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Experimental analysis of the seismic vulnerability of earth masonry reinforced with horizontal bands

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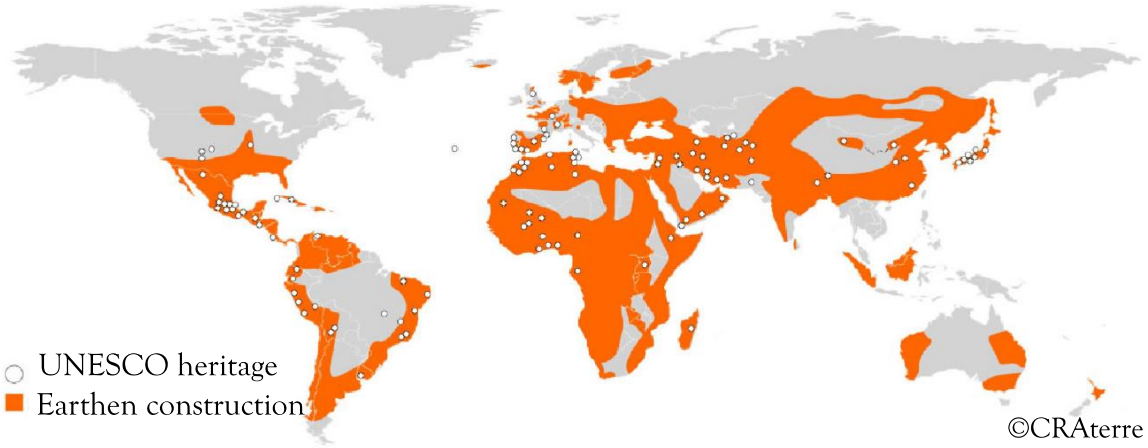
Outlines

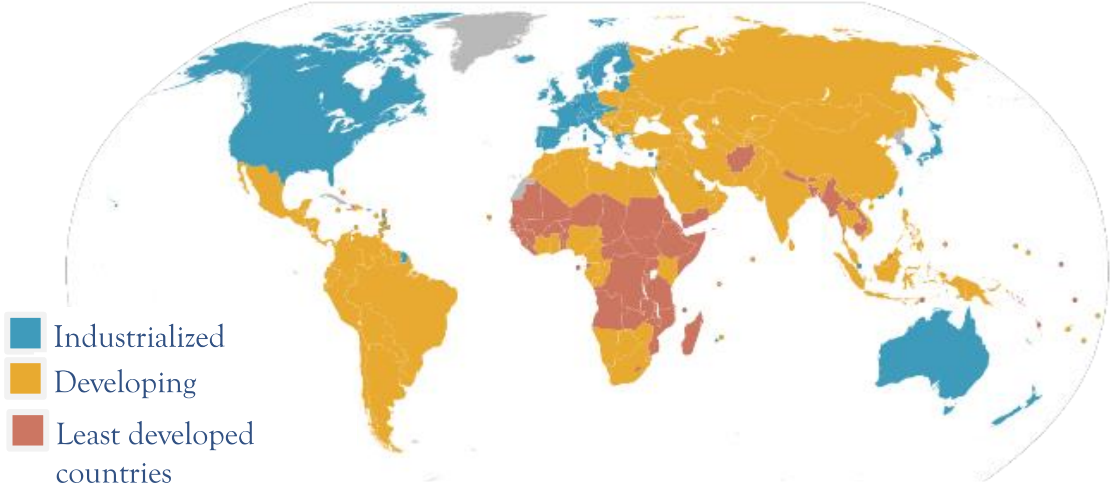
Introduction → Objectives → Material / Wall / Building → Conclusions

Earthen construction



1/3 of the world's population lives in earthen dwellings

Global scenario



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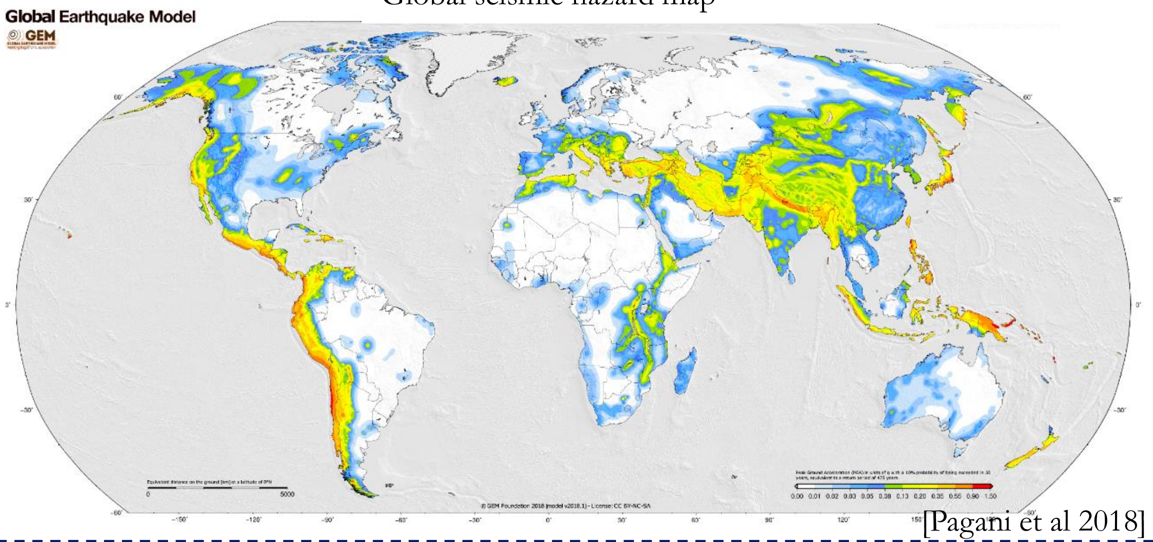
Global seismic hazard map



[Pagani et al 2018]

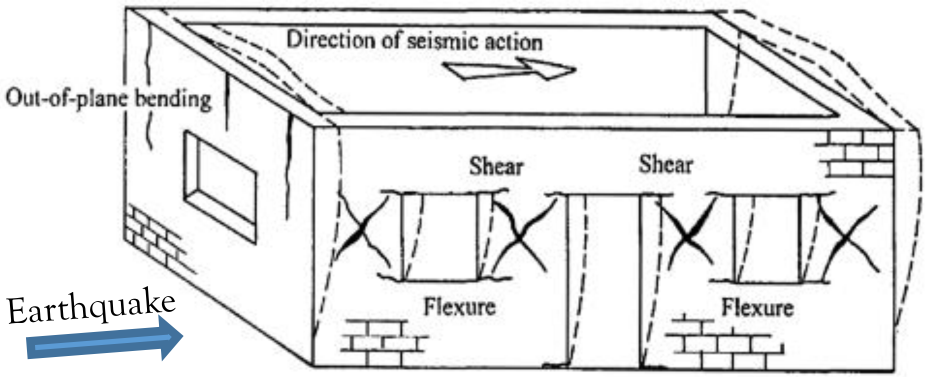
- ❖ Earthen construction common in developing and least developed countries
- ❖ Seismically vulnerable

Seismic risk

[Source: https://www.bbc.com/news/world-europe-37176601]

"Earthquake doesn't kill, buildings do"

Failure mode



[Tomaževič 1999]

Minimized the effects of seismic action on the structure and prevent it from collapse

Modern approach

- ❑ Industrial products

Traditional approach

- ❑ Local available material
- ❑ Affordable

Horizontal seismic band

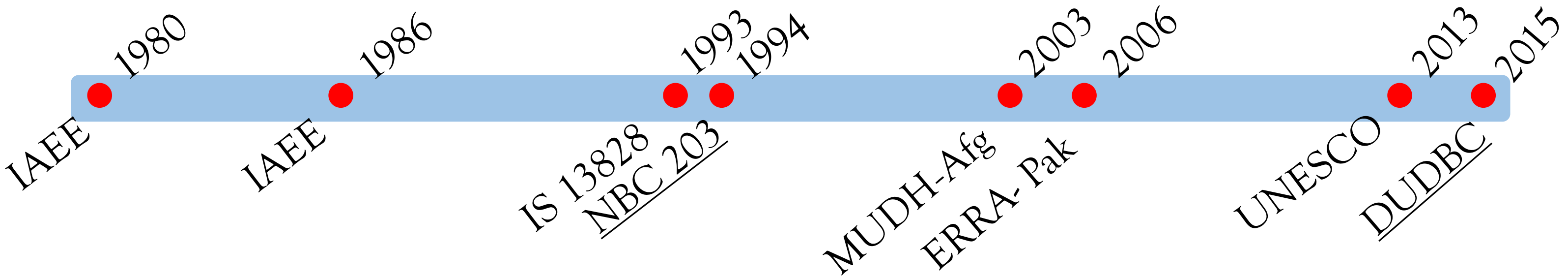
Horizontal seismic band

Seismic bands are a constructive device specific to the traditional masonry constructions in seismic zone, which can be continuous (at plinth, lintel and roof level), or discontinuous (at the level of opening/sill) or even punctual (at the level of the angles).

Minoan civilization in Bronze Age Crete 3000 BC [Ortega 2015]

On-site practice

Guidelines and Building code



Variation in codes

Dimension of band

Band material

Placement/location

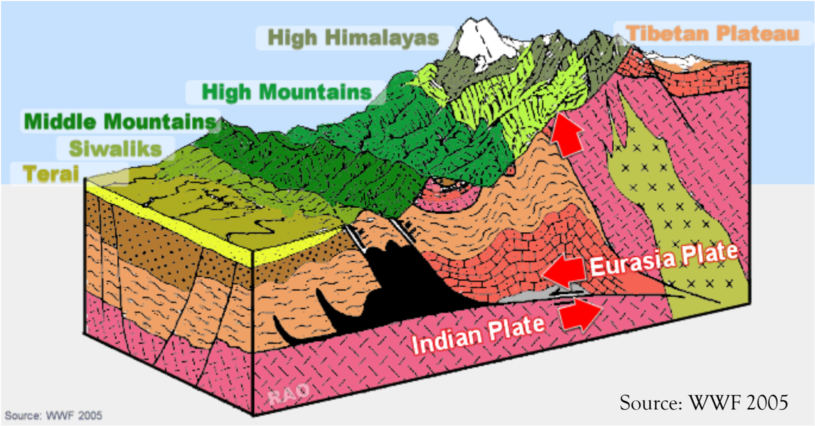
Lack of quantified knowledge

Challenges

Which material
Where
How

Rationale

Geology of Nepal



Source: WWF 2005

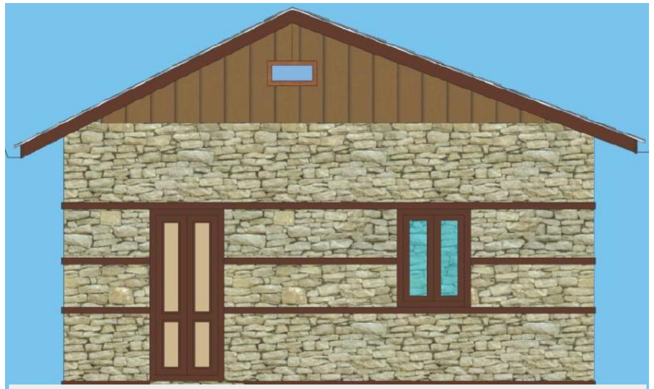
2015 Earthquake

7.8 Mw, 25th April

775782	Building collapsed
9000	Death

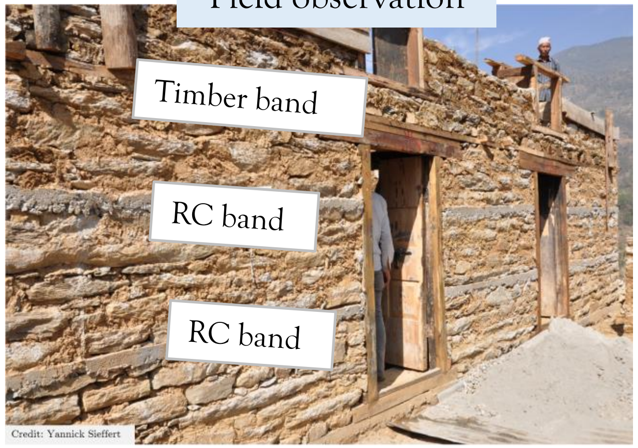
Reconstruction

Model building CRAterre , AE&CC, ASF-Nepal

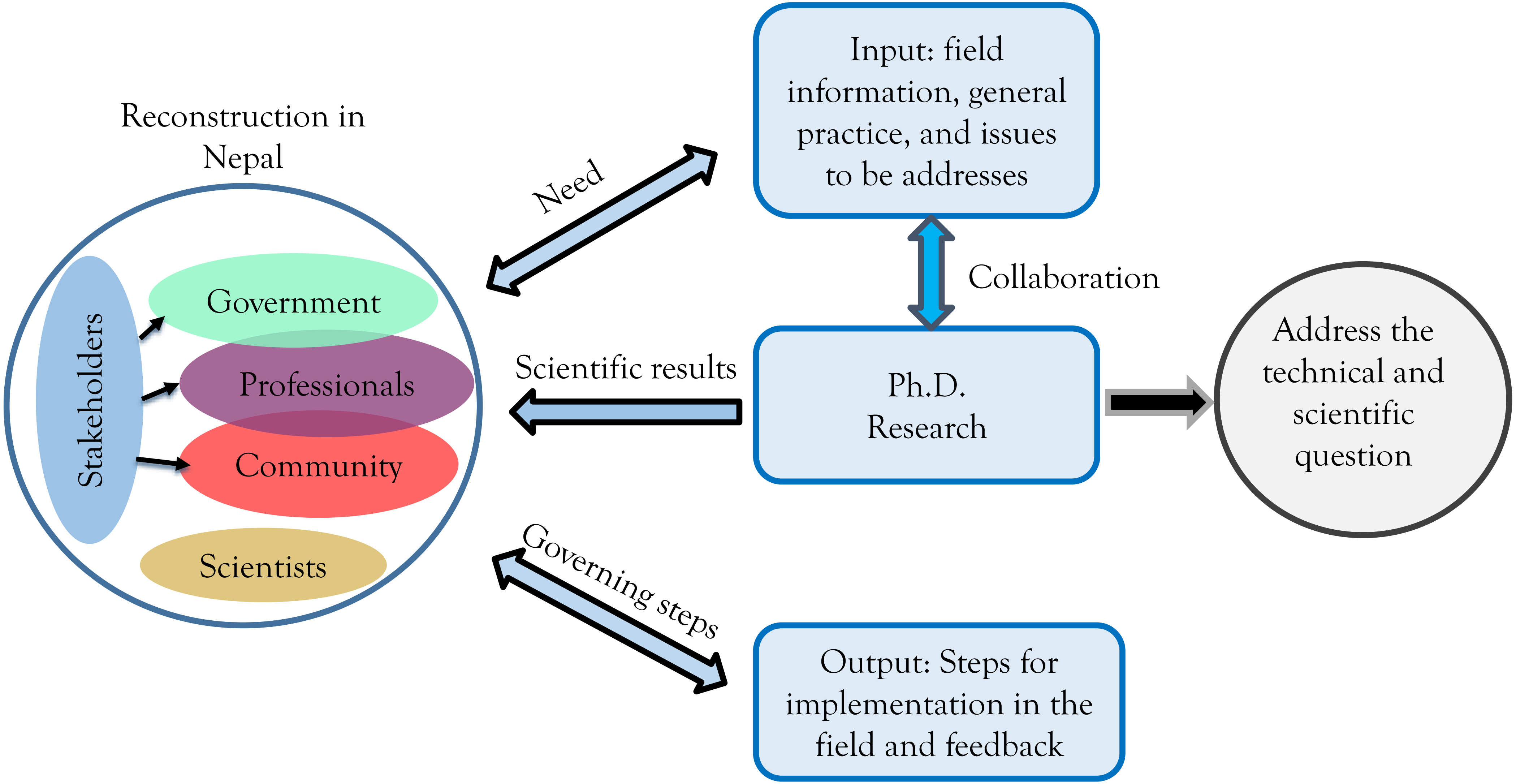


Reconstruction guidelines SMM model [DUDBC 2015]

