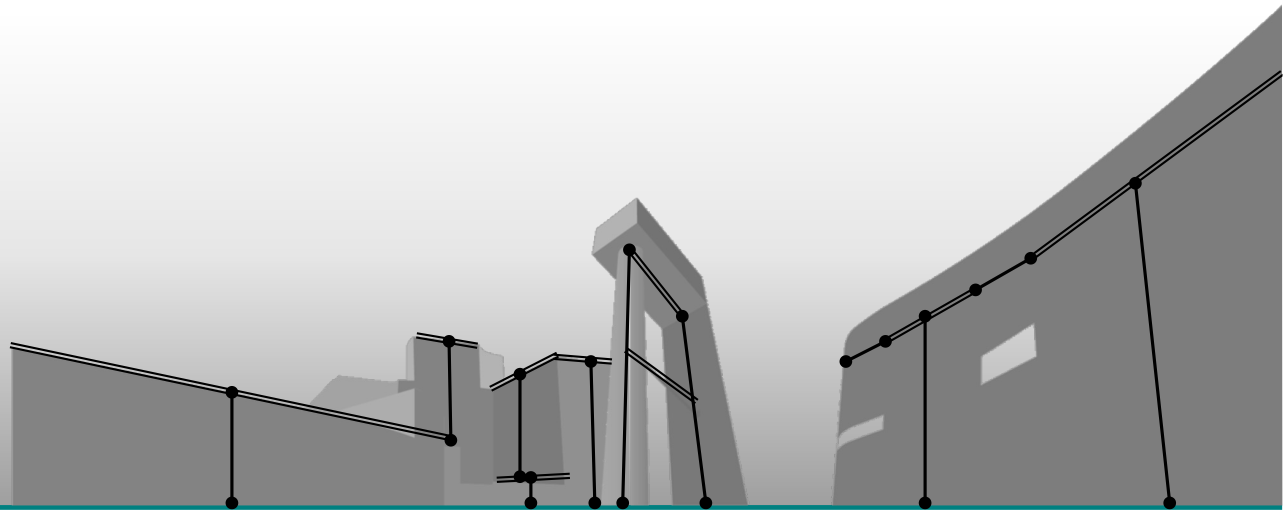
Course: Infrastructure Engineering

BIM-based methodology for the seismic performance assessment of existing URM-RC buildings

Gonçalo Correia Lopes

Scientific supervision:

Romeu Vicente (U. Aveiro)
Miguel Azenha (U. Minho)
Tiago Miguel Ferreira (UWE Bristol)



Presentation summary

I. Motivation, Research questions and Methodology
Mixed URM-RC building typologies

II. Development of the BIM-based methodology
Expeditious modelling and analysis framework

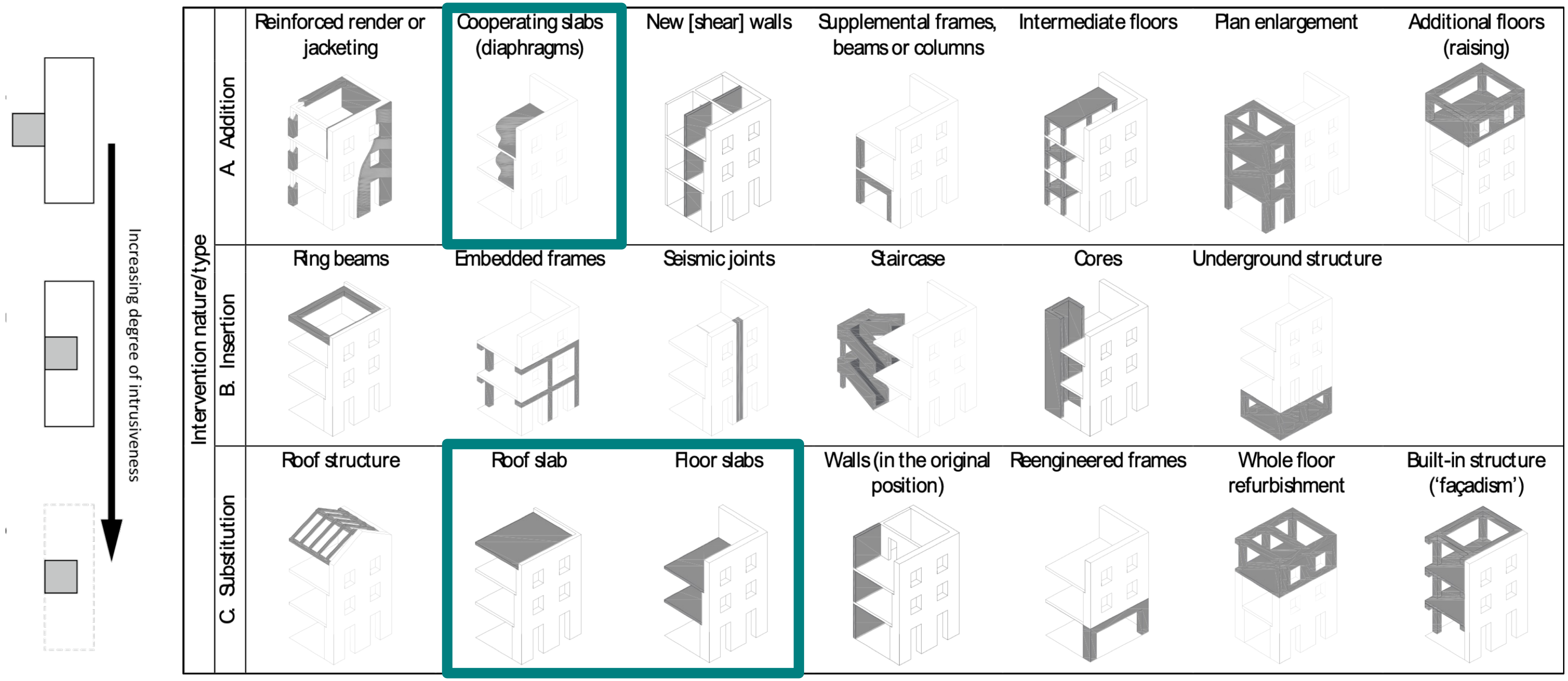
III. Seismic performance assessment of existing URM-RC buildings
Case studies

IV. Contributions

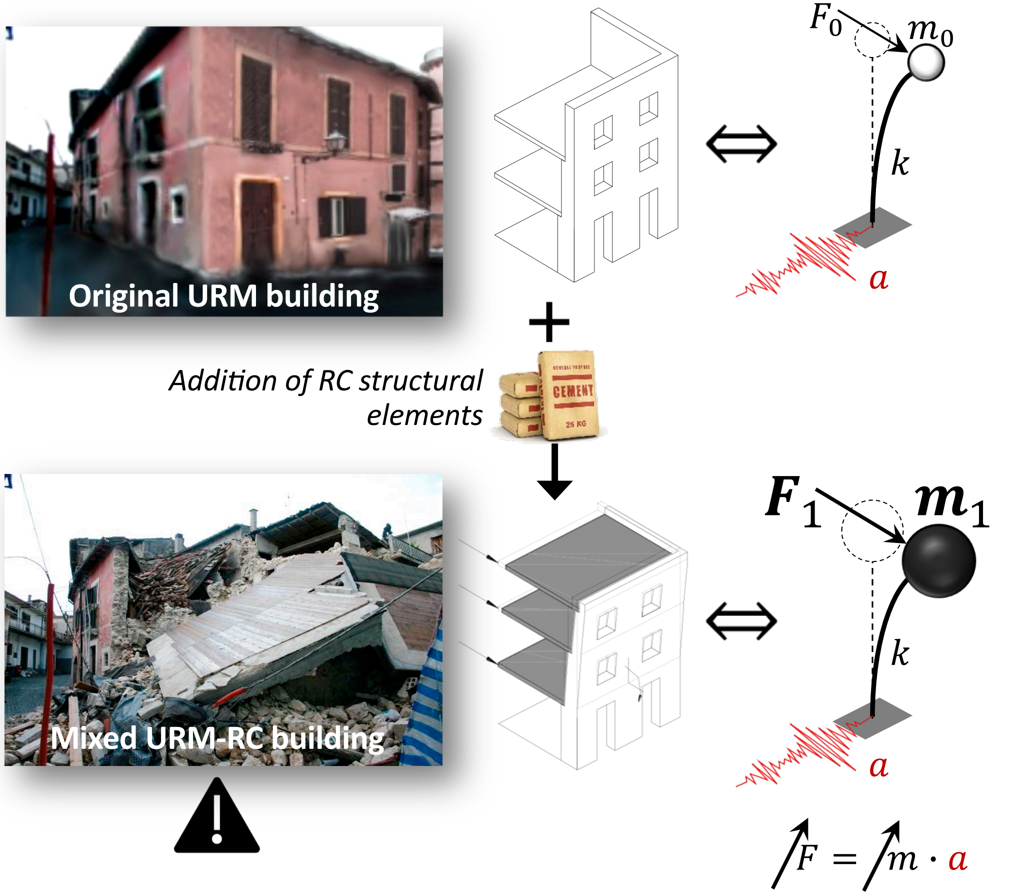
I. Motivation, Research questions and Methodology

Mixed URM-RC building typologies

Mixed URM-RC building typologies



Research questions



- Is the utilization of Reinforced Concrete (RC) a suitable approach for the **seismic strengthening** of old masonry buildings?
- How **vulnerable** are current mixed URM-RC buildings to earthquakes?
- Which **numerical modelling** and **analysis methods** can tackle the different complex aspects related to these typologies?

Motivation / Goals

- Faster numerical analysis
- Robustness and accuracy of the 3D models
- Automation of processes (numerical modelling and analysis, and results)
- Convenience in engineering practice

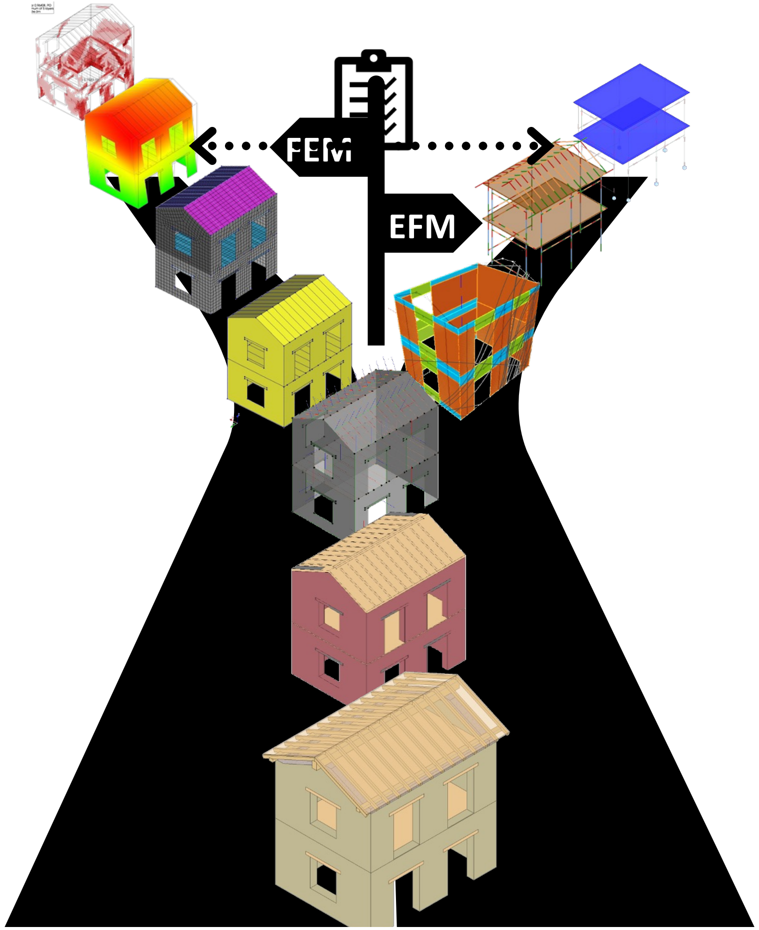
Research methodology (from BIM to FEM/EFM)

Advanced numerical modelling

- Finite Element Models (FEM)
- 2D shell elements

- More time-consuming
- Higher accuracy

Software: DIANA FEA



Simplified numerical modelling

- Equivalent Frame Models (EFM)
- 1D bar elements

- Faster
- Reasonable accuracy

Software: SAP2000

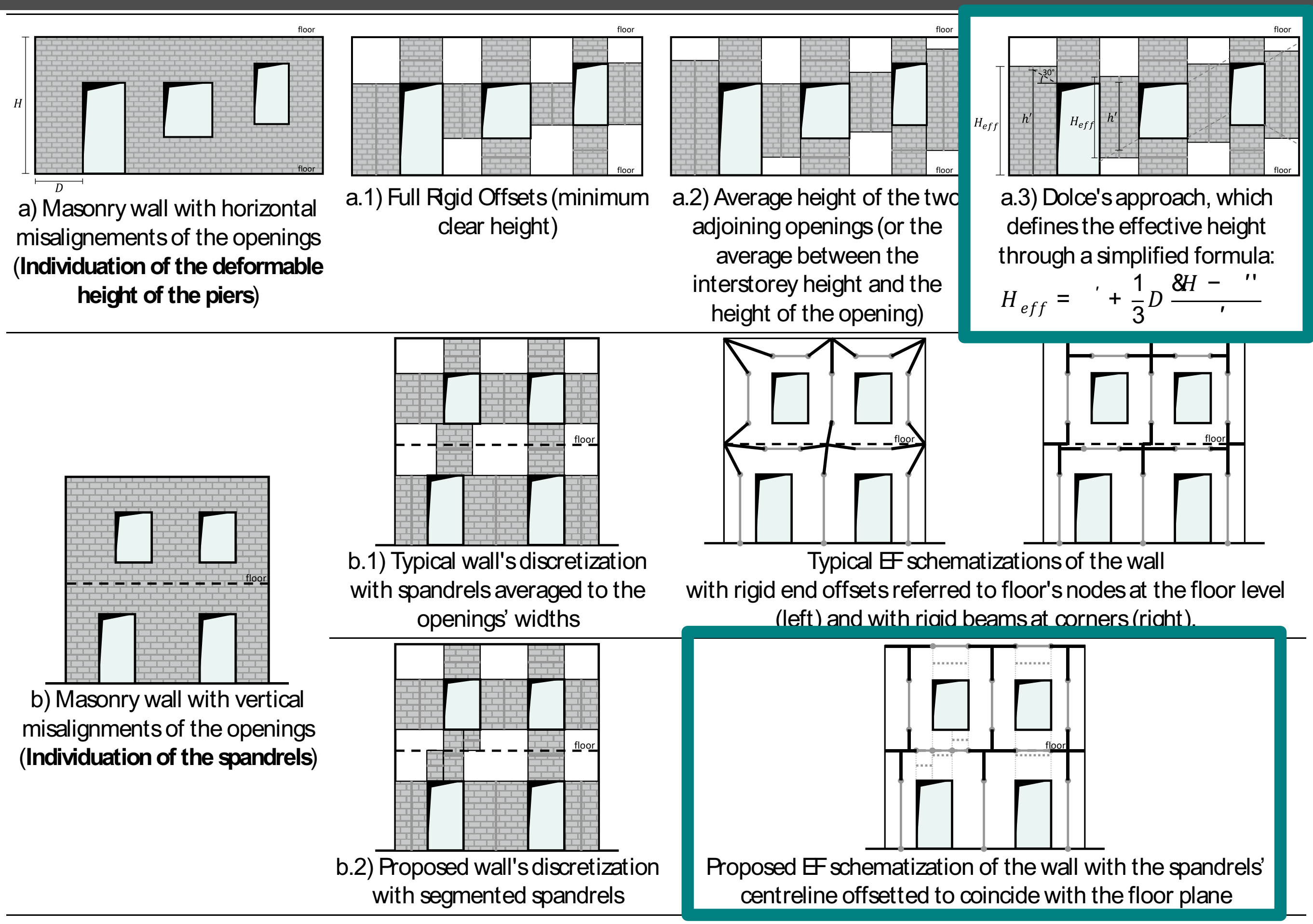
II. Development of the BIM-based methodology

Expeditious modelling and analysis framework

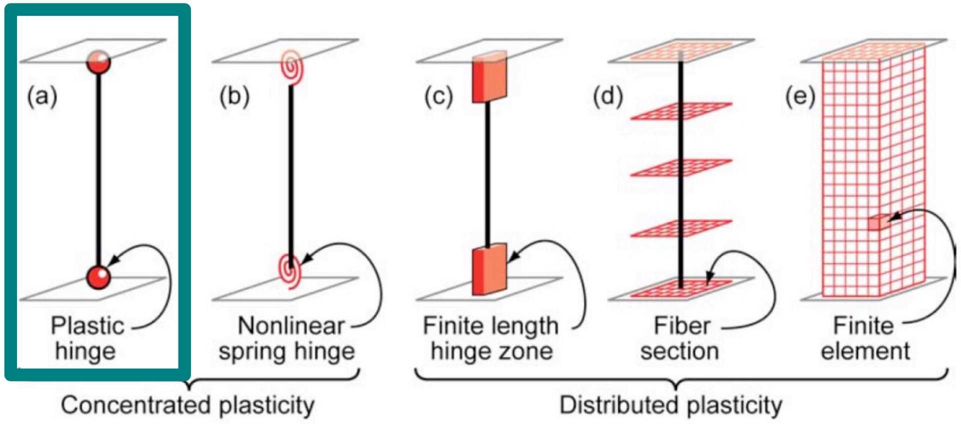
EFM – Criteria for the individuation of the macroelements

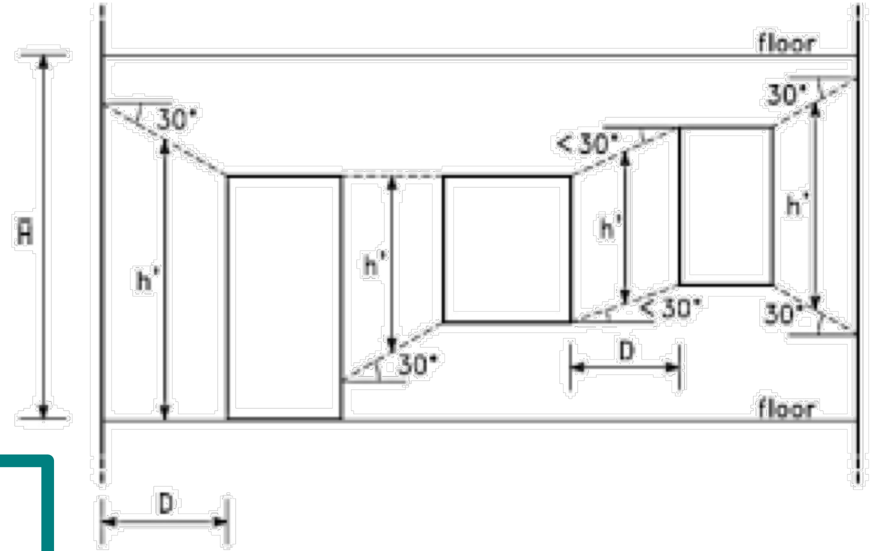
Multiple criteria for

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

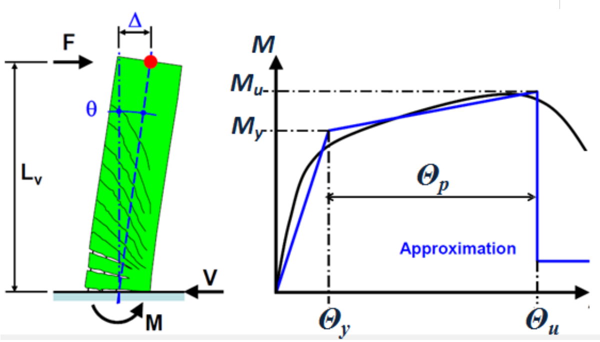


Definition of non-linear behaviour: plasticity models

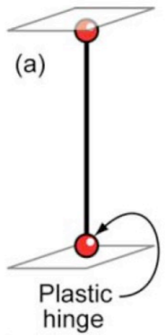




Plastic Hinge: is used to describe the deformation of a section of a structural element where plastic deformation occurs.

