XVI INTERNATIONAL CONFERENCE ON
STRUCTURAL REPAIR AND REHABILITATION
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ONLINE CONFERENCE

Seismic vulnerability and strengthening of heritage structures using advanced analysis and Fiber Reinforced Cementitious Matrix (FRCM)

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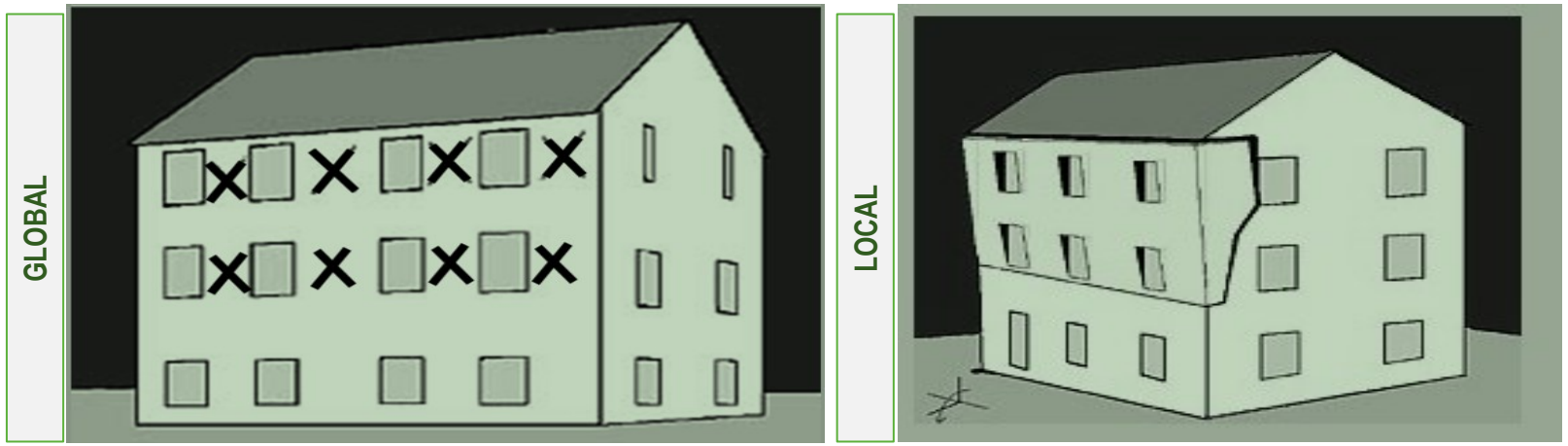
MODELING HERITAGE STRUCTURES

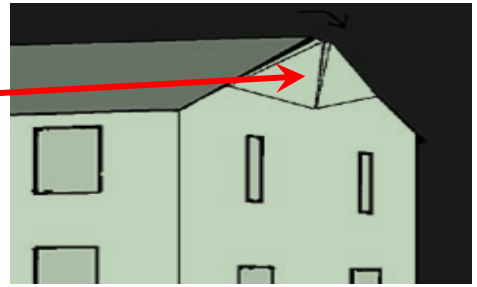
- **INTRODUCTION**
- NONLINEAR MODELING
- EQUIVALENT-FRAME MODEL
- MICRO/MACRO MODELING
- MASONRY STRENGTHENED WITH FRCM
- CONCLUSIONS

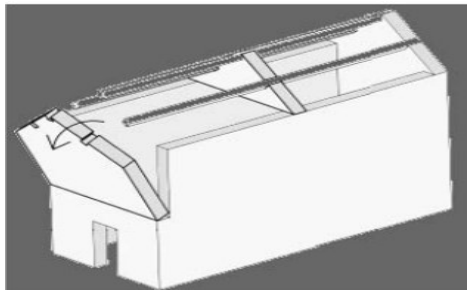
INTRODUCTION

- Global mechanism: the structural elements work together to contrast the seismic action
- Local mechanism: each element or part of the element behaves independently



INTRODUCTION

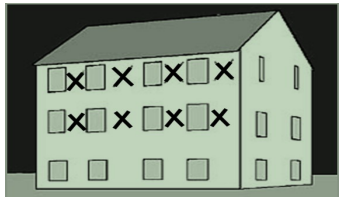




INTRODUCTION

GLOBAL COLLAPSE

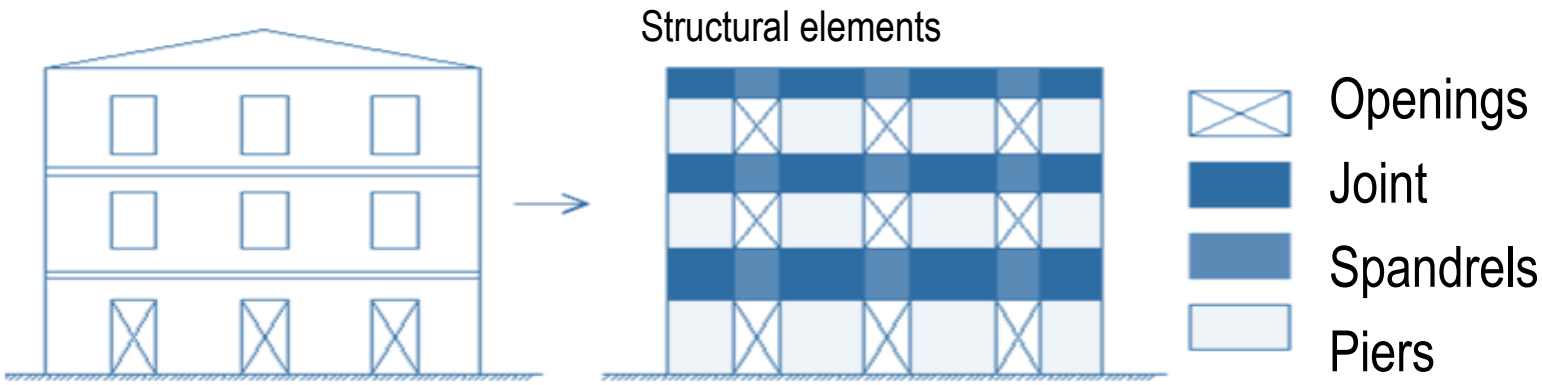
Earthquake 24 Aprile 2016; M_w=6.0 Centro Italia



Pier shear failure

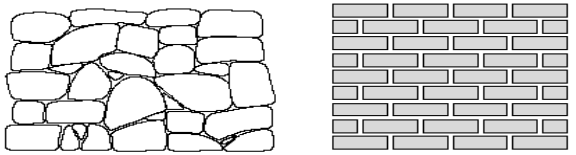
MASONRY BEHAVIOR

Structural elements
- Piers
- Spandres
- Joints



Material:

- non homogenous
- very low tensile strength
- medium to low compressive strength



MODELING HERITAGE STRUCTURES

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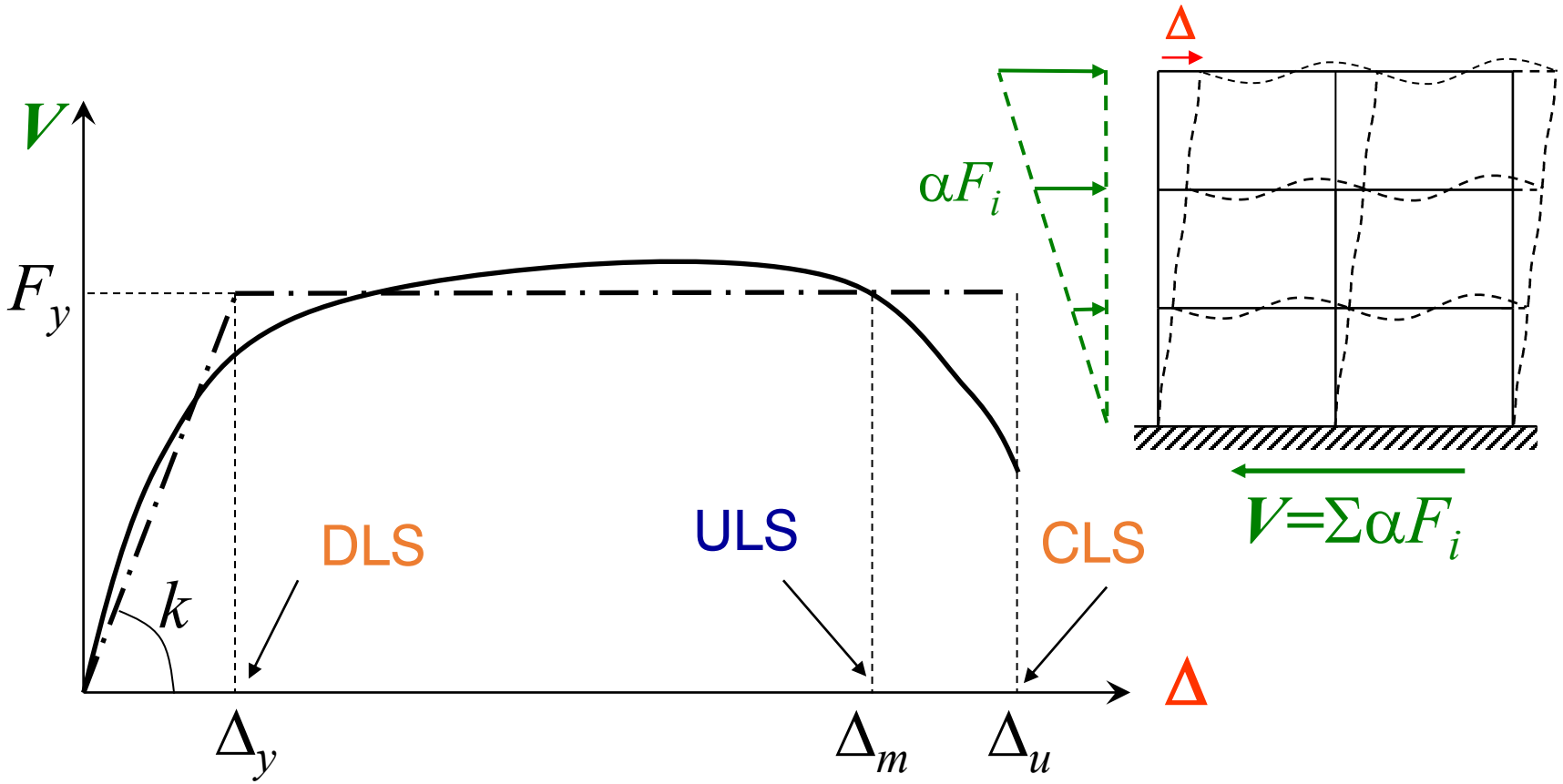
NONLINEAR MODELING

- **N**on linear methods are becoming more popular among professional engineers because they can describe accurately the static and dynamic behavior of structures.



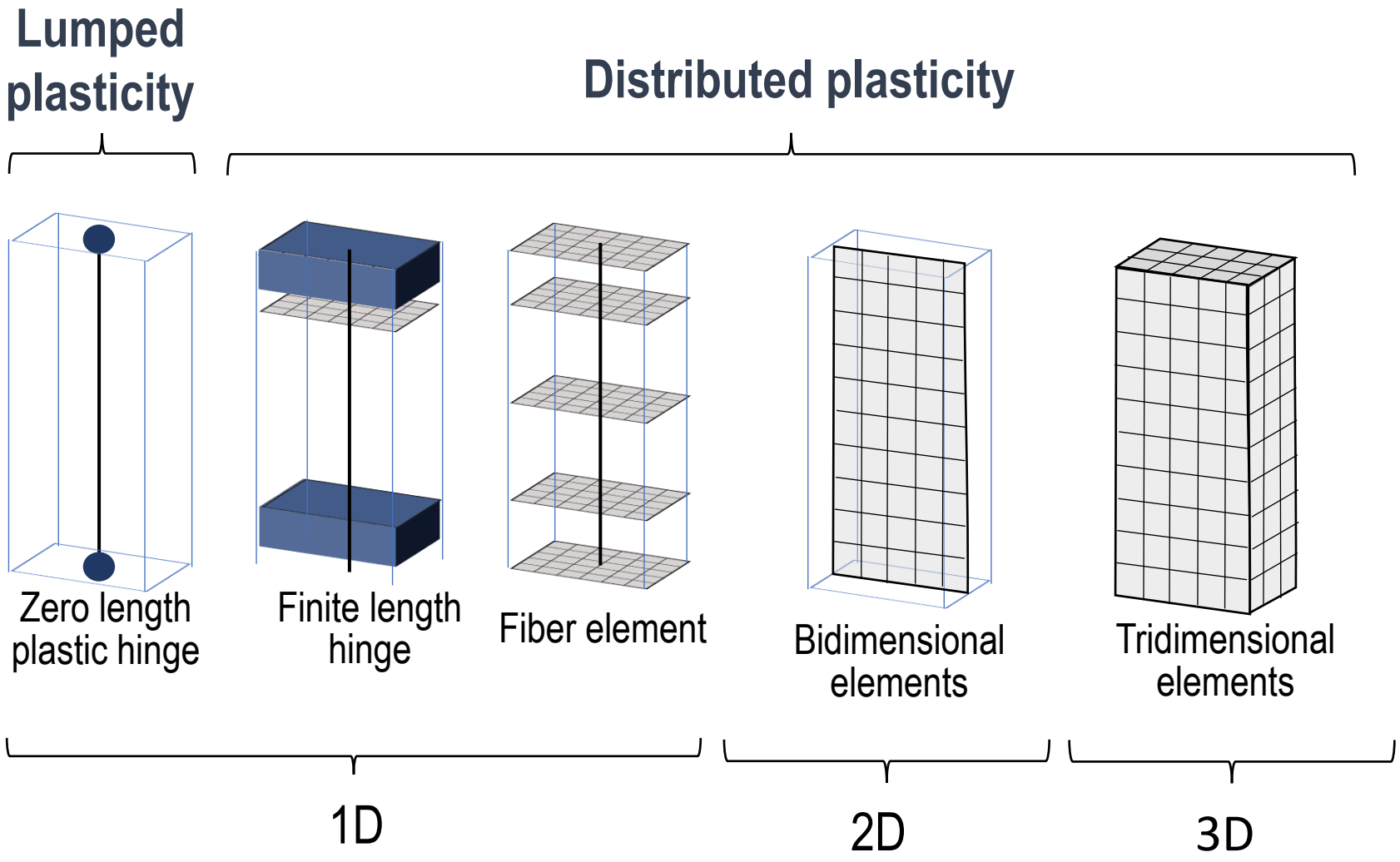
WHY ADVANCED ANALYSES FOR MASONRY STRUCTURES ?

- **M**asonry structures behave nonlinearly after cracking
- **N**onlinear analyses track the structural failure more accurately
- **S**maller approximation compared to linear analysis at DLS and ULS, this often reduce the quantity of material
- **E**fficient method to evaluate the safety and vulnerability of existing structures.
- **I**n case of earthquake loads, Pushover and Nonlinear Time History Analyses are very powerful methods to evaluate the capacity and the ductility of the structures

ISSUES

- The application of these advanced methods to real problems has raised several questions on the procedures defined in the codes and on the selection of the appropriate calculation methodologies.
- These methodologies required extensive experience
- Assumptions have an important impact on the results:
  - Element selection,
  - Convergence criteria,
  - Definition of load history and load application,
  - Seismic input selection,
  - **Constitutive law selection for unreinforced and strengthened elements**
  - Mesh discretization.

NONLINEAR MODELING IDEALIZATION



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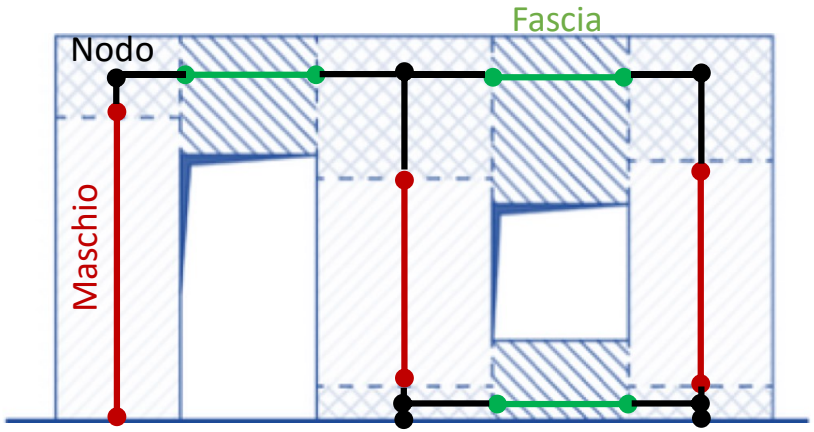
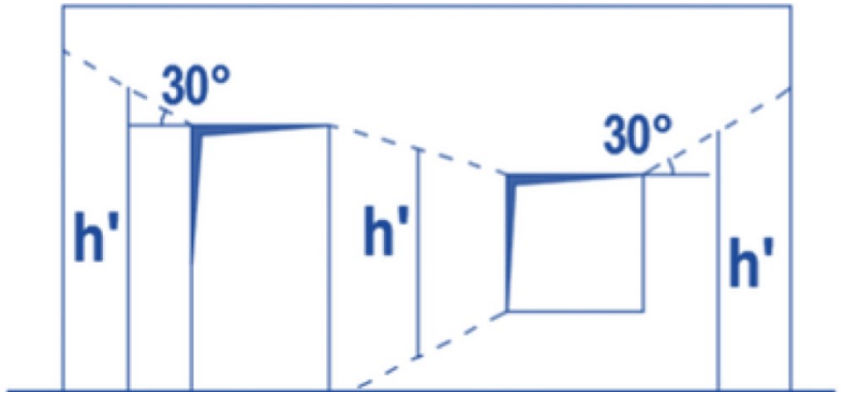
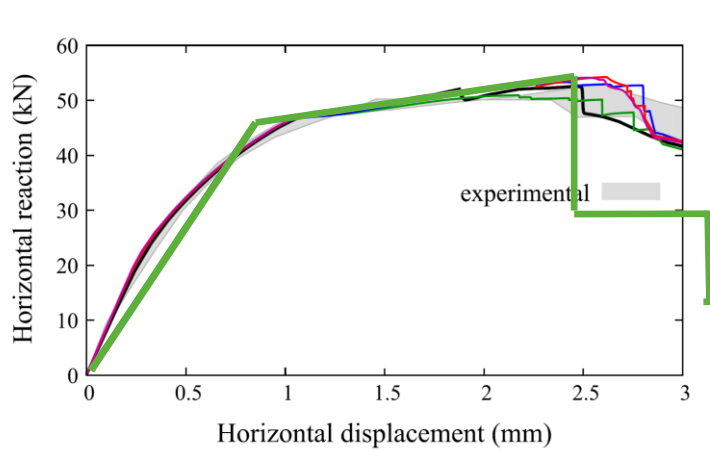
EQUIVALENT FRAME MODEL

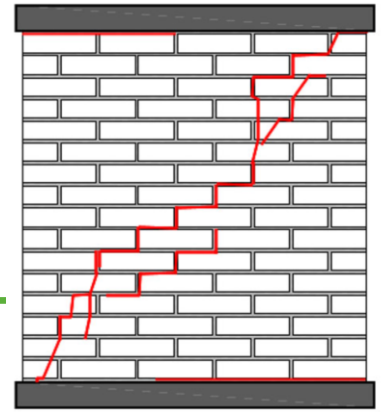


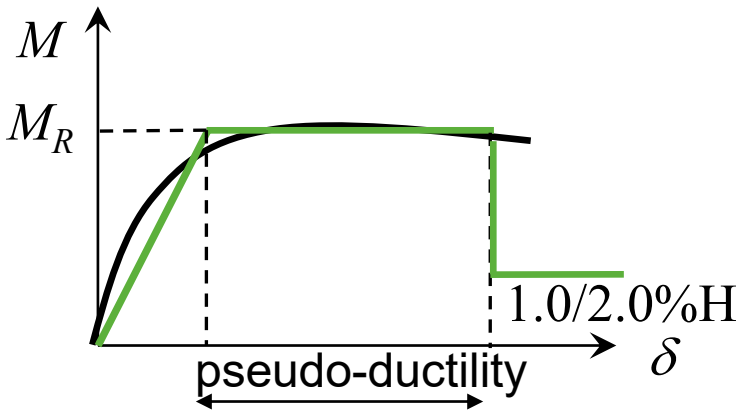


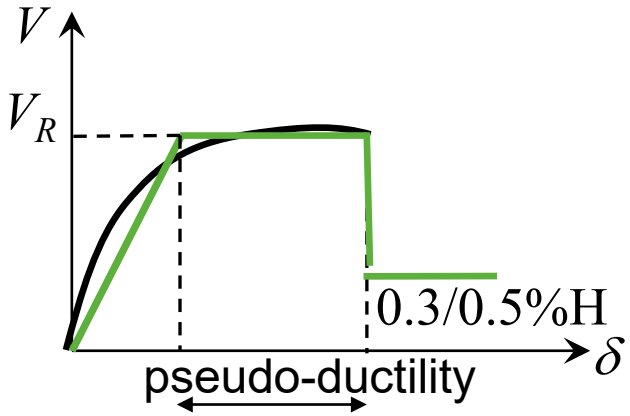
- If the geometry is ‘sufficiently’ regular it is possible to model the masonry walls with equivalent frame models
- Piers and spandrels are modelled with beam elements and panel joints with rigid elements
- The nonlinearity is modelled either with distributed plasticity (fiber models) or with lumped plasticity (plastic hinges)

