Infrastructures and Geotechnics

Fatigue loading in historic brick masonry under moderate stress levels. Experimentally based investigations and monitoring strategies

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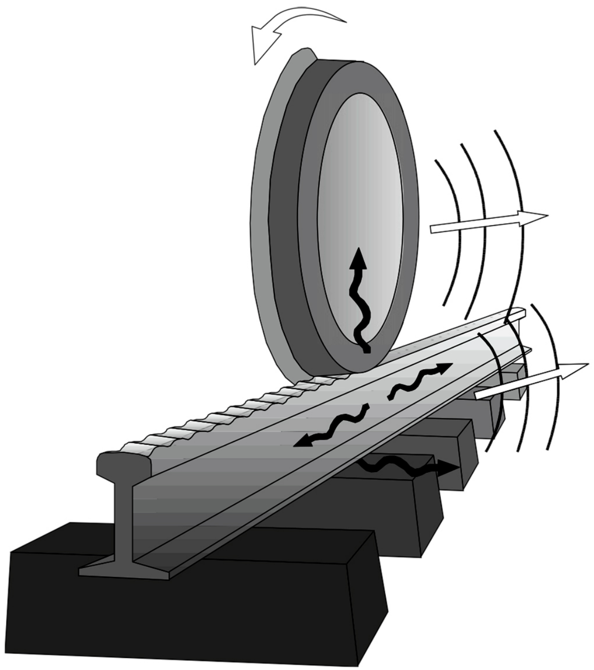
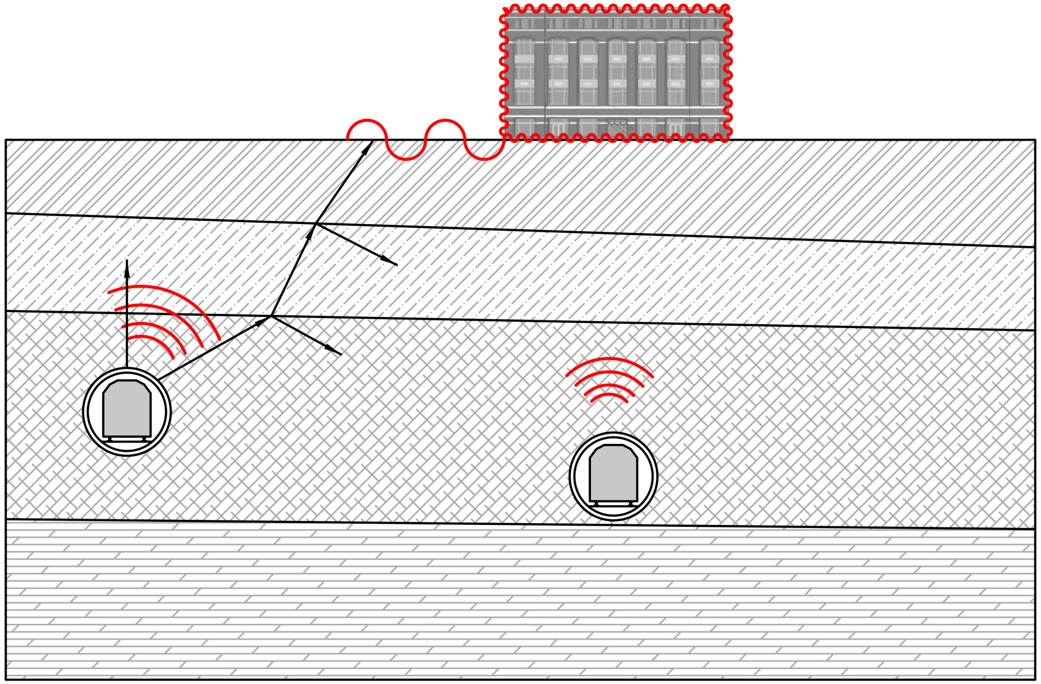
Supervision: Paulo Lourenço (UMinho), João Bilé Serra (LNEC)



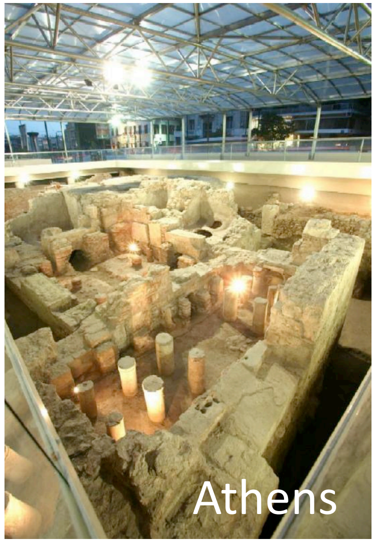
Thompson et al. 2009



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 – Cyclic low-stress rate fatigue tests on masonry

Literature review	Experimental work	Monitoring strategies - NDTs	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

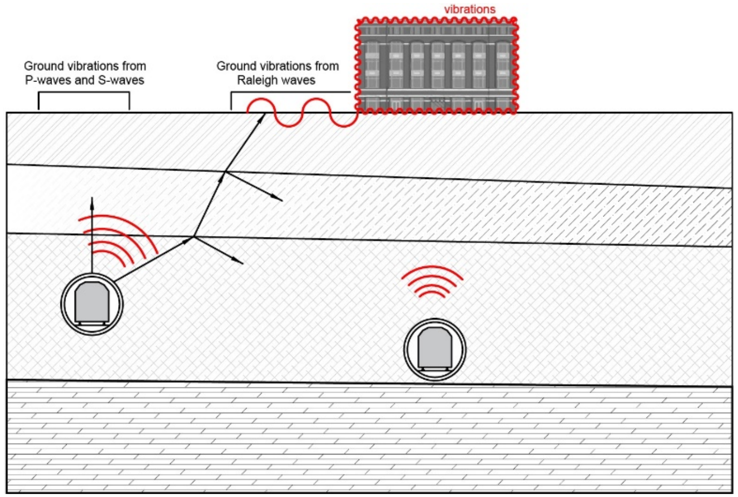
Objectives

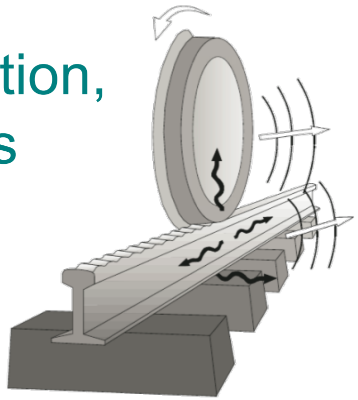
- **Long term performance and stages of fatigue deterioration under low rate strain evolution and moderate stress levels.**
- **Application of damage detection ND strategies for monitoring damage and stiffness degradation in structural elements**
- **Thresholds of damage for elements of architecture; i.e. frescos**
- **Propose a mathematical model for the evolution of strain and Young's modulus for low-strength masonry during compressive and tensile cyclic long-term loading**

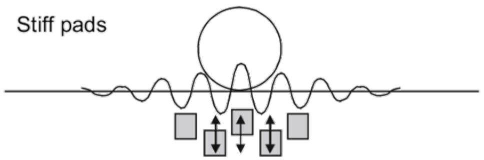
Underground structures in urban environment

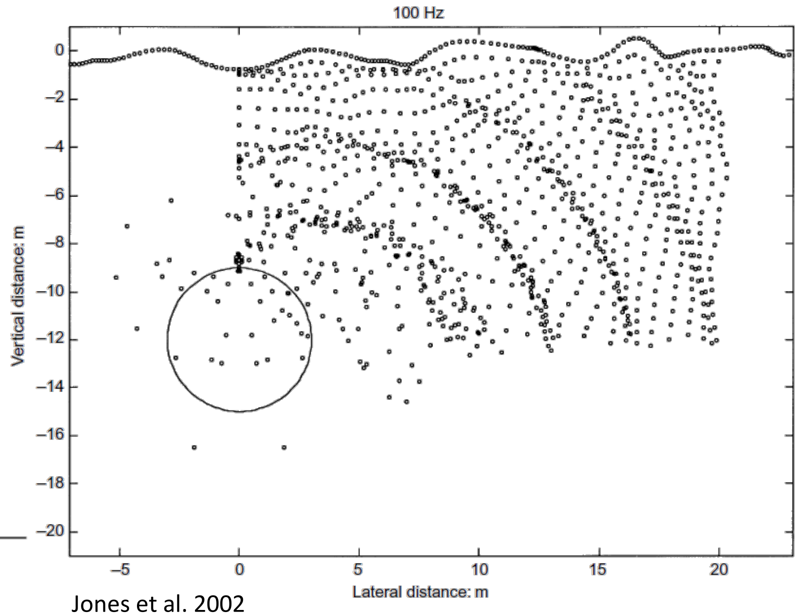
Groundborne vibrations • Underground railways

