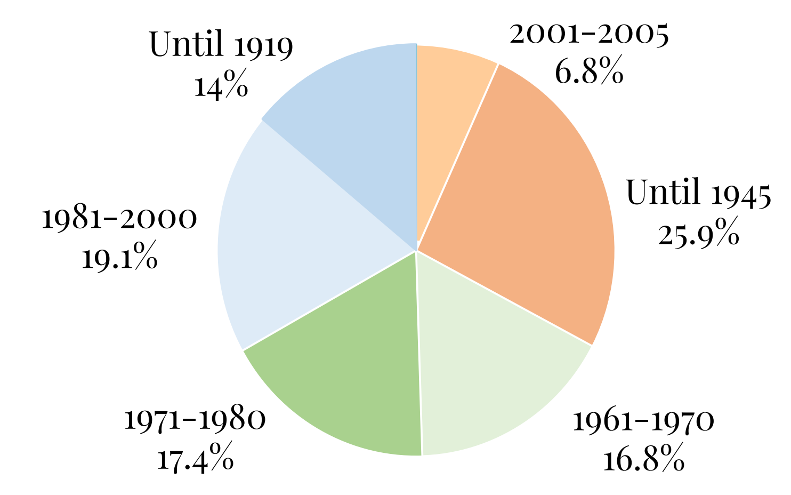
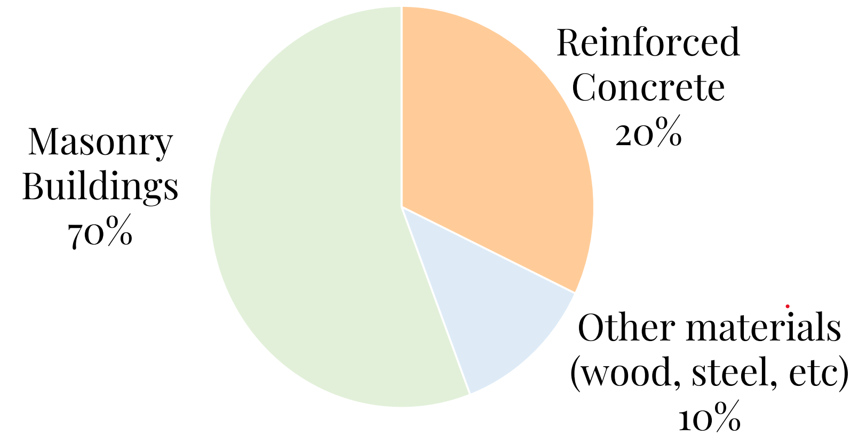
# Design of Sustainable Composite Materials FRLM for the Seismic and Energy Requalification of the Masonry Building Heritage

This research covers an integrated assessment of new composite materials to reduce the seismic vulnerability of historic masonry buildings while complying with sustainable conservation requirements, emissions reduction, and energy saving.

### PERIOD OF CONSTRUCTION



### TYPE OF CONSTRUCTION MATERIAL FOR BUILDINGS*



A large part of the building heritage is constituted by masonry buildings built before 1945

**VULNERABLE TO SEISMIC ACTIONS**

**HIGHLY ENERGY-INTENSIVE**

In this scenario, it is important to promote the development and the use of integrated intervention techniques paying attention to:

**ECONOMIC SUSTAINABILITY**

**ENVIRONMENTAL SUSTAINABILITY**

* C. Wang, W. Sarhosis, N. Nikitas
Strengthening/retrofitting techniques on unreinforced masonry structure/element subjected to seismic loads: a literature review
(2018)

F. Yavartanoo, T.H. Kang
Retrofitting of unreinforced masonry structures and considerations for heritage sensitive constructions
(2022)

---

Testing innovative **FRLM** (Fiber Reinforced Lime Matrix) systems composed of:

### THERMAL PLASTERS PRODUCED USING NATURAL HYDRAULIC LIME MORTAR

&

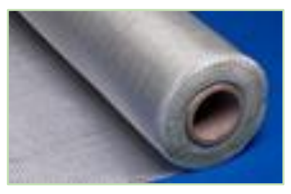
### REINFORCEMENT FIBERS WITH DIFFERENT CHEMICAL STRUCTURES

The inorganic matrix of FRLM composite material is based on **Natural Hydraulic Lime NHL** which can be added with natural, recycled, or recyclable aggregates that improve its thermo-hygrometer performance.