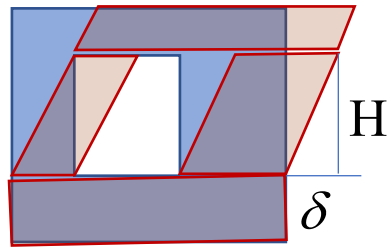
CAPACITY DEFINITION







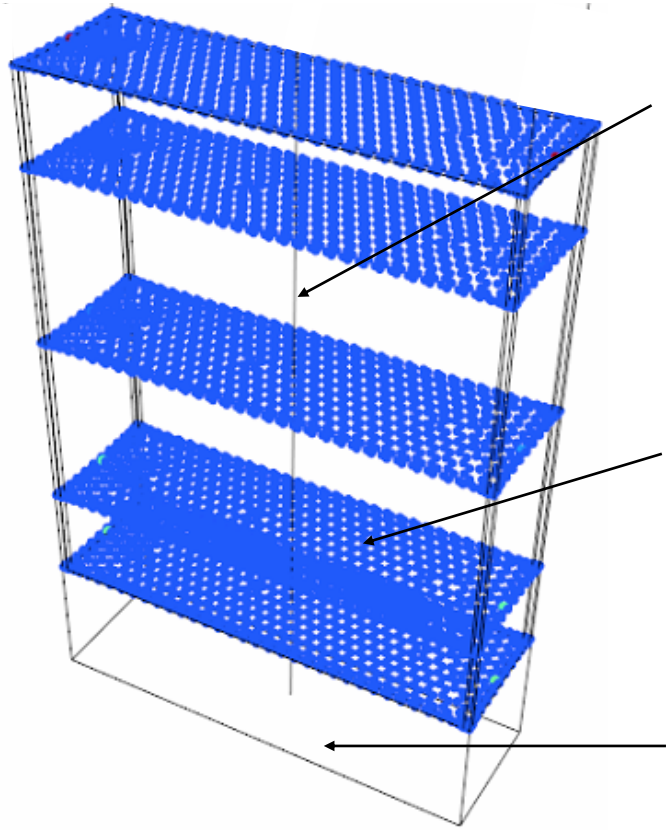




EQUIVALENT-FRAME MODEL

Macro-element modeling for un-reinforced masonry (URM) structural analysis with forced-based elements and fiber sections

- For each pier : **1 macro-element**
- Rigid zone: **1 macro-element**
- Gauss-Lobatto integration : **5 integration points**
- Materials: **Uniaxial Constitutive law**

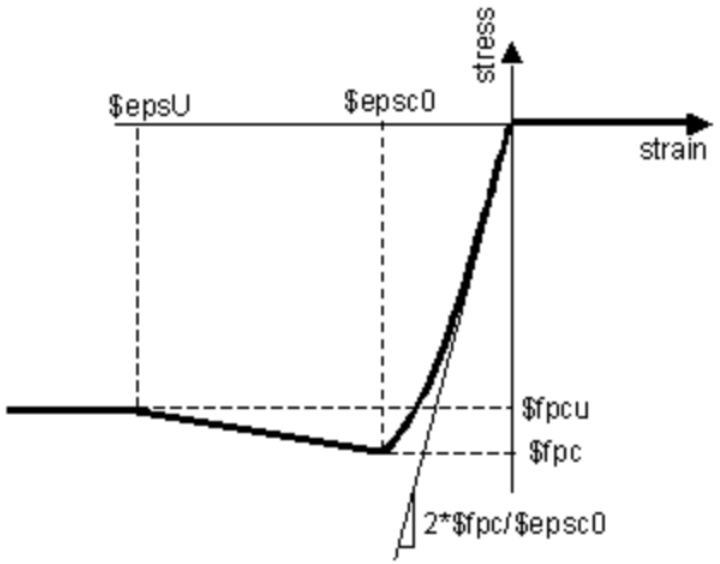


EQUIVALENT-FRAME MODEL

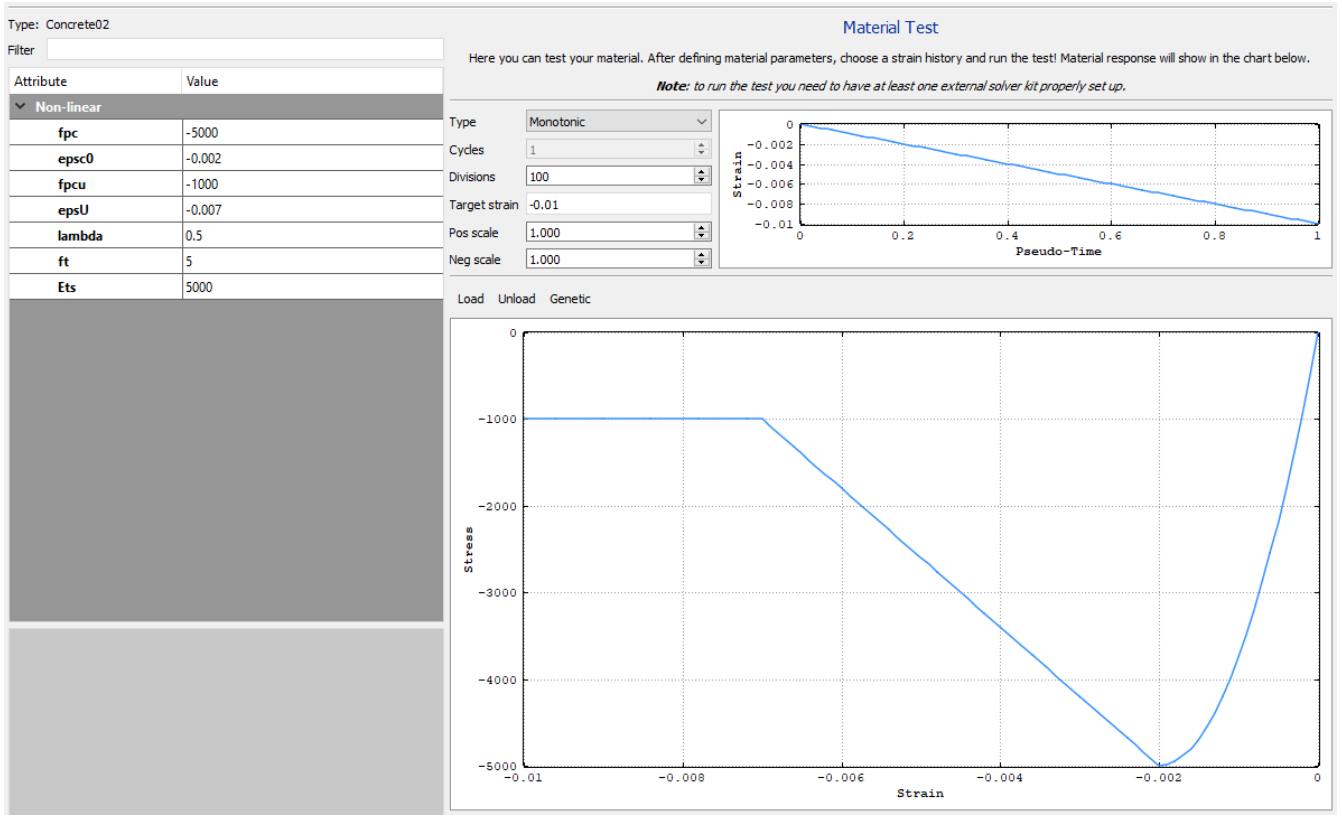
Nonlinear constitutive law for material

- Contrete01 – No tension
- Concrete02 – Tension linear softening

Kent-Scott-Park – Masonry Fibers



Physical Properties

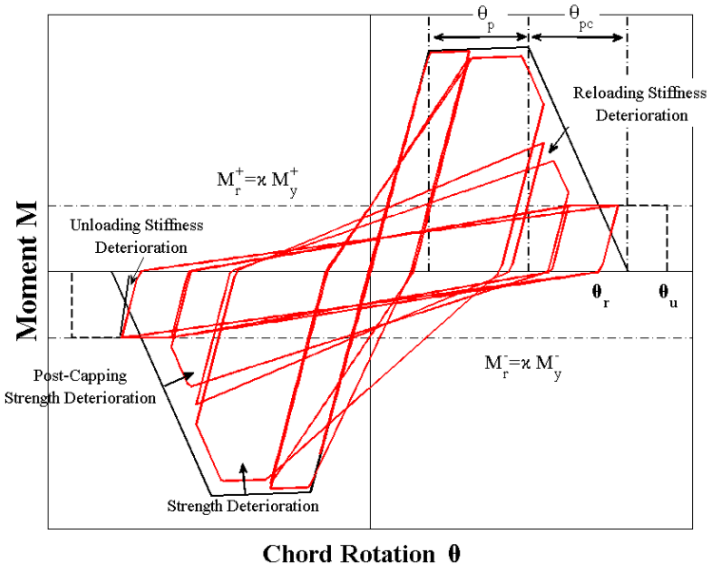


EQUIVALENT-FRAME MODEL

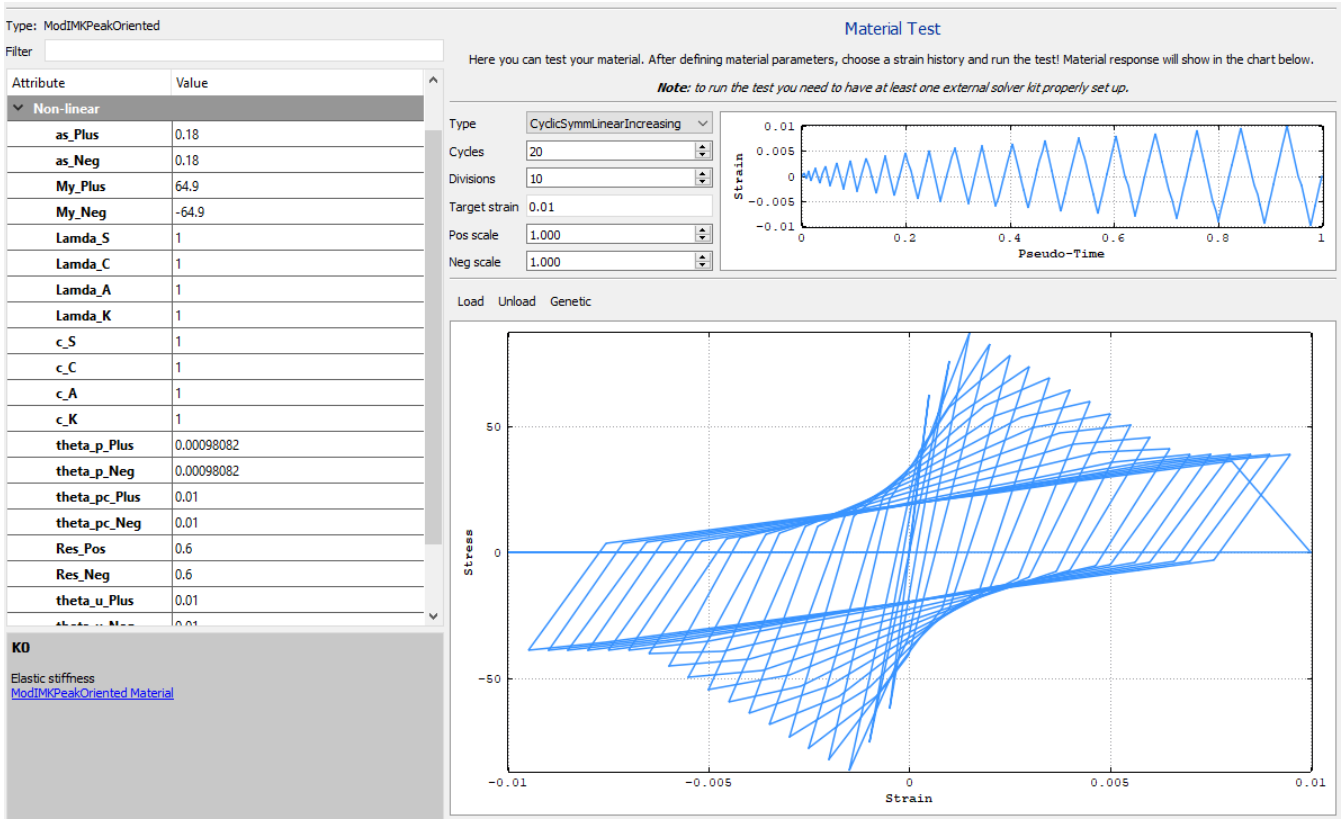
Non-linear constitutive law phenomenological based for shear

- Monotonic – Multilinear
- Cyclic – ModIMKPeakOriented

Modified Ibarra-Medina-Krawinkler

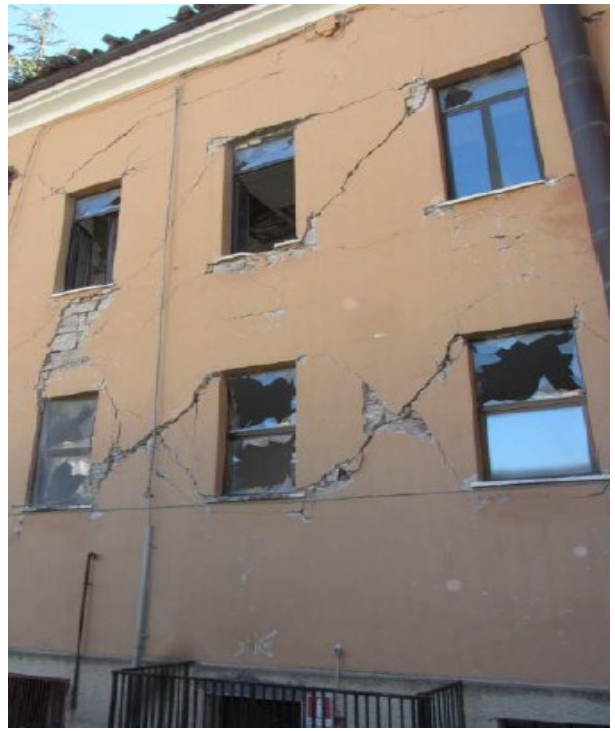


Physical Properties



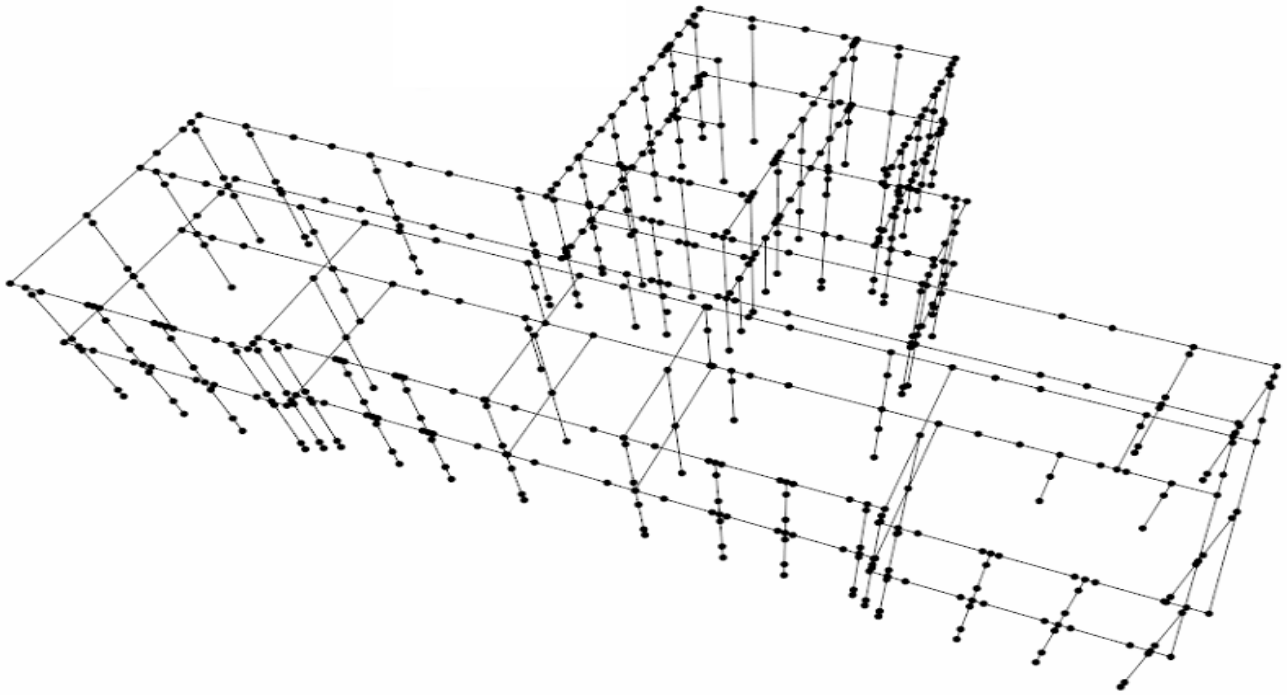
EQUIVALENT-FRAME MODEL

School ‘Pietro Capuzi’ – Visso – Macerata – Italy – Central Italy earthquake



RESULTS

School ‘Pietro Capuzi’ – Visso – Macerata – Italy - Earthquake Central Italy



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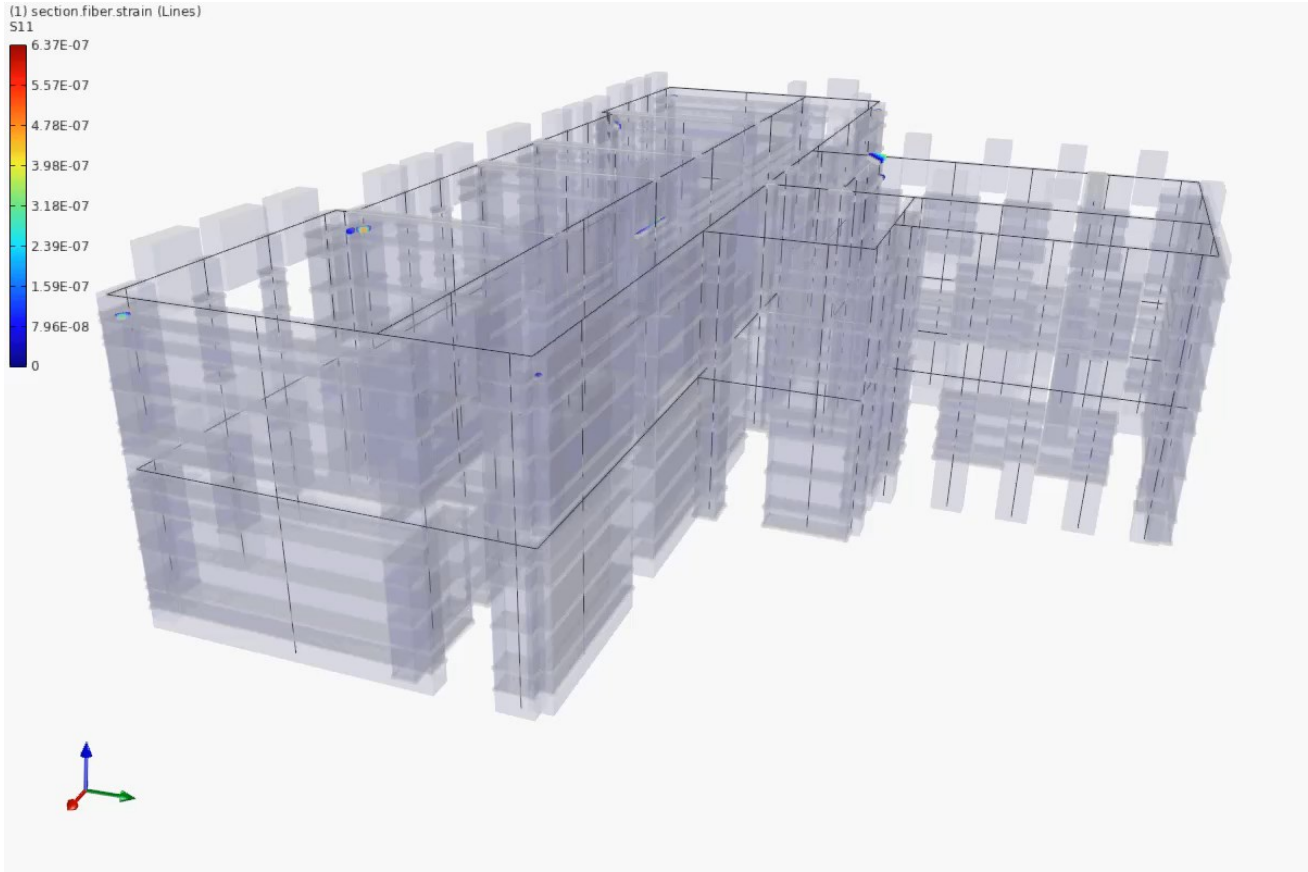
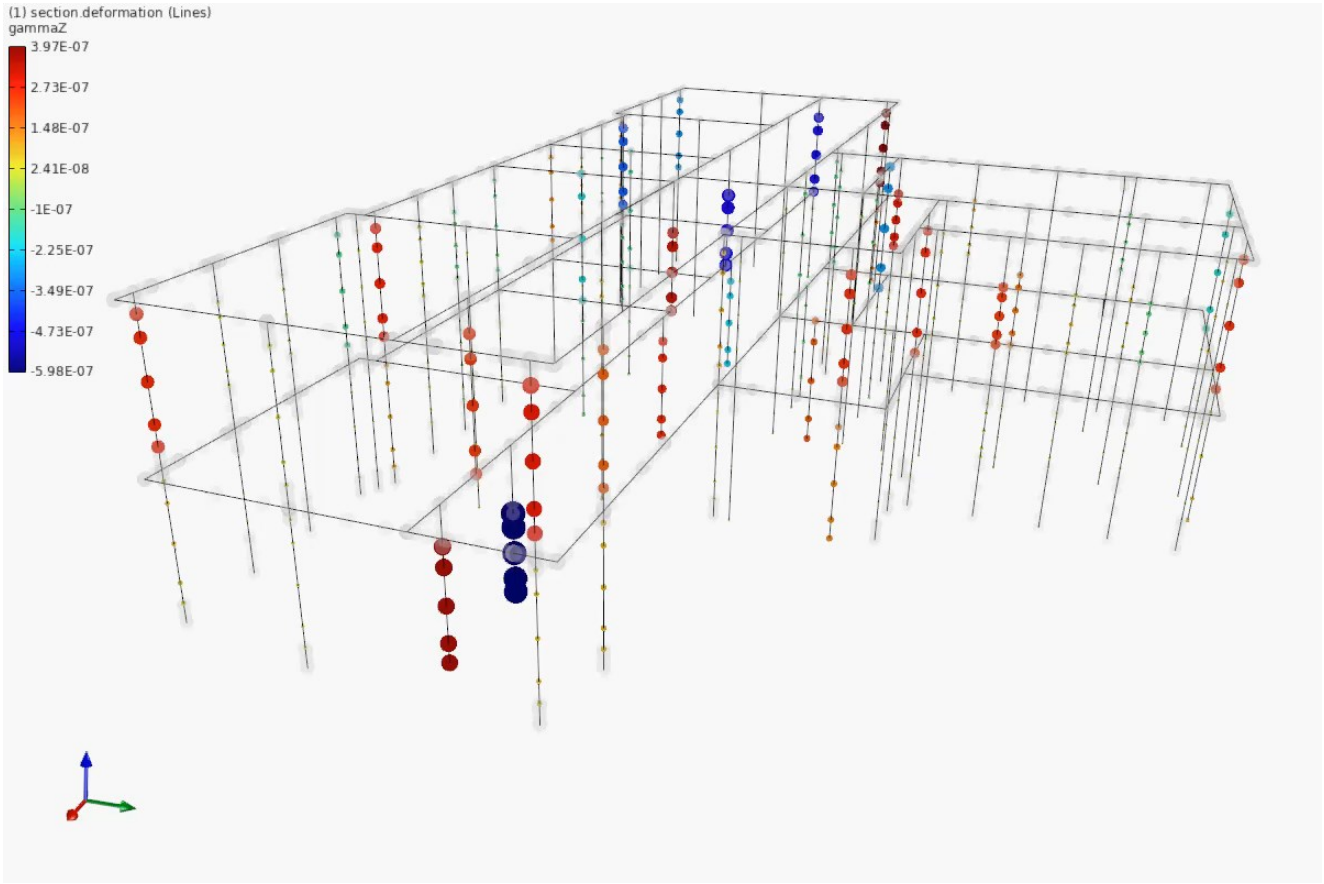