- ❑ Wave propagation in the elastic half-space
  P-wave, S-waves, Rayleigh waves
- ❑ Quasi-static, dynamic axle loads
  Unevenness of wheels and track lines
- ❑ High frequency content 30-250 Hz
- ❑ The type of building: dimensions, structural system and material properties
- ❑ The level of exposure: duration, amplitude, number of cycles
- ❑ Soil type: energy content in different frequency range









Jones et al. 2002

Underground structures in urban environment

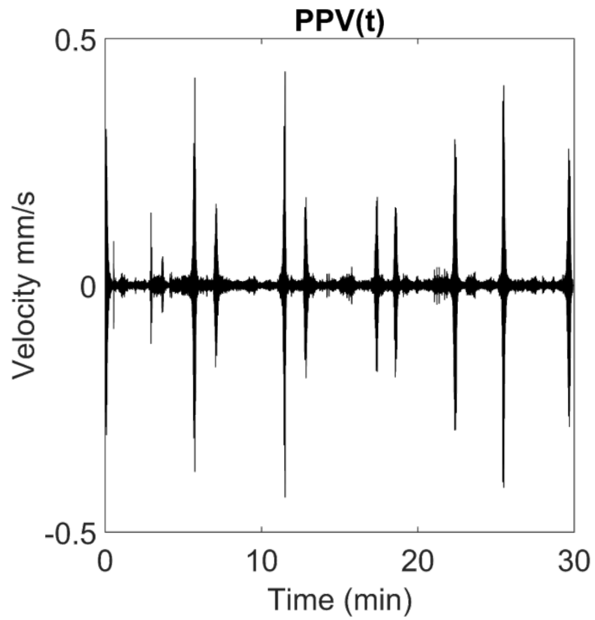
Groundborne vibrations • Thresholds from international standards

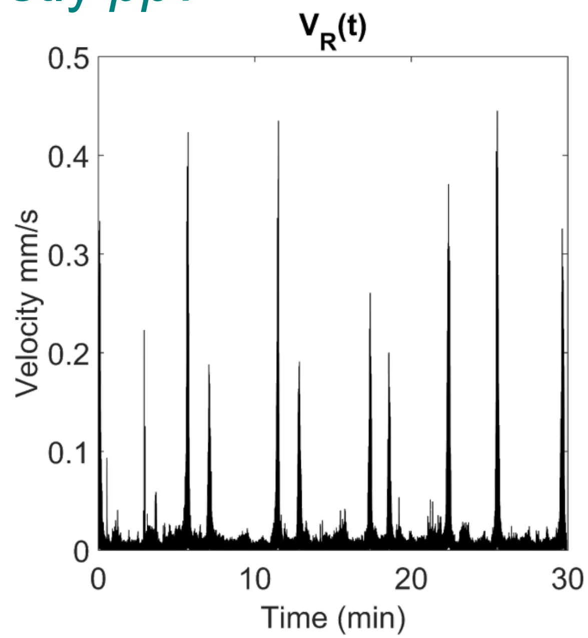
- ❑ Guidelines on: Measurement / Instrumentation / Processing / Evaluation
- ❑ Indicative vibration levels for cosmetic damage
- ❑ Permanent / interminent type
- ❑ Peak-to-peak level analysis of kinetic quantities, mostly *ppv*

$$|V_{MAX}|$$

$$|V_R| = \sqrt{v_{xi}^2 + v_{yi}^2 + v_{zi}^2}$$

ISO 4866:1990
Pv: 0.2-50 mm/s
Pa: 0.002-0.10g





- ❑ Any rise from dynamic magnification ↓50%
- ❑ Fatigue under low vibrations (10^5-10^{10} cycles) • Load bearing capacity

Underground structures in urban environment

Groundborne vibrations • Thresholds from international standards

- 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	3	$\lvert V_{max} \rvert$	DIN 4150 3:1999 Germany
				10-50	3-8		
				50-100	8-10		
		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	1.5-3	$\lvert V_R \rvert$	SN 640312 1992 Switzerland
				30-60	2-4		
				>60	3-6		
Historical buildings under state protection	-	Vibrations at highest level		Wave speed (m/s)			GB/T 50452 2008 China
			Brick	<1600	0.15	$\lvert V_{max} \rvert$	
				1600-2100	0.15-0.2		
				>2100	0.2		
			Stone	<2300	0.20	$\lvert V_{max} \rvert$	
				2300-2900	0.20-0.25		
				>2900	0.25		
			Timber	<4600	0.18	$\lvert V_{max} \rvert$	
				4600-5600	0.18-0.22		
				>5600	0.22		

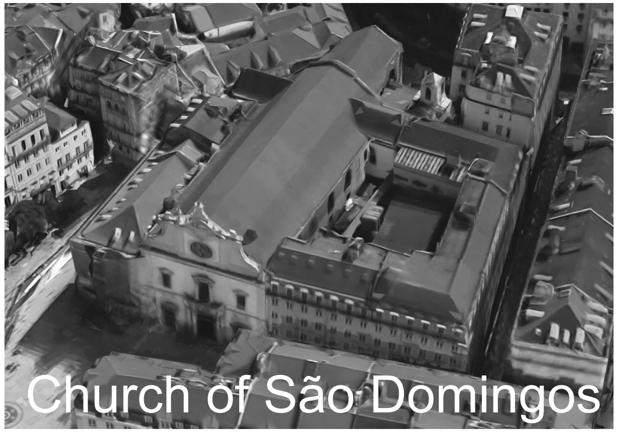
Structural monitoring of induced vibrations

