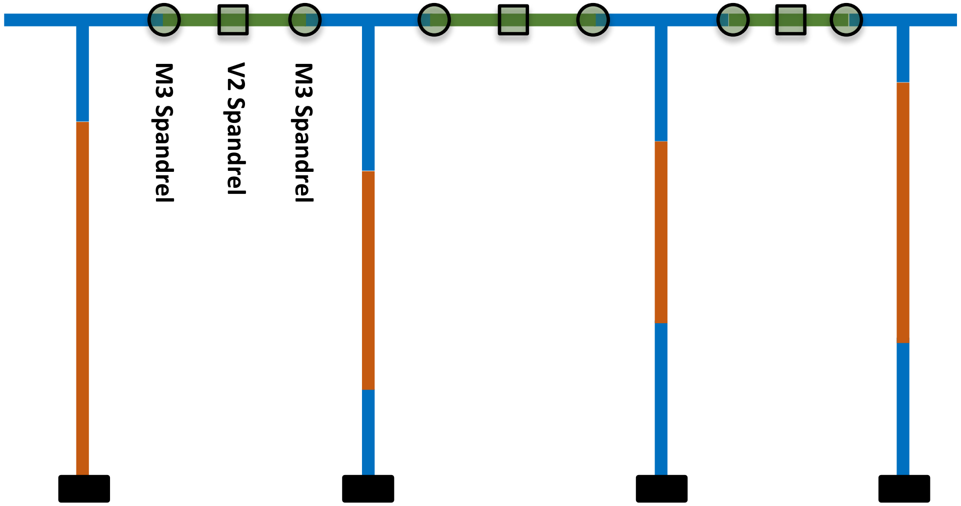


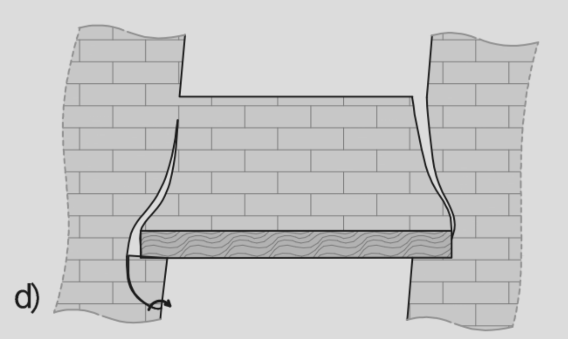


Failure mode	Pier (out-of-plane)[b]		
	Δ_{DL}	Δ_{SD}	Δ_{NC}
Rocking Shear[a]	0.04*t*	0.18*t*	0.66*t*

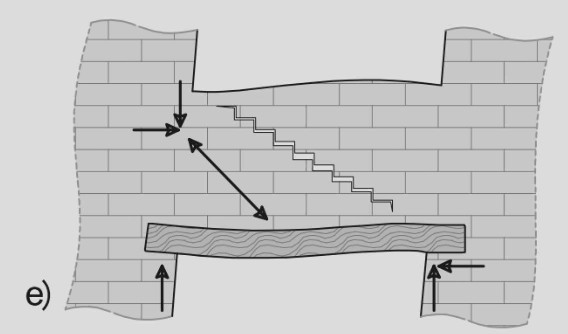
3. Definition of non-linear behaviour: plastic hinges

Spandrels' mechanisms

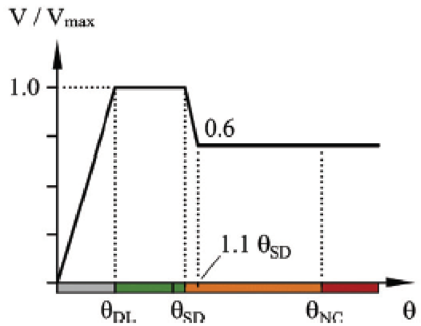




Flexural failure



Shear failure



Failure mode	Spandrel		
	θ_{DL}	θ_{SD}	θ_{NC}
Rocking	0.002	$0.008 l_{sp}/h_{sp}$	0.015
Shear[a]	0.001	0.004	0.02

III. Case-study URM-RC buildings

Practical examples: From BIM to FEM/EFM

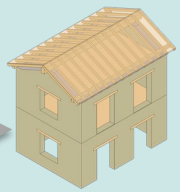
Validation strategy of the seismic assessment methodology

