Infrastructures and Geotechnics

Field monitoring and experimental investigations of vibrations and fatigue loading in cultural heritage buildings, induced by underground structures

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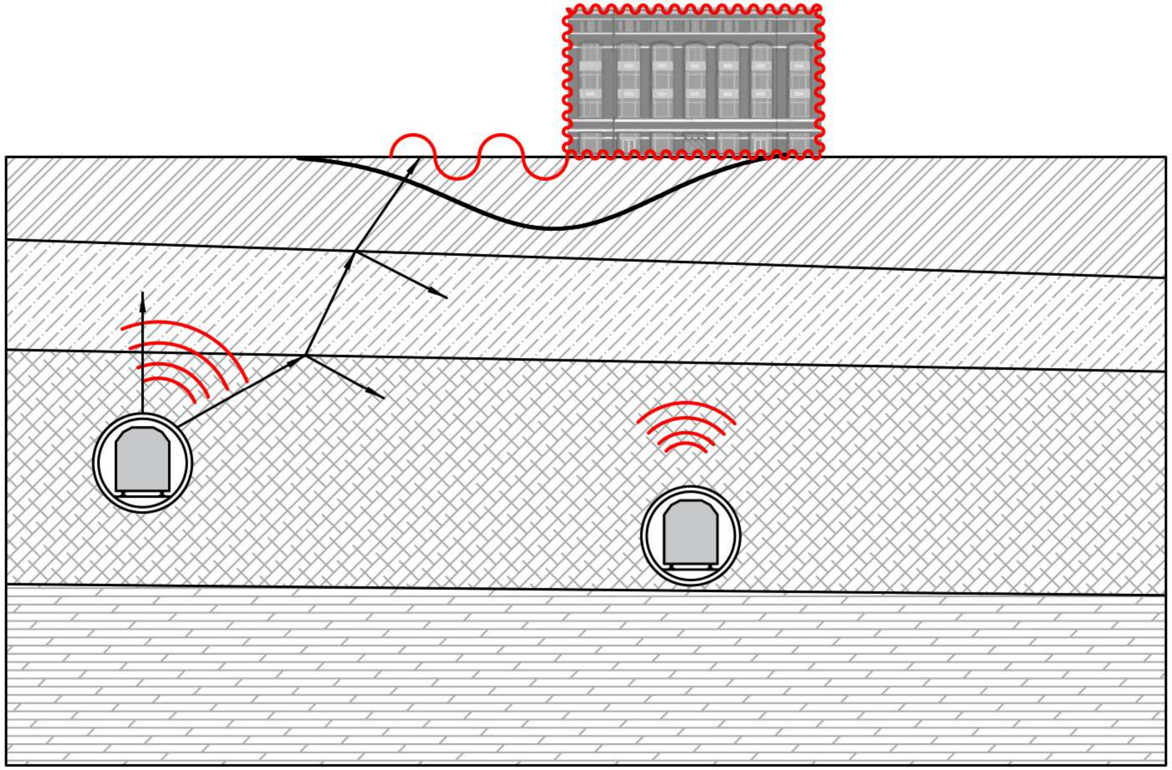


Experimental and numerical methods for investigating the effects of soil settlements and vibrations in cultural heritage buildings, induced by underground structures

Overview

- ❑ Induced soil settlements and vibrations from underground structures

• tunnelling in soft ground • induced soil settlements • induced vibrations from underground railway traffic • analytical and numerical applications

- ❑ Material characterization for simulated historic masonry, repair and retrofit

• hydraulic lime mortar • solid fired bricks • hydraulic lime-based renders and fluid binders • mechanical tests on simulated historic masonry assemblies

- ❑ Field monitoring of induced groundborne vibrations

• criteria and aspects from international standards • field monitoring acquisitions and assessment techniques

- ❑ Fatigue tests on masonry wallets under diagonal compression
- ❑ Tests of differential settlements on piers and spandrel specimen. Repair and retrofit applications

Underground structures in urban environment

Cultural heritage buildings

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

Multitude, long-term actions on masonry structures have not been fully evaluated and are not accounted in the structural assessment process of historical masonry buildings

- Experimental activity in cyclic low-stress rate fatigue tests under high static shear stresses on simulated historic brick masonry
- Field monitoring protocols and methods for induced vibrations in historic masonry structures
- Damage detection strategies for monitoring stiffness degradation in structural elements
- Damage for elements of architecture - frescos/plaster -, are mainly through structural shear failure

Field monitoring campaign

Induced groundborne vibrations from underground railway traffic

Cultural heritage buildings

Structural monitoring of induced vibrations

Groundborne vibrations • underground railway traffic

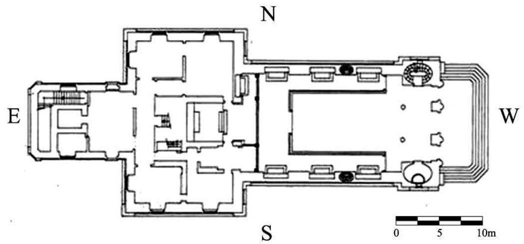
Karanikoloudis, G., Lourenço, P.B., Mendes, N., Bile J. S., Boroschek, R. (2020) Monitoring of induced groundborne vibrations in cultural heritage buildings. Miscellaneous errors and aliasing through integration and filtering, International Journal of Architectural Heritage. (DOI: 10.1080/15583058.2020.1802532)

- 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	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

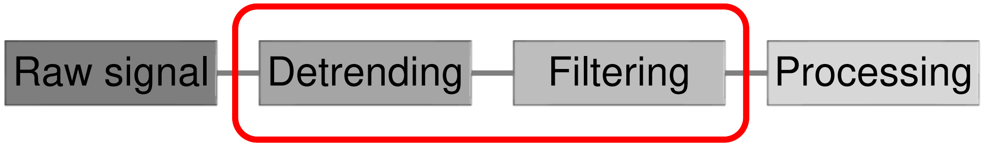


- ❑ Monitoring of metro induced vibrations in three cultural heritage buildings
  Church of the Angels, in Lisbon ✓

- ❑ 1 passing train every 3-5 min

- ❑ Use of kinetic quantities

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

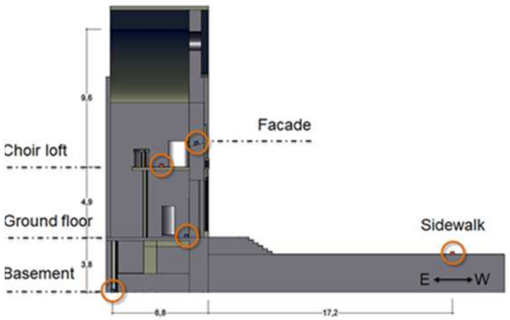


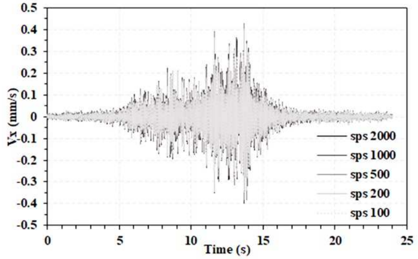
- ❑ Triaxial seismographers with GPS time base
  Triaxial geophone ✓

- ❑ Sampling frequency 1000-2000Hz

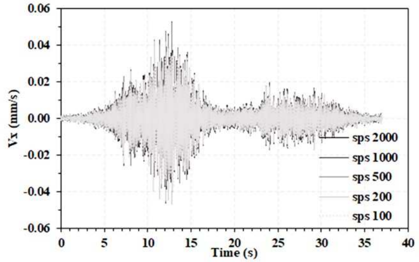
Structural monitoring of induced vibrations