Groundborne vibrations • underground railway traffic


Carmo Convent

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

- ❑ 16-20 passing trains per hour


Church of São Domingos

- ❑ Assessment through different national standards • use of kinetic quantities

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

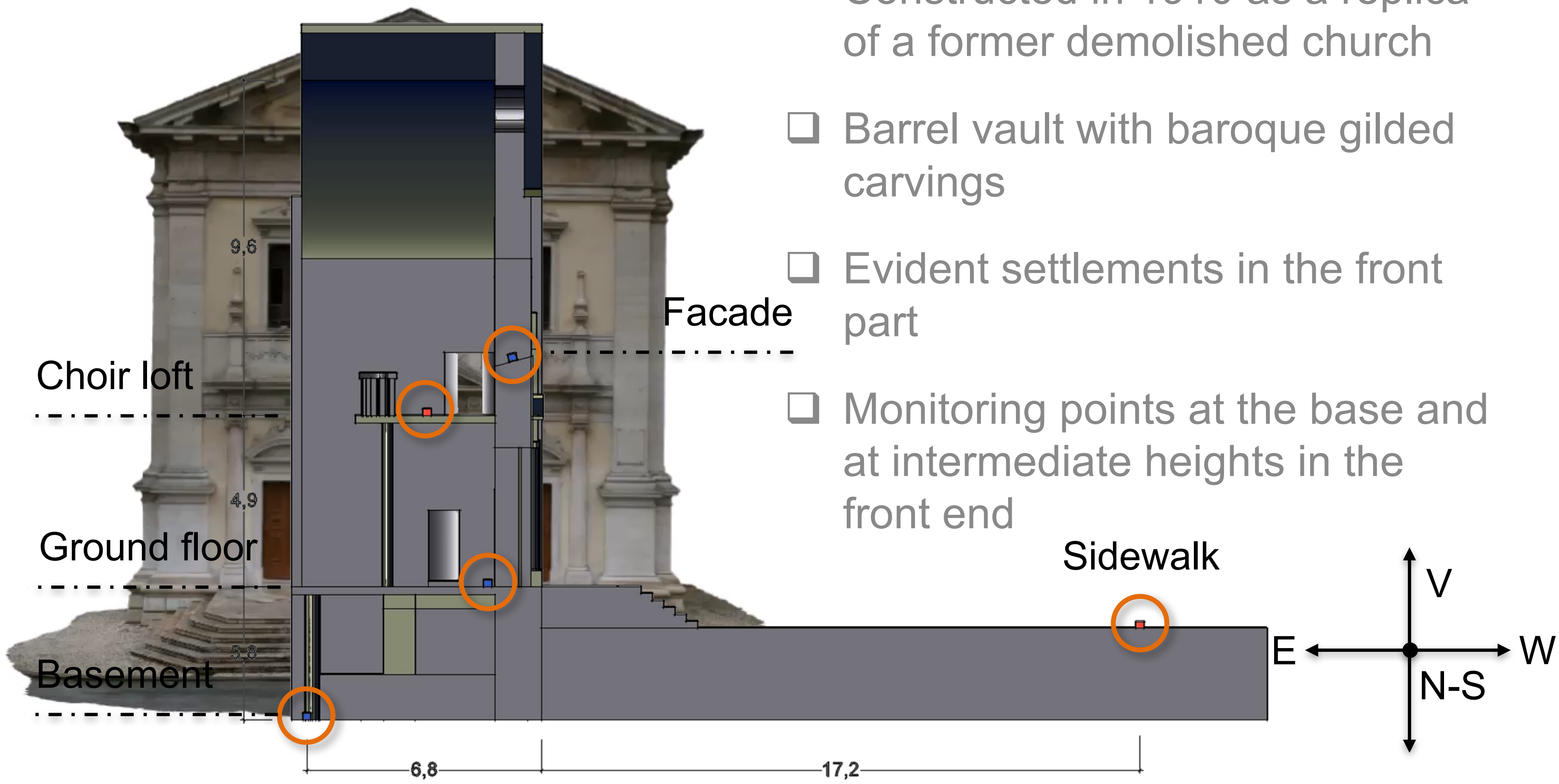
- ❑ Triaxial seismographers with GPS time base
  Triaxial geophone

- ❑ Sampling frequency 1000-2000Hz


Church of the Angels

Structural monitoring of induced vibrations

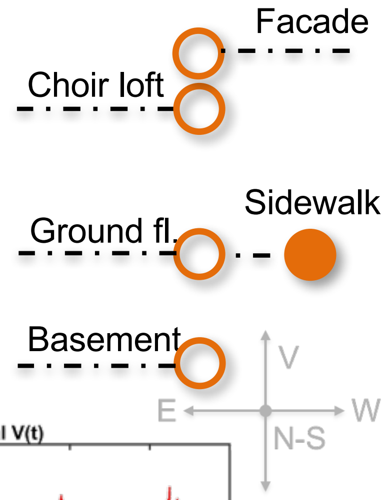
Church of the Angels, Lisbon



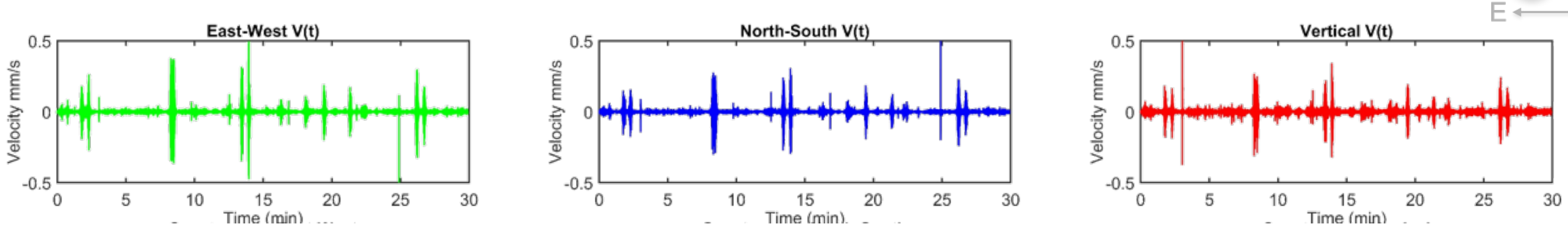
- Baroque and neoclassical style Constructed in 1910 as a replica of a former demolished church
- Barrel vault with baroque gilded carvings
- Evident settlements in the front part
- Monitoring points at the base and at intermediate heights in the front end

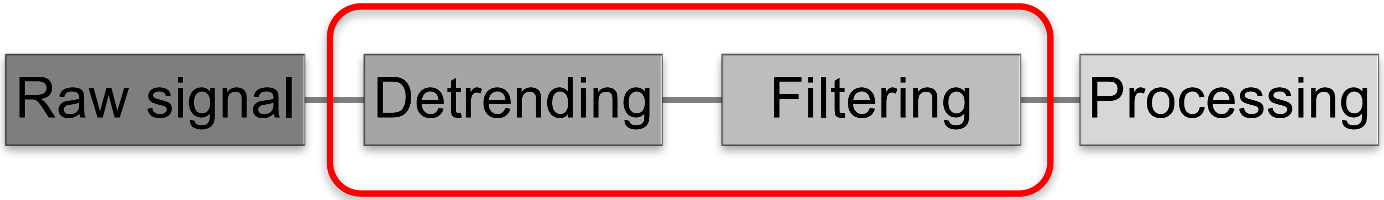
Structural monitoring of induced vibrations

Church of the Angels, Lisbon



- ❑ Vibrations from passing underground trains
- ❑ Signal visualization-analysis in time & frequency domain





- ❑ Sampling rate of 1000 Hz for durations of ½ hour
- ❑ Cut-off frequencies with filtering according to PSD functions
- ❑ Smoothing • Preserving information content
- ❑ Band-pass IIR Chebyshev Type II filter

Structural monitoring of induced vibrations

Church of the Angels, Lisbon

- ❑ Vibrations from passing underground trains

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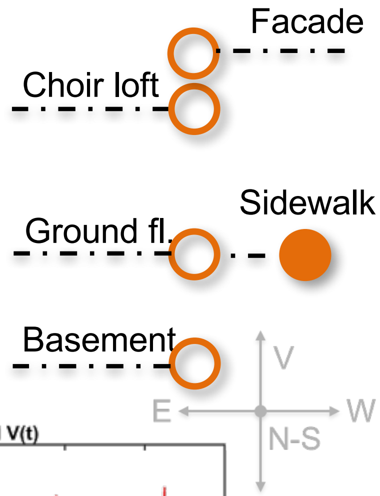