Comparison amongst different types of:

- **Building geometries** (pier H/D ratio, opening ratio, number of storeys)
- **Material properties**

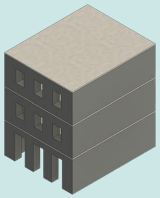
Case-study URM-RC buildings

- EUCENTRE buildings – Model from experimental seismic table test campaign (unreinforced and reinforced typologies)

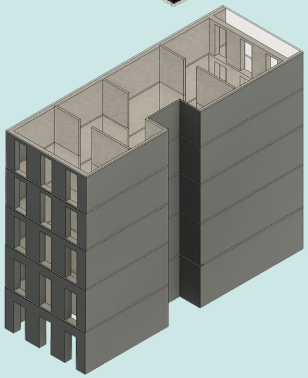


- 2 storey building – Model from laser scanning survey + ambient vibration testing

- 3 storey building – Model based on statistical study of the Portuguese building stock (Lovon, H., et al. 2021)



- 5 storey building – Model follow the minimum dimensions recommended by the Health Regulation for Buildings (RSEU, 1903)



Validation strategy of the seismic assessment methodology

Comparison amongst different types of:

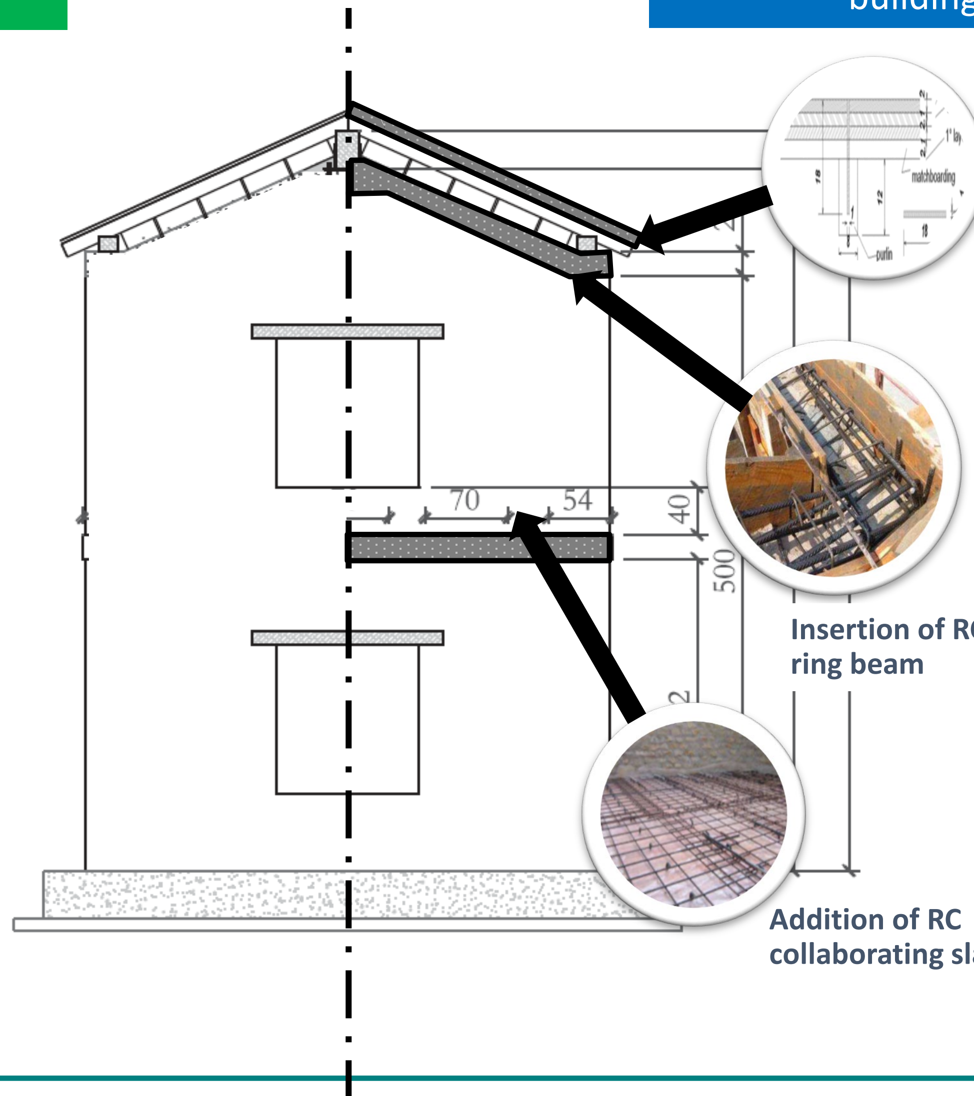
- Building geometries (pier H/D ratio, opening ratio, number of storeys)
- Material properties
- **Analysis methods** (experimental and numerical), based on:
  - Damage observation (damage patterns, failure modes and severity of cracking)
  - Modal analysis (modal shapes, frequencies)
  - Pushover analysis (target displacement, stiffness, capacity)