Church of the Angels, Lisbon

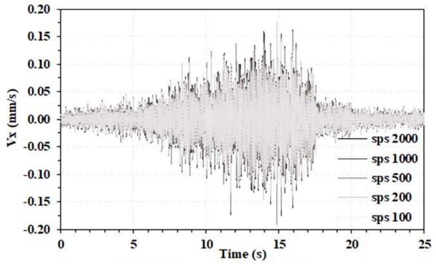




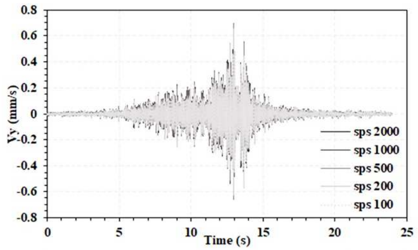
sps	2000	1000	500	200	100
V_x,max (mm/s)	0.43	0.43	0.43	0.40	0.34
Difference (%)	-	0.0%	0.0%	6.6%	26.1%



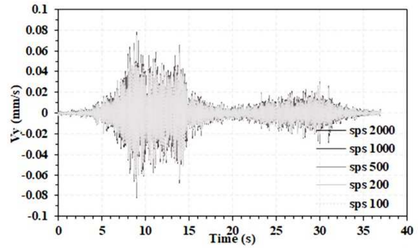
sps	2000	1000	500	200	100
V_x,max (mm/s)	0.05	0.05	0.05	0.05	0.04
Difference (%)	-	1.1%	1.1%	13.7%	32.7%



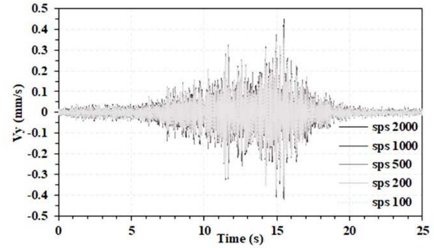
sps	2000	1000	500	200	100
V_x,max (mm/s)	0.19	0.19	0.19	0.18	0.14
Difference (%)	-	0.0%	0.0%	7.8%	34.4%



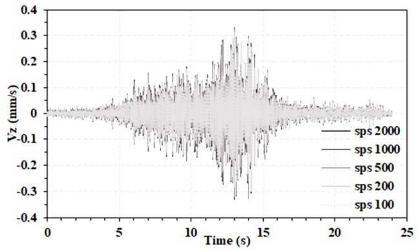
sps	2000	1000	500	200	100
V_y,max (mm/s)	0.70	0.70	0.70	0.65	0.57
Difference (%)	-	0.0%	0.0%	7.2%	22.6%



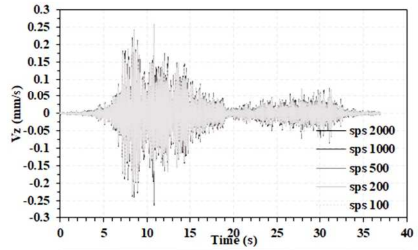
sps	2000	1000	500	200	100
V_y,max (mm/s)	0.08	0.08	0.08	0.07	0.07
Difference (%)	-	1.0%	1.0%	10.3%	10.3%



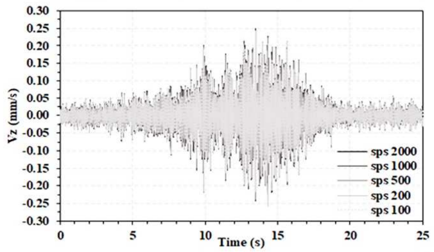
sps	2000	1000	500	200	100
V_y,max (mm/s)	0.45	0.45	0.43	0.41	0.37
Difference (%)	-	0.0%	5.2%	8.9%	22.7%



sps	2000	1000	500	200	100
V_z,max (mm/s)	0.33	0.33	0.33	0.32	0.30
Difference (%)	-	1.1%	1.5%	5.4%	10.7%



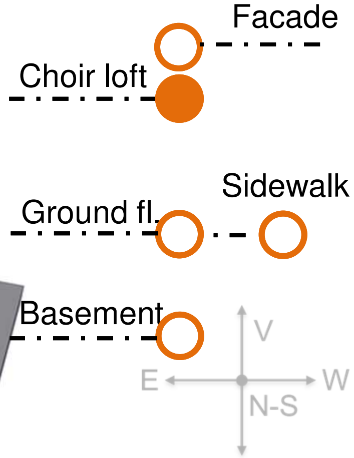
sps	2000	1000	500	200	100
V_z,max (mm/s)	0.26	0.26	0.26	0.26	0.23
Difference (%)	-	1.2%	2.7%	2.0%	13.3%

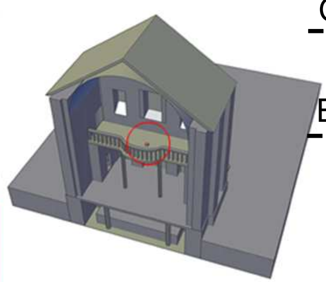


sps	2000	1000	500	200	100
V_z,max (mm/s)	0.26	0.26	0.24	0.26	0.24
Difference (%)	-	0.0%	5.7%	0.0%	5.7%

