Infrastructures and Geotechnics

Risk management applied to cultural heritage buildings. The effect of soil settlements and vibrations induced by underground structures.

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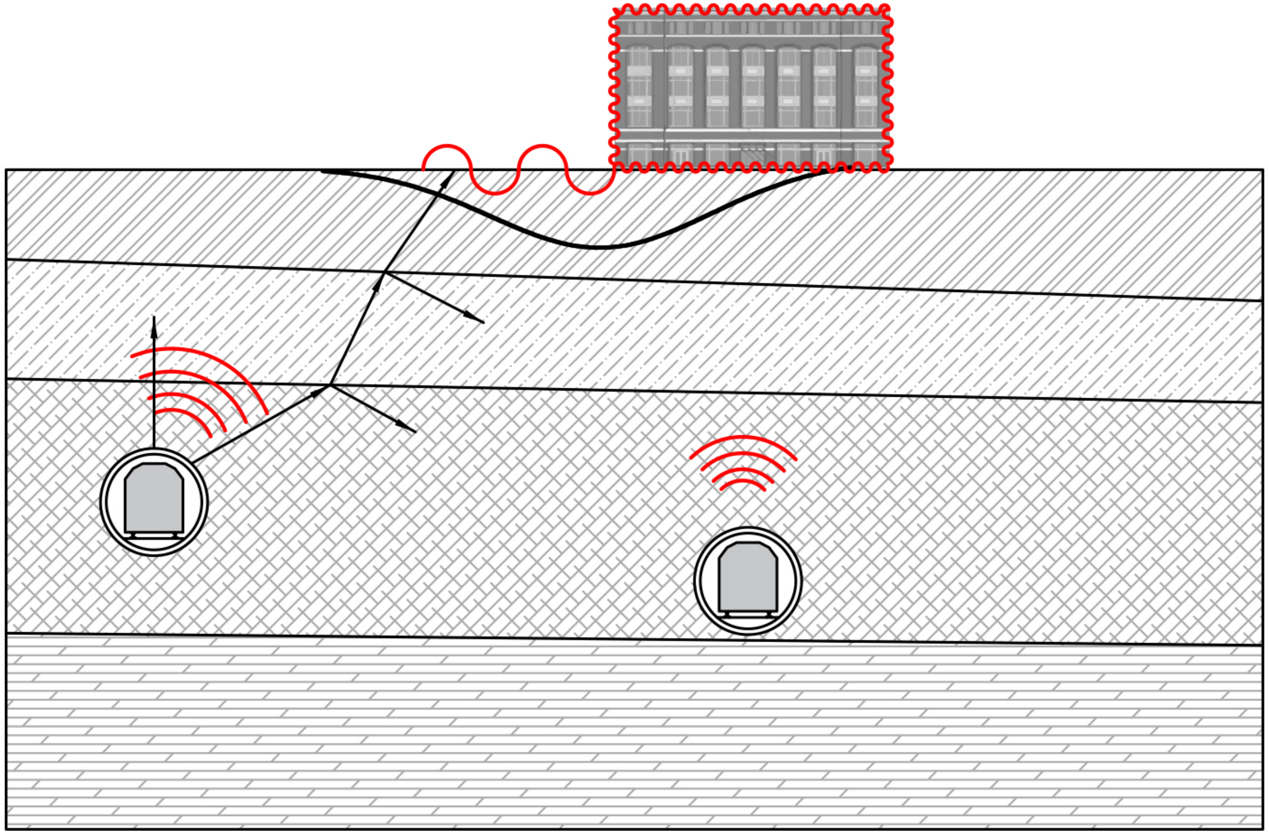


Underground structures in urban environment
Cultural heritage buildings

- Historical constructions • of high social and cultural value • extremely susceptible to damage and deterioration due to weathering and environmental actions • Low mechanical properties and brittle failure

- Emerging demand on underground constructions • aspects of efficacy, time transferring needs and obstruction in over-concentrated overground urban networks

- Cumulative damage propagation in structural and non-structural elements • assessment through monitoring and experimental strategies, modelling • employment of appropriate mitigation techniques

Underground structures in urban environment

Research activities – Cyclic low-stress rate fatigue tests on masonry

Literature review ✓	Experimental work …	Monitoring - NDTs ✓	Numerical analysis …

Long-term effects on durability have not been fully evaluated and many times are not accounted in the assessment process of historical masonry buildings

Objectives

- **Long term performance and stages of fatigue deterioration under low-medium rate strain evolution and high stress levels.**
- **Application of damage detection NDT strategies for monitoring damage and stiffness degradation in structural elements (vibrations + settlements)**
- **Damage for elements of architecture; i.e. frescos/plaster**
- **In-plane capacity of URM perforated walls (piers and spandrels) and issues on reparability, under differential settlements**

Structural monitoring of induced vibrations

Groundborne vibrations • underground railway traffic

❑ Guidelines on: Measurement / Instrumentation / Processing / Evaluation

Type and condition of structure	Vibration source/type	Description	Dominant vibration frequency (Hz)	PPV (mm/s)	Indicator	Reference
Sensitive structures of high intrinsic value	Short-term	At foundation level	1-10 10-50 50-100	3 3-8 8-10	$\lvert V_{max} \rvert$	DIN 4150 3:1999 Germany
		At highest horizontal plane	-	8	$\lvert V_{max} \rvert$	
	Long-term	At highest horizontal plane	-	2.5	$\lvert V_{max} \rvert$	
Historical buildings or under protection	Occasional Frequent	At foundation level	<30 30-60 >60	1.5-3 2-4 3-6	$\lvert V_R \rvert$	SN 640312 1992 Switzerland
			Wave speed (m/s)			
Historical buildings under state protection	-	Vibrations at highest level: Brick	<1600 1600-2100 >2100	0.15 0.15-0.2 0.2	$\lvert V_{max} \rvert$	GB/T 50452 2008 China
		Stone	<2300 2300-2900 >2900	0.20 0.20-0.25 0.25	$\lvert V_{max} \rvert$	
		Timber	<4600 4600-5600 >5600	0.18 0.18-0.22 0.22	$\lvert V_{max} \rvert$	

Structural monitoring of induced vibrations

Groundborne vibrations • underground railway traffic

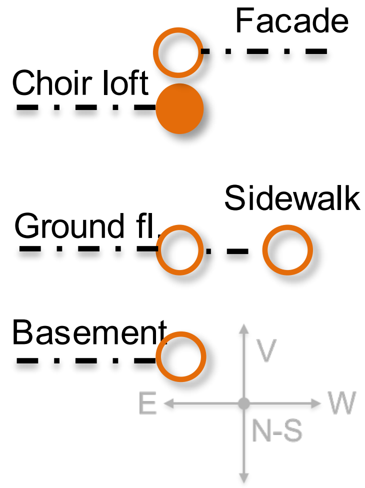
- ❑ Monitoring of metro induced vibrations in three cultural heritage buildings
  Church of the Angels, in Lisbon ✓
- ❑ 1 passing train every 3-5 min
- ❑ Use of kinetic quantities
- ❑ Response is mass controlled since $f_n < f_s$
  Attenuation is expected

