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Survey on non-linear cyclic responses of Unreinforced Masonry buildings by means of commercial finite-element codes

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Abstract

This work presents a comparison about the nonlinear cyclic response of unreinforced masonry structures obtained by using commercial calculation codes and on the base of the type of modeling approaches currently available. In particular, several elasto-plastic modeling methodologies are considered, representative of a good part of the state of the art for this type of construction: mechanical-based concentrated plasticity macro-element (Tremuri), macro-element with diffuse fiber-based plasticity for flexure and concentrated springs for shear (SeismoStruct) and macro-element with phenomenological-based concentrated plasticity (NextFEM Designer). The purpose of the present research is to evaluate the ability of the different codes to represent the proper hysteretic response of masonry structures. To this aim, several experimental tests from literature are analyzed and compared; two different masonry panels, characterized by different resistant mechanisms, and an entire perforated wall have been studied through nonlinear cyclic static analyses. The reported comparison, mainly focused on the numerical cyclic behaviour exhibited by each computer program, is conducted on the basis of the path of the cycles obtained and on the amount of dissipated energy.

Keywords: Nonlinear seismic analysis; cyclic response; unreinforced masonry; finite element modeling; reliability of computational codes

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1. Introduction

In recent years, a major research effort has been directed toward the development of numerical models capable of adequately predicting the seismic response of ordinary masonry structures. Actual performance of Unreinforced Masonry (URM) structures, especially in post-cracking phase, are treated with dedicated finite-element programs, in order to simulate a proper response. This is mainly due to the strong dependence of URM behaviour of piers from the actual axial load, that changes during analyses and clearly affects also design checking, as outlined by Rinaldin et al. (2019).

In European earthquake-prone areas, designers uses purposely developed software to handle non-linear analysis. In particular, the major differences between software packages are related to modelling strategy and quality of cyclic response. Many modelling approaches have taken place over time, ranging from Equivalent Frame modelling (EF) to usage of macroelement to represent an entire panel. In EF approach, beam elements are used for piers and spandrels, and rigid links to represent nodal zones. Conversely, macroelements have been implemented in software packages in many flavors, as listed in Marques & Lourenço (2014).

Push-over analysis is typically the first non-linear approach, which is able to estimate capacity of a URM structure and also ductility request or behaviour factor. This approach is the most prominent, as the finite-element solver is not required, in this case, to reproduce the cyclic behaviour but the backbone curve only.

The purpose of the present work is to evaluate the quality of numerical simulation of non-linear cyclic behavior of masonry structures. Results will be validated through experimental tests data and the different calculation codes will be compared.

The issue of assessing the reliability of software is of great interest, especially for designers. This is emphasized in Italian regulations for structures MIT (2018), which indicates that it is the responsibility of the designer to "check the reliability of the codes used, to review the documentation accompanying the software to assess its reliability and suitability for the specific case and to make a reasoned judgment of the reliability of the results provided by the software".

It has to be pointed out that several authors investigated the quality of numerical simulation of URM. Cattari et al. (2017, 2019) and ReLUIS (2020) focused on capacity curves obtained with different finite-element solvers, by using shared benchmarks to compare results. Calderoni et al. (2015) investigated the limits of EF approach in several software packages, by comparing capacity curves of façades. De Falco et al. (2017) statistically investigated non-linear results obtained by means of different software, excluding out-of-plane mechanisms.

Only a few software can simulate the cyclic behaviour; amongst all the available packages, only the ones having a purposely implemented cyclic law for masonry have been selected. Hence, comparison is limited to 3 software packages: Tremuri (Lagomarsino et al., 2013, Bracchi et al., 2021a,b), which uses a macro-element with mechanical-based concentrated plasticity; SeismoStruct (Seismosoft, 2020), a macro-element with diffuse fiber-based plasticity for flexure and concentrated shear springs; and NextFEM Designer (NextFEM, 2022), implementing a macro-element with phenomenological-based lumped plasticity. All the three software use a macro-element approach, even with different formulations.