Structural monitoring of induced vibrations

Church of the Angels, Lisbon

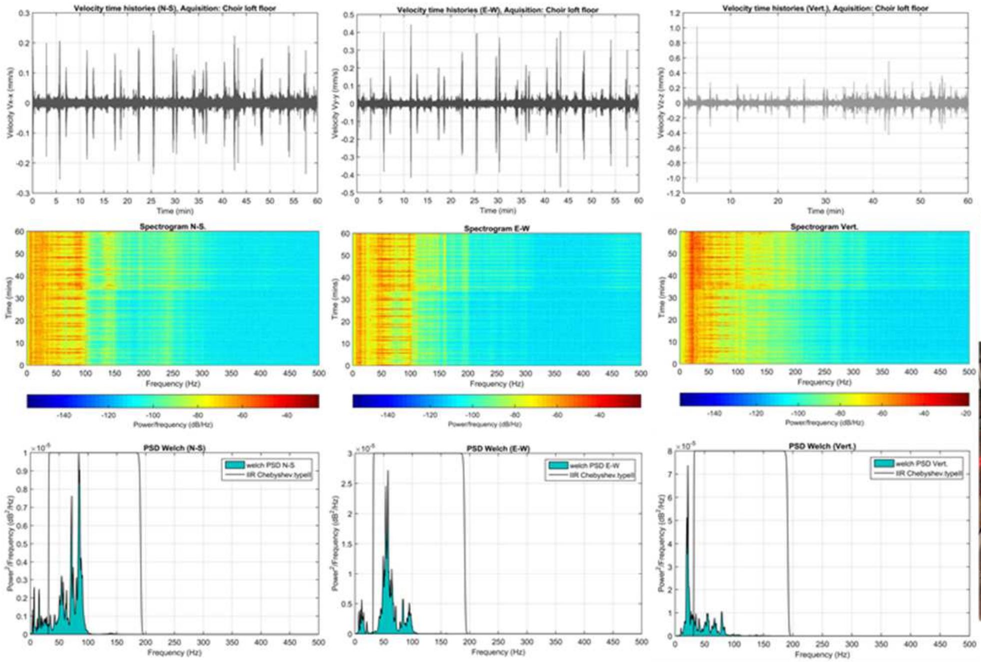




Raw data

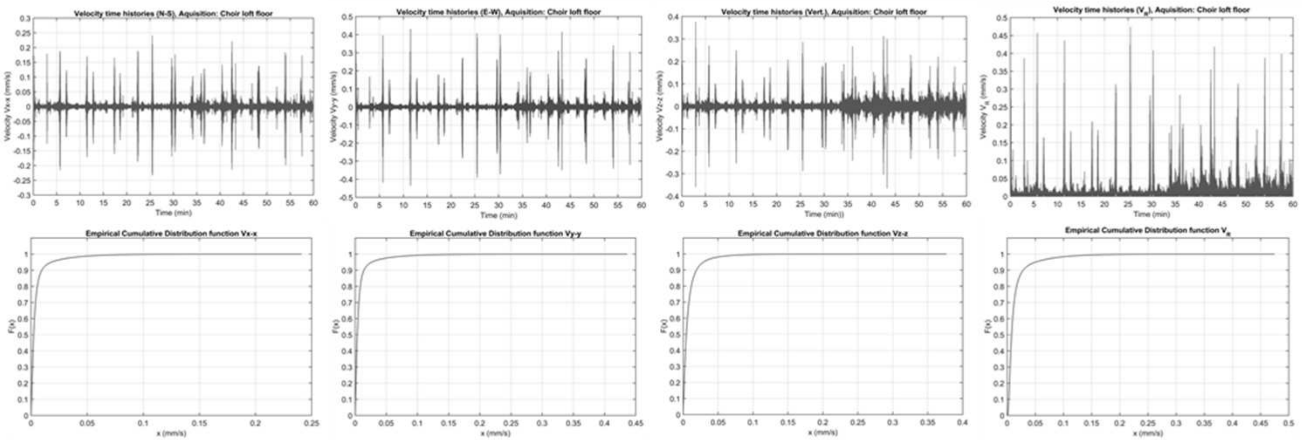
Spectrogram

Window filtering



Filtered data

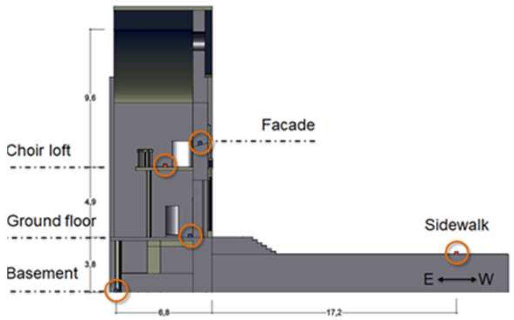
cdfplot(V_R)



$F(x) = 1\text{-}10^{-6}, x = 0.23$ 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



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

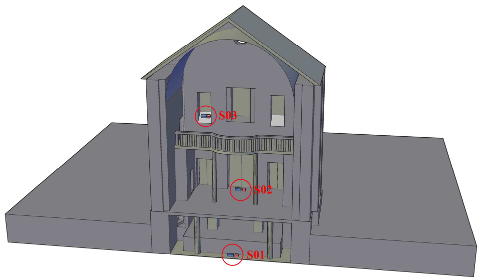
[2] Refers to the confidence interval for 90% probability of exceedance for ppv≥0.05mm/s

[3] Refers to the confidence interval for 90% probability of exceedance for ppv≥0.025mm/s

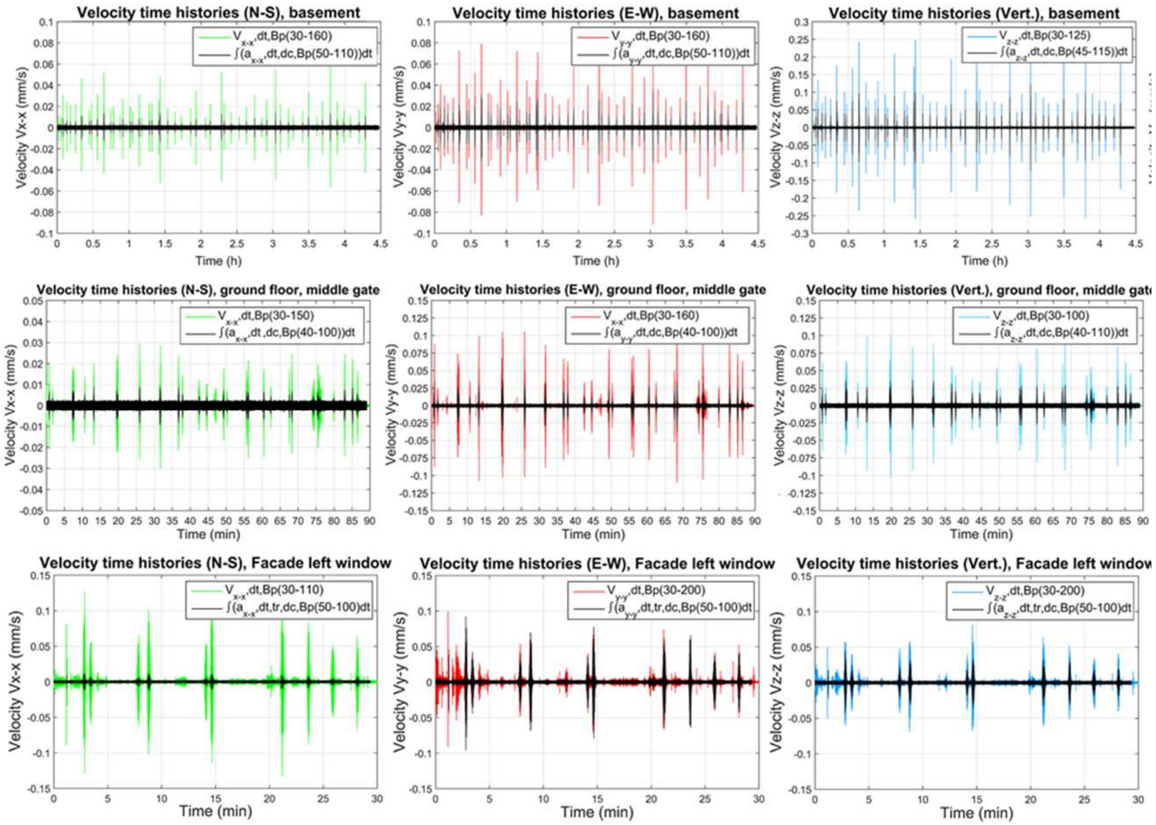
[4] Refers to the maximum velocity vector V_R

Structural monitoring of induced vibrations

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

Aliasing

- ❑ Velocity as the primary measurement

Experimental campaign

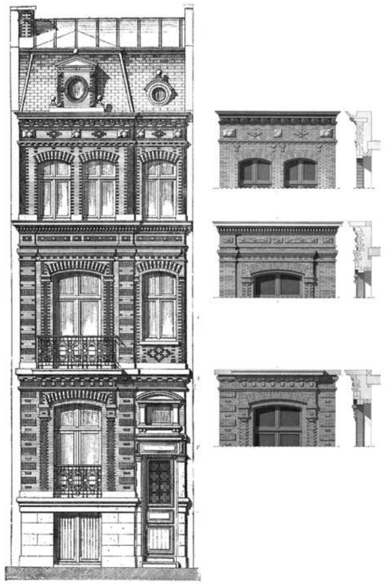
Historic masonry facades

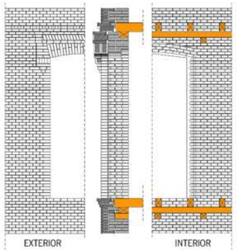
Material characterization for simulated historic masonry, repair and retrofit

