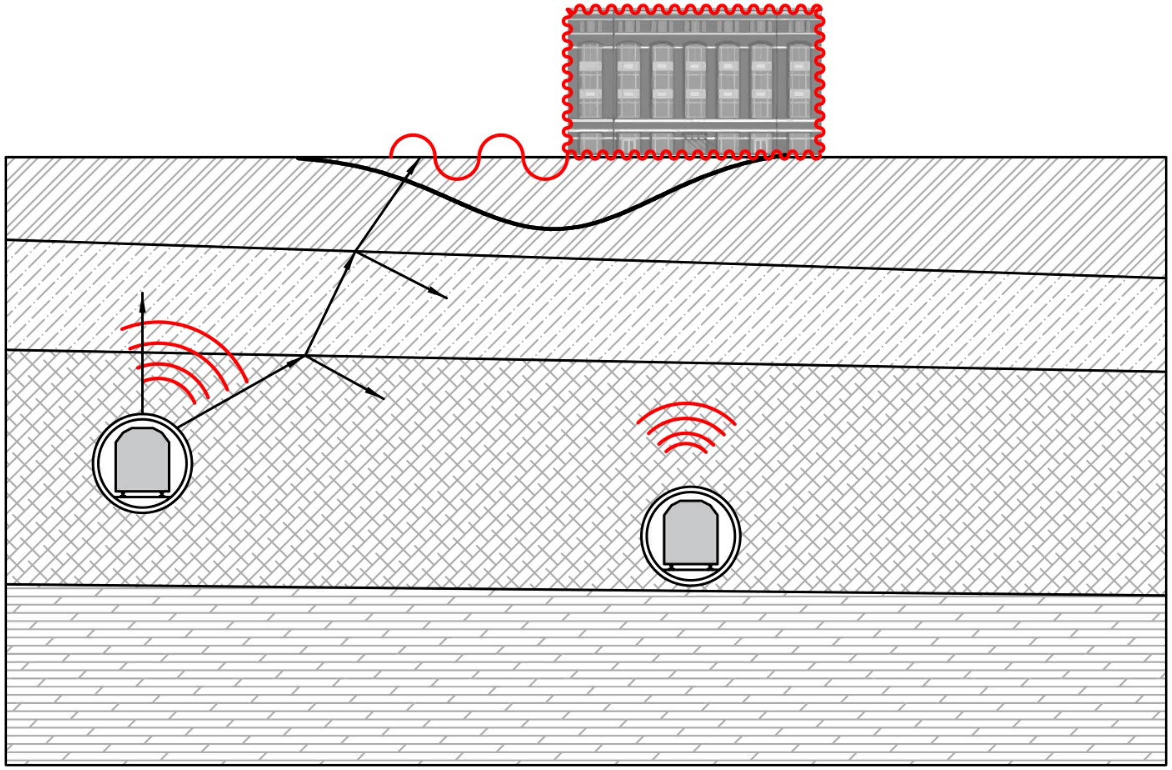
Infrastructures and Geotechnics

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

Georgios Karanikoloudis

Supervision:

Prof. Paulo Lourenço (UMinho)
P.I. João Bilé Serra (LNEC)



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, employment of appropriate mitigation techniques

Underground structures in urban environment

Research activities: Settlements and cyclic low-stress rate fatigue tests on cultural heritage masonry buildings

Literature review ✓	Field monitoring strategies ✓	Experimental work 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.**
- **Field monitoring protocols and methods for induced vibrations in historic masonry structures**
- **Application of damage detection ND 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 and retrofitting, under differential settlements**

Underground structures in urban environment

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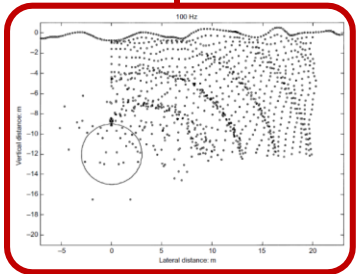
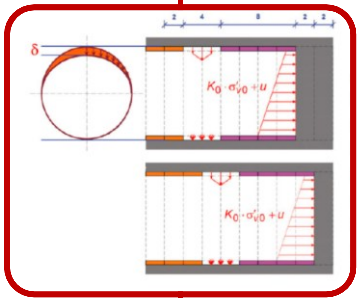
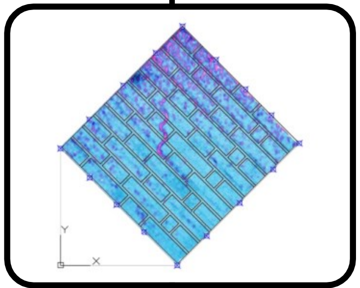
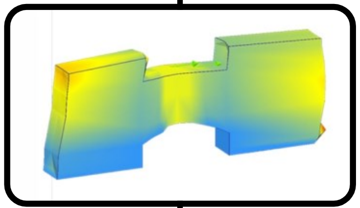


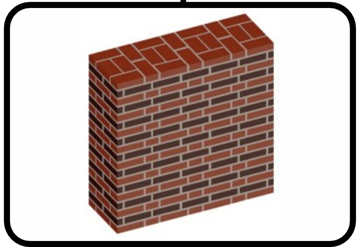


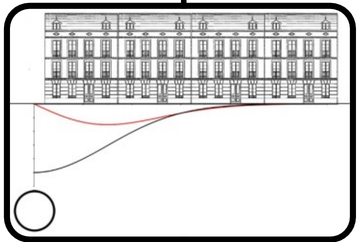
Monitoring strategies - NDTs ✓

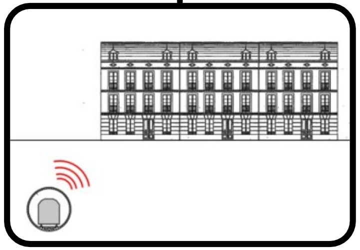




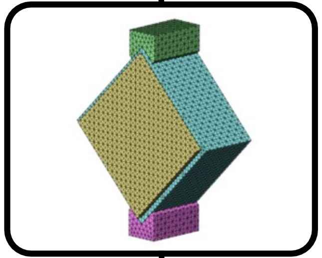
Experimental work ✓

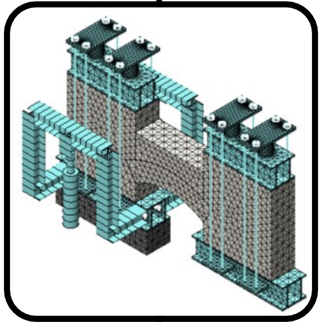


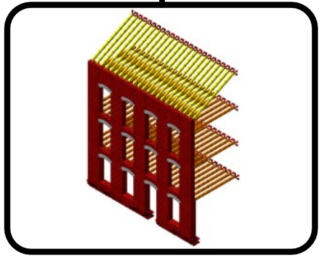




Numerical analysis …







Underground structures in urban environment

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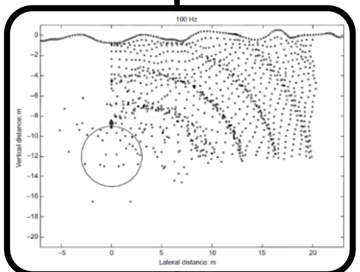

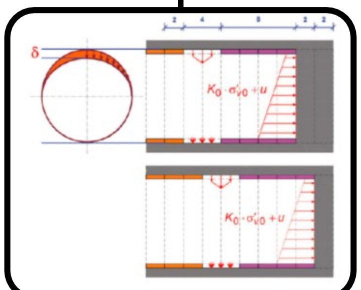

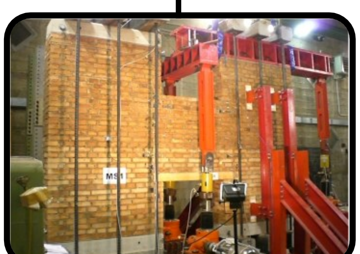

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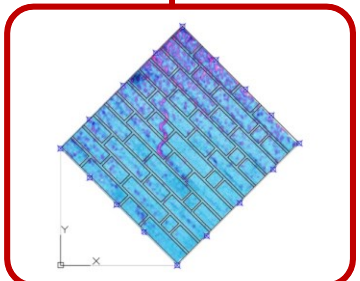

