

University of Chieti-Pescara

Ph.D. Program in Engineering Science

A.Y. 2025–26

# Non-linear Analyses of Structures

## Part 4: Non-linear Analyses of Masonry Structures

Course syllabus and teaching programme

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<b>Dates</b>	Wednesday, July 1st and Thursday, July 2nd, 2026
<b>Time and venue</b>	2:00–6:00 pm, Room 38
<b>Contact hours</b>	8 hours
<b>Language</b>	English

**Course focus.** This short Ph.D.-level module introduces the nonlinear modelling of masonry structures and masonry infills, with emphasis on mechanical behaviour, material and interface nonlinearity, modelling strategies, and interpretation of the governing failure mechanisms.

## Course description

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Masonry is a heterogeneous, anisotropic, and strongly typology-dependent structural material. Its nonlinear response is governed by the interaction among units, mortar joints, interfaces, construction patterns, boundary conditions, and pre-existing damage. This course addresses how these features can be translated into numerical models for the nonlinear analysis of masonry structures and masonry infills.

The module moves from mechanical interpretation to modelling practice. It first discusses fabric, scale effects, material variability, interlocking, in-plane and out-of-plane mechanisms. It then introduces the mechanical properties of units, mortar, interfaces, and masonry assemblages, including composite behaviour in compression and tension, failure surfaces, and empirical or code-based estimates of mechanical parameters. The core part of the course is devoted to modelling strategies, ranging from equivalent-frame macroelements and spring models to micromodelling, discrete-element and geometry-based approaches. The final part focuses on masonry infills in reinforced-concrete frames, including equivalent-strut idealizations, contact effects, and infill-induced shear demand.

## Learning objectives

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At the end of the course, participants are expected to be able to:

1. identify the main sources of nonlinear behaviour in masonry, including cracking, sliding, crushing, rocking, interlocking, and out-of-plane instability;
2. interpret the role of masonry typology, fabric, scale, material variability, and workmanship in structural response and model calibration;
3. describe the mechanical properties required for nonlinear masonry modelling at component, interface, and assemblage scales;
4. compare analytical, empirical, code-based, and experimental approaches for estimating masonry strength, stiffness, fracture energy, and interface parameters;
5. select a modelling strategy consistent with the scale of analysis, available information, computational cost, and target failure mechanisms;
6. critically discuss the assumptions and limitations of equivalent-frame models, macroelements, spring models, micromodels, discrete-element models, and geometry-based approaches;
7. interpret the influence of masonry infills on reinforced-concrete frames and identify the key modelling parameters of equivalent-strut and contact-based formulations.

## Prerequisites and scope

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### Recommended prerequisites

Participants should be familiar with structural mechanics, basic finite-element modelling, seismic behaviour of structures, and the fundamentals of nonlinear structural analysis. The course assumes that concepts such as stiffness, strength, plasticity, damage, cyclic degradation, and nonlinear static or dynamic analysis have already been introduced elsewhere in the broader course.

### Topics intentionally not covered

The course does not provide a full treatment of:

- fundamentals of nonlinear analysis algorithms and solution strategies;
- detailed code checks and design or assessment procedures;
- vulnerability-assessment workflows at building-stock or territorial scale;
- retrofit and strengthening design;
- confined, reinforced, or prestressed masonry systems.

## Course structure and workload

Chapter	Title	Core theme	Indicative weight
1	Mechanical behavior of masonry	Fabric, mechanisms, typological variability, interlocking, and nonlinear response.	5%
2	Nonlinear mechanical and constitutive properties	Strength, stiffness, cracking, friction, crushing, anisotropy, degradation, and parameter calibration.	35%
3	Numerical modelling strategies	Micro-, meso-, macro-, equivalent-frame, spring, contact, DEM, and geometric-based approaches.	45%
4	Masonry infills	Modelling approaches and interaction with reinforced-concrete frames.	15%