Hemp Fiber

Carbon Fiber

Flax Fiber



Glass Fiber

Jute Fiber

Basalt Fiber

**ADVANTAGES OF FRLM SYSTEMS**

- Compatibility with the Masonry Substrate
- High Resistance to Fire
- Permeability
- Ease of Installation
- Reversibility

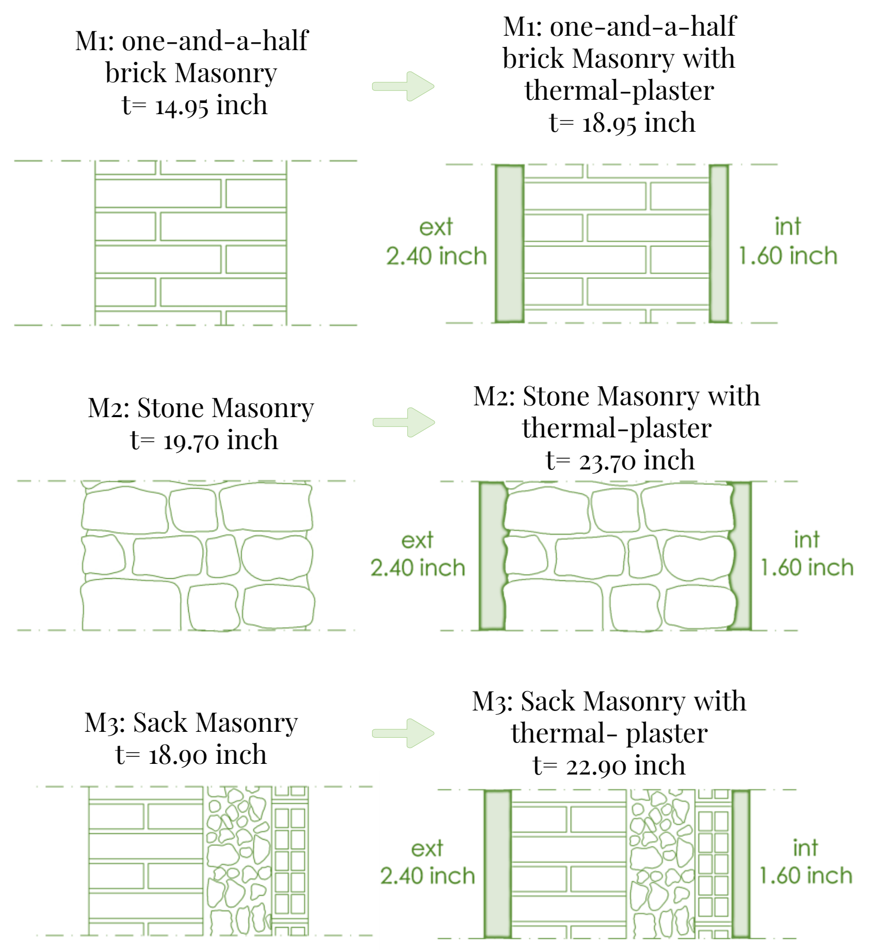
---

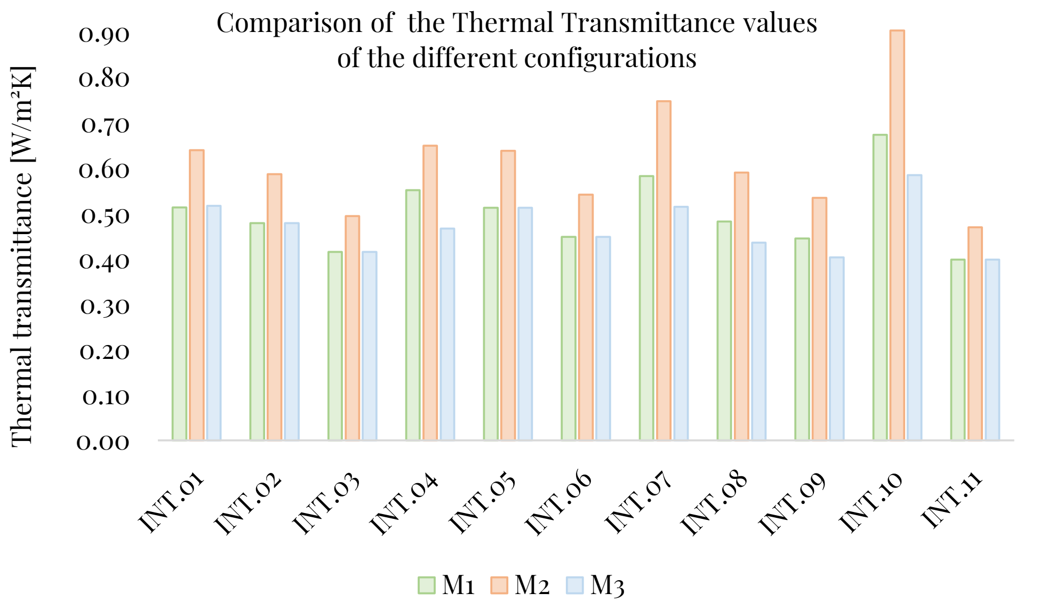
A series of thermo-dynamic simulations were carried out with **WUFI® Pro software**. The climatic reference conditions of Florence (IT) with a simulation time of ten years were considered.

Three specific technical solutions were analyzed*:

- M1: one-and-a-half brick masonry, with a thickness of 14.95 inch;
- M2: stone masonry, with a thickness of 19.70 inch;
- M3: sack masonry with weakly bonded filling, with a thickness of 18.90 inch.

With the aim of seismic and energy upgrades, each thermal- plaster (INT.01- INT.11) was applied on both sides of the wall, with a thickness of 2.40 inch on the exterior layer and 1.60 on the interior layer.





All the products investigated demonstrate good thermo-hygrometric properties. **INT.06** shows good hygrometric performances with a low amount of water accumulated inside the wall.

Water Content in the internal plaster layer max. 0.40 pcf min. 0.27 pcf.

Total Water Content inside the wall 0.62- 0.70 pcf.

Thermal Transmittance of M1, M2, M3 solutions 0,48 W/m²K

* UNI/TR 11552:2014– Opaque envelope components of buildings – Thermo-physical parameters (2014)

---