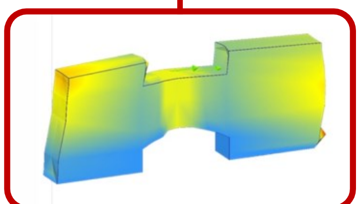

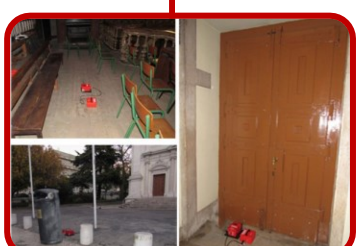

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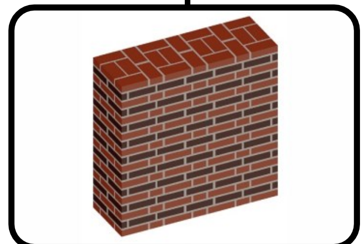

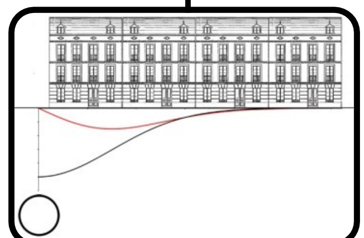

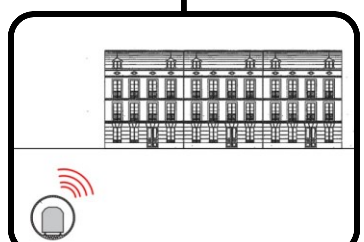

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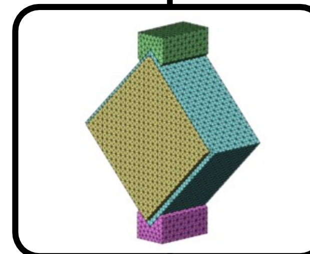

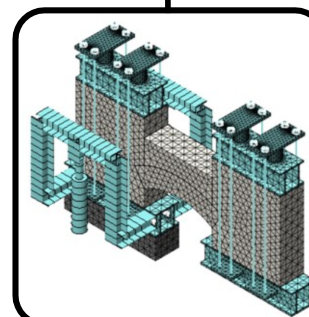

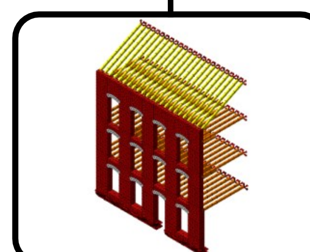

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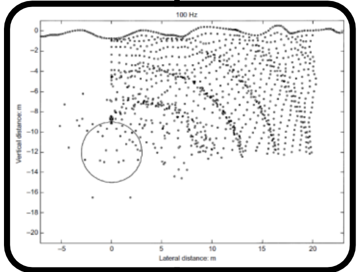

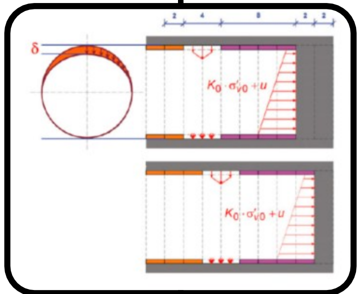

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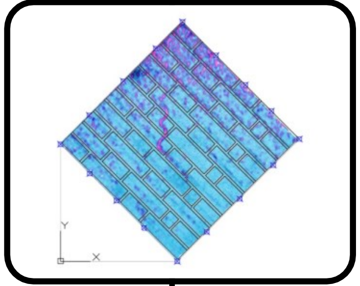

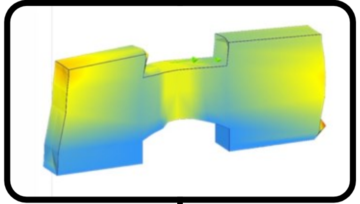

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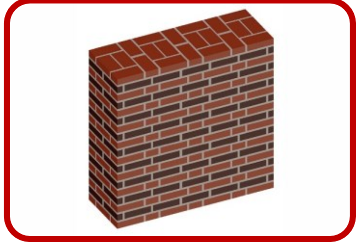

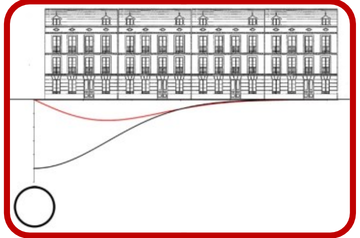

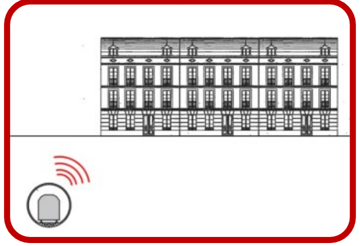

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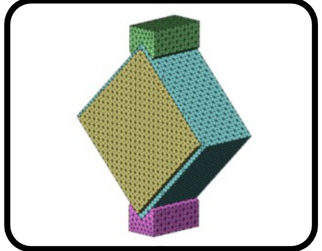

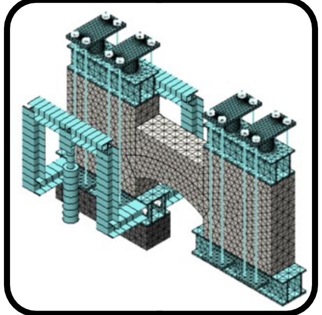

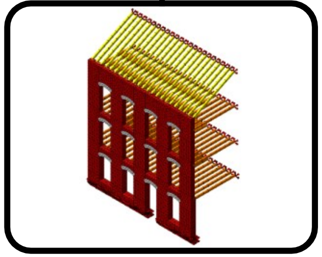

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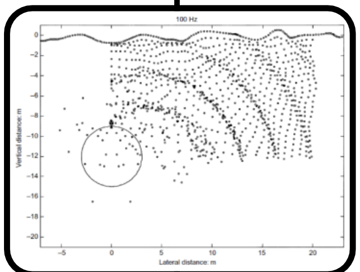

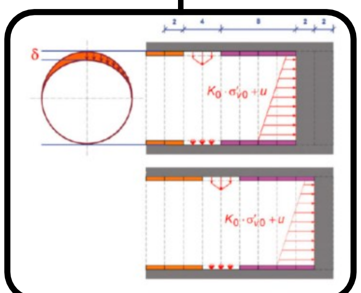

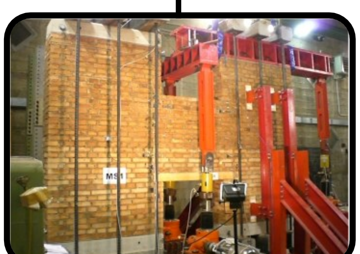

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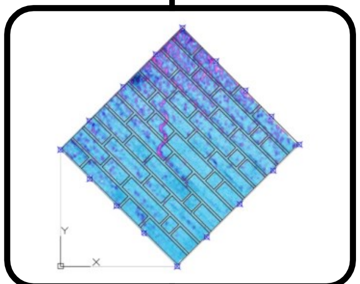

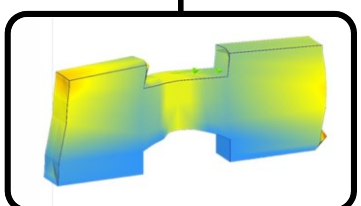

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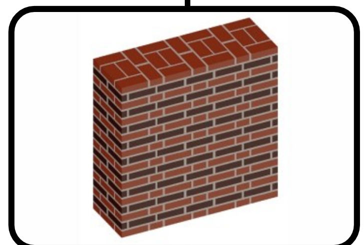