Distributed plasticity/ fiber model/strain stresses

RESULTS

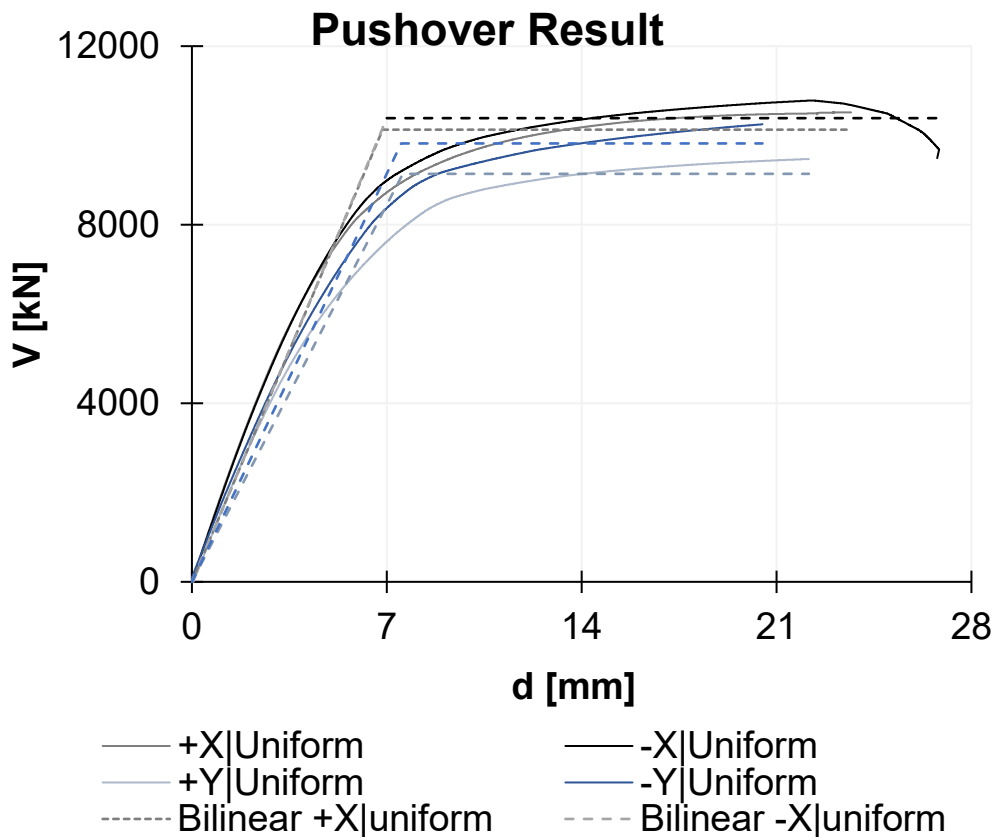
School ‘Pietro Capuzi’ – Visso – Macerata – Italy - Earthquake Central Italy

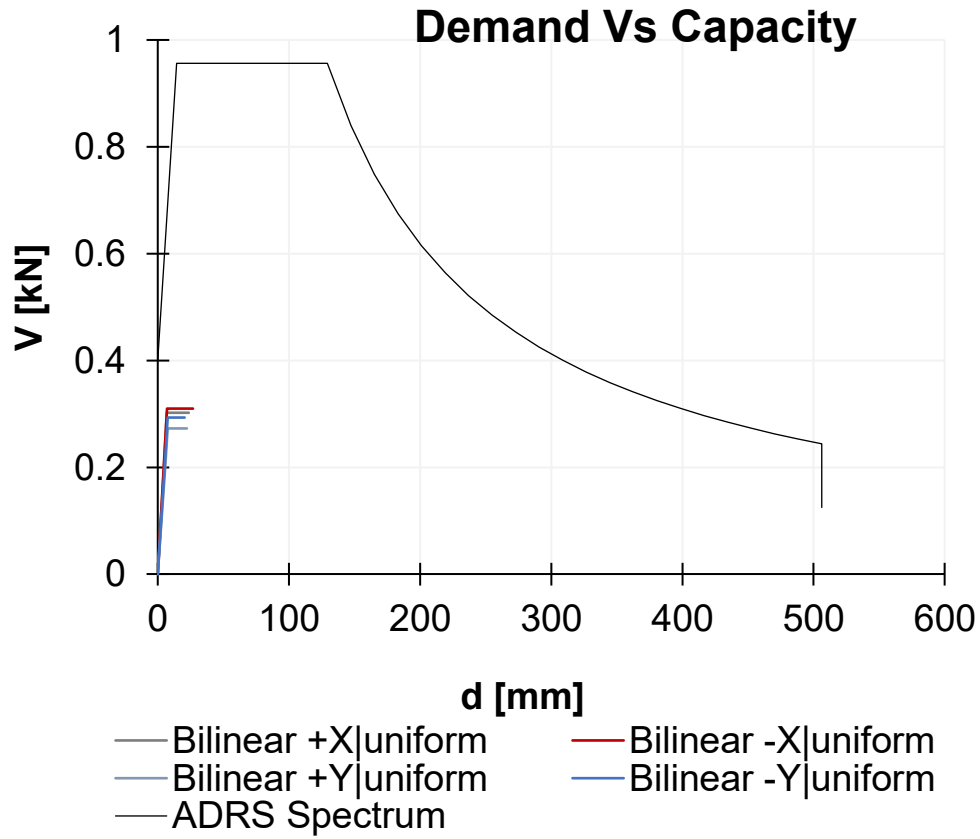


Gauss plots/section deformation/Lumped plasticity

RESULTS

School ‘Pietro Capuzi’ – Visso – Macerata – Italy - Earthquake Central Italy





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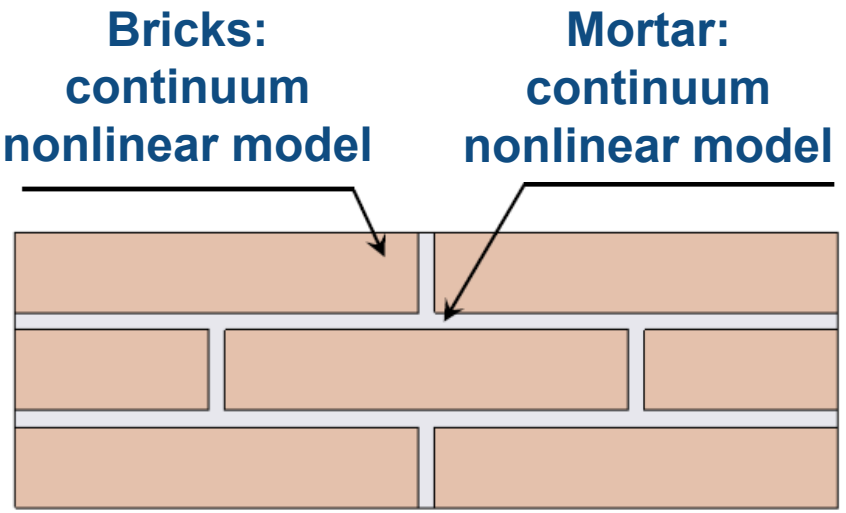
IMPLEX MICRO MODEL

Tension-compression damage model with Impl-ex algorithm for micro-modeling of masonry structures

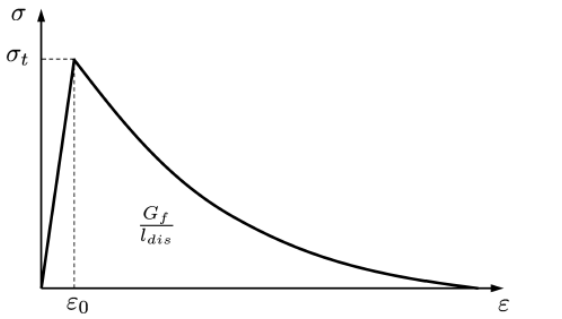
- For each pier : **Splitting to brick and mortar**
- Continuum damage model (d^+, d^-): **Based on Faria et al. 1998**
- Failure criteria: **Based on the work of Lubliner et al. 1989**
- Using appropriate integration algorithms: **Impl-ex**



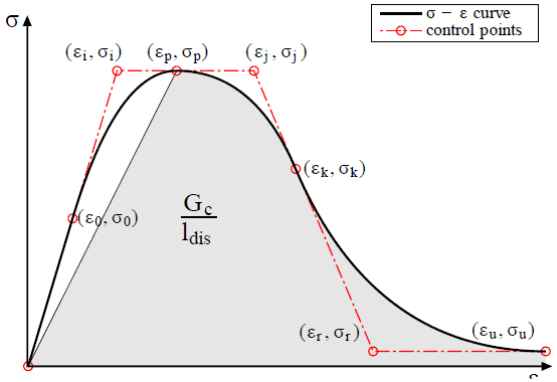
IMPLEX MICRO MODEL

Nonlinear constitutive law for material

- Tension – Rankine
- Compression – Lubliner

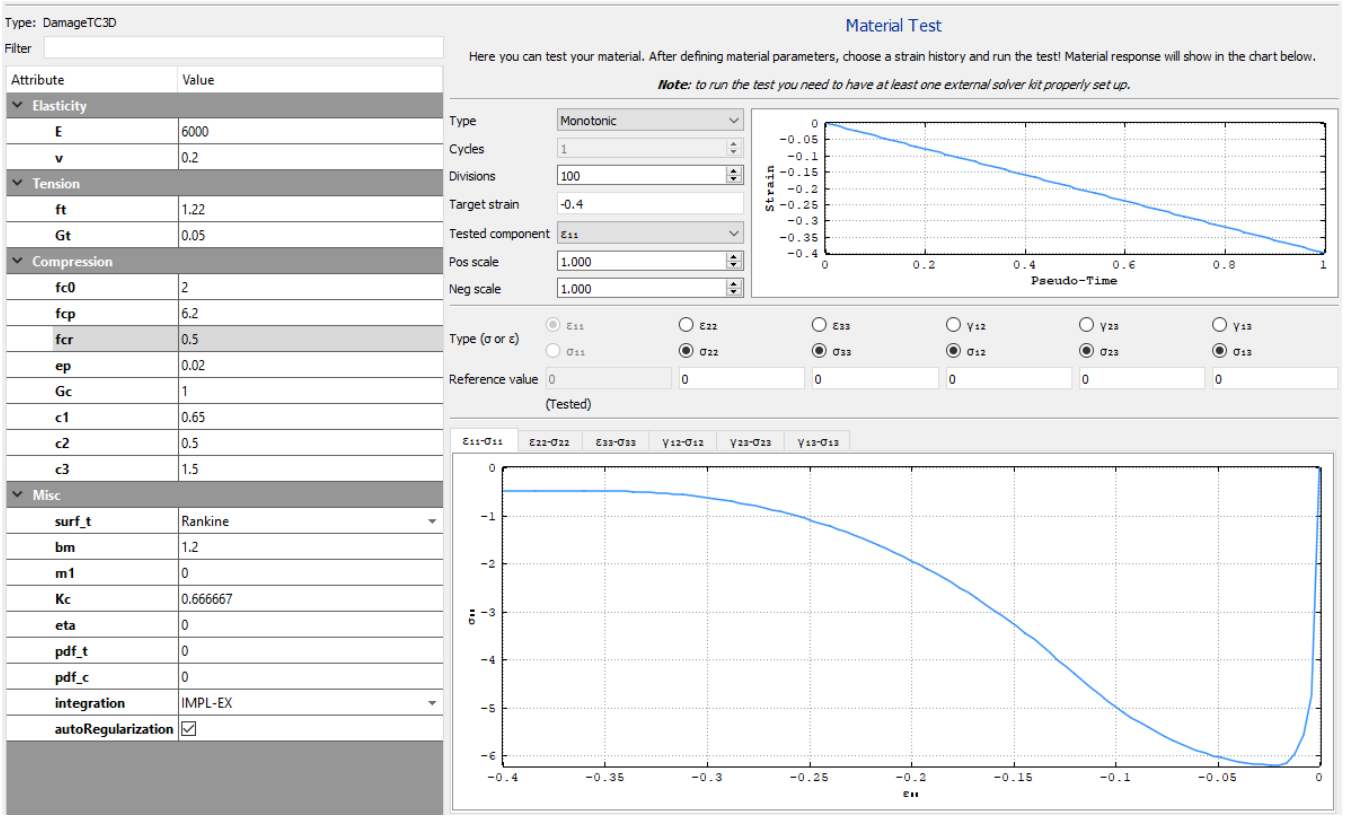


Tension



Compression

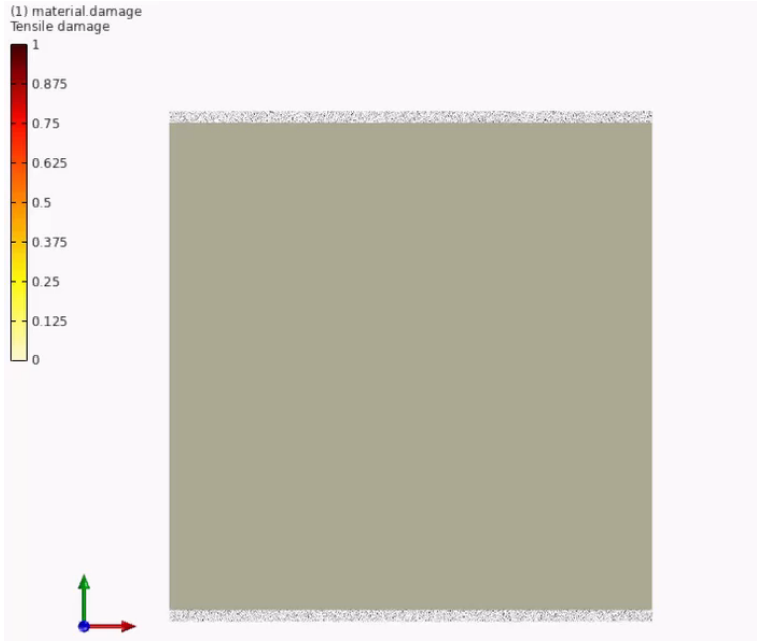
Physical Properties



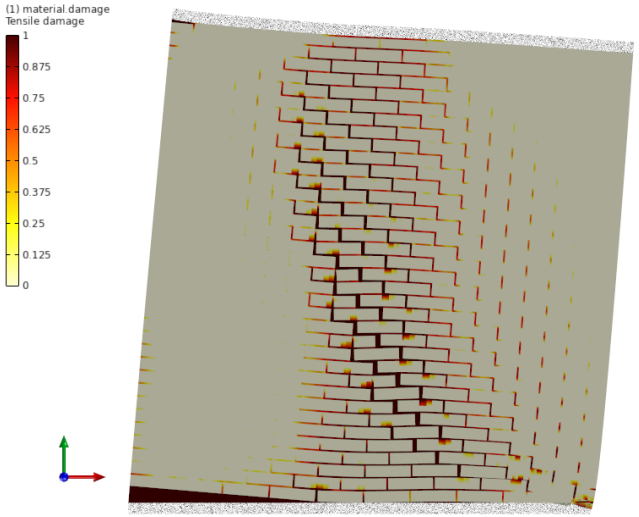
MICRO MODEL RESULTS

Micro-modeling of masonry wall of different shapes

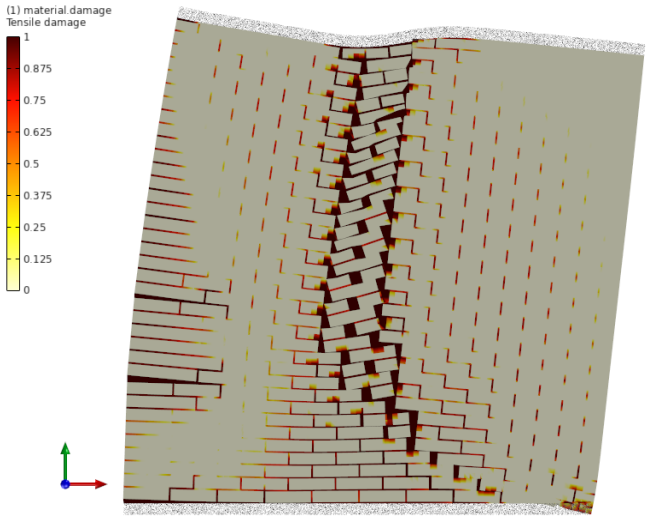
- **Cantiliver Square Wall - Rocking**



P = 400 kN (12% f_m)



P = 600 kN (18% f_m)

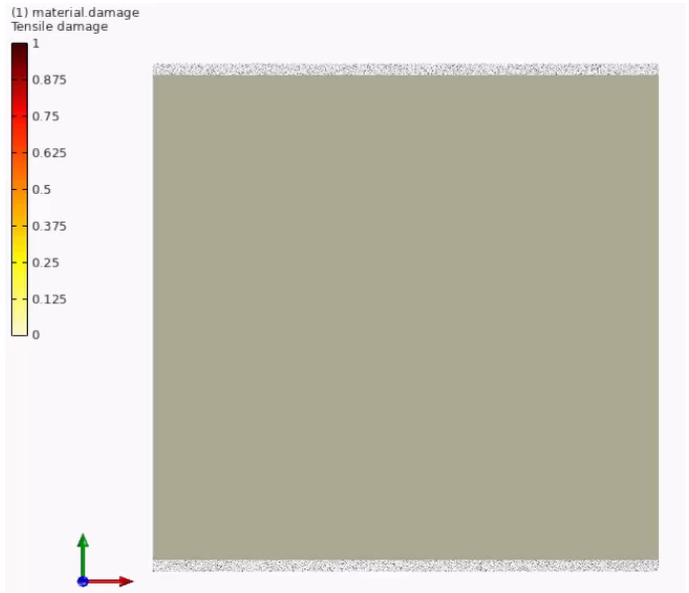


P = 1000 kN (30% f_m)