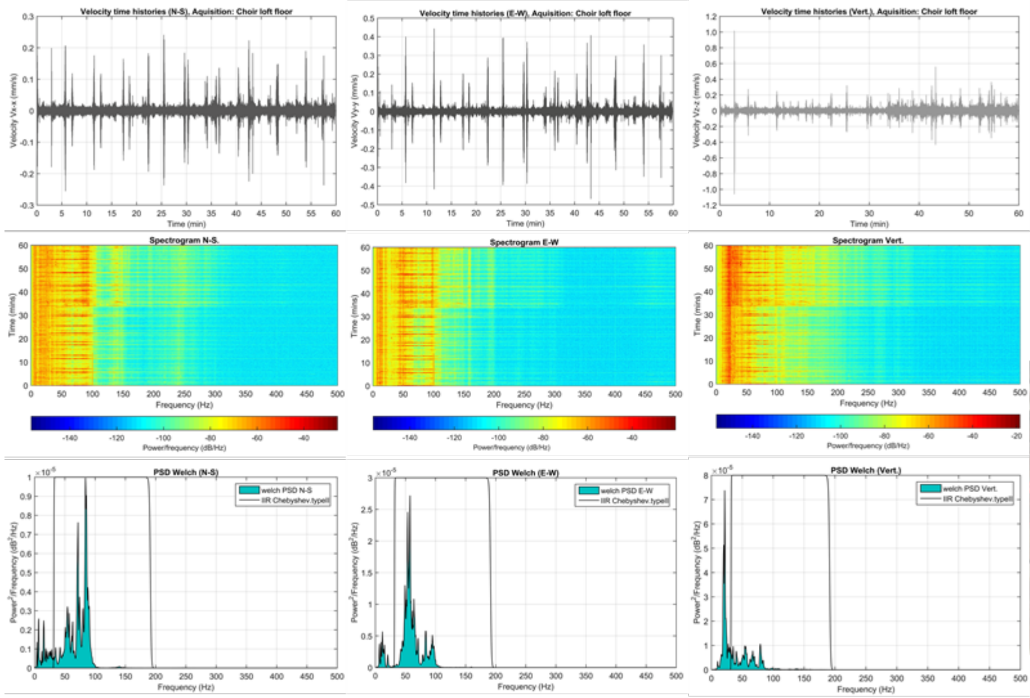
Raw signal — Detrending — Filtering — Pro

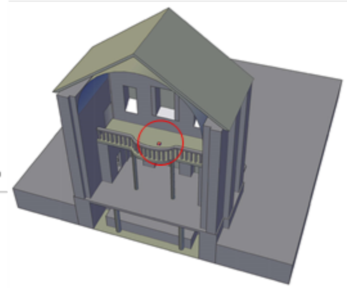
- ❑ Triaxial seismographers with GPS time base
  Triaxial geophone ✓
- ❑ Sampling frequency 1000-2000Hz

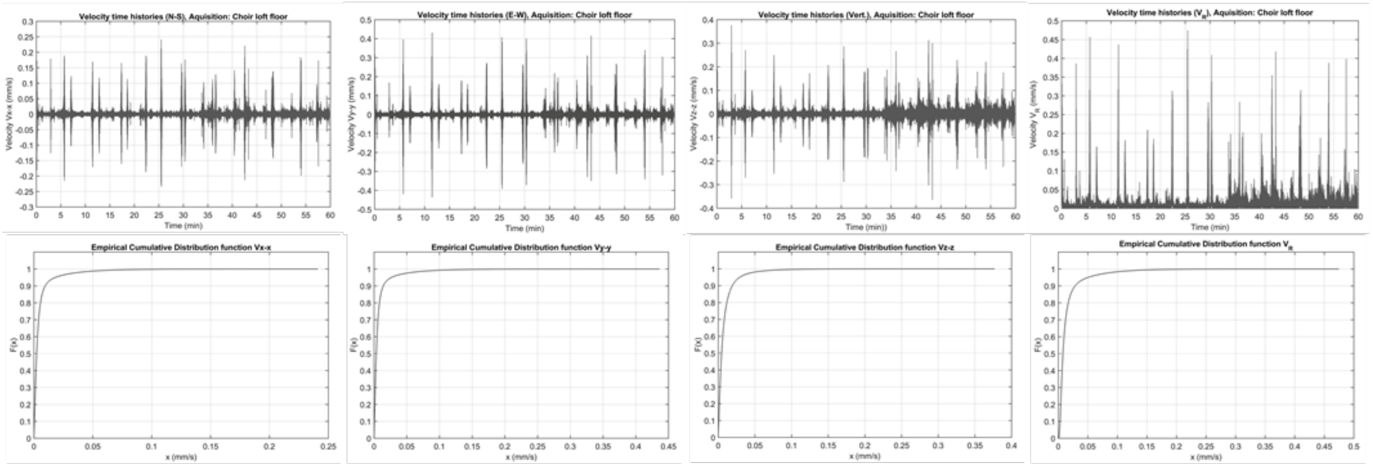
Structural monitoring of induced vibrations

Church of the Angels, Lisbon





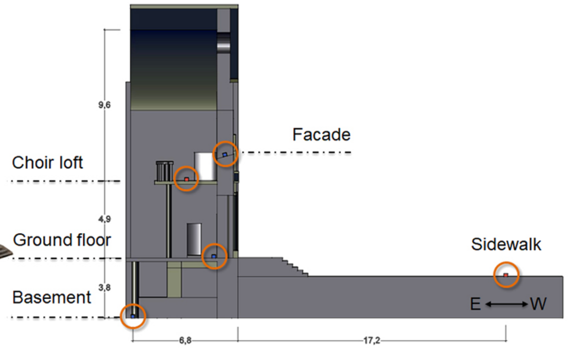


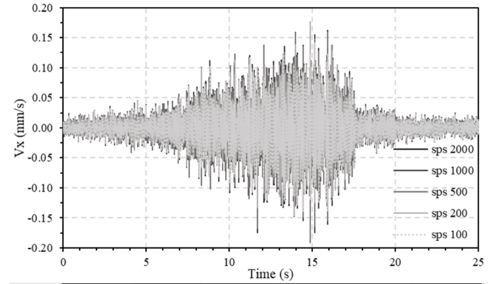


$F(x) = 1\text{-}10^{-6}$, $x = 0.23$ mm/s $F(x) = 1\text{-}10^{-6}$, $x = 0.42$ mm/s $F(x) = 1\text{-}10^{-6}$, $x = 0.36$ mm/s $F(x) = 1\text{-}10^{-6}$, $x = 0.44$ mm/s