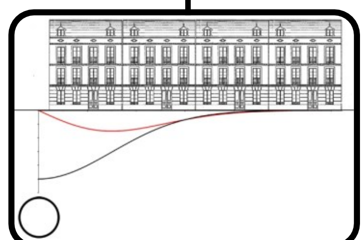

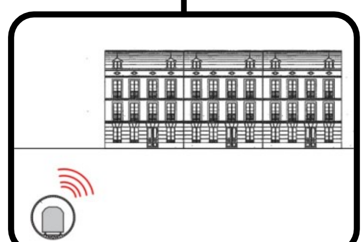

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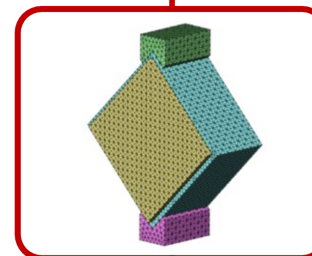
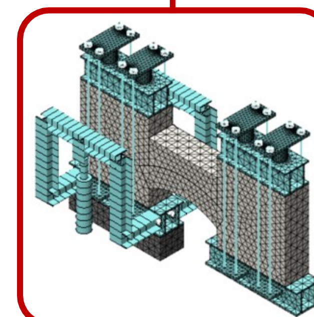
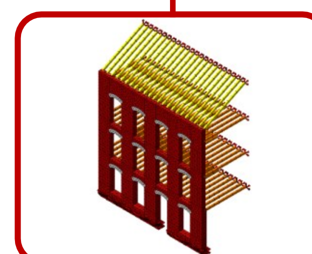




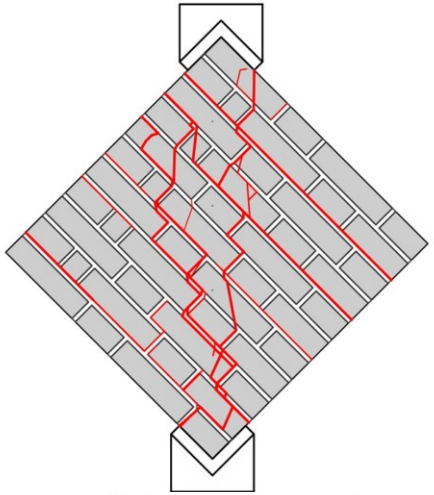


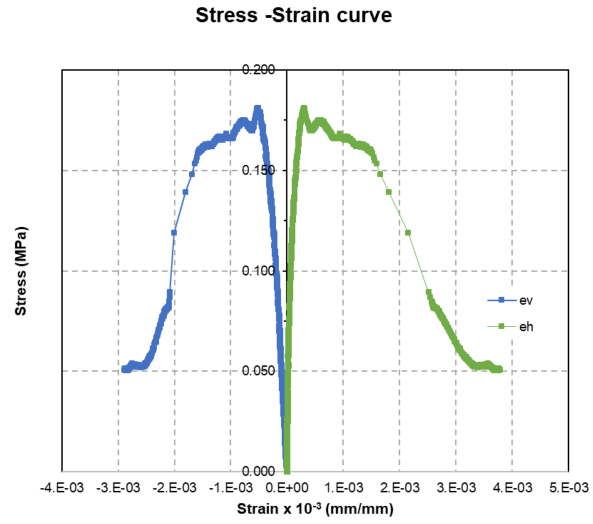
Material characterization of simulated historic masonry

Masonry constituents • wallets • repair material

- ❑ Basic mechanical characterization tests

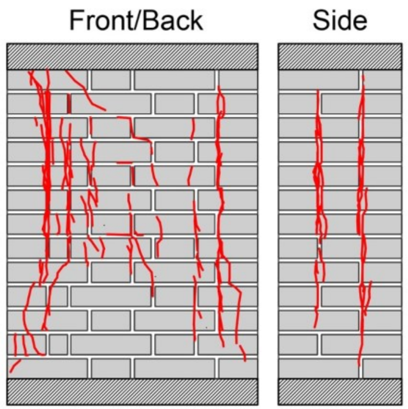
Diagonal compression

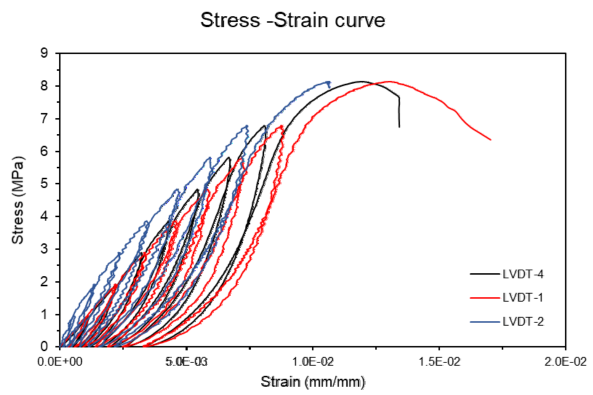




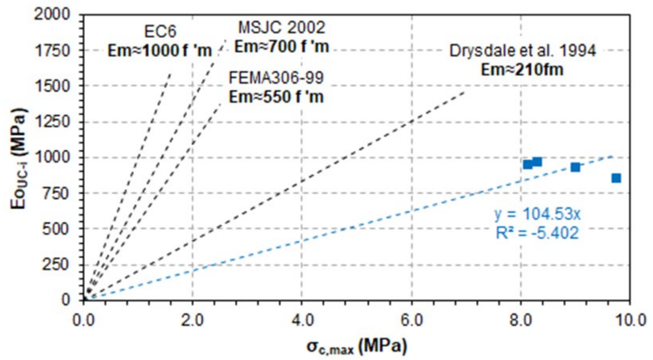
- ❑ $\sigma_{t,average}$ = 0.36MPa (56%)

Uniaxial compression





- ❑ $\sigma_{c,average}$ = 8.80MPa (8%)



Field monitoring campaign

Induced groundborne vibrations from underground railway traffic

Cultural heritage buildings

Structural monitoring of induced vibrations

Groundborne vibrations • underground railway traffic

Karanikoloudis, G., Lourenço, P.B., Mendes, N., Bile J. S., Boroschek, R. (2020) Monitoring of induced groundborne vibrations in cultural heritage buildings. Miscellaneous errors and aliasing through integration and filtering, International Journal of Architectural Heritage. (DOI: 10.1080/15583058.2020.1802532)

❑ 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
Historical buildings under state protection	-	Vibrations at highest level	Wave speed (m/s)			GB/T 50452 2008 China
		Brick	<1600 1600-2100 >2100	0.15 0.15-0.2 0.2	$\lvert V_{max} \rvert$	
		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

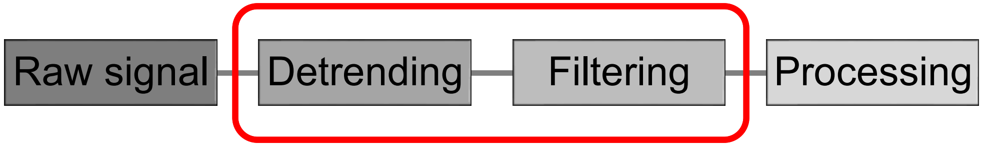
Groundborne vibrations • underground railway traffic

- ❑ Monitoring of metro induced vibrations in three cultural heritage buildings
  Church of the Angels, in Lisbon ✓

- ❑ 1 passing train every 3-5 min

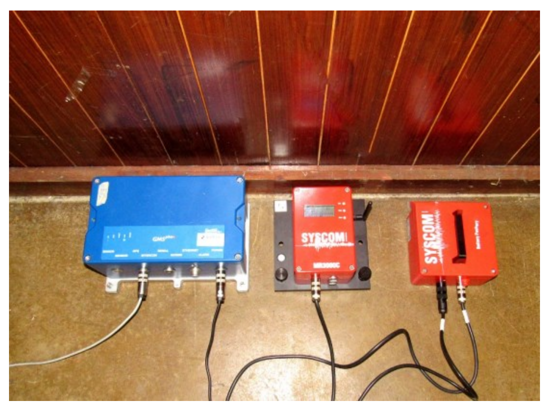
- ❑ Use of kinetic quantities

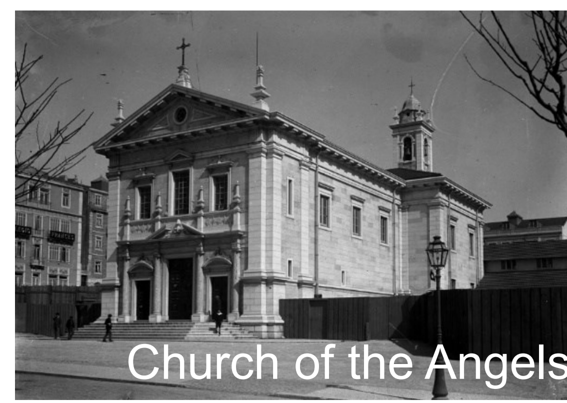
- ❑ Response is mass controlled since $f_n < f_s$
  Attenuation is expected



