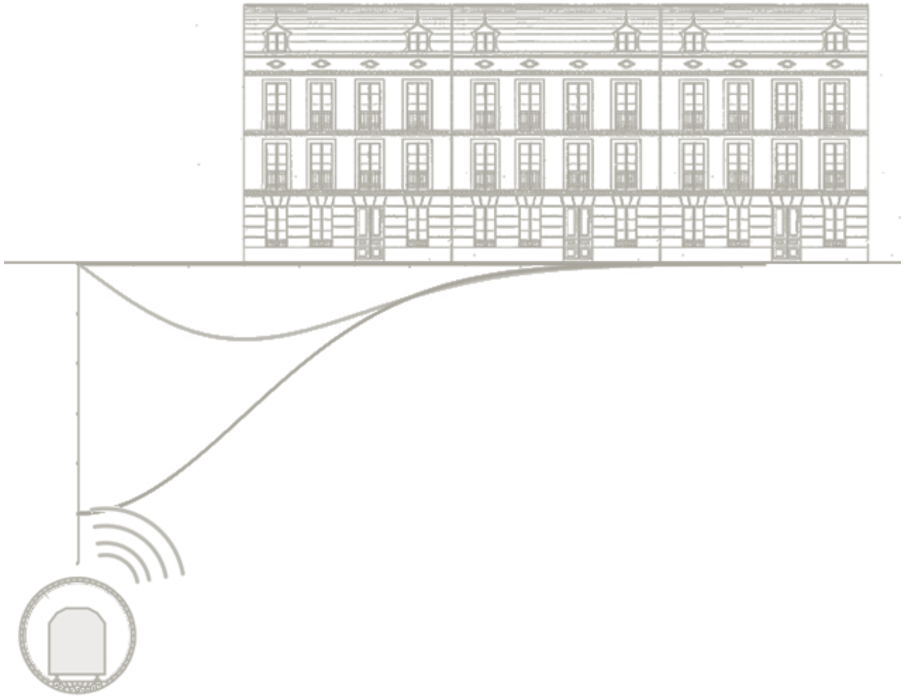
Hydrology, Infrastructures & Geotechnics

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

Georgios Karanikoloudis

Supervisors:

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

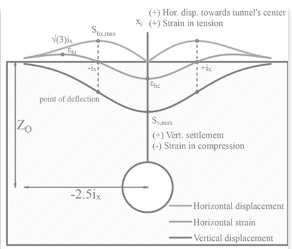
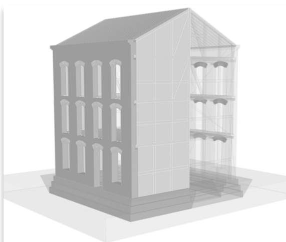
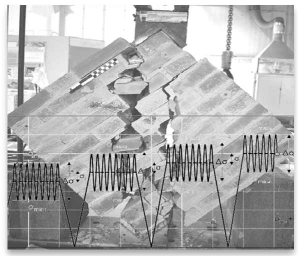
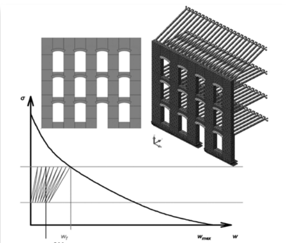


Experimental methods for investigating the effects of soil settlements and vibrations in cultural heritage buildings, induced by underground structures

Contents

- Problem statement: Cultural heritage masonry buildings in the proximity of underground railway structures • induced soil settlements and vibrations

- Thesis outline

Research background	Research basis	Experimental work and analytical applications		Conclusions
				
• Induced settlements in soft ground • Wave propagation from railway traffic • Damage criteria, numerical and analytical models	• Experimental research on masonry • Mechanical characterization tests • Criteria from standards and codes • Acquisitions of induced vibrations	• Experimental fatigue tests on masonry specimens in diagonal compression • Fatigue testing protocols • Analytical stress-strain applications	• Experimental vertical uplift tests in piers and spandrel masonry specimens • Structural repair and retrofit applications • Mechanical strength models	• Numerical reproduction of experimental results • Numerical applications under the combined effect of settlements and induced vibrations

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

Contents

- ❑ Problem statement: Cultural heritage masonry buildings in the proximity of underground railway structures • induced soil settlements and vibrations
  - ✓ Cyclic deterioration is often not incorporated in FE modelling
  - ✓ Multi-hazard structural response assessment in masonry structures has not been fully investigated
- ❑ Objectives: Reliable experimental data, for settlement-vibration induced damages on simulated historic masonry specimens

  Structural performance of engineered repair and retrofit applications

  Correlate testing results with analytical formulations

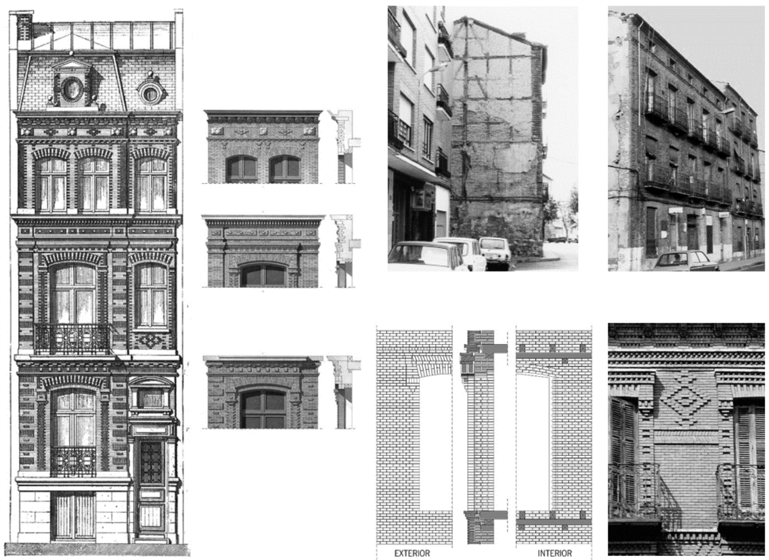
  fatigue curves, strain-stiffness functions