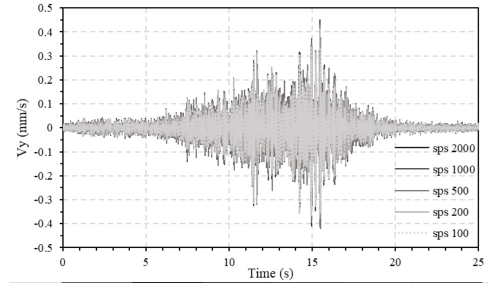
Structural monitoring of induced vibrations

Church of the Angels, Lisbon

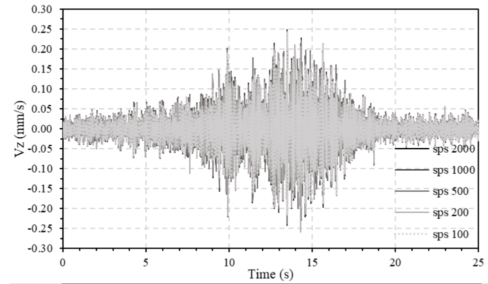




sps	2000	1000	500	200	100
V_x,max (mm/s)	0.19	0.19	0.19	0.18	0.14
Difference (%)	-	0.0%	0.0%	7.8%	34.4%



sps	2000	1000	500	200	100
V_y,max (mm/s)	0.45	0.45	0.43	0.41	0.37
Difference (%)	-	0.0%	5.2%	8.9%	22.7%



sps	2000	1000	500	200	100
V_z,max (mm/s)	0.26	0.26	0.24	0.26	0.24
Difference (%)	-	0.0%	5.7%	0.0%	5.7%

Location	max PPV (mm/s)	max V_R (mm/s)	Frequency content[1] (Hz)		Spatial wave frequency (Hz)	ΔVdB[4] attenuation
Choir loft Timber floor	0.42	0.44	x-x y-y z-z	30-200 30-200 30-200	76.9[2]	4
Choir loft Facade windows	0.12	0.13	x-x y-y z-z	30-110 30-200 30-200	125[3]	15
Ground floor	0.11	0.12	x-x y-y z-z	30-150 30-160 30-100	66.7[3]	16
Basement	0.27	0.27	x-x y-y z-z	30-160 30-160 30-125	66.7[2]	9
Sidewalk (Ref.)	0.65	0.72	x-x y-y z-z	30-100 30-100 30-100	71.4[2]	0

1 Refers to the maximum frequency range
2 Refers to the confidence interval for 90% probability of exceedance for ppv≥0.05mm/s
3 Refers to the confidence interval for 90% probability of exceedance for ppv≥0.025mm/s
4 Refers to the maximum velocity vector V_R

Experimental campaign

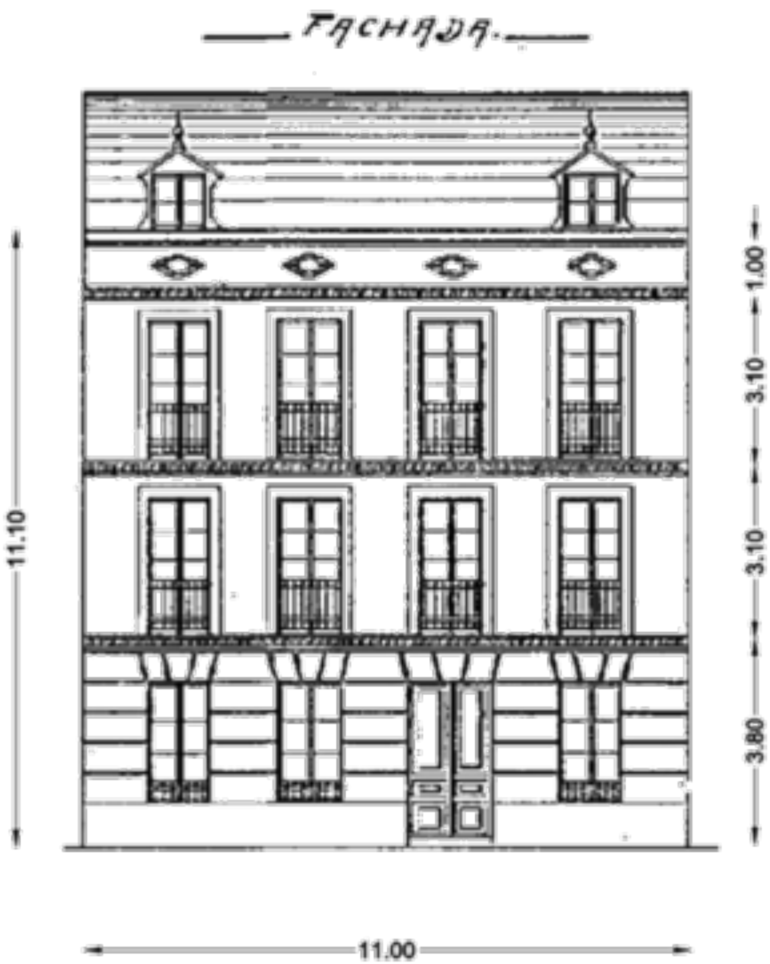
Historic masonry facades
Brick masonry piers and spandrels
Numerical model validation

Experimental campaign

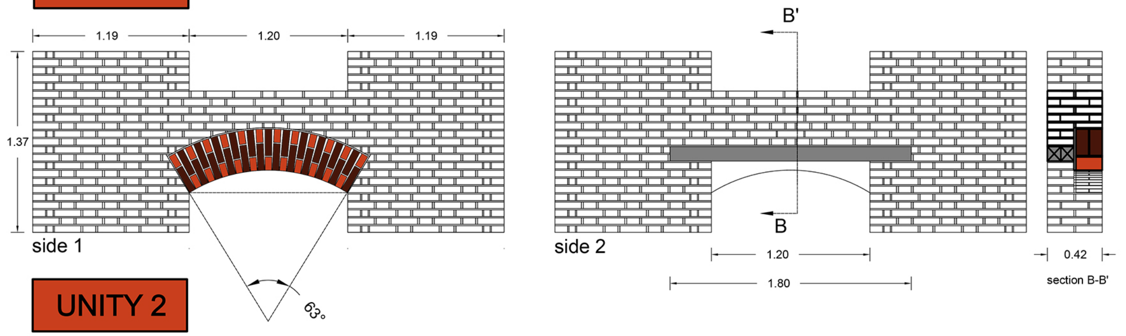
Historic masonry facades • Brick masonry piers and spandrels