- ❑ Triaxial seismographers with GPS time base
  Triaxial geophone ✓

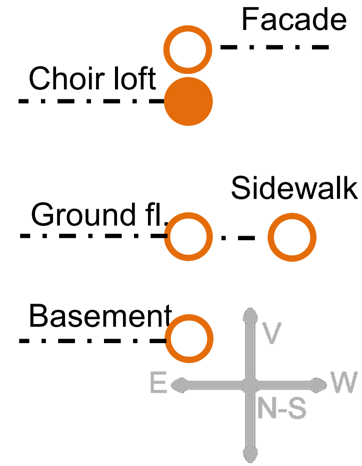
- ❑ Sampling frequency 1000-2000Hz

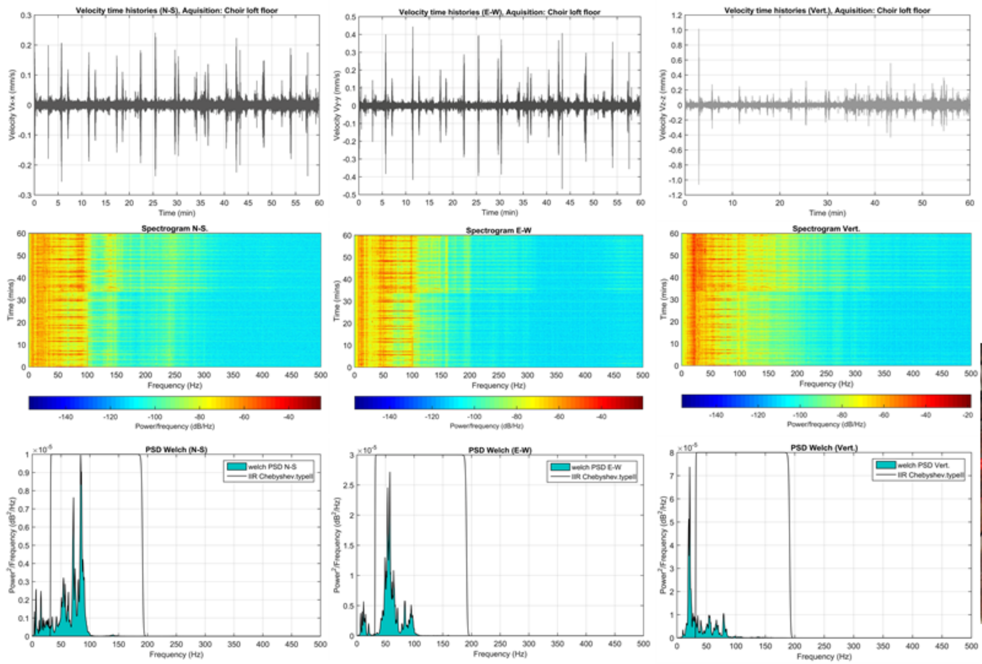


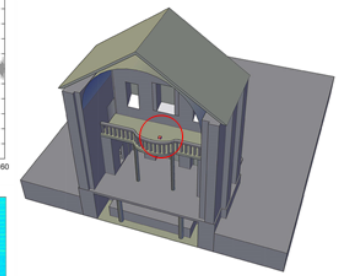


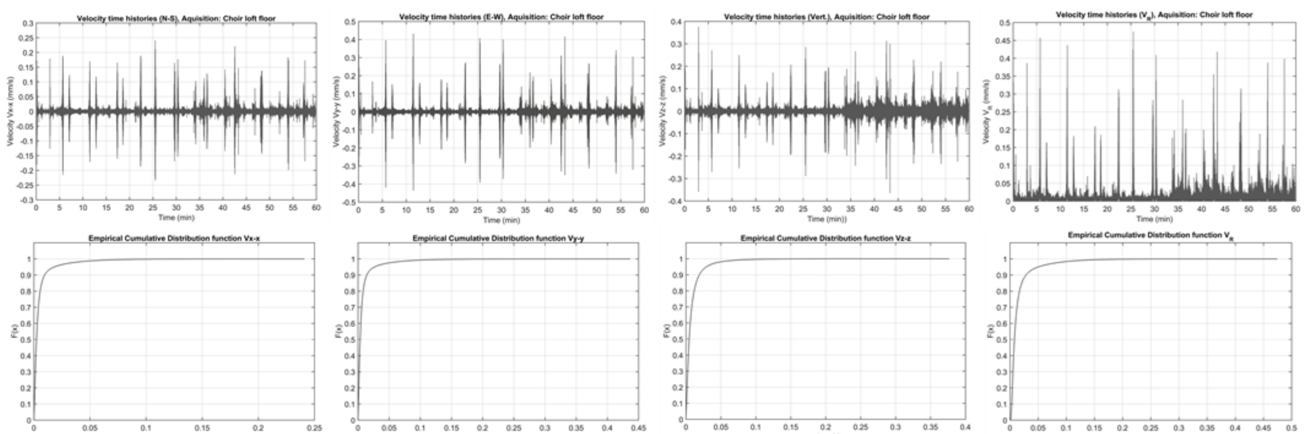
Structural monitoring of induced vibrations

Church of the Angels, Lisbon





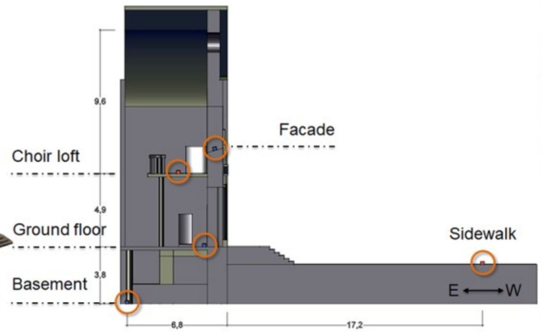


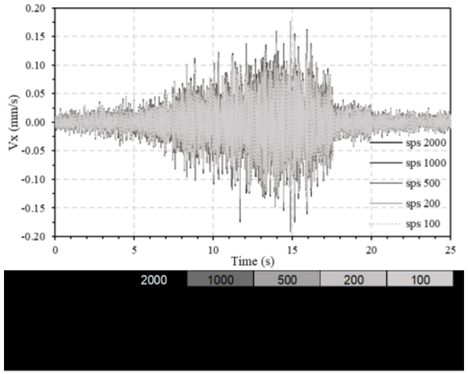


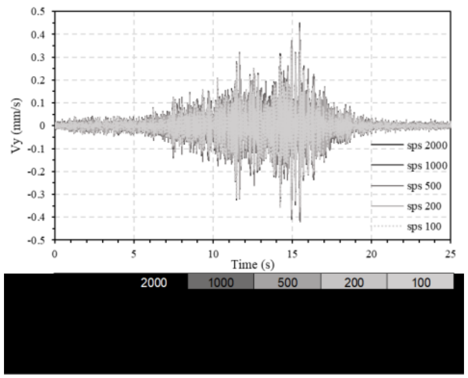
$F(x) = 1 - 10^{-6}, x = 0.23$ mm/s $F(x) = 1 - 10^{-6}, x = 0.42$ mm/s $F(x) = 1 - 10^{-6}, x = 0.36$ mm/s $F(x) = 1 - 10^{-6}, x = 0.44$ mm/s

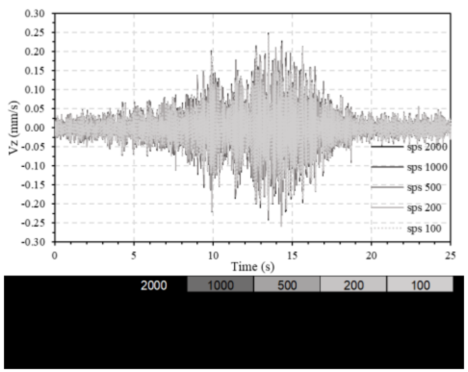
Structural monitoring of induced vibrations