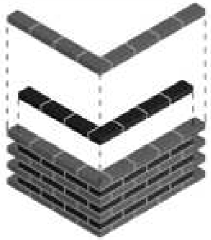
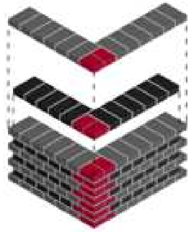
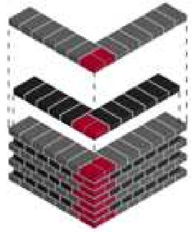
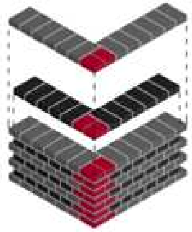
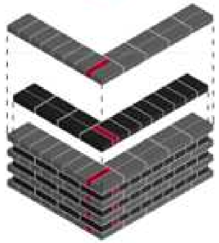
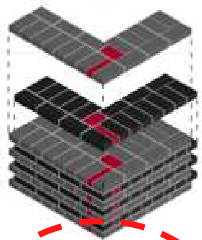
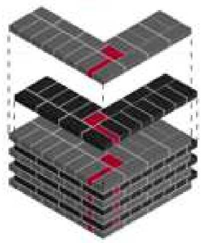
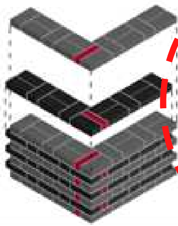
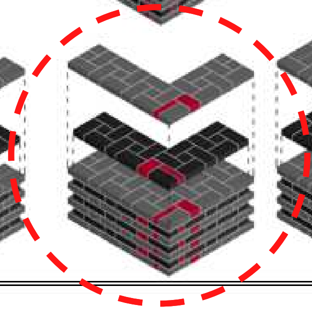
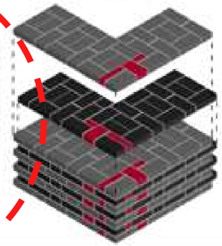
Material characterization of simulated historic masonry

Masonry constituents • wallets • repair material

- 19th cen. brick masonry buildings



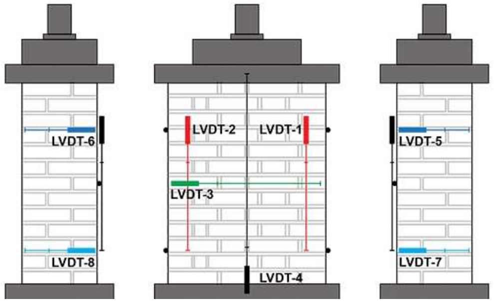


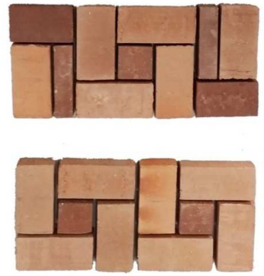
Bond	Thickness: ½ Brick	1 Brick	1 ½ Bricks	2 Bricks
Stretcher		—	—	—
Header	—			
English	—			
Flemish	—			

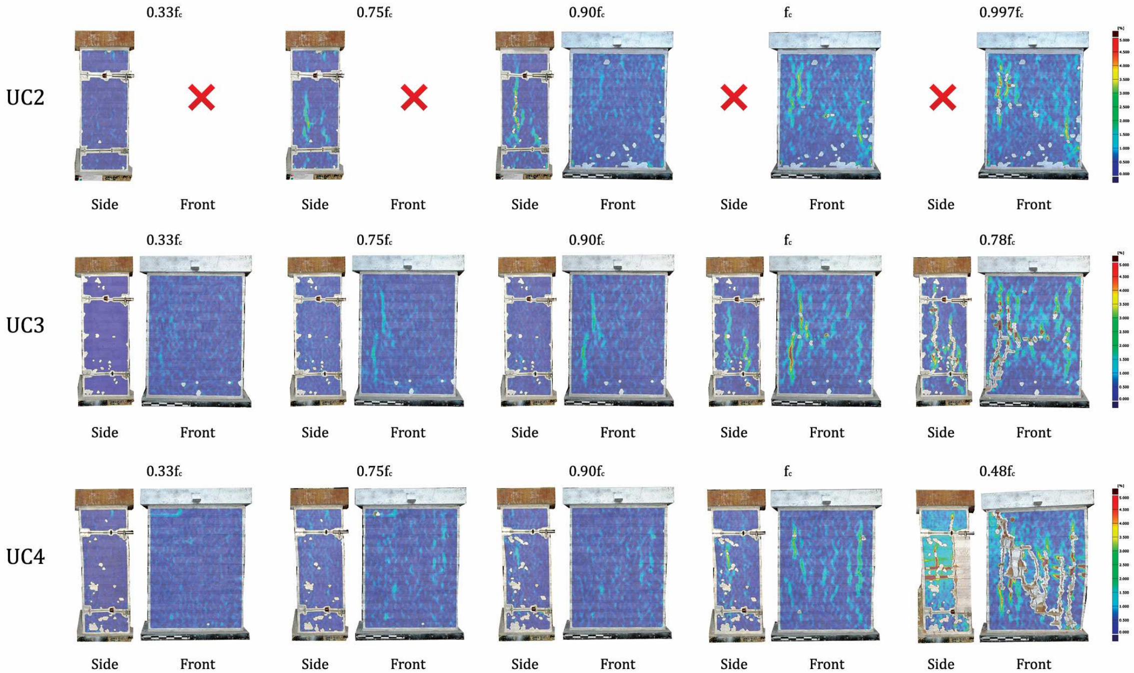
Material characterization of simulated historic masonry

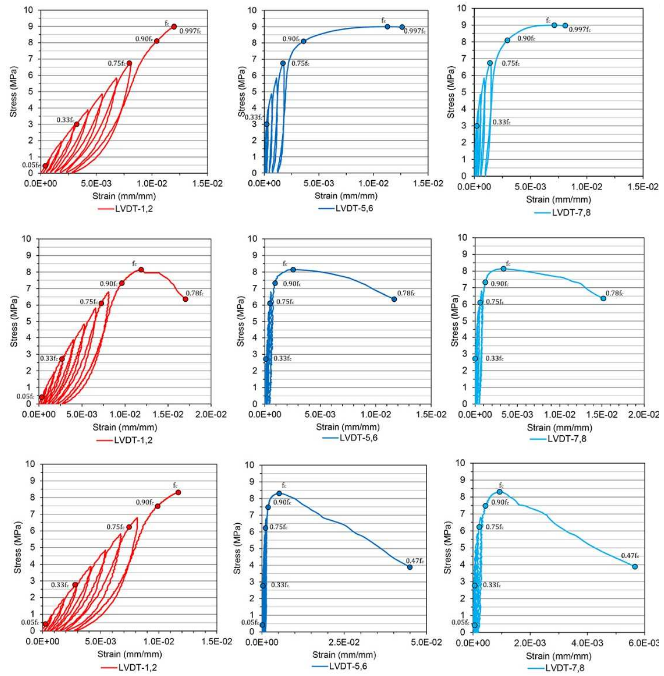
Masonry constituents • wallets • repair material

- ❑ Solid fired bricks ($f_{c,mean} \simeq 17$ MPa) and M4-NHL mortar
- ❑ Uniaxial compression tests in masonry wallets