- In-plane capacity of URM perforated walls (piers and spandrels) and reparability, under differential settlements

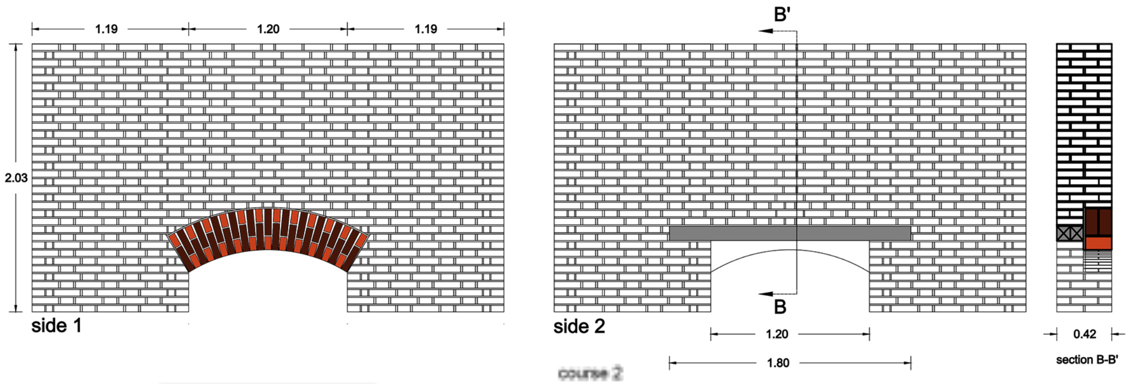
Reference facade / brick masonry with lime mortar
Location: Valladolid, Spain / Construction date: 1908
Source: Camino Olea,M.S. (2001) PhD Thesis: Construcción y ornamentación de las fachadas de ladrillo prensado, al descubierto, en la ciudad de Valladolid University of Valladolid, Spain.