A selection of commercial **Thermal- Plasters** was performed according to the mechanical and thermal characteristics to improve the seismic and energy performances of existing masonry buildings perimeter walls.

A further examination was imposed regarding the sustainability problem; in particular, the choice was restricted to the matrices made with natural, environmentally friendly, and green building materials and those obtained from recycled and recyclable materials.

| Thermal Plaster | Binder | Aggregates | Compressive Strength σ [psi] | Thermal conductivity λ [BTU/hftF°] | Density [pcf] |
|---|---|---|---|---|---|
| INT.01 ✓ ⌘ | Natural hydraulic lime | Mixed | > 217.55 | 0.044 | 24.97 |
| INT.02 ♻ ✓ ⌘ | Natural hydraulic lime | Minerals | 58.00÷362.60 | 0.043 | 23.72 |
| INT.03 ✓ ⌘ | Natural hydraulic lime | Vegetables | 507.60÷1087.80 | 0.028 | 24.66 |
| INT.04 ✓ ⌘ | Natural hydraulic lime | Mixed | ≥ 290.07 | 0.049 | 24.03 |
| INT.05 ♻ ✓ ⌘ | Natural hydraulic lime | Vegetables | 290.07 | 0.037 | 22.79 |
| INT.06 ✓ ⌘ | Natural hydraulic lime | Mixed | 290.07 | 0.048 | 23.72 |
| INT.07 ♻ ✓ ⌘ | Slaked lime | Mixed | 217.55 | 0.027 | 24.97 |
| INT.08 ✓ ⌘ | Natural hydraulic lime | Minerals | 58.00÷362.60 | 0.043 | 24.35 |
| INT.09 ✓ ⌘ | Natural hydraulic lime | Minerals | 290.07 | 0.038 | ≤ 24.97 |
| INT.10 ✓ ⌘ | Natural hydraulic lime | Mixed | 58.00÷362.60 | 0.079 | 81.15 |
| INT.11 ✓ ⌘ | Natural hydraulic lime | Minerals | 58.00÷362.60 | 0.032 | 24.97 |