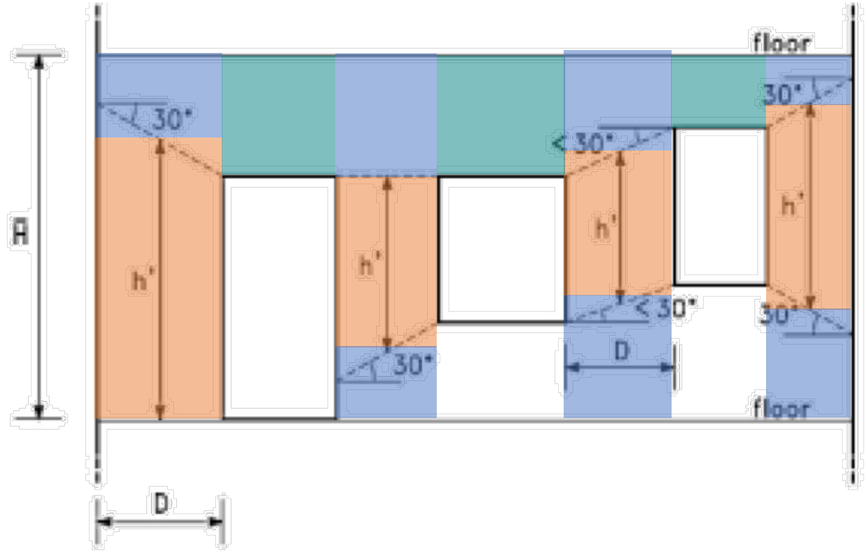


Definition of non-linear behaviour: plasticity models

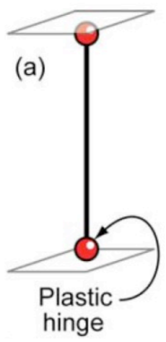


Macroelements

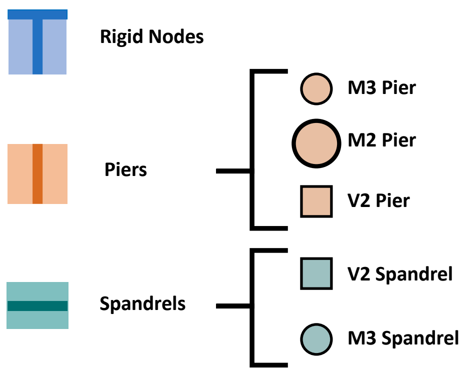
- Rigid Nodes
- Piers
- Spandrels

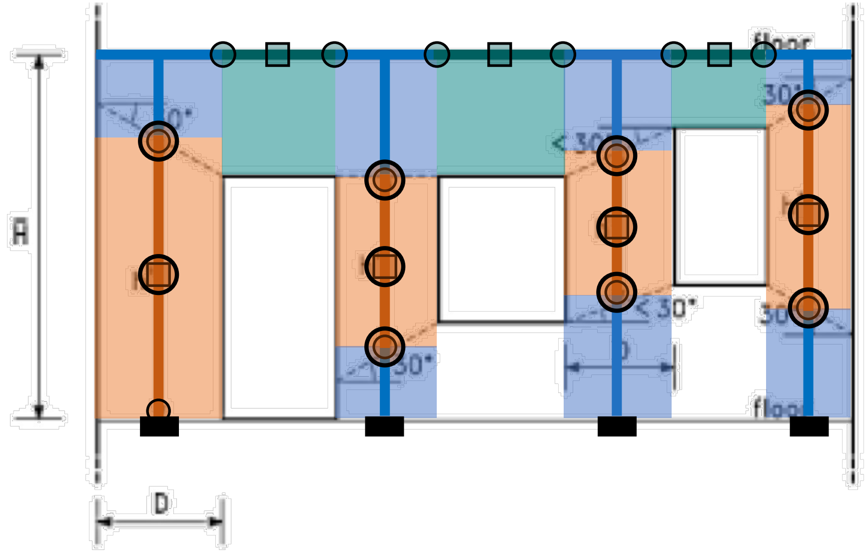


Definition of non-linear behaviour: plasticity models



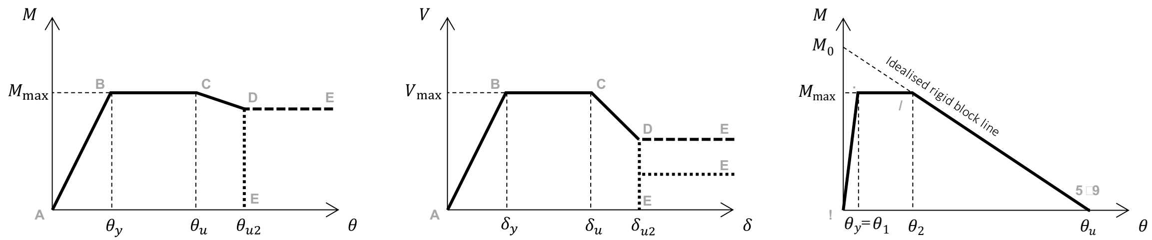
Macroelements' Plastic hinges





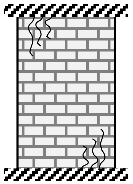
In-plane hinges

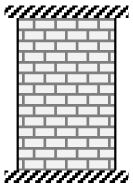
Out-of-plane hinges

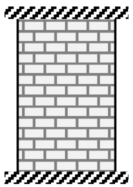


a) Flexural hinges (M3-θ) b) Shear hinges (V2-δ) c) Flexural hinges (M2-θ)

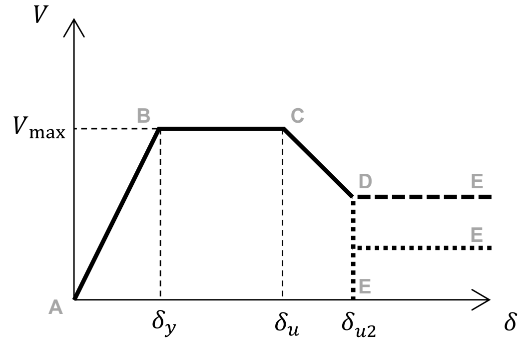
In-plane plastic hinges

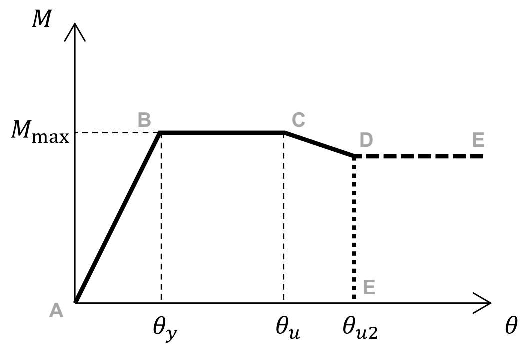




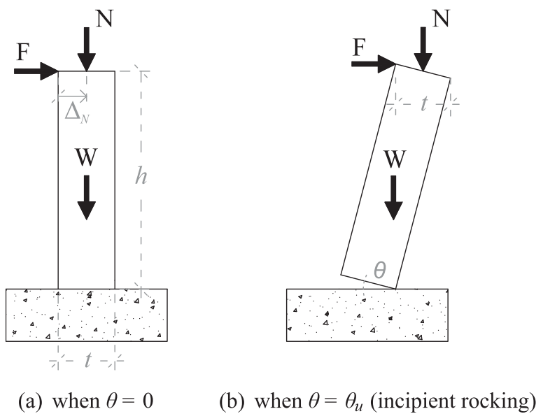


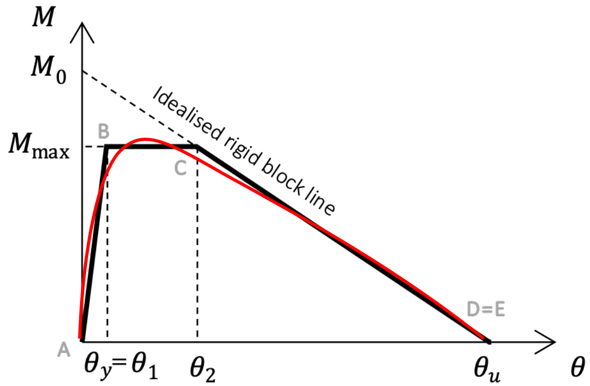
Failure mechanisms			Max. shear strength (Resistance levels)	Eq.	Reduced shear force	Residual strength	Yield drift (Deformation capacities)	Ultimate drift	2nd ultimate drift
			V_{max}		V_{red}	V_{res}	$\theta_y = \theta_{DL}$	$\theta_u = \theta_{SD}$	$\theta_{u2} = \theta_{NC}$
			B-C		D	E	B	C	D
Flexural rocking	Piers	**of irregular masonry**	$V_f = \frac{DN}{2H_0}\left(1 - \frac{N}{\kappa f D t}\right)$	(1)	$0.8V_f$	Idem	θ_{cr}	$0.01\left(1 - \frac{N}{Dtf}\right)$	
		of regular masonry			$0.9V_f$				
	Spandrels	coupled with tensile resisting elements (e.g.: lintel)	$V_{f,S} = \frac{{}_S N_S}{2l_{S,0}}\left(1 - \frac{N_S}{\kappa f \; {}_S t_S}\right)$	(2)	$0.9V_f$	Idem	0.002	0.016	$\frac{4}{3}\theta_{f,u}$
		not confined failing through units	$V_{f,S} = 1.15\frac{{}_S{}^2 t_S}{3 \times 2l_{S,0}} f_t$	(3)	$0.8V_f$	Idem		0.012	
		not confined failing along the joints	$V_{f,S} = \frac{{}_S{}^2 t_S}{2l_{S,0}(1 + f_t / f')} f_t$	(4)					
Diagonal cracking	Piers	**of irregular masonry**	$V_d = \frac{Dt}{b} f_t \sqrt{1 + \frac{N}{Dtf_t}}$	(5)	$0.3V_d$	0	θ_{cr}	0.005	$\frac{4}{3}\theta_{d,u}$
		of regular masonry	$V_d = \frac{Dt}{b}\left(f_{v0} + \mu \frac{N}{Dt}\right)$	(6)	$0.5V_d$	$0.2V_d$		0.006	
		of regular masonry failing through units	$V_{d,lim} = \frac{Dt}{b}\frac{f_{bt}}{2.3}\sqrt{1 + \frac{N}{Dtf_{bt}}}$	(7)					
	Spandrels	**of irregular masonry**	$V_{d,S} = \frac{{}_S t_S}{b} f_t \sqrt{1 + \frac{N_S}{f_t \; {}_S t_S}}$	(8)	steel/RC: $0.6V_d$ timber: $0.4V_d$ ineffective: $0.1V_d$	Idem	0.001	0.005	
		of regular masonry (pre-modern)	$V_{d,S} = \frac{{}_S t_S}{b}\left(f_{v0} + \mu \frac{N_S}{{}_S t_S}\right)$	(9)				0.006	
Shear sliding	Piers	of regular masonry	$V_s = \frac{N(3f_{v0}Dt + 2\mu N)}{2N + 3f_{v0}\alpha H t}$	(10)	$\mu N = 0.4N$	Idem	θ_{cr}	0.008	$\frac{4}{3}\theta_{s,u}$
		of regular masonry failing through units	$V_{s,lim} = \frac{0.195 f_b D t N}{2N + 0.195 f_b \alpha H t}$	(11)		$0.5V_{s,lim}$		0.005	





Out-of-plane performance of URM walls

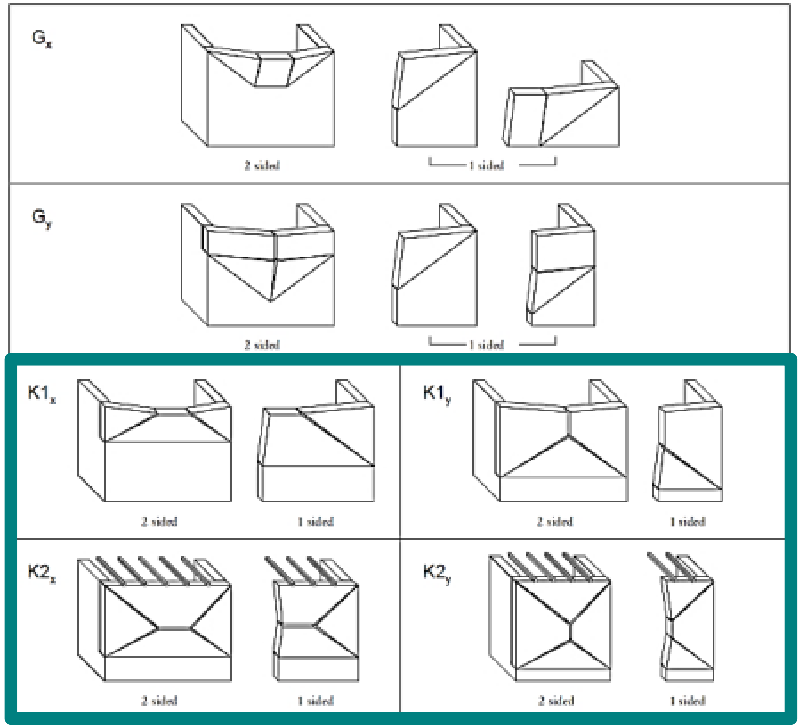




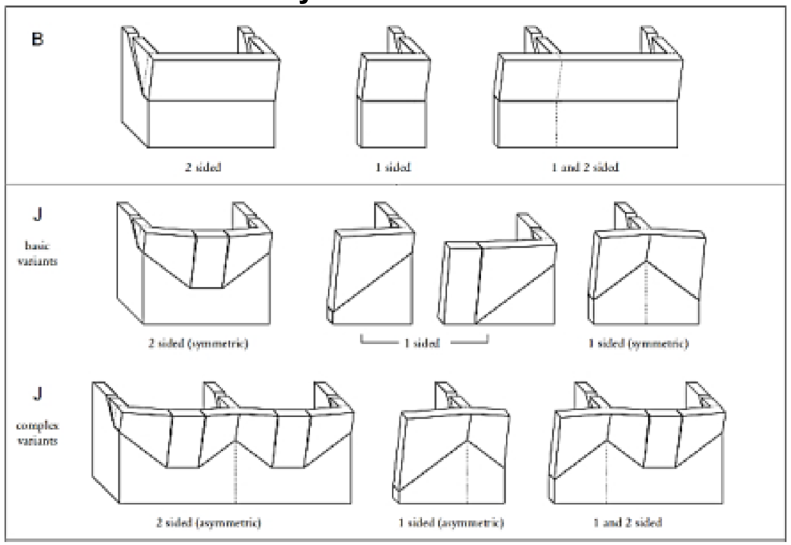
[1] T.M. Ferreira, A.A. Costa, R. Vicente, H. Varum, A simplified four-branch model for the analytical study of the out-of-plane performance of regular stone URM walls, Eng. Struct. 83 (2015) 140–153. doi:10.1016/j.engstruct.2014.10.048.

Out-of-plane failure mechanisms of URM walls

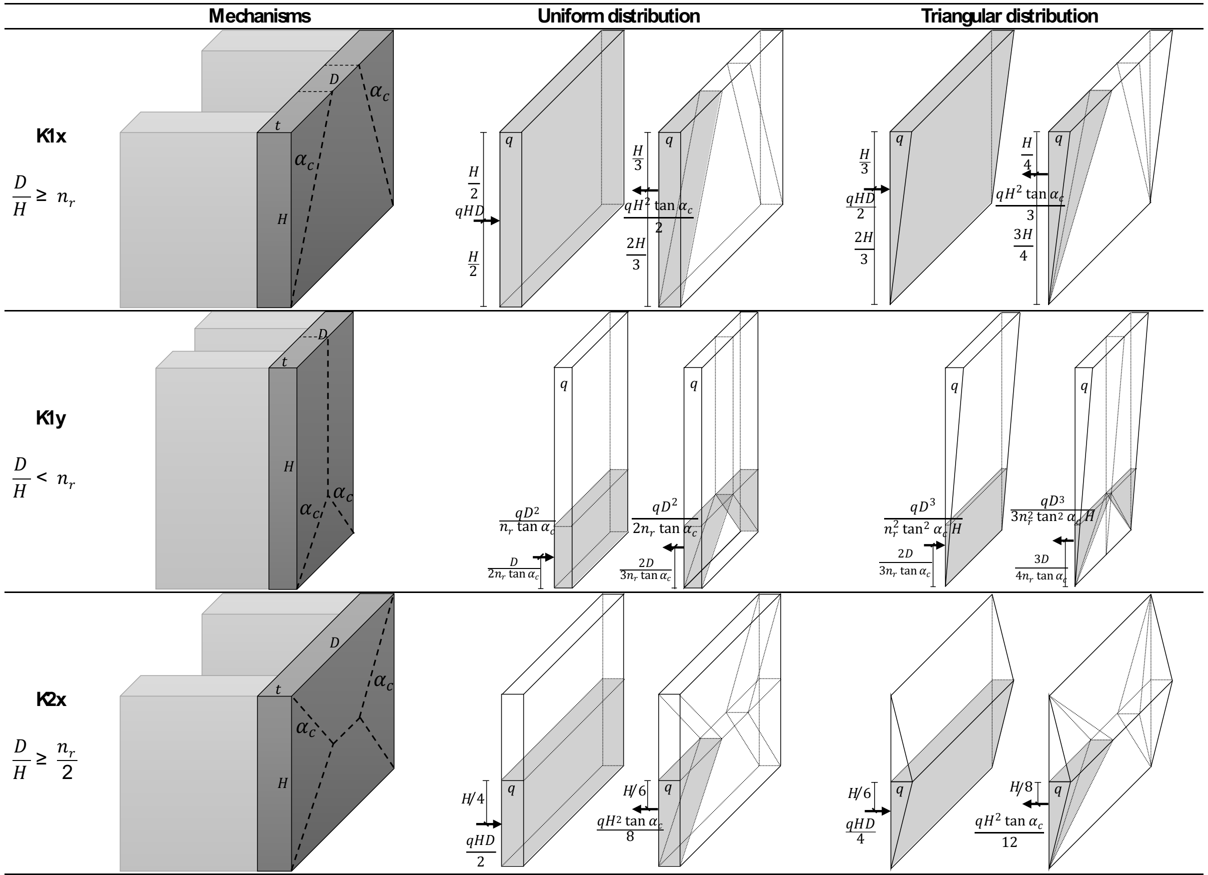
Pure out-of-plane mechanisms



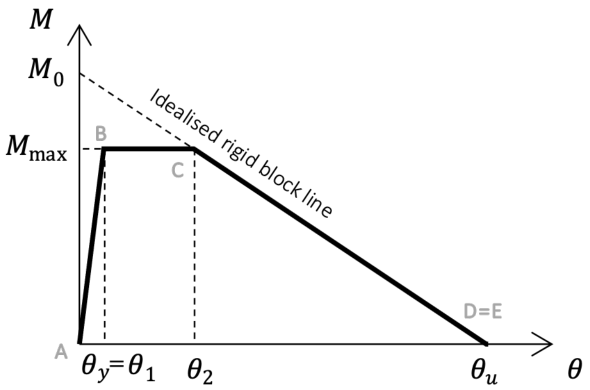
Hybrid mechanisms



Simplified failure mechanisms for walls with returns



Out-of-plane plastic hinges



$$M_{\max} = \boldsymbol{M_0} \cdot \xi$$

State of degradation at cracked joint	Δ_1/Δ_u	$\theta_1 = \theta_u \Delta_1/\Delta_u$	Δ_2/Δ_u	$\theta_2 = \theta_u \Delta_2/\Delta_u$	$\xi = (\theta_u - \theta_2)/\theta_u$
New	0.06	$0.04t/H$	0.28	$0.19t/H$	0.715
Moderate degraded	0.13	$0.09t/H$	0.40	$0.27t/H$	0.595
Severe degraded	0.20	$0.13t/H$	0.50	$0.33t/H$	0.505