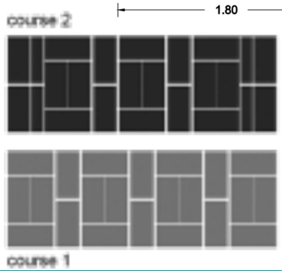


UNITY 1



UNITY 2

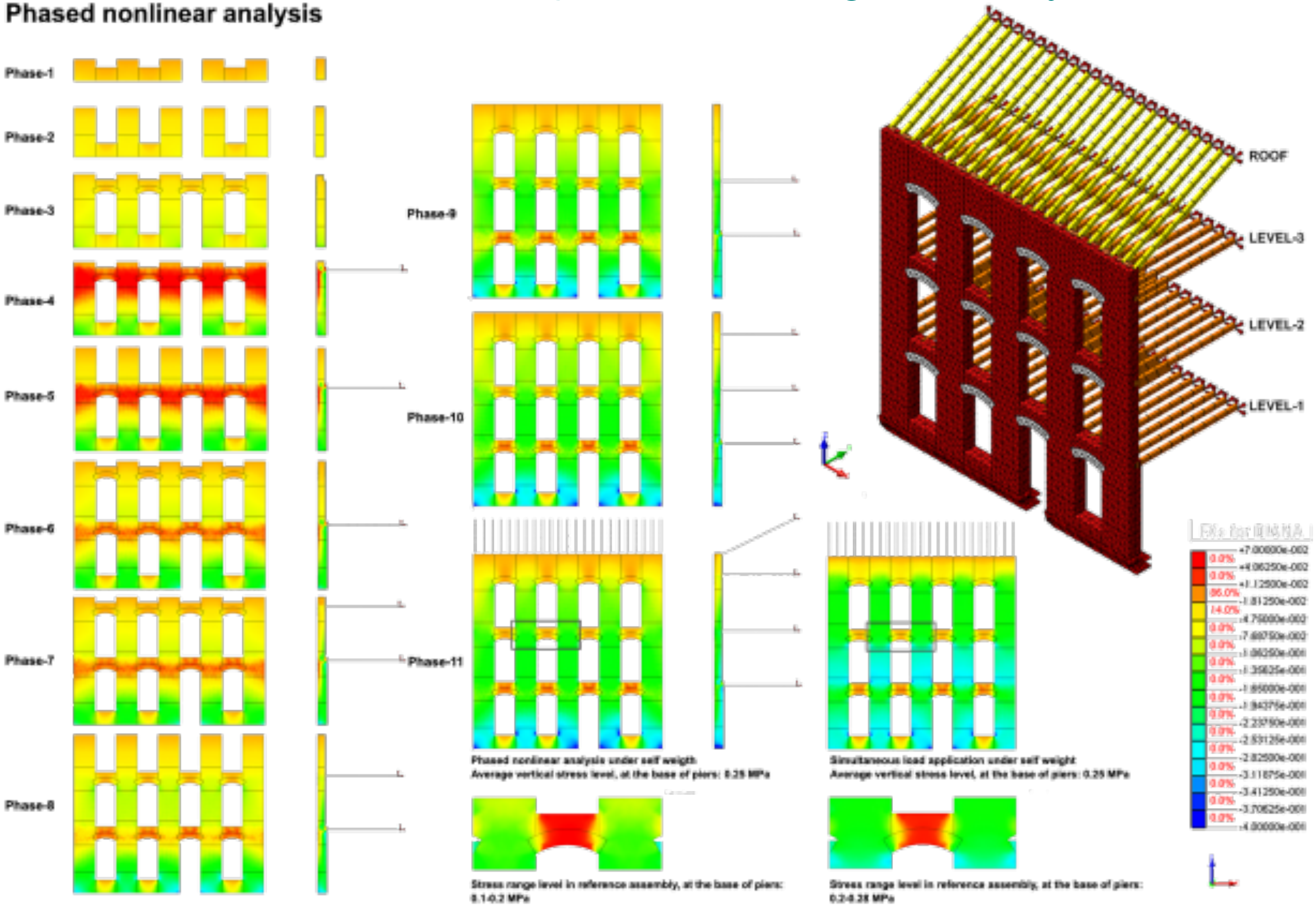




Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

FE model validation: Historic façade ⇔ Testing assembly

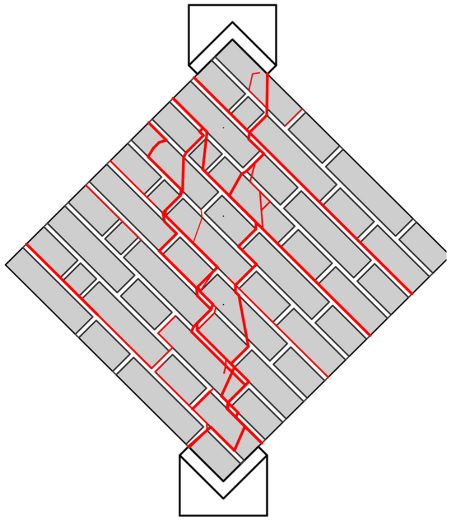


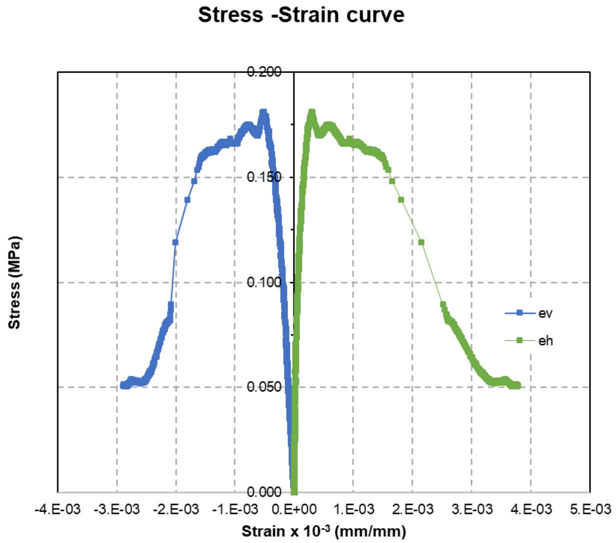
Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

❑ Basic mechanical characterization tests (90days)

Diagonal compression





$\sigma_{t,m}$ = 0.36MPa (56%)

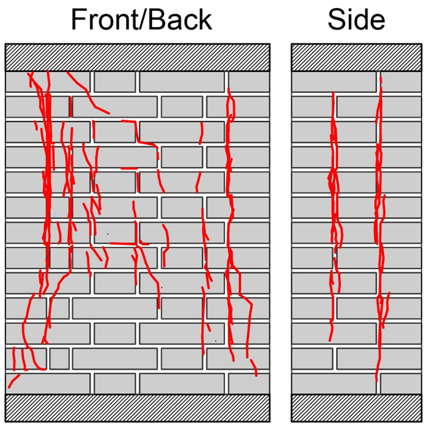
G_m = 350 MPa

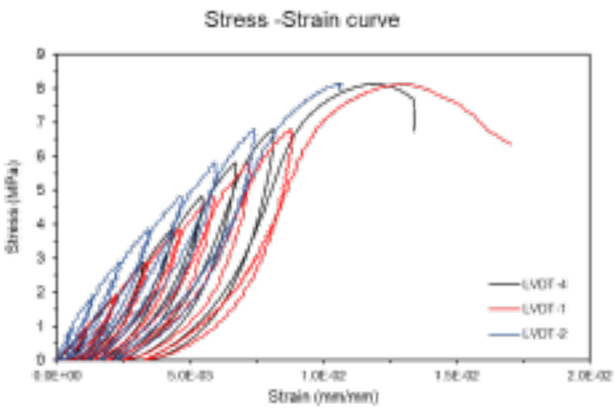
$\sigma_{c,m}$ = 8.80MPa (8%)

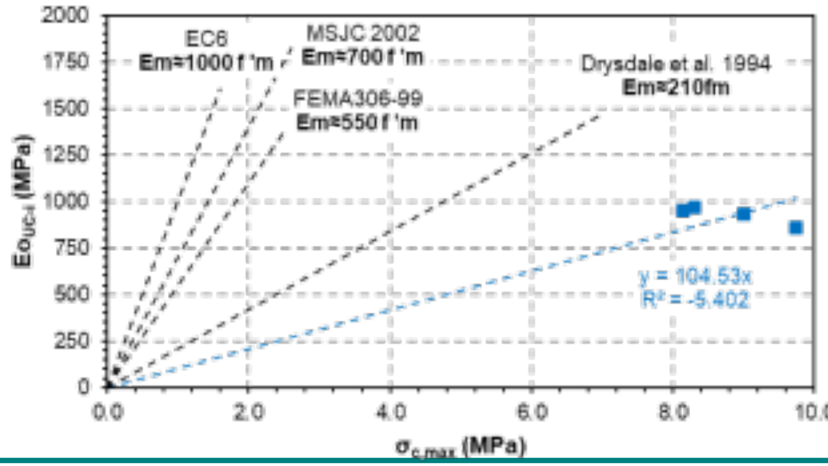
$E_{mod,m}$ = 927 MPa (5%)