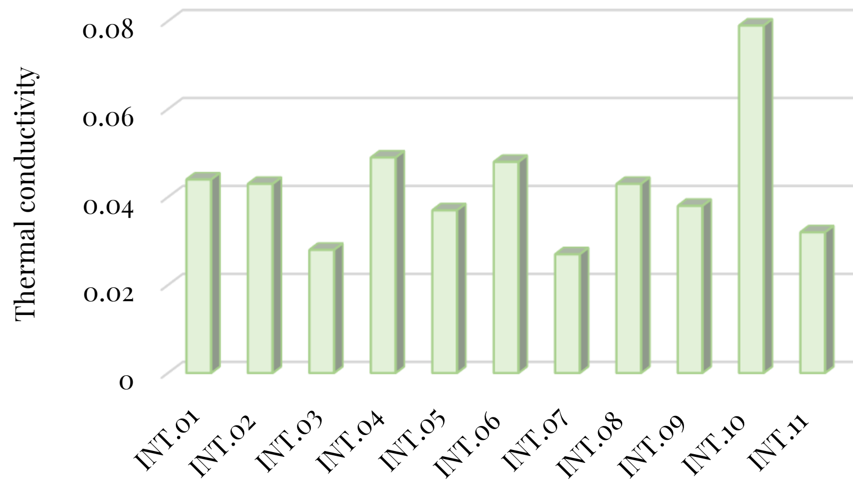
The symbols next to the codes (Int.01- Int.11) indicate the type of the mixture, in particular:

✓ indicates that the thermal plaster is characterized by a σ ≥ 217.55 psi and λ ≤ 0.060 BTU/hftF°;

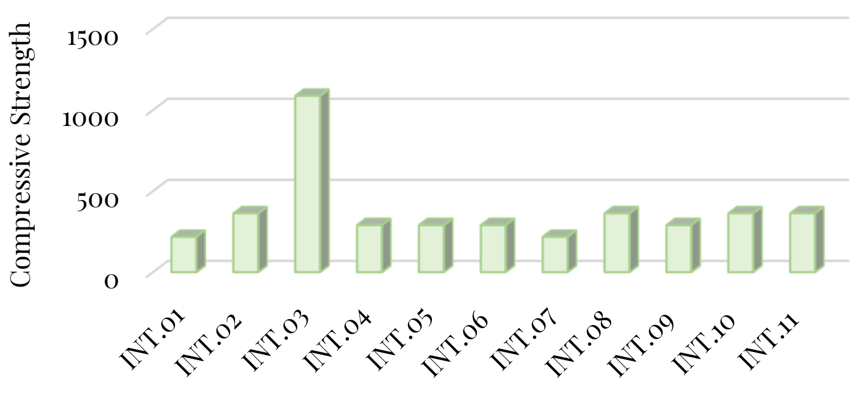
⌘ indicates that the thermal plaster is made of natural materials;

♻ indicates that the thermal plaster is made of recycled or recyclable materials.

Vertical bar histograms relating to the Thermal Conductivity λ [BTU/hftF°]



Vertical bar histograms relating to the Compressive Strength σ [psi]



---

The experimental campaign involved:

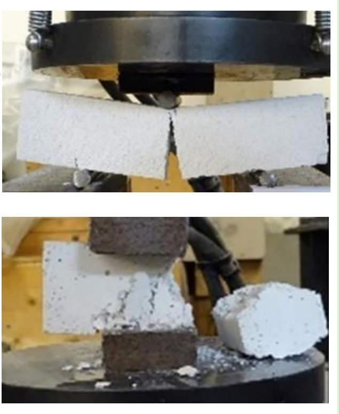
**1.** Bending tests for three points and uniaxial compression tests of the 11 selected thermal plasters.

**2.** Direct tensile test on basalt textile.

**3.** Direct Tensile Test on the FRLM Composite Material constituted by the **Basalt Textile** embedded in the better thermal-plaster from the structural and energetic point of view.