Results of the analyses conducted on models, properly calibrated by means of experimental tests from literature. Firstly, the behavior of two individual wall panels tested by Anthoine et al. (1995), subject to different resistant mechanisms, has been numerically reproduced. Then, an entire masonry wall with a regular distribution of openings investigated in Magenes & Calvi (1997) has been analyzed. The validation process is carried out by performing cyclic nonlinear static analyses, reproducing the displacements imposed during the experimental tests. All the analysis have been conducted to investigate the in-plane response of macroelements.

2. Adopted software packages

The adopted software is briefly described in the following, with particular emphasis on the description of in-plane behaviour of URM implemented in each one. For URM buildings, the Italian code MIT (2019) proposes different expressions: (i) the Mohr-Coulomb criterion is commonly used for block masonry; (ii) the minimum value between Turnsek & Sheppard (1980) and Mann-Muller (1973) criteria is considered for brick or regular stone blocks; (iii) the Turnsek relationship criterion has to be used for irregular stone masonry

2.1. Tremuri

Tremuri adopts the equivalent frame method for the non-linear seismic analyses of URM buildings by means of a purposely developed macroelement. Structural elements (piers and spandrels) are implemented through non-linear beam models with concentrated plasticity springs. Such macroelement proposed in Lagomarsino et al. (2013) and in Penna et al. (2014), and later modified in Bracchi et al. (2021a, b), is formed by a 2-nodes element capable of representing the in-plane cyclic behaviour of a masonry panel, both for shear and flexural/crushing mechanisms. The element is ideally subdivided into three parts: a central body, only subjected to shear deformations, and two lateral interfaces, characterized by a distributed system of "zero-length" springs, subjected to axial displacements and rotations.

The Tremuri macroelement is a mechanical-based model and not a phenomenological one, despite the definition of some parameters that govern the nonlinearity in shear behaviour and the subsequent degradation of the strength. The cyclic deterioration may occur as a result of two mechanisms, that are simulated:

- the loss of shear strength, that in a Coulomb-macroscopical model tends to be the friction force only (the effect of the cohesion is progressively lost);
- the crushing at the corners due to the coupled axial and in-plane bending response.

2.2. SeismoStruct

SeismoStruct uses fiber approach to model the inelastic behaviour of the elements (Seismosoft, 2020).

The masonry element, implemented in the software and valid for both piers and spandrels, is a combination of two sub-elements:

- the "internal sub-element", given by a 3-dimensional force-based frame element with distributed plasticity and capable of simulating the axial-bending coupled behaviour;
- the "external links", used to simulate the shear behaviour, whose degrees of freedom are active in the translational directions for the in- and out-of-plane shear.

The sub-elements are in series connected, by ensuring shear and flexural internal equilibrium.

The internal sub-element behaviour is governed by the uniaxial stress-strain relationship of the masonry. Typically, the concrete confinement model is used to define the hysteretic behaviour as per law described in Mander et al. (1988) and Madas & Elnashai (1992). Seven parameters are needed to completely describe the mechanical characteristics of the material: compression strength, tension strength, Young's modulus, Poisson's ratio, peak deformation, slope of softening branch and weight density of masonry.

The shear strength evaluation is done on the basis of the masonry characteristics, the block/brick size and the standard selected. The capacity curve for shear mechanism is completely defined by calibration of softening and unloading branches. The hysteretic behavior is governed by the deterioration modified curve of Ibarra-Medina-Krawinkler (2005) with bilinear hysteretic response, lately modified by Lignos & Krawinkler (2012).