Case-study URM-RC buildings

"Building 1" – original URM building

"Building 3" – mixed URM-RC building

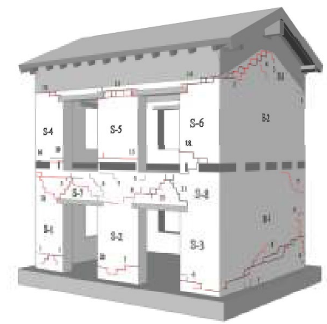
Experimental setup (shaking table tests)



Strengthened roof diaphragms

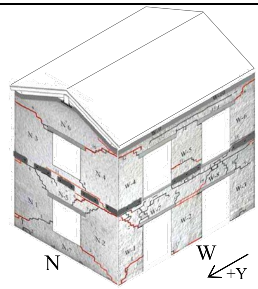
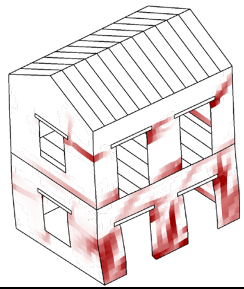
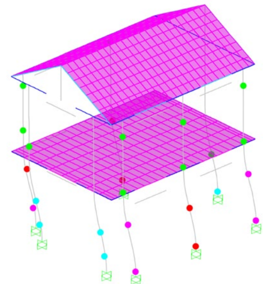
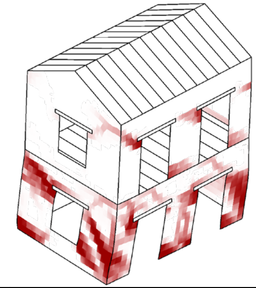
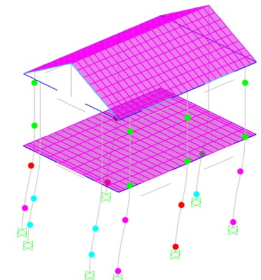
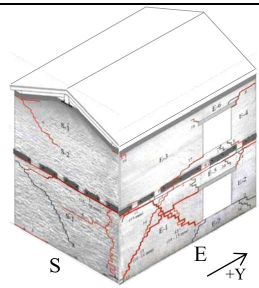
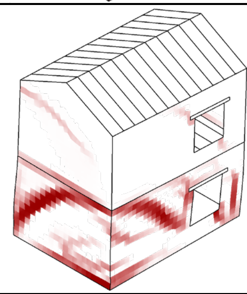
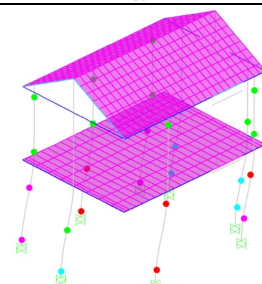
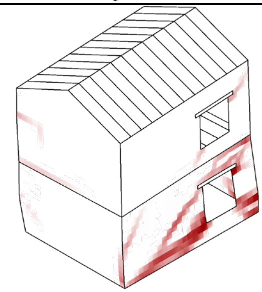
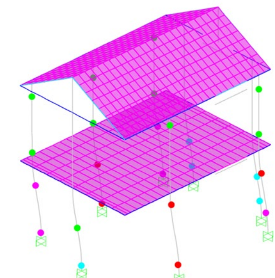
Insertion of RC ring beam