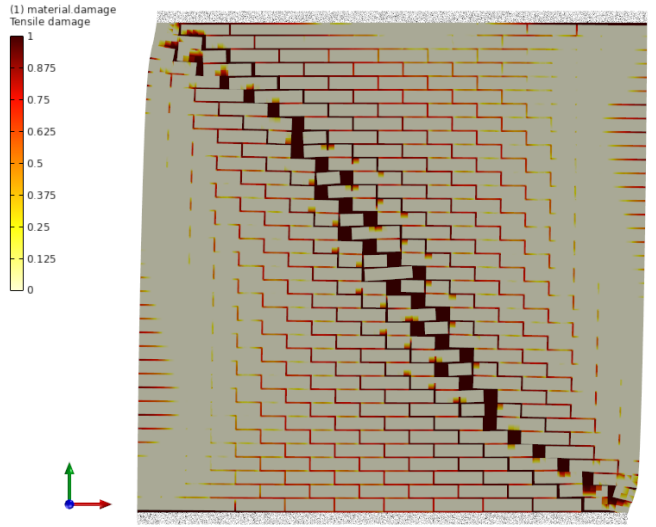
MICRO MODEL RESULTS

Micro-modeling of masonry wall of different shapes

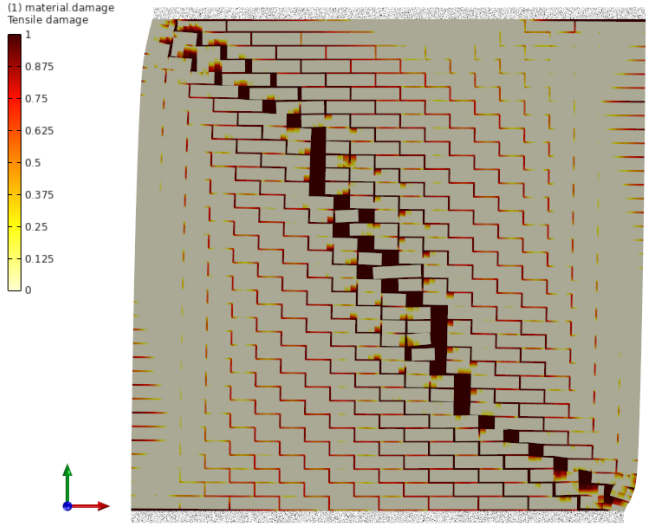
- **Fixed/fixed Square Wall – Diagonal Shear**



P = 400 kN (12% f_m)



P = 600 kN (18% f_m)

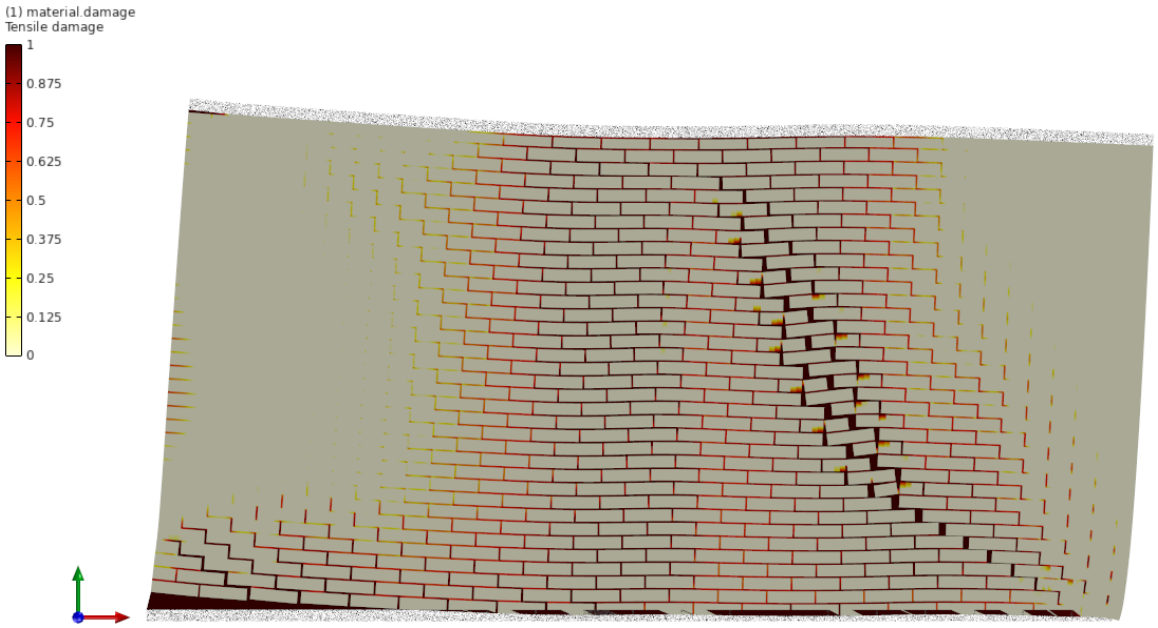


P = 1000 kN (30% f_m)

MICRO MODEL RESULTS

Micro-modeling of masonry wall of different shapes

- **Squat Wall – Rocking and Shear**

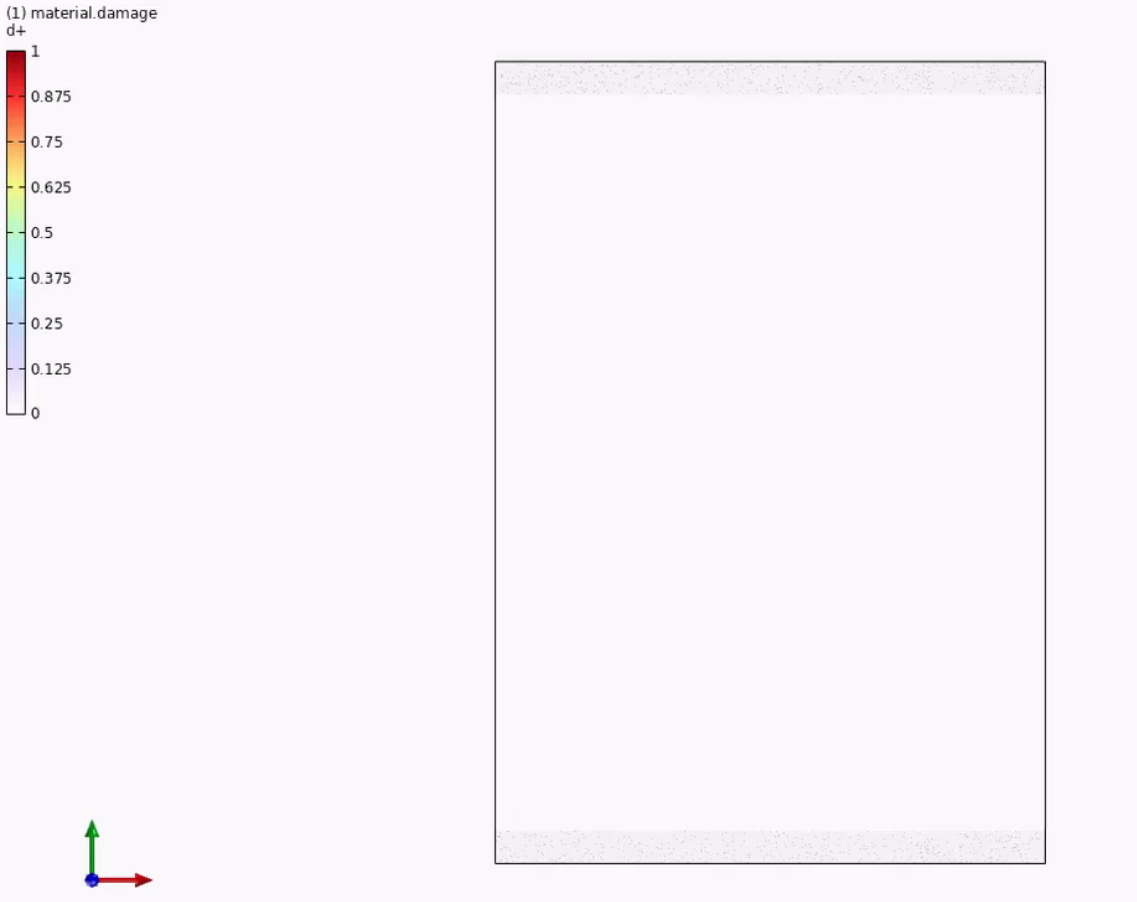


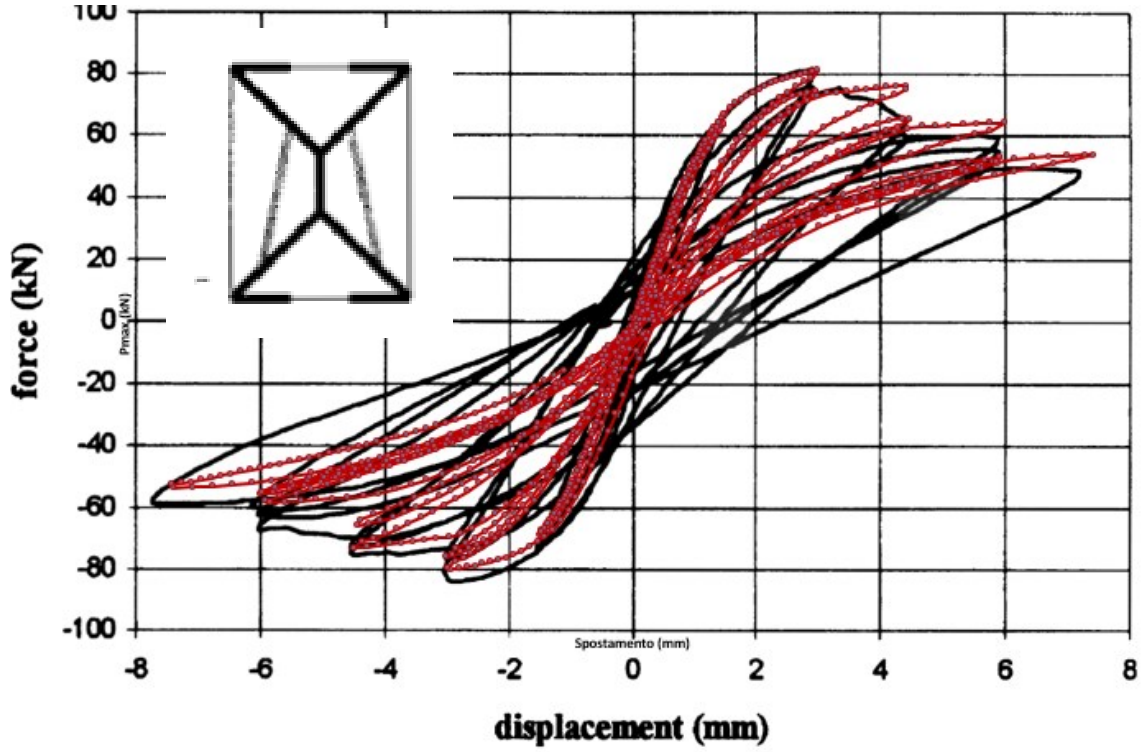
P = 800 kN (12% f_m)

P = 1200 kN (18% f_m)

MICRO MODEL RESULTS

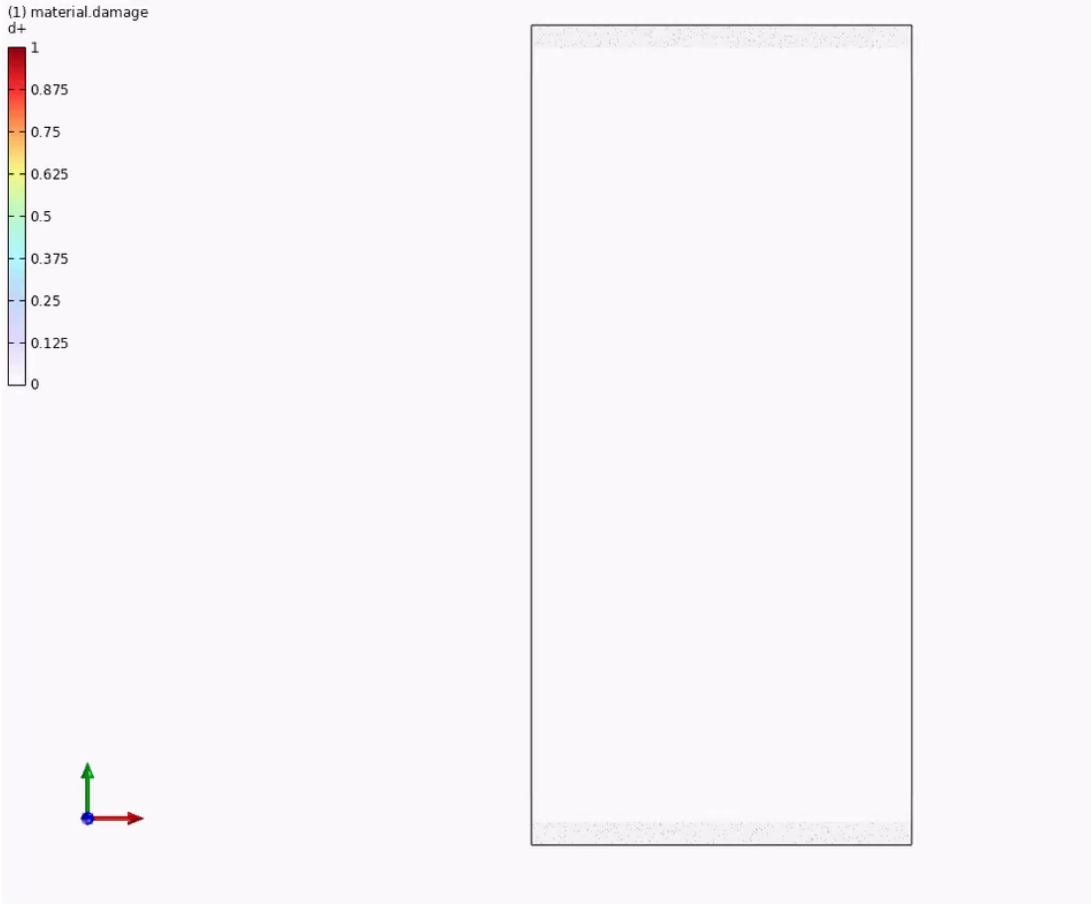
Micro-modeling of masonry wall 100x135 cm² – Cyclic Test

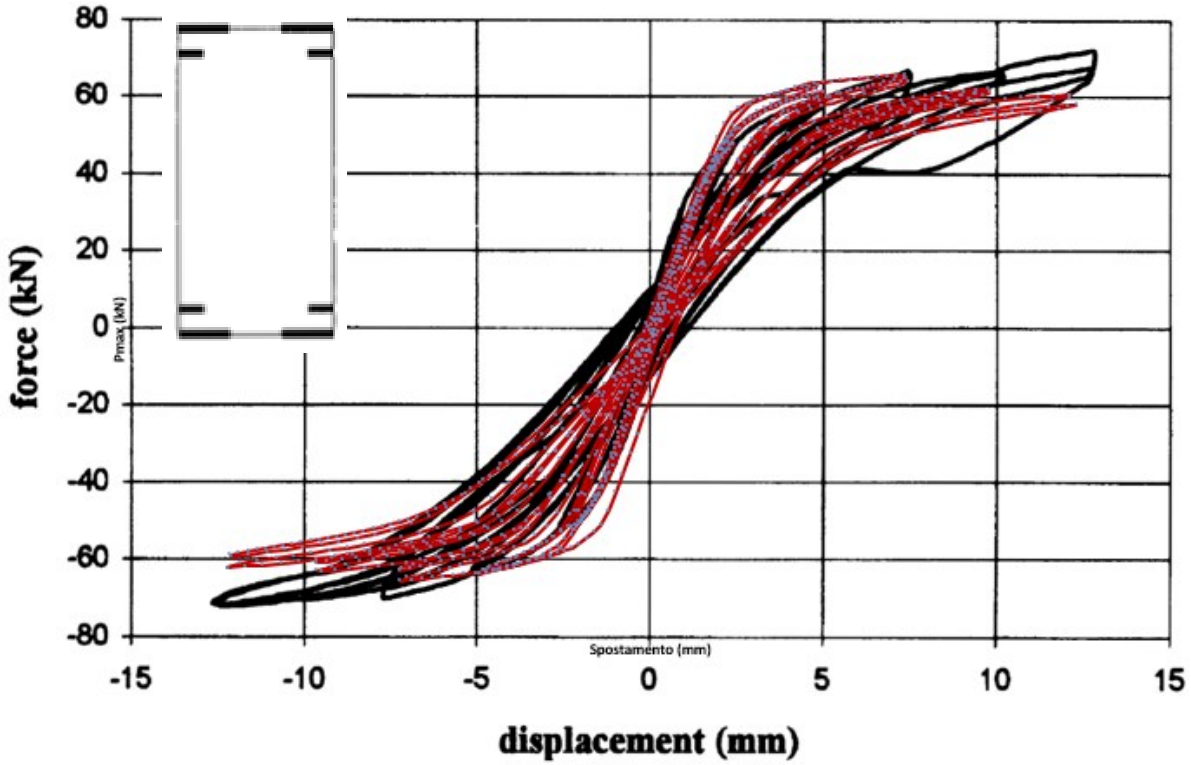




MICRO MODEL RESULTS

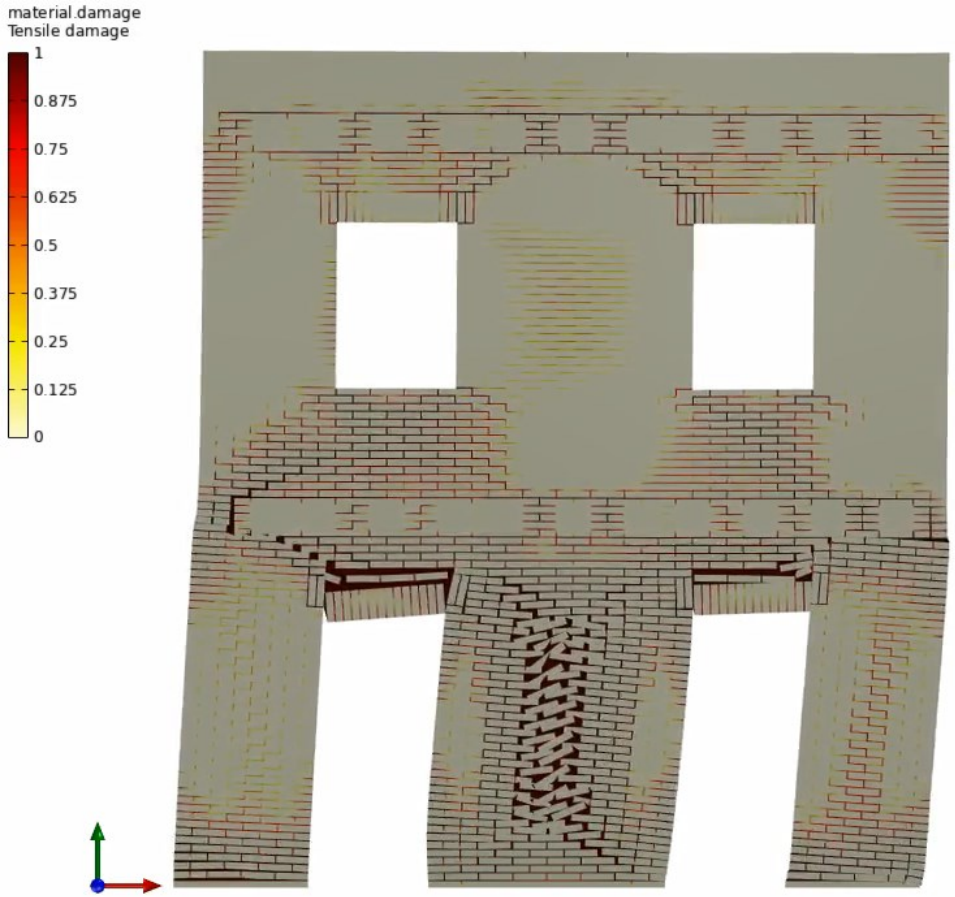
Micro-modeling of masonry wall 100x200 cm² – Cyclic Test