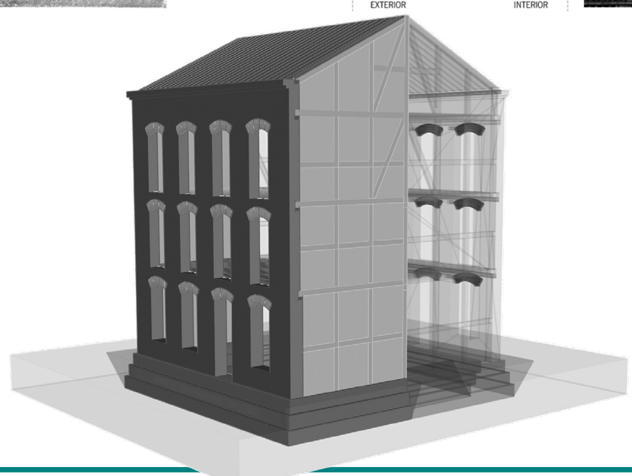
  macro-element capacity models

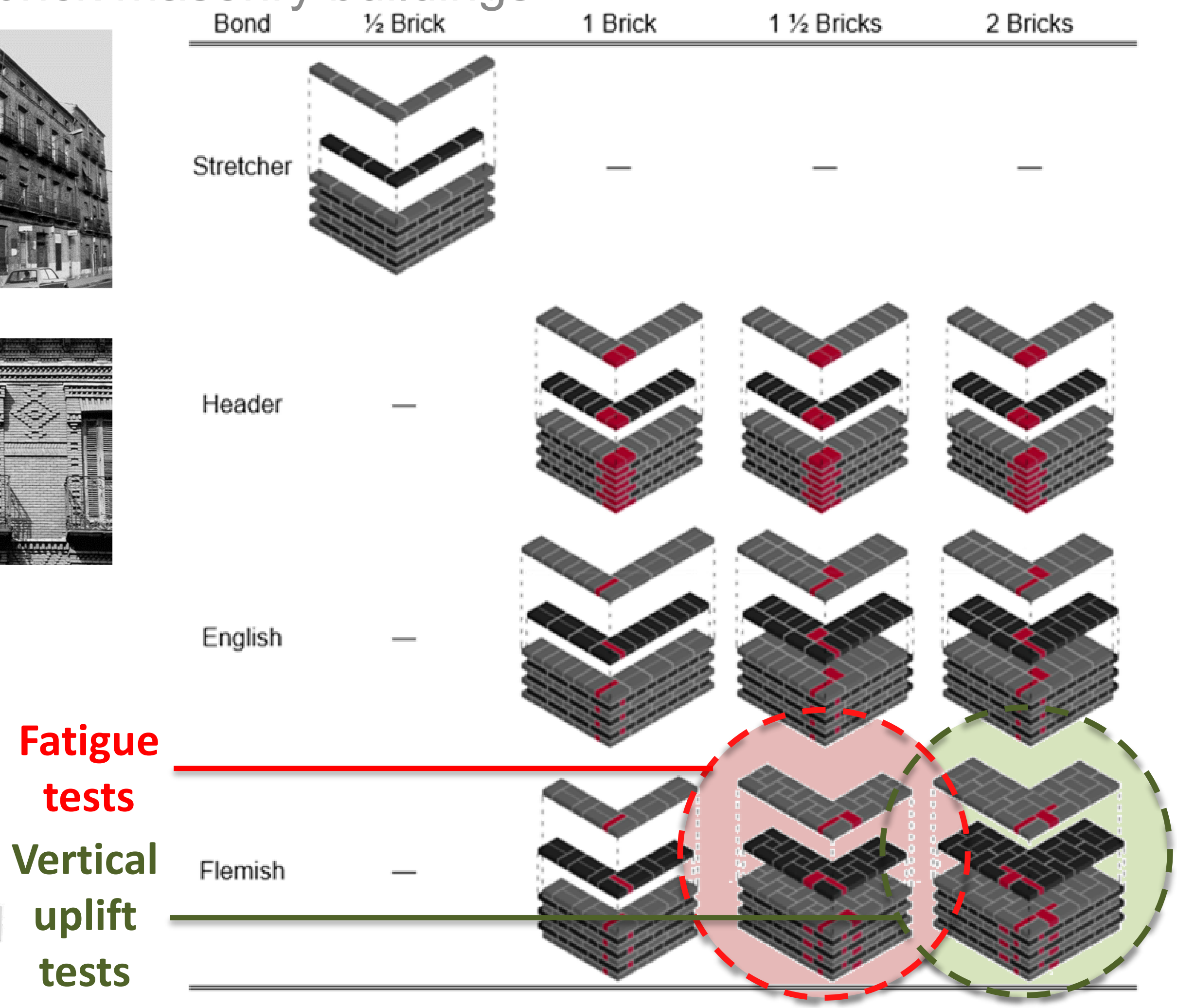
  Non-destructive testing

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

Reference of 19th century brick masonry buildings







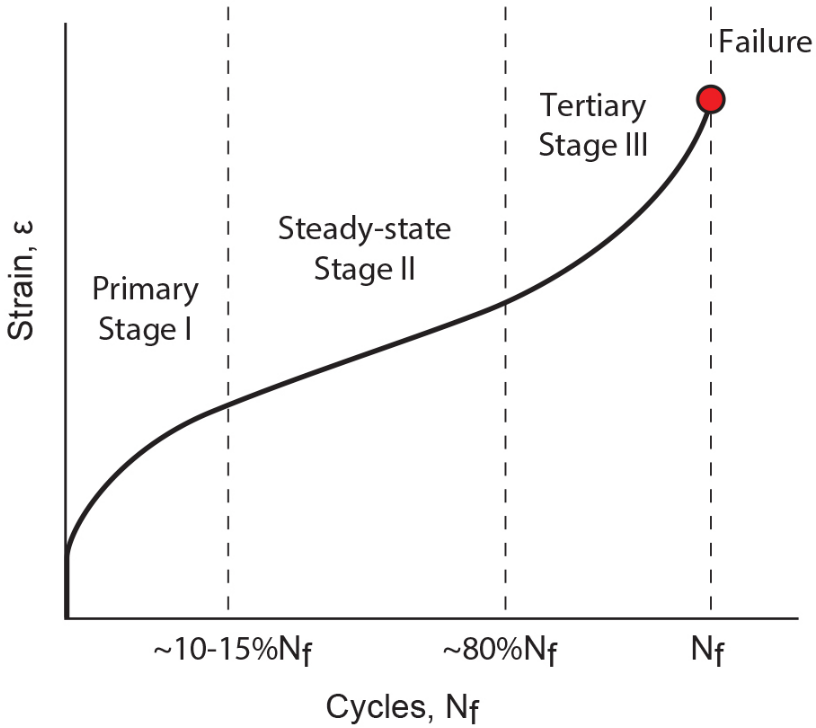
Experimental campaign

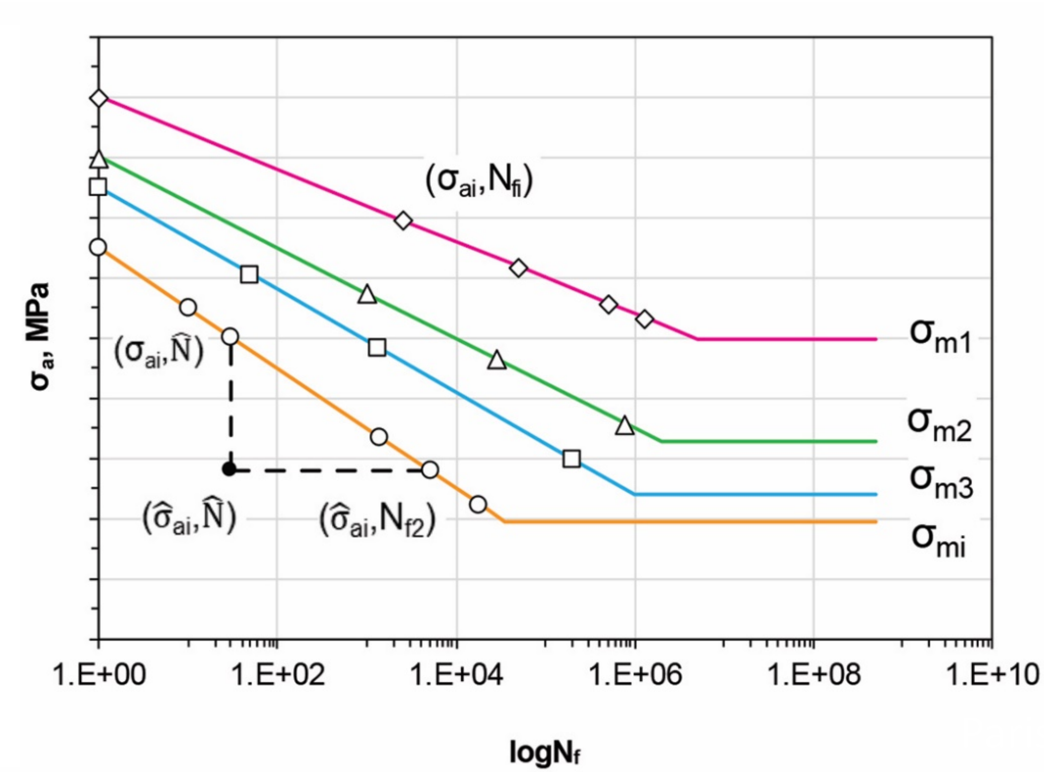
Cyclic-fatigue tests on rendered masonry wallets under diagonal compression