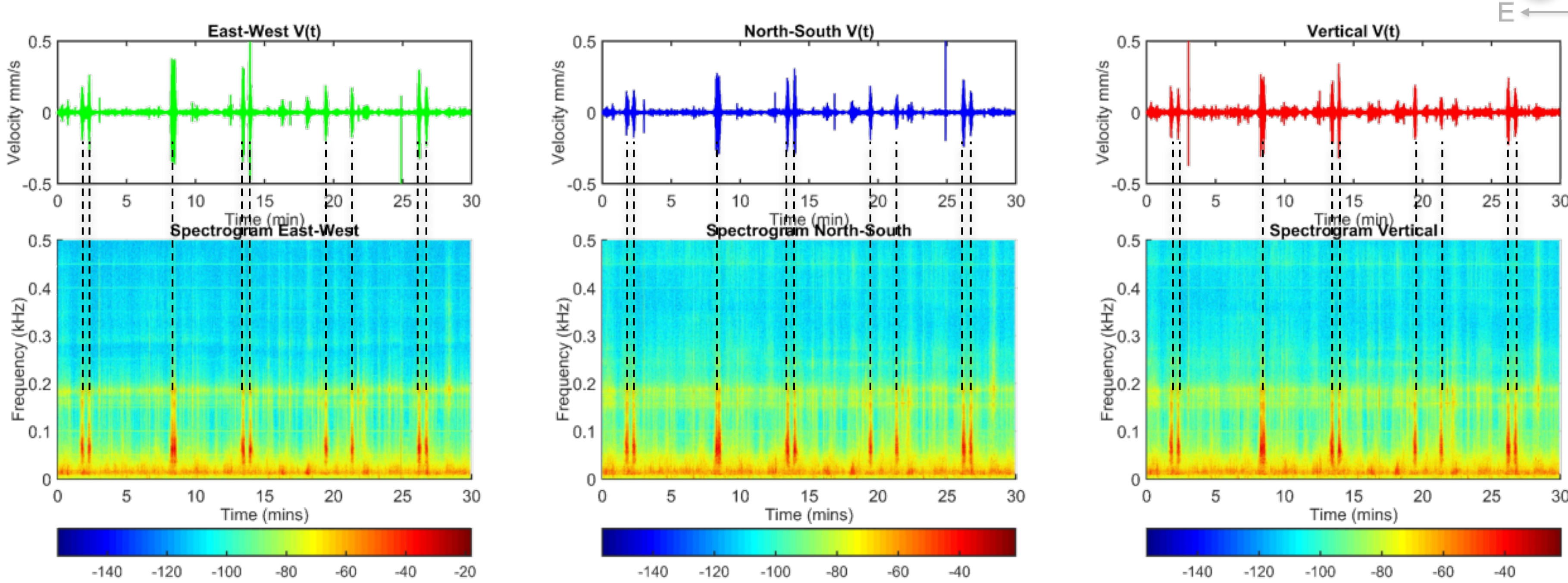

Structural monitoring of induced vibrations

Church of the Angels, Lisbon

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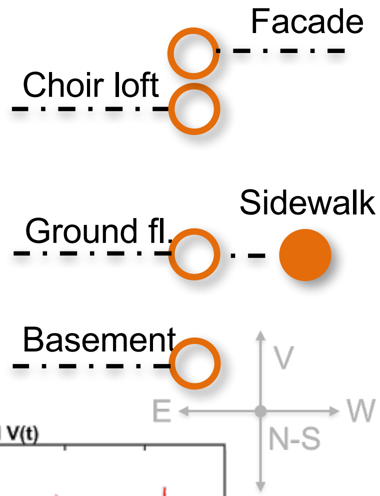
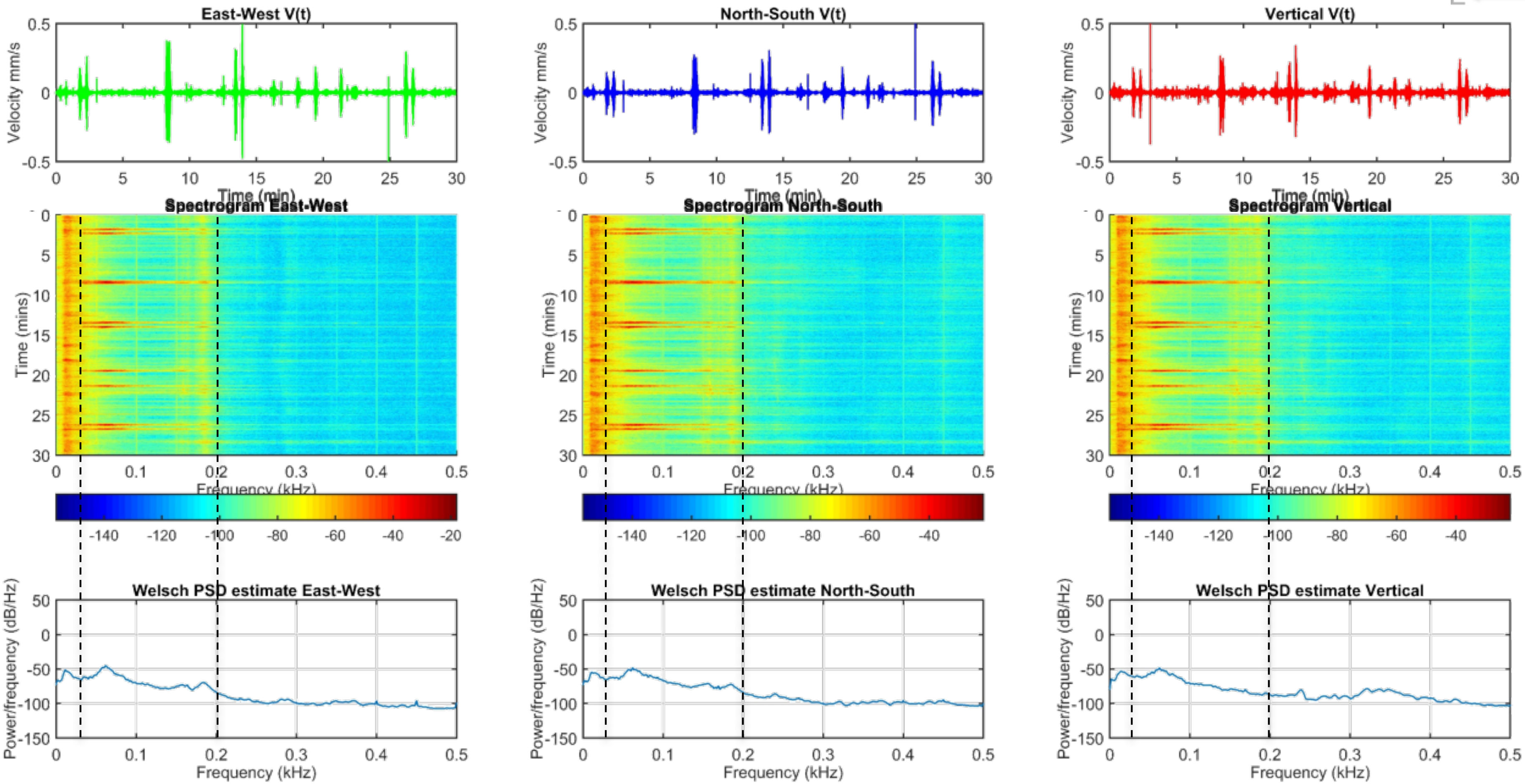
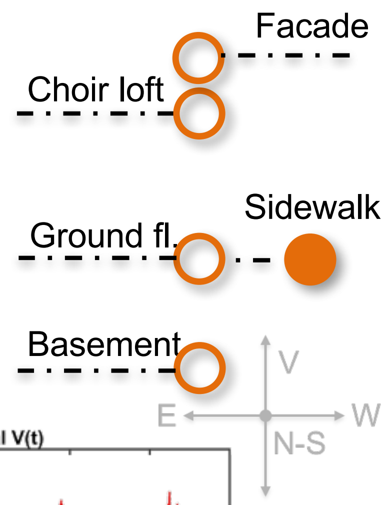