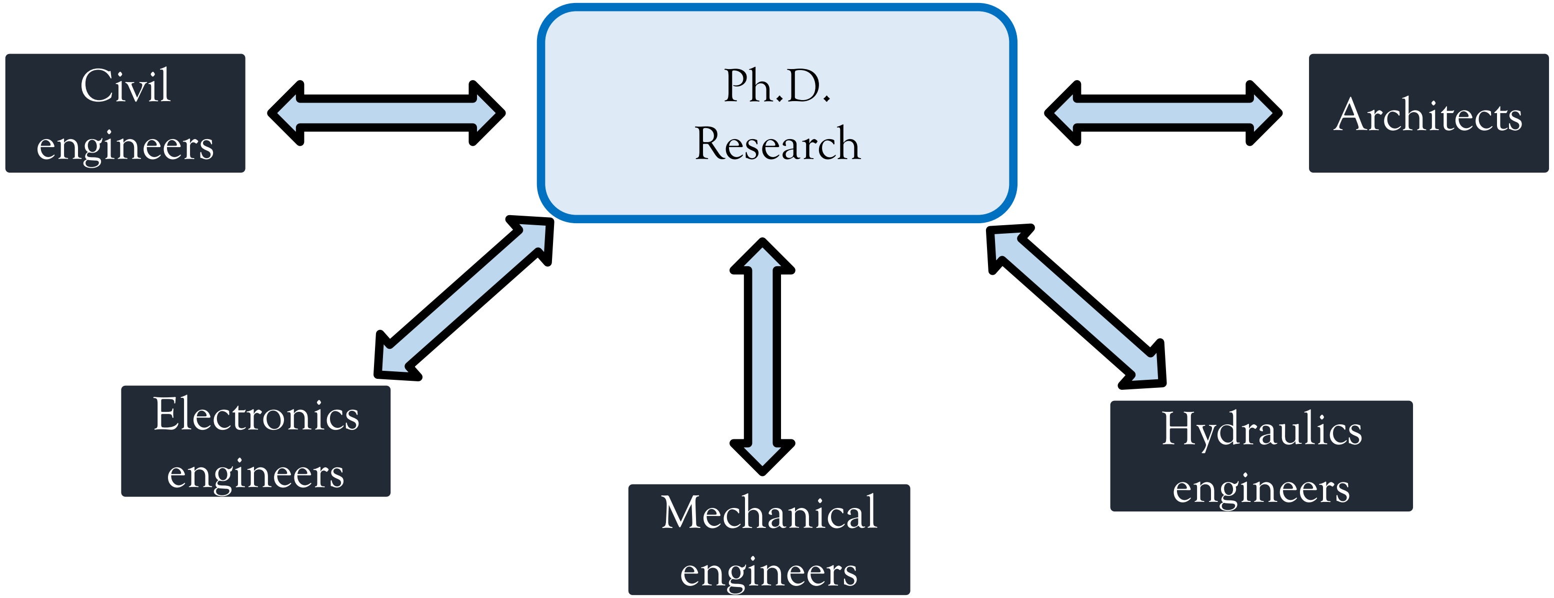
Field observation



Interdisciplinarity

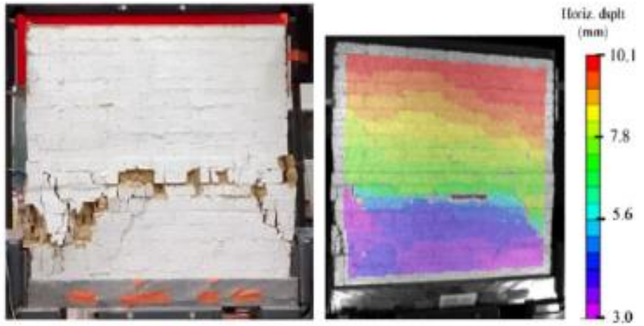


Scientific to Interdisciplinarity



State of arts - Mechanical aspect

Quasi-static experimental



[Jairo 2020]

- ❑ Helps in energy dissipation
- ❑ Control crack propagation
- ❑ Increase the peak load and displacement capacity

Dynamic experimental

Both survived 1.0g PGA

(a) One of the 2/3rd scale model buildings (DT 1)

(b) One of the 1/3rd scale model buildings (DT 4)

[Bothara 2019]

- ❑ Dynamic test: useful for the study of behavior of seismic band
- ❑ Band enhances the shear resistance
- ❑ Limited study carried out so far

Numerical

Numerical simulation

Proper validation required

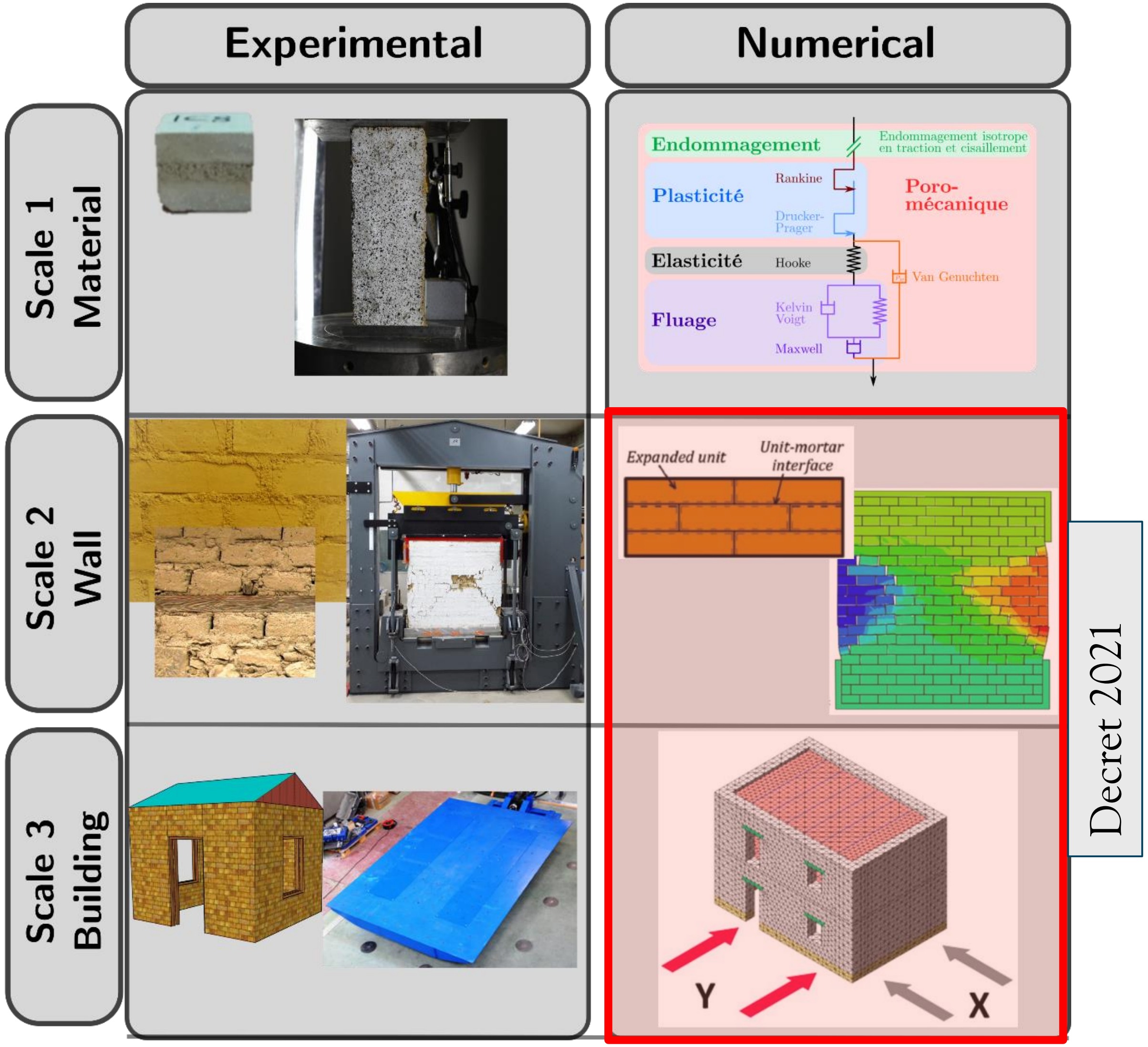
Fast, economic and parametric analysis

- ❖ Few scientific research available
- ❖ Lack of comparison using different material (for seismic band) at material, wall, building scale

Goals

Study the paraseismic behavior of structure using a horizontal seismic band

Compare the influence of band materials in seismic response of structure



Methodology

Material to be used: Adobe



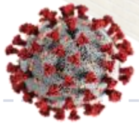
Adobe

Extruded adobe


Sept'18 Sept'19 Sept'20 Sept'21

3SR lab

23-24 Feb'20



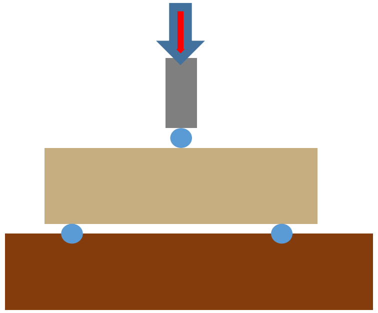
Pandemic

PhD methodology necessarily revised

Test outlines

Compression test

Compressive strength



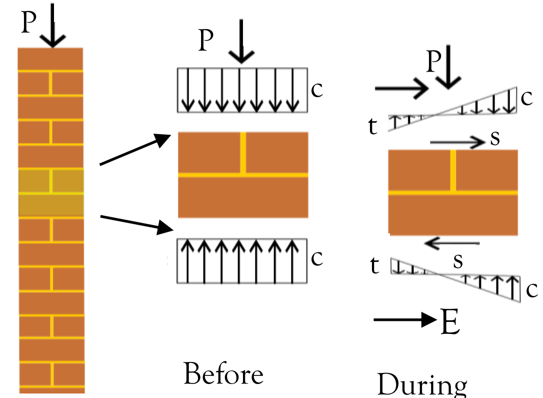
Flexural 3 point bending test

Flexural strength

Sandwich shear test

Shear strength

Stress scenario



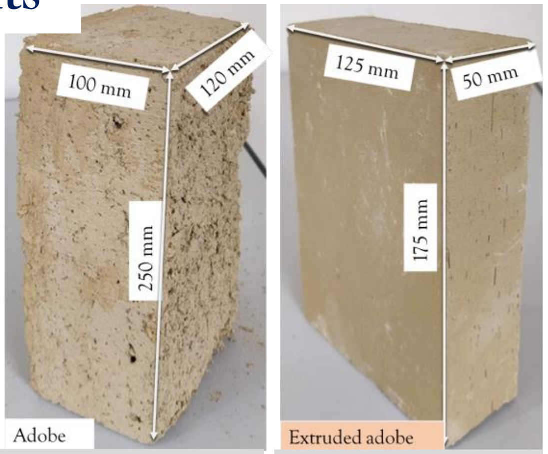
Wall

Before Earthquake

During Earthquake

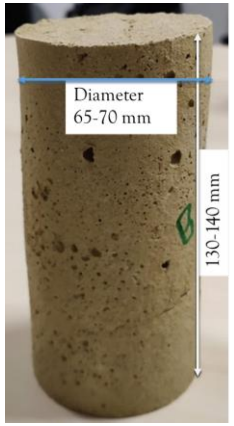
P: vertical load
E: earthquake load
c: compressive stress
t: tensile stress
s: shear stress

Brick units



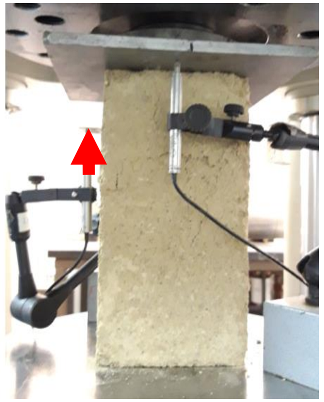
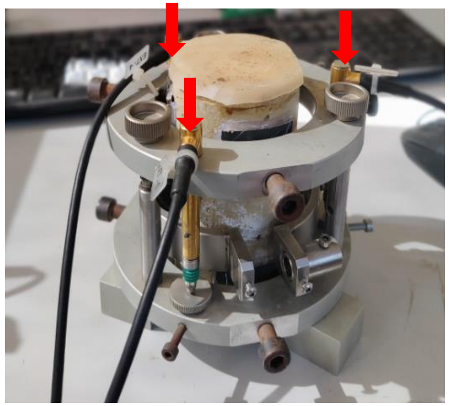
Density= 1806 kg/m^3 | 2054 kg/m^3

Mud mortar

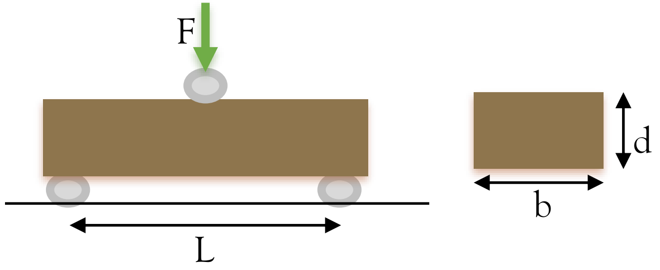


Adobe_M_C_F_S	Extruded_M_C_S
20% Fiber 10% Sand	2:1 (soil : sand)
Density= 1712 kg/m^3	1960 kg/m^3

Compression test

Flexural test



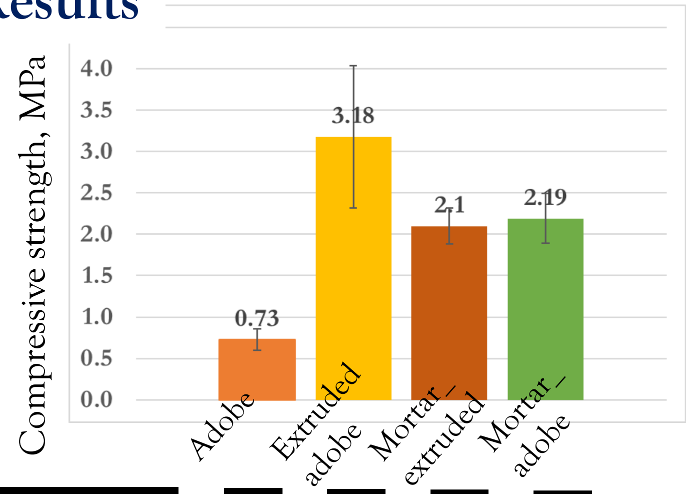
$$\sigma_f = \frac{3FL}{2bd^2}$$

Shear test

Adobe-adobe	N=6	50 kPa	SD= 11.4
Extruded- extruded adobe	N=3	6 kPa	SD= 2.8
Extruded adobe- concrete	N=3	8.4 kPa	SD= 2.1