## Detailed teaching programme

### Day 1 - Wednesday, July 1st, 2026

Time	Module	Topics
2:00–2:20 pm	Course framing	Scope of the module, expected prerequisites, limits of the course, and overview of the four chapters.
2:20–3:00 pm	Mechanical behaviour of masonry	Historical development, global relevance of masonry buildings, typological diversity, scale effects, anisotropy, and the statement that “masonry” is not a single material class.
3:00–3:40 pm	Masonry components and fabric	Units, mortar, bed and head joints, artificial and natural units, construction patterns, single- and multi-leaf walls, rubble-filled sections, interlocking, and through-stones.
3:40–4:00 pm	Break	Informal discussion.
4:00–4:45 pm	Failure mechanisms	In-plane mechanisms: diagonal cracking, sliding shear, toe crushing, rocking and flexural response. Out-of-plane mechanisms: overturning, vertical bending, two-way bending, and local instability.
4:45–6:00 pm	Nonlinear mechanical and constitutive properties	Unit, mortar, interface, and assemblage properties; moisture and scale effects; composite behaviour in compression and tension; interface failure, friction, cap-type domains, analytical strength models, code-based estimates, biaxial behaviour, and Masonry Quality Index.

**Day 2 - Thursday, July 2nd, 2026**

<b>Time</b>	<b>Module</b>	<b>Topics</b>
2:00–3:00 pm	Equivalent-frame and macroelement models	Pier-spandrel-node idealization; advantages and limitations of equivalent frames; beam-based macroelements; flexural, shear, sliding, and shear-flexure interaction models; role of spandrels and floors.
3:00–3:40 pm	Spring-based and 3D macroelements	One-dimensional, two-dimensional, and three-dimensional spring models; flexural, rocking, sliding, and diagonal shear mechanisms; out-of-plane response, rocking dynamics, and wall-to-wall connections.
3:40–4:00 pm	Break	Informal discussion.
4:00–4:40 pm	Micro-, discrete-, and geometry-based models	Detailed and simplified micromodelling, interfaces, Rankine and plastic-damage criteria, discrete-element modelling, contact, block separation, large displacements, and thrust-line stability.
4:40–5:15 pm	Structural performance and demand parameters	Global and local assessment concepts, capacity models, chord rotation, inter-storey drift, element-scale and structure-scale engineering demand parameters, and interpretation of nonlinear-analysis outputs.
5:15–6:00 pm	Masonry infills in RC frames	Infill-frame interaction, additional shear demand, failure modes, equivalent single-strut macro-models, strut width, nonlinear strut laws, contact length, and column shear demand.

**Chapter-level content****Chapter 1 - Mechanical behavior of masonry**

- Masonry as a historical and contemporary structural material.
- Masonry typologies: artificial units, natural units, regular, irregular, rubble, and multi-leaf walls.
- Anisotropy, scale, construction patterns, workmanship, and material variability.
- In-plane and out-of-plane failure mechanisms.
- Threefold view of masonry structures: load-bearing walls, arches/vaults, and infill panels.
- Three assessment phases: historical-critical analysis and inspection, material testing, and structural analysis.

**Chapter 2 - Nonlinear mechanical and constitutive properties**

- Mechanical properties of units, mortar, interfaces, and masonry assemblages.
- Experimental characterization and uncertainty: compression, tension, shear, triplets, flat-jack, shove, and sonic tests.
- Interface behaviour: opening, sliding, friction, dilatancy, cap behaviour, fracture energy, and softening.
- Composite behaviour in axial compression and tension; unit-mortar interaction and lateral confinement effects.

- Analytical and empirical estimates of masonry compressive strength, tensile strength, Young's modulus, shear modulus, and fracture energy.
- Masonry Quality Index and empirical correlations for existing masonry typologies.

### Chapter 3 - Numerical modelling strategies

- Equivalent-frame idealization and identification of piers, spandrels, and rigid nodes.
- Beam macroelements, force-based elements, lumped and distributed inelasticity, shear hinges, and strength-domain formulations.
- Spring-based macroelements for flexure, rocking, sliding, and diagonal shear.
- Three-dimensional macroelements for in-plane and out-of-plane interaction, rocking response, and wall-to-wall connections.
- Micromodelling: detailed and simplified approaches, interfaces, continuum damage and plastic-damage models, Rankine and Lubliner-type criteria.
- Discrete-element and geometry-based models for discontinuities, block separation, large displacements, rocking, and thrust-line stability.
- Performance models and engineering demand parameters for nonlinear static and dynamic analyses.