Addition of RC collaborating slab

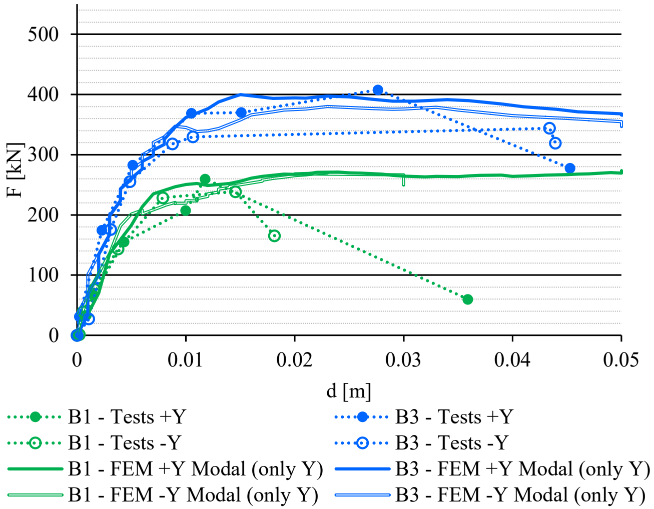


Initial damage before experimental tests

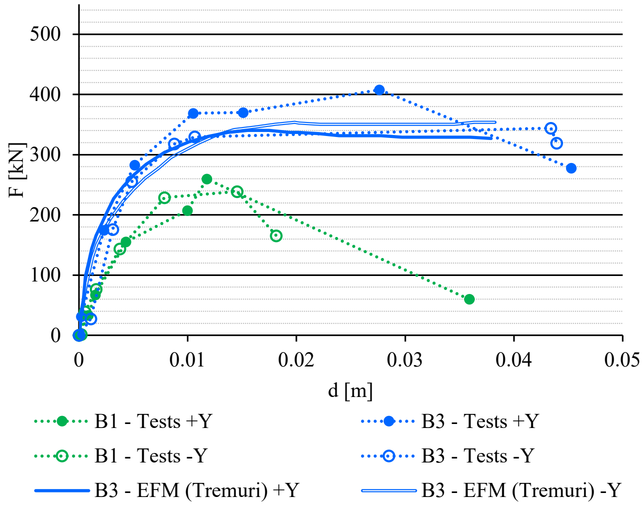
Observed damage patterns and failure mechanisms

	Seismic table tests	FEM +Y	EFM +Y	FEM -Y	EFM +Y
NW					
SE					

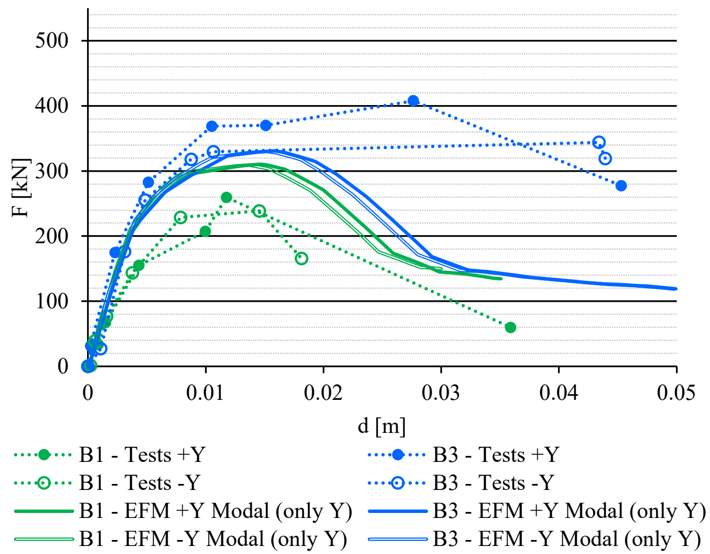
Numerical vs experimental pushover results



(a) FEM (DIANA)