Cyclic-fatigue tests on rendered masonry wallets under diagonal compression

Overview

- Fatigue direct shear strength parameters: • ultimate tensile strength • stiffness properties • static stresses • cyclic stress range • the cycling frequency • number cycles $N_f \simeq 10^5\text{-}10^{10}$

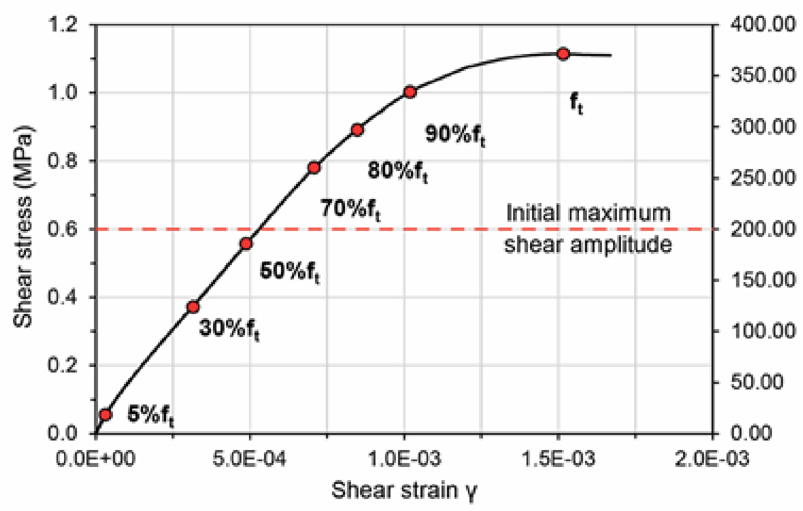


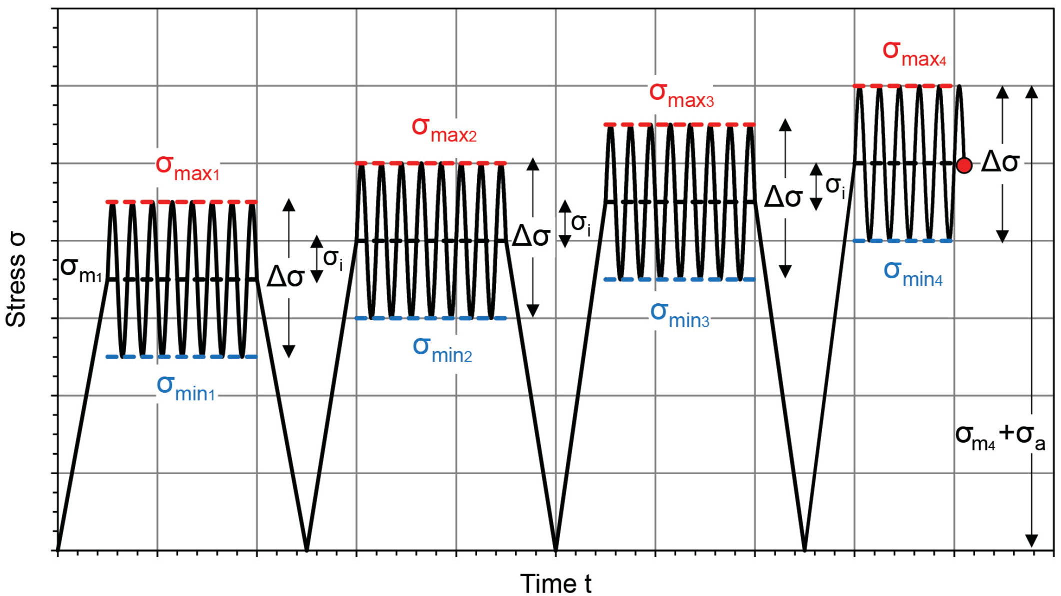


Experimental campaign: Fatigue tests on masonry wallets with rendering under diagonal compression

Testing objectives

- Fatigue under high static stresses
  Local stress close to peak capacity
- Fatigue at real-time conditions in a structure • constant fatigue loading conditions and a static service load increase • time period of 1.5 years





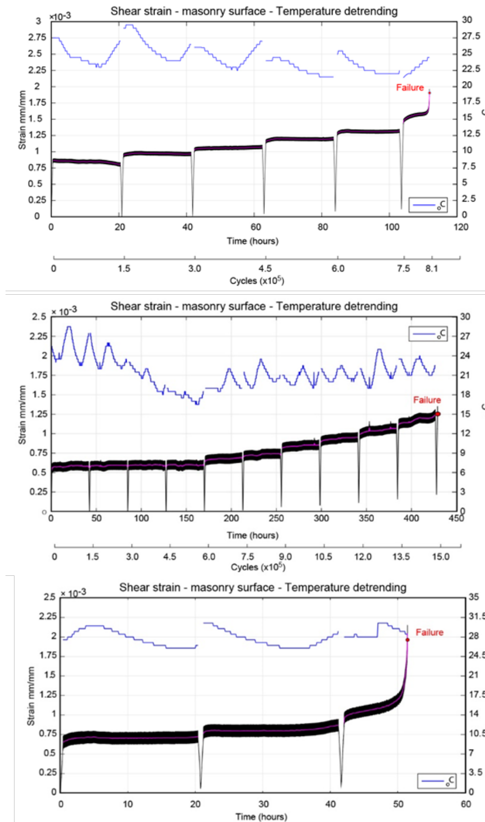
Cyclic-fatigue tests on rendered masonry wallets under diagonal compression