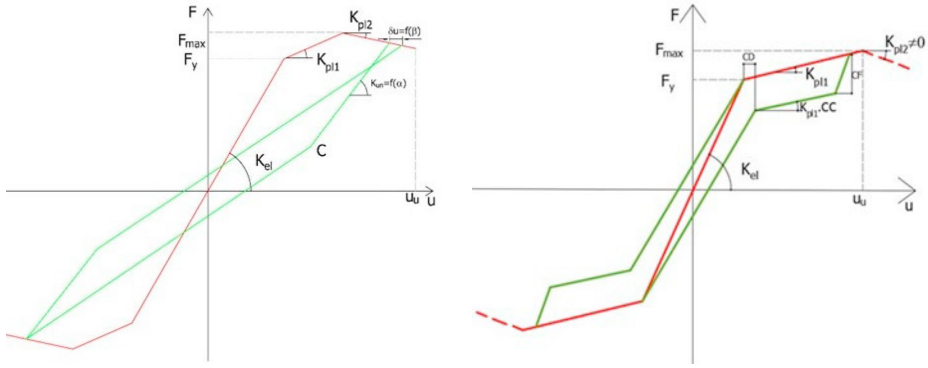
2.3. NextFEM Designer

NextFEM Designer treats analysis and checking of URM through one of its modules, called MasonryCheck (NextFEM, 2022). Macroelement, which is visually represented by a planar 4-nodes element, is formed by the assemblage of 2 springs at both ends of the a simple Euler-Bernoulli beams. The stiffness of the spring shear DoFs contains the additional shear deformation given by Timoshenko contribution for beams. Finally, 4 rigid links connect the ends of this assemblage to the 4 nodes forming the panel.

In such springs, all the plastic response of a masonry pier or spandrel is lumped in the phenomenological cycles depicted in Figure 1a for shear DoFs and in Figure 1b for flexural DoFs. Adopted cyclic laws are described in Rinaldin et al. (2016a, b); they also includes stiffness and strength degradation, and can be used also for out-of-plane response.

The shear strength is calculated as the minimum value between diagonal cracking (governed by relationship described in Turnsek-Sheppard, 1980), shear-sliding as per Mohr-Coulomb formulation and rocking strength as per Italian regulations (MIT, 2018 & 2019). Strength evaluation is performed for every load increment, allowing to assess the capacity of the backbone curve, which varies in strength by maintaining the given displacement.

Macroelement is able to switch between the shear law (Figure 1a) and flexural cycle (Figure 1b) on the basis of panel slenderness and axial law detected the in the pier. For spandrels, pure shear and Turnsek shear mechanisms are considered. This purposely-developed macroelement is available for both NextFEM default solver (Patzak & Rypl, 2012) and for OpenSees (McKenna et al., 2000).



(a) (b)

Figure 1. Backbone curve and cyclical behavior of shear DoF (a) and flexural DoF (b), from NextFEM users' manual (2022).

3. Test cases and comparison

Firstly, software packages are compared using material characteristics needed to get models capable of correctly simulate the experimental response. Models are calibrated ensuring equality in terms of geometry, loads applied and masses. The comparison is carried out first on single wall panels and then on an entire perforated wall.

3.1. Single masonry piers

Experimental tests reported in Anthoine et al. (1995) are considered. Two different brick masonry panels were tested by applying a vertical constant load equal to 150kN (9,5% of the axial strength of the panels) and then by imposing horizontal cyclical displacements on the top. The two samples, called "Low wall" (LW) and "High wall" (HW), have the same cross-section 1.0 × 0.25 m², but different height, of 1.35m and 2m respectively. The experimental results showed the strong influence of the height/thickness ratio on the failure mechanism of the panel. The squat panel (LW) exhibits a brittle shear failure, while the slender panel (HW) shows a crushing mechanism, with large horizontal cracks at the ends of the wall. The development of the two different failure mechanisms has led to as many different hysteretic cycles, with dissipative capacity and cycles significantly wider for the squat than the slender panel. Material properties are listed in Table 1.

Table 1. Mean mechanical characteristics of masonry for Low wall (LW), High wall (HW) and Wall D

Mechanical characteristics		LW - HW	Wall D
Young's modulus	E [MPa]	1900	1600
Shear modulus	G [MPa]	570	480
Compressive strength	f_m [MPa]	6.2	3.1
Tensile strength	f_t [MPa]	0.2	0.12
Mass density	ρ [Kg/m³]	1900	1900

For each software package and for all the specimens analysed, hysteretic cycles have been characterized by the following main parameters: in Tremuri, peak shear strength deformability as 1.5 and shear softening parameter equal to 0.1; in Seismostruct, cyclic deterioration parameters for shear strength and stiffness equal to 50, ratio of the force at the start of reloading to the maximum deformation equal to 0.2 and a number of fibers of 150; in NextFEM Designer, unitary ratio between maximum and yielding strength, force loss percentage in first unloading equal to 0.4 and degraded unloading stiffness ratio at failure as 0.8.