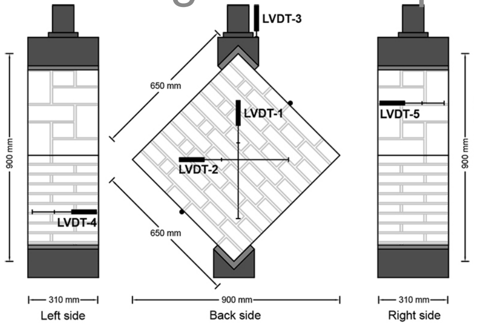


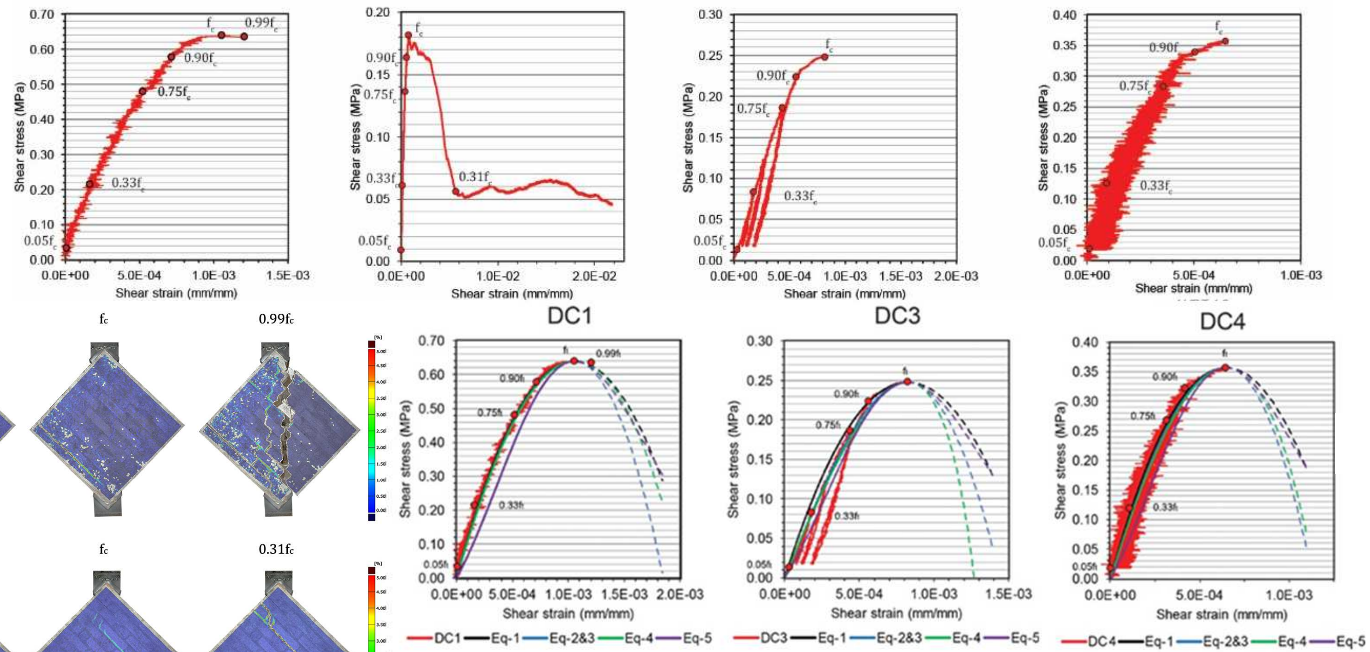


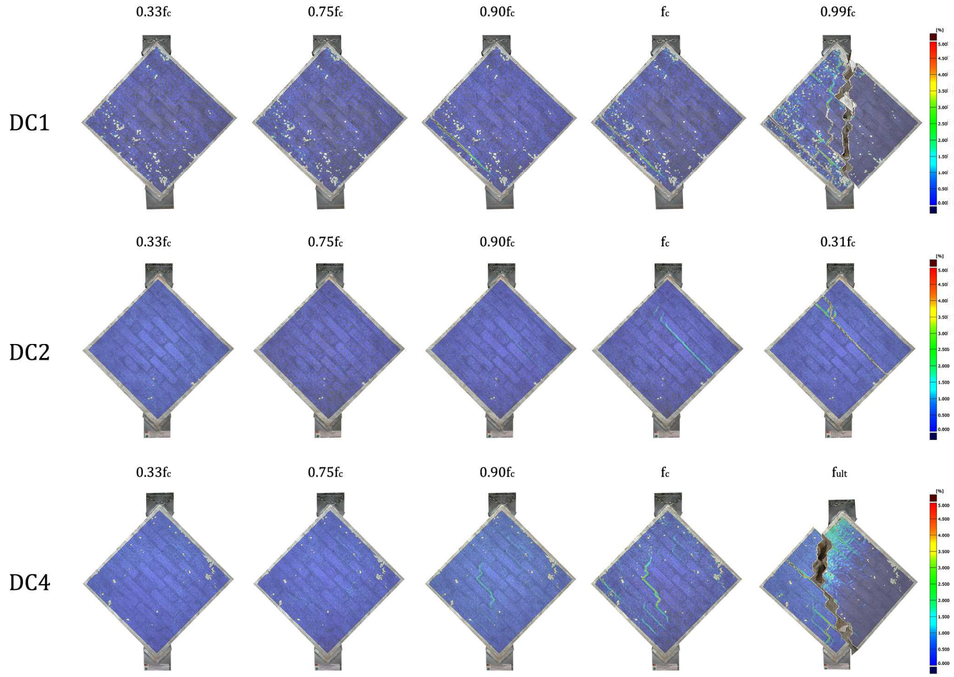
Material characterization of simulated historic masonry

Masonry constituents • wallets • repair material

- ❑ Solid fired bricks ($f_{c,mean} \simeq$ 17 MPa) and M4-NHL mortar
- ❑ Diagonal compression tests in masonry wallets







$$f = -f_t \cdot \left(2\frac{\gamma}{\gamma_t} - \left(\frac{\gamma}{\gamma_t}\right)^2\right) \qquad \text{Equation 1}$$

$$f = -G\gamma\left[1 - \frac{1}{n}\cdot\left(\frac{\gamma}{\gamma_t}\right)^{n-1}\right], \quad n = \frac{G}{G - G_{SEC}}, \quad G_{SEC} = \frac{f_t}{\gamma_t} \qquad \text{Equation 2}$$

$$f = -f_t \cdot \left[1 - \left(\frac{\gamma - \gamma_t}{\gamma_u - \gamma_t}\right)^2\right] \qquad \text{Equation 3}$$

$$f = \gamma_t \frac{k_o\eta - \eta^2}{1 + (k_o - 2)\eta}, \quad \eta = \frac{\gamma}{\gamma_t}, \quad k_o = \frac{G\gamma_t}{f_t} \qquad \text{Equation 4}$$

$$f = -G_{SEC}\gamma \cdot e^{\left(1 - \frac{\gamma}{\gamma_t}\right)\frac{\gamma}{\gamma_t}} \qquad \text{Equation 5}$$

Experimental campaign

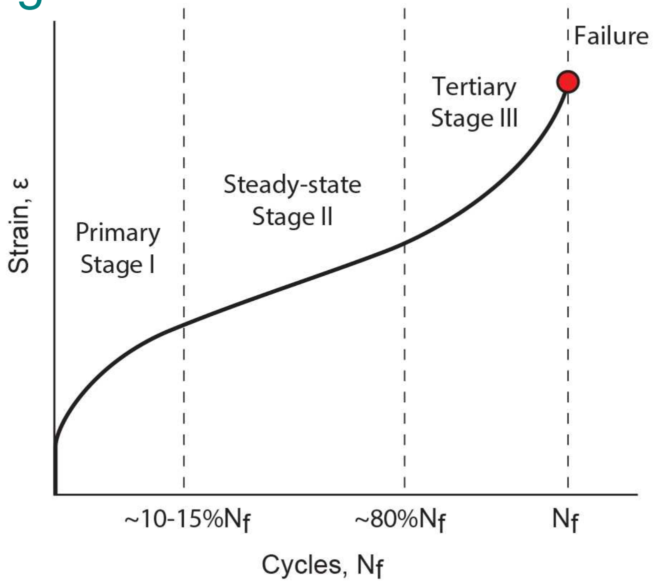
Simulated historic masonry

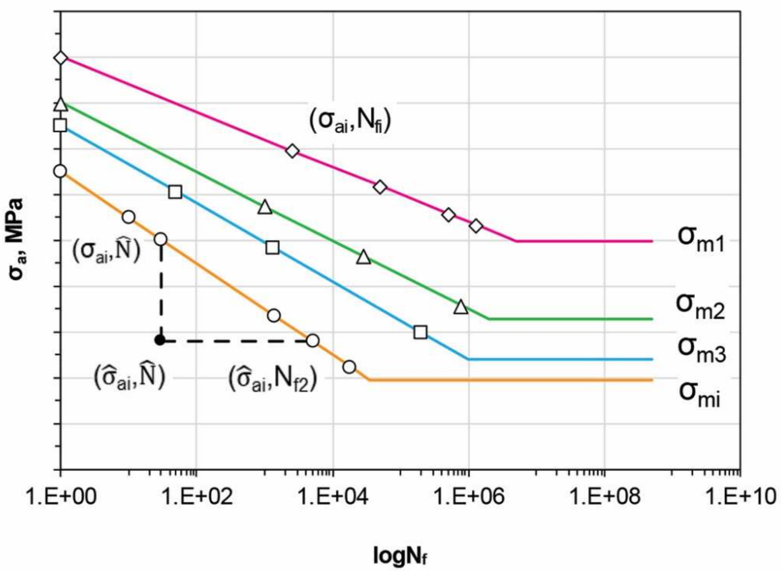
Fatigue tests on masonry wallets under diagonal compression