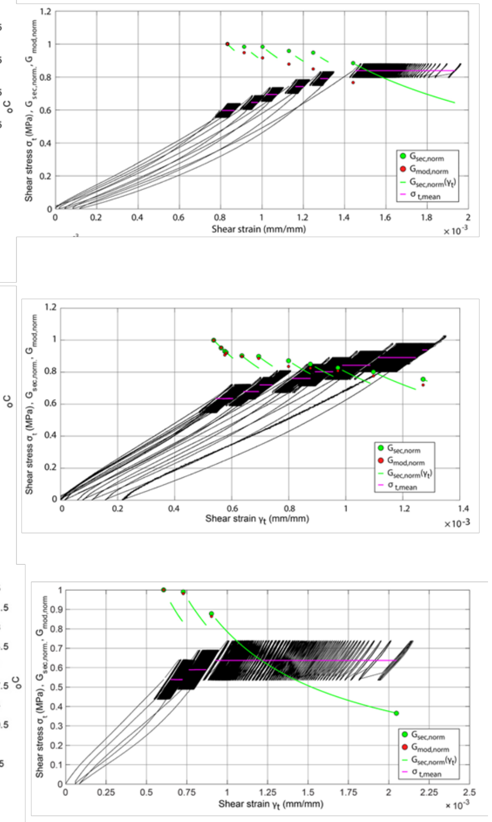
Data acquisitions

Dcf4

Dcf2

Dcf3





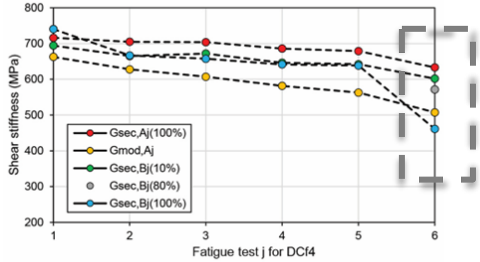
Specimen DCfi	Target ppv (mm/s)	Reference dominant radial frequency ω (rad/s)	Reference dominant frequency f (Hz)	Target ppd $\delta_o = \frac{u_o}{\omega}$ (mm)	$K_{chord}^{(100-200)kN}$ * (kN/mm)	Target shear force amplitude P_a (kN)
DCf4	8			0.018	758.41	14
DCf2	10	408	65	0.025	1113.92	28
DCf3	16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

* Average chord stiffness from loading and unloading branch.

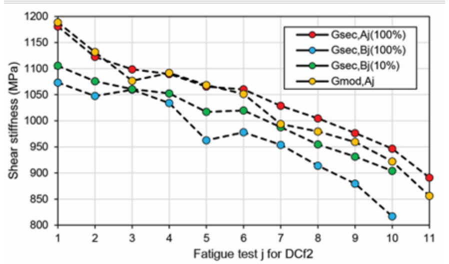
Cyclic-fatigue tests on rendered masonry wallets under diagonal compression

Stiffness evolution $G_{sec,norm}(N_i)$

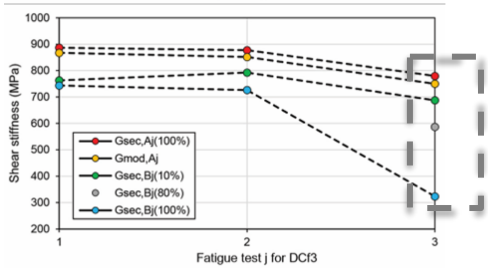
Dcf4

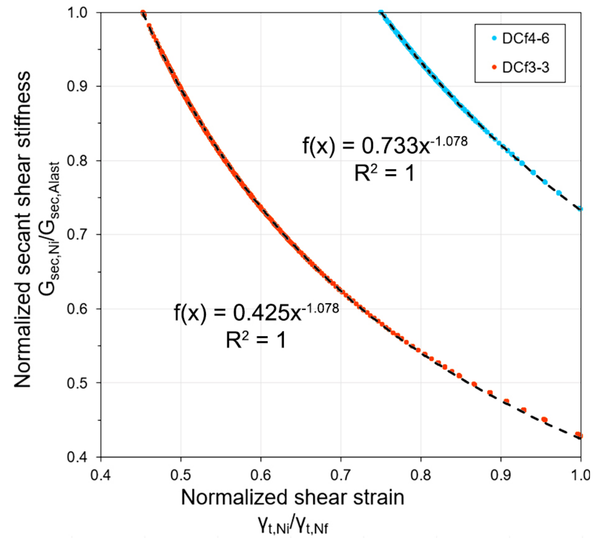


Dcf2

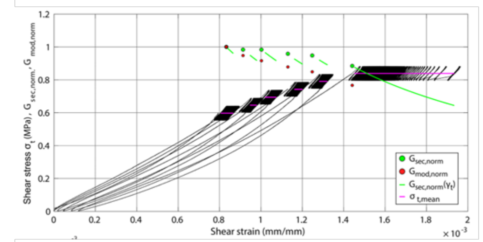


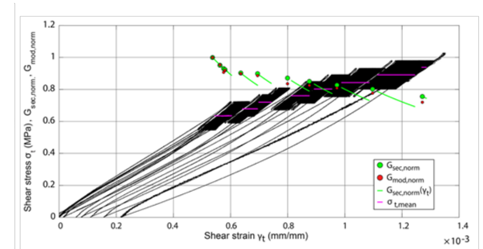
Dcf3

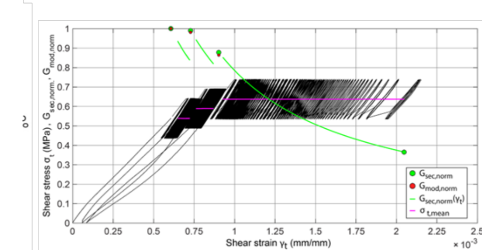




$$y = ax^b, a > 0 \text{ and } b < 0$$







Specimen DCfi	Target ppv (mm/s)	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.

- ❑ Exponential decay in secant shear stiffness of same order

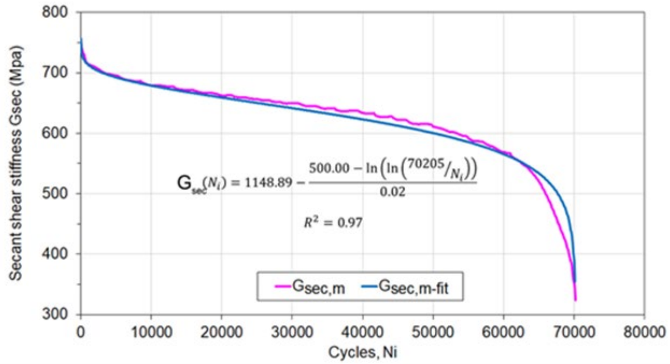
Cyclic-fatigue tests on rendered masonry wallets under diagonal compression

Analytical formulations

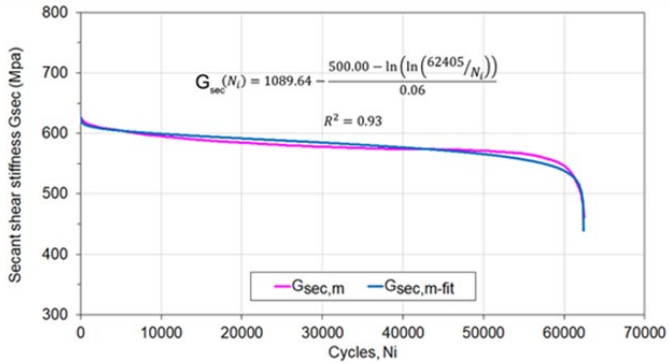
- Reverse Gompertz curve least square fit • Holmen 1982 hypothesis of equal fatigue failure properties

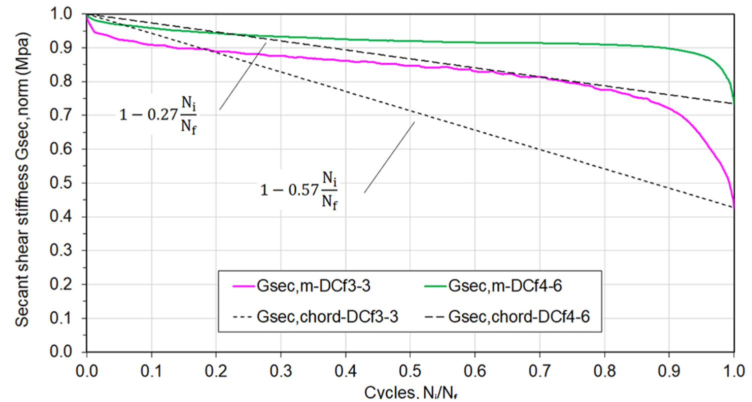
$$\frac{G_{sec,N_i}}{G_{sec,N=1}} = 1 - \lambda \frac{N_i}{N_f}$$