**1. Results of the Three-Point Bending and Compression Tests**

| Matrix | Compressive Strength fc [psi] | Compressive Young Modulus [psi] | Flexural Strength [psi] |
|---|---|---|---|
| Int.01 | 349.54 | 20116.73 | 43.51 |
| Int.02 | 55.11 | 11008.36 | 10.15 |
| Int.03 | 66.71 | 1551.90 | 8.70 |
| Int.04 | 105.87 | 19144.98 | 8.70 |
| Int.05 | 129.08 | 9238.90 | 14.50 |
| Int.06 | 361.14 | 292.5 | 39.16 |
| Int.07 | 15.95 | 42423.53 | 14.50 |
| Int.08 | 178.39 | 32227.38 | 2.90 |
| Int.09 | 166.79 | 30646.47 | 4.35 |
| Int.10 | 269.77 | 55854.03 | 10.15 |
| Int.11 | 110.22 | 11211.41 | 17.40 |

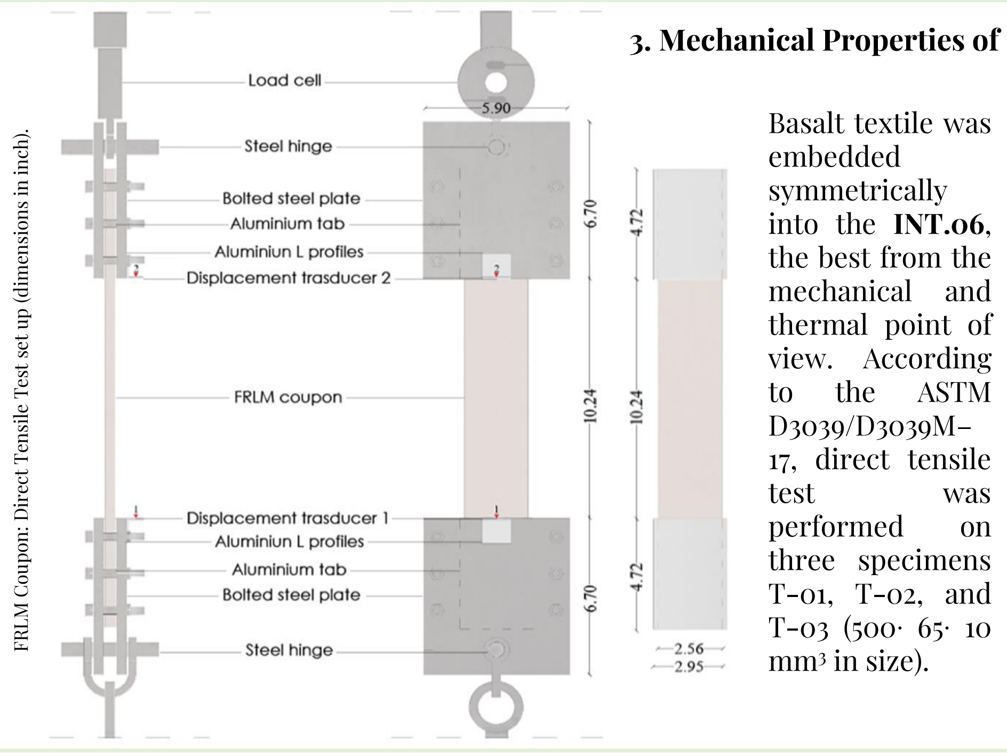


**2. Results of the Direct Tensile Test on Basalt Textile**

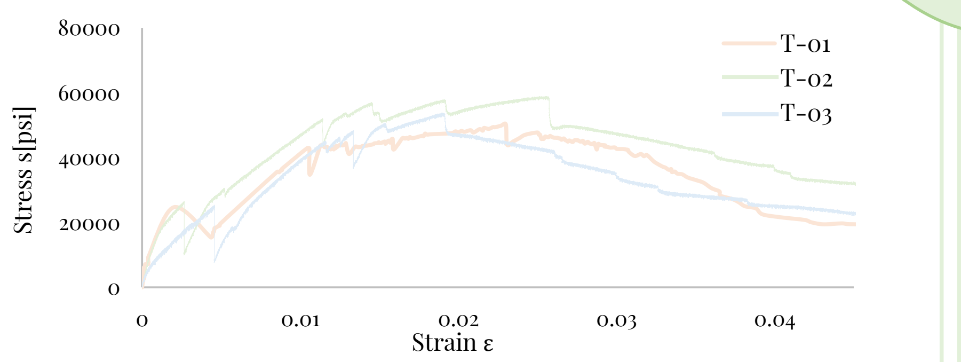
Four **basalt textile** specimens with a mesh of 17·17 mm consisting of one (BT.01), two (BT.02), three (BT.03), and four (BT.04) longitudinal multifilaments were tested under direct tension.