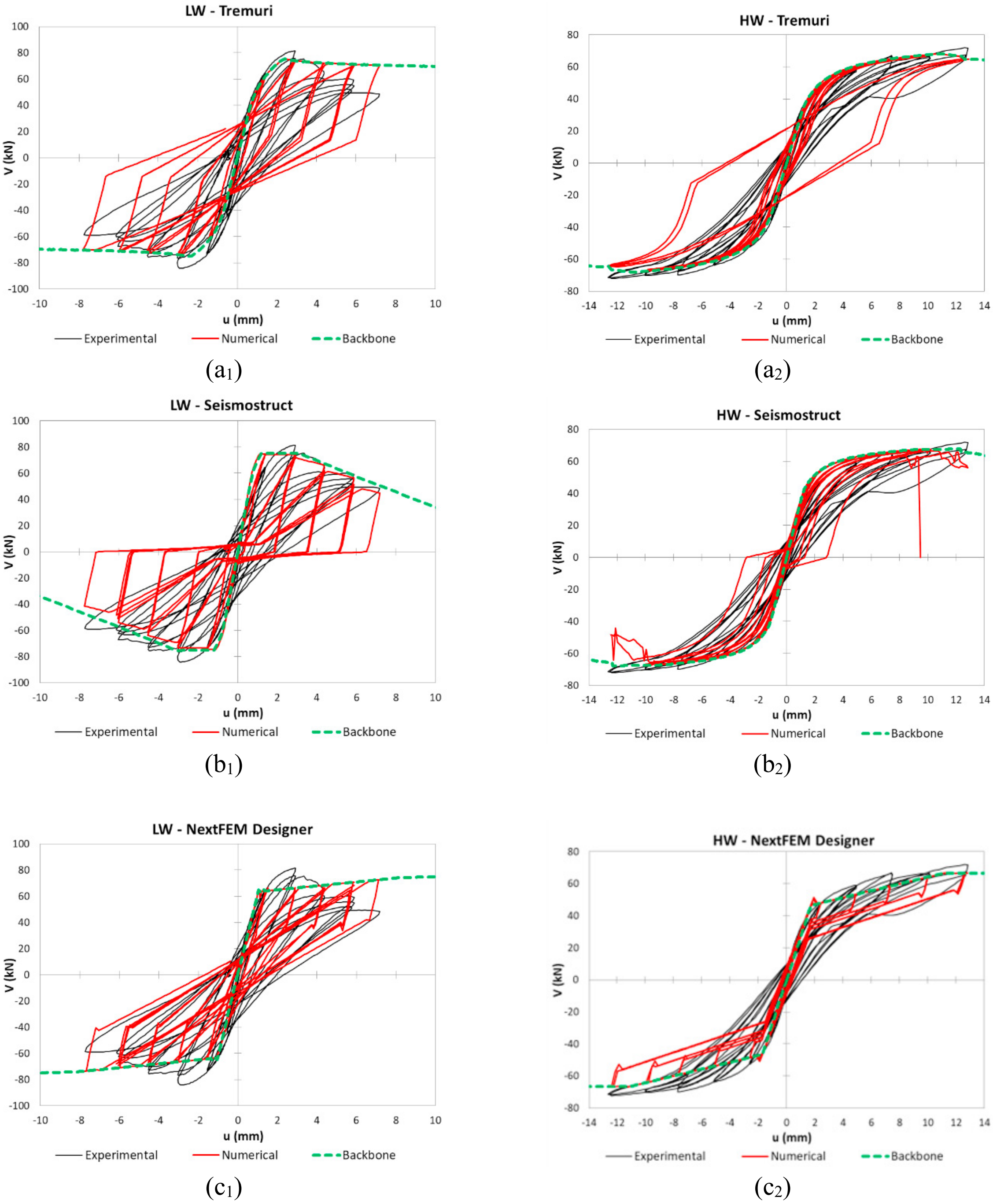


Figure 2. Capacity curves and cycles obtained with Tremuri (a), SeismoStruct (b) and NextFEM Designer (c) for Low Wall (LW, 1) and for High Wall (HW, 2)

3.1.1. Low Wall (LW)

It can be observed from Figure 2 that hysteretic cycles obtained with Tremuri and NextFEM macroelements are basically adherents to the experimental one. On the contrary SeismoStruct shows a quite far trend, despite having a close behavior in terms of dissipate energy (only +9.46%, Table 2). The cycle (Figure 2 b2) has a very pronounced pinching, due to the characteristics of the hysteretic ley defined in the "external links" (L.F. Ibarra, R.A. Medina, H. Krawinkler, 2005 and D.G. Lignos, H. Krawinkler, 2012). However, the defined calibrations allow to grasp the monotonic behavior (the envelope curve of the cycle) for all cases.