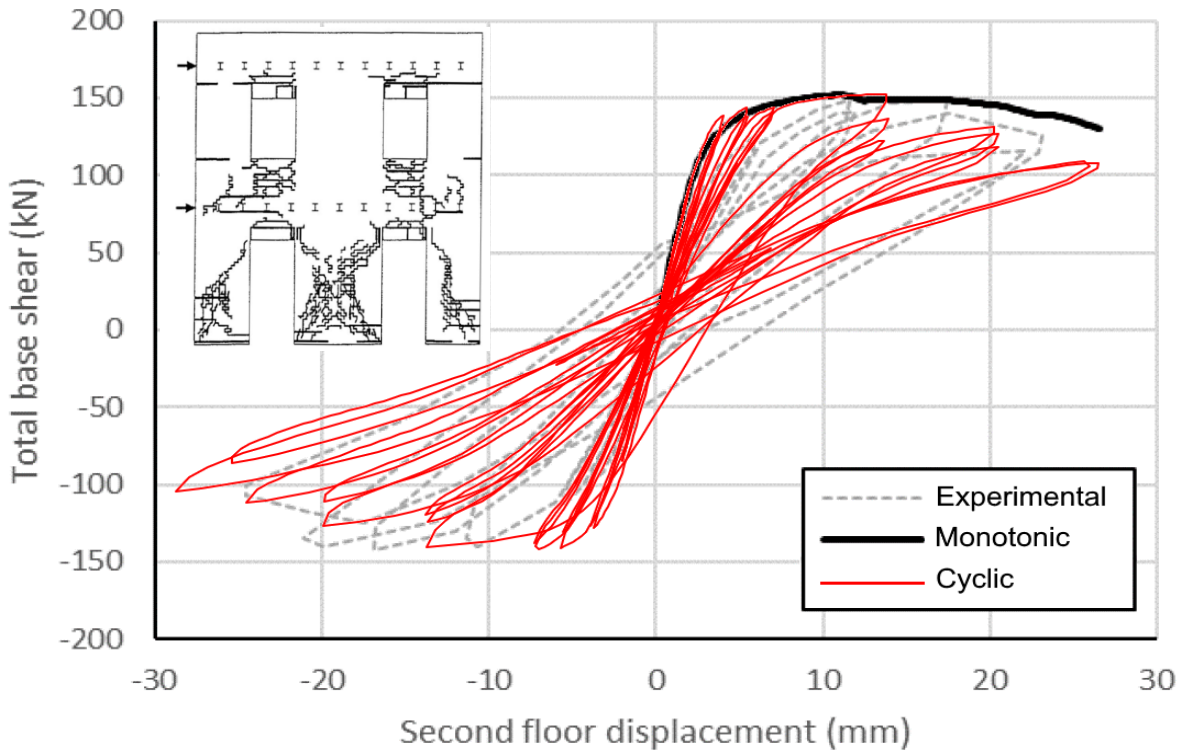




MICRO MODEL RESULTS

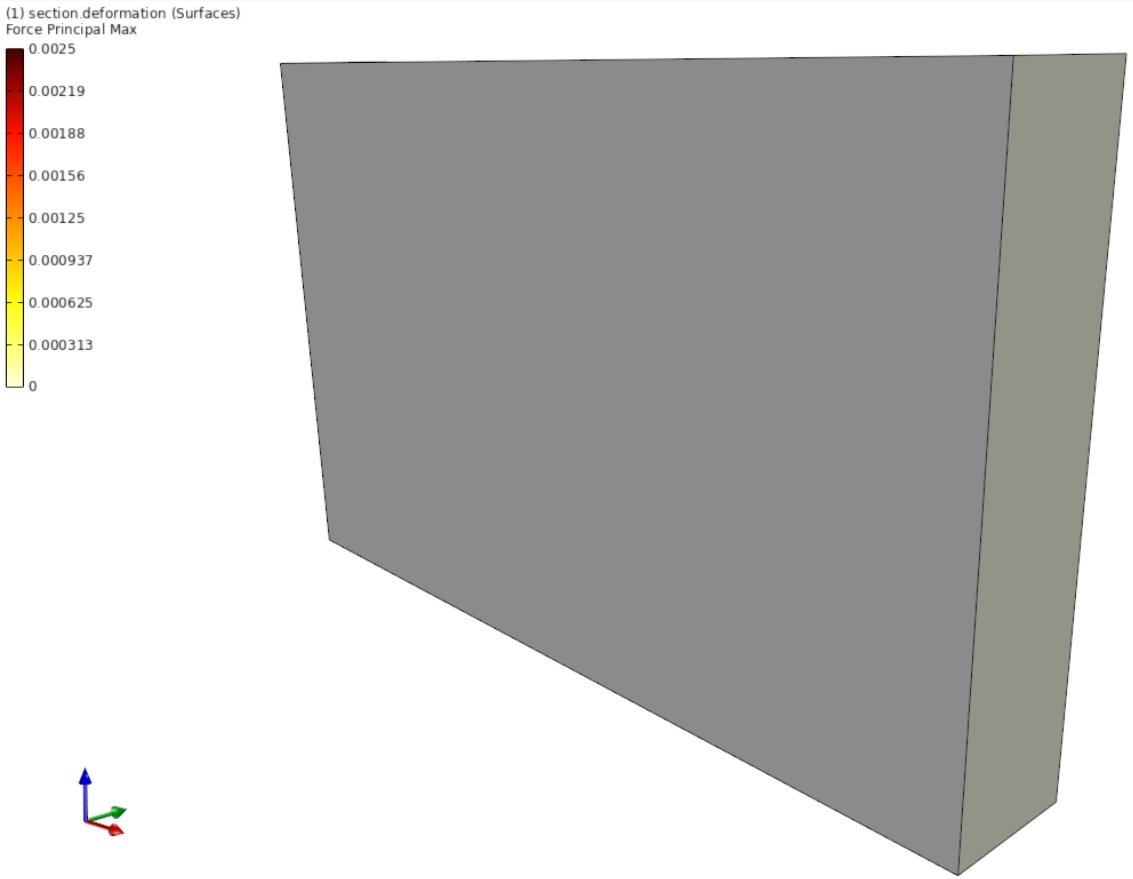
Micro-modeling of two-story masonry building – Cyclic Test

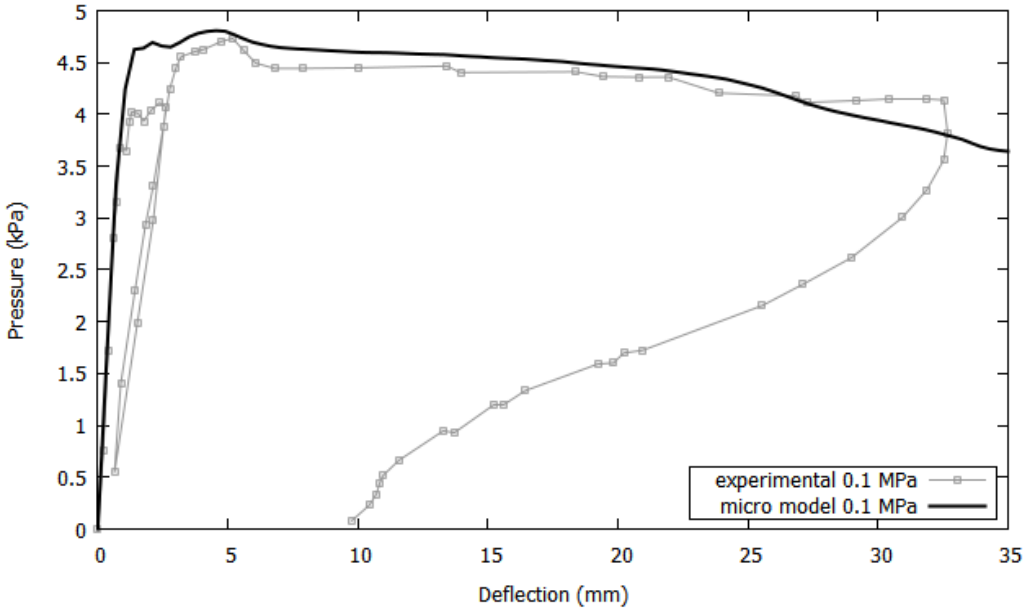


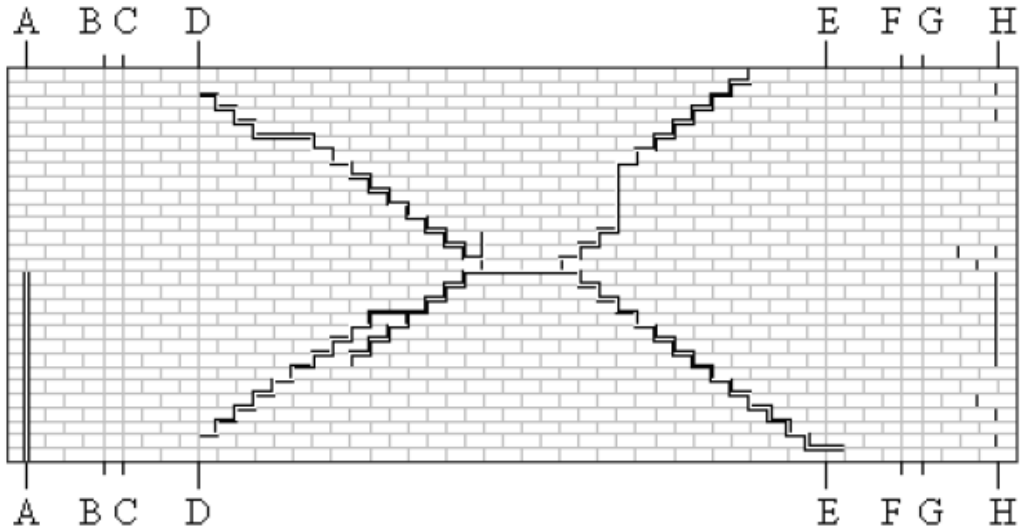


MICRO MODEL RESULTS

Micro-modeling out of plane Test

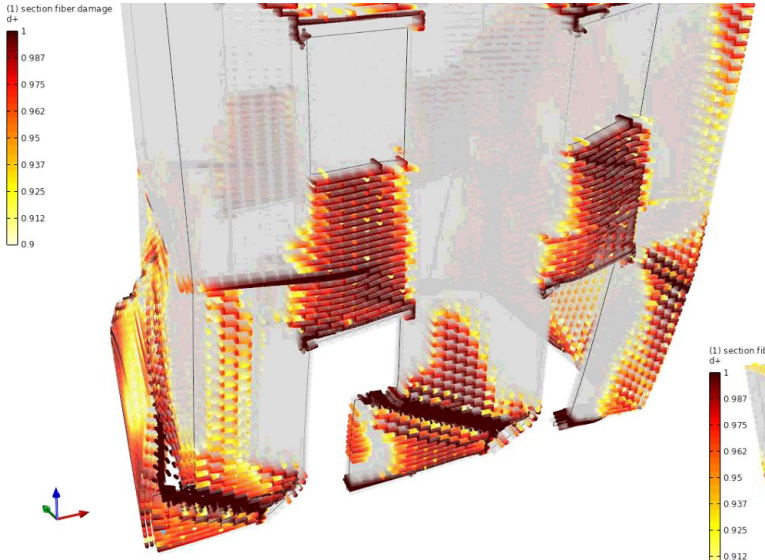


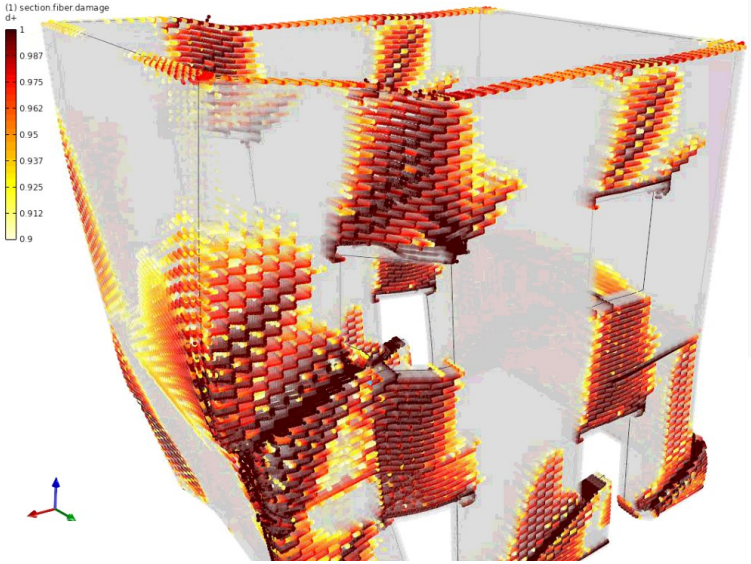


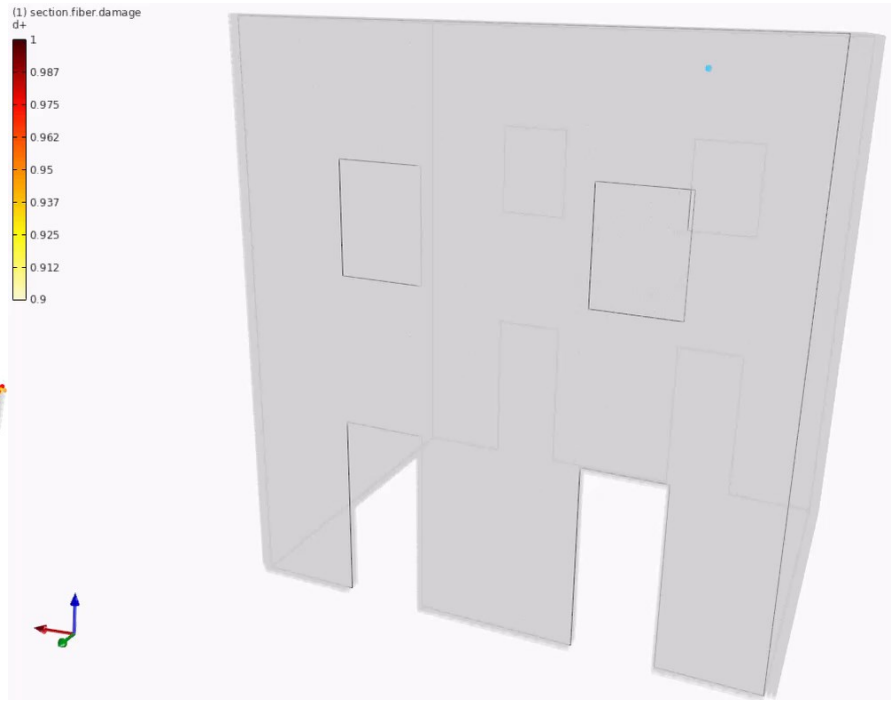


MICRO MODEL RESULTS

Micro-modeling of two-story masonry building

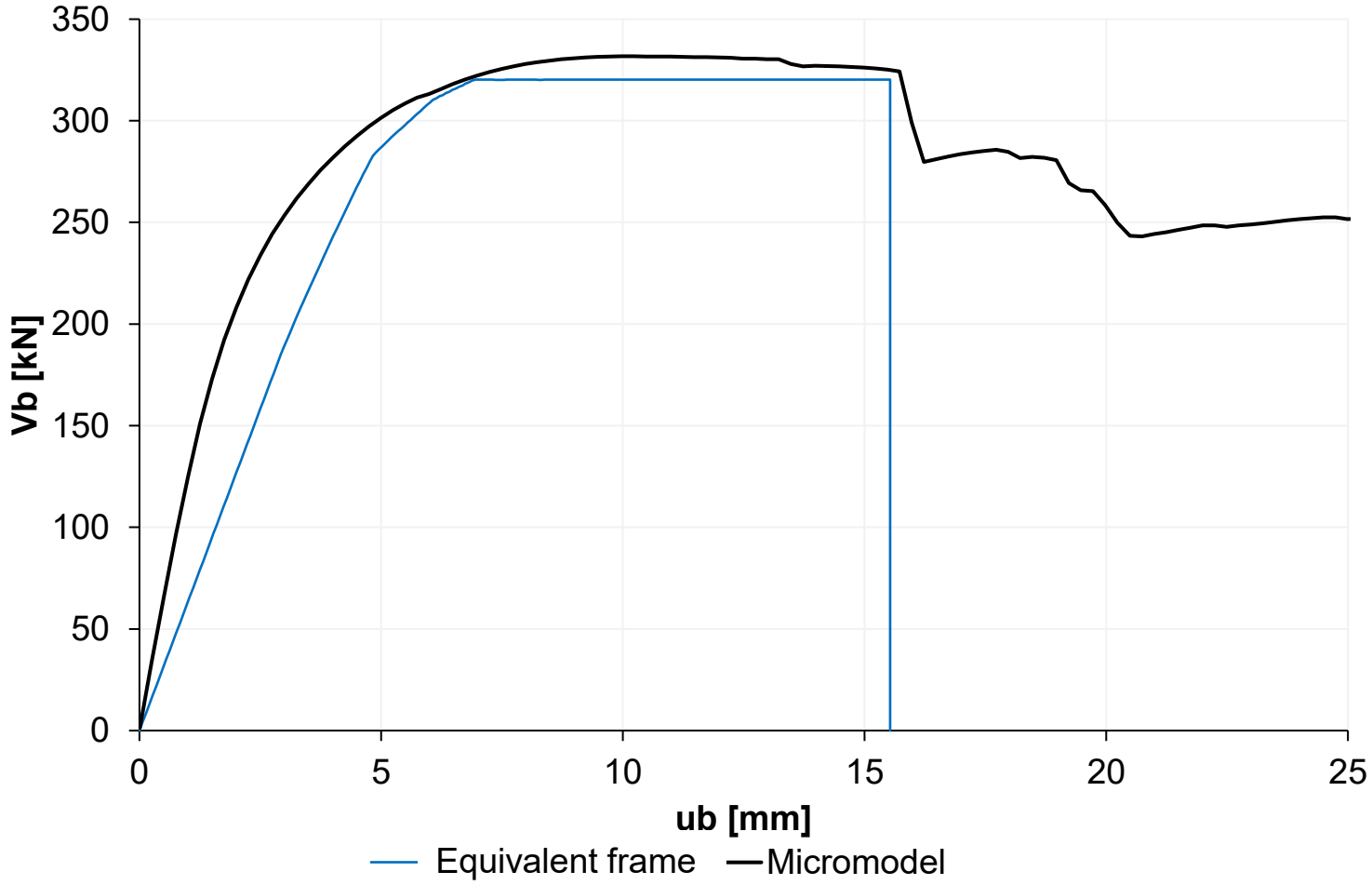






MICRO MODEL RESULTS

Capacity curve of two-story masonry building



MODELING HERITAGE STRUCTURES

- INTRODUCTION
- NONLINEAR MODELING
- EQUIVALENT-FRAME MODEL
- MICRO/MACRO MODELING
- **MASONRY STRENGTHENED WITH FRCM**
- CONCLUSIONS

FABRIC REINFORCED CEMENTITIOUS MATRIX

- FRCM systems consist of fibers embedded in a cementitious matrix.
- FRCM is also known as Textile Reinforced Concrete (TRC), or Textile Reinforced Mortar (TRM).
- The function of the fibers is to carry tensile stresses, while the function of the mortar is to bind the fibers