Mechanism	Condition	Uniform distribution	Triangular distribution	Eq.
K1x top hinge	$\frac{D}{H} \geq n_r$	$M_{0,top} = \frac{3D\ N_{top}\ t}{6D - 2n_r\ H}$	$M_{0,top} = \frac{D\ N_{top}\ t}{2D - n_r\ H}$	(1)
K1x bottom hinge	$\frac{D}{H} \geq n_r$	$M_{0,bot} = \frac{3D\ t\ \bar{y}N_{top} + W\bar{y}}{6D - 4n_r H}$	$M_{0,bot} = \frac{2D\ t\ \bar{y}N_{top} + W\bar{y}}{4D - 3n_r\ H}$	(2)
K1y bottom hinge	$\frac{D}{H} < n_r$	$M_{0,bot} = \frac{3H^2\ n_r^2\ t\ \bar{y}N_{top} + W\bar{y}}{2D^2}$	$M_{0,bot} = \frac{2H^3\ n_r^3\ t\ \bar{y}N_{top} + W\bar{y}}{5D^3}$	(3)
K2x middle hinge	$\frac{D}{H} \geq \frac{n_r}{2}$	$M_{0,mid} = \frac{3D\ t\ (2N_{top} + W)}{12D - 2n_r\ H}$	$M_{0,mid} = \frac{D\ t\ (2N_{top} + W)}{4D - n_r\ H}$	(4)

III. Seismic performance assessment of existing URM-RC buildings

Case studies

Validation strategy of the seismic assessment methodology

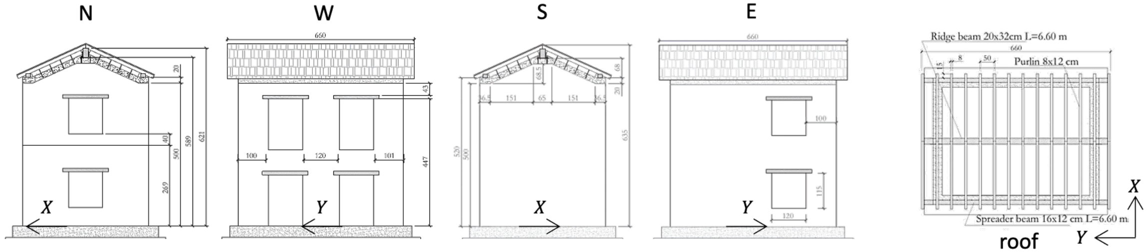
Comparison amongst different types of:

- 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 buildings

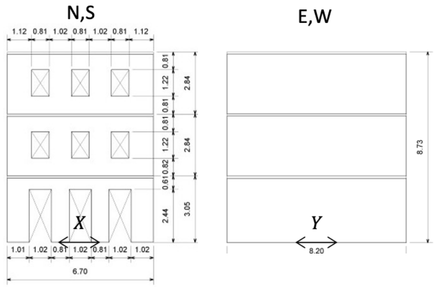
Building 1 (B1)

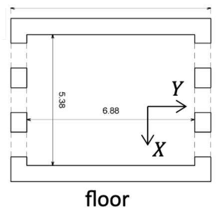
2-storey prototype building (EUCENTRE experimental campaign) (Penna 2015)



Building 2 (B2)

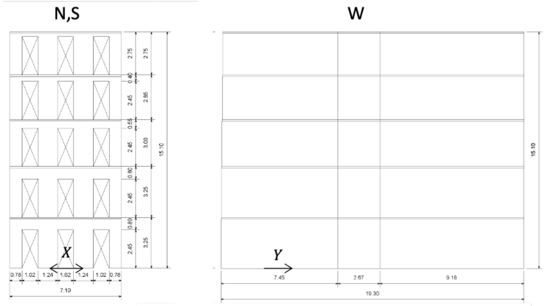
3-storey limestone Portuguese building (Lovon et al. 2021)

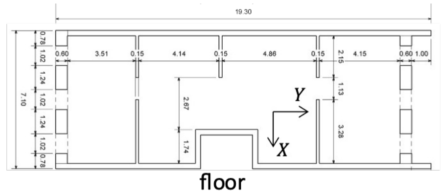




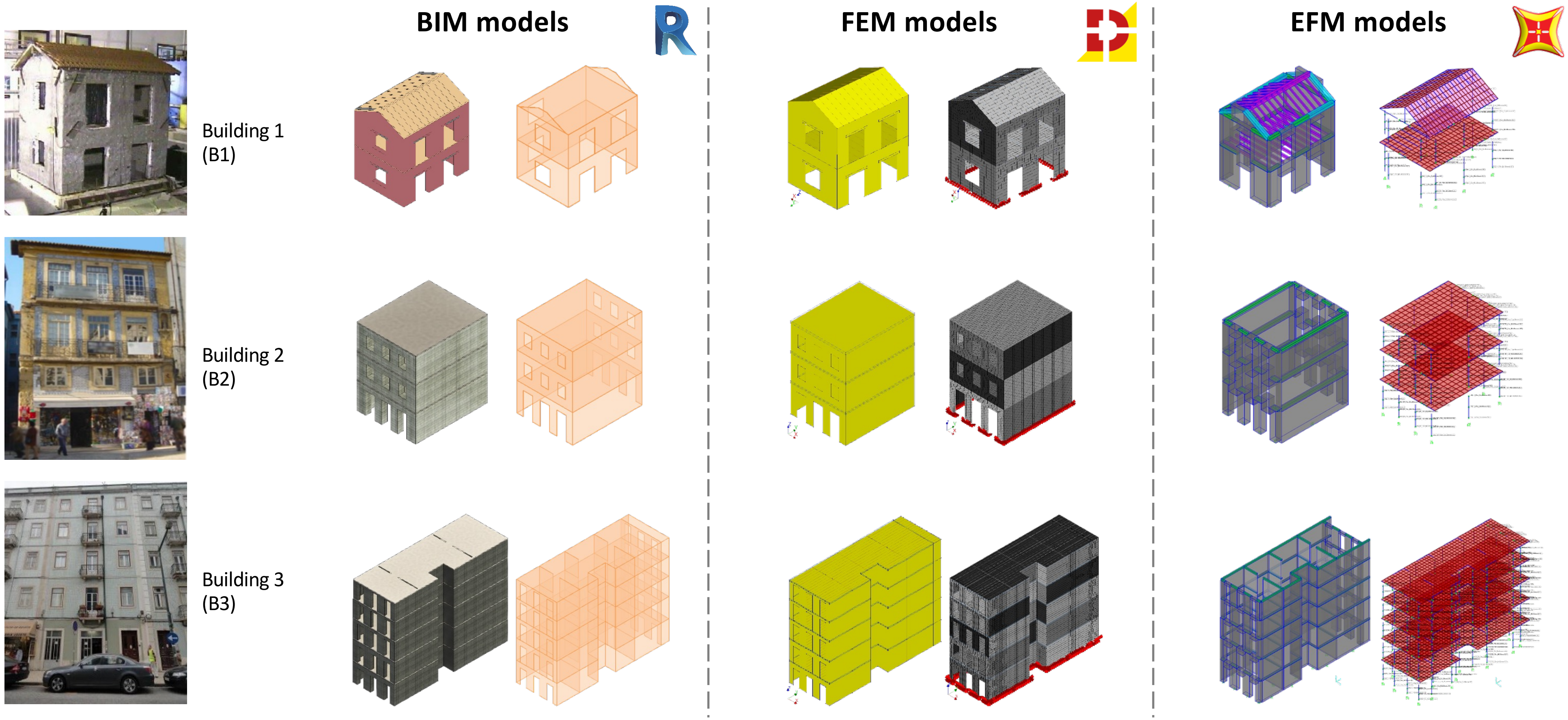
Building 3 (B3)

5-storey Portuguese “Gaioleiro” building (Simões et al. 2013)

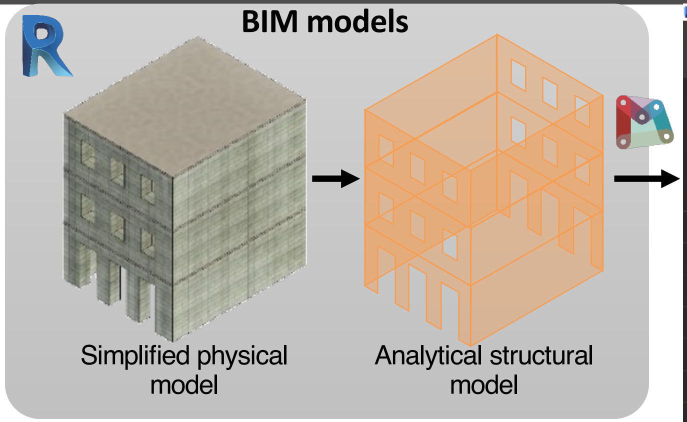


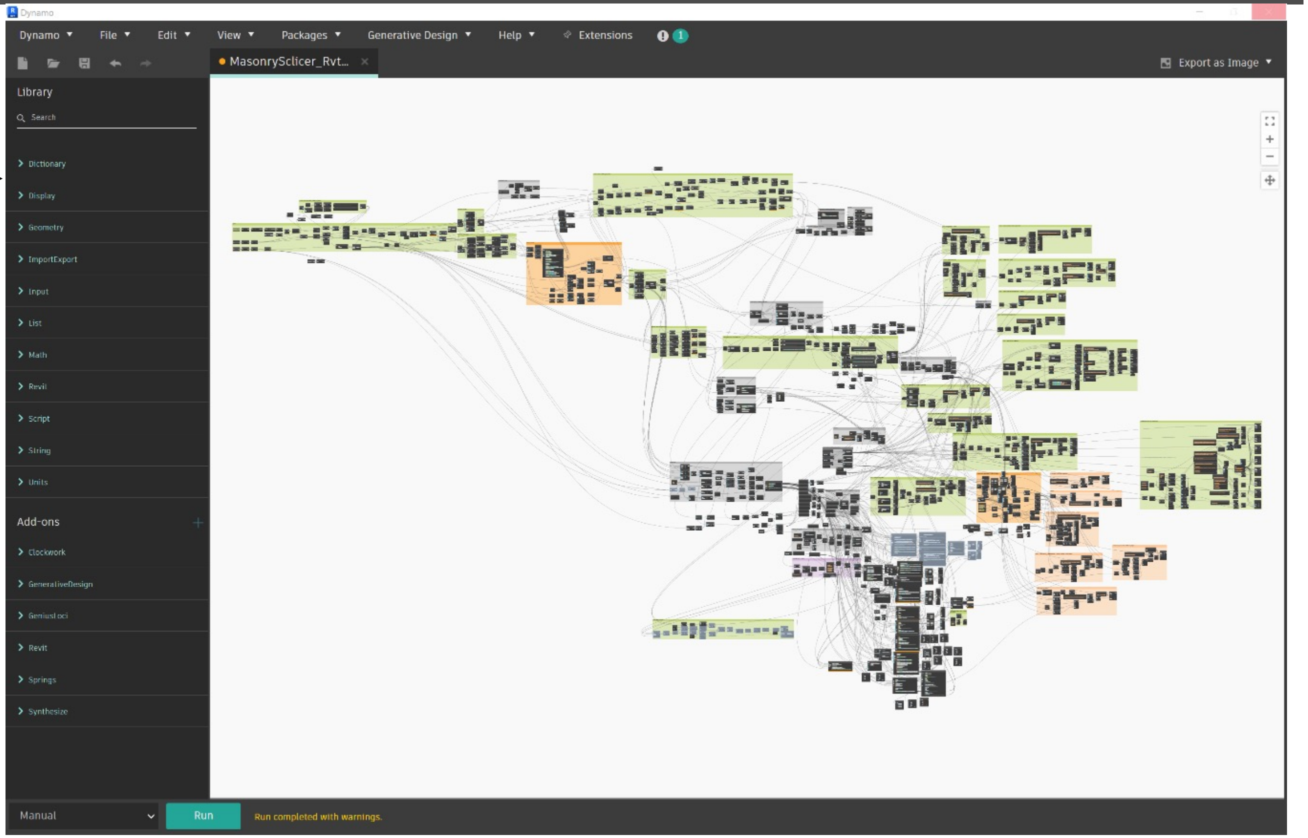


Construction of the numerical models (FEM and EFM)

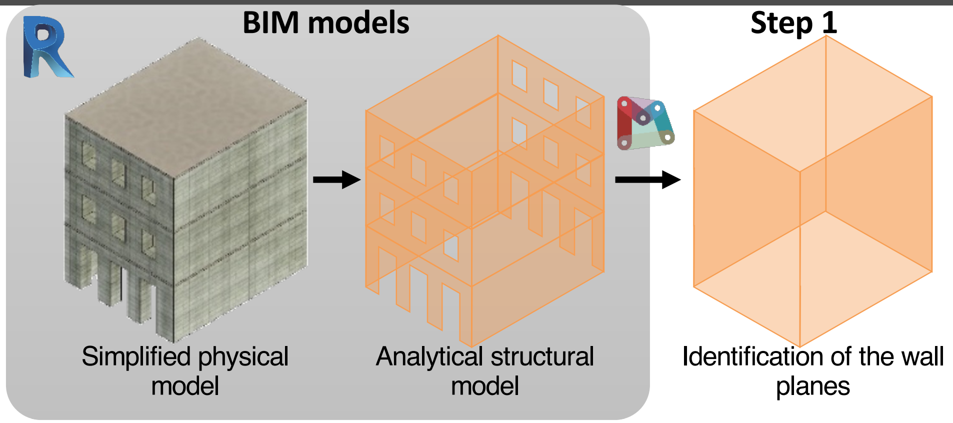


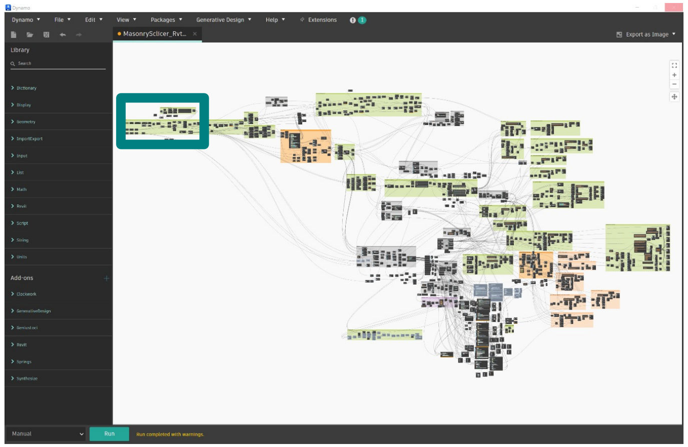
Workflow for the definition of the EFM (VPL script)



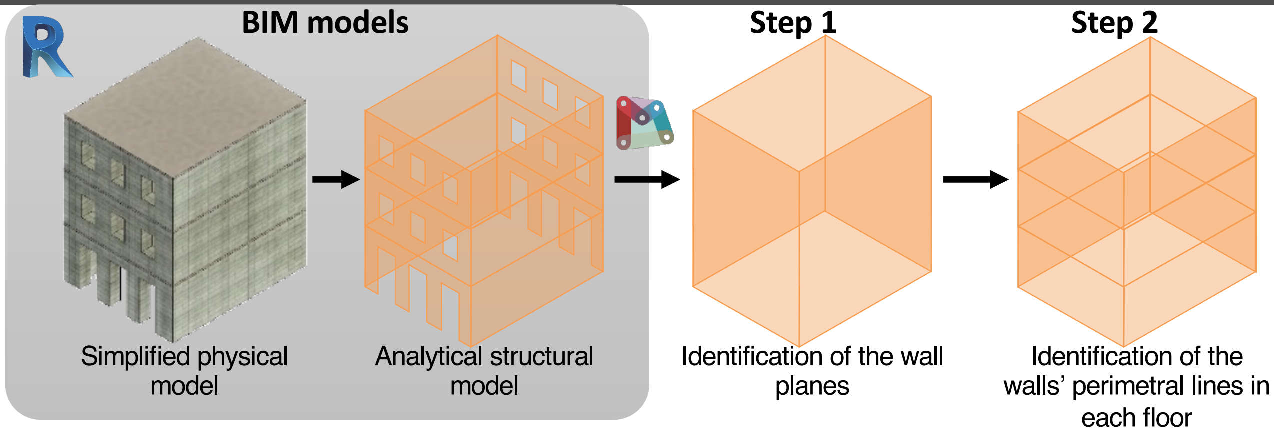


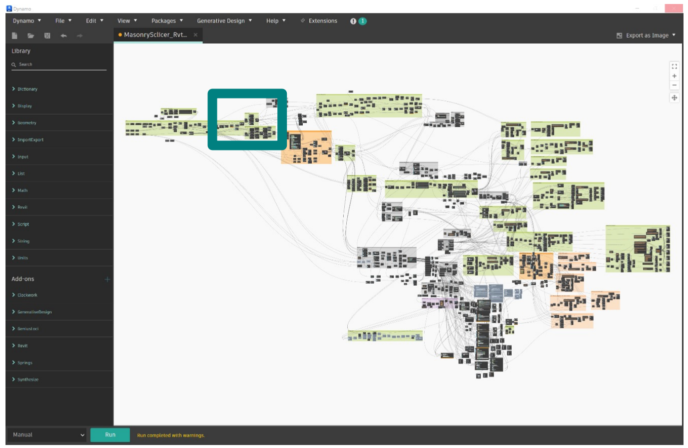
Workflow for the definition of the EFM (VPL script)