❖ Surface rugosity → important

Results



No. of samples, N	7	7	3	7

Results

			SD
Adobe brick	N=7	0.42 MPa	0.08
Extruded adobe brick	N=6	2.55 MPa	0.36

Brittle failure mode

Flexural strength ↔ Tensile strength

Effect of composition and manufacturing process

❖ Adobe and mud mortar – heterogeneous nature

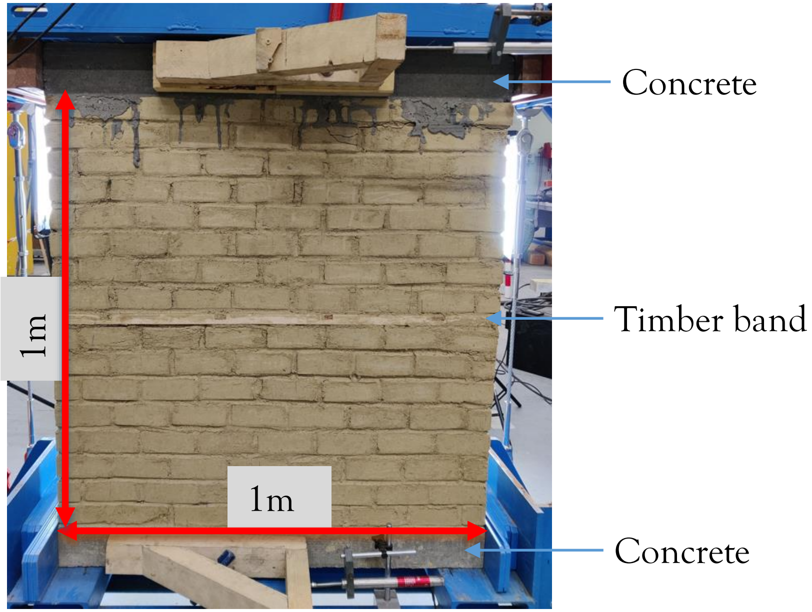
Quasi-static cyclic test

Adobe wall

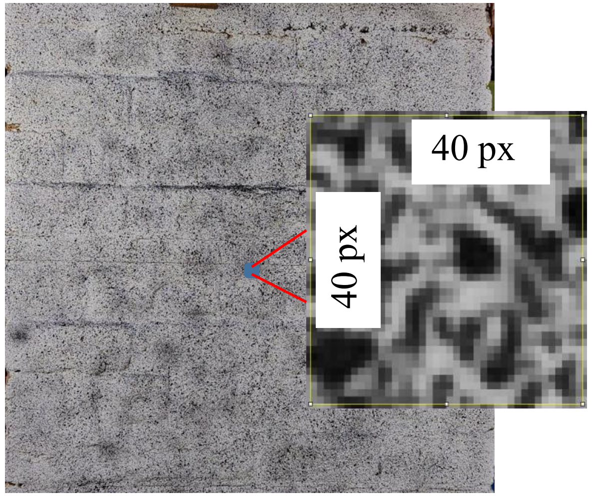
- Without band
- Timber band
- RC band

Extruded adobe wall

- Without band
- Timber band



DIC surface preparation



Results analysis

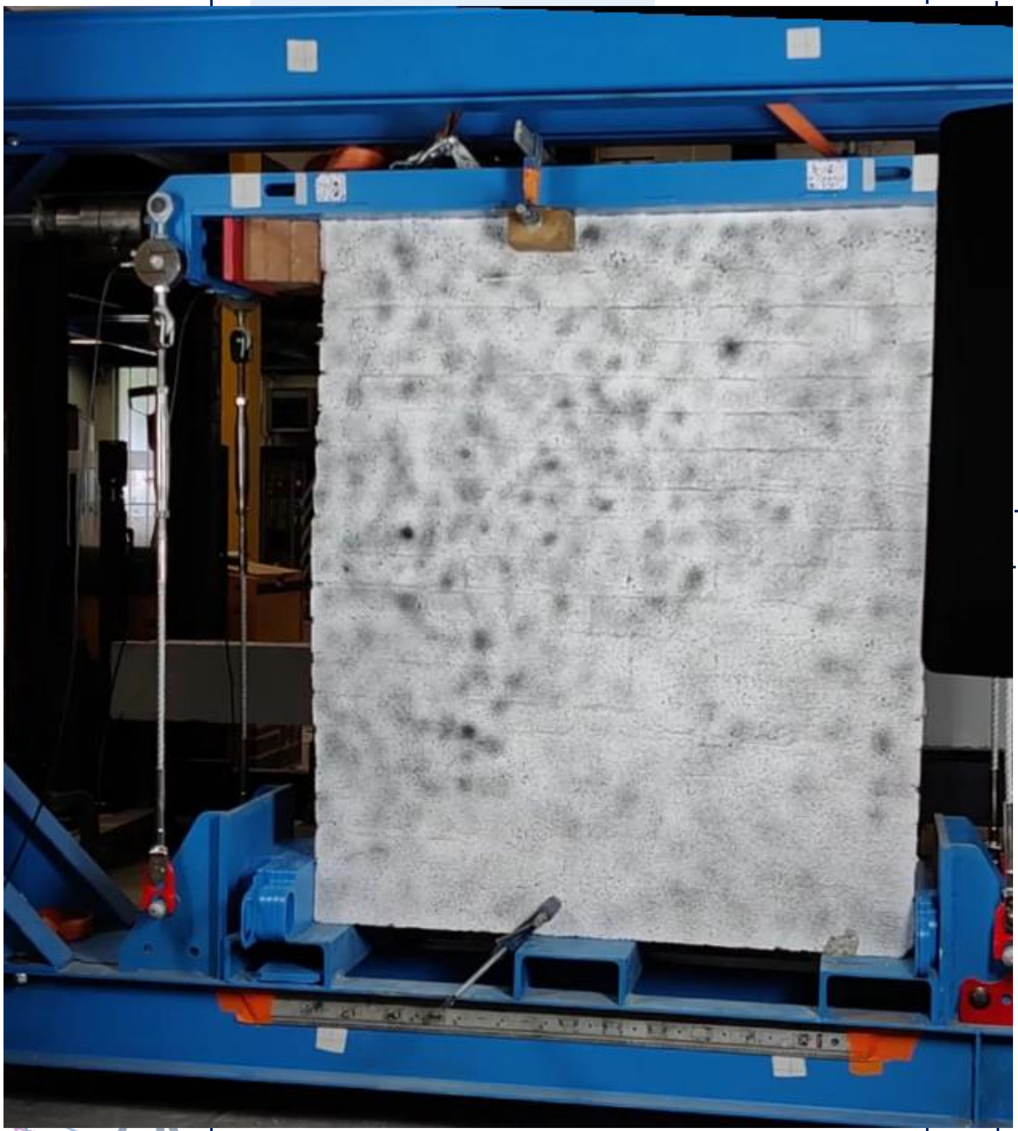
Force and displacement

- Modulus of rigidity
- Bilinear idealization
- Energy dissipation
- Equivalent viscous damping ratio

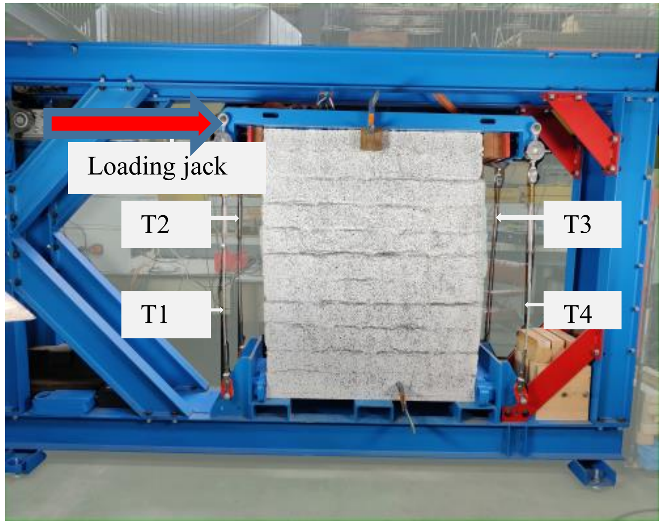
Crack pattern observation

- Qualitative
- DIC

Shear test setup



Reaction frame setup

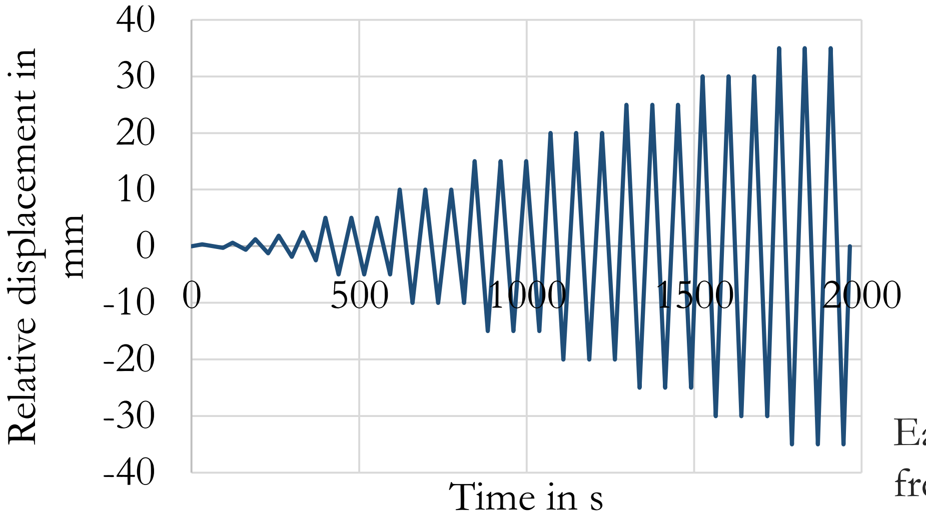


Capacity

Force limit = 40 kN

Displacement = 220-250 mm

Loading protocol



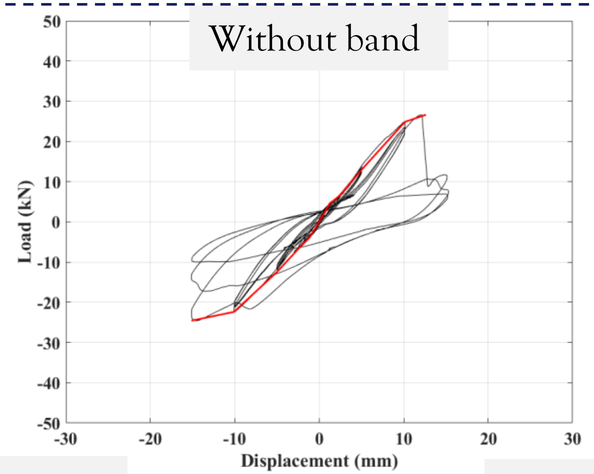
Quasi-static cyclic

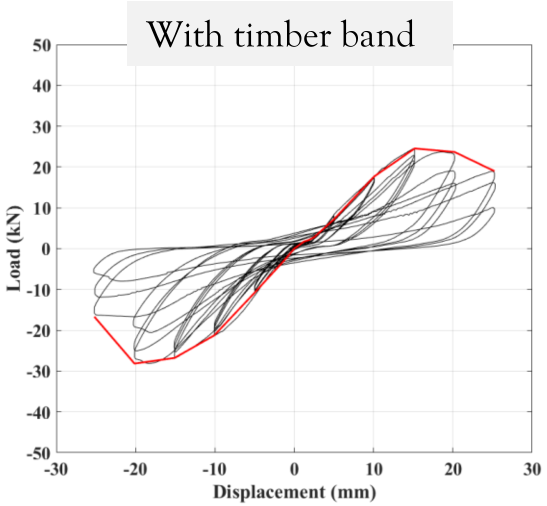
ISO 21581, 2010

Each cycle with constant frequency = 0.013 Hz

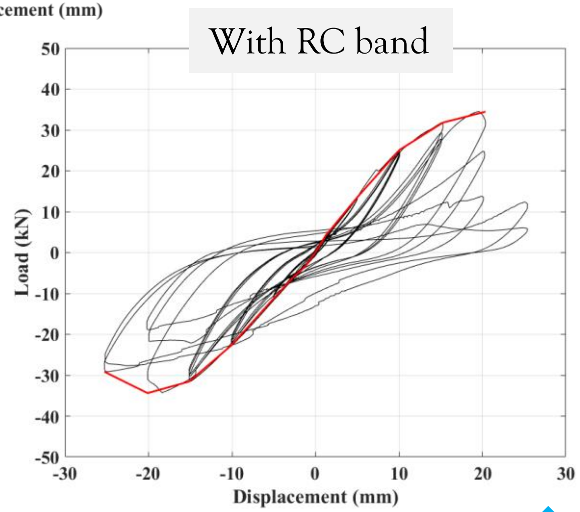
Force-displacement

Adobe



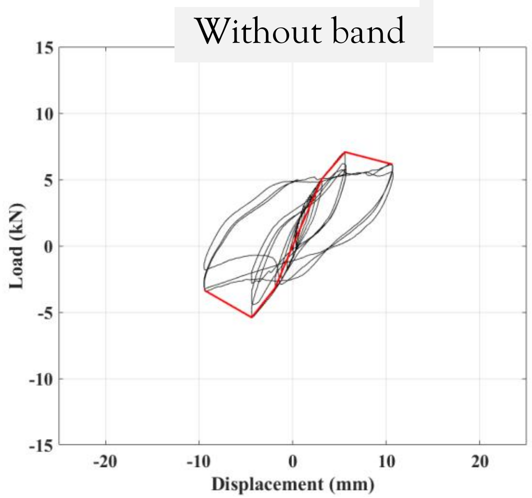


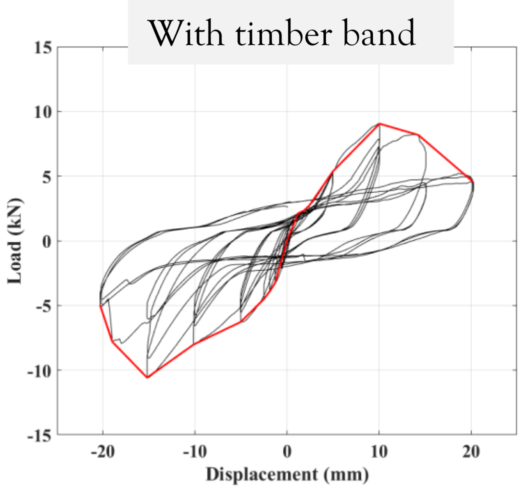
Peak force	5.7% ↑
Displacement	52.1% ↑



Peak force	29.5% ↑
Displacement	52% ↑

Extruded adobe





Peak force

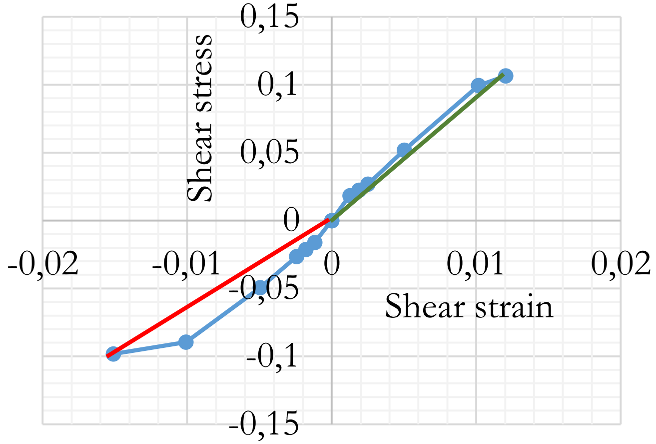
47.1% ↑

Displacement

170.8% ↑

Peak force and displacement capacity enhanced with seismic band

Modulus of rigidity



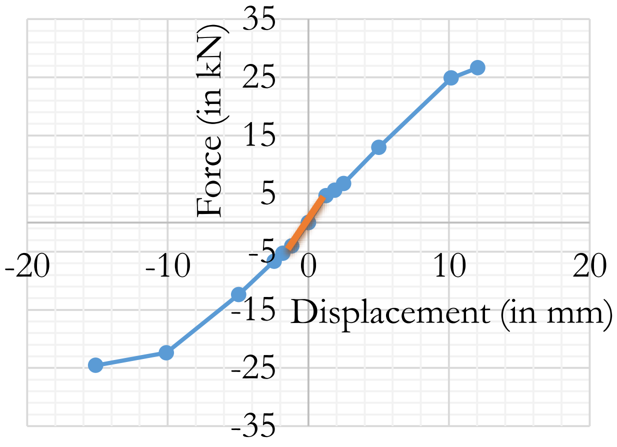
Adobe wall

Secant modulus, MPa	
7.7 (SD=1.67)	Without band
6.0 (SD=0.62)	Timber band
7.3 (SD=0.40)	RC band