INCREASE CAPACITY AND DUCTILITY

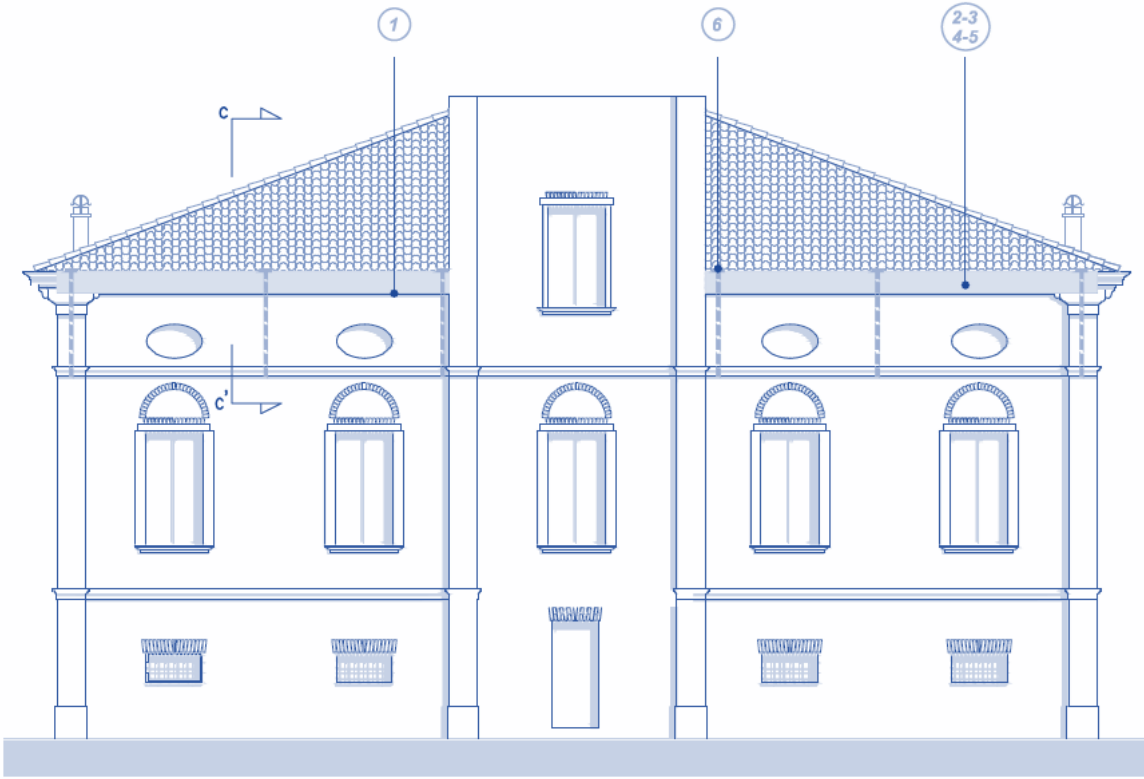
Injections

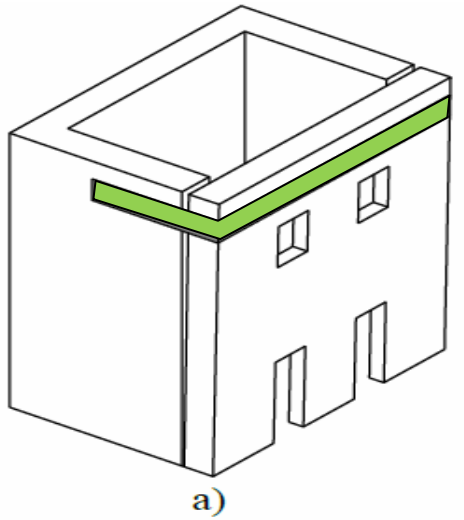
Flexure
Shear
Stiffness
increase

FRCM

Flexure
Shear
Ductility
increase
Capacity
increase

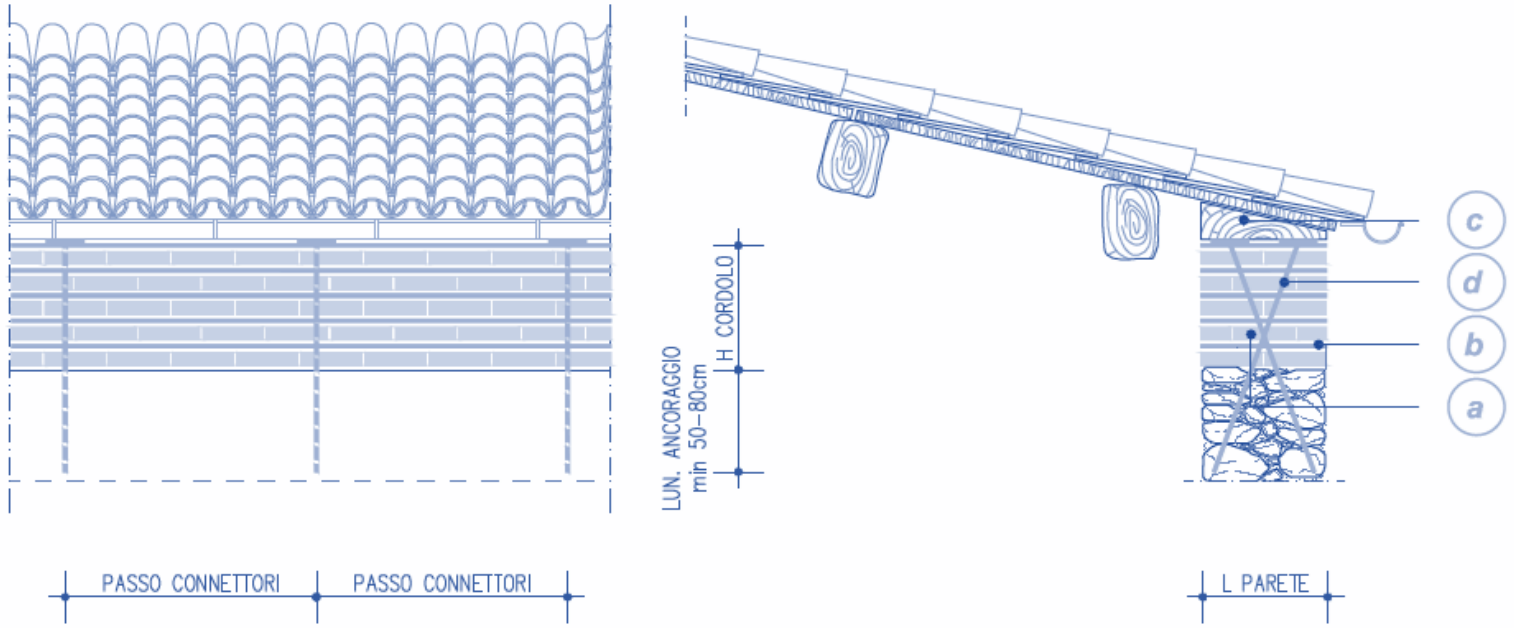
IN AND OUT OF PLANE STRENGTHENING





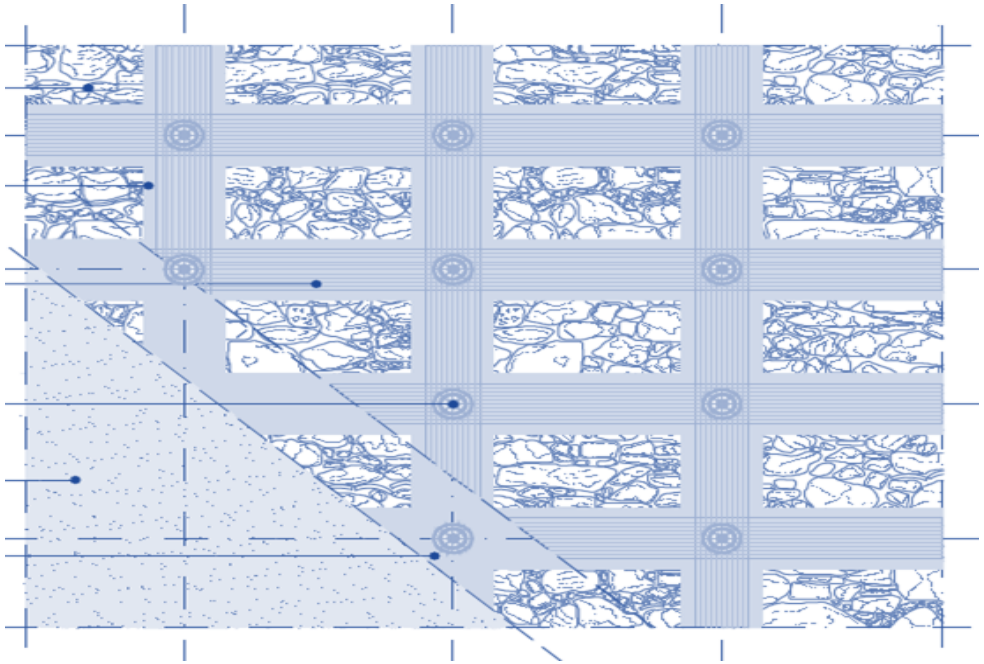
FRCM strips prevent out of plane collapse

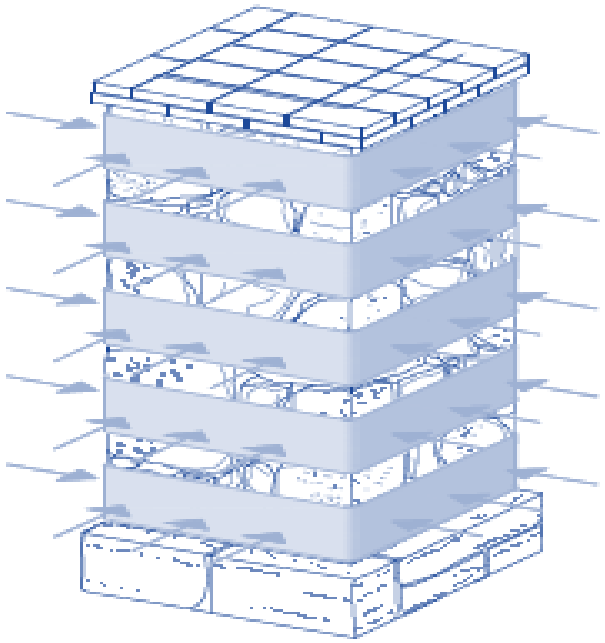
IN AND OUT OF PLANE STRENGTHENING



FRCM for chord tensile strengthening

IN AND OUT OF PLANE STRENGTHENING



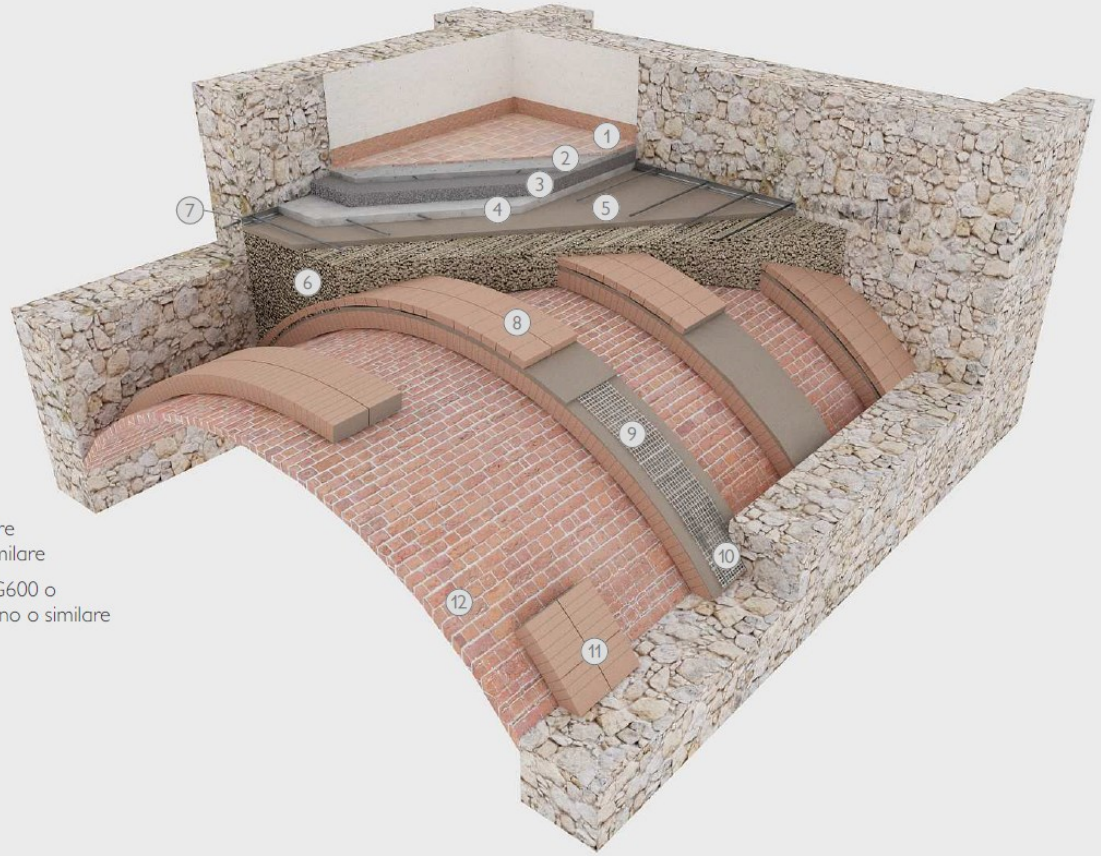


FRCM pier and column flexural and shear strengthening and confinement

MASONRY VAULTS. MULTI-LAYER STIFFENING AND STRENGTHENING

CONSOLIDAMENTO DELLE VOLTE A BOTTE CON MATTONI IN FOLIO MEDIANTE REALIZZAZIONE DI ARCHI DI RINFORZO MULTISTRATO

1. Finitura superficiale
2. Massetto sotto-pavimentazione realizzato mediante calce naturale NHL 3.5 tipo BioCalce Massetto o similare
3. Massetto alleggerito porta-impianti
4. Soletta in FRC (Fiber Reinforced Concrete)
5. Strato di livellamento realizzato mediante un impasto di calce naturale NHL 3.5 tipo BioCalce Massetto ed argilla espansa tipo Leca o similari
6. Riempimento alleggerito realizzato con argilla espansa
7. Cordolo in acciaio L 60x60x8 connesso alla muratura mediante barre Ø16/40 inghisate con malta di calce idraulica naturale NHL 3.5
8. Mattoni pieni posti di piatto
9. Fascia di rinforzo in fibra di acciaio galvanizzato tipo GeoSteel G600 o similare applicata con malta di pura calce naturale NHL 3.5 tipo GeoCalce Fino o similare
10. Connettori meccanici a fiocco in fibra di acciaio galvanizzato tipo GeoSteel G600 o similare inghisati tramite malta fluida di pura calce naturale tipo GeoCalce Fino o similare
11. Arco di rinforzo in mattoni pieni posti a coltello
12. Volta a botte esistente con mattoni pieni posti in folio



MASONRY VAULTS. SINGLE-LAYER STRENGTHENING

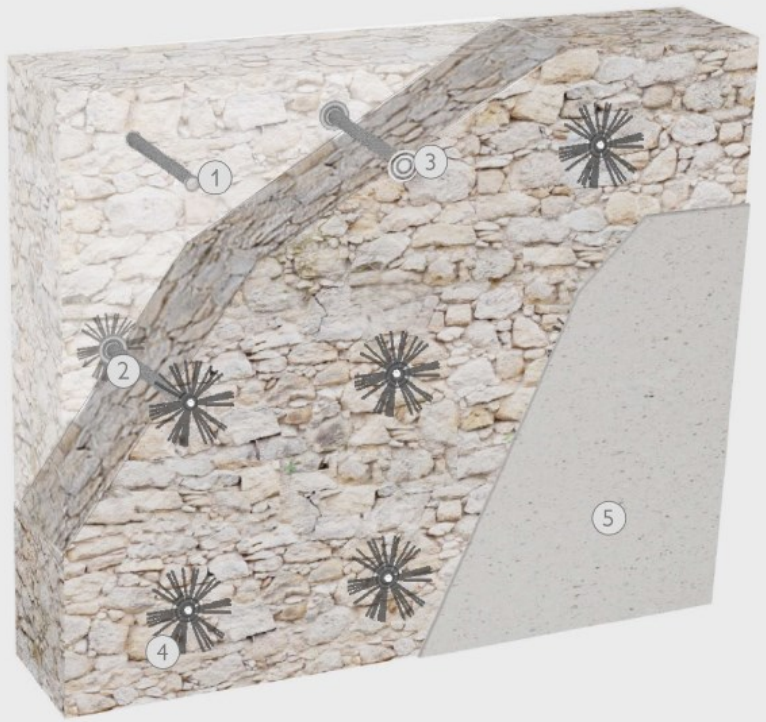
RINFORZO VOLTE A CROCIERA CON FIBRE IN ACCIAIO E MALTA DI CALCE IDRAULICA NATURALE

1. Finitura superficiale
2. Massetto sotto-pavimentazione realizzato mediante calce naturale NHL 3.5 tipo BioCalce Massetto o similare
3. Riempimento alleggerito
4. Soletta in FRC
5. Barre Ø16/40 inghisate nella muratura con malta di calce idraulica naturale NHL 3.5
6. Cordolo in acciaio L 60x60x8
7. Strato di livellamento realizzato mediante un impasto di calce naturale NHL 3.5 tipo BioCalce Massetto ed argilla espansa tipo Leca o similari
8. Riempimento alleggerito
9. Fascia di rinforzo in fibra di acciaio galvanizzato tipo GeoSteel G600 o similare inghisata tramite malta fluida di pura calce naturale tipo GeoCalce Fluido o similare
10. Connettori meccanici a fiocco in fibra di acciaio galvanizzato tipo GeoSteel G600 o similare inghisati tramite malta fluida di pura calce naturale tipo GeoCalce Fluido o similare
11. Volta a crociera esistente con mattoni pieni

THREE-LEAF MASONRY WALLS' STRENGTHENING

INSERIMENTO DIFFUSO DI DIATONI ARTIFICIALI A FIOCCO IN FIBRA DI ACCIAIO GALVANIZZATO E DI INIEZIONI DI MALTA DI CALCE IDRAULICA NATURALE NHL3.5

1. Fori utilizzati per l'inserimento dei diatoni artificiali e per le iniezioni di malta fluida tipo GeoCalce Fluido o similare
2. Diatoni artificiali a fiocco in fibra di acciaio galvanizzata tipo GeoSteel G600 o similare
3. Tassello di chiusura del diatono tipo Iniettore & Connettore GeoSteel o similare
4. Sfioccatura delle fibre alle estremità del connettore per consentire l'ottimale ancoraggio al paramento
5. Intonaco di finitura



FASI DI MONTAGGIO

Fase I: esecuzione del foro

Esecuzione dei fori sulla parete tramite strumenti a carotaggio continuo; pulire i fori con aria compressa per asportare polveri e detriti residui.

Fase II: inserimento diatono

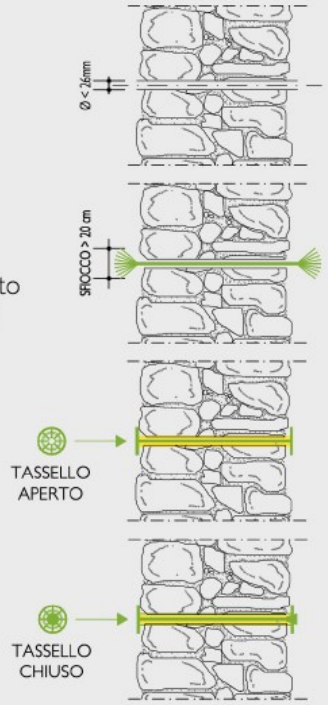
Inserimento dei **diatoni artificiali a fiocco in fibra di acciaio** galvanizzato ad altissima resistenza tipo GeoSteel G600 o similare

Fase III: inserimento tassello

Inserimento del **tassello aperto** per sfioccare il diatono e permetterne l'ancoraggio

Fase IV: iniezioni di malta fluida

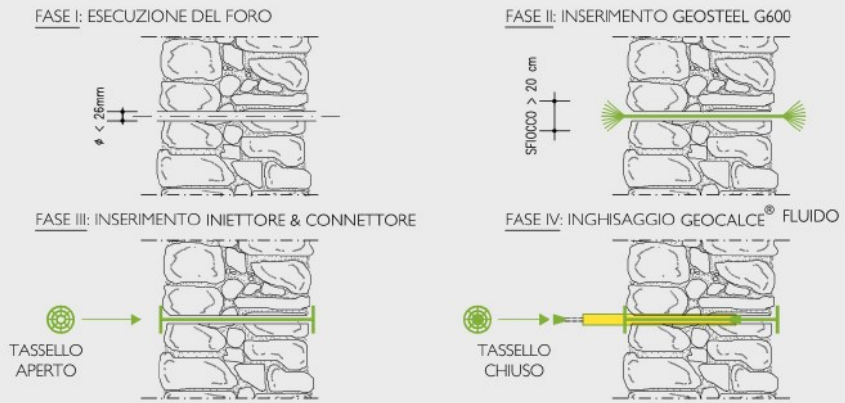
Iniezione di malta fluida tipo GeoCalce Fluido o similare per **intervento combinato di consolidamento della muratura** ed inghisaggio dei diatoni artificiali

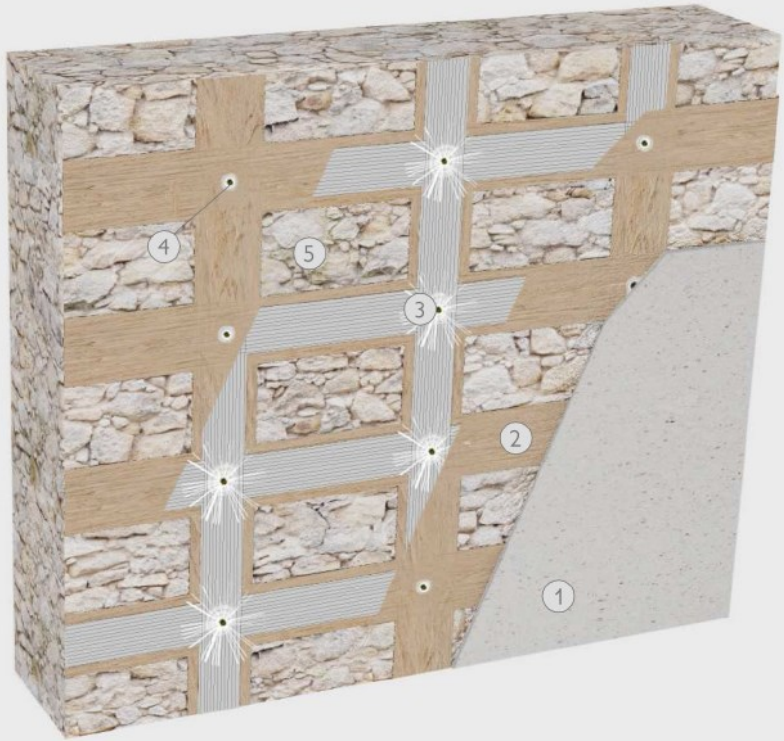


THREE-LEAF MASONRY WALLS' STRENGTHENING

CONSOLIDAMENTO DEI MASCHI MURARI MEDIANTE FIBRE IN ACCIAIO E MALTA DI CALCE IDRAULICA NATURALE NHL3.5

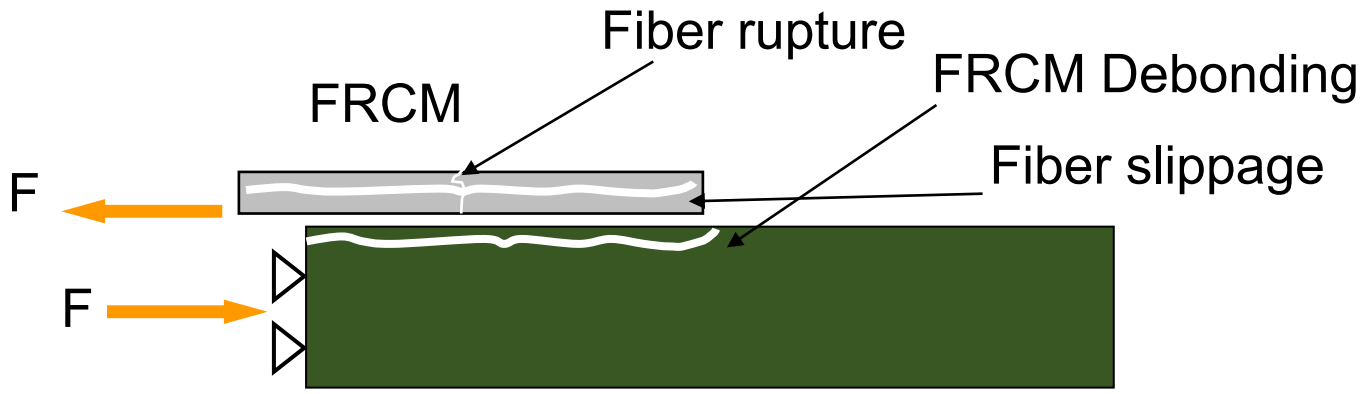
1. Eventuale intonaco da demolire e ricostruire dopo l'intervento di rinforzo
2. Fascia di rinforzo in fibra di acciaio galvanizzato tipo GeoSteel G600 o similare applicata con malta di pura calce naturale NHL 3.5 tipo GeoCalce Fino o similare
3. Diatoni a fiocco GeoSteel G600 o similare inghisati con malta colabile GeoCalce Fluido o similare
4. Iniezioni di malta fluida tipo GeoCalce Fluido o similare all'interno degli stessi fori utilizzati per l'inserimento dei diatoni
5. Muratura esistente