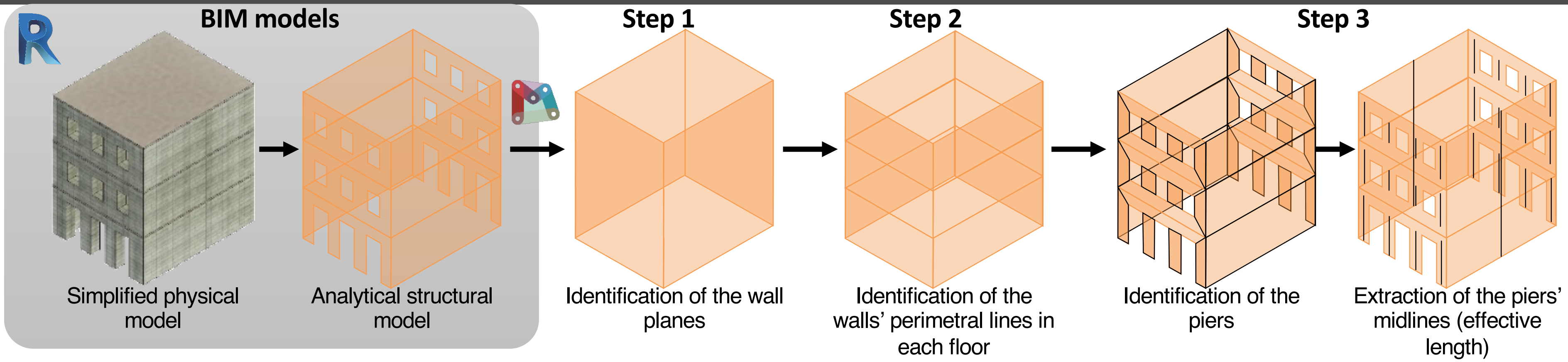


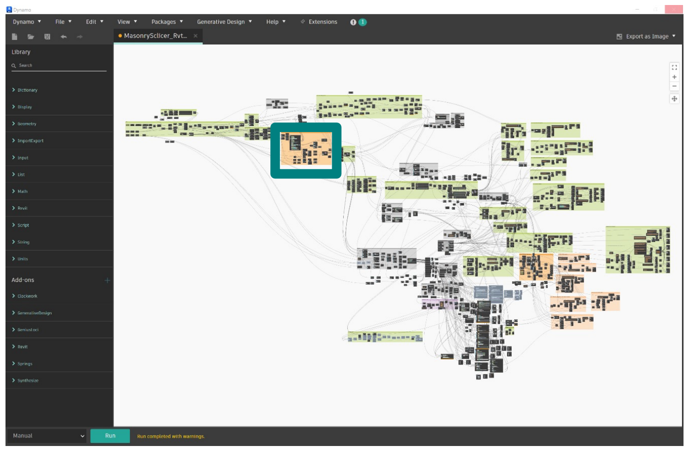
Workflow for the definition of the EFM (VPL script)



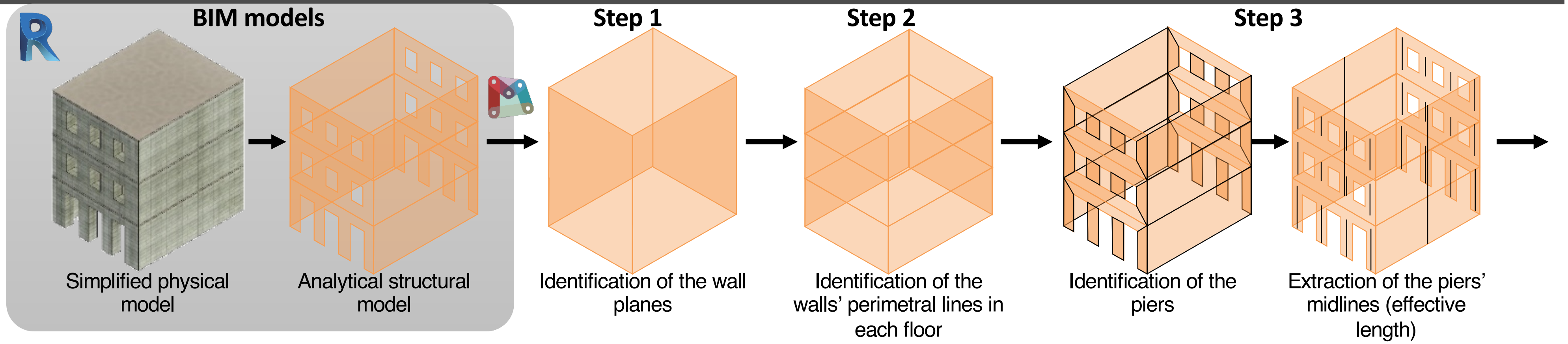


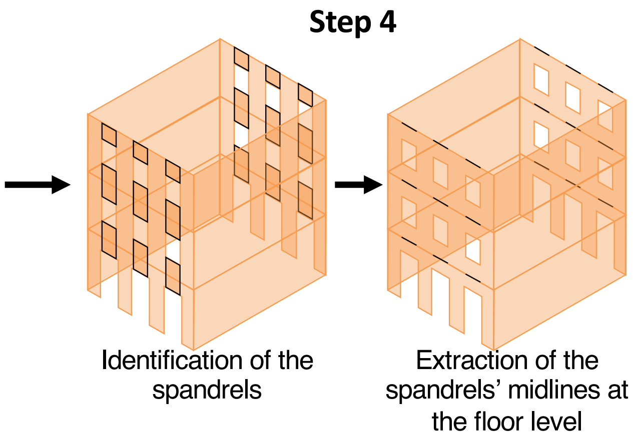
Workflow for the definition of the EFM (VPL script)

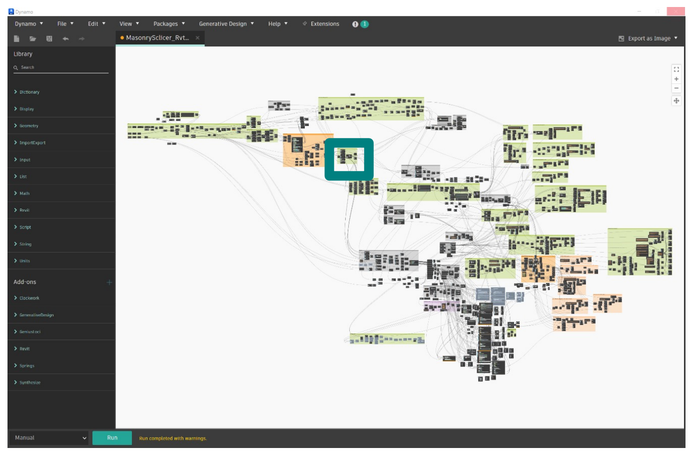




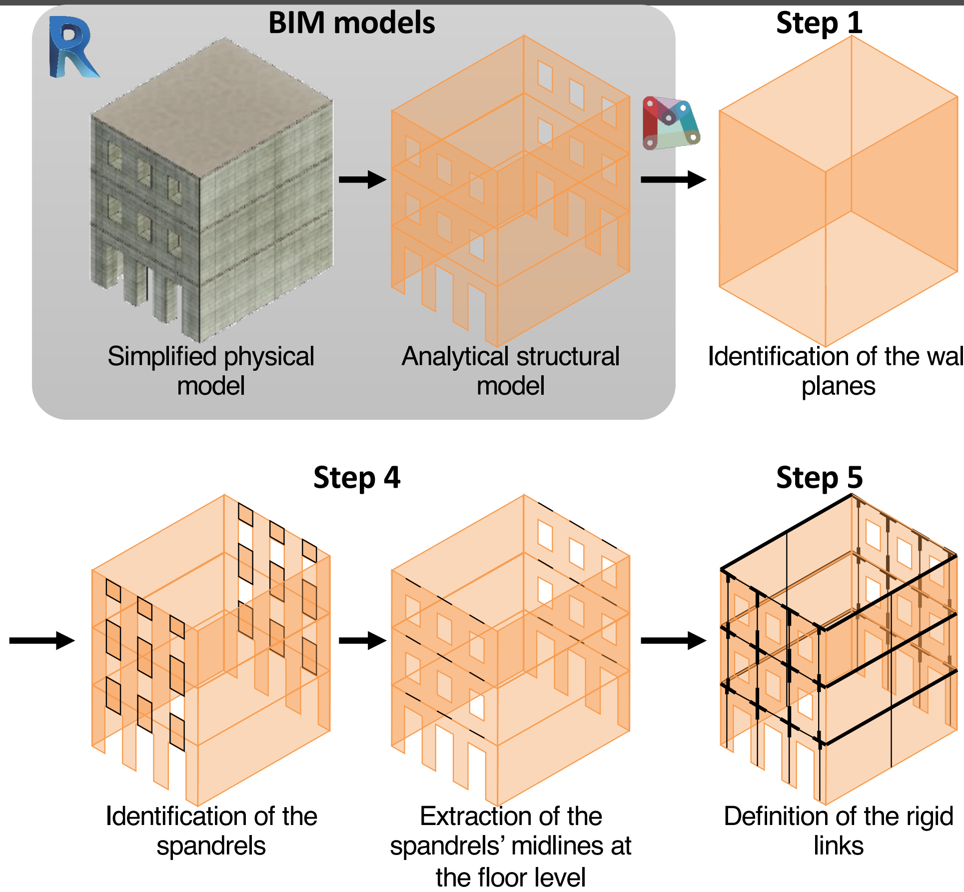
Workflow for the definition of the EFM (VPL script)

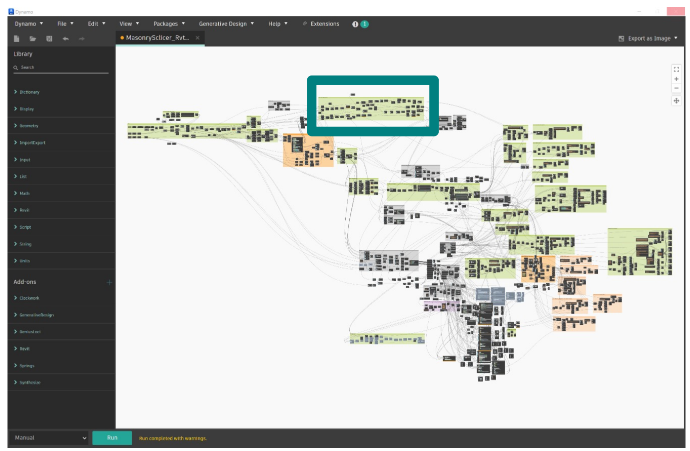




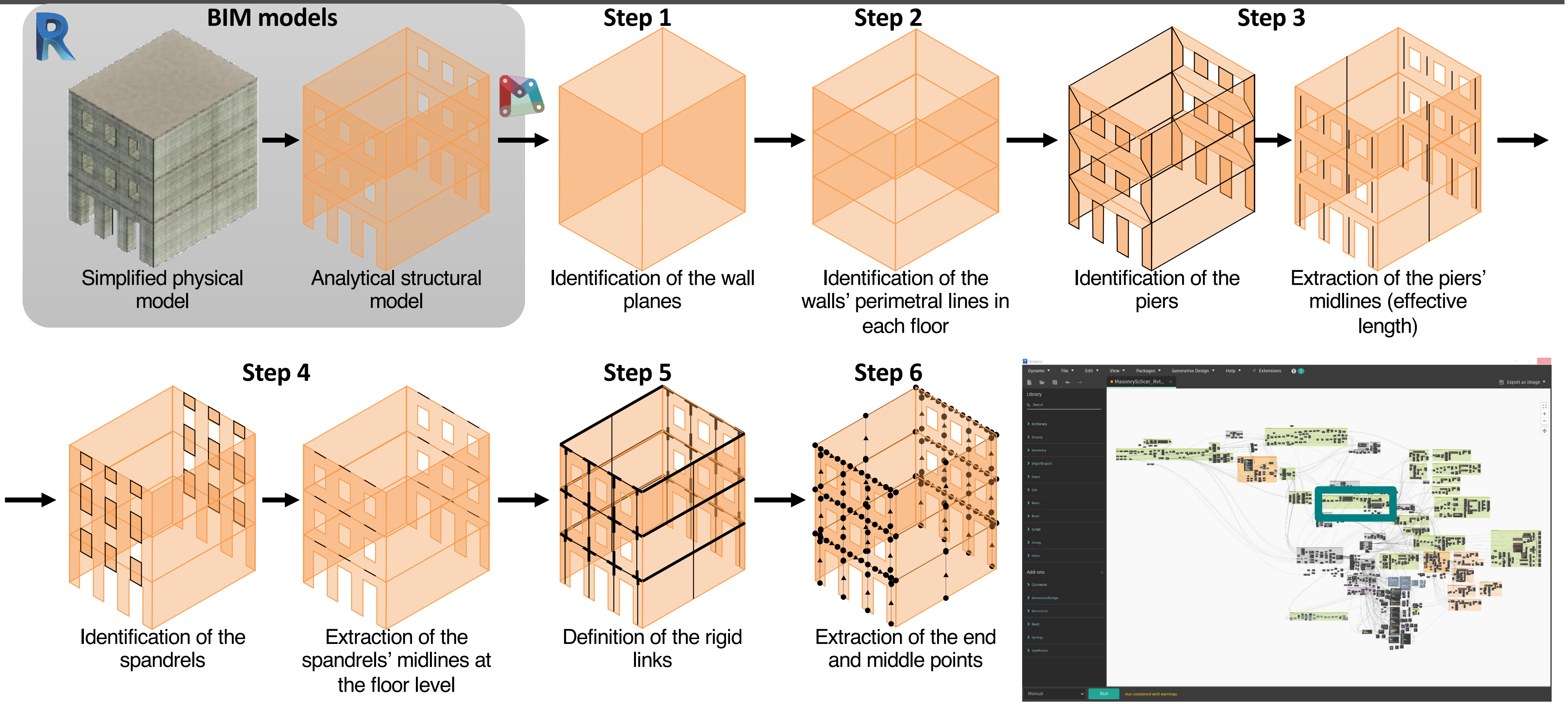


Workflow for the definition of the EFM (VPL script)

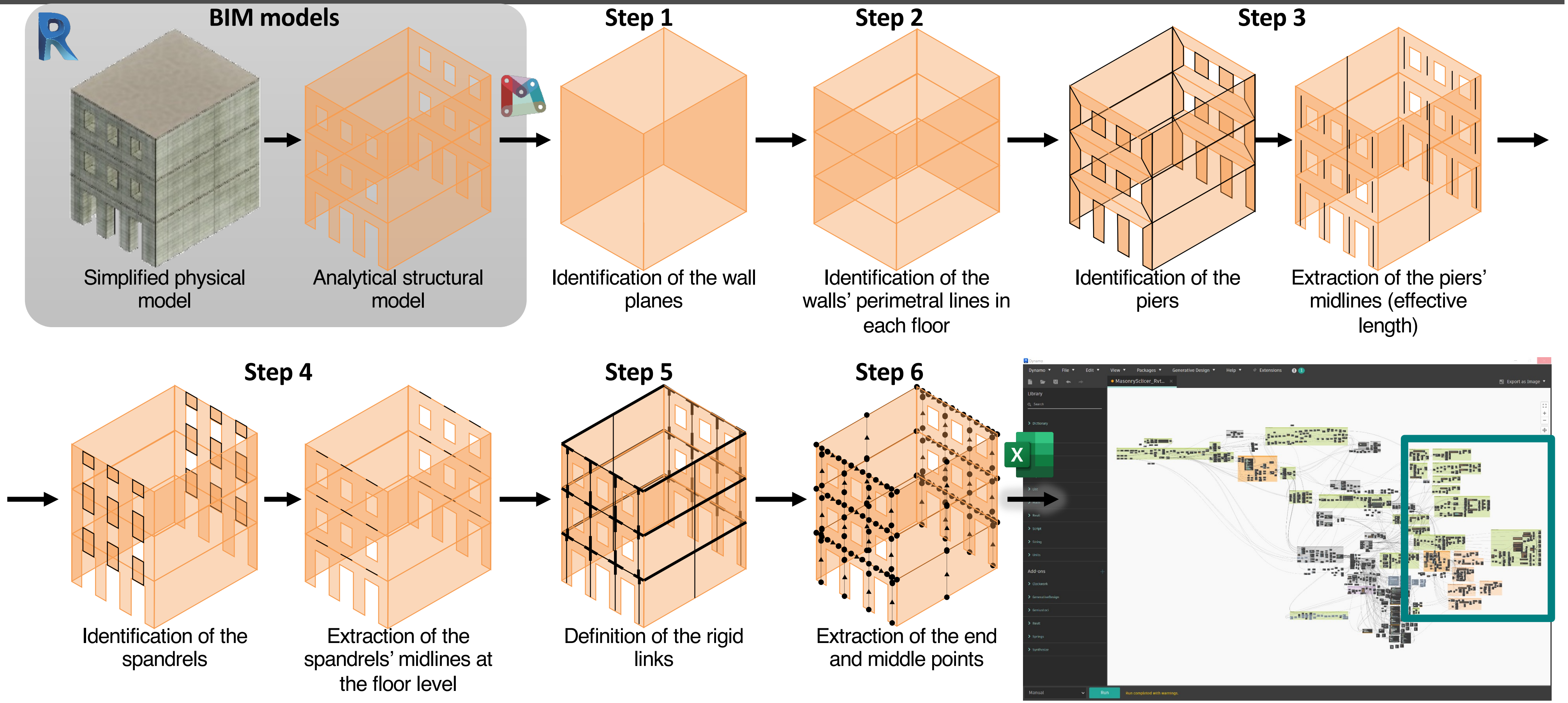




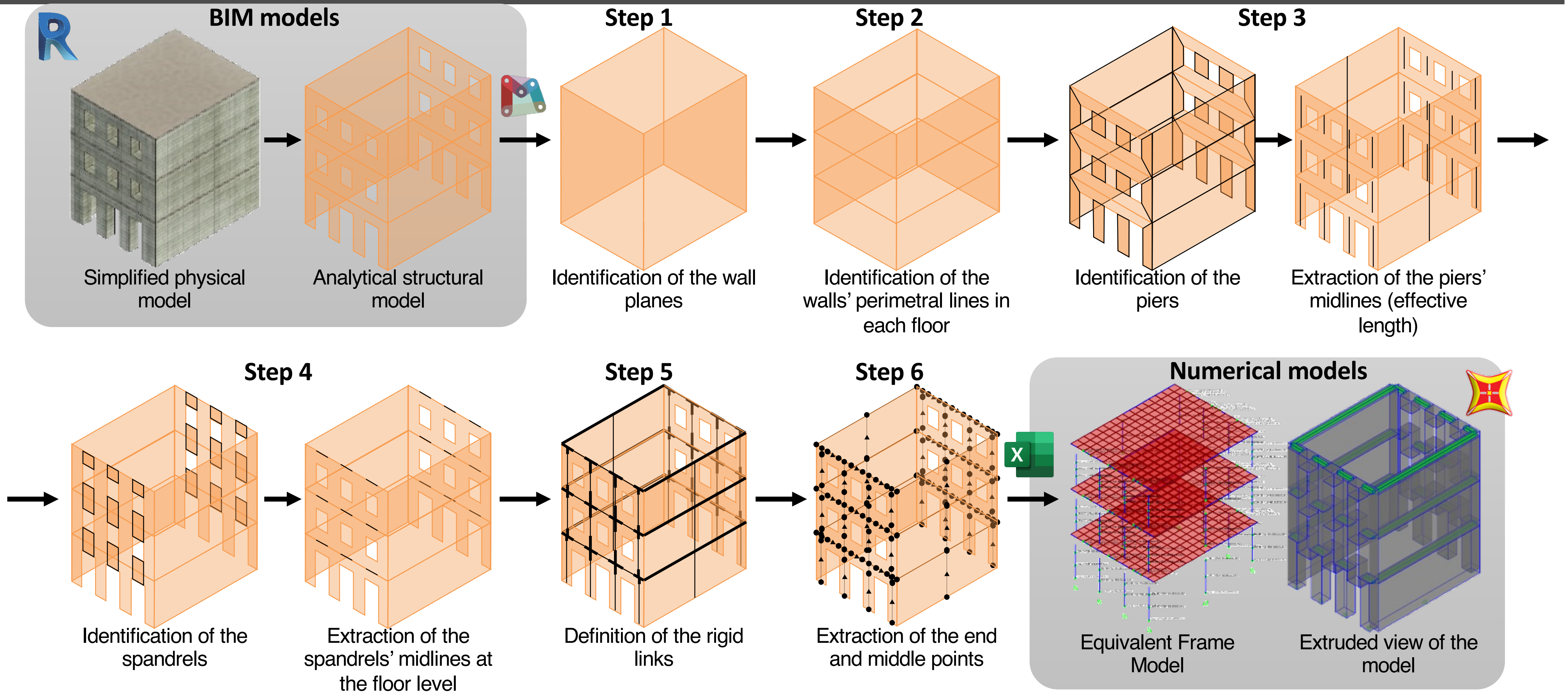
Workflow for the definition of the EFM (VPL script)