Experimental campaign: Fatigue tests on masonry wallets with rendering under diagonal compression

Overview

- Fatigue shear strength is a multitude and complex process, relative to: the ultimate tensile strength • the fracture parameters • the stiffness properties • the natural frequencies • the static loading conditions • the stress range • the cycling frequency • the number cycles $N_f \simeq 10^5$-10^{10}
- Fatigue is attributed to traffic loads, wind, ringing bells, temperature and humidity • EC2: Fatigue is considered for the ULS, $\gamma_{c,fat} = 1.5$ • EC0: Fatigue for monuments under the design working life cat. 5 (100 years)

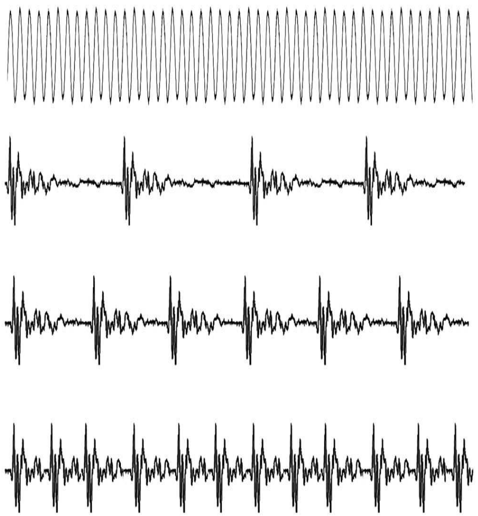


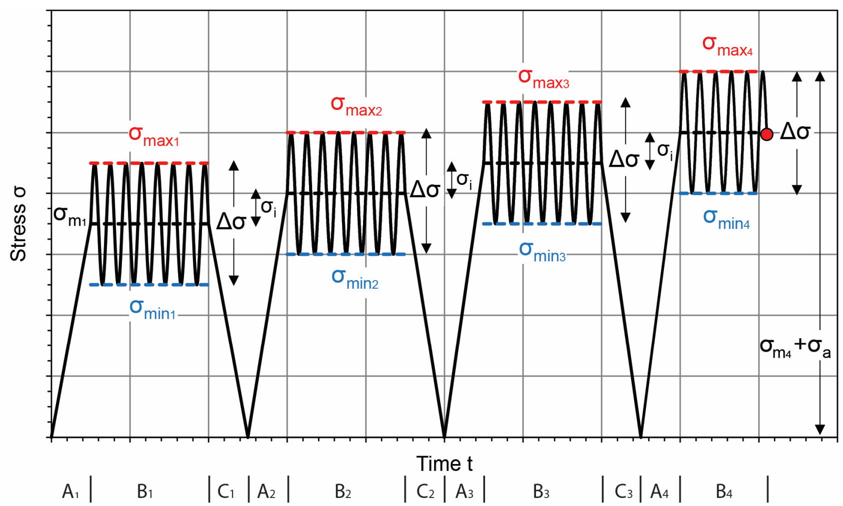


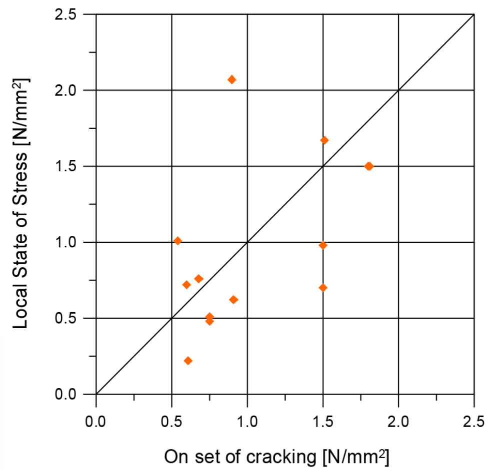
Experimental campaign: Fatigue tests on masonry wallets with rendering under diagonal compression

Testing objectives

- ❑ Fatigue under high static loads • addressing local stress intensities close to the ultimate capacity
- ❑ Accelerated fatigue experimental tests, under continuous cyclic vibrations • sinusoidal load







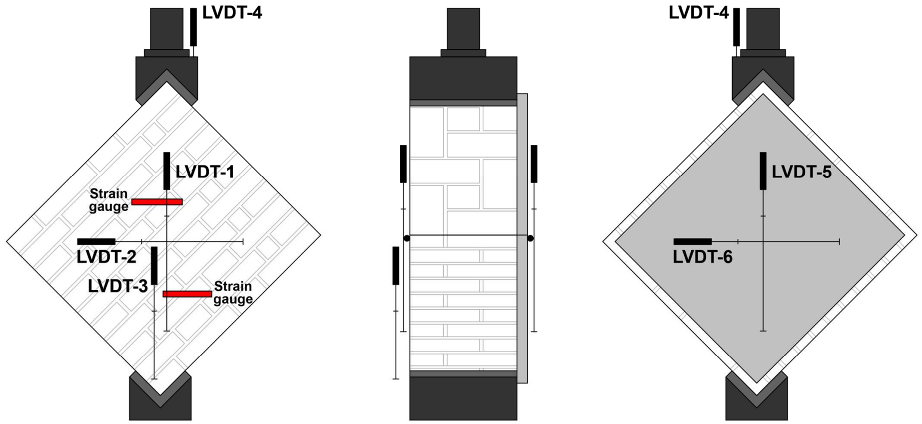
Binda et al. 2007

- ❑ Fatigue associated with real-time conditions in a structure • constant fatigue loading conditions and a static service load increase • fatigue period of 1.5 years • deterministic approach

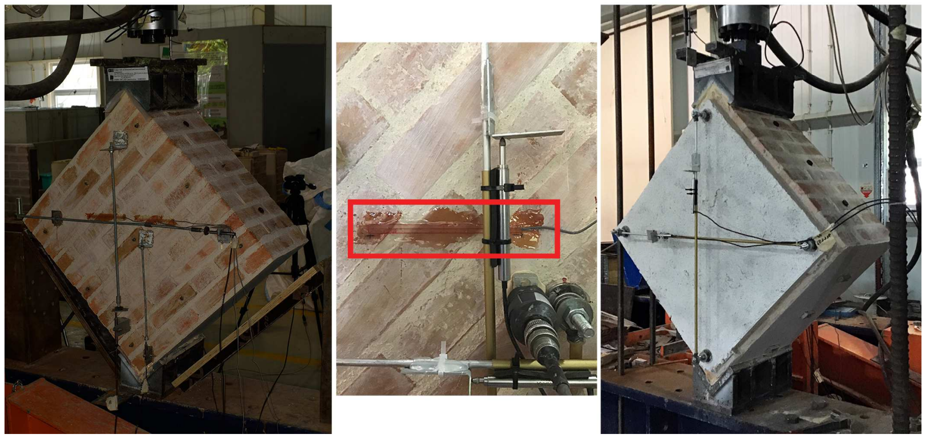
Experimental campaign: Fatigue tests on masonry wallets with rendering under diagonal compression