DESIGN BASES

- The FRCM composite material bonded to surfaces masonry members may be used to enhance the elements' capacity by acting as external tension reinforcement.
- Failure modes:
  - Masonry crushing in compression
  - Debonding of the FRCM from the masonry substrate (FRCM debonding)
  - Slippage of the fiber mesh within the cementitious matrix

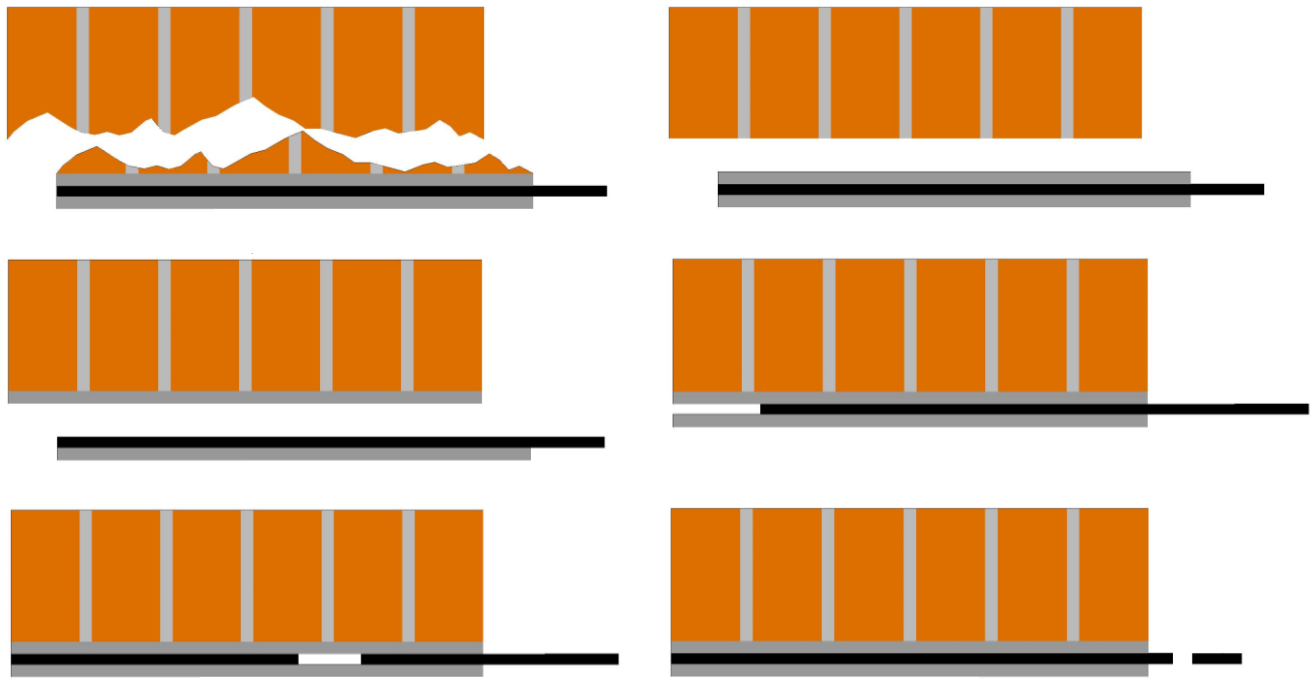


Fmax = min (Fiber rupture, FRCM debonding, fiber slippage)

FRCM STRENGTHENING

Bond Test

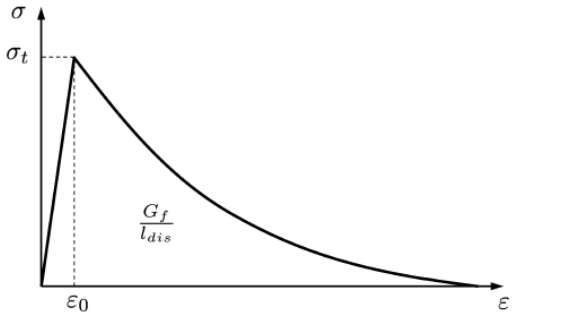
- Masonry: **Splitting to brick and mortar**
- Matrix:
  - **Tension – Rankine**
  - **Compression – Lubliner**
- Fiber: **Tension – Rankine**



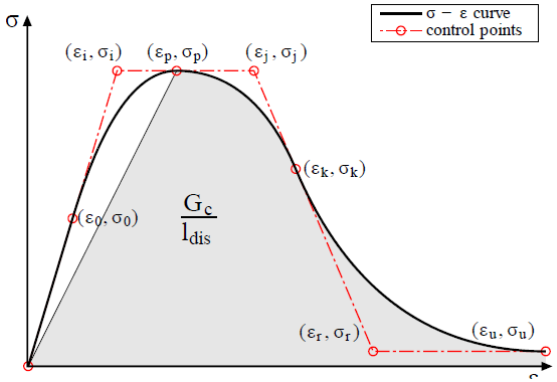
FRCM STRENGTHENING

Bond test - Nonlinear constitutive law fibers

- Tension – Rankine
- Compression – Lubliner



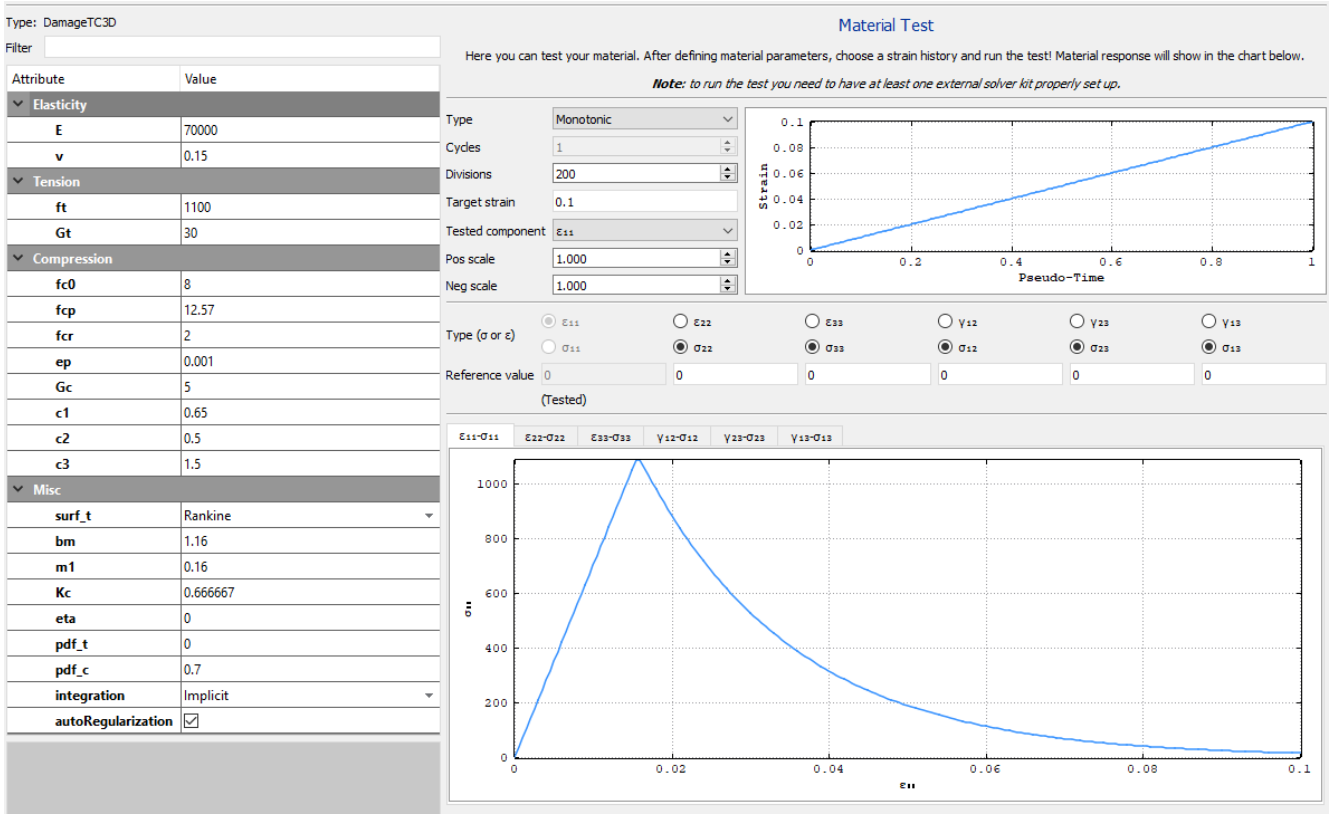
Tension



Compression

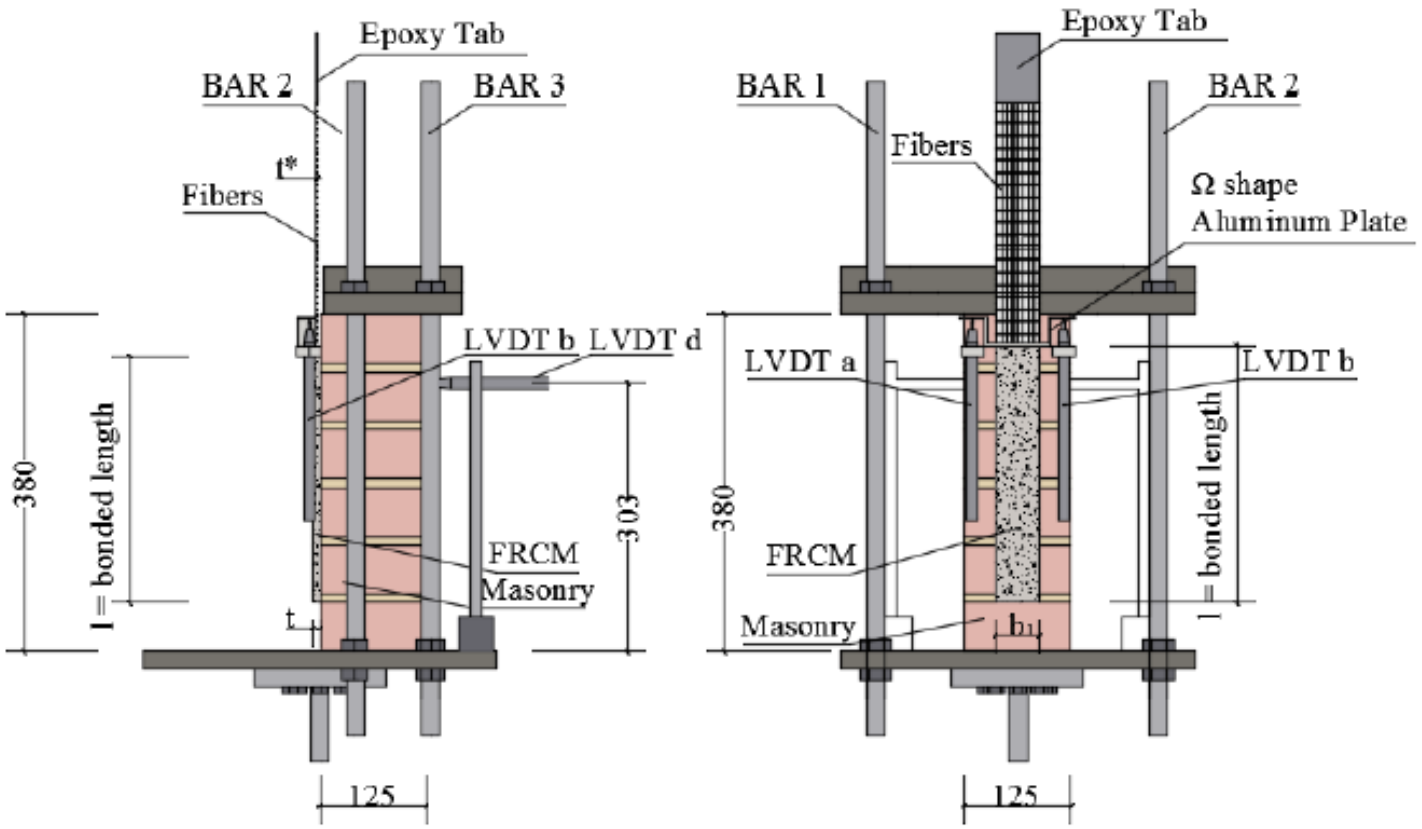
Physical Properties

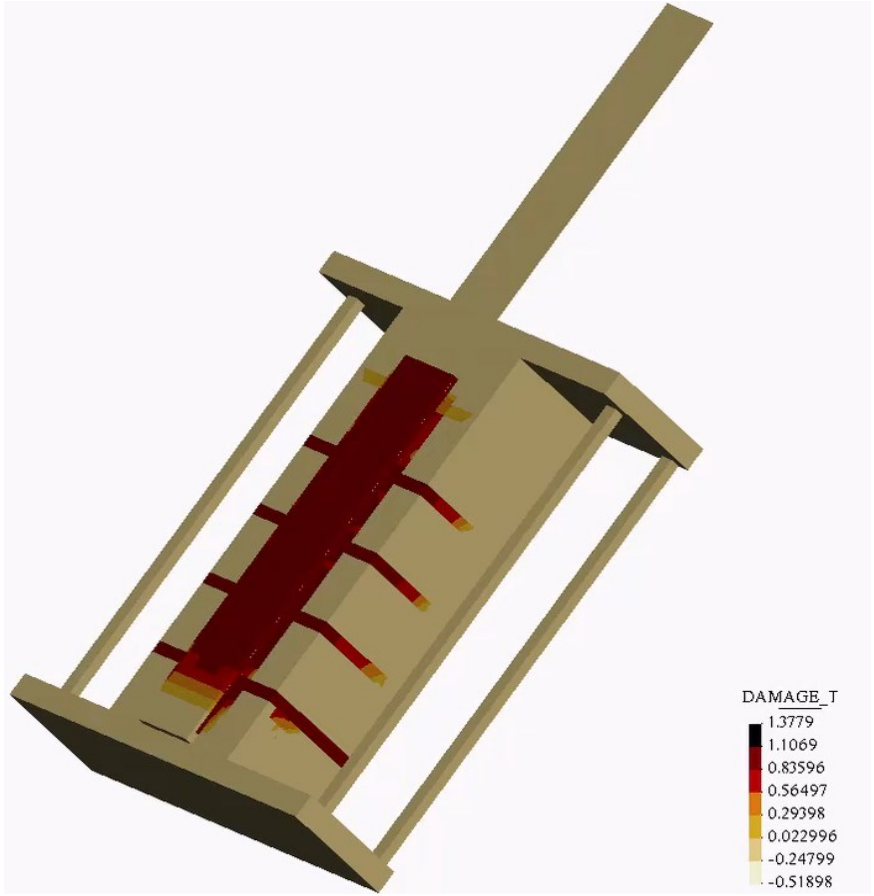
fiber basalt



FRCM STRENGTHENING

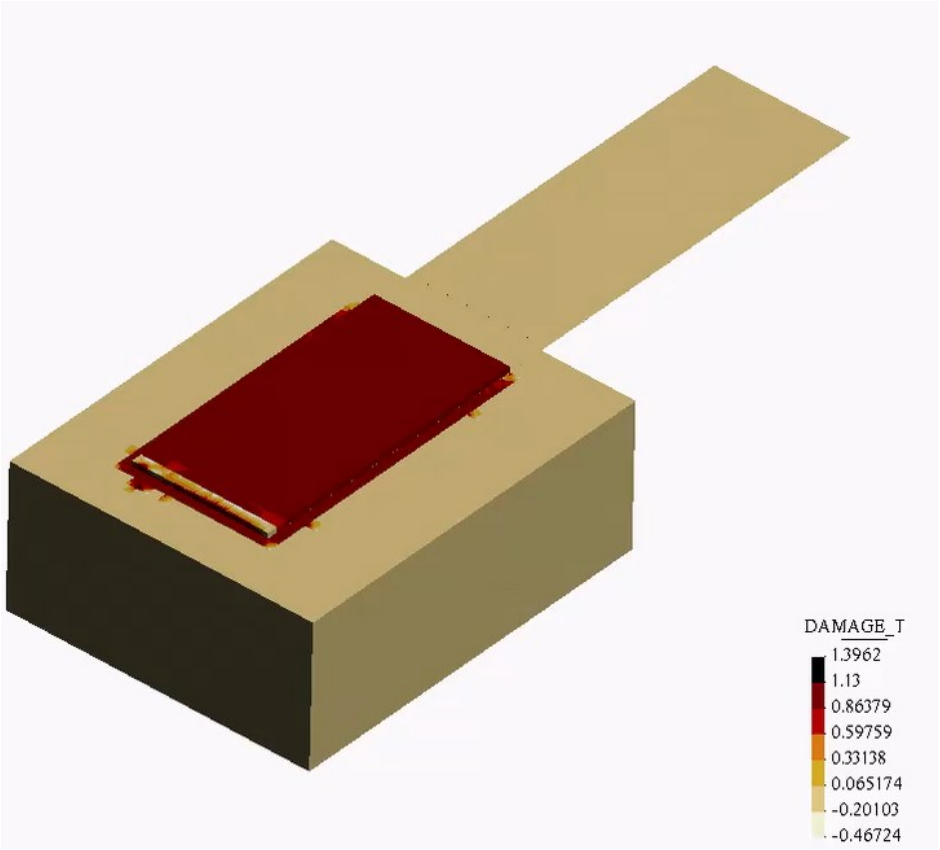
Bond test – University of Bologna





FRCM STRENGTHENING

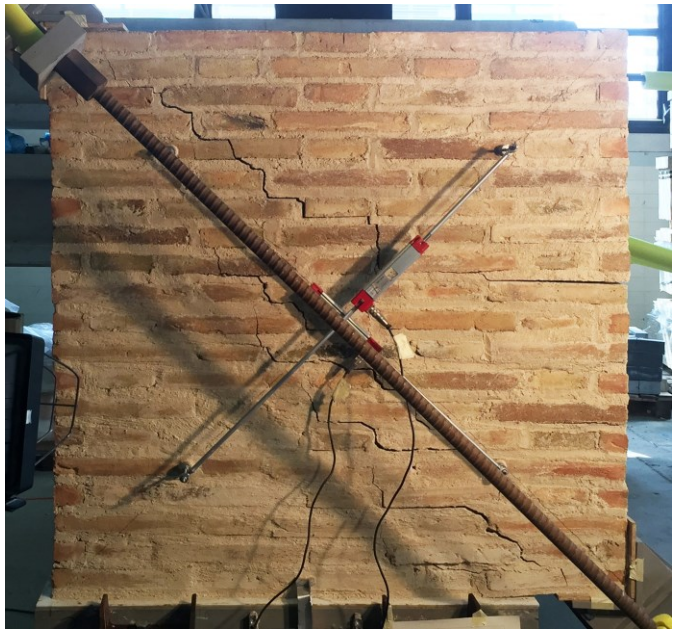
Bond test – In collaboration with Pontifical Catholic University of Perù – prof. Nicola Tarque