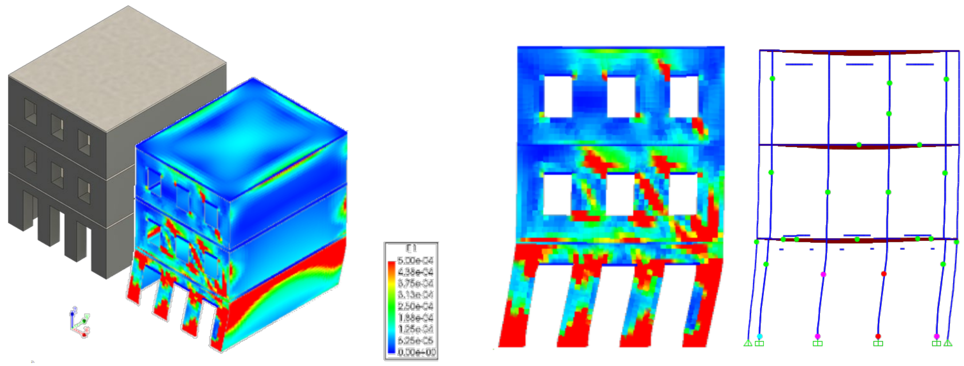


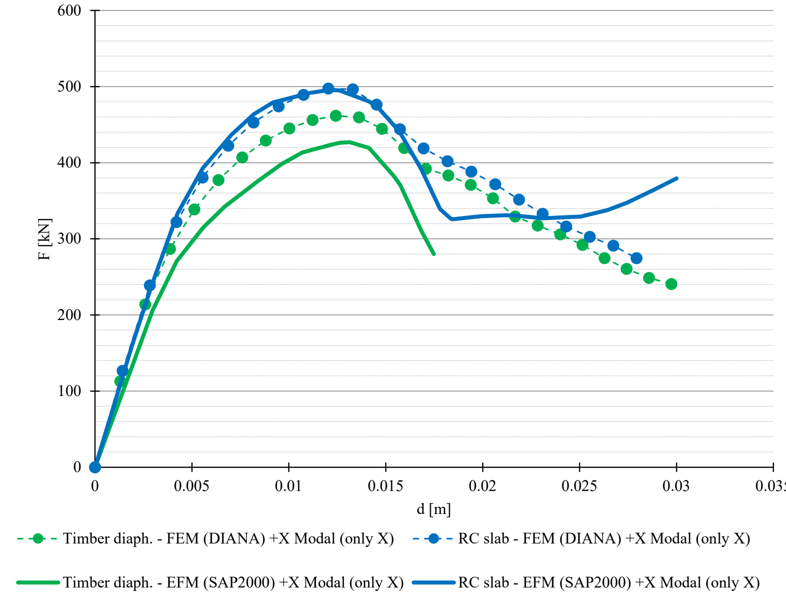
(b) EFM (Tremuri)