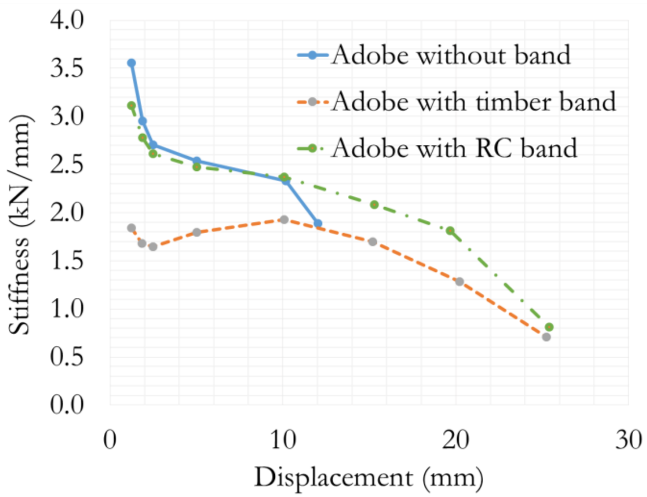
Extruded adobe wall

Secant modulus, MPa	
7.2 (SD=0.48)	Without band
4.6 (SD=0.82)	Timber band

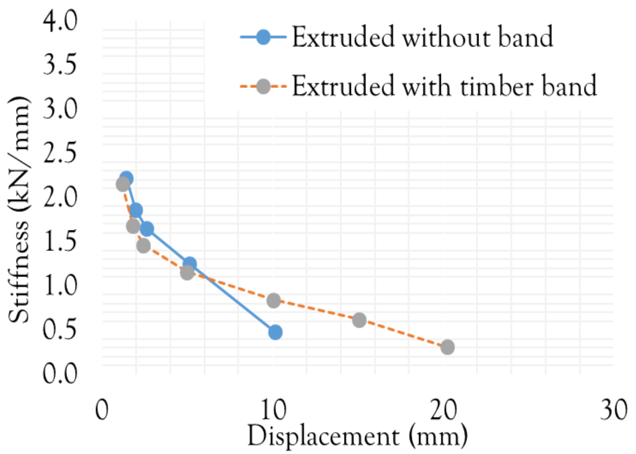
Stiffness calculation



Adobe wall



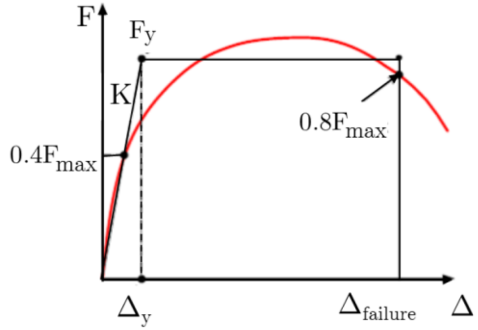
Extruded adobe wall



Seismic band modifies the stiffness and degradation rate

Bilinear idealization

EEEP (Equivalent Energy Elastic-Plastic) method

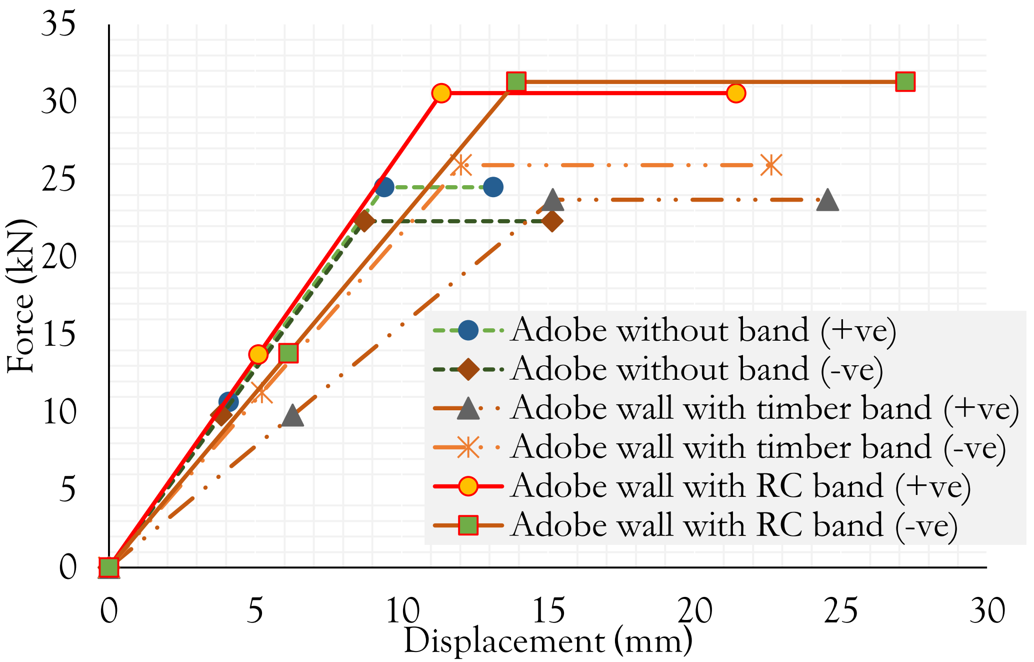


$$F_y = \left[\Delta_{failure} - \sqrt{\Delta_{failure}^2 - \frac{2w_{failure}}{K}}\right] \times K$$

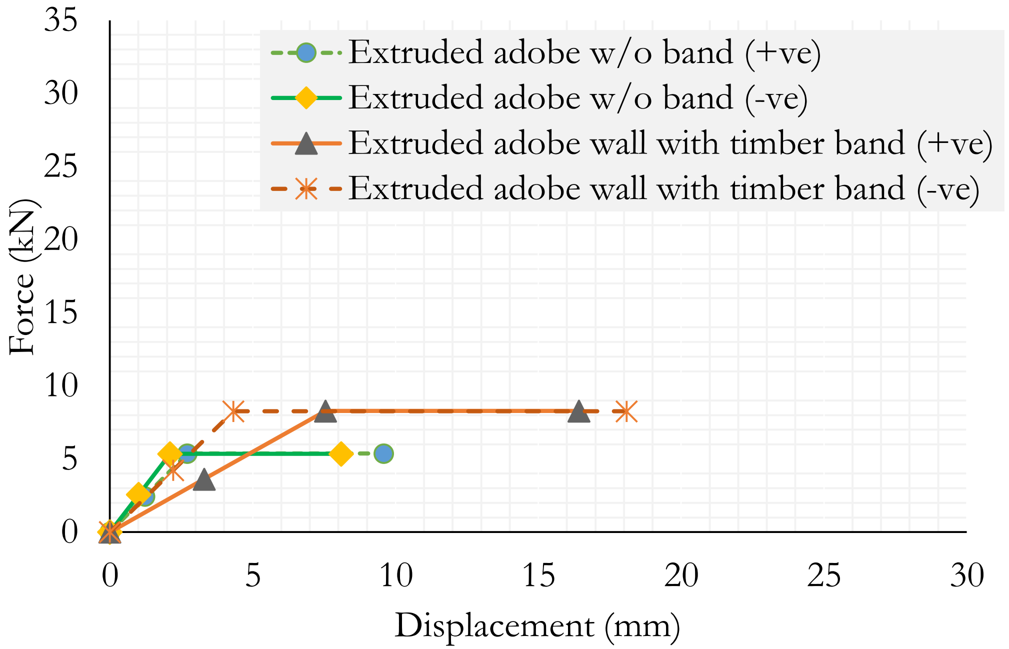
$w_{failure}$ = Energy dissipated until failure limit

[Muñoz et al., 2008]

Adobe wall



Extruded adobe wall

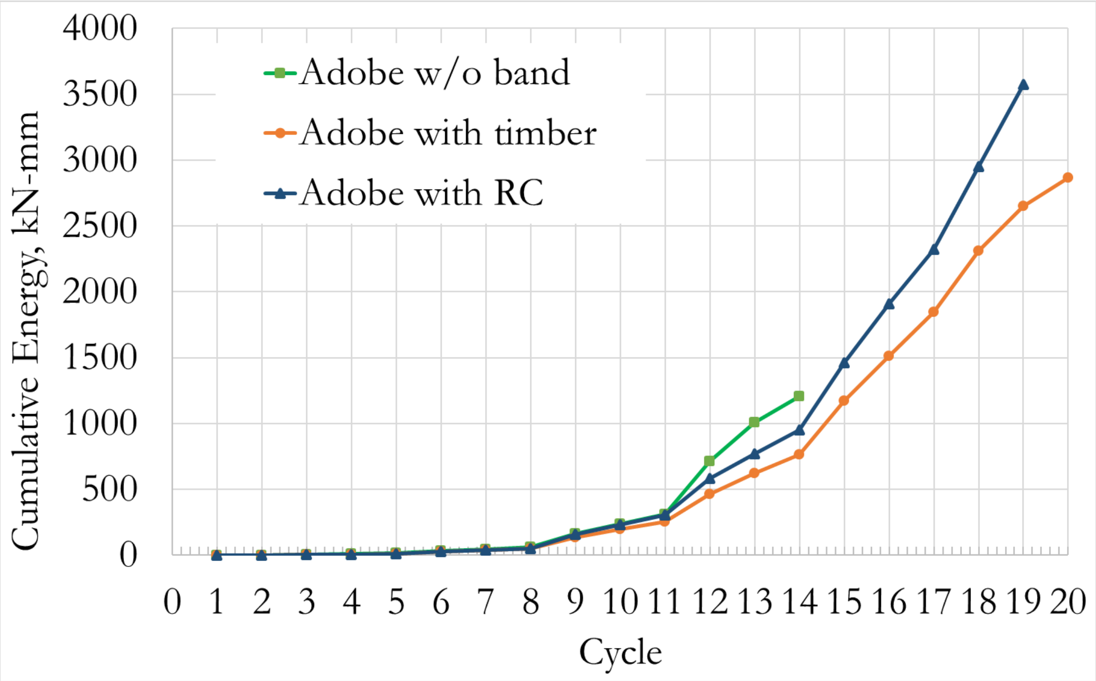


- ❖ Seismic band increase the capacity and ductility limit

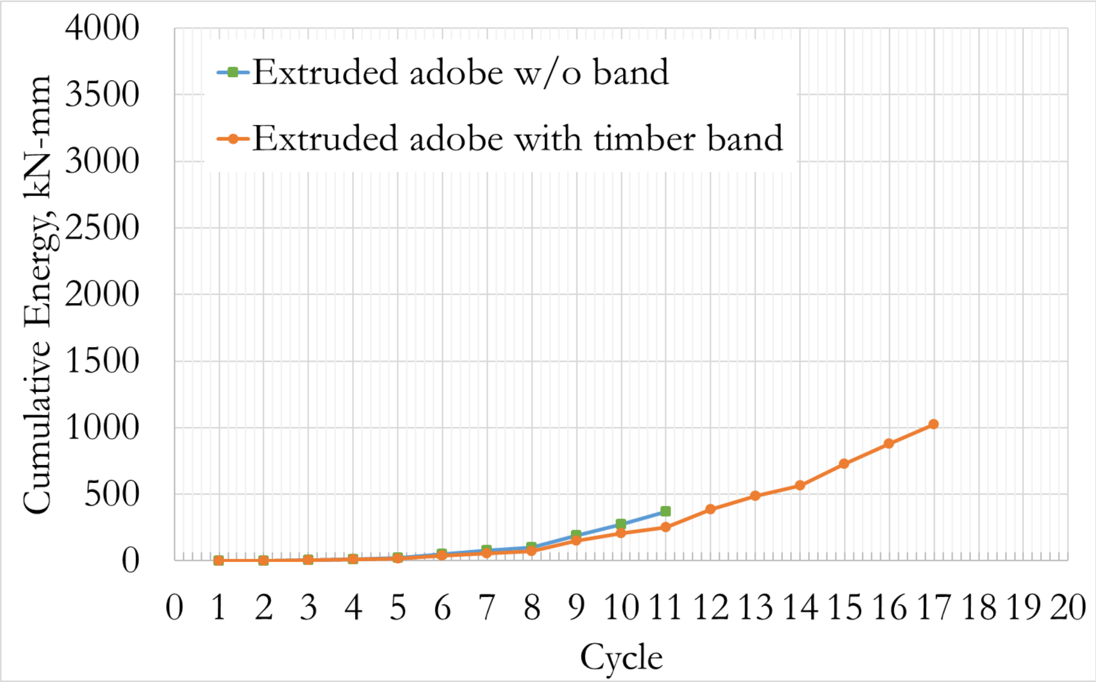
Laboratoire Sols • Solides • Structures • Risques

Hysteresis energy dissipation

Adobe wall



Extruded adobe wall

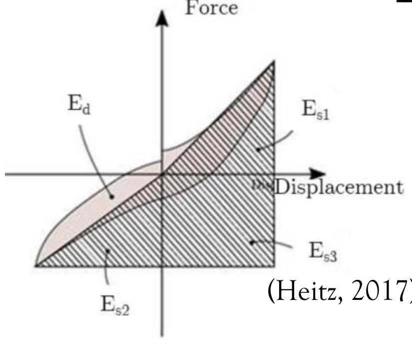


Energy dissipation = Kinetic energy + Thermal energy

Energy dissipation is increased with the application of seismic band

Equivalent Viscous Damping ratio

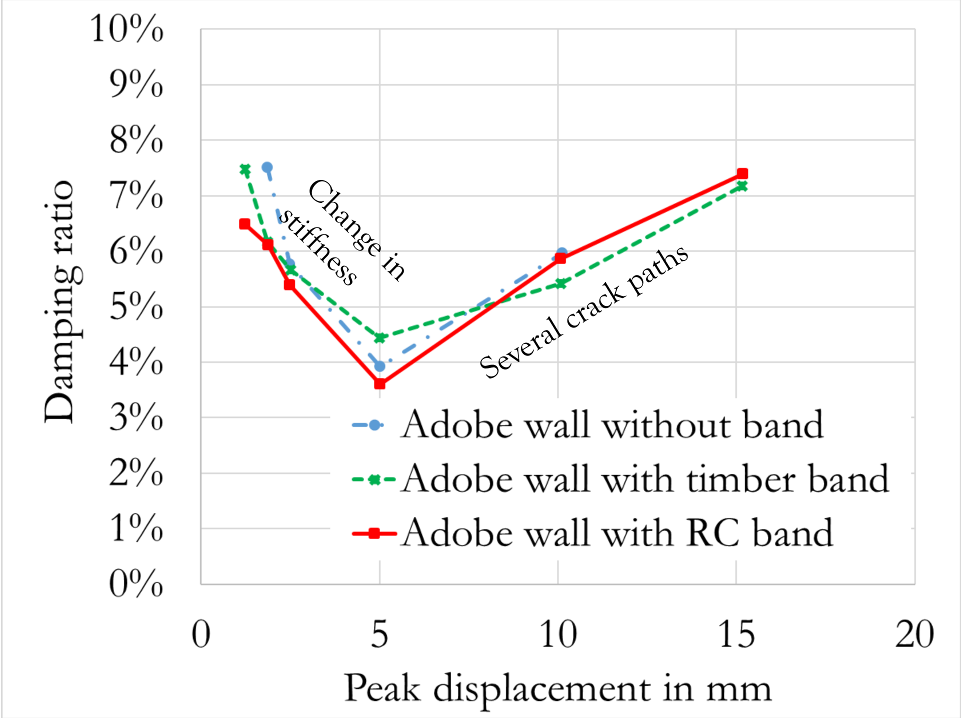
Energy dissipated per cycle
≈
Energy dissipated by viscous damper



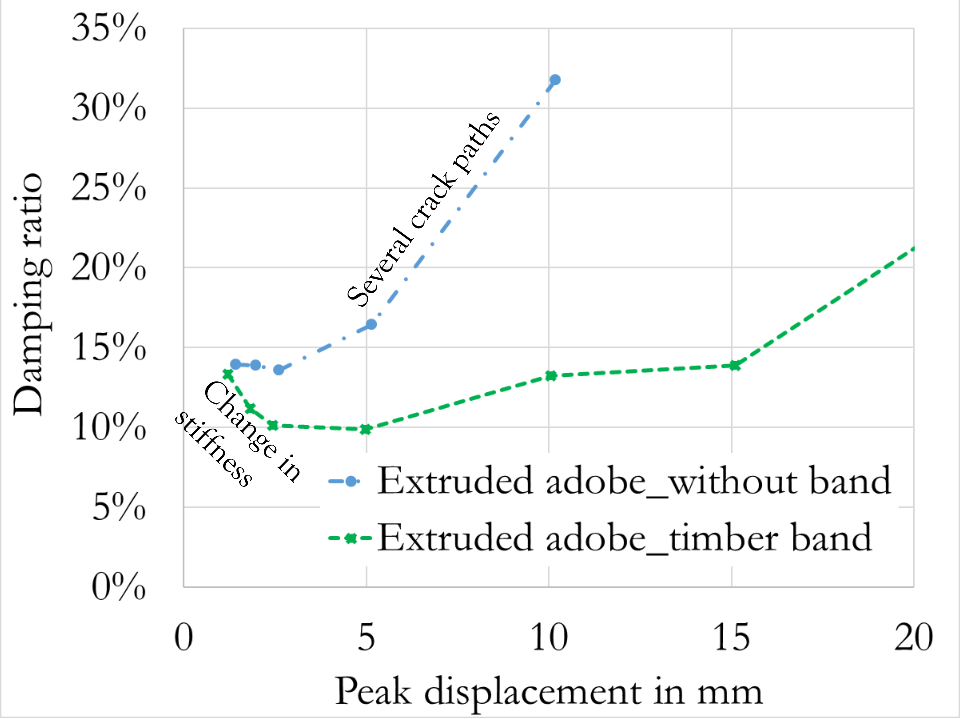
(Heitz, 2017)

$$\xi_{eq\_full} = \frac{1}{\pi} \frac{E_d}{(E_{S1} + E_{S2} + E_{S3})}$$

Adobe wall



Extruded adobe wall



- ❖ Comparable behavior in case of adobe wall
- ❖ Surface roughness influence the EVDR