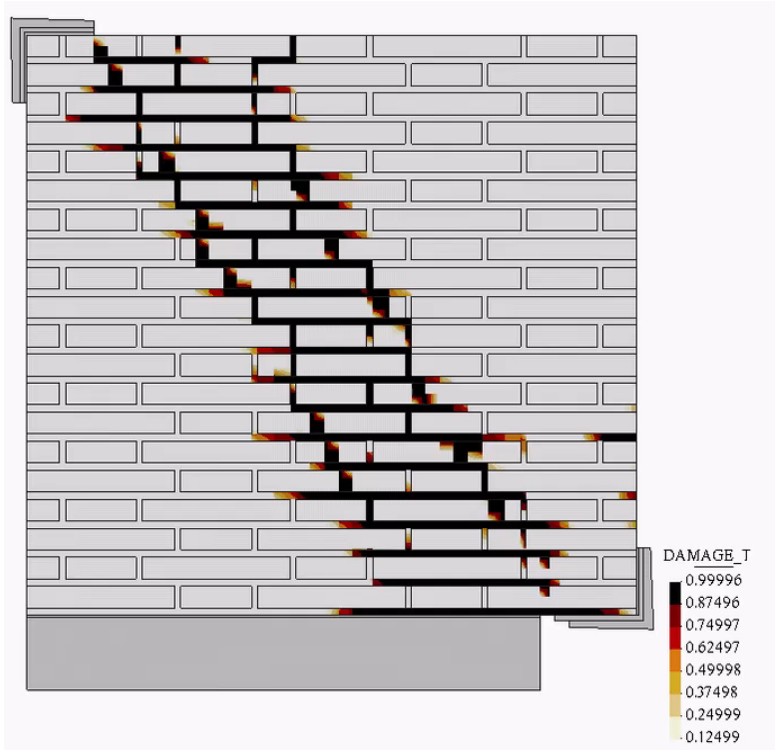


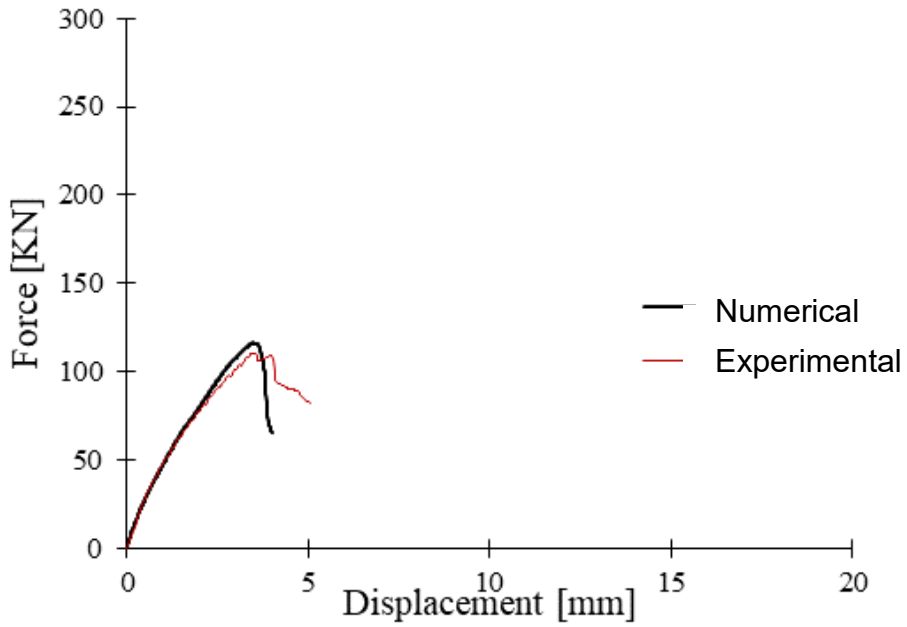
FRCM STRENGTHENING

In-plane shear behaviour by diagonal compression testing of brick masonry walls strengthened with basalt and steel textile reinforced mortars

In collaboration with Universitat Politecnica de Catalunya – prof. Luca Pelà

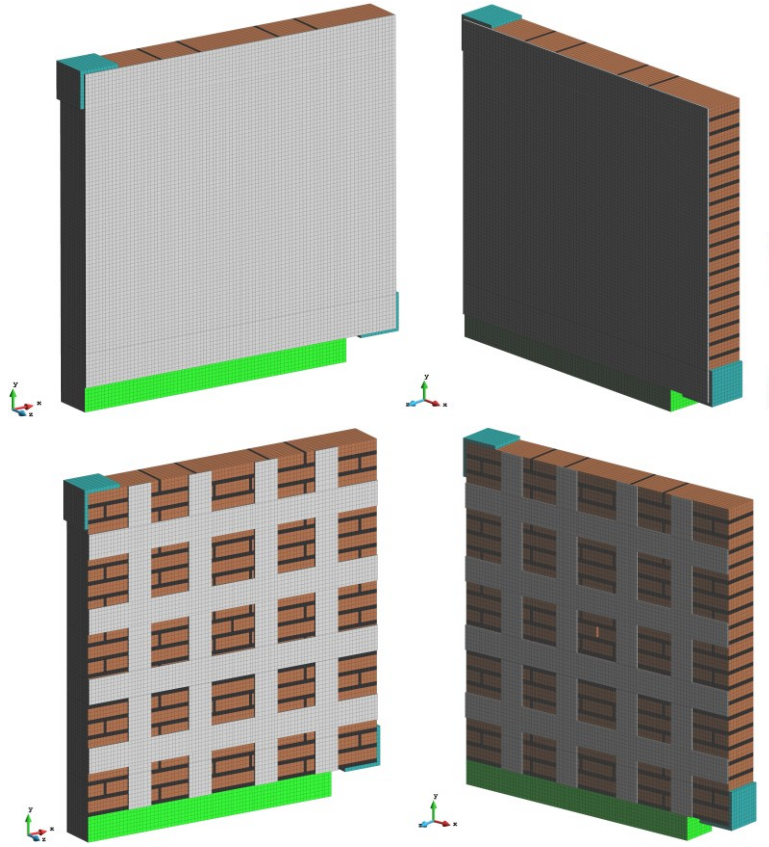






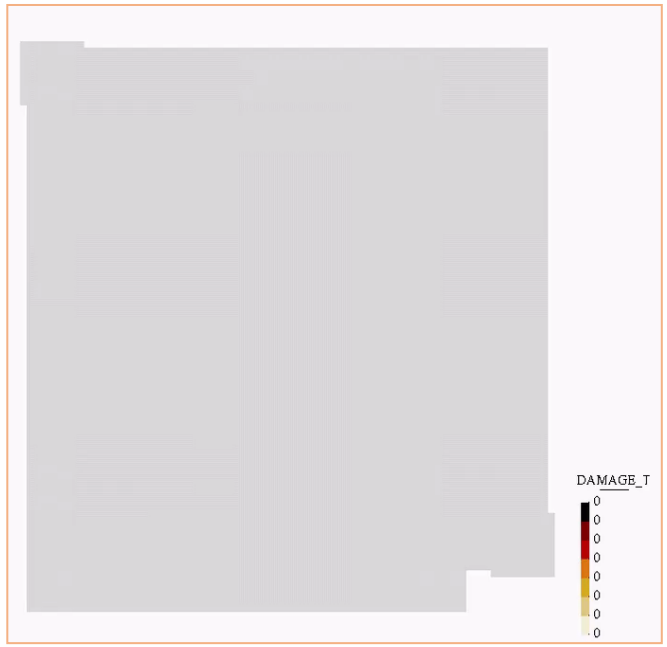
FRCM STRENGTHENING

In-plane shear behaviour by diagonal compression testing of brick masonry walls strengthened with basalt and steel textile reinforced mortars

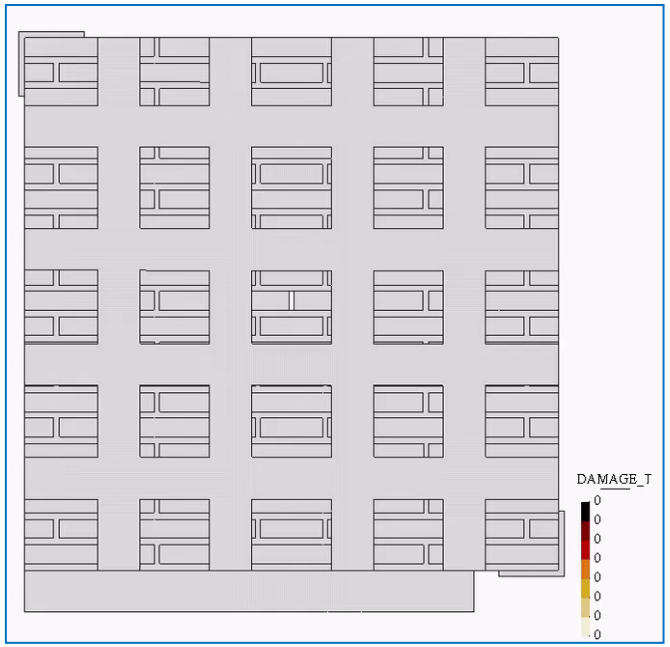


FRCM STRENGTHENING

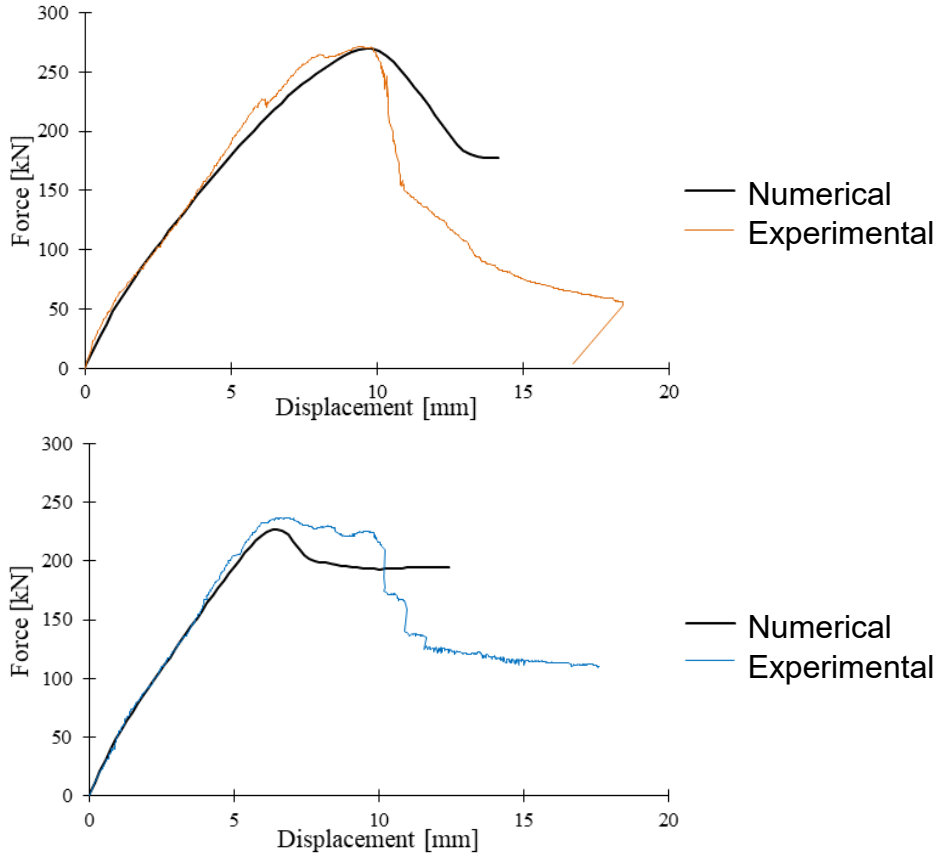
In-plane shear behaviour by diagonal compression testing of brick masonry walls strengthened with basalt and steel textile reinforced mortars



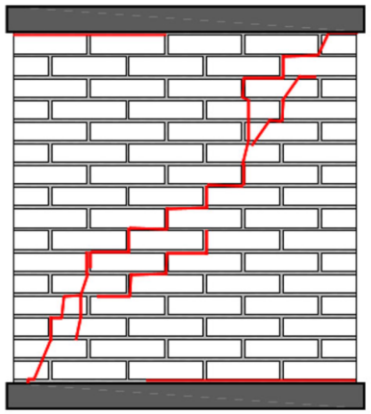
wall with basalt

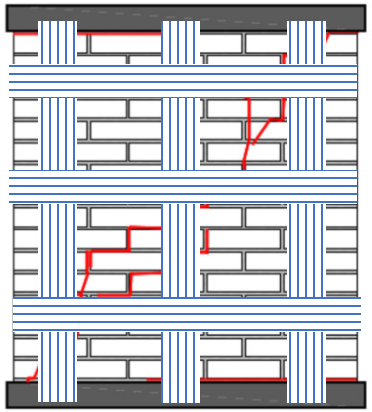


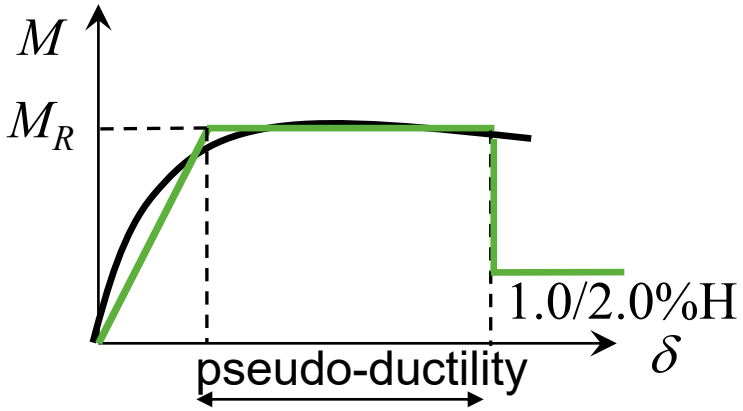
wall with steel textile

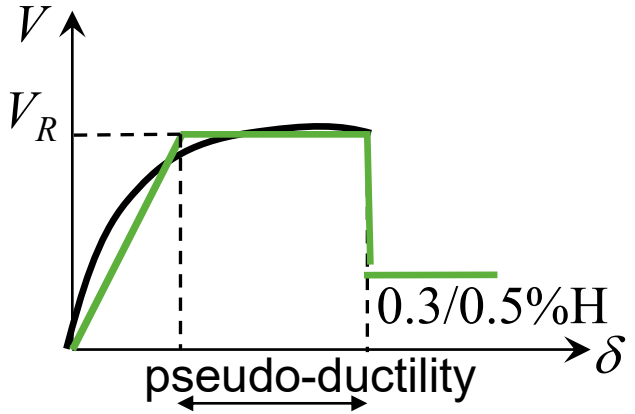


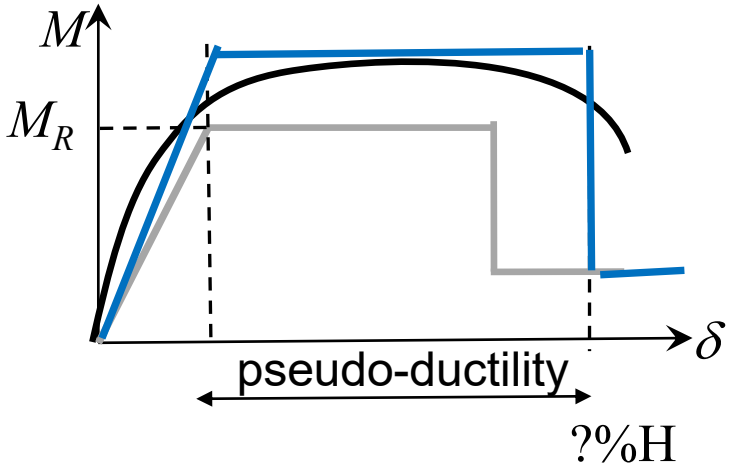
NONLINEAR BEHAVIOR OF STRENGTHENED ELEMENTS

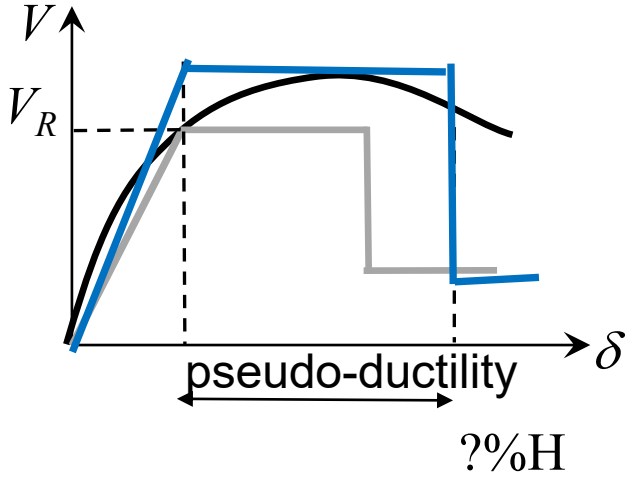








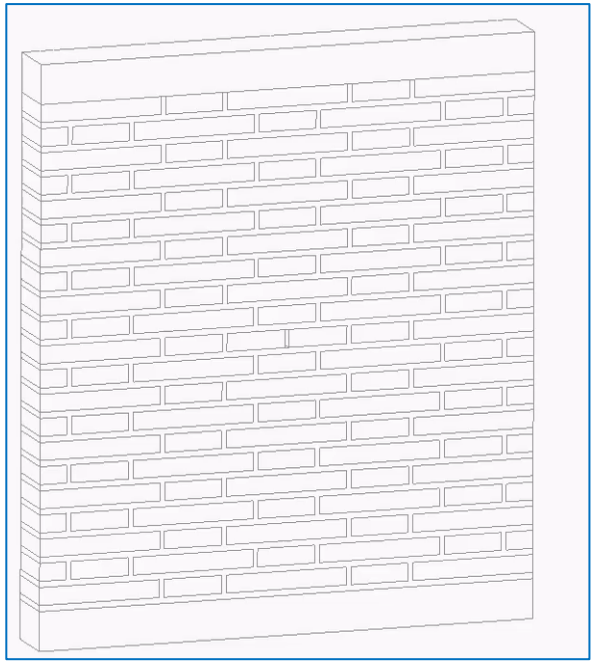


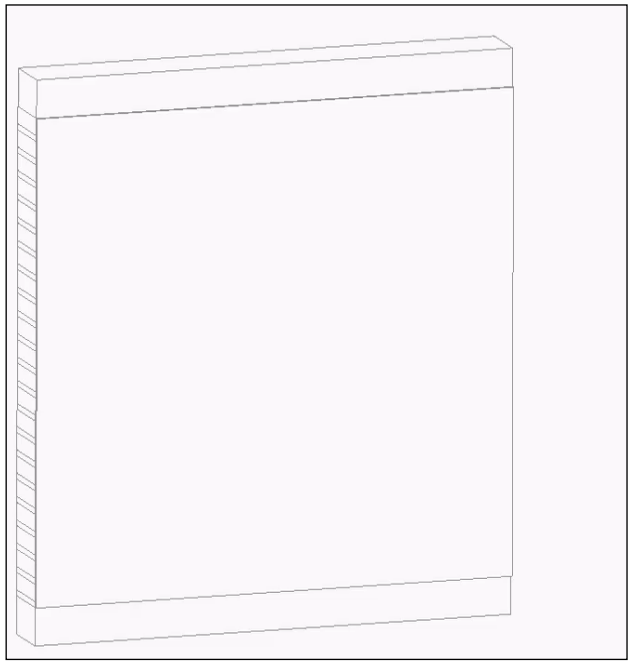


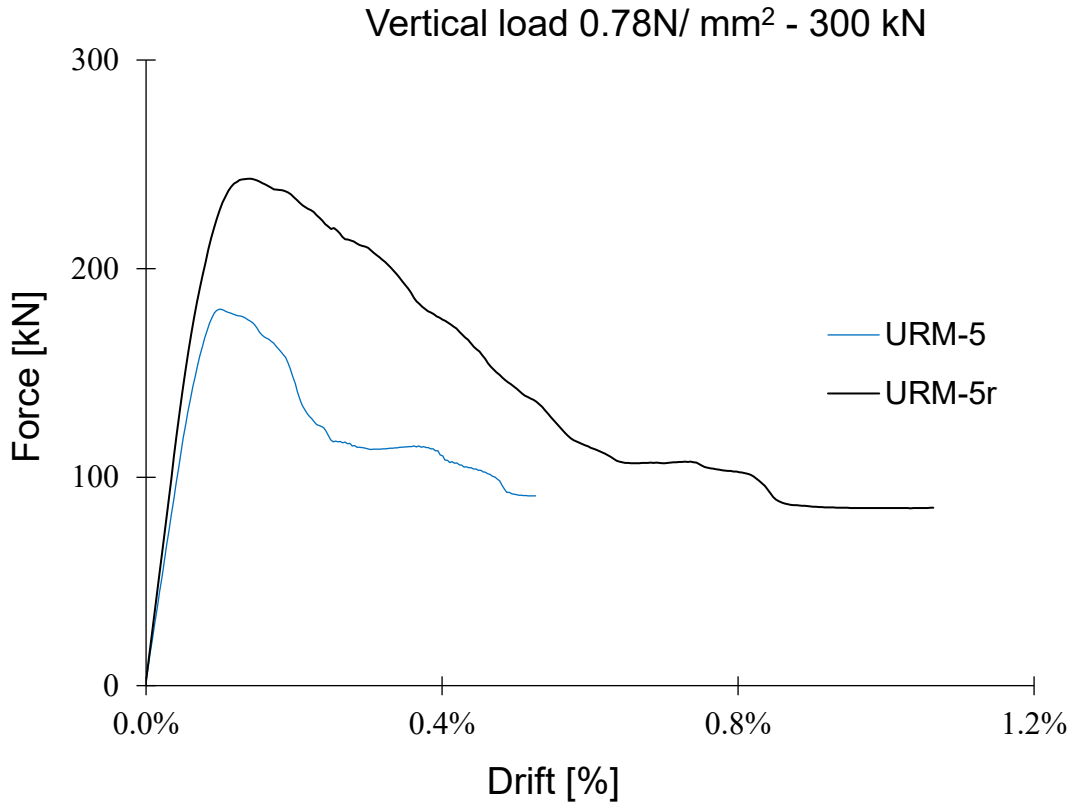
In many cases it is possible to modify the failure mode from shear to flexural

ADVANCED ANALYSIS OF MASONRY BUILDINGS

Shear-compression masonry URM and brick masonry walls strengthened with basalt







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- **CONCLUSIONS**

CONCLUSIONS

- Advanced nonlinear numerical analyses can predict accurately the seismic response of existing and strengthened masonry structures and should be used to evaluate the vulnerability of heritage structures
- The widespread application of these procedures applied to unreinforced and strengthened structures will clarify the still unsolved doubts, this can only be done through a strong integration between research and profession.
- However, in our opinion, research has so far failed to resolve the needs of the professional field. Most of the research efforts are in the direction of the development of elements, constitutive laws, analysis methods and increasingly sophisticated models. Often, the goal is the development concentrate on the calibration of sophisticated materials/elements on simple structures or elements.
- We are convinced that, research should focus on the study of sophisticated structures, it is necessary to acquire more experience in explaining the behavior of more complex and real structures that present needs and problems that are encountered daily in the professional field.

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Thank you!

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