### Chapter 4 - Masonry infills

- Mechanical role of infills in reinforced-concrete frames and consequences for lateral stiffness, strength, and failure mechanisms.
- Infill and frame perspectives: frame failure, sliding shear, diagonal cracking, diagonal compression, and corner crushing.
- Equivalent single-strut models: geometry, strut width, compression-only behaviour, axial stiffness, strength, and post-peak degradation.
- Contact between infill and frame, contact length, shear decomposition, frictional transfer, and infill-induced column shear demand.
- Comparison between macro- and micromodelling strategies for infilled frames.

## Recommended references

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### Books and reports

- Lourenco, P. B., and Gaetani, A. (2022). *Finite Element Analysis for Building Assessment: Advanced Use and Practical Recommendations*. Routledge.
- Ghiassi, B., and Milani, G. (eds.) (2019). *Numerical Modeling of Masonry and Historical Structures: From Theory to Application*. Woodhead Publishing, Elsevier.
- Angelillo, M. (ed.) (2014). *Mechanics of Masonry Structures*. CISM International Centre for Mechanical Sciences, Vol. 551, Springer.
- Abrams, D. P., and Calvi, G. M. (eds.) (1994). *Proceedings of the U.S.-Italian Workshop on Guidelines for Seismic Evaluation and Rehabilitation of Unreinforced Masonry Buildings*. NCEER-94-0021.

### Selected papers and theses

- Lourenco, P. B. (1996). *Computational Strategies for Masonry Structures*. Ph.D. thesis, Delft University of Technology.
- Cattari, S., Calderoni, B., Calio, I., Camata, G., de Miranda, S., Magenes, G., Milani, G., and Saetta, A. (2022). "Nonlinear modeling of the seismic response of masonry structures: critical

review and open issues towards engineering practice.” *Bulletin of Earthquake Engineering*, 20, 1939–1997.

- D’Altri, A. M., Sarhosis, V., Milani, G., Rots, J., Cattari, S., Lagomarsino, S., Sacco, E., Tralli, A., Castellazzi, G., and de Miranda, S. (2019). “A review of numerical models for masonry structures.” In *Numerical Modeling of Masonry and Historical Structures*, Elsevier, 3–61.
- Lagomarsino, S., Penna, A., Galasco, A., and Cattari, S. (2013). “TREMURI program: An equivalent frame model for the nonlinear seismic analysis of masonry buildings.” *Engineering Structures*, 56, 1787–1799.
- Addessi, D., Mastrandrea, A., and Sacco, E. (2014). “An equilibrated macro-element for nonlinear analysis of masonry structures.” *Engineering Structures*, 70, 82–93.
- Chen, S.-Y., Moon, F. L., and Yi, T. (2008). “A macroelement for the nonlinear analysis of in-plane unreinforced masonry piers.” *Engineering Structures*, 30(8), 2242–2252.
- Calio, I., Marletta, M., and Panto, B. (2012). “A new discrete element model for the evaluation of the seismic behaviour of unreinforced masonry buildings.” *Engineering Structures*, 40, 327–338.
- Vanin, F., Penna, A., and Beyer, K. (2020). “A three-dimensional macroelement for modelling the in-plane and out-of-plane response of masonry walls.” *Earthquake Engineering and Structural Dynamics*, 49, 1365–1387.
- Asteris, P. G., Antoniou, S. T., Sophianopoulos, D. S., and Chrysostomou, C. Z. (2011). “Mathematical macromodeling of infilled frames: state of the art.” *Journal of Structural Engineering*, 137(12), 1508–1517.
- Saneinejad, A., and Hobbs, B. (1995). “Inelastic design of infilled frames.” *Journal of Structural Engineering*, 121(4), 634–650.

## Expected teaching outcome

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The course is intended to provide a structured conceptual map of nonlinear masonry modelling. Rather than focusing on a single software or code procedure, it emphasizes the connection between physical mechanisms, material parameters, modelling assumptions, numerical idealizations, and interpretation of nonlinear-analysis results. Participants should leave the module with the ability to select, justify, and critically evaluate modelling strategies for masonry structures and masonry-infilled frames.