Workflow for the definition of the EFM (VPL script)



Workflow for the definition of the EFM (VPL script)



Workflow for the definition of the EFM (VPL script)

Excel I: Model definition

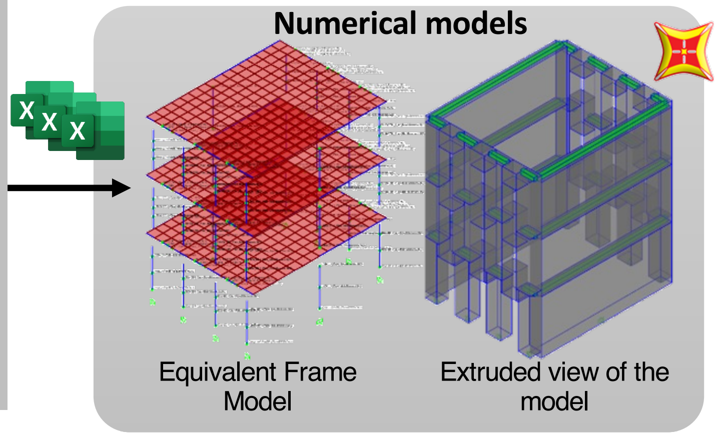
- Joint Coordinates
- Connectivity – Frame
- Frame Section Assignments
- Frame Props 01 - General
- Joint Restraint Assignments
- Connectivity – Area
- Frame Local Axes 1 – Typical
- Frame Offset (Length) Assigns
- Frame Insertion Point Assigns
- MatProp 01 - General
- MatProp 02 - Basic Mech Props
- 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

Excel II: Static forces

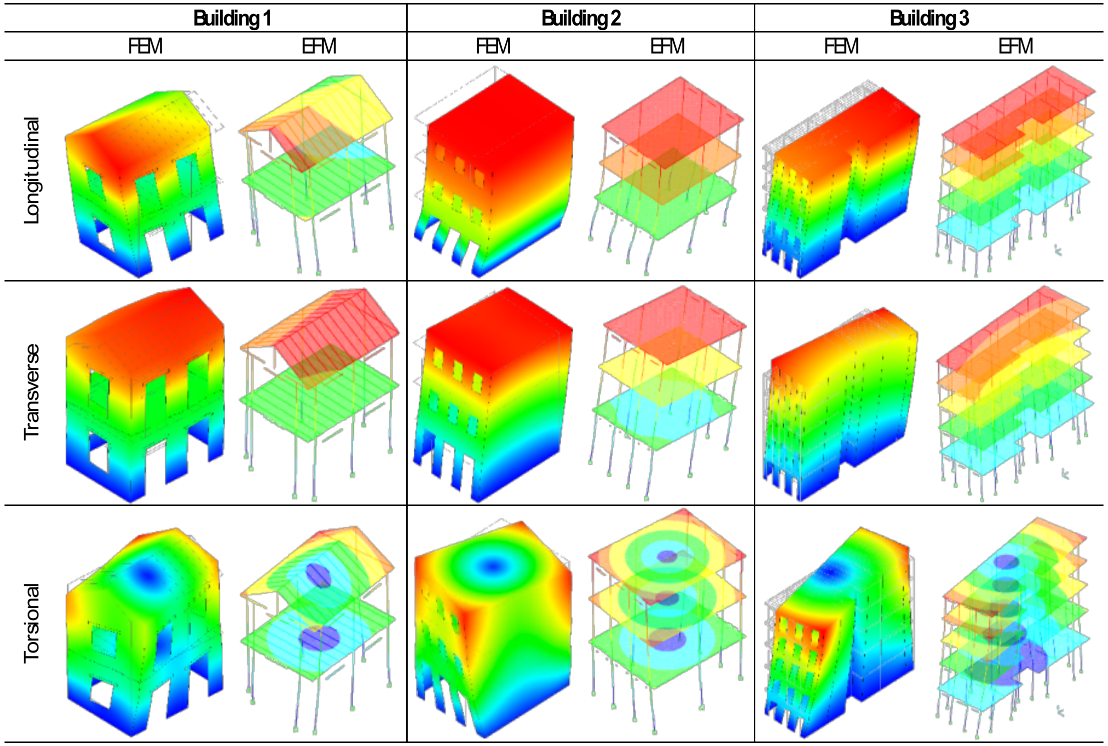
- Base Reactions
- Element Forces – Frames
- Program Control

Excel 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

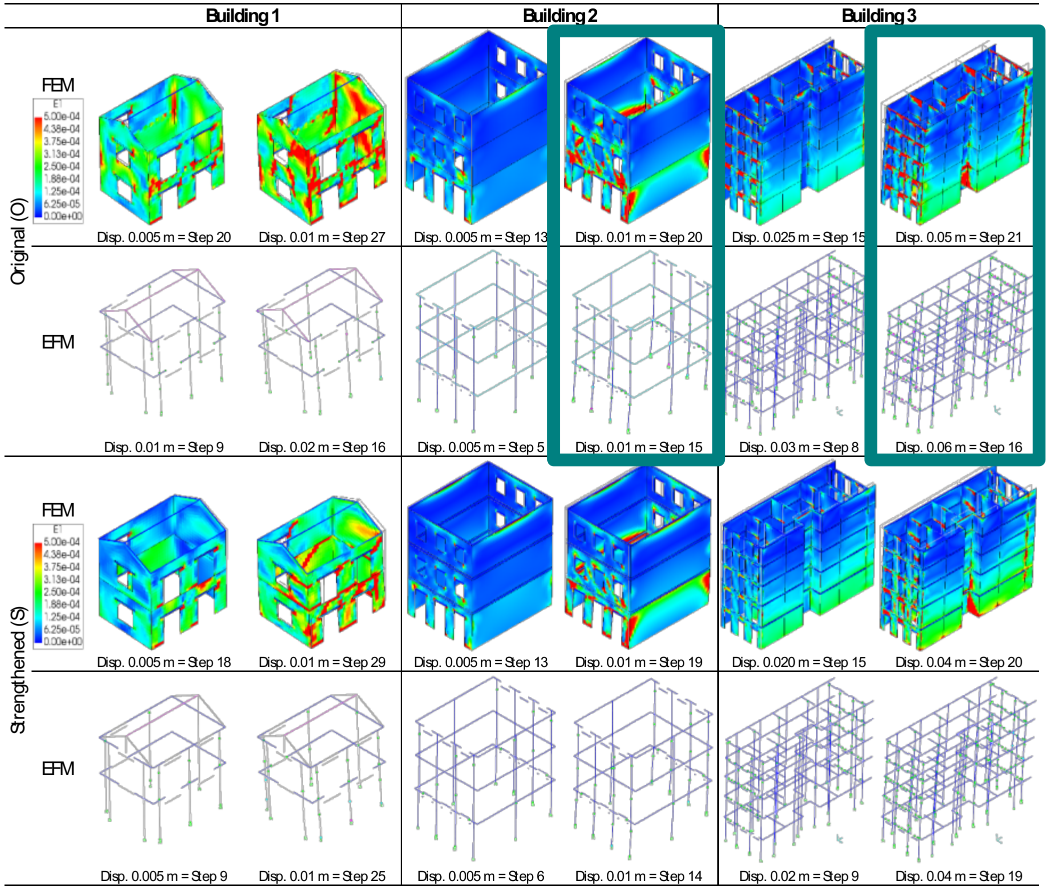


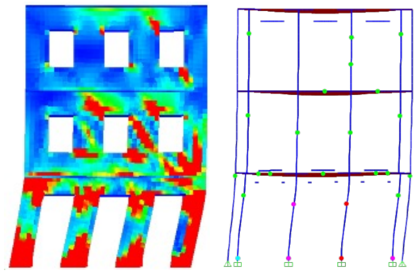
Eigenmode analysis – fundamental modes of vibration and frequencies

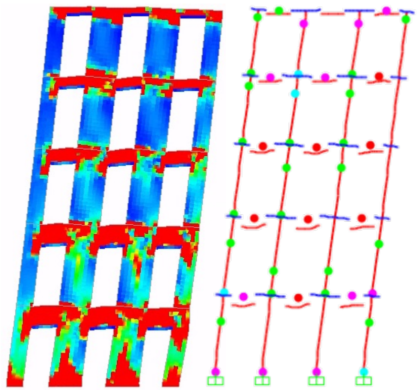


	Mode type	FEM (DIANA) Mode No.	FEM (DIANA) Freq. [Hz]	EFM (SAP2000) Mode No.	EFM (SAP2000) Freq. [Hz]	Modal participating ratios UX	UY	UZ	(1- FEM/EFM) Δf (%)
	Longitudinal (Y)	**1**	**5.55**	**1**	**5.05**	0.25	**0.57**	0.00	**-9.9%**
O	Transverse (X)	2	6.03	2	5.28	0.61	0.30	0.00	-14.2%
	Torsional	3	8.56	3	7.84	0.05	0.04	0.00	-9.2%
B1	**Longitudinal (Y)**	**1**	**5.76**	**2**	**5.32**	0.30	**0.62**	0.00	**-8.3%**
S	Transverse (X)	2	5.88	1	5.08	0.57	0.27	0.00	-15.7%
	Torsional	3	9.21	3	7.71	0.04	0.03	0.00	-19.5%
	Longitudinal (X)	**16**	**3.04**	**10**	**2.73**	**0.97**	0.00	0.00	**-11.4%**
O	Transverse (Y)	-	-	-	-	-	-	-	-
	Torsional	-	-	-	-	-	-	-	-
B2	**Longitudinal (X)**	**1**	**2.953**	**1**	**3.10**	**0.94**	0.00	0.00	**4.7%**
S	Transverse (Y)	2	6.100	2	5.85	0.00	0.84	0.00	-4.3%
	Torsional	3	7.459	3	7.04	0.00	0.00	0.00	-6.0%
	Longitudinal (X)	**1**	**1.60**	**1**	**1.67**	**0.78**	0.00	0.00	**4.2%**
O	Transverse (Y)	-	-	-	-				-
	Torsional	2	2.89	2	2.92	0.00	0.02	0.00	1.0%
B3	**Longitudinal (X)**	**1**	**1.76**	**1**	**1.79**	**0.81**	0.00	0.00	**1.5%**
S	Transverse (Y)	3	3.41	3	3.13	0.00	0.79	0.00	-8.8%
	Torsional	2	2.88	2	2.89	0.00	0.05	0.00	-0.3%

Pushover analysis – damage patterns and failure mechanisms





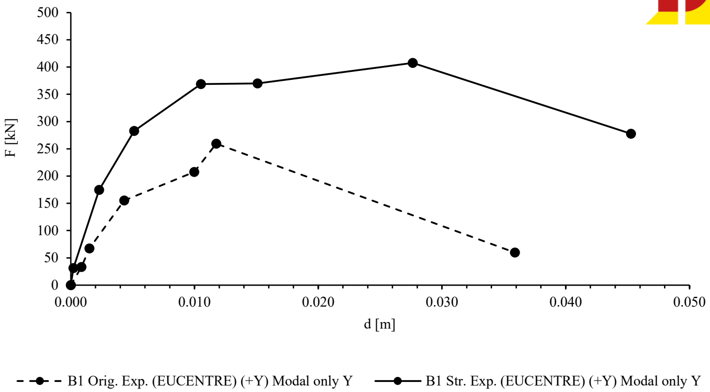


Pushover analysis – validation against experimental results

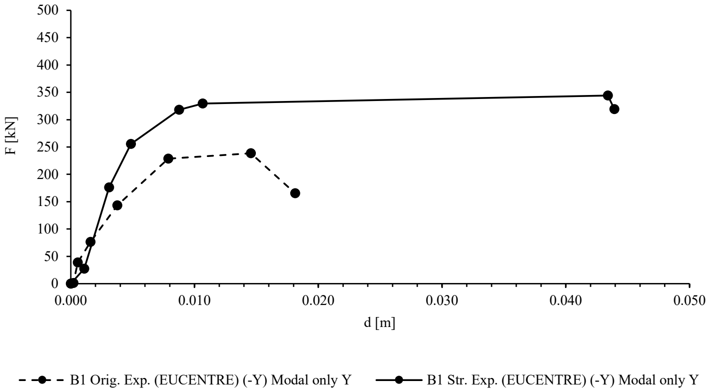
Building 1 (B1)
2-storey prototype building
(EUCENTRE experimental campaign)
(Penna 2015)

FEM (DIANA)

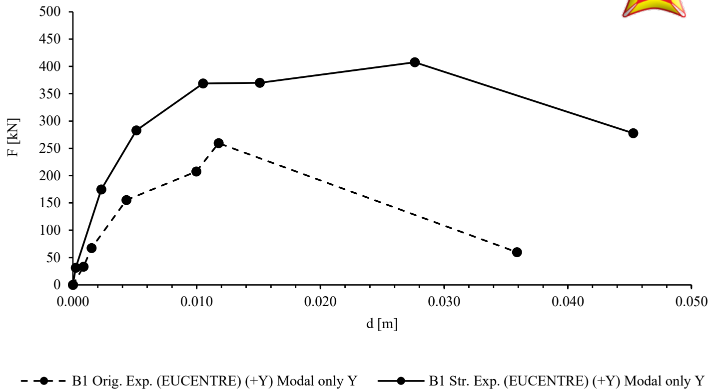
+Y

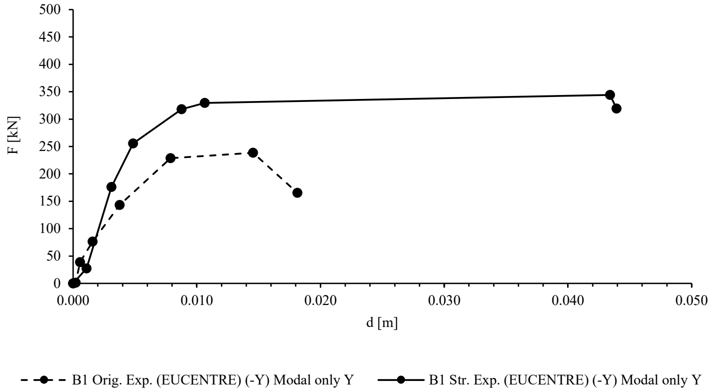


-Y



EFM (SAP2000)





Pushover analysis – validation against experimental results

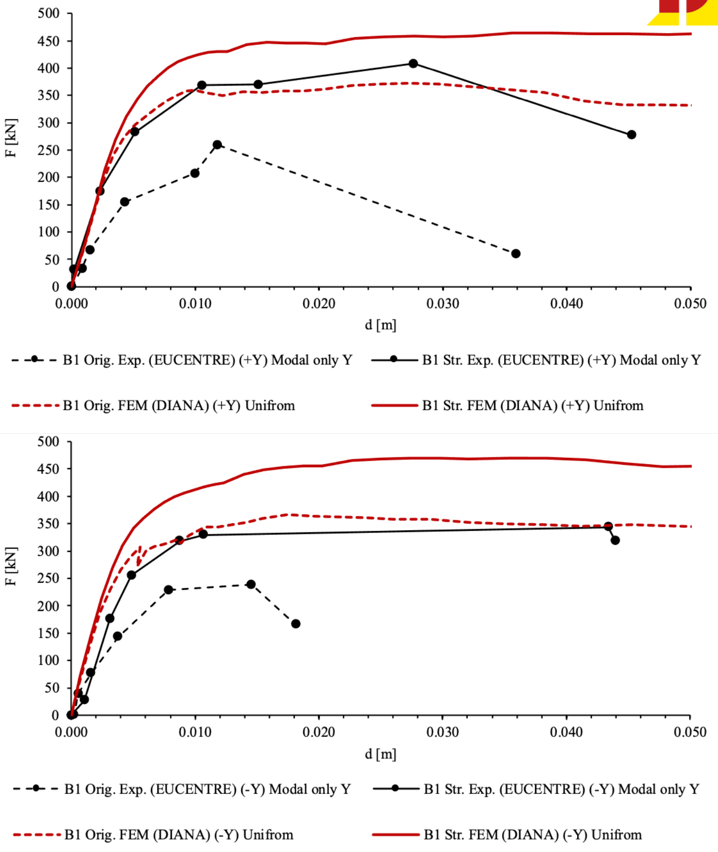
Considered load patterns:

- **Uniform pattern**, with an equivalent acceleration proportional to the mass distribution;
- **Modal pattern in all directions**, proportional to the first fundamental global mode shape, with the greater modal participating ratio in the analysis direction;
- **Modal pattern only in the analysis direction**, which corresponds to the previous load pattern, but neglecting the component of the load in the perpendicular direction of the pushover.