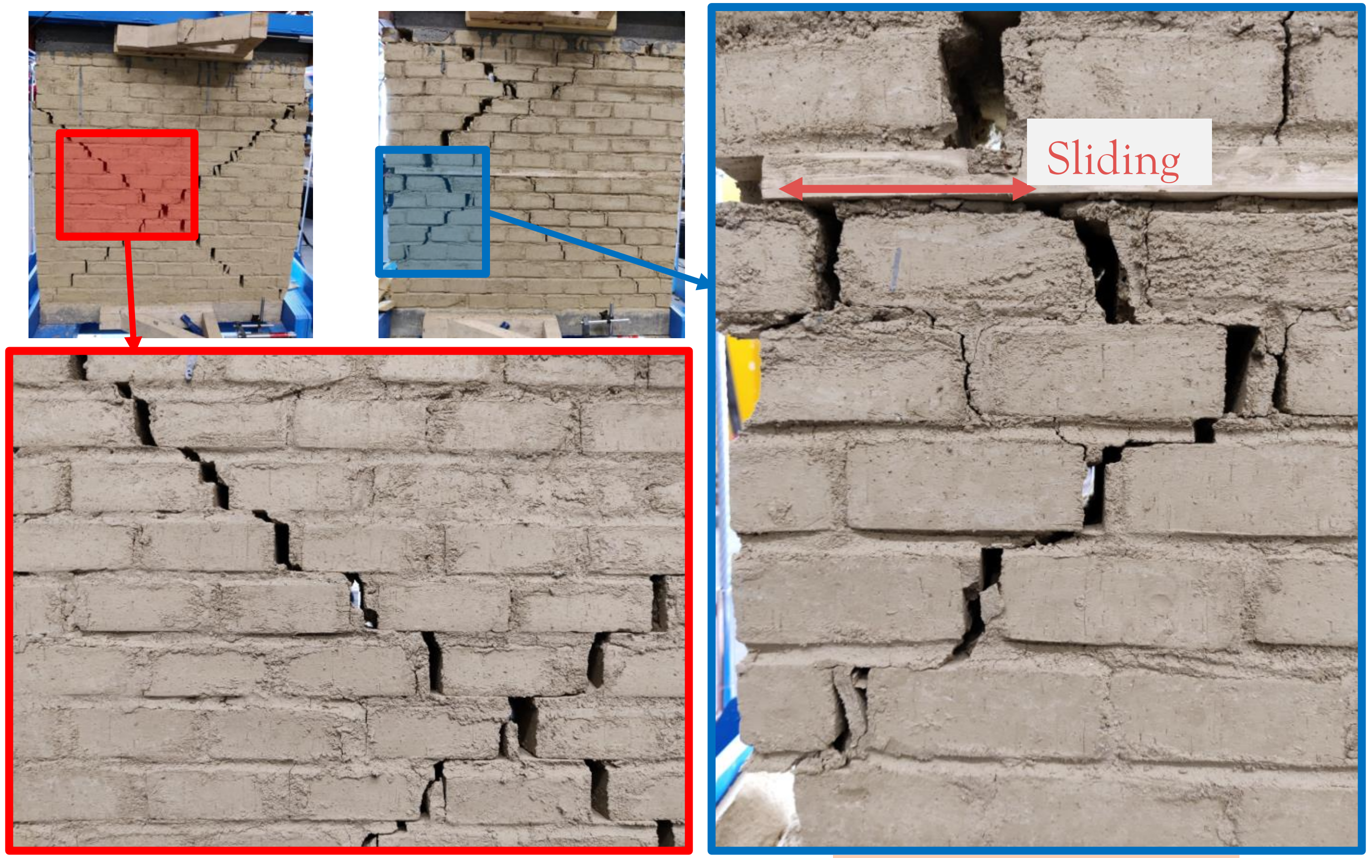
Crack pattern

Adobe wall

With timber band

With RC band

Extruded adobe wall



Without band

With timber band

Tensile strength lower in adobe leads to failure through the brick unit

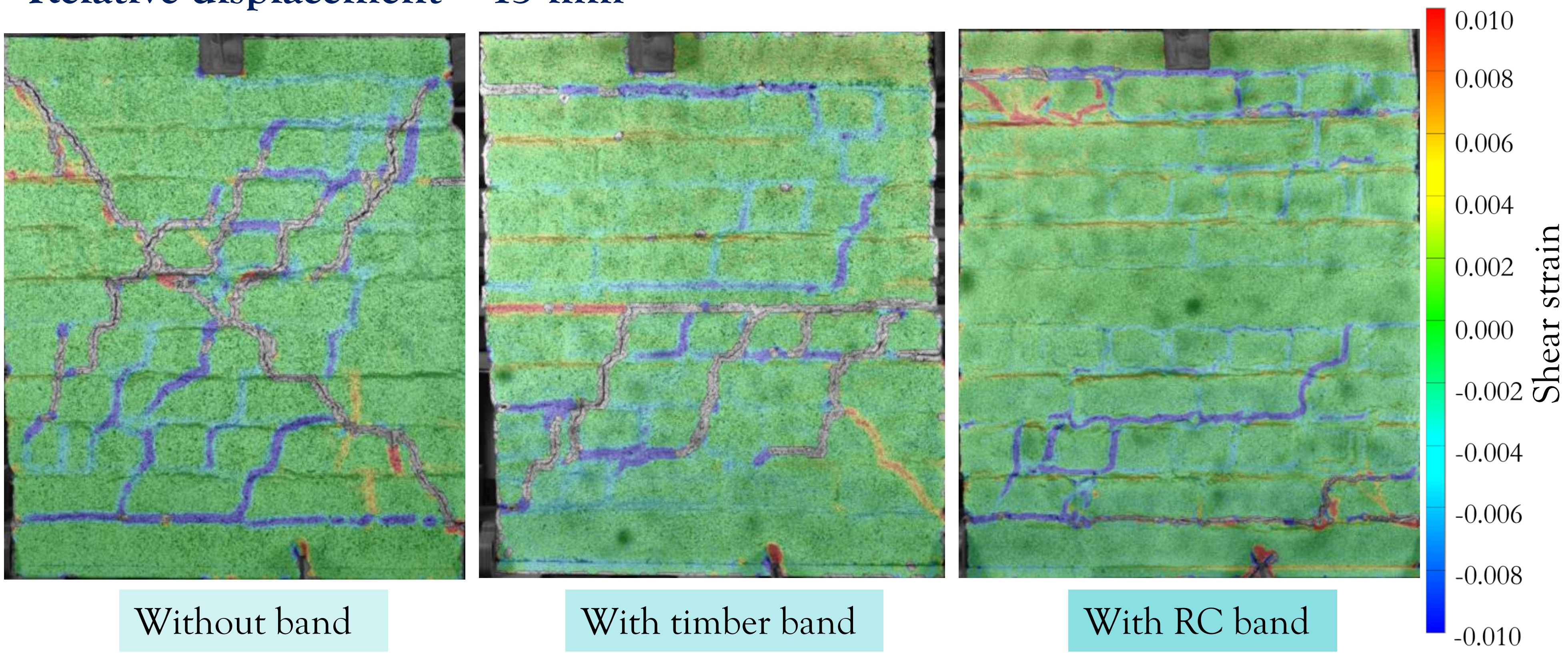
Failure at the mortar-unit interface

DIC analysis for adobe wall

Tools: GOM correlate

Resolution = 0.216- 0.221 mm/px

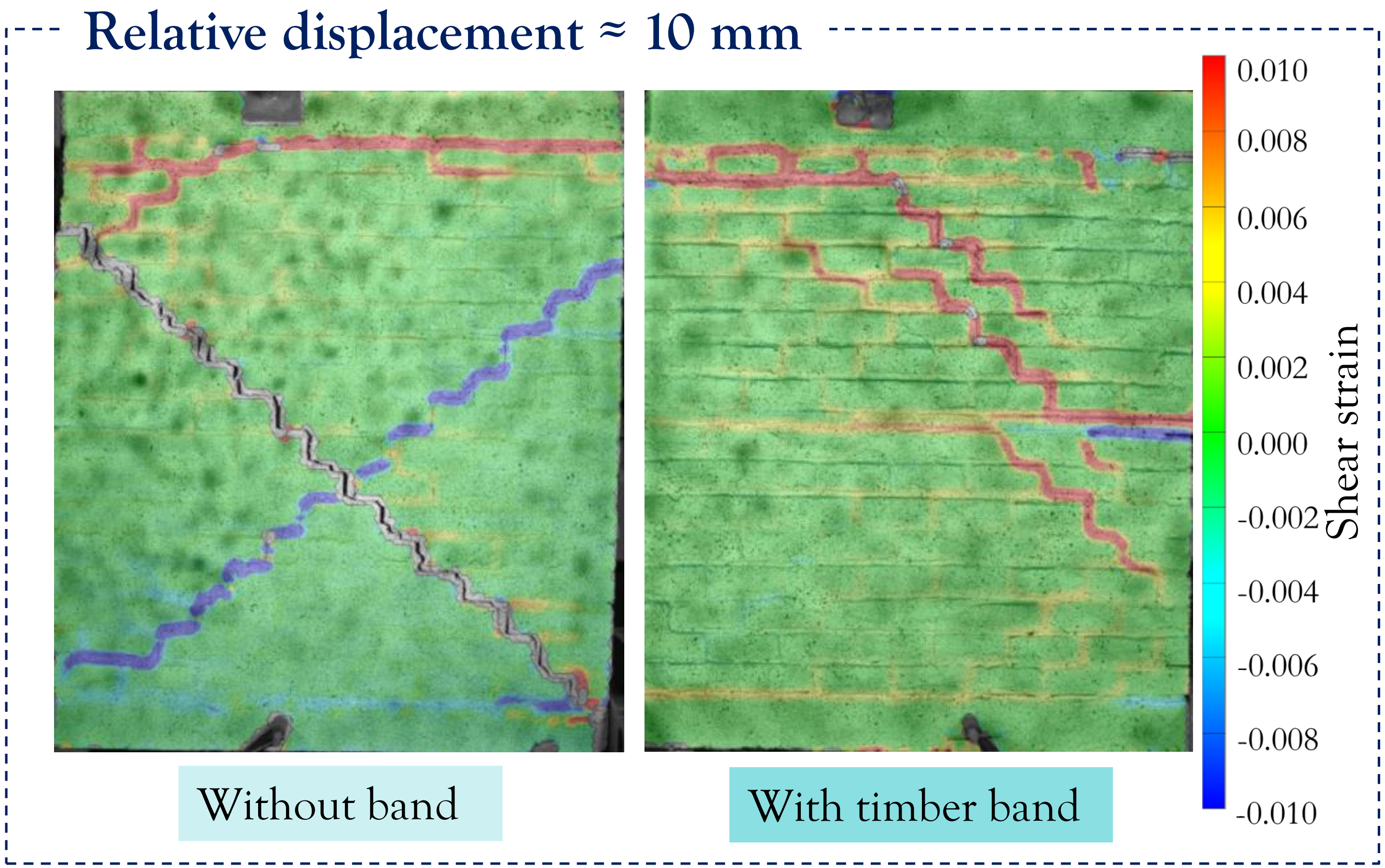
Relative displacement ≈ 15 mm



Without band | With timber band | With RC band

Seismic band helps to limit the crack propagation and modifying the crack path

DIC analysis for extruded adobe wall



- ❖ Without band: Diagonal crack through the mortar-extruded adobe interface
- ❖ With seismic band: helps in modifying the crack path

Shake table

3SR Laboratory


Unidirectional shake table

200 kN servo-hydraulic actuator

Surface area 3.5 m × 2.5 m

- Up to 4 tonnes load
- Maximum limit
  - Acceleration = 5.2g
  - Velocity = 0.77 m/s
  - Displacement = ± 0.120 m

[Damerji, Yadav et al. 2021]

FCBA, Bordeaux

Unidirectional shake table

250 kN servo-hydraulic actuator

Surface area 6 m × 6 m

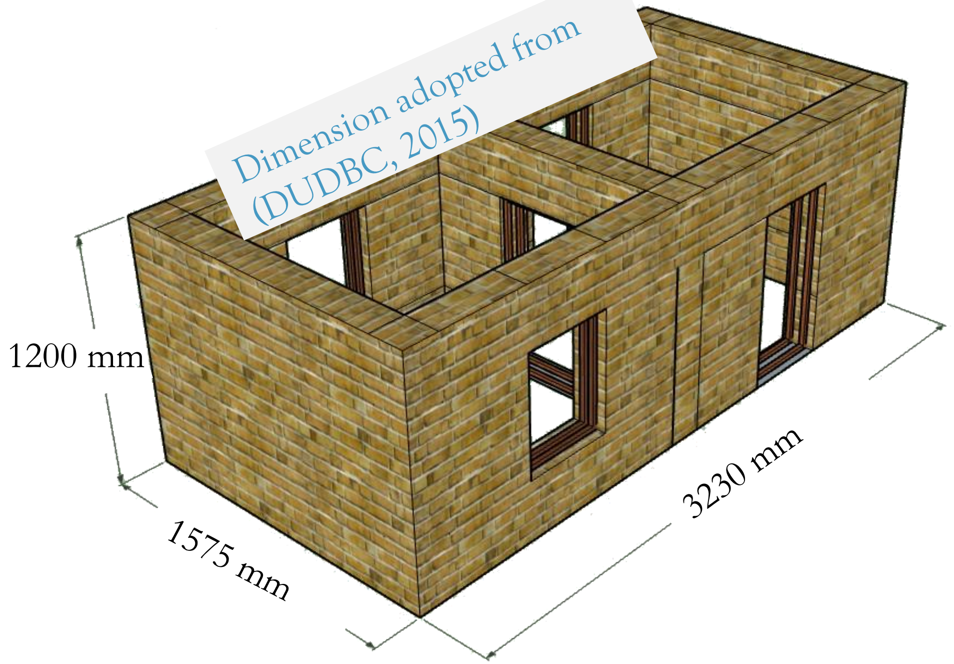
- Up to 5 tonnes load
- Maximum limit
  - Acceleration = 4g
  - Velocity = 0.75 m/s
  - Displacement = ± 0.125 m

Dynamic tests

Reduced scale building

1:2 reduced scale

- Without band
- Timber band
- RC band



Dynamic similitude

Cauchy Law: $\text{Cauchy value} = \frac{\rho v^2}{E}$

Parameter	Equation	Scale Factor	Scaling factor
Length (L)	$\lambda_L = L_p/L_m = \lambda$	λ	0.50
Linear displacement (d)	$\lambda_d = \lambda_L$	λ	0.50
Velocity (v)	$\lambda_v = v_p/v_m$	1	1.00
Acceleration (a)	$\lambda_a = a_p/a_m = t_m/t_p$	λ^{-1}	2.00
Time (t)	$\lambda_t = L_p/L_m * \lambda_v$	λ	0.50

Modify the earthquake signal

Results analysis

- Fundamental frequency
- Peak acceleration
- Equivalent viscous damping
- Out-of-plane wall

- DIC analysis
  - Crack pattern
  - Energy dissipation
  - Sliding at interface

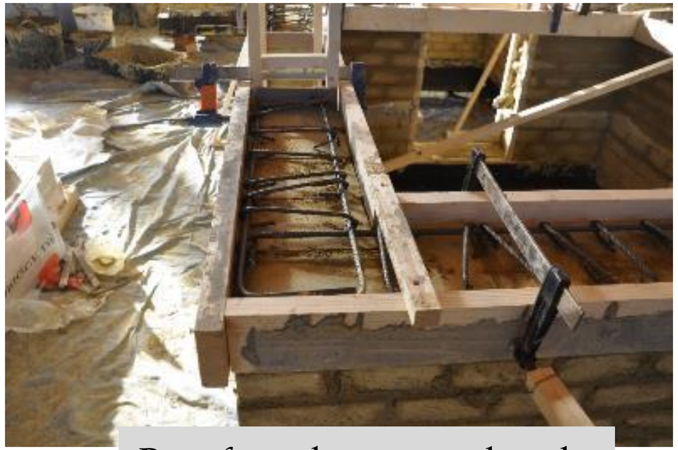
Specimens and test preparation

Model without band

Model with timber band

Model with RC band

Timber band



Reinforced concrete band

Timelines

Construction: 22/10 to 06/11/2020

Drying @ Temp=23 ± 2 °C
RH=50 ± 5%

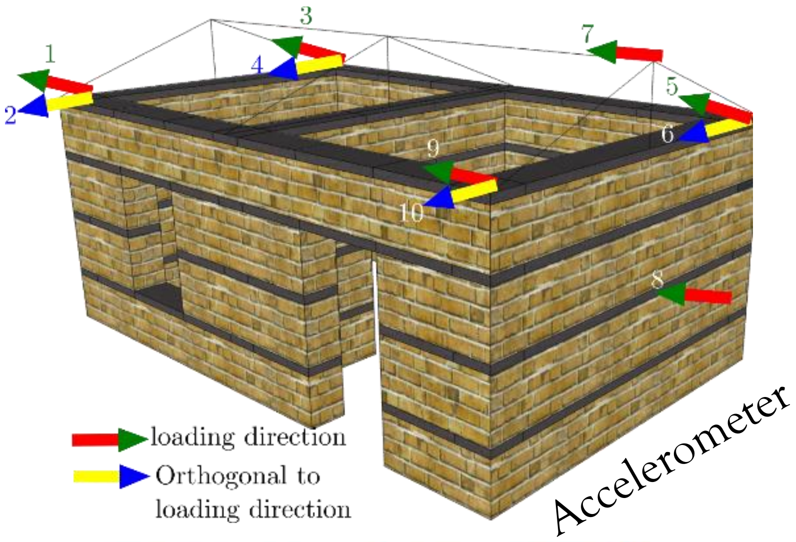
Testing: 26/11 ; 30/11 ; 02/12/2020

Construction of 3 reduced scale buildings

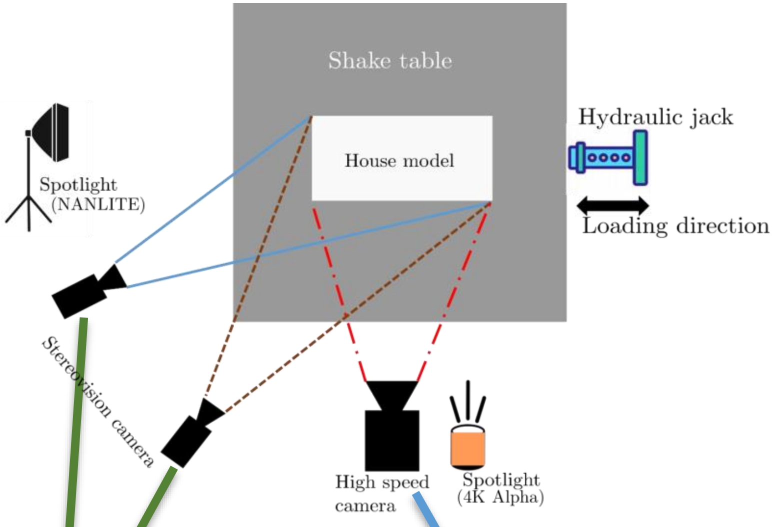
Placement of the building on the shake table