Table 2. Variation of total energy on the sample models.

	Low Wall (LW)		*High Wall (HW)*		*Wall D*	
	Total energy [kN m]	Variation [%]	Total energy [kN m]	Variation [%]	Total energy [kN m]	Variation [%]
Experimental test	2.26	/	1.78	/	14.25	/
Tremuri	3.44	+52.26%	1.97	+11.10%	14.51	+1.78%
SeismoStruct	2.47	+9.46%	1.44	-18.87%	-1.20	-108.43%
NextFEM Designer	2.07	-8.47%	1.87	5.28%	10.14	-28.85%

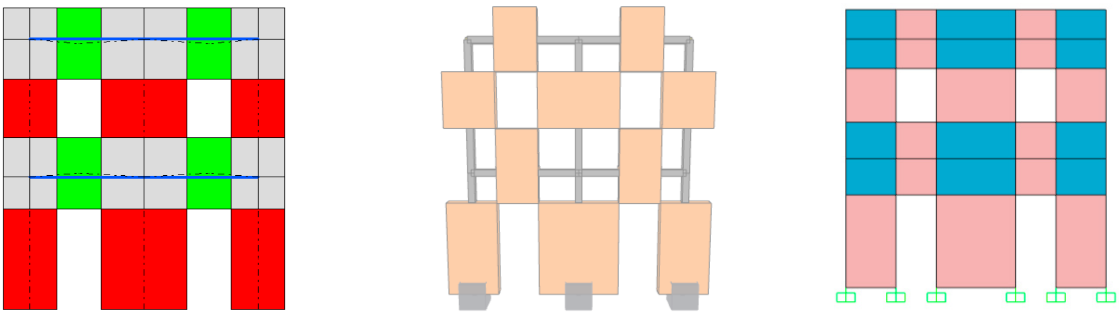
3.1.2. High Wall (HW)

The cycles of the slender models (Figure 2 a2, b2, c2) show a maximum shear equal to the experimental one. The axial-flexural behavior is correctly caught for the elastic and first-plastic branches (monotonic pushovers are substantially the same). This can't be said for the cyclic behavior, as the only code capable of providing some degradation is the phenomenological one (Figure 2 c2), through a correct calibration of the axial-flexural spring (without activating the shear spring). For this reason, phenomenological macroelement is the only one able to provide a similar dissipated energy.

3.2. Masonry façade with openings

The so called "Wall D", experimentally tested by Calvi and Magenes (1997), is a wall with regular distribution of openings, belonging to a two-storey building. Wall-D is disconnected from the rest of the structure and it is individually analyzable, also due to the flexible floors. Imposed displacement was applied at 1st and 2nd floor levels.

The models are made according to the equivalent frame approach, by considering a length of piers and spandrels equal to the one of the openings, as shown in Figure 3. Material properties are listed in Table 1, and have been obtained after a calibration process conducted with the aim to minimize the difference backbone curves amongst software responses. The mechanical parameters defining shear, axial and flexural behavior are significantly different between the codes, as reported in Figure 4: Tremuri and NextFEM Designer models leaded to good results: numerical curves are close to the experimental one and dissipated energies are similar, while the SeismoStruct solution appears worse in terms of cycle paths. Finally, differences in terms of energy are listed in Table 2.



(a) (b) (c)

Figure 3. Models developed for Tremuri (a), SeismoStruct (b) and NextFEM Designer (c).

4. Conclusions

Three widespread software packages have been tested in reproducing cyclic behaviour of masonry. They have been chosen on the base of their ability to simulate cyclical response of URM. Experimental tests taken from literature have been used as reference to compare numerical results. The main focus was on cyclic response, and the quality of response have been estimated in terms of ability to reproduce experimental cycles and on the variation of total energy for all cycles.