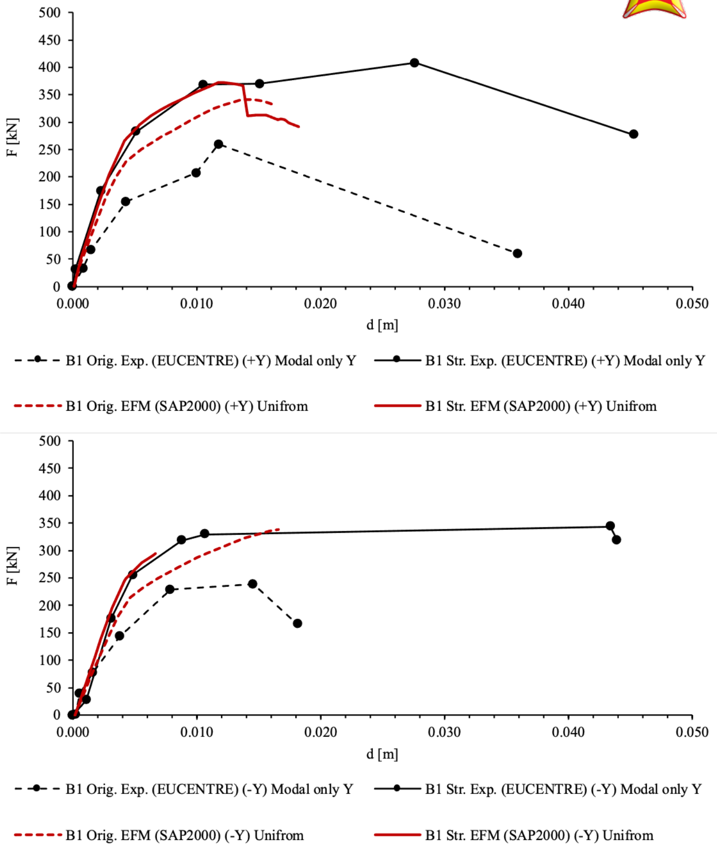
FEM (DIANA)

+Y

-Y



EFM (SAP2000)



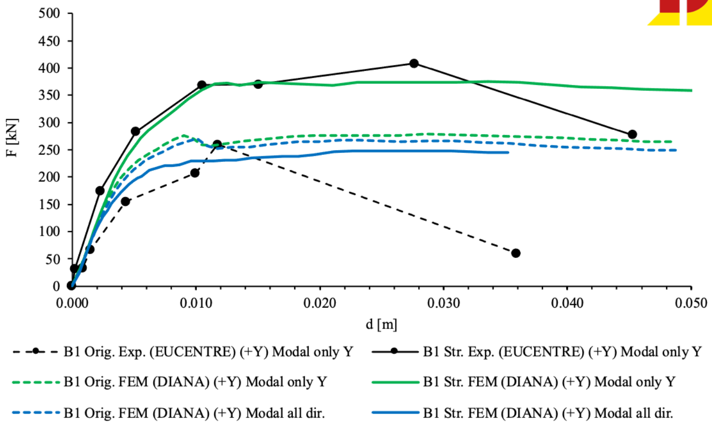
Pushover analysis – validation against experimental results

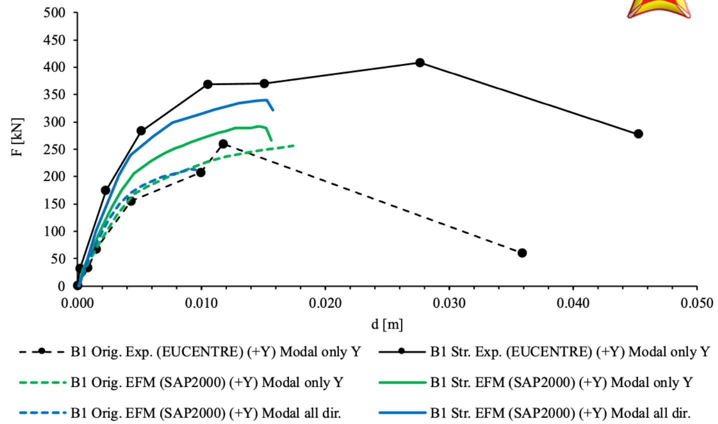
Considered load patterns:

- **Uniform pattern**, with an equivalent acceleration proportional to the mass distribution;
- **Modal pattern in all directions**, proportional to the first fundamental global mode shape, with the greater modal participating ratio in the analysis direction;
- **Modal pattern only in the analysis direction**, which corresponds to the previous load pattern, but neglecting the component of the load in the perpendicular direction of the pushover.

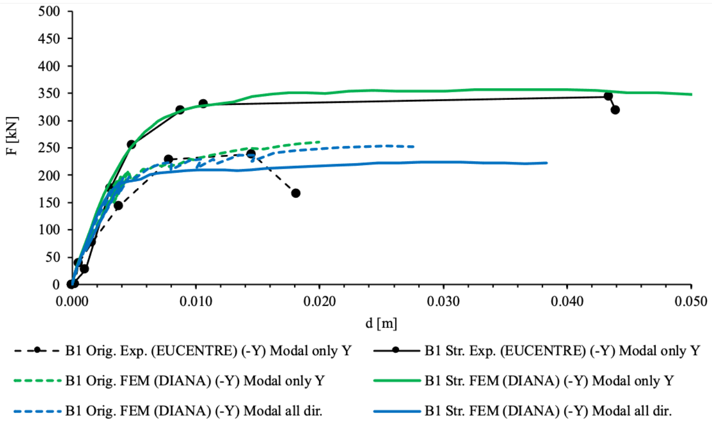
FEM (DIANA) | **EFM (SAP2000)**

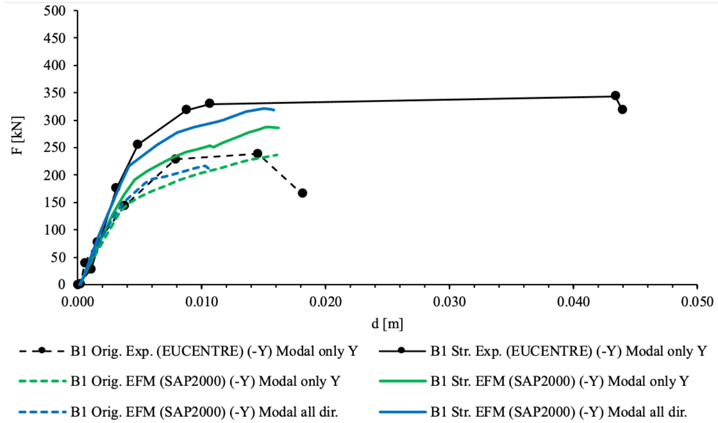
+Y





-Y





Pushover analysis – comparison FEM vs EFM

Original configuration | **Strengthened configuration**

Building 2

Building 3

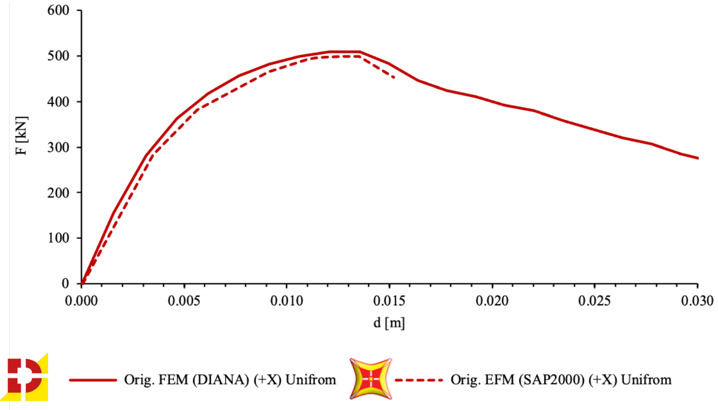
Pushover analysis – comparison FEM vs EFM

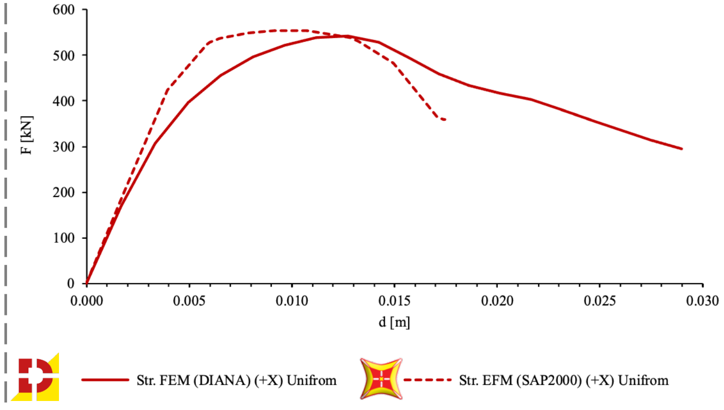
Considered load patterns:

- **Uniform pattern**, with an equivalent acceleration proportional to the mass distribution;
- **Modal pattern in all directions**, proportional to the first fundamental global mode shape, with the greater modal participating ratio in the analysis direction;
- **Modal pattern only in the analysis direction**, which corresponds to the previous load pattern, but neglecting the component of the load in the perpendicular direction of the pushover.

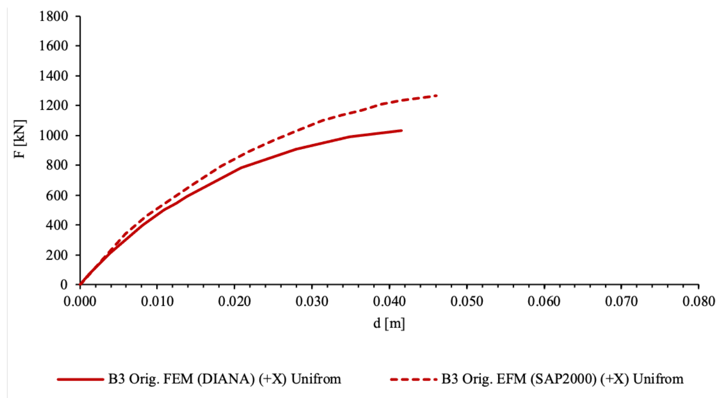
Original configuration | **Strengthened configuration**

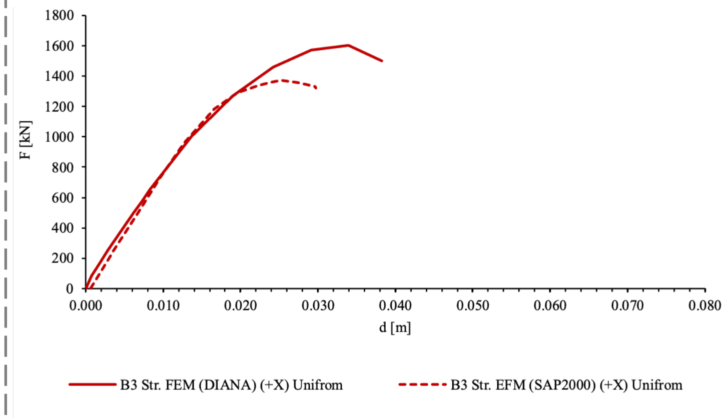
B2





B3





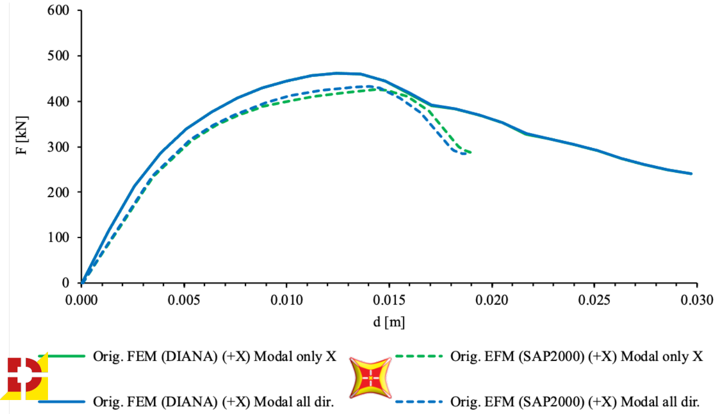
Pushover analysis – comparison FEM vs EFM

Considered load patterns:

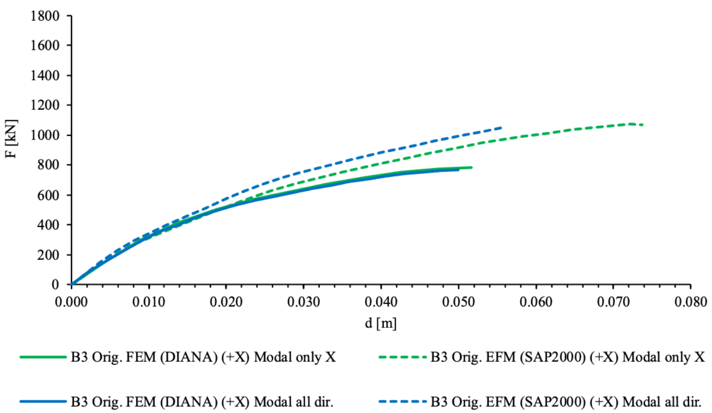
- **Uniform pattern**, with an equivalent acceleration proportional to the mass distribution;
- **Modal pattern in all directions**, proportional to the first fundamental global mode shape, with the greater modal participating ratio in the analysis direction;
- **Modal pattern only in the analysis direction**, which corresponds to the previous load pattern, but neglecting the component of the load in the perpendicular direction of the pushover.

Original configuration

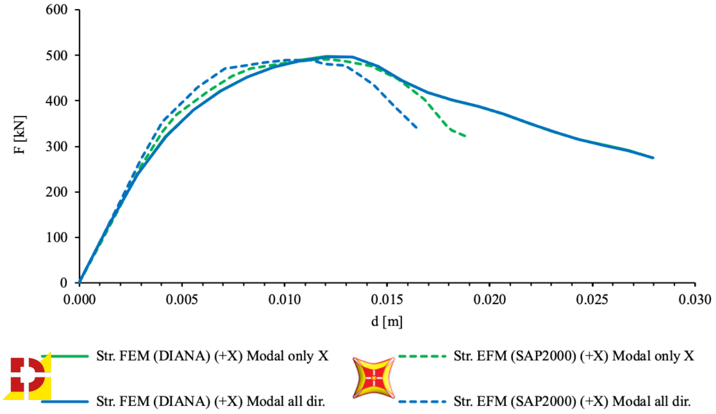
B2

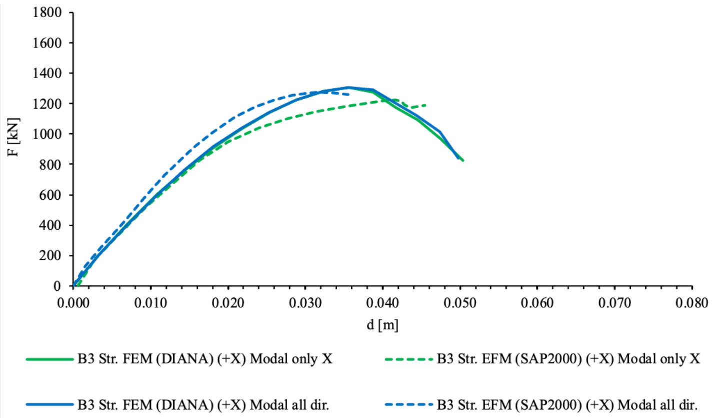


B3



Strengthened configuration





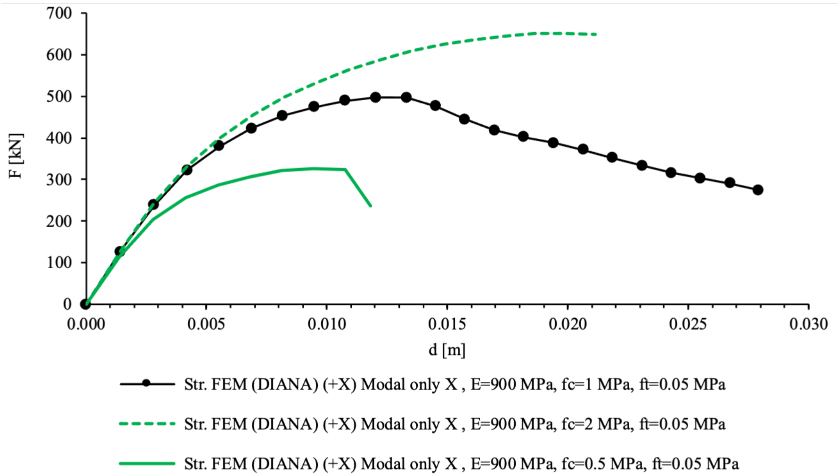
Parametric study of the seismic performance of URM-RC structures

A. Influence of linear material properties
B. Influence of the ultimate flexural drift limit
C. Influence of the out-of-plane resistance
D. Influence of the strengthening intervention

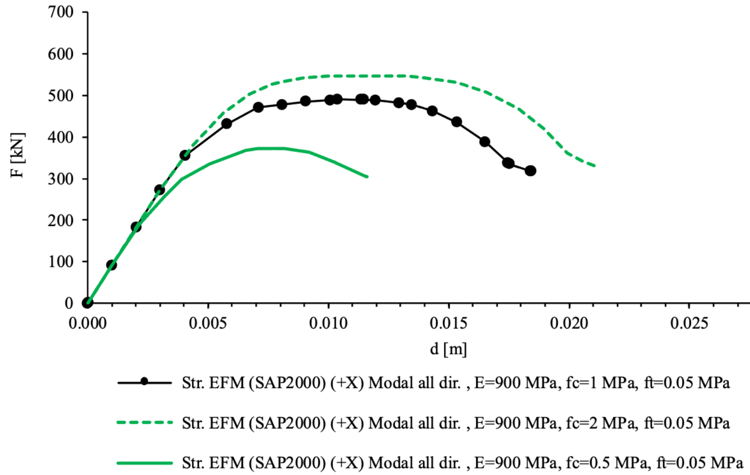
A. Influence of linear material properties

Considered cases:

- $\boldsymbol{f} = 0.5,\ \mathbf{1.0}$ and 2.0 MPa (with compressive fracture energy $G_{f_c} = f \times 1.6$ mm for the FEM);
- $\boldsymbol{f_t} = 0.025,\ 0.05$ and 0.1 MPa (with tensile fracture energy $G_{f_t} = f_t \times 0.001$ for the FEM);
- $\boldsymbol{E} = 800,\ 900$ and 1000 MPa.



FEM (DIANA)

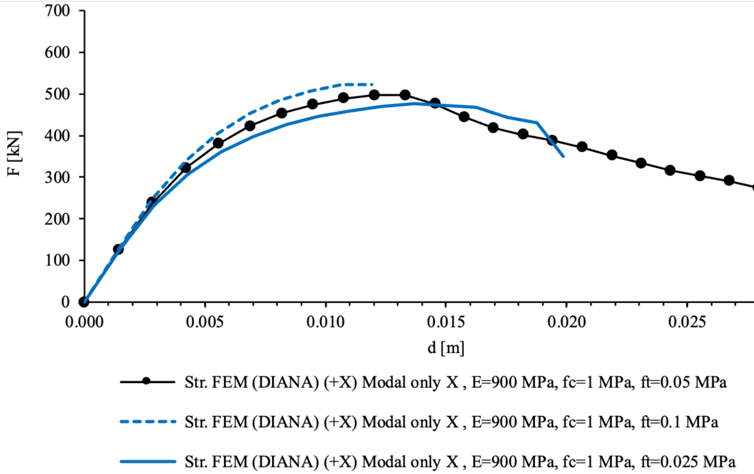


EFM (SAP2000)

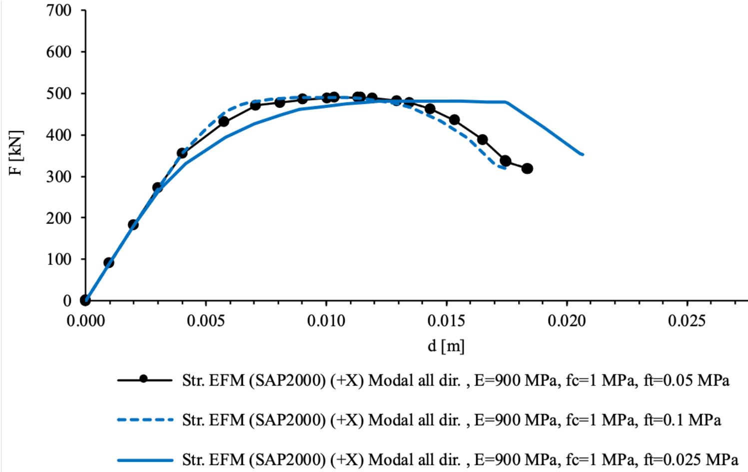
A. Influence of linear material properties

Considered cases:

- f = 0.5, 1.0 and 2.0 MPa (with compressive fracture energy $G_{f_c} = f \times 1.6$ mm for the FEM);
- f_t = 0.025, $\mathbf{0.05}$ and 0.1 MPa (with tensile fracture energy $G_{f_t} = f_t \times 0.001$ for the FEM);
- E = 800, 900 and 1000 MPa.