Structural monitoring of induced vibrations

Church of the Angels, Lisbon



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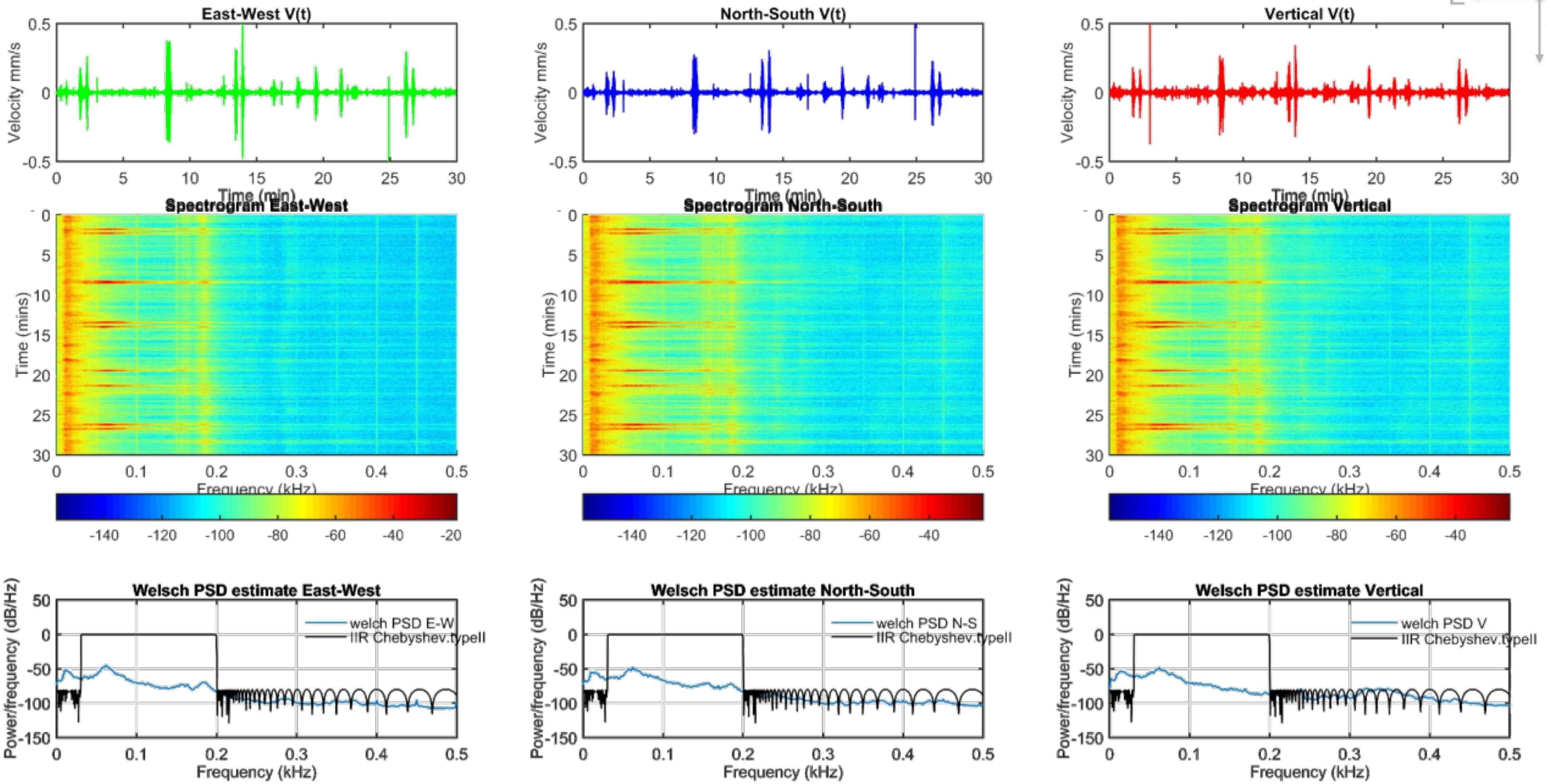
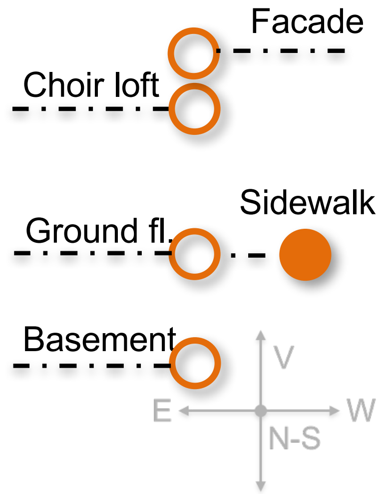


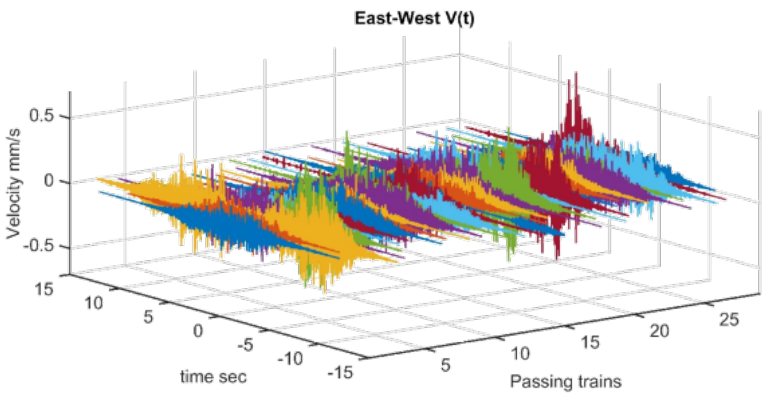
Structural monitoring of induced vibrations

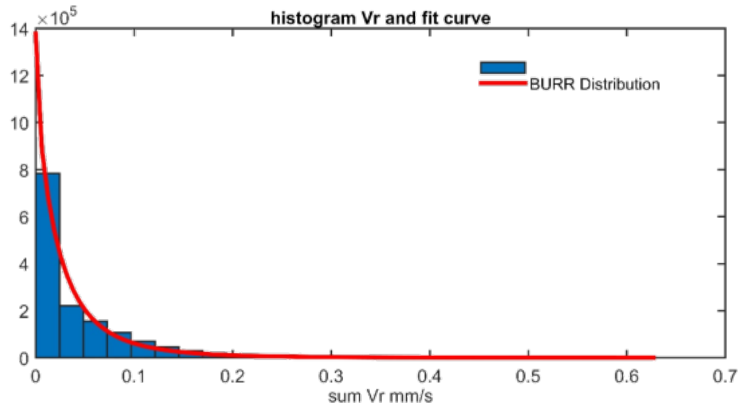
Church of the Angels, Lisbon

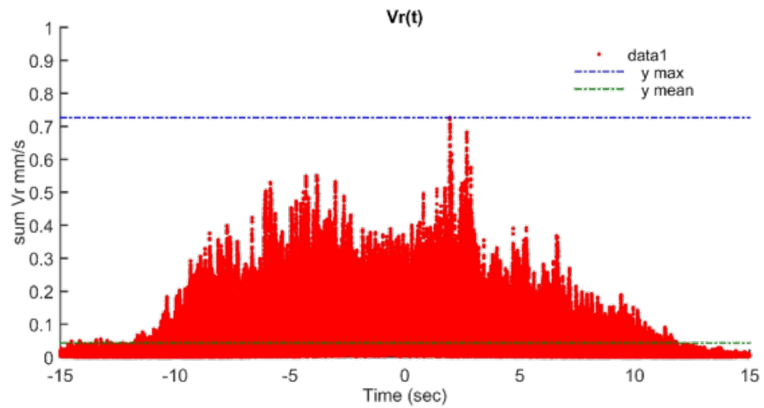


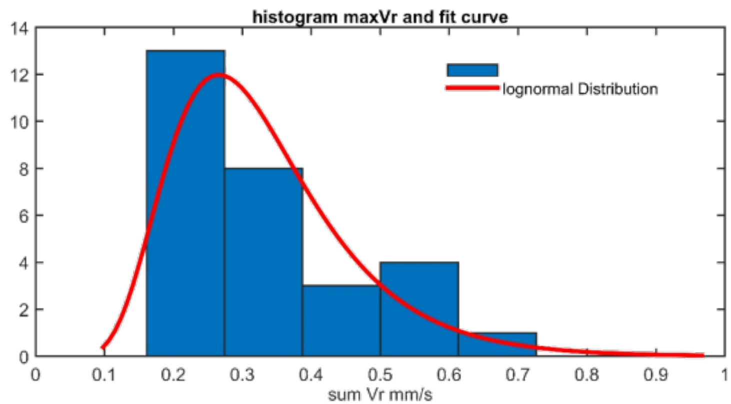
- Max incidental ppv V_R = 0.7 mm/s
  For each event: Mean (0.33), Std (13%)

- Mean spatial frequency of 91 Hz (6%Std)