Dcf3-3



Dcf4-6





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

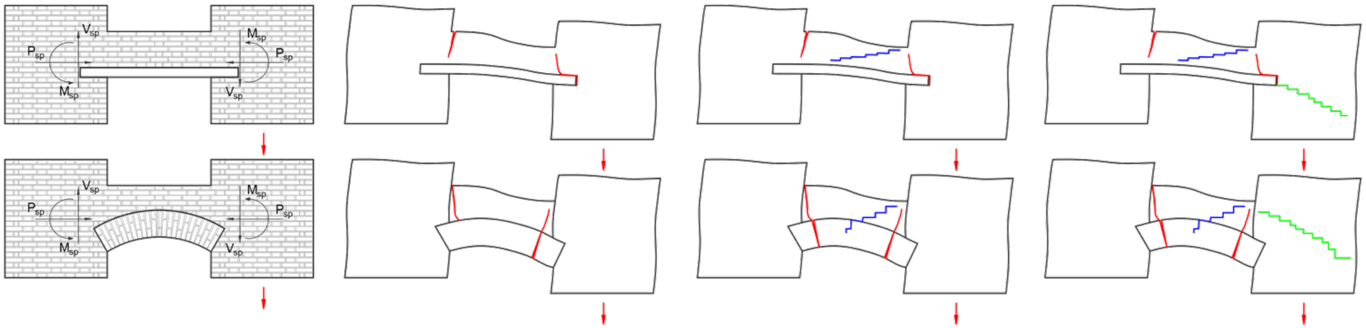
Historic brick masonry facades

In-plane tests of differential vertical uplift in pier and spandrel specimens

In-plane tests of differential vertical uplift in pier and spandrel specimens

Overview

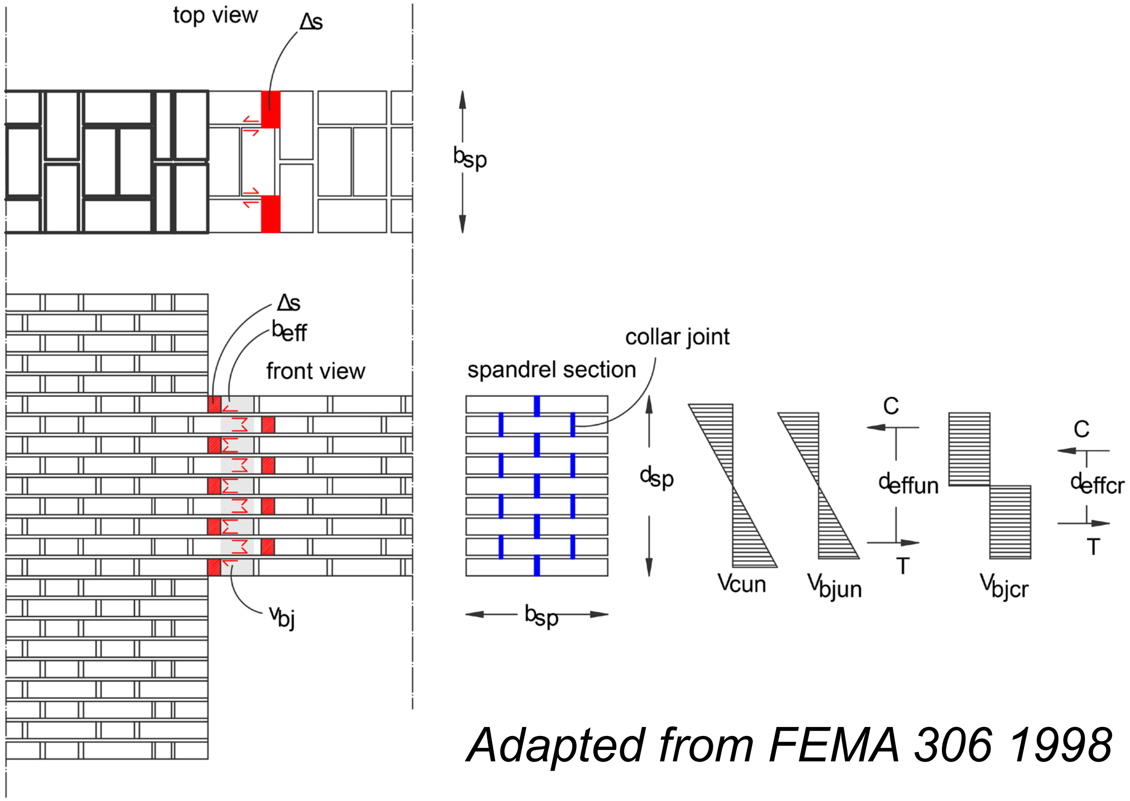
- ❑ In-plane capacity in piers and spandrel exhibits a variety of failure modes, under flexure, diagonal or sliding shear, rocking and compressive crushing, under a sequential progression



- ❑ Parameters that control the response: • relative stiffness of structural sub-systems • axial compressive stresses in the spandrel • vertical prestress in the piers • in-plane rotational restrain
- ❑ Resistance mechanisms in the spandrel: • interlocking bricks • shear bond strength in bed and collar joints • presence of lintels and in-plane strengthening elements

In-plane tests of differential vertical uplift in pier and spandrel specimens

Overview



Adapted from FEMA 306 1998

- ❑ Resistance mechanisms in the spandrel: • interlocking bricks • shear bond strength in bed and collar joints • presence of lintels and in-plane strengthening elements
- ❑ Performance of engineered structural repair and retrofit techniques

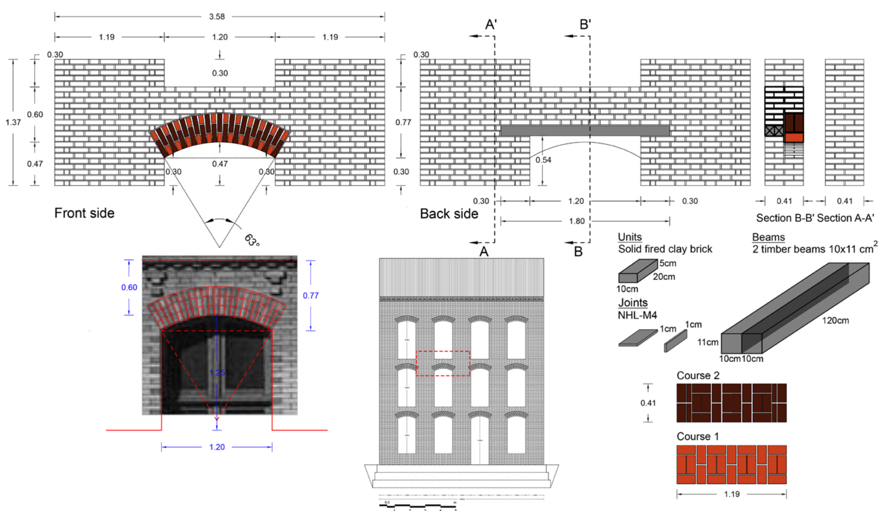
In-plane tests of differential vertical uplift in pier and spandrel specimens