FEM (DIANA)

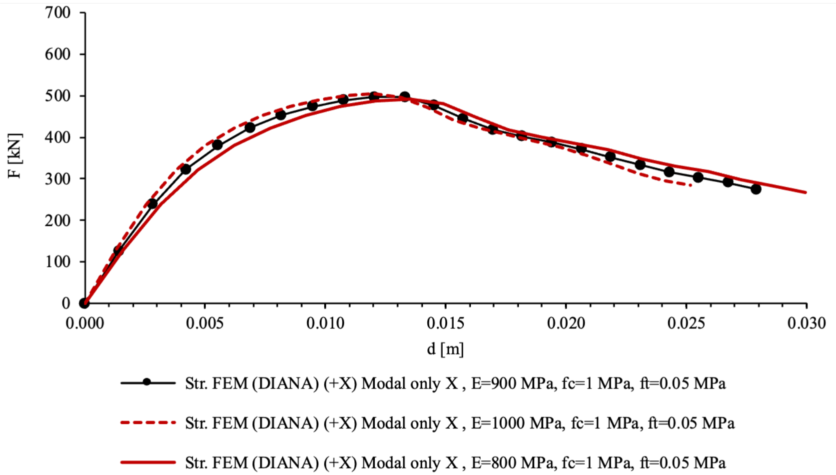


EFM (SAP2000)

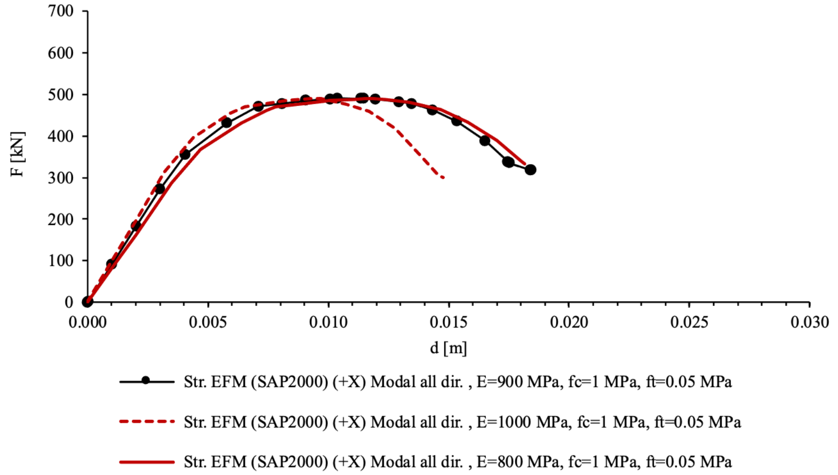
A. Influence of linear material properties

Considered cases:

- $f = 0.5$, 1.0 and 2.0 MPa (with compressive fracture energy $G_{f_c} = f \times 1.6$ mm for the FEM);
- $f_t = 0.025$, 0.05 and 0.1 MPa (with tensile fracture energy $G_{f_t} = f_t \times 0.001$ for the FEM);
- $\boldsymbol{E} = 800$, $\mathbf{900}$ and 1000 MPa.



FEM (DIANA)

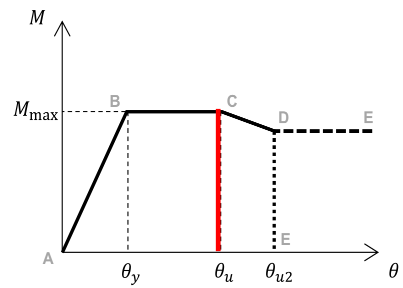


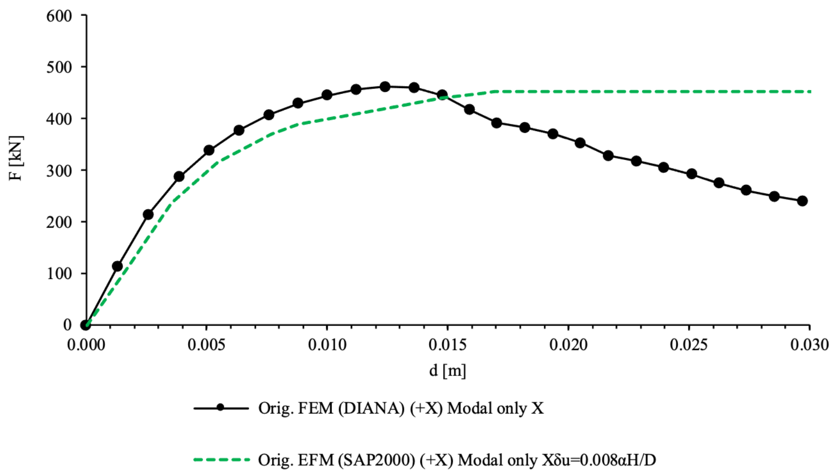
EFM (SAP2000)

B. Influence of the ultimate flexural drift limit

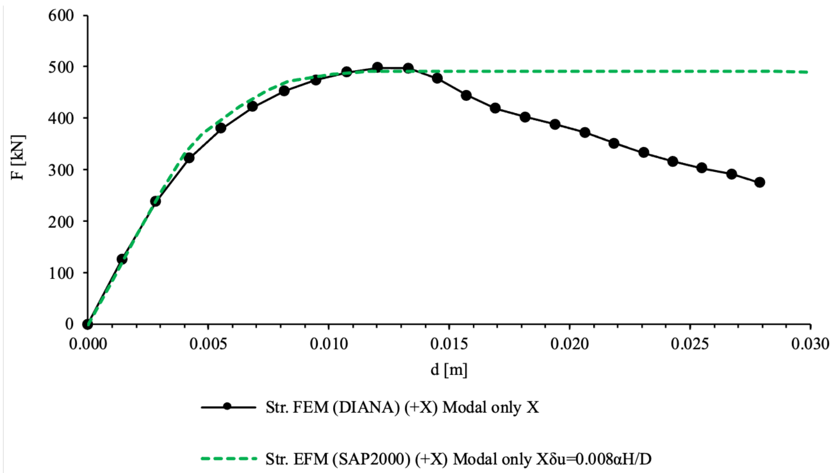
Considered cases:

- **According to the actual version of EC8-3 (CEN 2005):** $\boldsymbol{\theta_u = 0.008\alpha H/D;}$
- According to the expected future version of EC8-3 (CEN 2022): $\theta_u = 0.01(1 - \sigma_0/f);$
- According to the "Modified SIA-model" (Salmanpour et al. 2015): $\theta_u = 0.008\alpha(1 - \sigma_0/f);$
- According to the Italian code (NTC 2008): $\theta_u = 0.006;$
- Proposed calibrated value (based on the "Modified SIA-model"): $\theta_u = 0.011\alpha(1 - \sigma_0/f).$





Original configuration

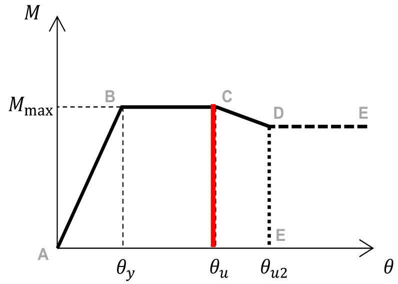


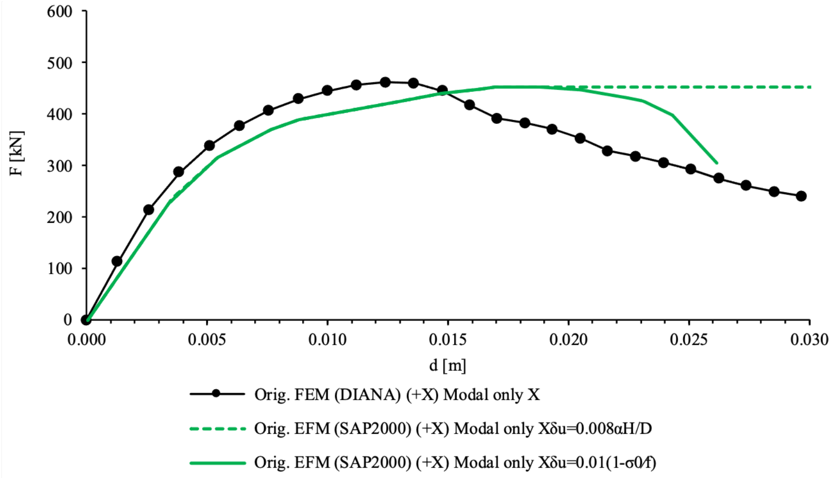
Strengthened configuration

B. Influence of the ultimate flexural drift limit

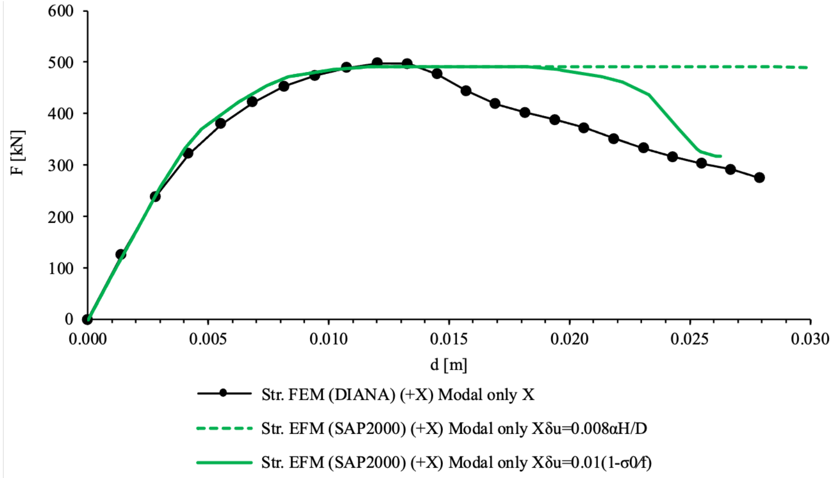
Considered cases:

- According to the actual version of EC8-3 (CEN 2005): $\theta_u = 0.008\alpha H/D;$
- **According to the expected future version of EC8-3 (CEN 2022):** $\boldsymbol{\theta_u = 0.01(1 - \sigma_0/f);}$
- According to the “Modified SIA-model” (Salmanpour et al. 2015): $\theta_u = 0.008\alpha(1 - \sigma_0/f);$
- According to the Italian code (NTC 2008): $\theta_u = 0.006;$
- Proposed calibrated value (based on the “Modified SIA-model”): $\theta_u = 0.011\alpha(1 - \sigma_0/f).$





Original configuration

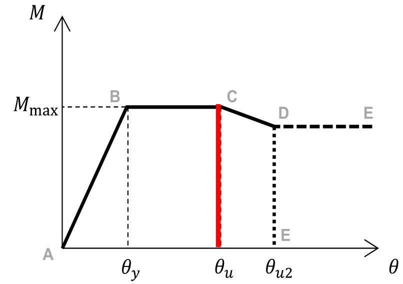


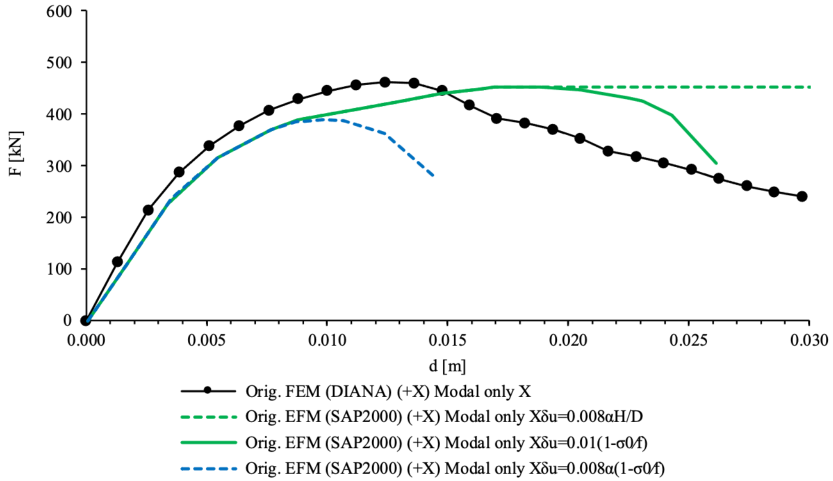
Strengthened configuration

B. Influence of the ultimate flexural drift limit

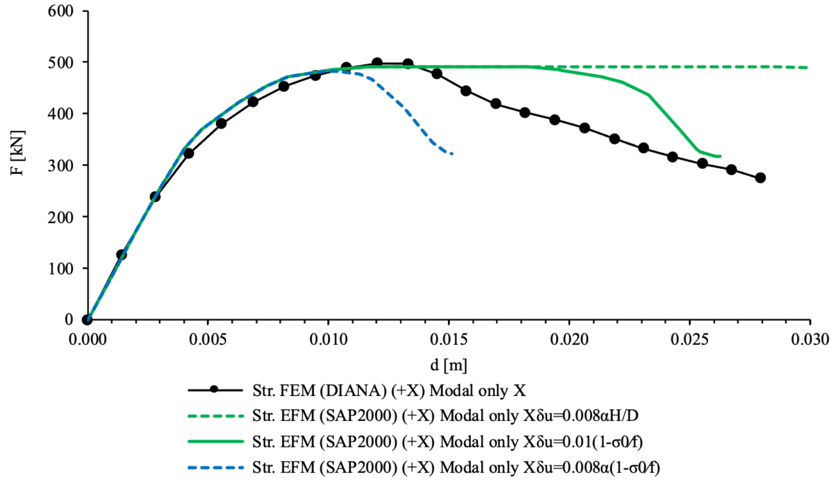
Considered cases:

- According to the actual version of EC8-3 (CEN 2005): $\theta_u = 0.008\alpha H/D;$
- According to the expected future version of EC8-3 (CEN 2022): $\theta_u = 0.01(1-\sigma_0/f);$
- **According to the "Modified SIA-model" (Salmanpour et al. 2015):** $\boldsymbol{\theta_u = 0.008\alpha(1-\sigma_0/f);}$
- According to the Italian code (NTC 2008): $\theta_u = 0.006;$
- Proposed calibrated value (based on the "Modified SIA-model"): $\theta_u = 0.011\alpha(1-\sigma_0/f).$





Original configuration

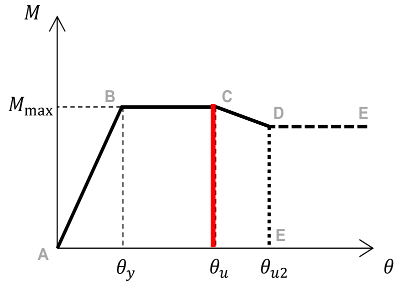


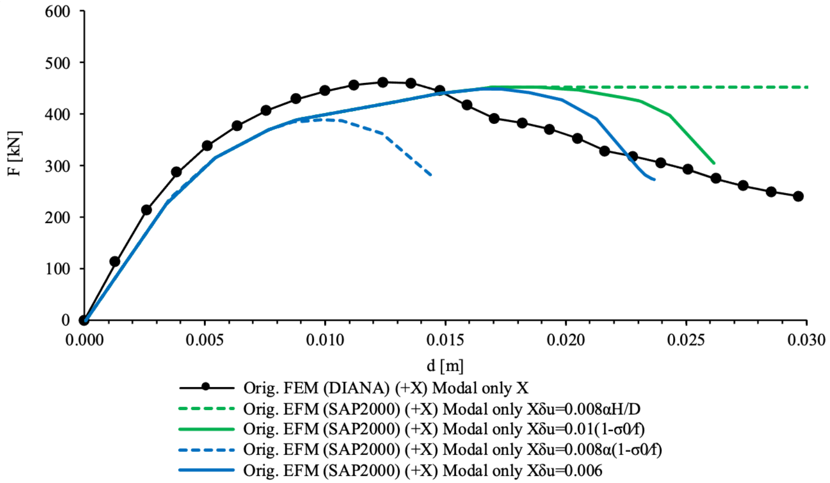
Strengthened configuration

B. Influence of the ultimate flexural drift limit

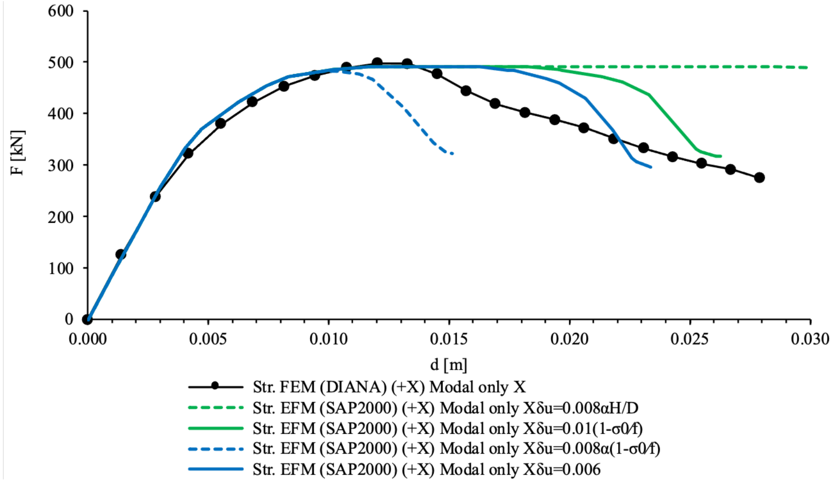
Considered cases:

- According to the actual version of EC8-3 (CEN 2005): $\theta_u = 0.008\alpha H/D;$
- According to the expected future version of EC8-3 (CEN 2022): $\theta_u = 0.01(1-\sigma_0/f);$
- According to the "Modified SIA-model" (Salmanpour et al. 2015): $\theta_u = 0.008\alpha(1-\sigma_0/f);$
- **According to the Italian code (NTC 2008):** $\boldsymbol{\theta_u = 0.006;}$
- Proposed calibrated value (based on the "Modified SIA-model"): $\theta_u = 0.011\alpha(1-\sigma_0/f).$