Building without band @ 386%GUA

Measurement sensor



Imaging setup

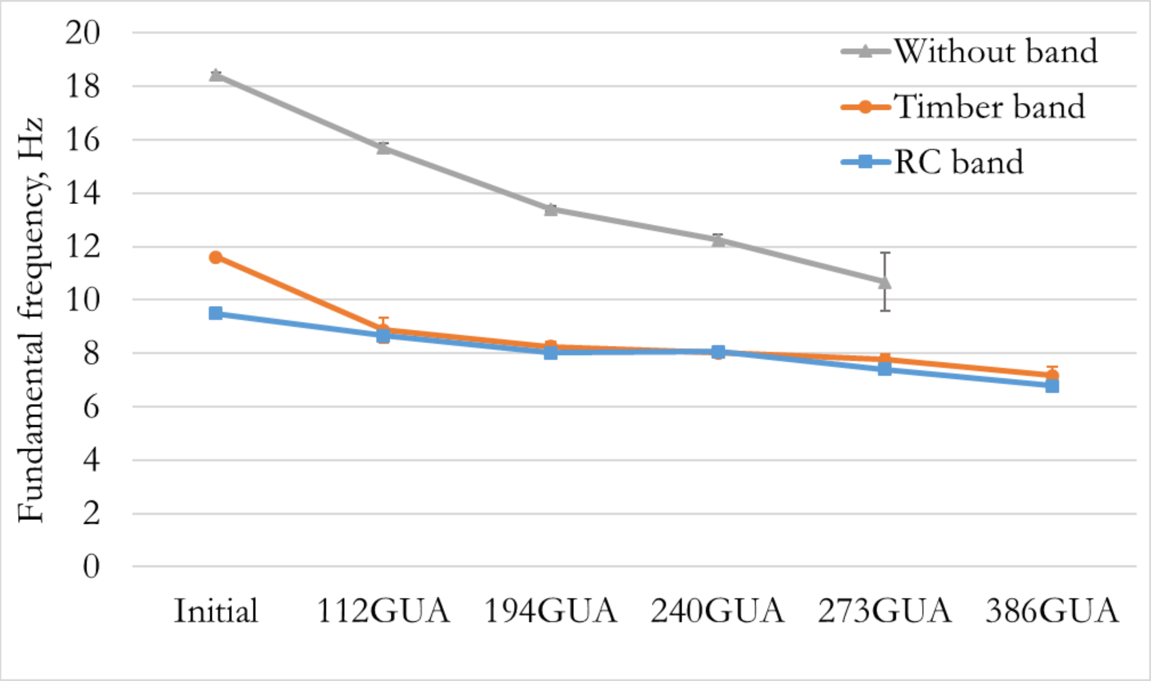


Model: FLIR Mono
Resolution: 5MP
Imaging rate: 55 fps

Model: Phantom V2640
Resolution: 4MP
Imaging rate: 1000 fps

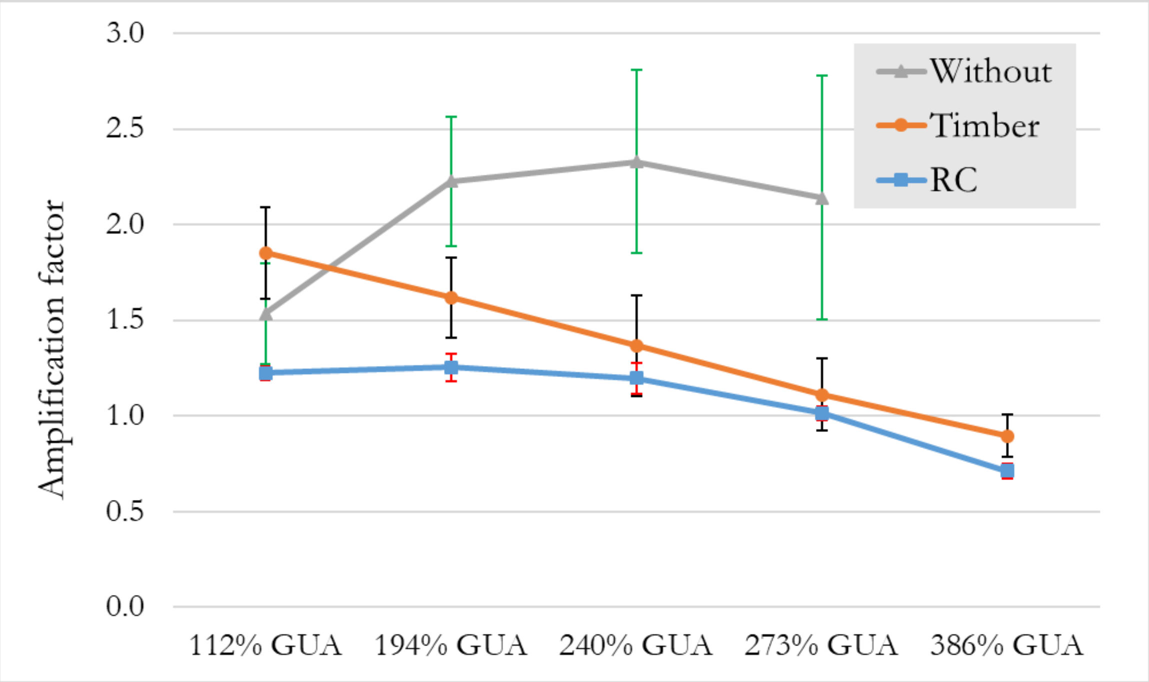
Global structural response

Frequency variation



Using Frequency Response Function | White noise signal

Acceleration amplification

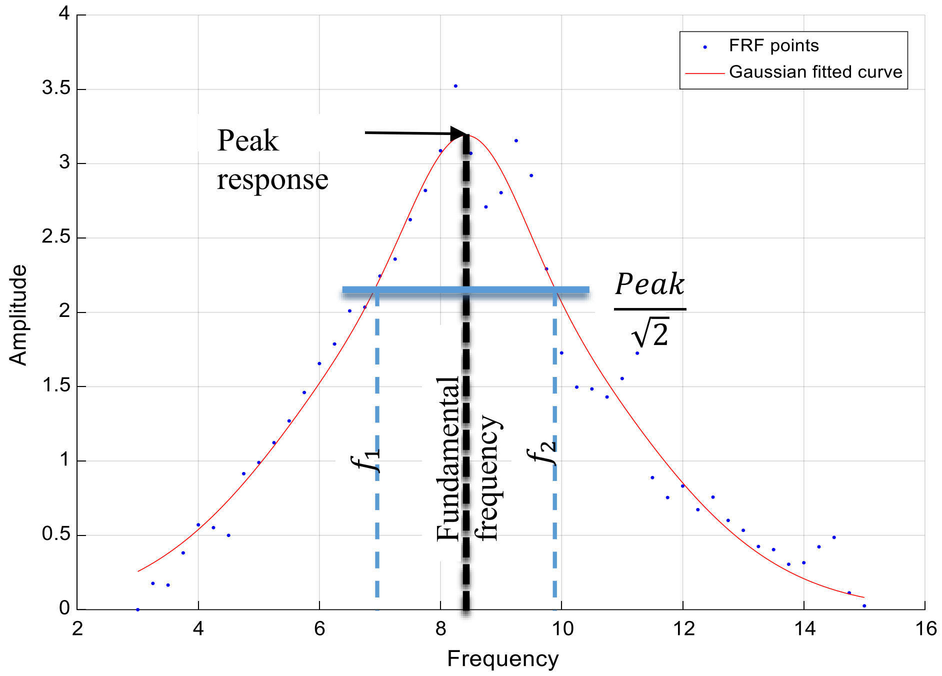


$$\text{Amplification} = \frac{\textbf{\textit{Peak acceleration at wall top}}}{\textbf{\textit{Peak acceleration applied on the table}}}$$

- ❖ Damage rate lower with the application of seismic bands
- ❖ Amplification reduced due to sliding at the band level