Church of the Angels, Lisbon









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 30-200 y-y 30-200 z-z 30-200	76.9[2]	4
Choir loft Facade windows	0.12	0.13	x-x 30-110 y-y 30-200 z-z 30-200	125[3]	15
Ground floor	0.11	0.12	x-x 30-150 y-y 30-160 z-z 30-100	66.7[3]	16
Basement	0.27	0.27	x-x 30-160 y-y 30-160 z-z 30-125	66.7[2]	9
Sidewalk (Ref.)	0.65	0.72	x-x 30-100 y-y 30-100 z-z 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

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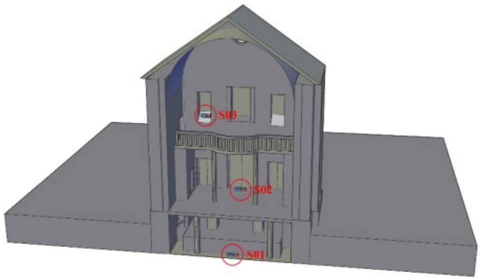
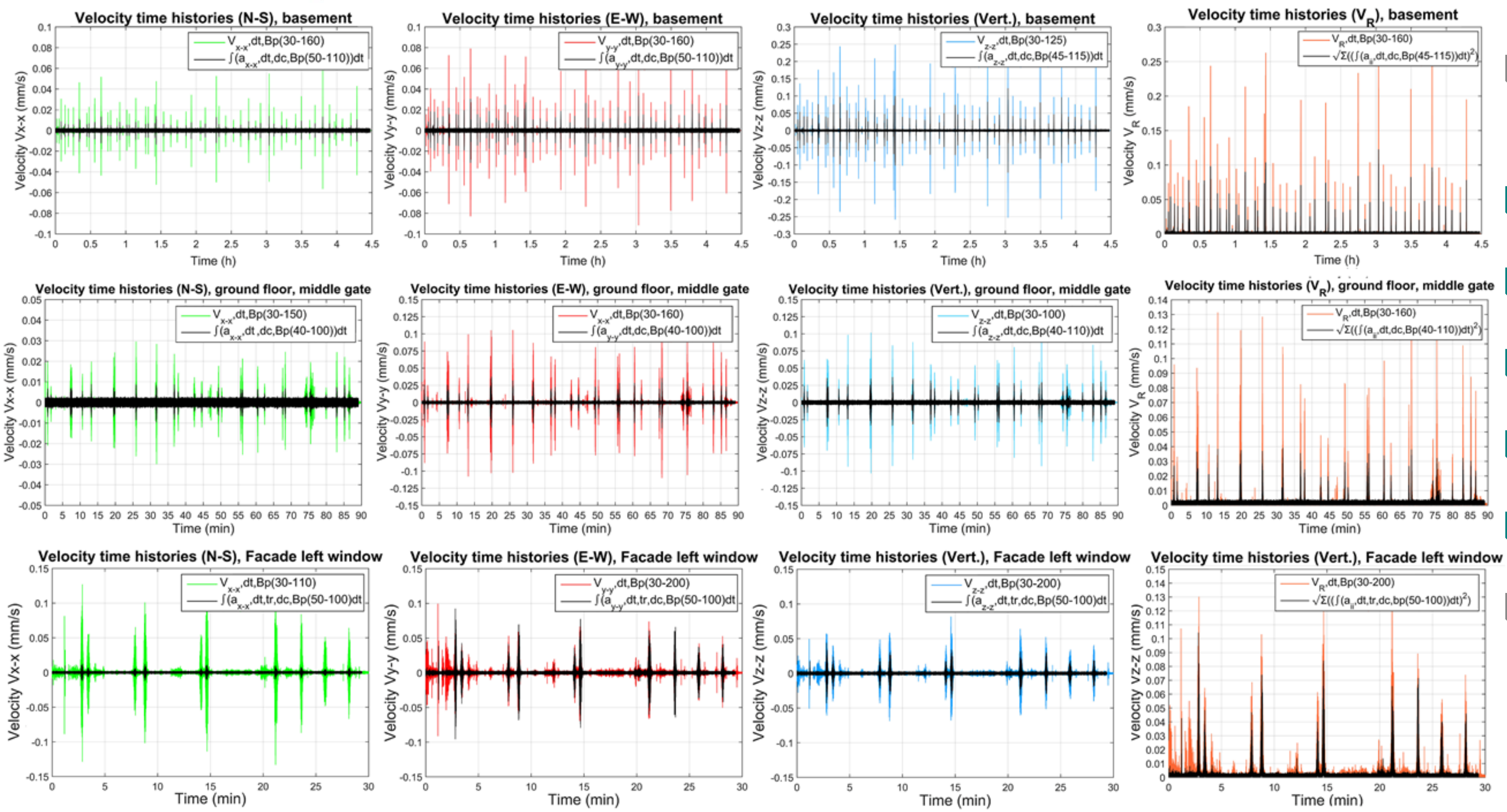
Church of the Angels, Lisbon



- ❑ Coupling recordings with geophones and seismographers
- ❑ Accelerations: numerical integration of low accuracy -blind processing-



- ❑ Differences: 40-170%
- ❑ Poor sampling
- ❑ Weak coupling
- ❑ High SNR
- ❑ Intense filtering
- ❑ Low sensitivity
- ❑ Velocity as the primary measurement

Experimental campaign

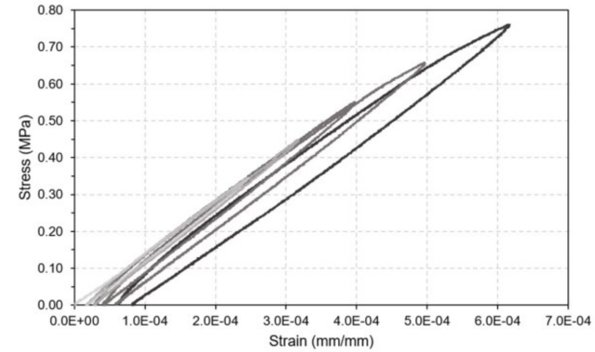
Historic masonry facades

Fatigue tests on masonry wallets under diagonal compression

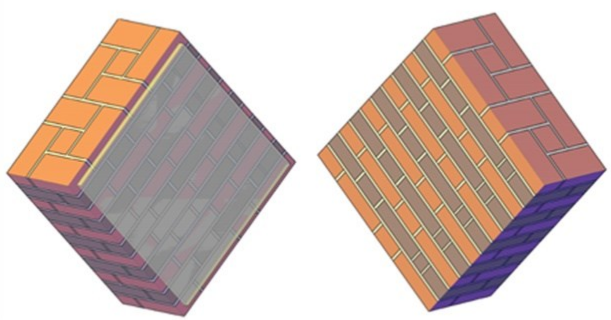
Experimental campaign

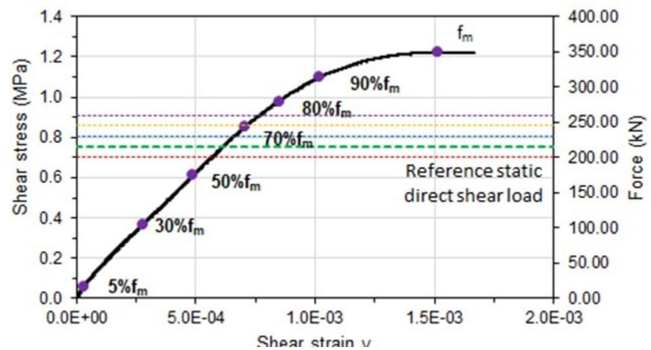
Fatigue tests on masonry wallets under diagonal compression