| Basalt Textile | Maximum Load $F_{max}$ [lb] | Ultimate Strain $\varepsilon_b$ | Tensile Strength $f_b$ [psi] | Young Modulus $E_b$ [psi] |
|---|---|---|---|---|
| BT.01 | 76.58 | 0.013 | 94233.91 | 7315490.28 |
| BT.02 | 213.67 | 0.019 | 126703.51 | 6744760.98 |
| BT.03 | 309.65 | 0.018 | 122411.85 | 6923266.18 |
| BT.04 | 37.64 | 0.018 | 129698.54 | 7056771.96 |
| Average Value | **159.38** | **0.017** | **118262.32** | **7010072.71** |

**3. Mechanical Properties of FRLM Composite Material**



Basalt textile was embedded symmetrically into the **INT.06**, the best from the mechanical and thermal point of view. According to the ASTM D3039/D3039M–17, direct tensile test was performed on three specimens T-01, T-02, and T-03 (500· 65· 10 mm³ in size).



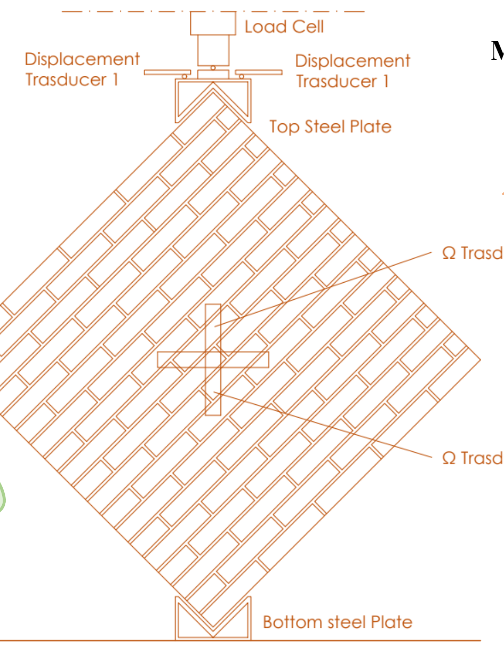
| FRLM Coupon | Maximum Load $F_{tmax}$ [lb] | Ultimate Strain $\varepsilon_t$ | Tensile Strength $f_t$ [psi] | Young Modulus $E_t$ [psi] |
|---|---|---|---|---|
| T-01 | 162.08 | 0.017 | 50275.88 | 2185876.79 |
| T-02 | 189.94 | 0.025 | 58917.22 | 2356665.98 |
| T-03 | 173.60 | 0.019 | 53853.96 | 2834404.34 |
| Average value | **175.21** | **0.020** | **54349.02** | **2458981.40** |

---

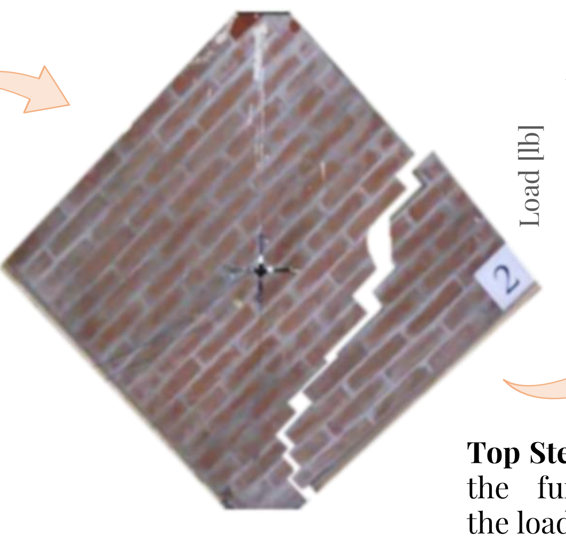
Numerical simulations were carried out using a FEM (Finite Element Method) developed through **Abaqus CAE software** to model the behaviour of a non-reinforced (NRP) and a reinforced masonry panel (RP) subjected to diagonal compression tests. A numerical study was conducted with the aim of comparing the experimental results provided by the diagonal compression tests.