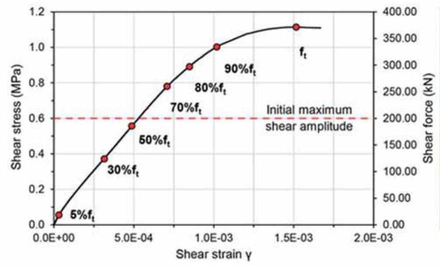
Setup, protocols and instrumentation

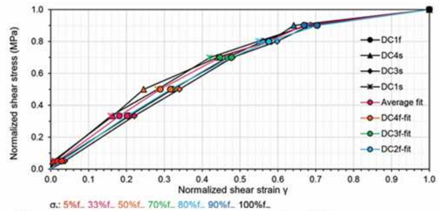
- Preliminary cyclic diagonal compression tests to acquire the shear stiffness and obtain a direct shear capacity envelope fit



Back side | Left side | Front side

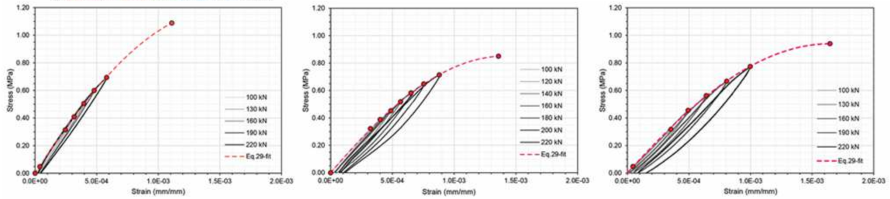






$$f = -E\varepsilon\left[1 - \frac{1}{n}\cdot\left(\frac{\varepsilon}{\varepsilon_c}\right)^{n-1}\right], \quad n = \frac{E}{E - E_{SEC}}, \quad E_{SEC} = \frac{f_c}{\varepsilon_c}$$

Hoshikuma et al 1997



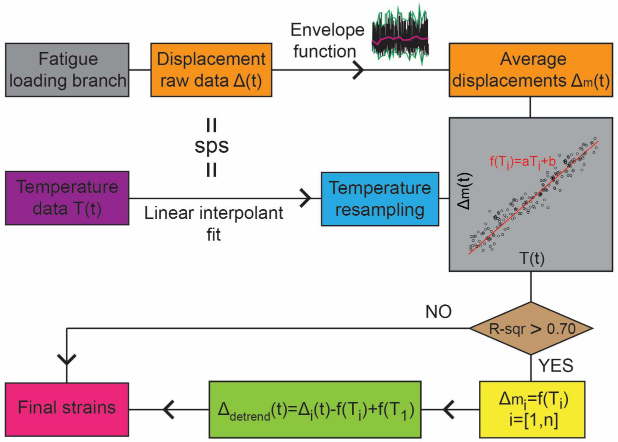
Specimen DCfi	Target ppv (mm/s)	Reference dominant radial frequency ω (rad/s)	Reference dominant frequency f (Hz)	Target ppd $\delta_o = \frac{u_o}{\omega}$ (mm)	$K_{chord}^{(100-200)kN}$* (kN/mm)	Target shear force amplitude P_a (kN)
DCf4	8			0.018	758.41	14
DCf2	10	408	65	0.025	1113.92	28
DCf3	16			0.040	771.64	31

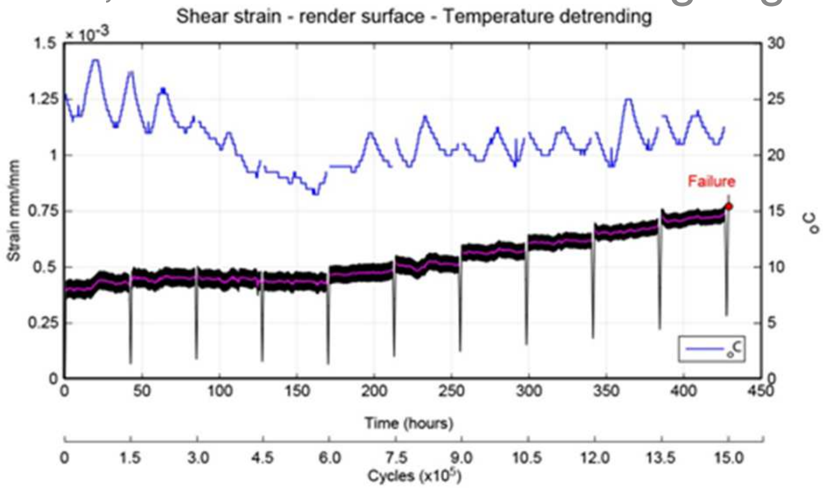
* Average chord stiffness from loading and unloading branch.

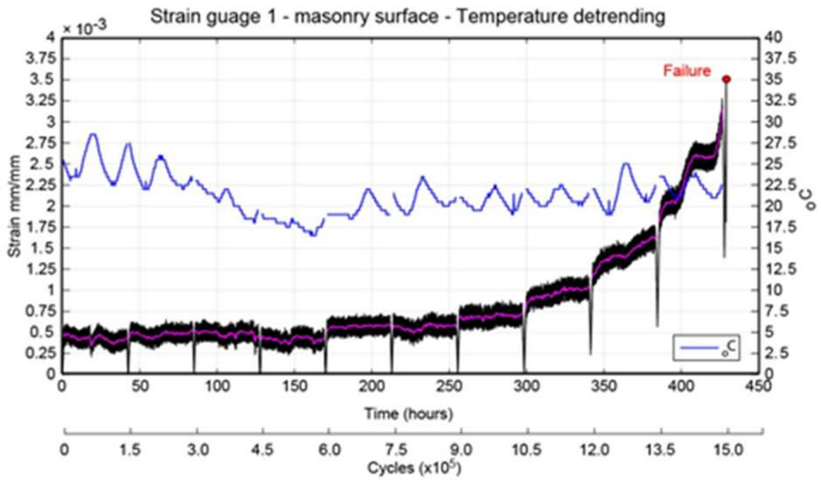
Experimental campaign: Fatigue tests on masonry wallets with rendering under diagonal compression

Data acquisitions

- ❑ Temperature compensation of raw data, from LVDTs and strain gauges







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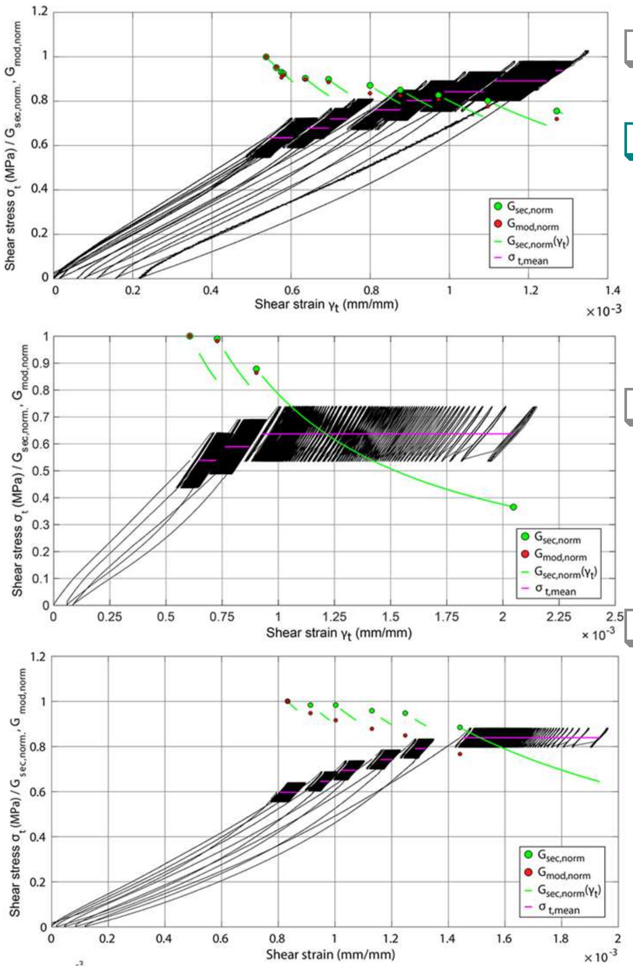
Stiffness monitoring