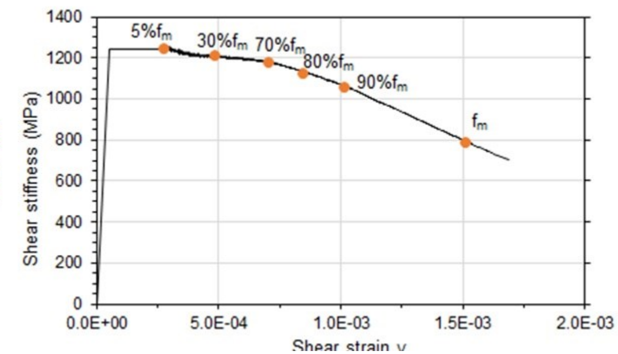
- ❑ **Static cyclic preload**
  Shear load: 100 (~30%ft), 120, 140, 160, 180, 200, 220 (~60%ft) kN



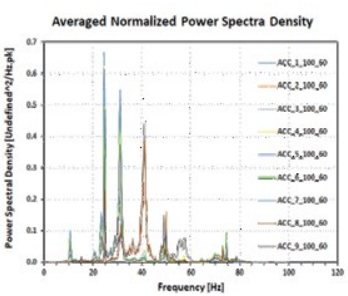
- ❑ **Stiffness degradation**
  Monitoring with NDTs

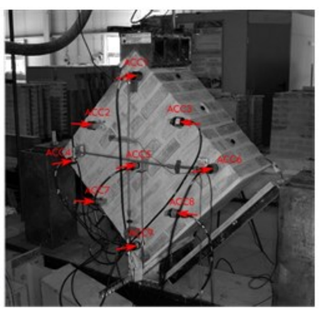




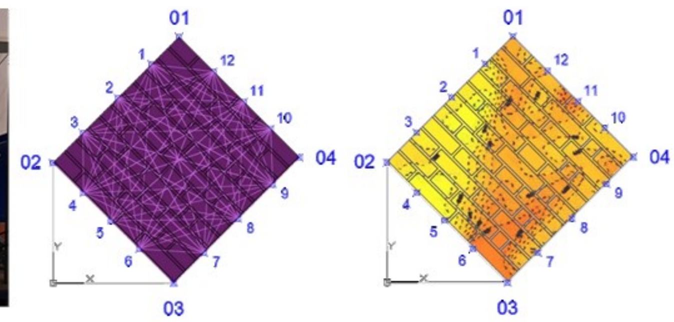


Ambient vibration test
Compressive static load: 2.5 kN

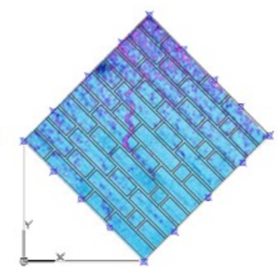




Sonic tomography



Digital image correlation (DIC)



Experimental campaign

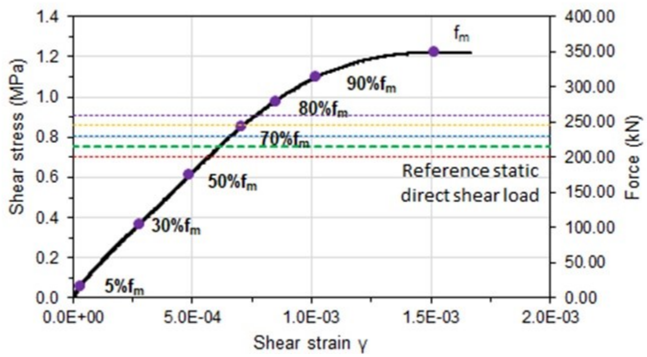
Fatigue tests on masonry wallets under diagonal compression

- Selection of sinusoidal load (amplitude, duration)

  Ground borne vibrations: ppv (mm/s) > ppd (mm) > Stress (MPa) > Force (kN)

$$\sigma_c(x,t) = E\frac{\partial}{\partial x}u(x,t) = -\frac{E}{c}\frac{\partial}{\partial t}u(x,t) = \frac{E\omega u_o}{c}\sin(kx-\omega t+\frac{\pi}{2})$$

- Duration: 16h daily train operation
- Number of cycles: 1 train every 5 min > 70.000 trains/year
- Plan: Division of fatigue tests in parts of 150.000 cycles (~20h)
- Specimen: Selection of a ppv level for increasing static loads, until failure



Upper bound of diagonal compression load

1: 200 kN
2: 215kN
3:230kN
4:245kN
5:260kN
...

	eq. ppv (mm/s)	eq. ppd (mm)	ω (rad/s)	f (Hz)
dcf2	10	0.021	471	75
dcf4	15	0.032		
dcf3	20	0.042		

- Equivalent ppv ~ ppd ~ σ ~ P adjusted according to stiffness properties

Experimental campaign

Fatigue tests on masonry wallets under diagonal compression

- Selection of sinusoidal load (amplitude, duration)

  Ground borne vibrations: ppv (mm/s) > ppd (mm) > Stress (MPa) > Force (kN)

$$\sigma_c(x,t) = E\frac{\partial}{\partial x}u(x,t) = -\frac{E}{c}\frac{\partial}{\partial t}u(x,t) = \frac{E\omega u_o}{c}\sin(kx - \omega t + \frac{\pi}{2})$$

- Duration: 16h daily train operation
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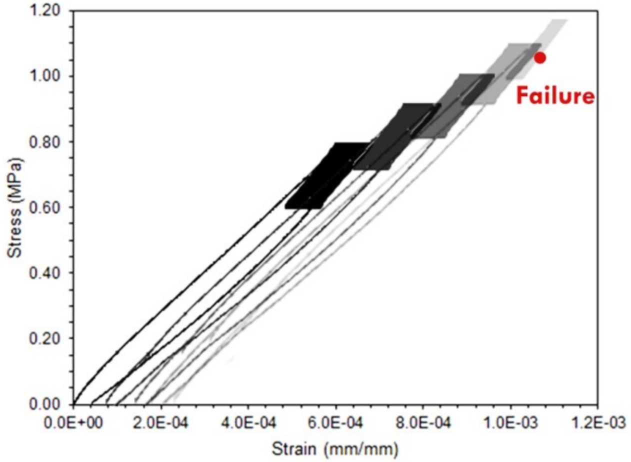
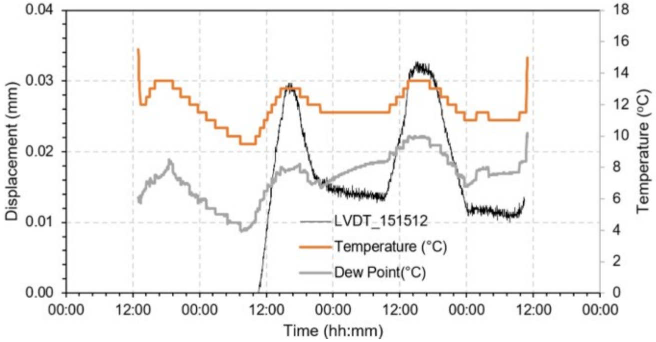




- Equivalent ppv ⇔ ppd ⇔ σ ⇔ P adjusted according to stiffness properties

Experimental campaign

Historic masonry facades

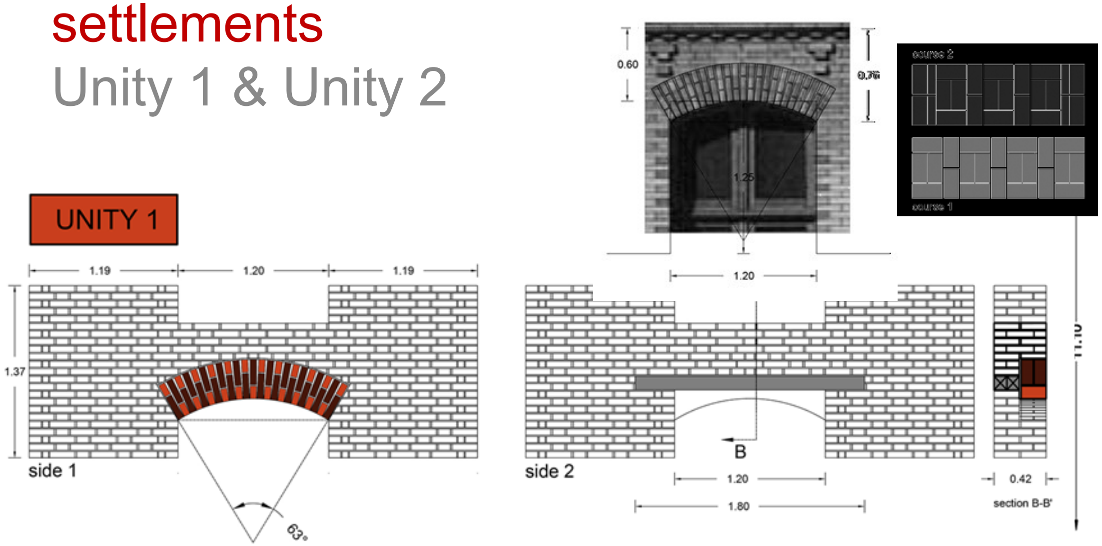
Tests of differential settlements on pier and spandrel specimen