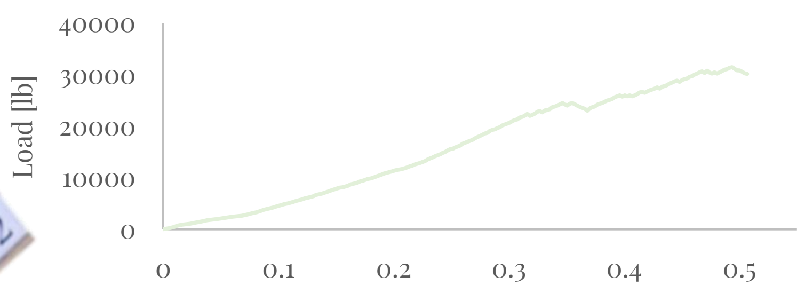
**Diagonal Compression Test carried out in Laboratory**

A panel in scale 1:1, of 47.24·47.24·4.72 Inch³ in size, assembled with cement–lime mortar joints and tested under Diagonal Compression Test according to the ASTM E519/E519M – 22.

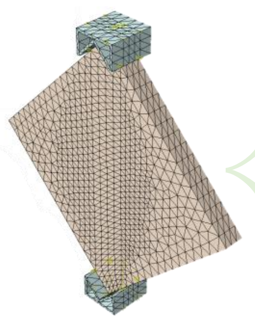


**Masonry panel subjected to Diagonal Compression Test**
Cracks developed along a non- diagonal direction





**Numerical Evaluation**

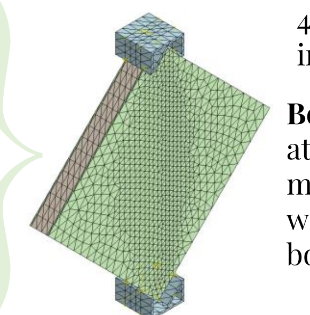


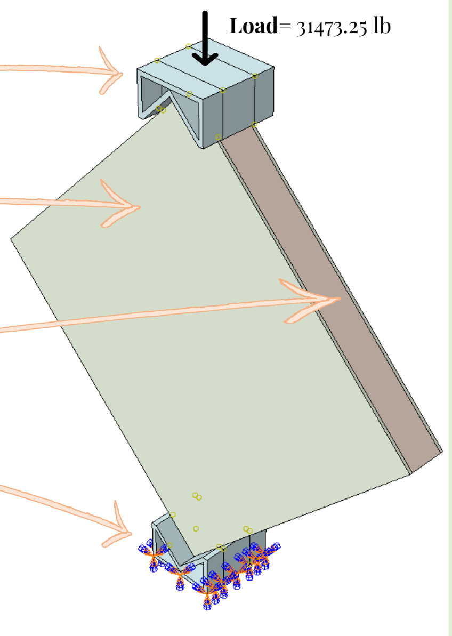
**LINEAR ANALYSIS**

*UNSTRENGTHENED PANEL* vs *PANEL STRENGTHENED WITH FRLM*

**NON-LINEAR ANALYSIS**

*UNSTRENGTHENED PANEL* vs *PANEL STRENGTHENED WITH FRLM*





**Top Steel Plate**: the plate has the function of distributing the load of 31473.25 lb.

**FRLM Composite:** 47.24·47.24·0.40 Inch³ in size.

**Masonry Panel:** 47.24·47.24·4.72 Inch³ in size.

**Bottom Steel Plate:** at the base of the masonry wall model was assigned a fixed boundary condition.

NUMERICAL ANALYSIS WORK IN PROGRESS ...

Ph.D. Student Dora Pugliese | Architecture, Design, Knowledge, and Safeguarding of the Cultural Heritage | University of Florence | Civil & Architectural Engineering | University of Miami