In-plane wall: Equivalent Viscous Damping Ratio

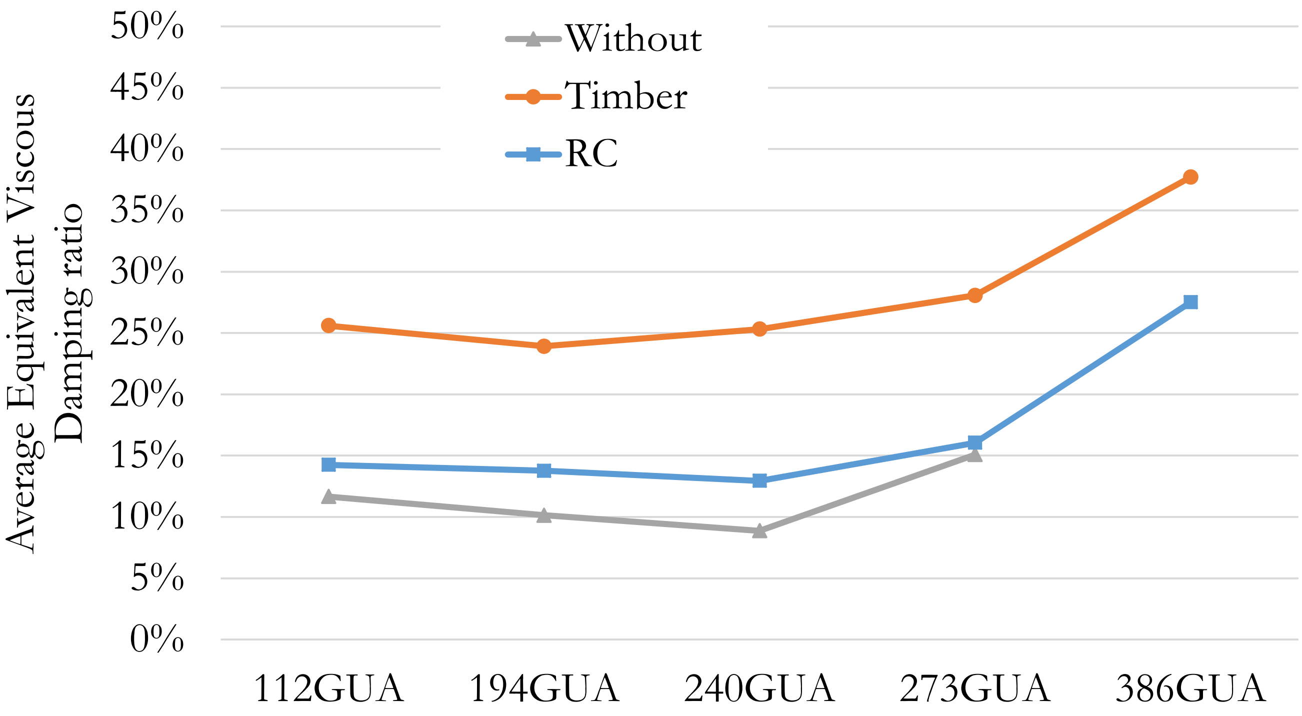
Half-power bandwidth method



Equivalent viscous damping ratio, EVDR

$$\xi = \frac{f_2 - f_1}{f_2 + f_1}$$

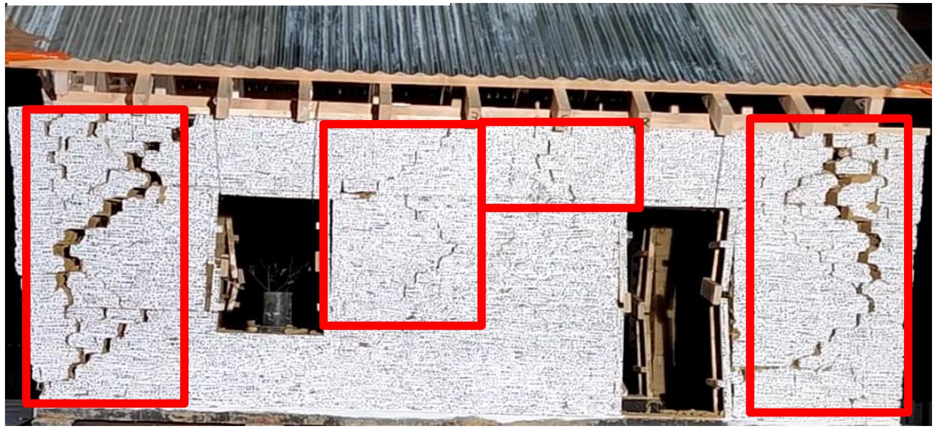
EVDR



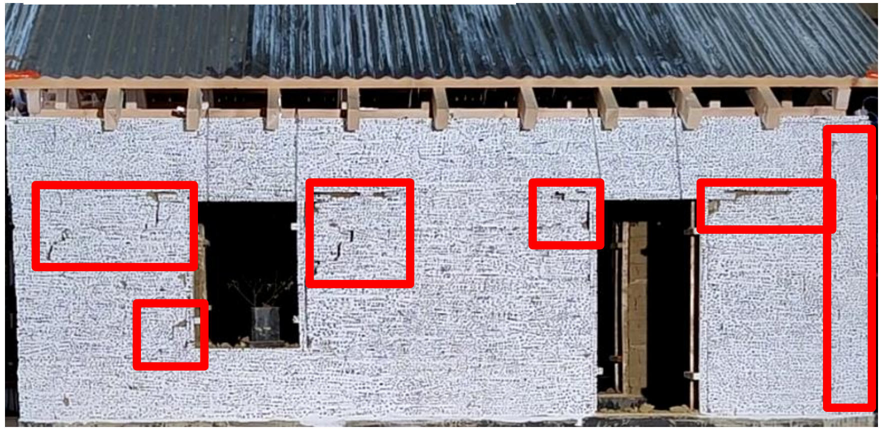
❖ Nature of curves are comparable

Qualitative analysis of crack: after 5 loadings

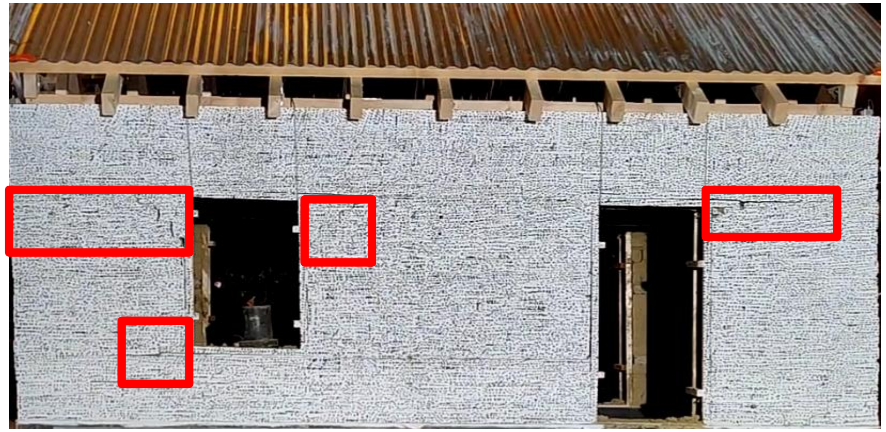
Without a band



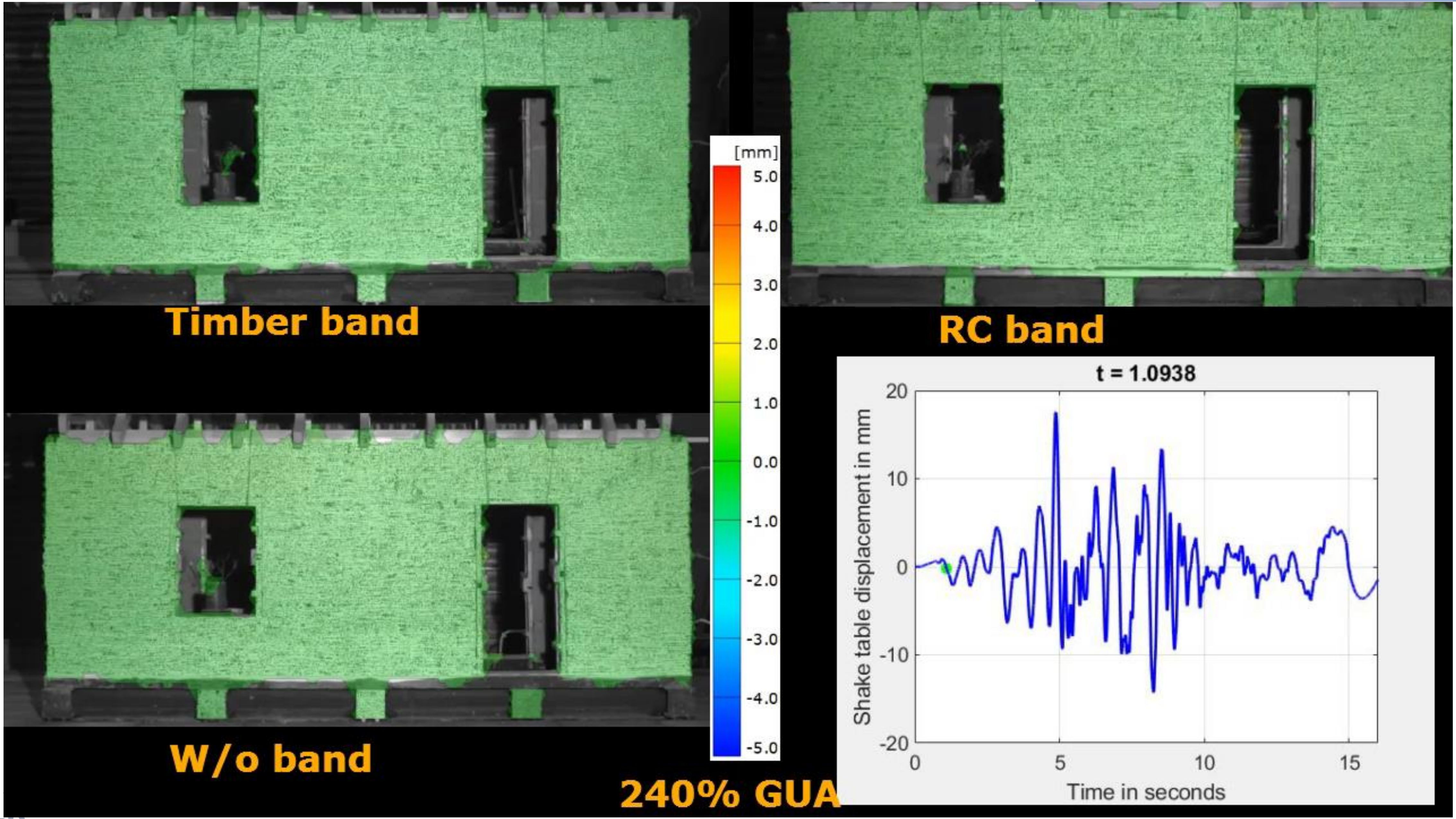
With timber band



With RC band

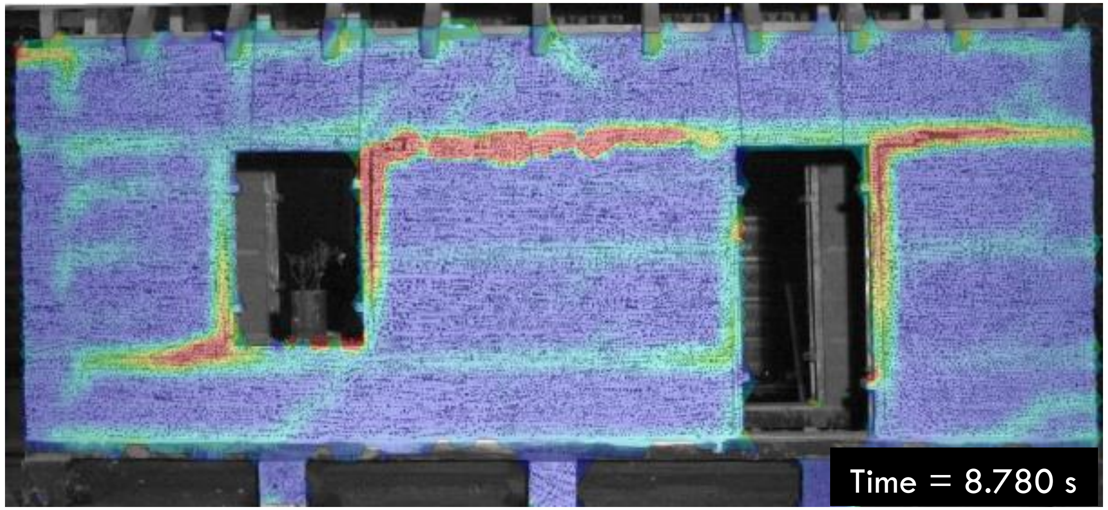


- ❖ Repairable damage in the house with seismic bands
- ❖ Failure along the mortar-extruded adobe interface

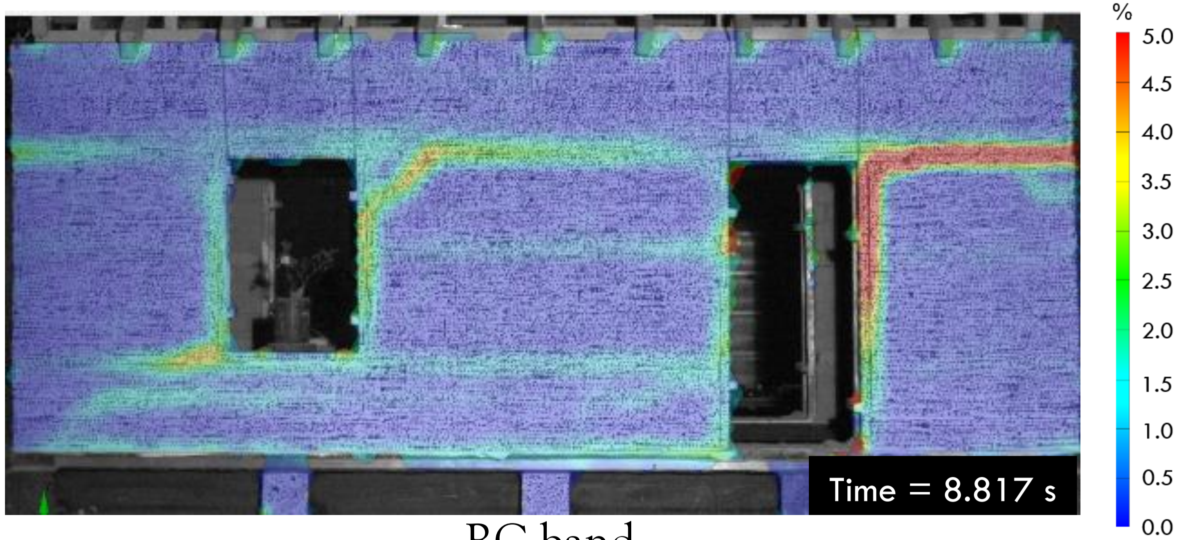


Relative displacement field using DIC

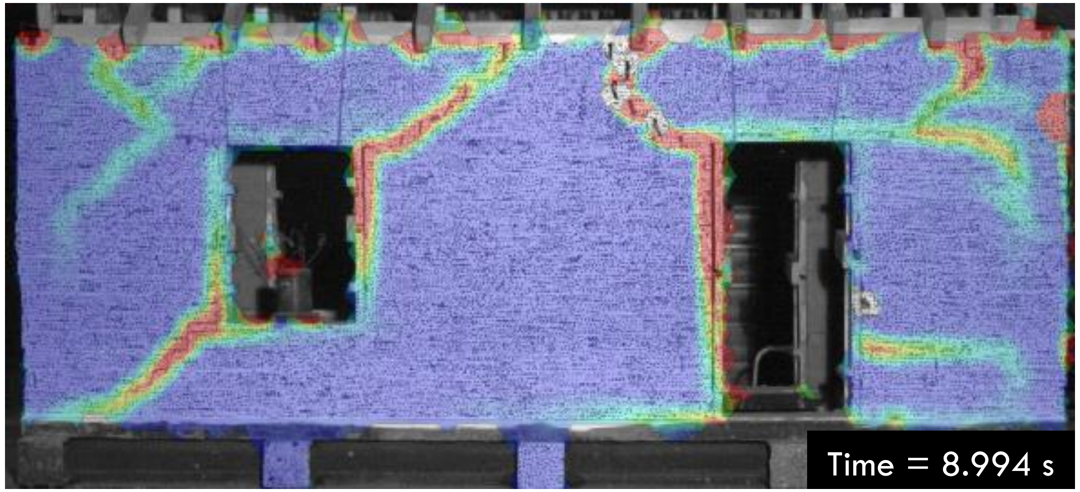
In-plane wall: DIC analysis



Timber band



RC band



Without band

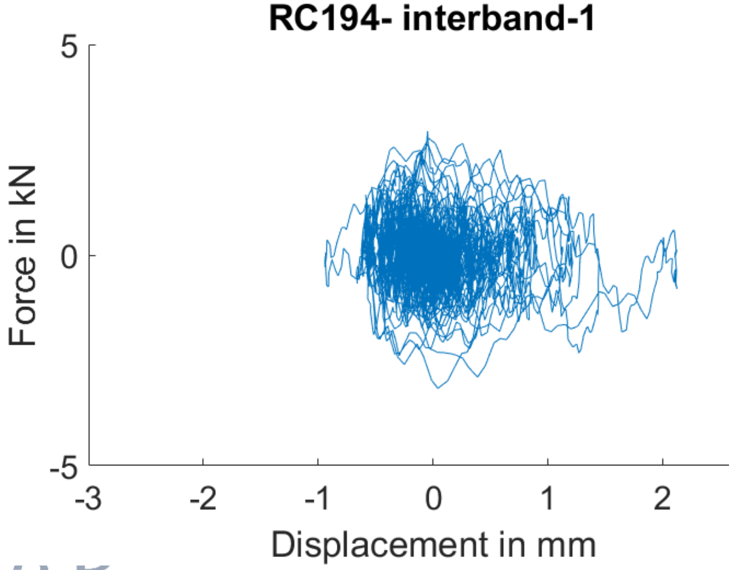
Major principal strain for GUA240

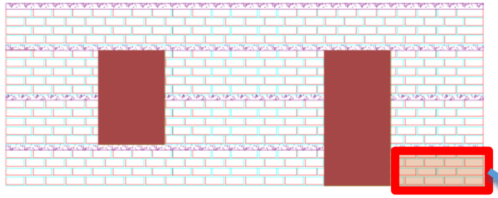
❖ Bands help in limiting the crack propagation

Hysteretic energy dissipation

DIC field data
- Displacement
- Acceleration

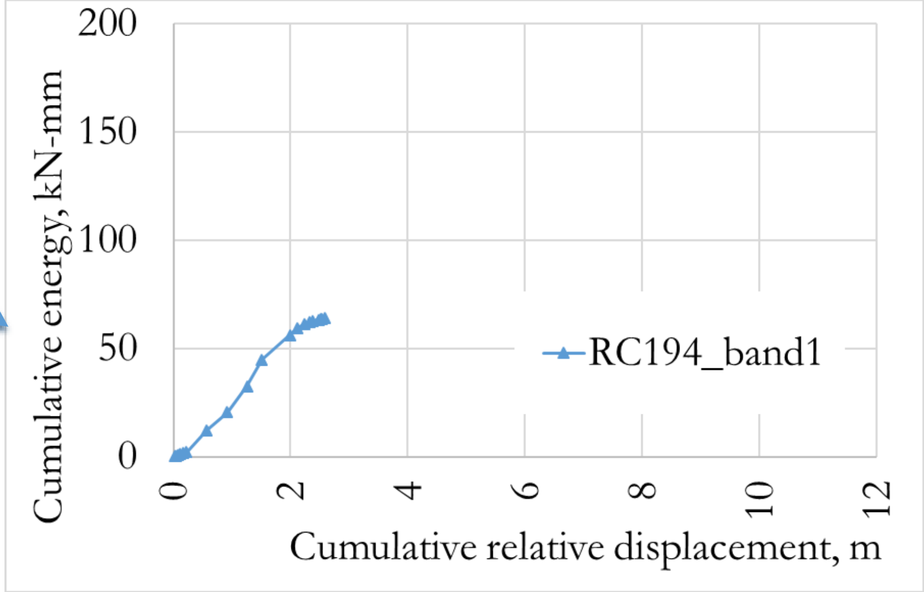
Calculation





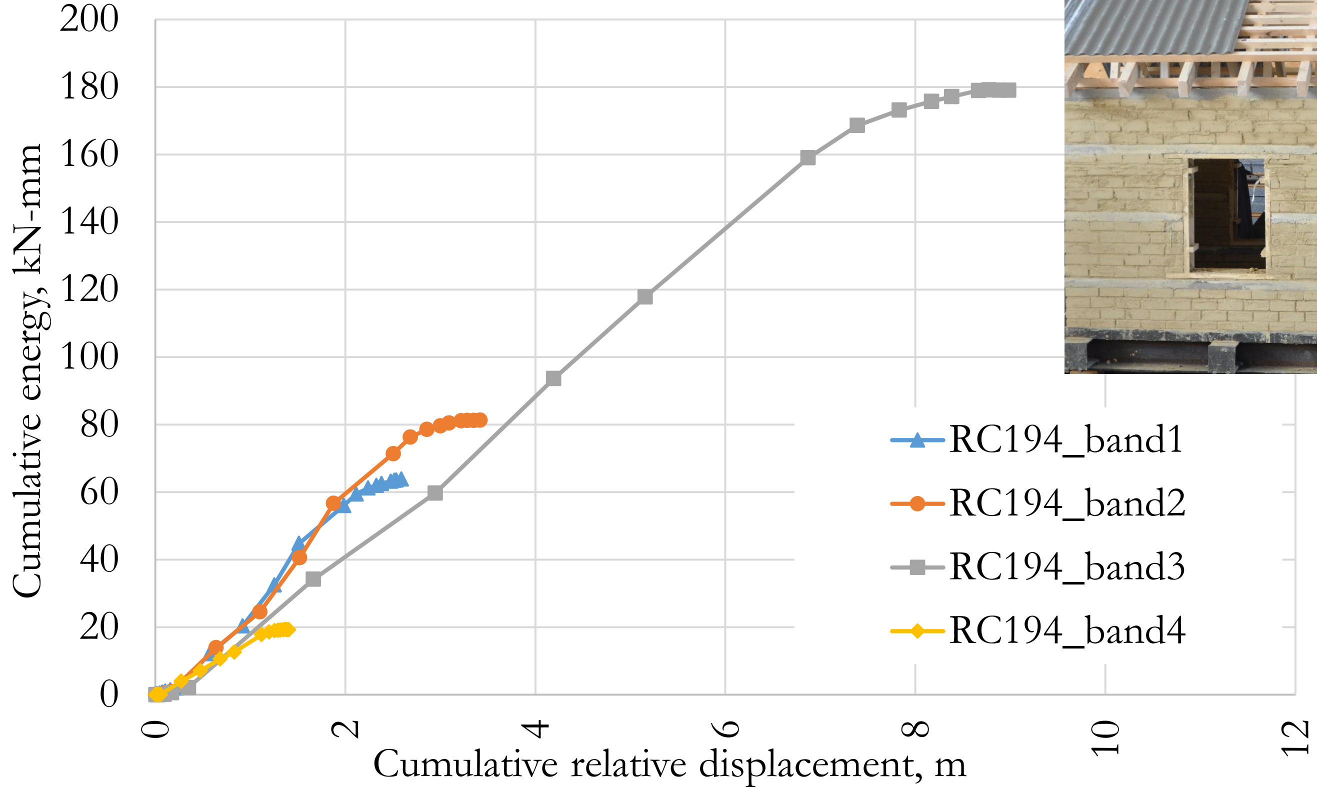
Data discretized at 1 second time interval