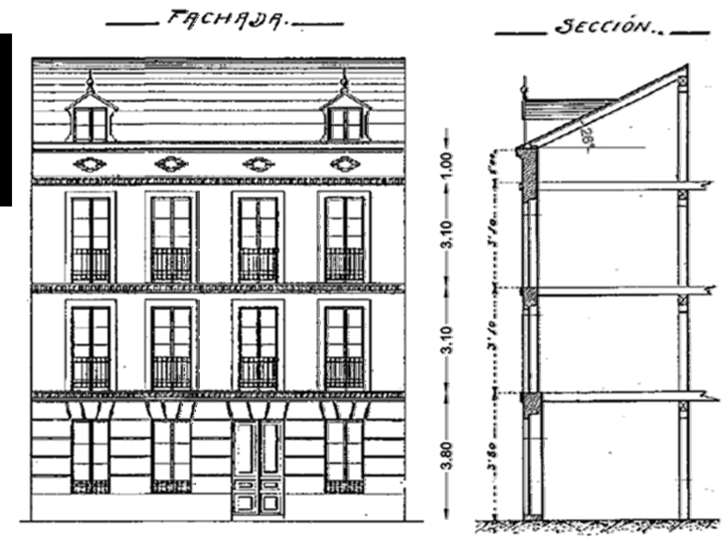
Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

- ❑ In-plane capacity under differential settlements
  Unity 1 & Unity 2

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

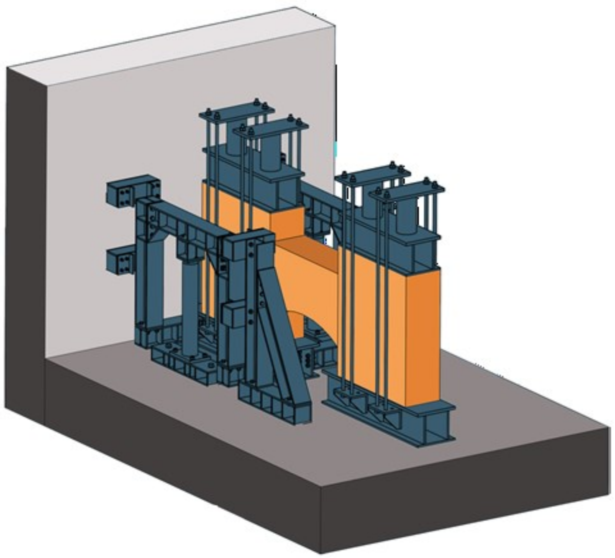


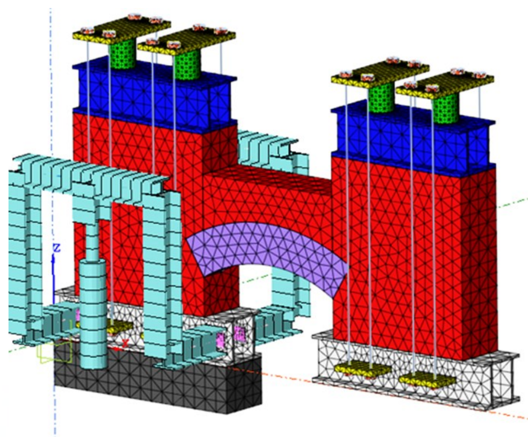


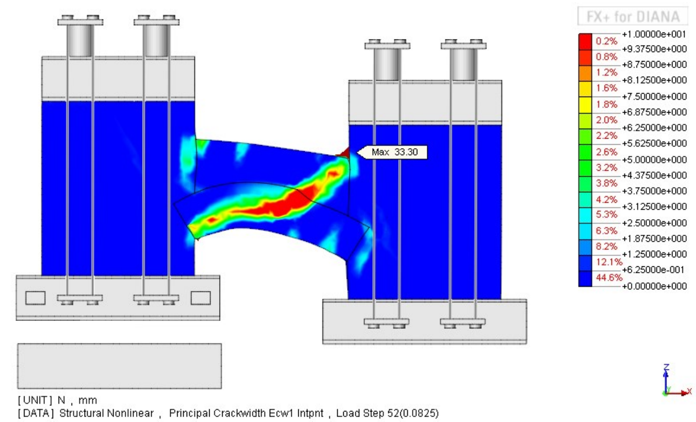
Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

- ❑ In-plane capacity under differential settlements

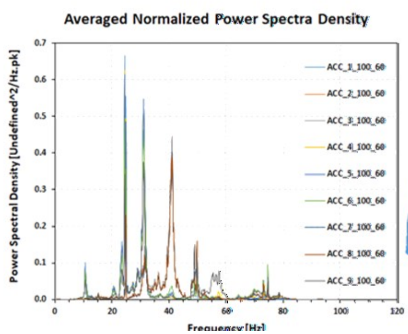


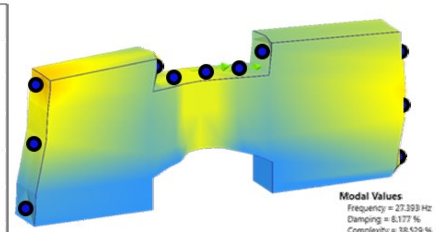




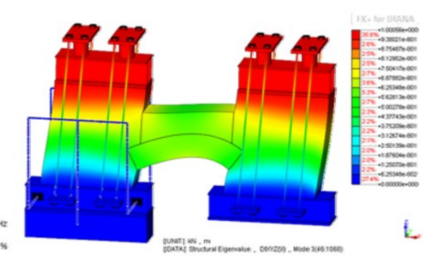
- ❑ Damage detection
- ❑ Modal updating

Ambient vibration test
Compressive static stress: 0.1 MPa





FEM - Modal updating
Material/Interface properties

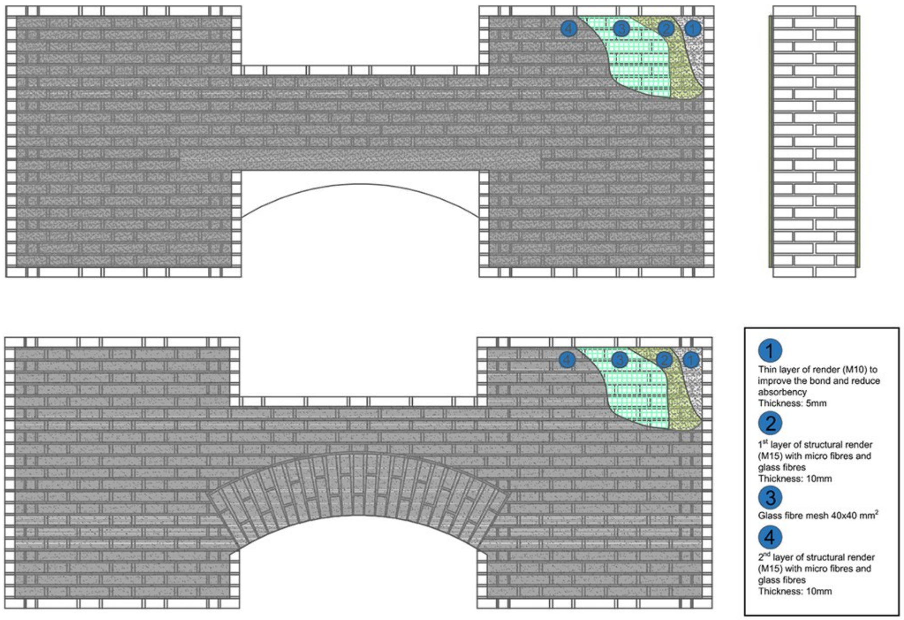


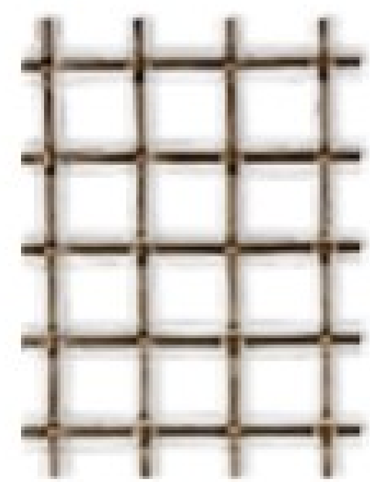
Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