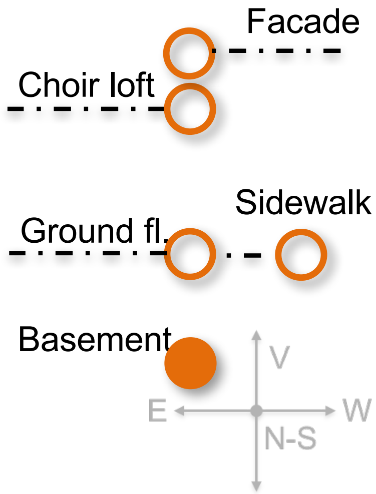






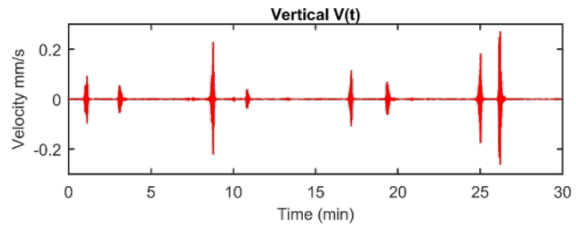
Structural monitoring of induced vibrations

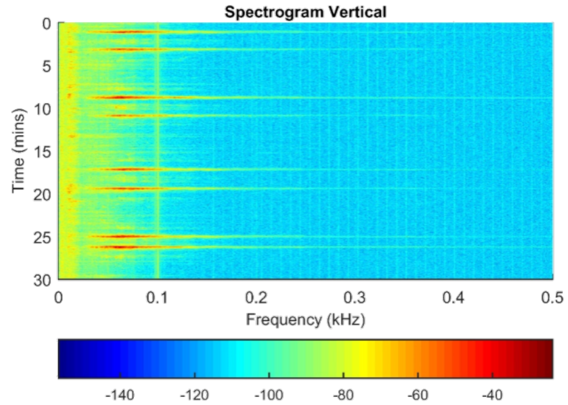
Church of the Angels, Lisbon

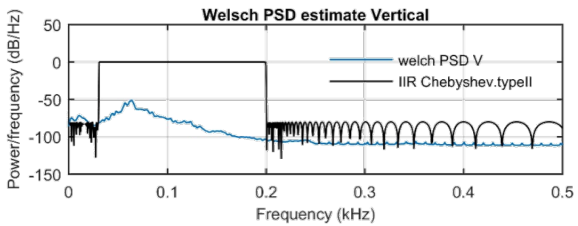


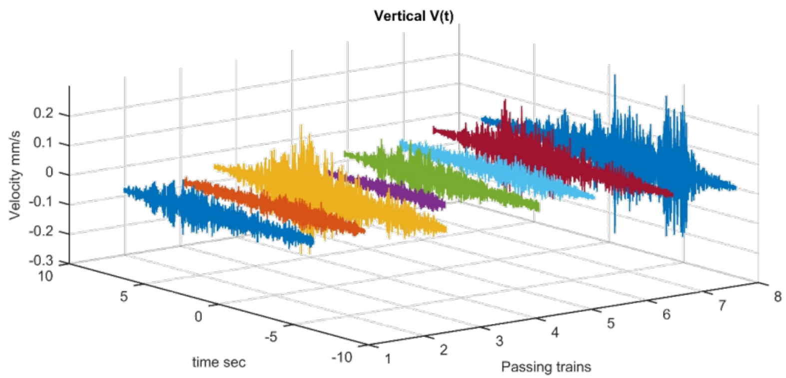
- ❑ Max incidental ppv V_R = 0.3 mm/s
  For each event: Mean (0.13), Std (8%)

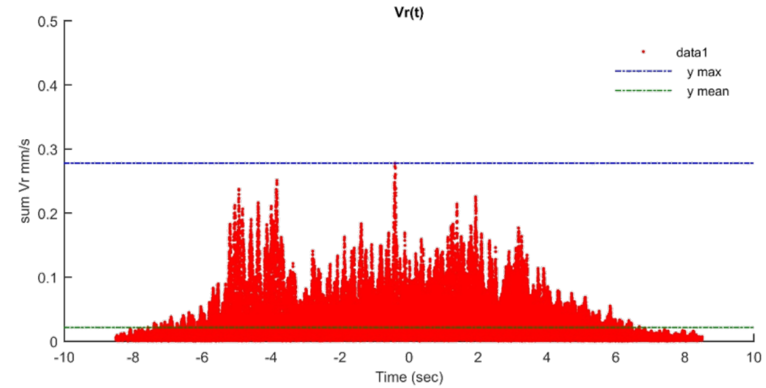
- ❑ Mean spatial frequency of 73 Hz (3%Std)

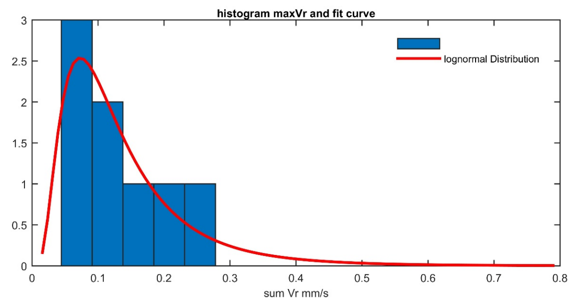










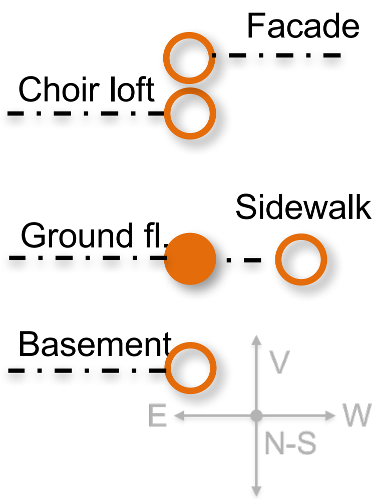


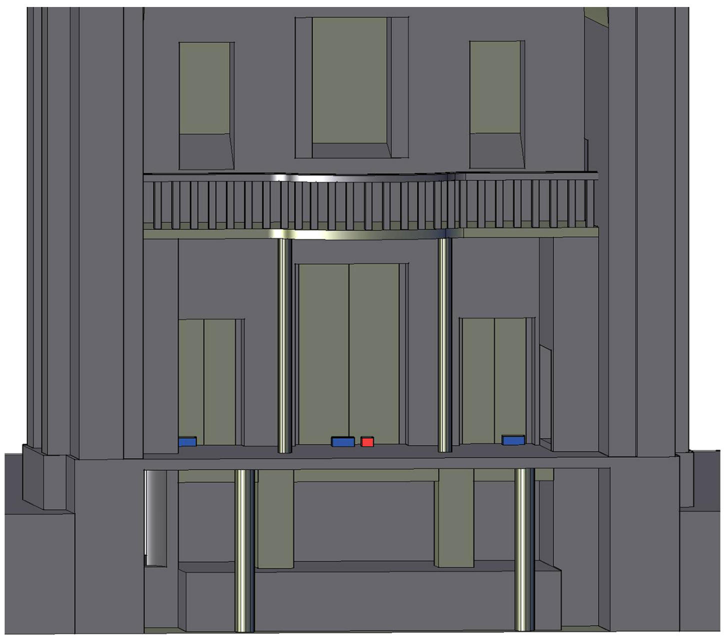
Structural monitoring of induced vibrations

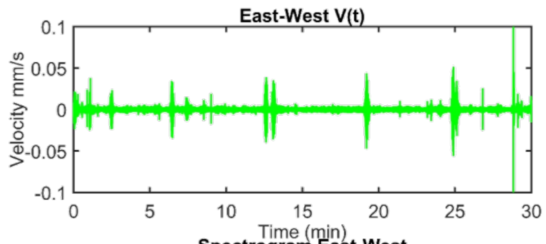
Church of the Angels, Lisbon

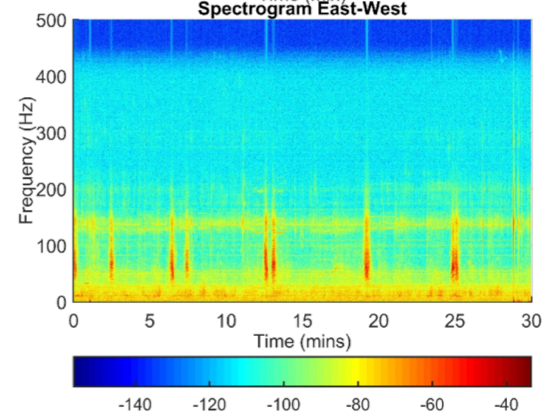
- ❑ Max incidental ppv V_R = 0.06 mm/s
  For each event: Mean (0.008), Std (1%)