The area under the curve and cumulative displacement calculated



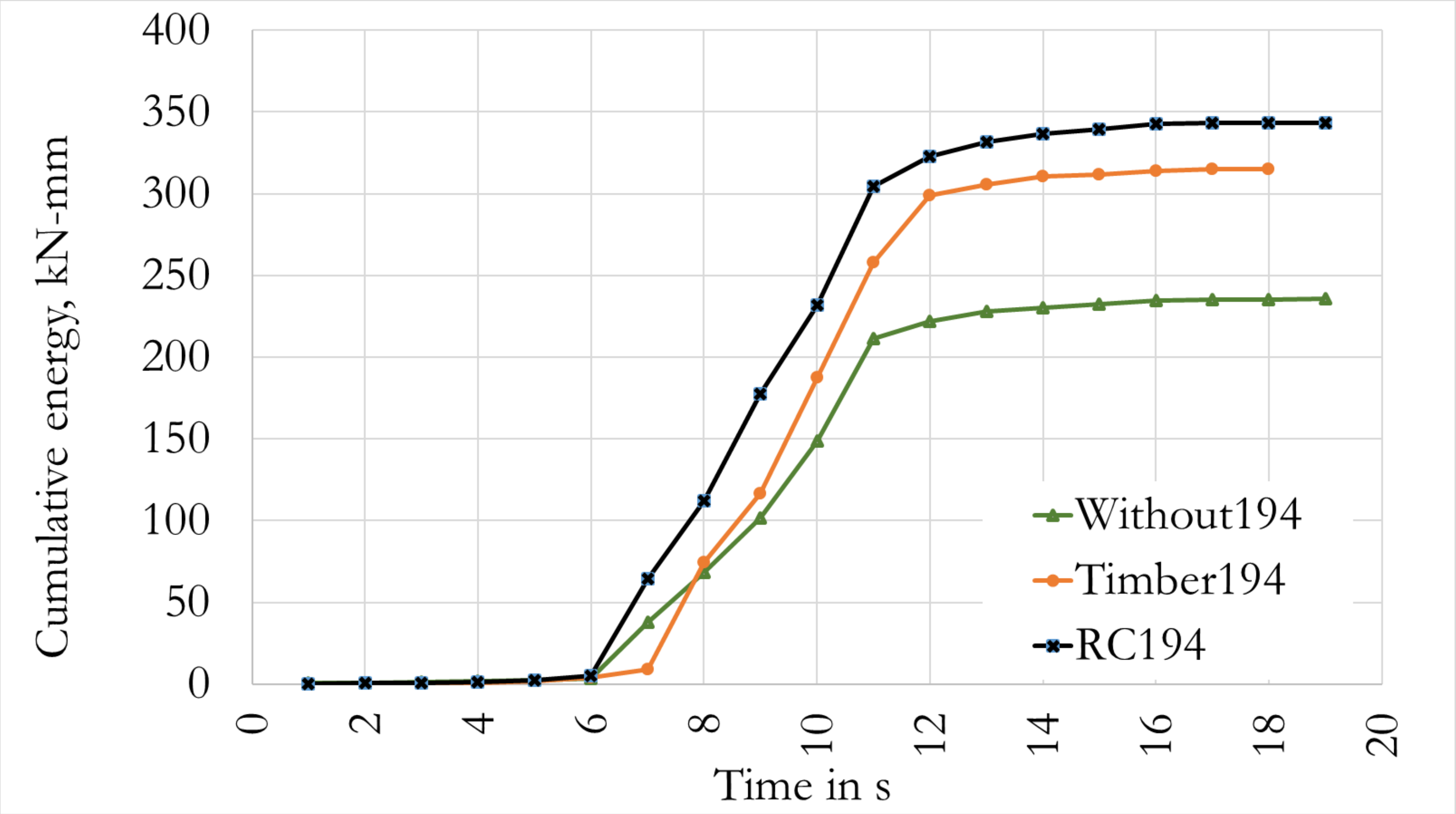
In-plane wall: Hysteretic energy dissipation

RC band



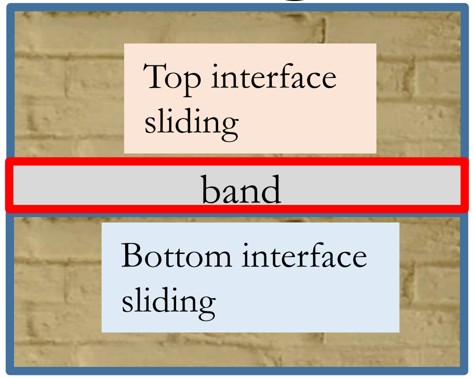
- ❖ Maximum energy dissipated = band3
- ❖ Least for band4

In-plane wall: Hysteretic energy dissipation



❖ Cumulative energy is increased with the application of seismic bands

Sliding at interface

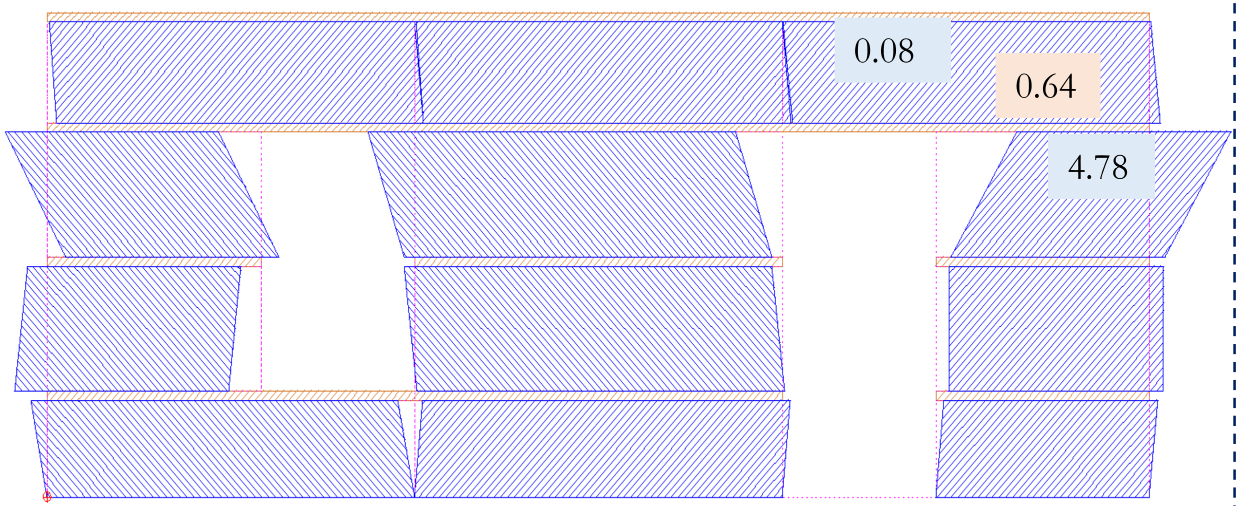


Deformed shape scaled by 50 times

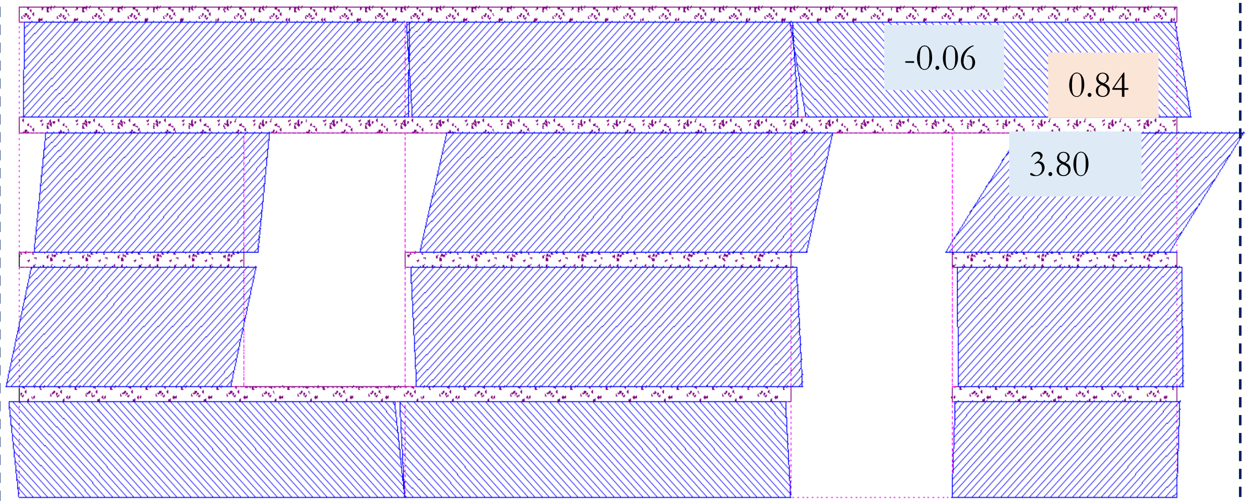
Time ≈ 9 s

Units in mm

With timber band @ 194GUA

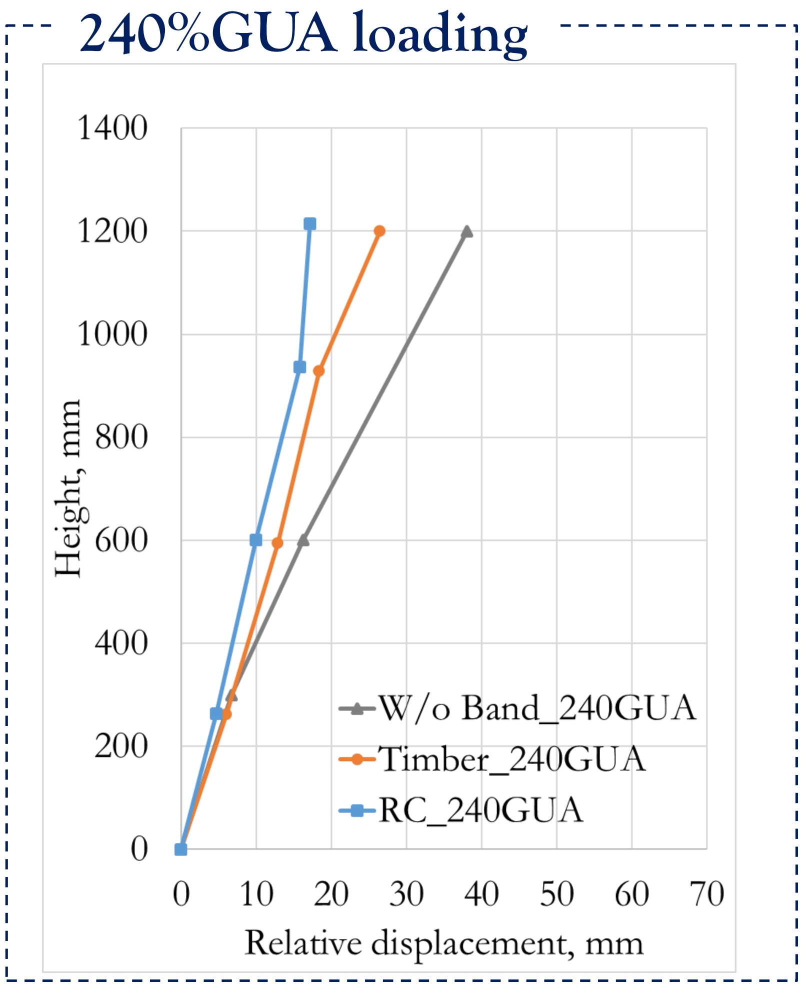


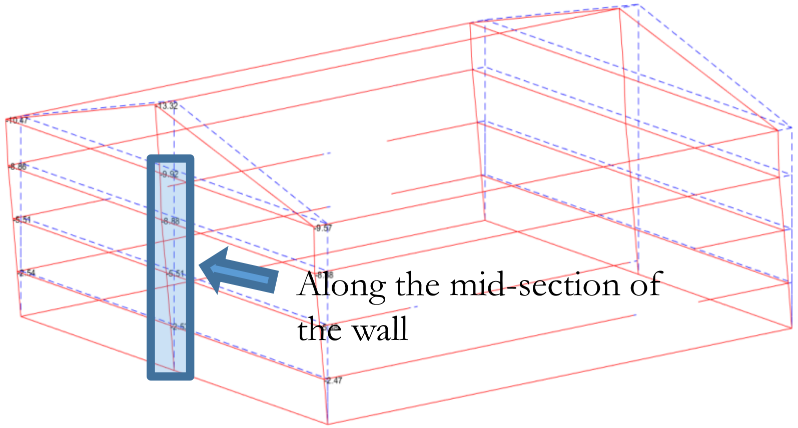
With RC band @ 194GUA



- ❖ Most significant sliding @ lintel band level
- ❖ Least sliding @ roof band level

Out-of-plane wall: Displacement





❖ Seismic band helps to reduce the maximum displacement at each level

Conclusions

Quasi-static test results

		Peak load capacity		Ductility		Energy dissipation	
		Adobe wall	Extruded adobe	Adobe wall	Extruded adobe	Adobe wall	Extruded adobe
	Without	1	1	1	1	1	1
Seismic band	Timber	1,06	1,47	1,08	1,09	2,38	2,76
	RC	1,29		1,13		2,97	

Dynamic test results

		Extruded adobe	
		Energy dissipation	Crack control
	Without	1	−
Seismic band	Timber	1,34	+
	RC	1,46	+

- ❖ Both band materials improve all the seismic characteristics of the structure
- ❖ Both timber and RC bands help in preventing collapse
- ❖ Dimension of timber bands are not same as RC band, so there is possibility to enhance timber band but not much for RC band
- ❖ Preparation of RC band takes time and also requires timber formwork
- ❖ Lintel band: most important

- ❖ Socio-technico-economical aspects of interdisciplinarity to be involved

Perspectives

Geometry and materials

- Investigate the effect by changing the size of the timber band and by modifying rugosity
- Influence of seismic band in slenderness modification and more study in focus to the role in out-of-plane
- Explore other materials, either geo/bio-based (e.g., Bamboo, Geo-grid polymer mesh, etc.) affordable and technically reliable solution

Mechanics

- Dynamic test: Loading directly with high magnitude loading
- Varying the normal axial stress level for shear wall test
- Investigate the influence of impact of curing/drying time of the sample

Socio-technical

- Quality sensitivity analysis from the field data is necessary to investigate their influence on the seismic behavior
- Investigate on adaptation to socio-technical context and compliance with standard or state of arts
- Develop a tool to help decision-makers to select the best options according to Social and Human Science criteria (e.g., cost, skills, durability, maintenance, easy and accessible technique for villagers/carpenter/mason, etc.)

Contributions

Influence of band materials in seismic response of structure → Multi-scale experiments → Numerical model

[Decret 2021]

Developed shake table and reaction frame setup at 3SR

Developed a method to optimize the shake table usages time

Innovative method to apply speckle pattern on large surface for DIC

List of publications

Journal article

Yadav, S., Sieffert, Y., Vieux-champagne, F., Debove, L., Decret , D., Malecot, Y. & Garnier, P. (2021). Optimization of the use time of shake table with specimen preparation outside the table surface. *Journal of Civil Engineering* (under review)

Yadav, S., Sieffert, Y., Vieux-champagne, F., Malecot, Y., Hajmirbaba, M., Arléo, L., Crété, E. & Garnier, P. (2021). Shake table tests on 1:2 reduced scale masonry house with application of horizontal seismic bands. *Journal of Engineering Structures* (under review)

Damerji, H., **Yadav, S.,** Sieffert, Y., Debove, L., Vieux-champagne, F., & Malecot, Y. (2021). Design of a Shake Table with Moderate Cost. *Experimental Techniques*.

Yadav, S., Damerji, H., Keco, R., Sieffert, Y., Crété, E., Vieux-Champagne, F., Garnier, P., & Malecot, Y. (2021). Effects of a horizontal seismic band on seismic response in masonry structure: Application of DIC technique. *Progress in Disaster Science*.

Yadav, S., Sieffert, Y., Crété, E., Vieux-Champagne, F., & Garnier, P. (2018). Mechanical behavior of a different type of shear band connections being used in reconstruction housing in Nepal. *Construction and Building Materials*, *174*, 701–712.

Conference article

ICSA 2022, Denmark

SAHC 2019, Peru

SAHC 2020, Spain

ECCOMAS 2019, Spain

NSNR 2020, Nepal

Inter-ISC 2018, Turkey

Chapter in Book & Research catalogue

Roadmap for research (2021): chapter "Incorporating Local Building Practices in Response."

Research catalogue (CRAterre, AE&CC, CDP Risk 2020)

THANK YOU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