Masonry assemblies • setup, protocols and instrumentation

- ❑ Four in-plane capacity tests in real scale piers and spandrel specimens

Testing assembly of piers and spandrel	Vertical prestressed rods	Lateral support at uplifting pier with rollers	Crack filling with grout	FRCM structural render, with in-plane adhesive anchors
UN1-US	✓			
UN1-DS-GR	✓	✓	✓	
UN2-US	✓	✓		
UN2-DS-GR-FRCM	✓	✓	✓	✓

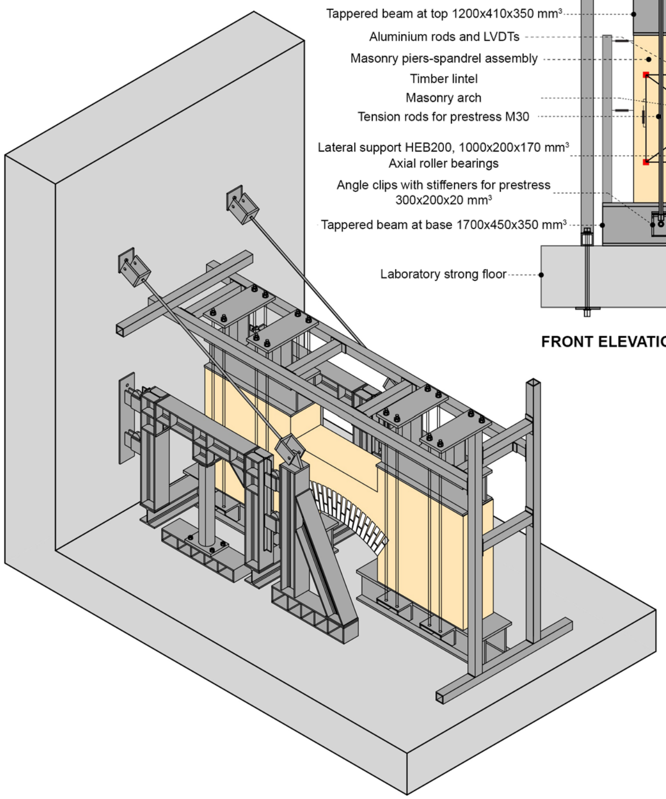
US: Undamaged state, DS: Damaged state, GR: Grouting, FRCM: Fiber Reinforced Cementitious Matrix system

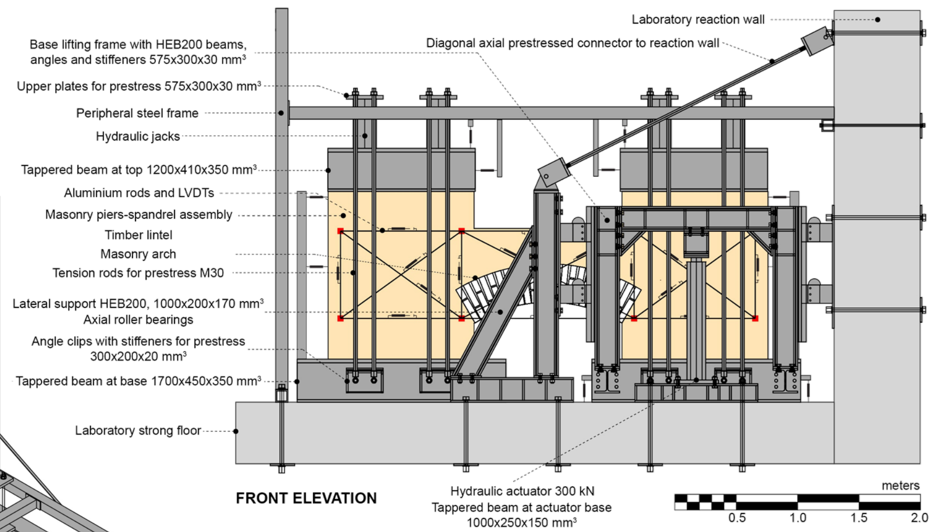


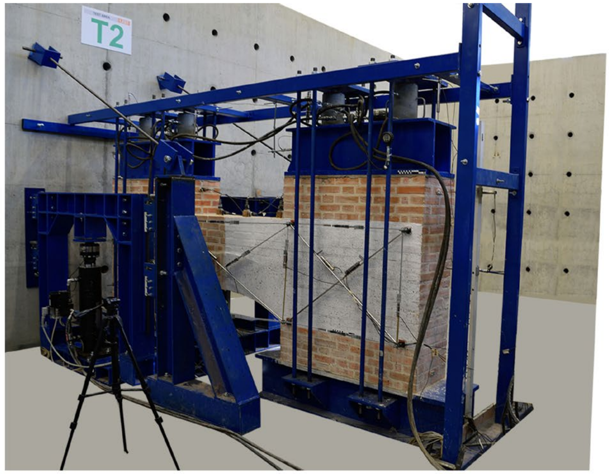
In-plane tests of differential vertical uplift in pier and spandrel specimens

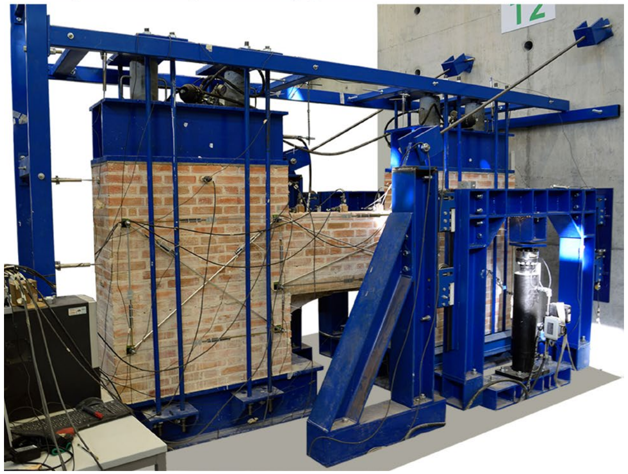
Masonry assemblies • setup, protocols and instrumentation