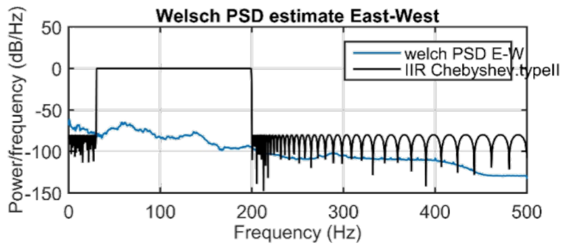
- ❑ Mean spatial frequency of 74 Hz (3%Std)

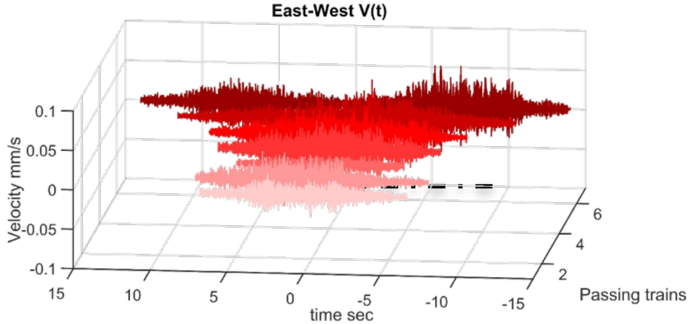


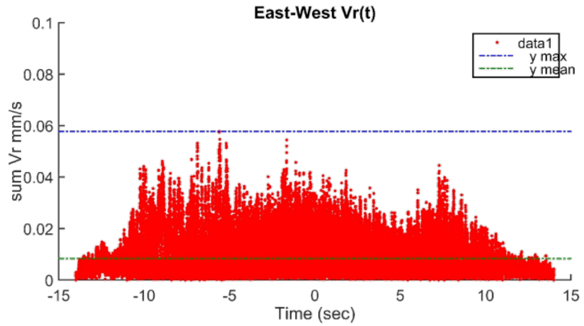






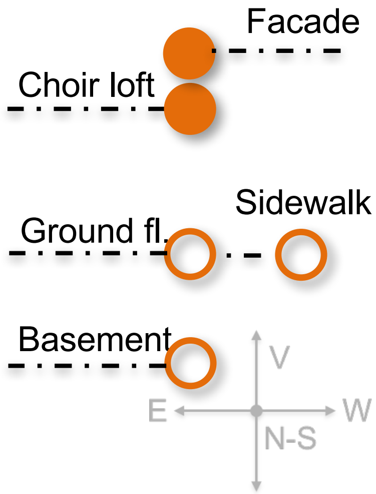






Structural monitoring of induced vibrations

Church of the Angels, Lisbon



Facade

Max incidental ppv V_R = 0.15 mm/s

For each event: Mean (0.02), Std (1%)

Mean spatial frequency of 106 Hz (7%Std)

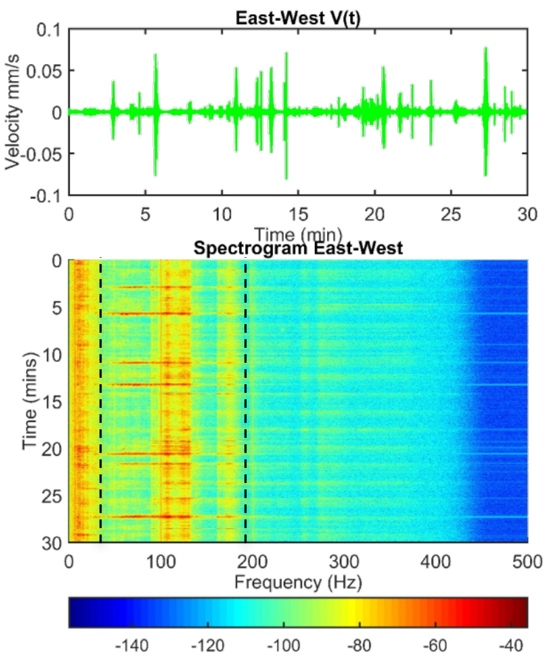
Choir loft floor

Max incidental ppv V_R = 0.50 mm/s

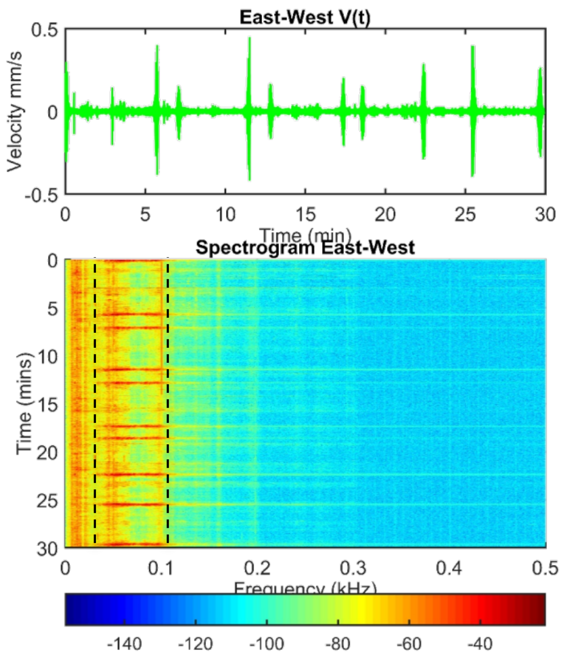
For each event: Mean (0.31), Std (10%)

Mean spatial frequency of 73 Hz (4%Std)

Facade

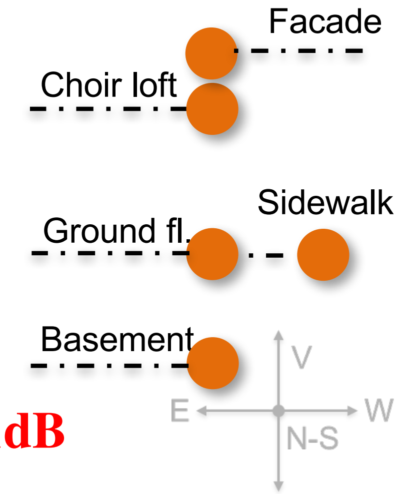


Choir loft floor



Structural monitoring of induced vibrations

Church of the Angels, Lisbon



Location	$maxV_R$ (mm/s)		Frequency content (Hz)	Spatial wave frequency (Hz)	ΔdB attenuation	
Choir loft Timber floor	0.50	x3.3	30-100	73 (4%Std)	**5**	**11dB**
Choir loft Facade windows	0.15		30-200	106 (7%Std)	**16**	
Ground floor	0.06		30-200	74 (3%Std)	**26**	
Basement	0.3	x2.3	30-200	73 (3%Std)	**6**	**6dB**
Sidewalk **(Ref.)**	0.7		30-200	91 (3%Std)	**0**	

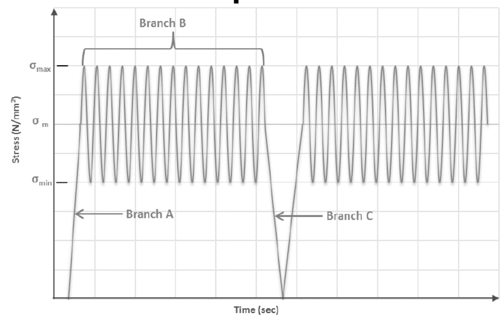
- ❑ Amplitude attenuation from exterior to interior starting from 5dB (≈ x2) lower
- ❑ Amplification in height. Vibration levels in slabs are generally amplified by 3 times *(Saurenman et al. 1982)*
- ❑ *All recorded peak values lower than the limits from standards*

Experimental campaign

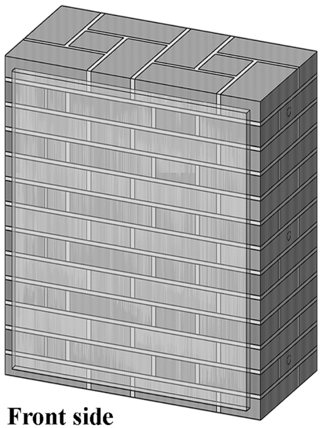
Brick masonry wallets under long-term cyclic loading