Original configuration

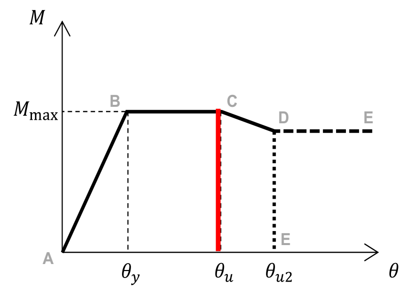


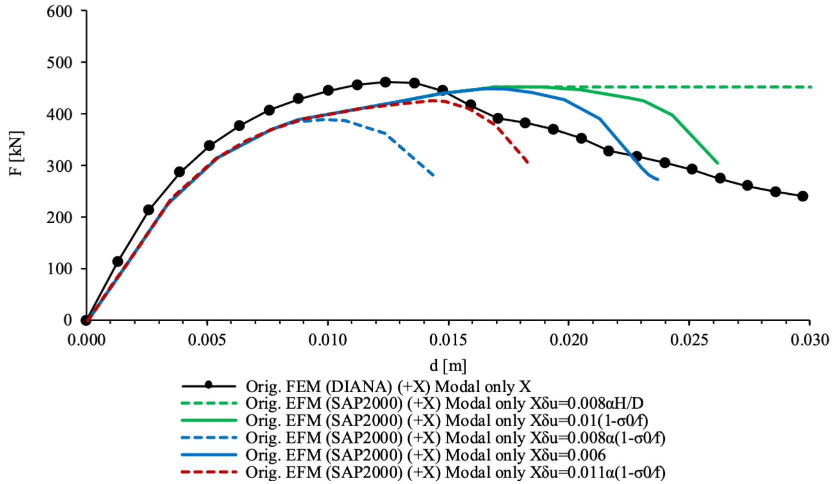
Strengthened configuration

B. Influence of the ultimate flexural drift limit

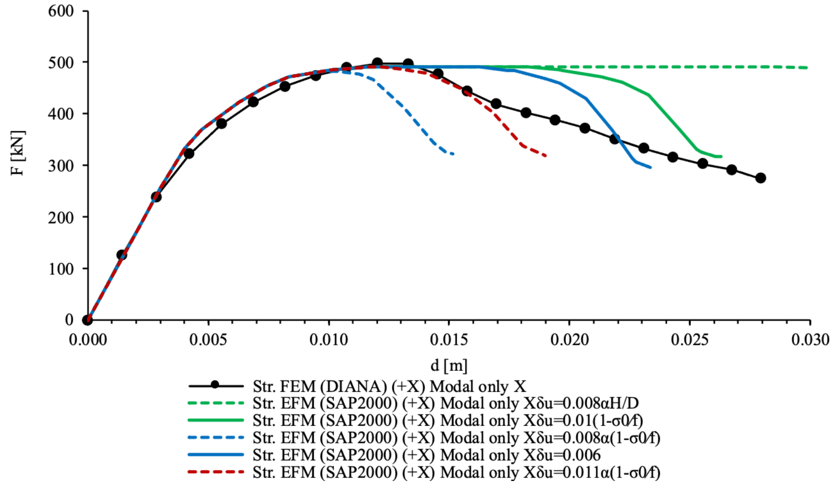
Considered cases:

- According to the actual version of EC8-3 (CEN 2005): $\theta_u = 0.008\alpha H/D;$
- According to the expected future version of EC8-3 (CEN 2022): $\theta_u = 0.01(1 - \sigma_0/f);$
- According to the "Modified SIA-model" (Salmanpour et al. 2015): $\theta_u = 0.008\alpha(1 - \sigma_0/f);$
- According to the Italian code (NTC 2008): $\theta_u = 0.006;$
- **Proposed calibrated value (based on the "Modified SIA-model"):** $\boldsymbol{\theta_u = 0.011\alpha(1 - \sigma_0/f)}$**.**





Original configuration

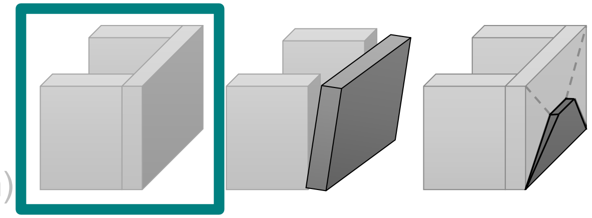


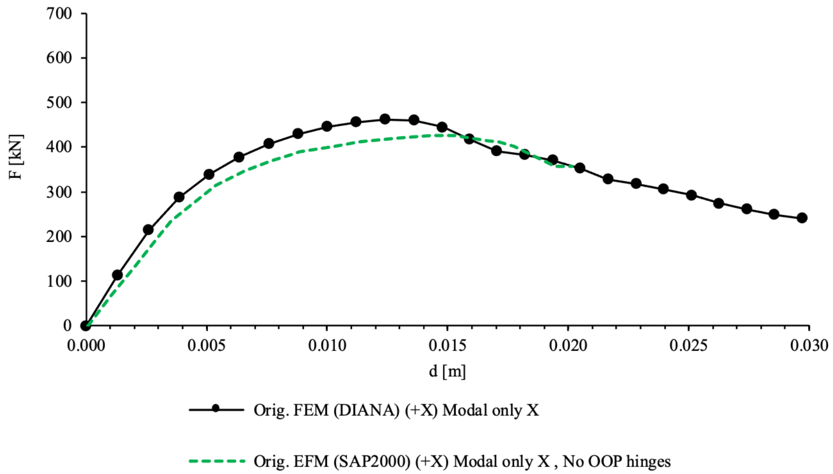
Strengthened configuration

C. Influence of the out-of-plane resistance

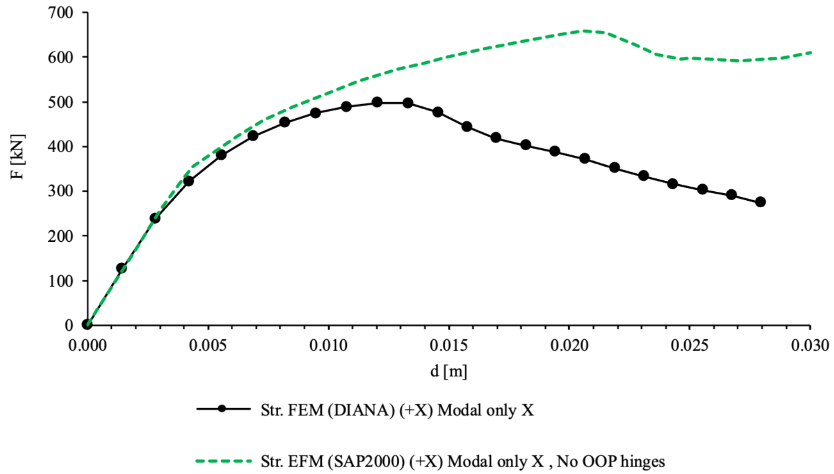
Considered cases:

- Piers without OOP hinges;
- Piers with OOP hinges neglecting the return walls;
- Piers with OOP hinges considering the return walls (proposed default configuration)





Original configuration

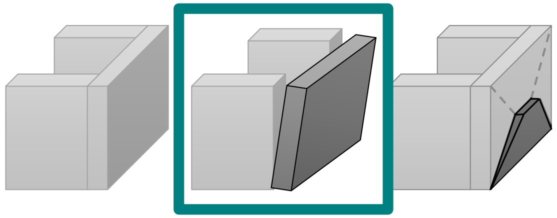


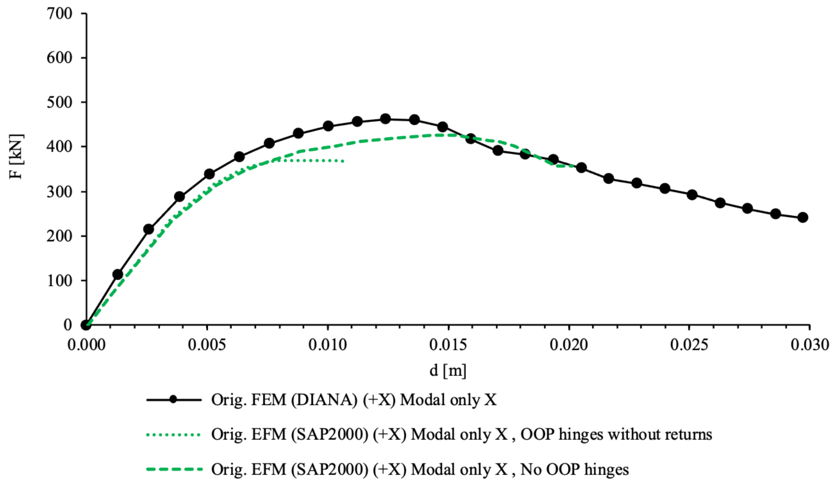
Strengthened configuration

C. Influence of the out-of-plane resistance

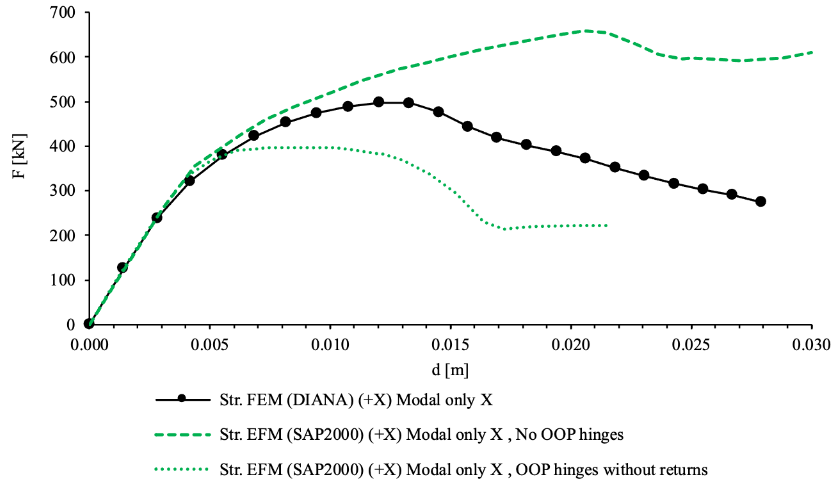
Considered cases:

- Piers without OOP hinges;
- Piers with OOP hinges neglecting the return walls;
- Piers with OOP hinges considering the return walls (proposed default configuration).





Original configuration

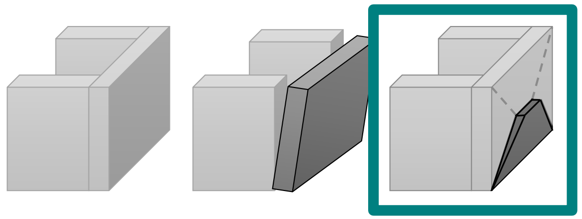


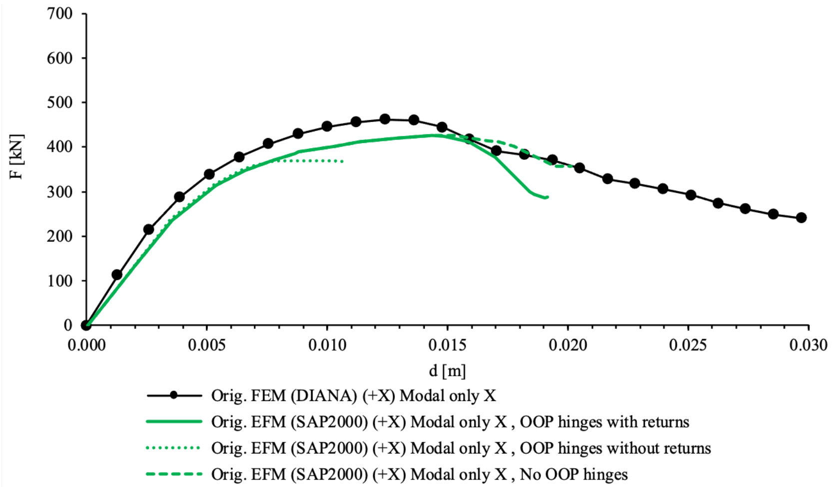
Strengthened configuration

C. Influence of the out-of-plane resistance

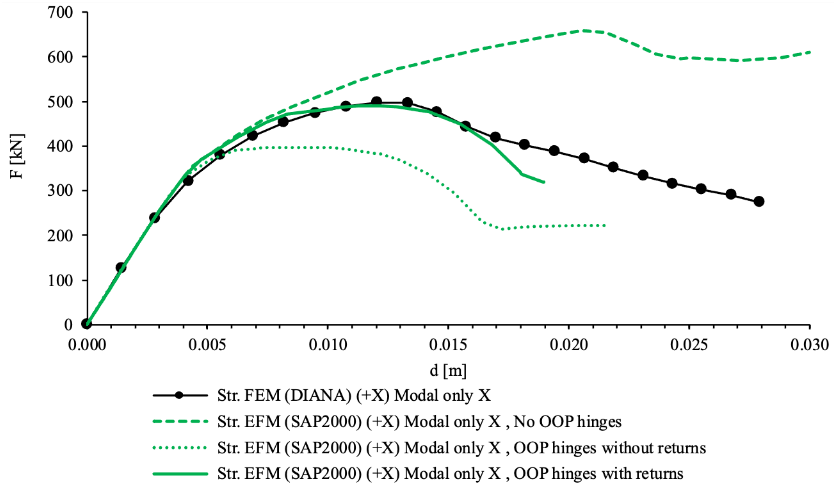
Considered cases:

- Piers without OOP hinges;
- Piers with OOP hinges neglecting the return walls;
- Piers with OOP hinges considering the return walls (proposed default configuration).





Original configuration



Strengthened configuration

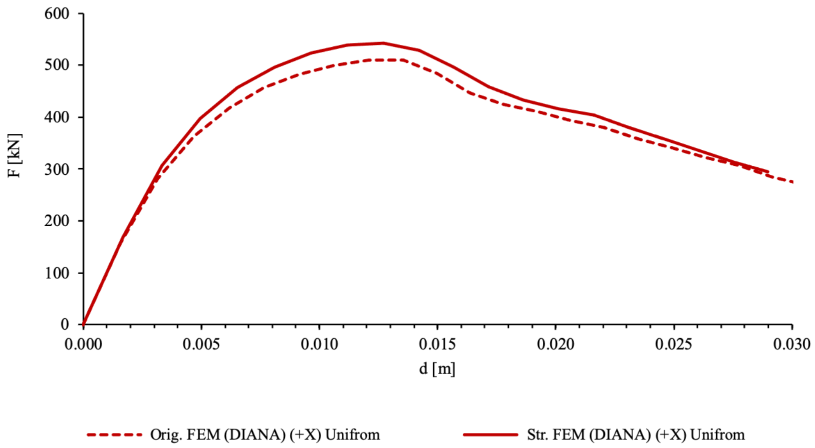
D. Influence of the strengthening intervention

Considered cases:

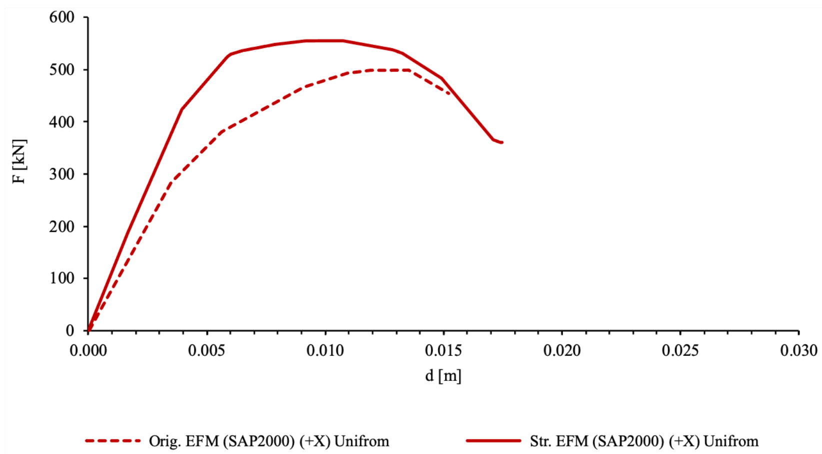
- Timber diaphragms (original configuration);
- RC slabs (strengthened configuration).

Considered load patterns:

- **Uniform pattern**
- **Modal pattern in all directions**
- **Modal pattern only in the analysis direction**



FEM (DIANA)



EFM (SAP2000)

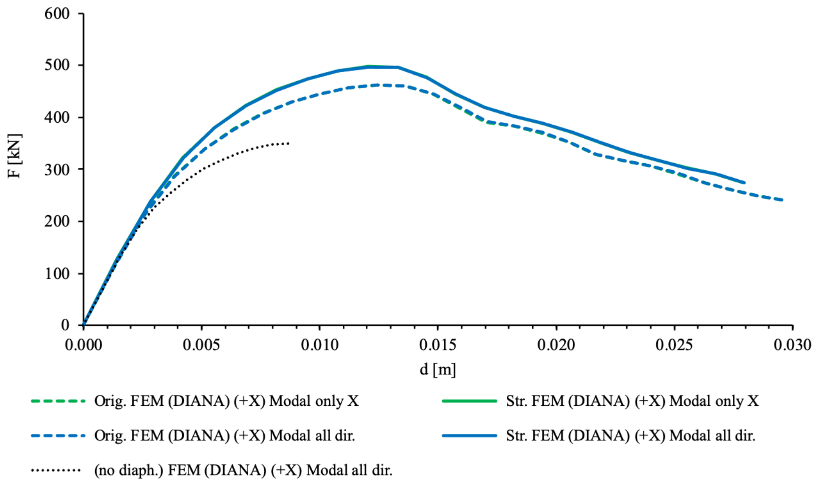
D. Influence of the strengthening intervention

Considered cases:

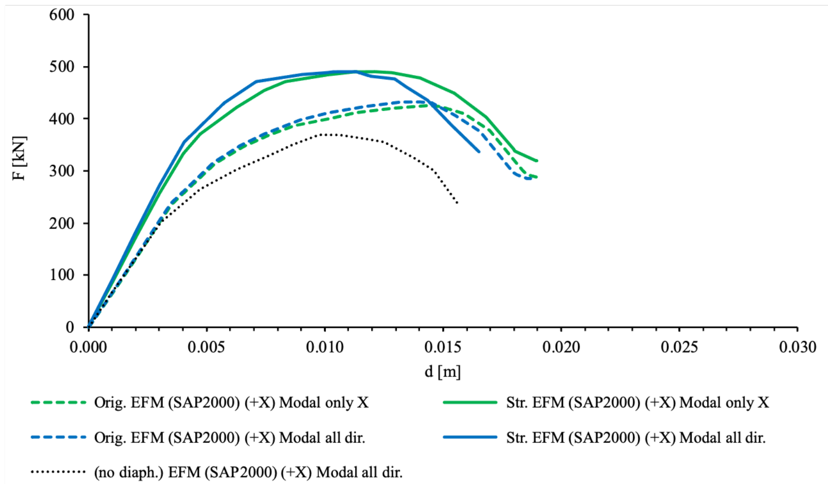
- Timber diaphragms (original configuration);
- RC slabs (strengthened configuration).

Considered load patterns:

- Uniform pattern
- **Modal pattern in all directions**
- **Modal pattern only in the analysis direction**



FEM (DIANA)



EFM (SAP2000)

IV. Contributions

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

List of publications

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.
7. G. Correia Lopes, R. Vicente, T.M. Ferreira, M. Azenha, **Desafios e Direções de Investigação na Identificação e Caracterização de Tipologias de Edifícios de Alvenaria Intervencionados com Recurso a Betão Armado**, in: 11o Congr. Nac. Sismol. e Eng. Sísmica, Lisbon [in portuguese], 2019.

Under review:

8. **Improved Equivalent Frame Model formulation for the seismic performance assessment of URM-RC buildings**.

9. **The effect of stiffened diaphragms on the seismic response of URM-RC buildings using the Equivalent Frame Model method**.

Acknowledgments

- Doctoral Program InfraRisk- Analysis and Mitigation of Risks in Infrastructures
- Foundation for Science and Technology (FCT) for the PhD grant (PD/BD/135201/2017)
- University of Aveiro, FCT/MEC for the financial support to the research Unit RISCO – Risks and Sustainability in Construction (FCT/UIDB/04450/2020)

Course: Infrastructure Engineering

BIM-based methodology for the seismic performance assessment of existing URM-RC buildings

Gonçalo Correia Lopes

Scientific supervision:

Romeu Vicente (U. Aveiro)
Miguel Azenha (U. Minho)
Tiago Miguel Ferreira (UWE Bristol)