$$\beta = \frac{\sigma_{t,m}}{\sigma_{c,m}} = 0.04$$

Uniaxial compression







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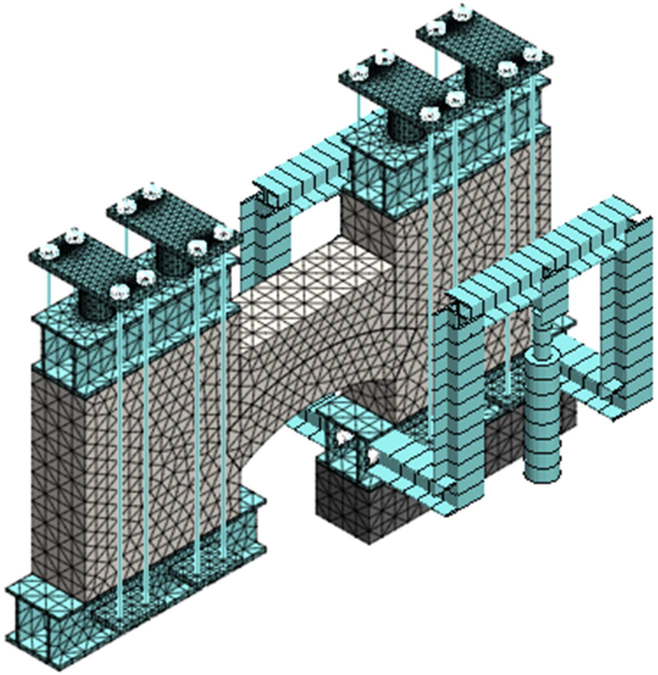
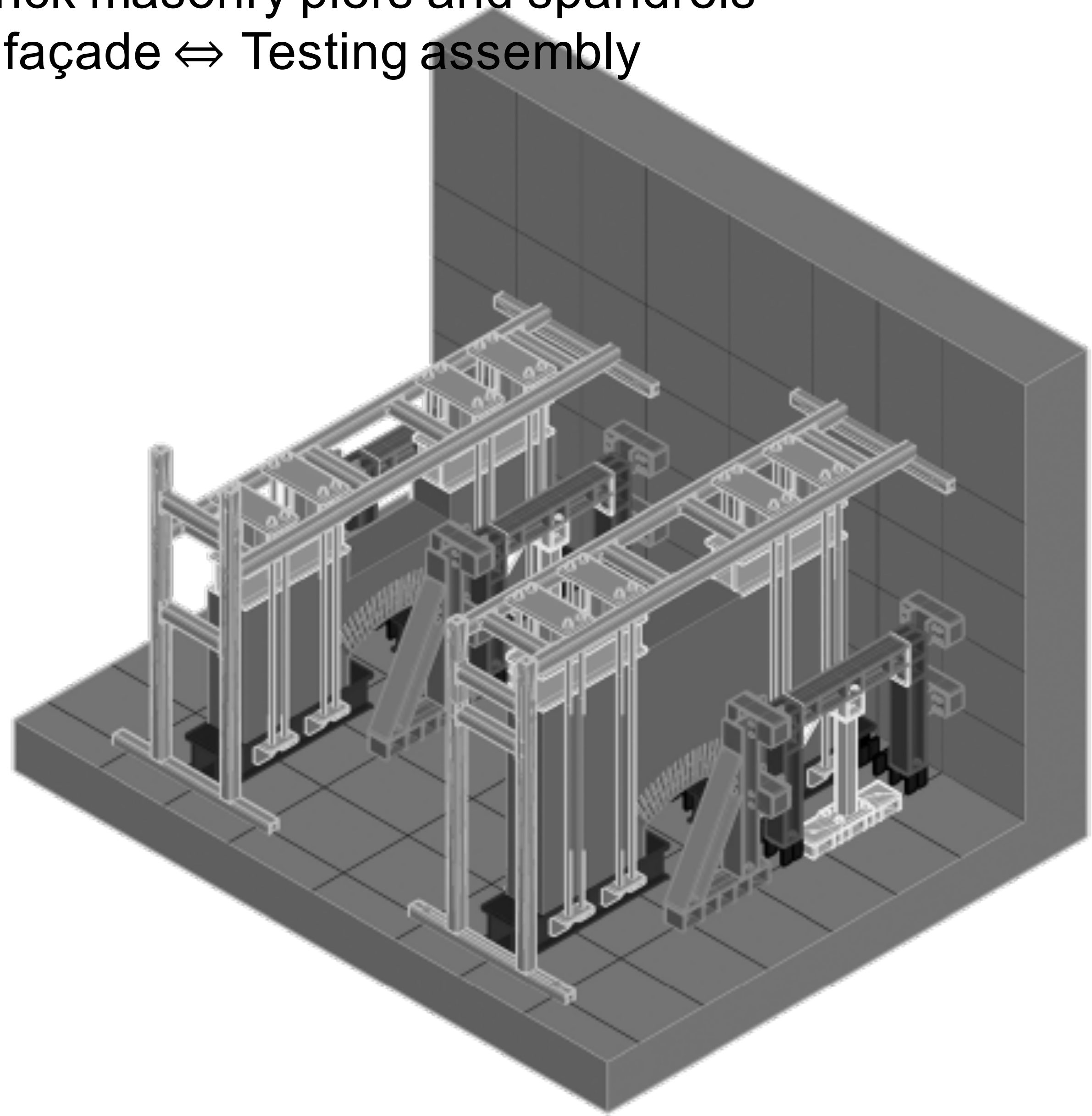
FE model validation: Historic façade ⇔ Testing assembly





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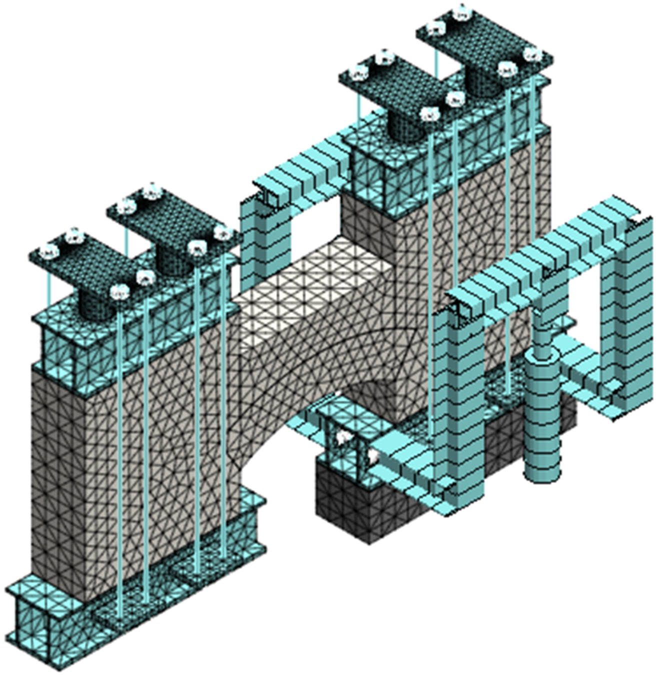
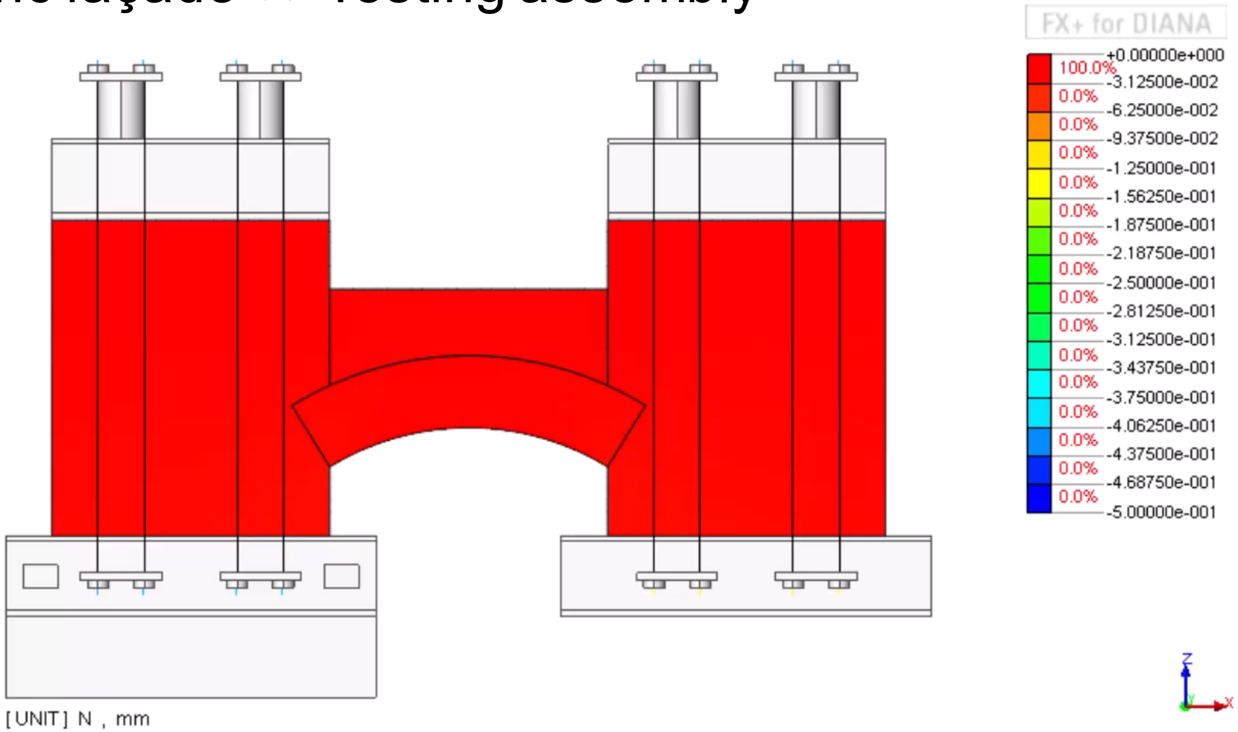