- ❑ Basic mechanical characterization tests (brick, mortar, prisms, wallets)
- ❑ Long-term fatigue tests under low stress rates — Structural / Non-structural
- ❑ Variation on stress range in different specimens, according to limits from standards.
- ❑ Monitor damage propagation, stiffness degradation and interface failure of plaster

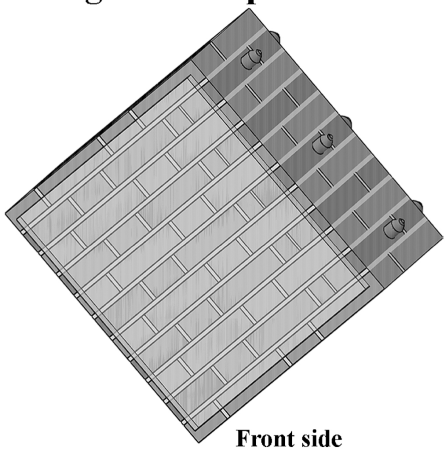
Load path/rate



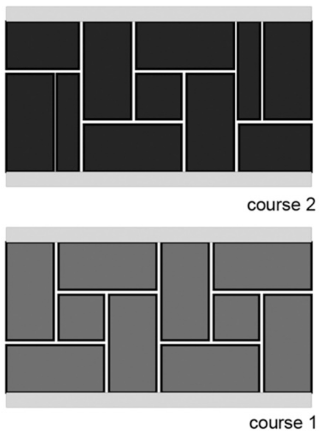
Uniaxial compression



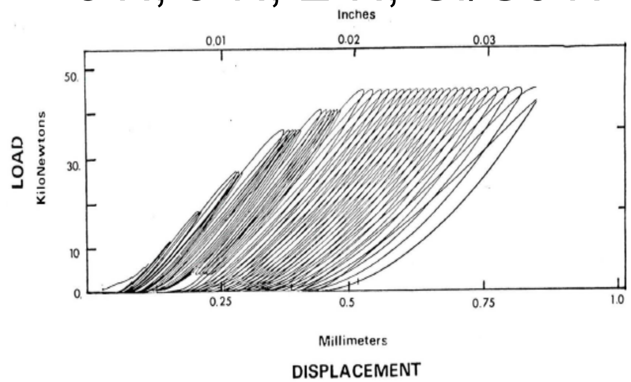
Diagonal compression



Double Flemish bond
1,5 brick thickness



Evolution curves
ε-N, σ-N, E-N, Gf/Gc-N



Abrams et al. 1985

Experimental campaign

Brick masonry wallets under long-term cyclic loading

- ❑ Fatigue is mostly associated with failure

  Fatigue limits set at 50% of the static capacity, although laboratory tests have dictated as low as 40% of the static capacity.

  http://www.sustainablebridges.net

- ❑ Fatigue is mostly associated with high stress reversals

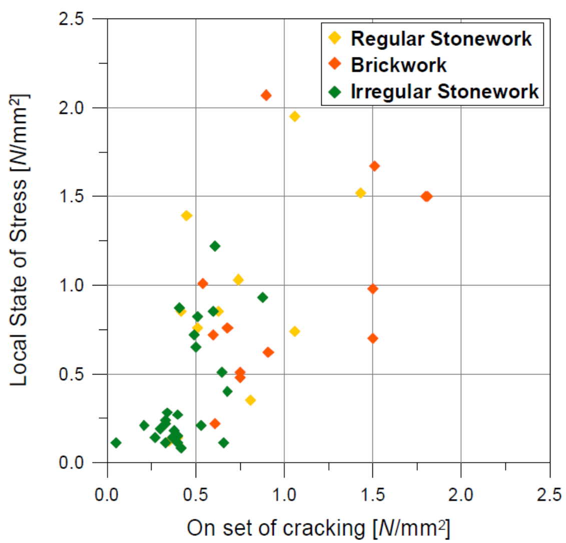
  $$R = \frac{\sigma_{min}}{\sigma_{max}} = 20 - 60\% f_c$$

  Breitenbucher et al. 2006

- ❑ Clay brick masonry: 20-30%f_c stiffness and strength are prone to deteriorate 'nonlinearity even before peak load'

  Alshebani et al. 2000

- ❑ Historic brick masonry (mid-high rise buildings) already perform under moderate safety of vertical stresses, even up to 70%fc



Binda et al. 2007

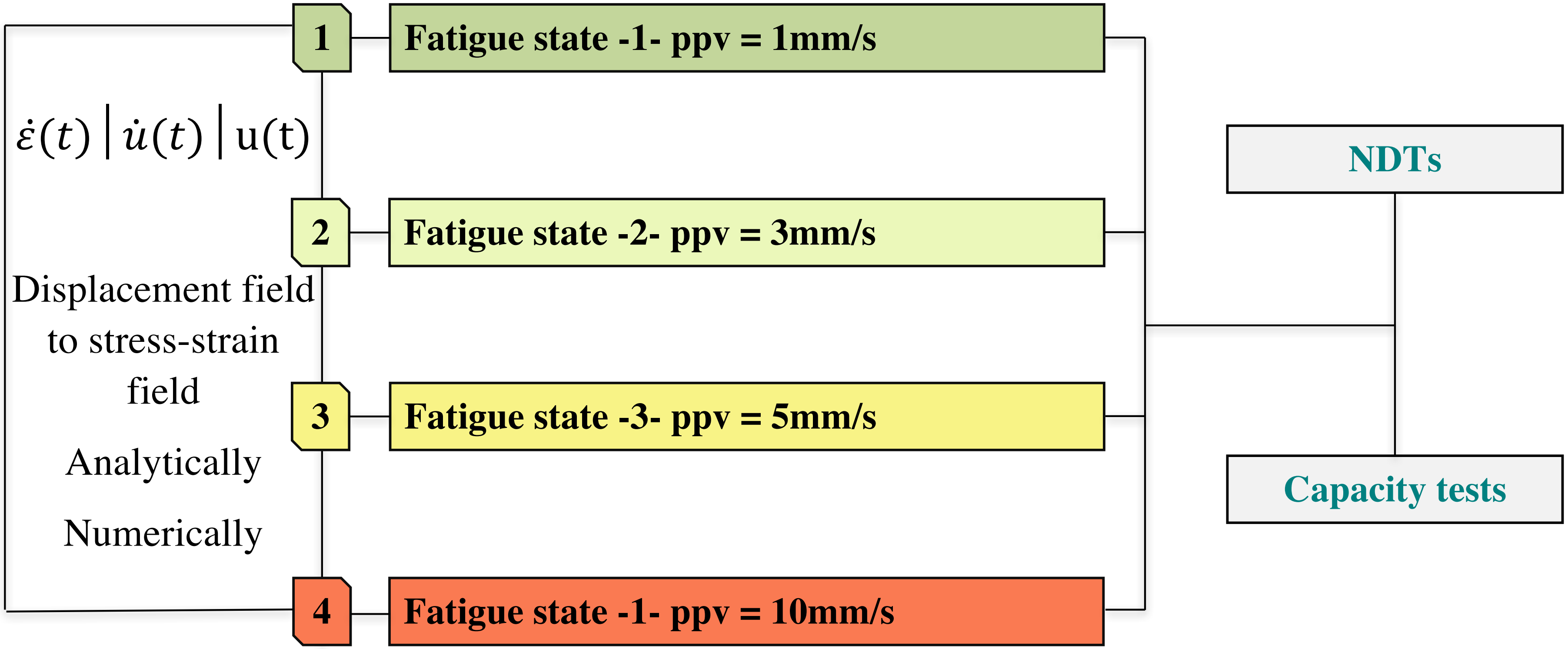
Experimental campaign

Brick masonry wallets under long-term cyclic loading

- Fatigue loading under moderate stress state and small load range is a realistic scenario for existing/historic brick masonry

  Uniaxial compression: σo =0.40fc

  Diagonal compression: τo =0.25ft



Thank you

Acknowledgments

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