All the analysed models are based on macroelements differently formulated but with close results. Form the comparison carried out on LW, HW and Wall D specimen, the in-plane behaviour exhibited some noticeable differences.

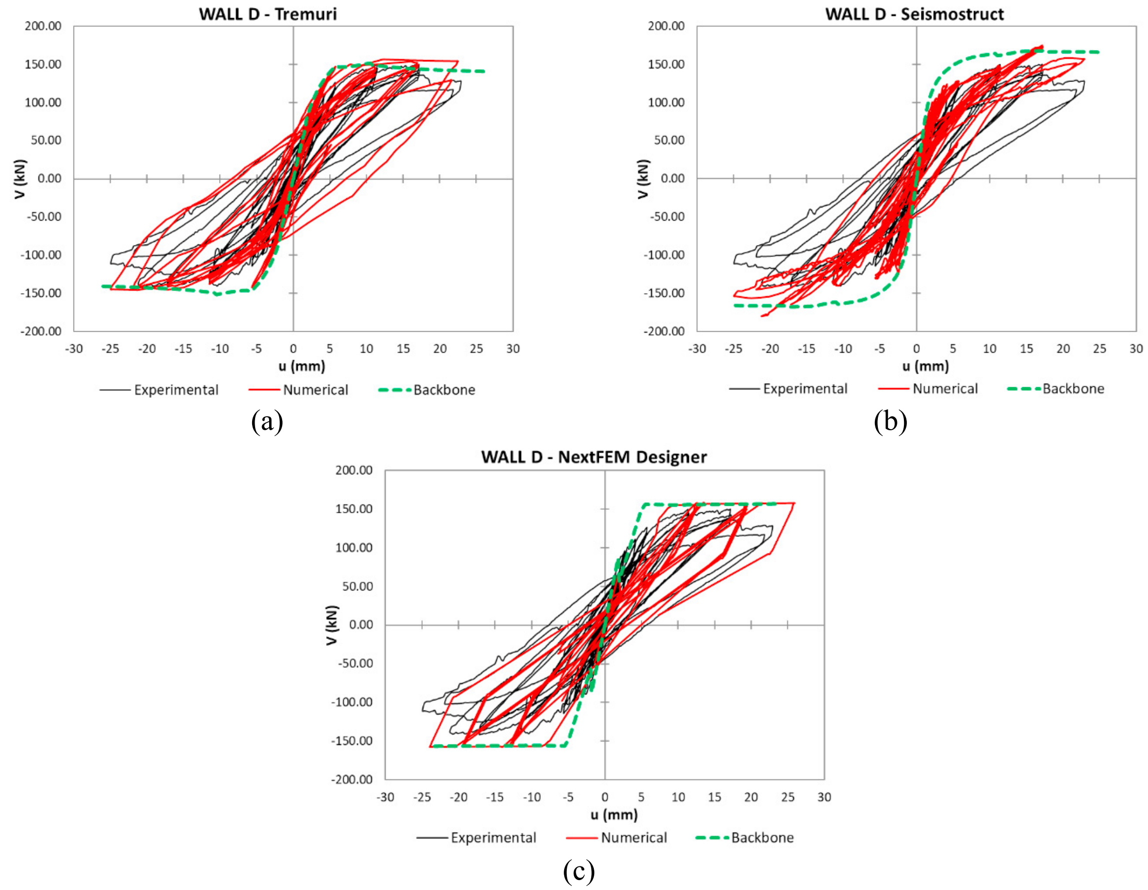


Figure 4. Capacity curves and cycles obtained with the software packages for Wall D.

From the structural designer standpoint, the most important feature is the strength level reached by piers and spandrels at a fixed ductility, and it seems to be realistically simulated from all the software employed. Ductility capacity is in particular the preeminent characteristic when URM structures are analysed in non-linear field, as concluded also in Rinaldin & Amadio (2018) in relation with N2 design method (MIT, 2018). Also dissipated energy is an important design parameter for a validation of cyclic response, the software packages able to reproduce a proper cyclic behaviour are a lot less than one expected. Tremuri and NextFEM Designer seem to give closer cycles to the experimental hysteretic behaviour of the considered specimens.

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