- shear force V_S and moment M_S in the spandrel

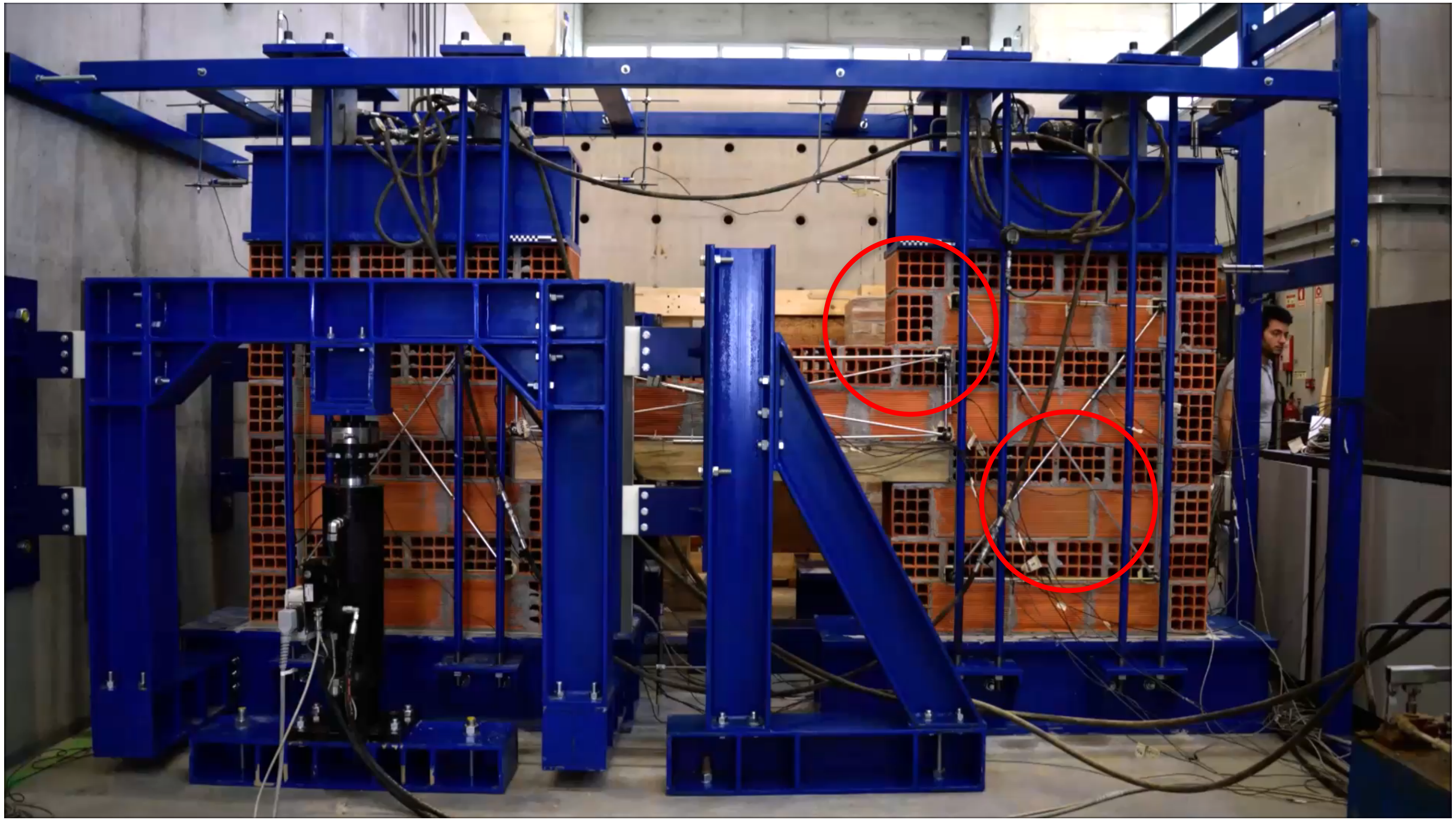
$$M_S = V_S \cdot \frac{L_S}{2}$$

Mechanical properties		Brick Masonry with lime mortar M3.5	Timber beam	Equivalent Concrete floor	Steel frame apparatus
Compressive strength	f_c (MPa)	8.80	-	-	-
Modulus of elasticity	E (MPa)	927	11000	1.0E+100	210000
Poisson's ratio	v (-)	0.25	0.2	0.2	0.3
Tensile strength	f_t (MPa)	0.36	0.06	-	-
Yield stress	f_y (MPa)	-	20.5	-	-
Fracture energy Mode I (tension)	G_f (N/mm)	0.05	-	-	-
Fracture energy (compression)	G_c (N/mm)	4.2	-	-	-
Specific weight	ρ (kN/m^3)	19	7.8	24	78.5

Experimental campaign

Mock-up test: Piers and spandrel from hollow commercial bricks

- ❑ Commercial hollow bricks 30x20x15; fm: 2.5-4.9 MPa; ρ: 5-7 kg [Martins 2018]



Experimental campaign

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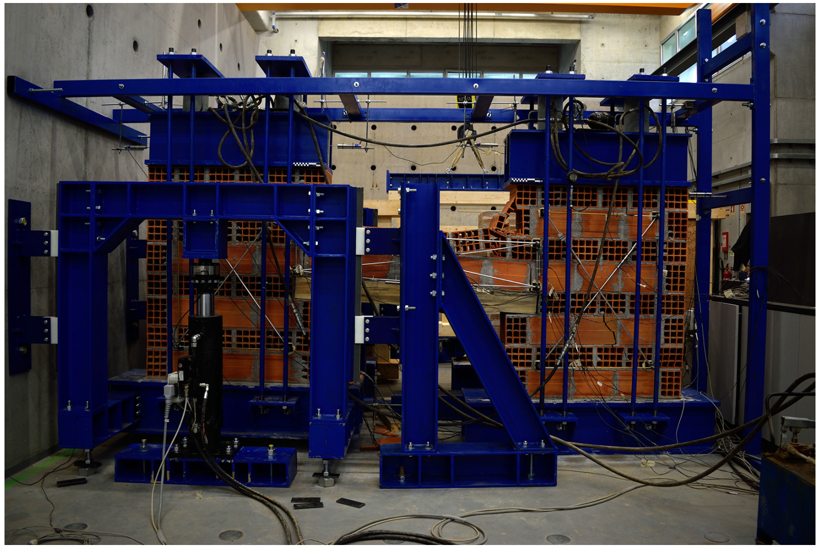