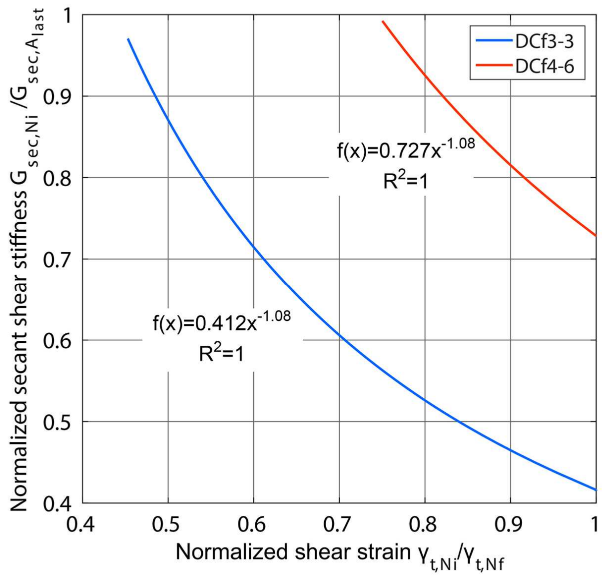
- ❑ Evolution of the average normalized secant shear modulus $G_{sec}(N_i)$



- ❑ Exponential law
- ❑ Decrease of:

  20% Stage I(0-10%N_f)
  20% Stage II(10-80%N_f)
  60% Stage III(80-100%N_f)

- ❑ Fatigue failure after stress limit of macrocracks (>0.7ft)
- ❑ Highest positive evolution rates in the range of 4.0×10^{-5}-1.9×10^{-4} MPa/cycle



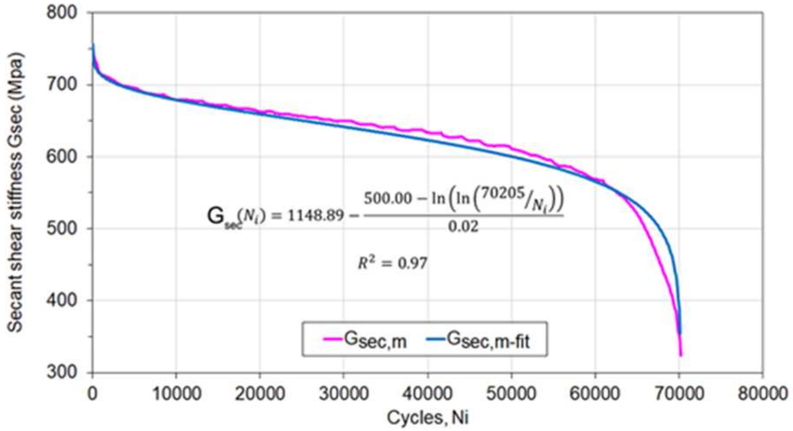
$$y = ax^b, a > 0 \text{ and } b < 0$$

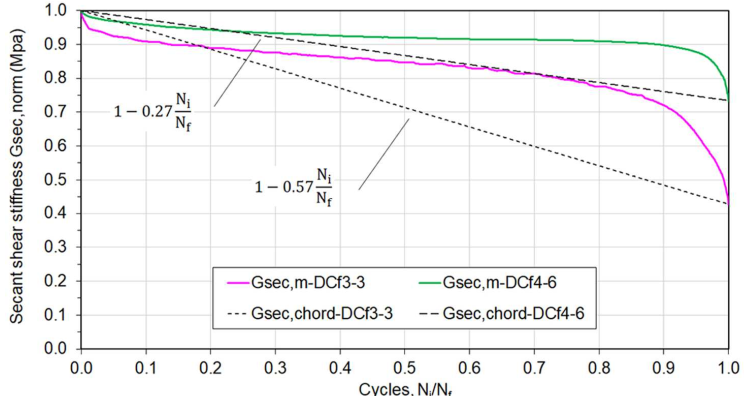
Experimental campaign: Fatigue tests on masonry wallets with rendering under diagonal compression

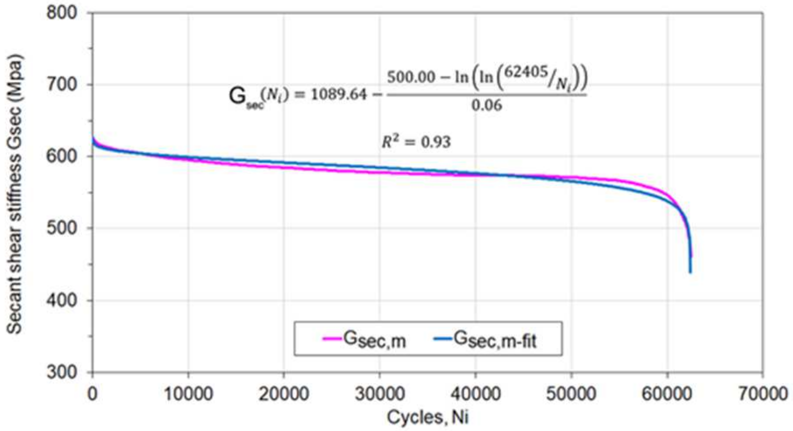
Conclusions

- Reverse Gompertz curve least square fit • Holmen 1982 hypothesis of equal fatigue failure properties

$$\frac{G_{sec,N_i}}{G_{sec,N=1}} = 1 - \lambda \frac{N_i}{N_f}$$







Wallet DCfi-j	Fatigue Bj Cycles	$G_{sec,N=1}$	$G_{sec,N_{Bj}}$	λ	$N_{f,est} = \frac{\lambda N_{Bj}}{1 - \frac{G_{sec,N_{Bj}}}{G_{sec,N=1}}}$
DCf3-1(0.54ft,±0.12ft)	1-1.5E+05	830.4	743.5		8.21E+05
DCf3-2(0.59ft,±0.12ft)	1-1.5E+05	837.6	726.2	0.57	6.46E+05
DCf3-3(0.64ft,±0.12ft)	7.02E+04	756.5	323.4		7.02E+04
DCf4-1(0.64ft,±0.04ft)	1-1.5E+05	691.1	740.3		-
DCf4-2(0.69ft,±0.04ft)	1-1.5E+05	680.0	666.5		2.01E+06
DCf4-3(0.73ft,±0.04ft)	1-1.5E+05	692.0	657.3	0.27	7.94E+05
DCf4-4(0.79ft,±0.04ft)	1-1.5E+05	663.6	641.5		1.20E+06
DCf4-5(0.84ft,±0.04ft)	1-1.5E+05	659.3	638.2		1.24E+06
DCf4-6(0.89ft,±0.04ft)	6.25E+04	628.0	461.1		6.25E+04

Experimental campaign: Fatigue tests on masonry wallets with rendering under diagonal compression

Conclusions

- ❑ Cyclic softening in masonry is a significant, reforming factor for the shear stress-strain relationship • damage tensors • updated yield surfaces
- ❑ Fatigue shear loading, under high static shear stresses and permissible ppv values (8-10 mm/s), can result to local shear cracking at relatively low number of cycles, namely 7-9 months
- ❑ The philosophy of concrete design building codes accounts for the fatigue loading regime: $\gamma_{c,fat}$ =1.5, design category 5(100 years) for monuments
- ❑ A resistance partial factor for fatigue strength in masonry structures for the ULS $\gamma_{m,fat}$ equal to 2.0 is advised
- ❑ Creep design approach for masonry structures, under a reduction creep coefficient φ_{∞} (0.5-1)

$$G_{mod,longterm} = \frac{G_{mod}}{1 + \varphi_{\infty}}$$

- ❑ Field monitoring of fatigue in masonry historic structures: groundborne vibrations, compressive and shear capacity, and strain evolution in identified shear stress concentration areas

Thank you

Acknowledgments

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