- ❑ Four in-plane capacity tests in real scale piers and spandrel specimens





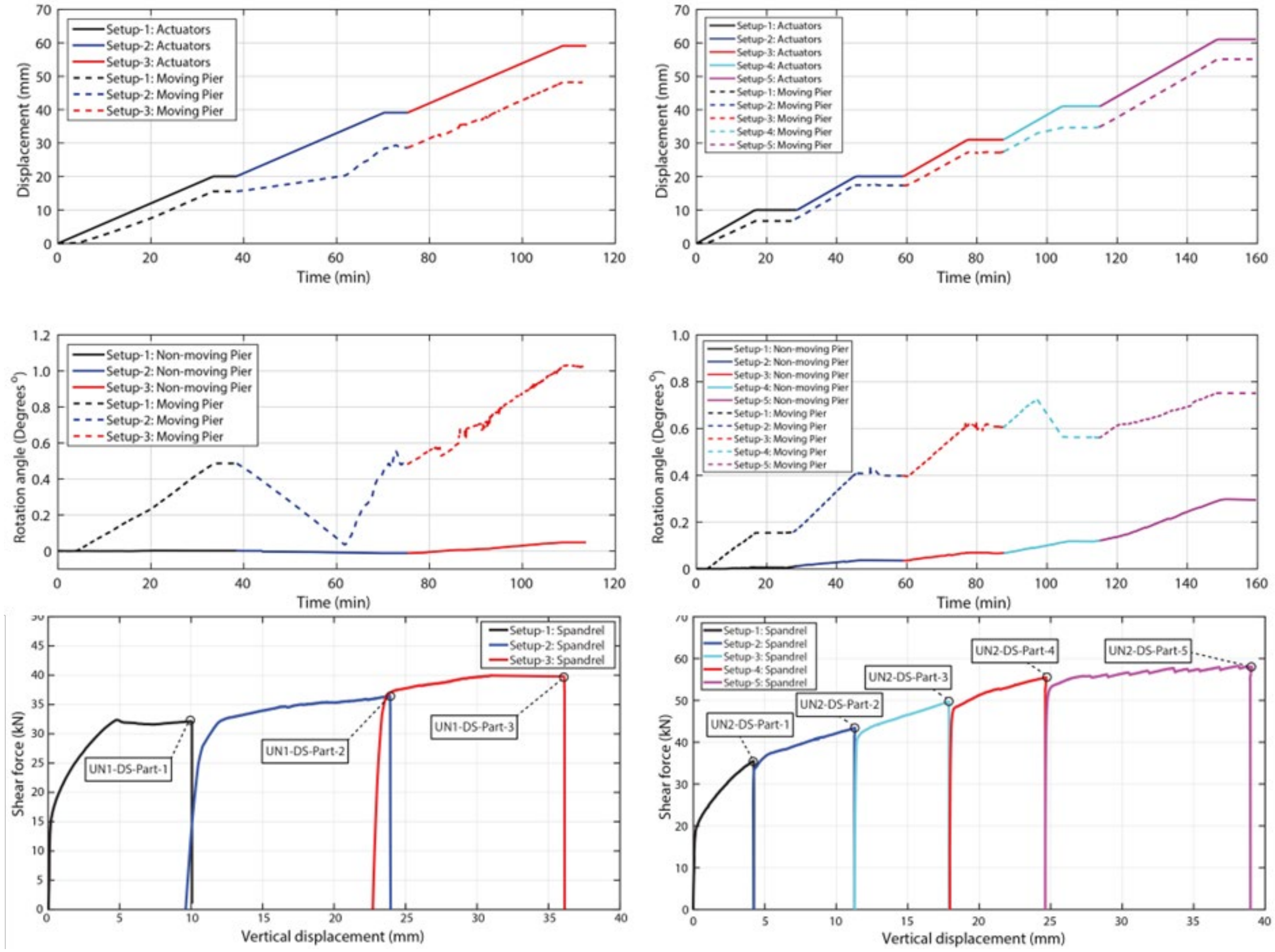




In-plane tests of differential vertical uplift in pier and spandrel specimens

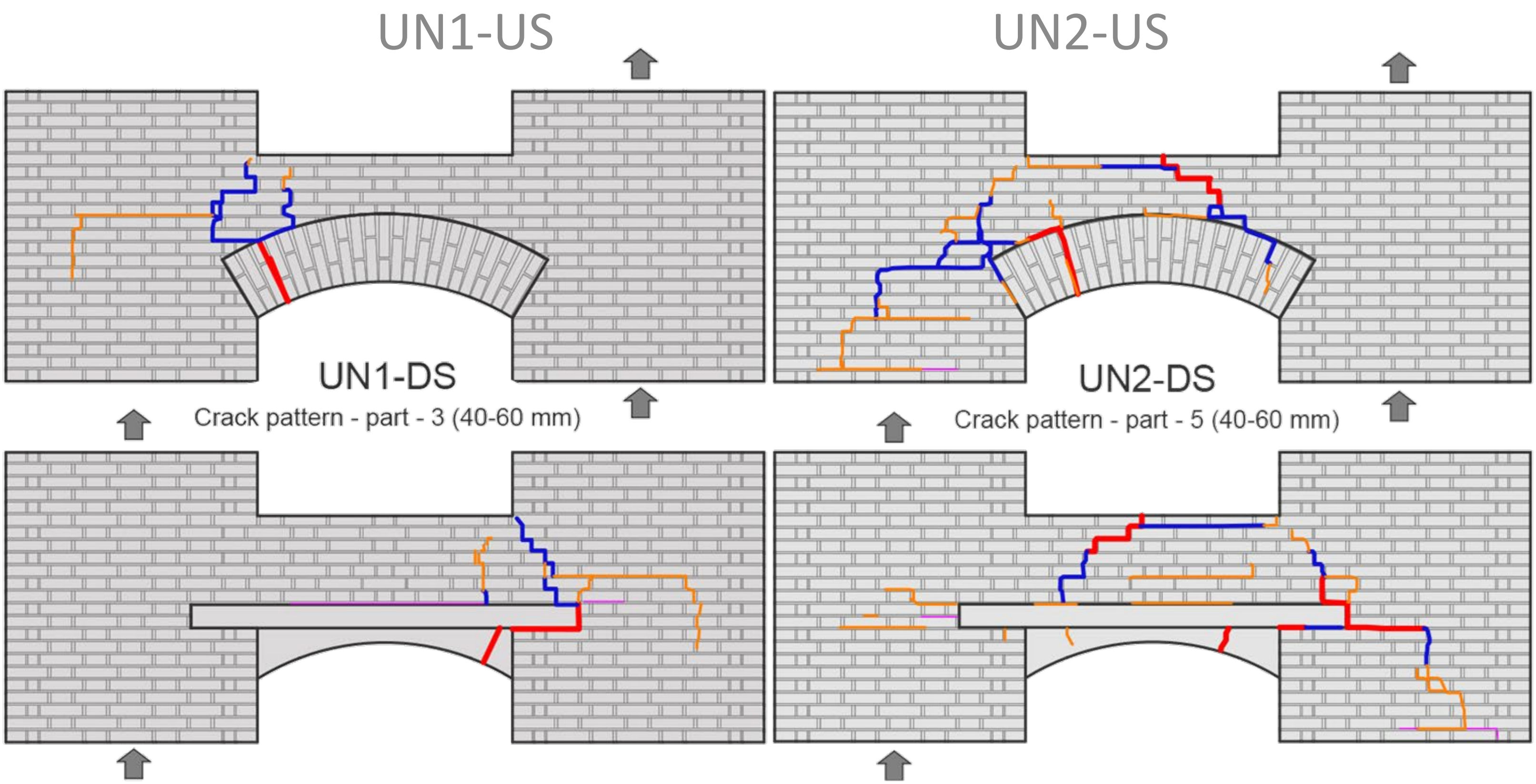
Data acquisition

UN1-US   UN2-US

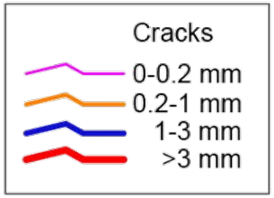


In-plane tests of differential vertical uplift in pier and spandrel specimens

Data acquisition



- ❑ flexural cracking in spandrel progressing vertically



- ❑ flexural cracking, shifted in pier
- ❑ Shear cracking in spandrel

In-plane tests of differential vertical uplift in pier and spandrel specimens

Data acquisition • structural repair and retrofit

UN1-DS-GR

Grouting injections with lime-based M15 grout

UN2-DS-GR-FRCM

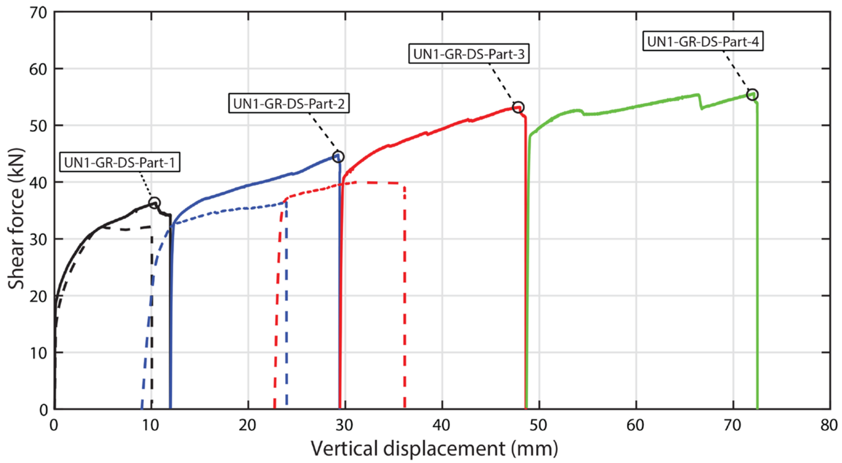
+FRSM structural render and FRCM anchors