- ❑ Repair and retrofit

  Unity 1 & Unity 2





- ❑ Consolidation with an injection grout of a lime-based fluid hydraulic binder (M15)

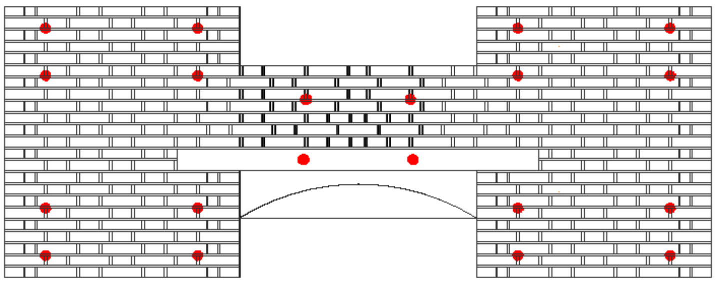
- ❑ FRCM system (Fibre Reinforced Cementitious Matrix), with mechanical anchors

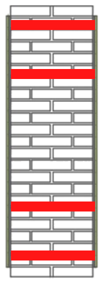
Experimental campaign

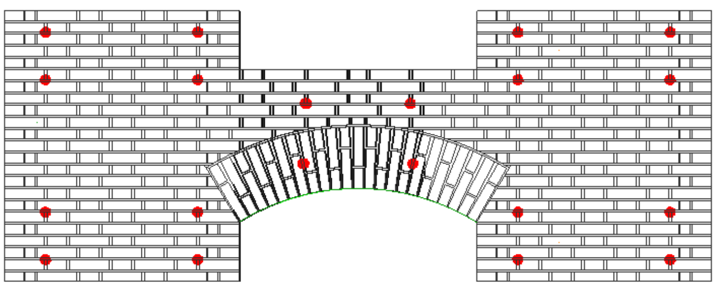
Historic masonry facades • Brick masonry piers and spandrels

- Repair and retrofit

  Unity 1 & Unity 2







1. Thin layer of render (M10) to improve the bond and reduce absorbency
   Thickness: 5mm
2. 1st layer of structural render (M15) with micro fibres and glass fibres
   Thickness: 10mm
3. Glass fibre mesh 40x40 mm^2
4. 2nd layer of structural render (M15) with micro fibres and glass fibres
   Thickness: 10mm

- Consolidation with an injection grout of a lime-based fluid hydraulic binder (M15)

- FRCM system (Fibre Reinforced Cementitious Matrix), with mechanical anchors

Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

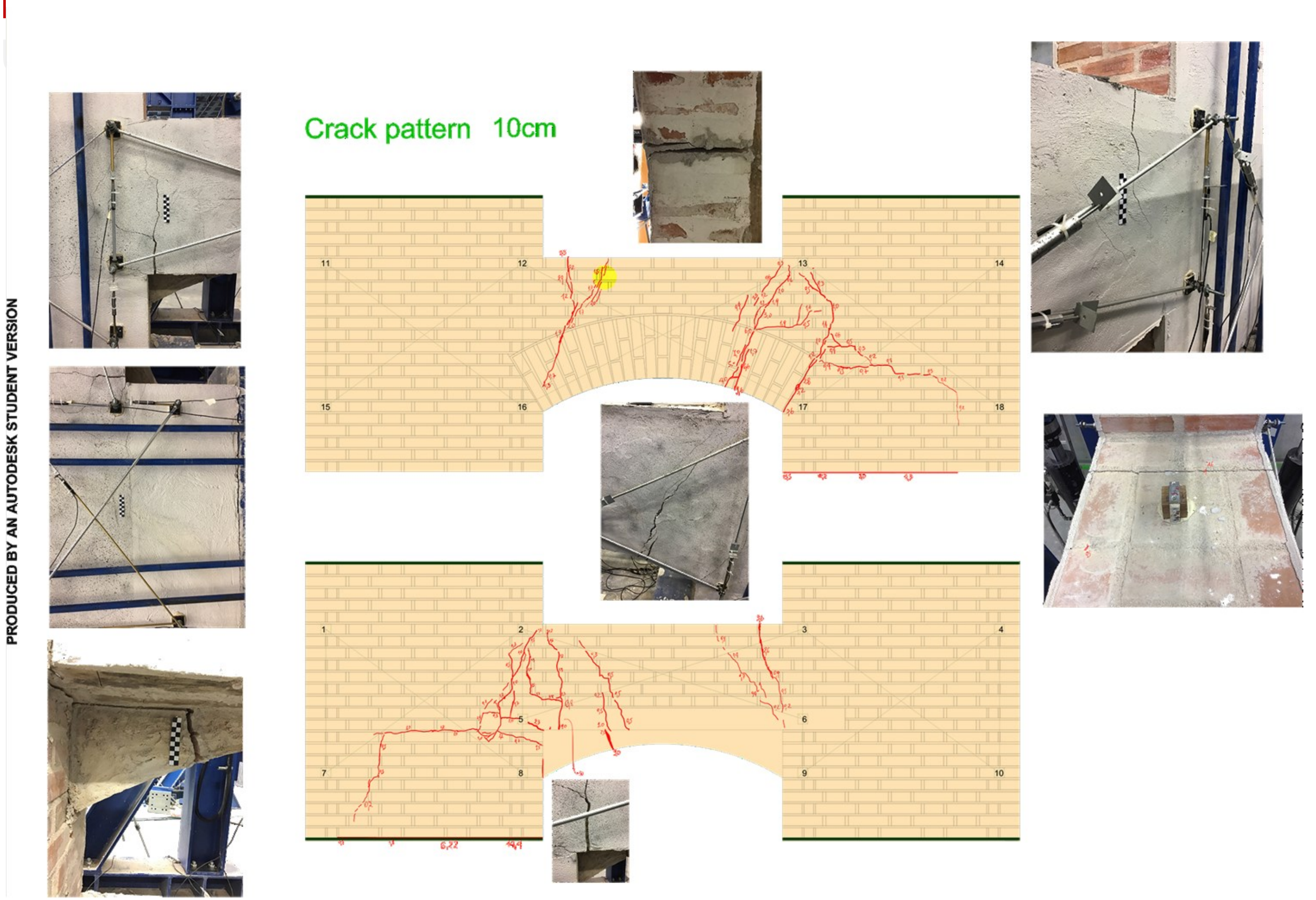
- Repair and retrofit

  Unity 1 & Unity 2

Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

- Repair and retrofit



Timeline

Scheduled completion and submission of the testing and modelling tasks

October 2020	November 2020	December 2020	February 2021	March 2021
Chapter 3 Material characterization of simulated historic masonry	**Chapter 4** Field monitoring campaign of induced groundborne vibrations	**Chapter 5** Fatigue tests on masonry wallets under diagonal compression	**Chapter 6** Tests of differential settlements on pier and spandrel specimen. Repair and retrofit applications	**Chapter 7** Multitude effects of induced groundborne vibrations and differential settlements in buildings of cultural heritage
			Submission in ISI journal of **Chapter 5**	Submission in ISI journal of **Chapter 6**

Thank you

Acknowledgments

Partly supported by FCT (Portuguese Foundation for Science and Technology) within ISISE project UID/ECI/04029/2013