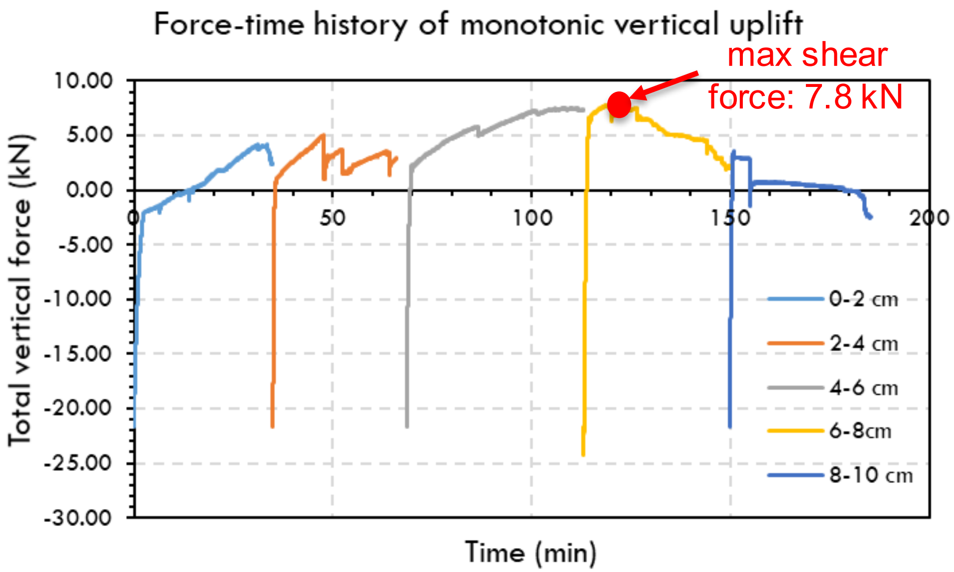

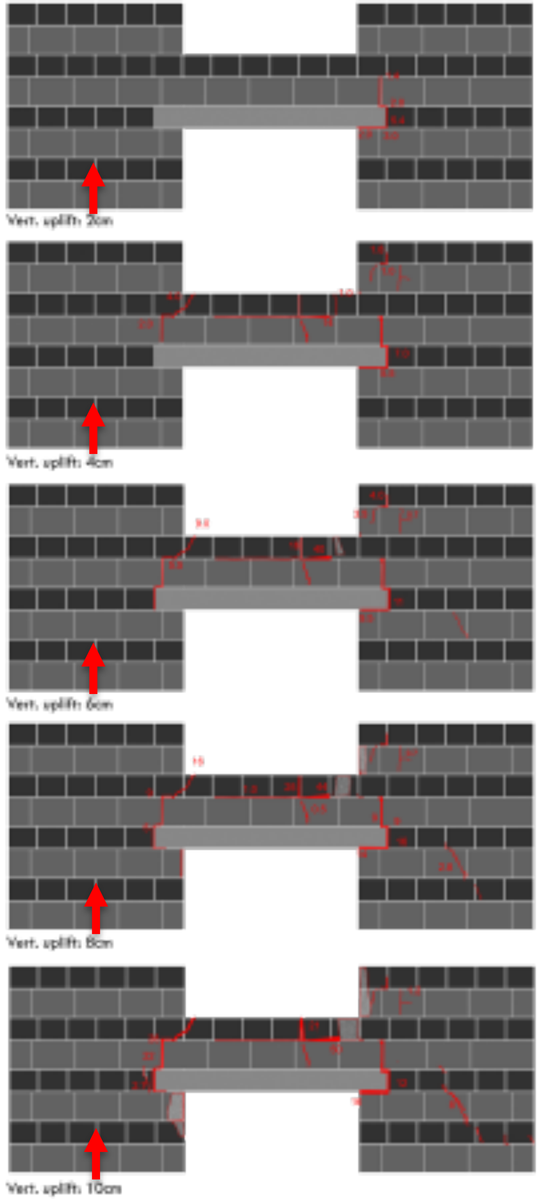

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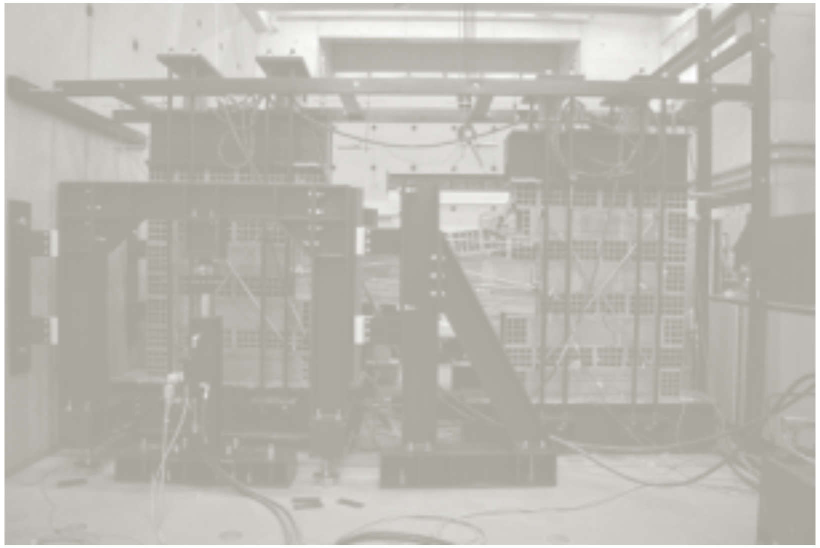

- In-plane capacity of URM perforated walls (piers and spandrels) and reparability, under differential settlements.
- Failure modes and resulting crack patterns. Influence of unit interlocking, lintels, boundary and loading conditions.
- Movable pier base to rotate freely, but not out-of-plane.
- Hydraulic system of jacks kept under a constant pressure.
- Acquisitions of intermediate steps for documentation and monitoring.
- Relative deformations, rotations, sliding, drifts.
- UN-1: Jul. 2019, UN-2: Nov. 2019, UN-3: Dec. 2019, UN-4: Feb. 2020

Thank you

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