In-plane tests of differential vertical uplift in pier and spandrel specimens

Data acquisition • structural repair and retrofit

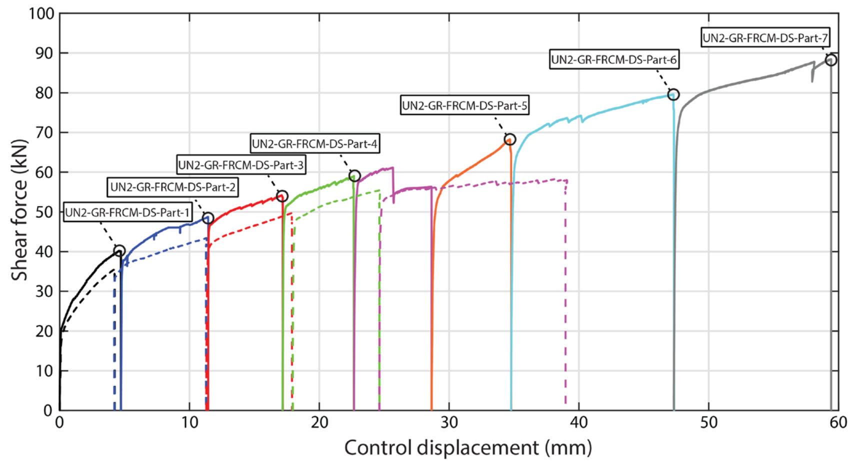
UN1-DS-GR

Grouting injections with lime-based M15 grout



UN2-DS-GR-FRCM

+FRSM structural render and FRCM anchors



Masonry assembly	d_y (mm)	$P_S(d_y)$ (kN)	d_{max} (mm)	$P_{S,max}$ (kN)	μ (-)	Hardening branch [1] (N/mm)/R^2
UN1-DS	4.50	31.97	31.08	39.95	6.91	370.8/0.99
UN1-DS-GR	-	-	72.13	55.61	16.03	477.3/0.99
UN2-DS	4.50	34.65	38.12	58.22	8.47	942.5/1.0
UN2-DS-GR-FRCM	-	-	59.43	88.45	13.21	844.5/1.0

In-plane tests of differential vertical uplift in pier and spandrel specimens

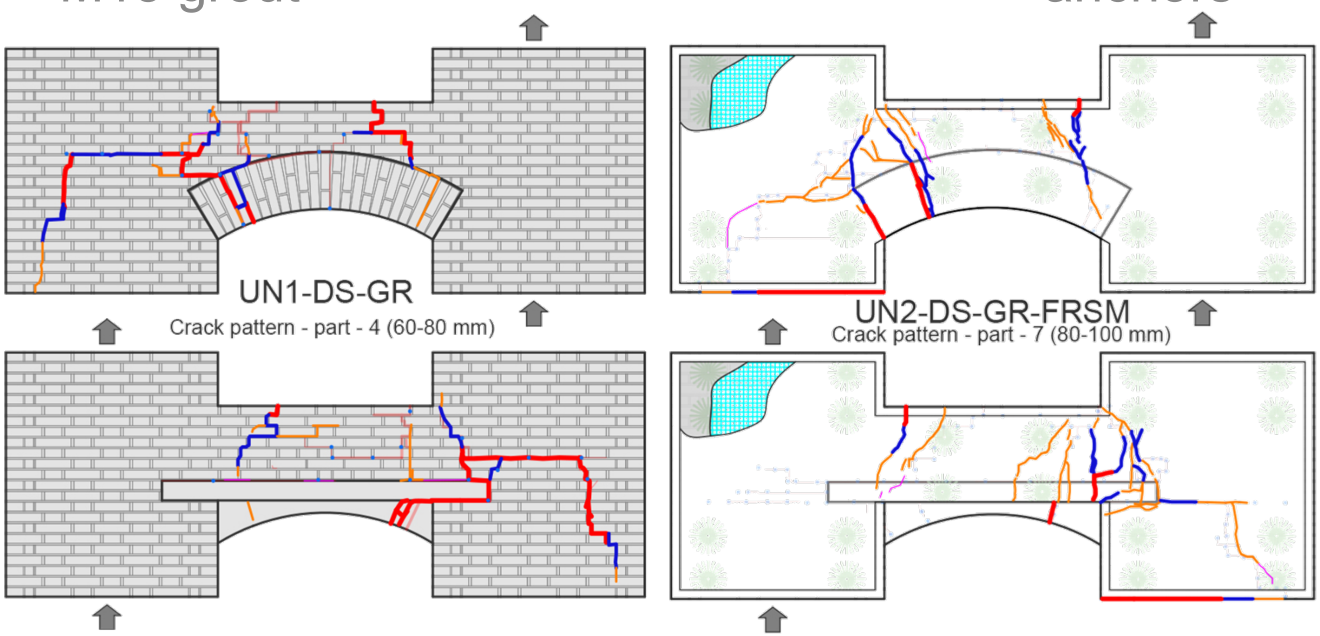
Data acquisition • structural repair and retrofit

UN1-DS-GR

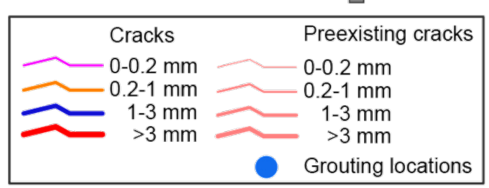
Grouting injections with lime-based M15 grout

UN2-DS-GR-FRCM

+FRSM structural render and FRCM anchors



- ❑ Shear capacity of undamaged masonry
- ❑ Higher hardening stiffness and ductility



- ❑ Shear capacity higher by 50%
- ❑ Higher hardening stiffness and ductility

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

Conclusions

- Durability in historic masonry structures, has not been fully evaluated and many times not incorporated in the structural assessment framework
- Many material constitutive models do not account for cyclic softening due to fatigue, and thus, multi-hazard structural assessment under induced settlements-vibrations is particularly complex
- Probabilistic approach for fatigue: S-N_f, ε-N_f curves and correlations of shear strain-stiffness, under static and cyclic stress combinations
- Fatigue tensile damage model in ATENA FE software: fracturing strain increment $\varepsilon_{fatigue}$ is added after N_i cycles, as a percentage of the failing fatigue strain

$$\frac{\sigma_{max}}{f_t} = 1 - \beta_{fatigue}(1 - R)\log N_f$$

- Numerical analyses for replicating the experimental tests for settlements and vibrations, and their combined effect, are part of future works

Thank you

Acknowledgments

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