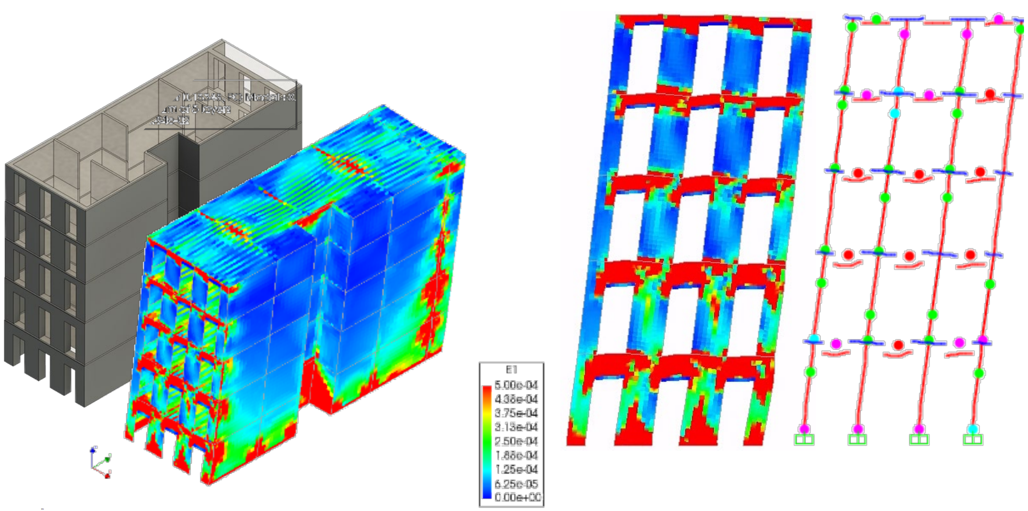


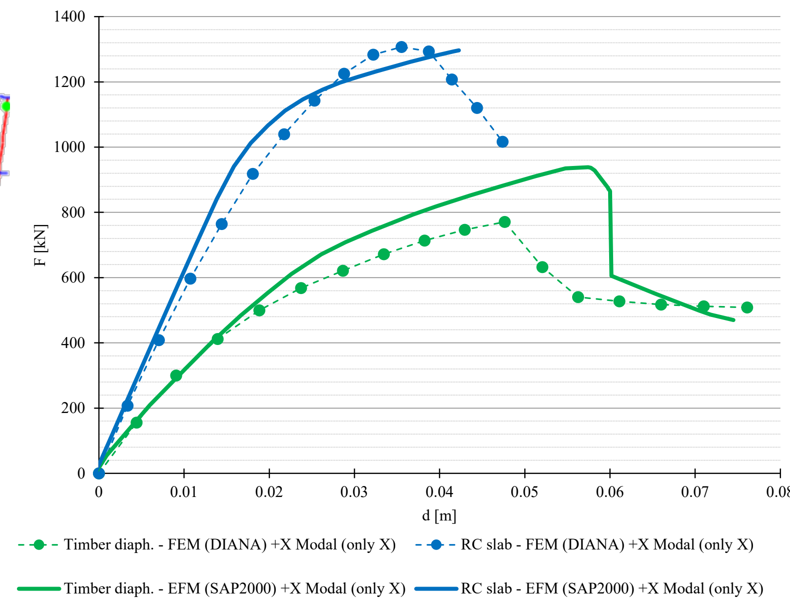
(c) EFM (SAP2000) with α calculated

Case-study URM-RC buildings









Contributions

Speed of the analysis: EFM vs FEM

Robustness of the model creation plug-in

- Able to handle irregular opening layouts and complex 3D structures

Automation and simplification of processes

- Modelling, analysis, and results

Convenience in engineering practice

- Easy to be implemented in practice-oriented commercial software
- Consistent with the recommendations of several seismic codes (namely the EC8-Part 3)
- Integrated multidisciplinary workflow:

  Architect – Engineer – Contractor – Client – User

Freedom of choice

- Not dependent on specific macroelement-based analysis software
- Not dependent on software version compatibility

Published references

- G. Correia Lopes, N. Mendes, R. Vicente, T.M. Ferreira, M. Azenha, Seismic performance assessment of existing URM-RC buildings: a BIM-based methodology, in: 3rd Eur. Conf. Earthq. Eng. Seismol., Bucharest, Romania, 2022.
- G. Correia Lopes, R. Vicente, T.M. Ferreira, M. Azenha, Intervened URM buildings with RC elements: typological characterisation and associated challenges, Bull. Earthq. Eng. 17 (2019) 4987–5019. doi:10.1007/s10518-019-00651-y.
- G. Correia Lopes, R. Vicente, T.M. Ferreira, M. Azenha, H. Rodrigues, BIM-based methodology for the seismic performance assessment of existing buildings, Port. J. Struct. Eng. III (2020) 45–54.
- G. Correia Lopes, R. Vicente, T.M. Ferreira, M. Azenha, J. Estêvão, Displacement-based seismic performance evaluation and vulnerability assessment of buildings: The N2 method revisited, Structures. 24 (2020) 41–49. doi:10.1016/J.ISTRUC.2019.12.028.
- G. Correia Lopes, R. Vicente, T.M. Ferreira, M. Azenha, H. Rodrigues, BIM-based Methodology for the Seismic Performance Assessment of Existing Buildings, in: 4º Encontro Conserv. E Reabil. Edifícios, LNEC, Lisbon, 2020: pp. 785–788.
- G. Correia Lopes, N. Mendes, R. Vicente, T.M. Ferreira, M. Azenha, Numerical simulations of derived URM-RC buildings: Assessment of strengthening interventions with RC, J. Build. Eng. 40 (2021) 102304. doi:10.1016/j.jobe.2021.102304.

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