A LARGE EXPERIMENTAL CAMPAIGN FOR THE SEISMIC PERFORMANCE ASSESSMENT OF URM STRUCTURES SUBJECTED TO INDUCED EARTHQUAKES

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Abstract

The Groningen region of the Netherlands, historically not prone to tectonic ground motions, in the last decades was subjected to seismic events induced by conventional gas extraction and consequent reservoir depletion, for which reason an extensive seismic risk assessment study was deployed. The peculiarity of the input ground motions, the distinctive structural features and consequent general lack of knowledge on the seismic response characteristics of the unreinforced masonry (URM) Dutch building stock, and the goal to also assess the full collapse capacity of the buildings drove the design and execution of a comprehensive test campaign comprising several *in-situ* tests and full-scale shaking table tests of URM buildings, briefly summarised in the present paper. The experimental programme was performed at the European Centre for Training and Research in Earthquake Engineering (EUCENTRE, Pavia, Italy) since 2014, and included: (i) characterisation tests on bricks, mortar and small masonry assemblies; (ii) in-plane cyclic shear-compression tests and dynamic out-of-plane tests on full-scale masonry piers in one- and two-way bending; and (iii) several full-scale uni-, bi- and tri-directional shake-table tests on different URM building typologies with and without retrofitting interventions.

Keywords: Induced seismicity; Unreinforced masonry (URM); In-situ testing; Quasi-static testing; Shake-table testing.

1. Introduction

The tests presented in this paper are part of a research project aimed at assessing the vulnerability of buildings typical of the Groningen region (located in the Northeast Netherlands). This area, historically not prone to tectonic ground motions, during the last two decades has been subjected to seismic events induced by reservoir depletion due to conventional gas extraction [1]. Seismicity induced by various anthropogenic activities has been studied for several decades while its effects on structures has been poorly investigated; this called for a large research effort specifically addressed at evaluating the vulnerability of the building stock [2], with a specific focus on the URM buildings. Launched in 2014, an extensive experimental campaign was designed to investigate the performance of masonry assemblages, components, structural members and building prototypes and consequently develop and improve state-of-the-art numerical and analytical methodologies addressing the same. The innovative and original contributions of the study were motivated by:

- the very limited knowledge of the seismic behaviour of the building stock, which was never conceived and built for earthquake resistance, and presents specific peculiarities in the common structural solutions (*e.g.* cavity walls, high slenderness of piers, lack of effective connections, flexible diaphragms, very large openings) that did not allow a complete and satisfactory reference to studies available in literature;
- short-duration low-magnitude (magnitudes smaller than 4) induced seismicity earthquake signals are usually not considered in engineering design. Very little, if any information is available in the literature on the effects of such earthquakes on buildings that were designed and constructed without any provision for seismic resistance;
- the requirement of a robust estimate of the probability of collapse of structural and non-structural elements within a building, considering uncertainties higher than those associated with other damage states. This is necessary for assessing the "Local Personal Risk" of buildings, defined as the annual probability of fatality for a hypothetical person continuously present inside or within 5 meters of a building [3]. Such requirements also translated into more challenges while designing the experimental campaign in order to allow for the execution and interpretation of collapse shake-table tests on structural components and building prototypes.

This paper reports an overview of the entire URM experimental campaign performed at the European Centre for Training and Research in Earthquake Engineering (EUCENTRE, Pavia, Italy), focusing on motivations, methodology and available results.

2. Description of the testing programme

The testing campaign was specifically designed to support the development of the fragility and consequence models [4] used in the framework of a project aimed at assessing the induced seismicity risk for the Groningen gas field [2]. Crowley *et al.* [3] described the input requirements of a risk analysis for the assessment of the "Local Personal Risk", including fragility models robustly estimating the probability of collapse of structural and non-structural elements within a building, for the estimation of casualties for a scenario earthquake, and consequence models requiring estimates of the amount of collapsed debris to provide the probability of injury or death to people hit by such debris. The experimental campaign was specifically designed to provide the information needed to define numerical models capable of predicting the response of structures up to collapse conditions, to be used in the calibration of the vulnerability models embedded in the engine used to compute the seismic risk [2], [4].

The experimental programme performed by EUCENTRE included *in-situ* mechanical characterisation tests and laboratory tests, such as: (i) characterisation tests on bricks, mortar and small masonry assemblies; (ii) in-plane cyclic shear-compression tests and dynamic out-of-plane tests on full-scale masonry piers in one- and two-way bending; and (iii) full-scale unidirectional, bidirectional and tridirectional shake-table tests on different URM building typologies, with and without retrofit solutions. Part of the tests was conducted on the shake table of the National Laboratory of Civil Engineering (LNEC, Lisbon, Portugal). A detailed overview of the first four years of the experimental campaign on URM structures is reported in Graziotti *et al.* [5]. A parallel complementary experimental campaign was also performed by the Delft University of Technology (TU Delft, the Netherlands) on similar URM structures related topics [6]. It is also noted that, always within the framework of the seismic risk assessment for Groningen, an additional experimental campaign, similar in scope but smaller in extent, was deployed by EUCENTRE for those type of Groningen reinforced concrete structural systems for which experimental or numerical seismic response data was not available [7], [8].

In order to design the tests, in particular for the shake-table ones, seismological information is essential to apply time-histories representing those that might hit the building stock to be assessed. Particular attention was paid to the selection of the most appropriate input motions, not only in terms of spectral shape but also taking into account other intensity measures of specific relevance to earthquakes induced by this gas field (*i.e.* peak ground velocity and significant duration). Furthermore, data on building typology, mechanical properties and detailing were necessary to set up the most appropriate tests on component and structures, in order to take advantage of the tested seismic response of structures similar to those of the building stock and subjected to motions compatible with those that could potentially hit the region.

On the other hand, the test campaign served as input for the calibration of exposure model, fragility functions and consequences model. All the data collected and elaborated from the laboratory tests constituted a reliable reference for the calibration of numerical models simulating the static and dynamic behaviour of structures or parts of them (*e.g.* [9], [10], [11], see Fig.1). Particular attention was focused on the testing and subsequent simulations of collapse of structures to develop the consequences model; shake-table collapse tests were performed at LNEC on full-scale buildings and at EUCENTRE on specific structural components. The material and geometrical properties of the reference building numerical models were extended to be compatible with the exposure model, which was developed taking into account the results of the *in-situ* material testing performed on the building stock. It is also noted that Dutch masons built the test specimens.

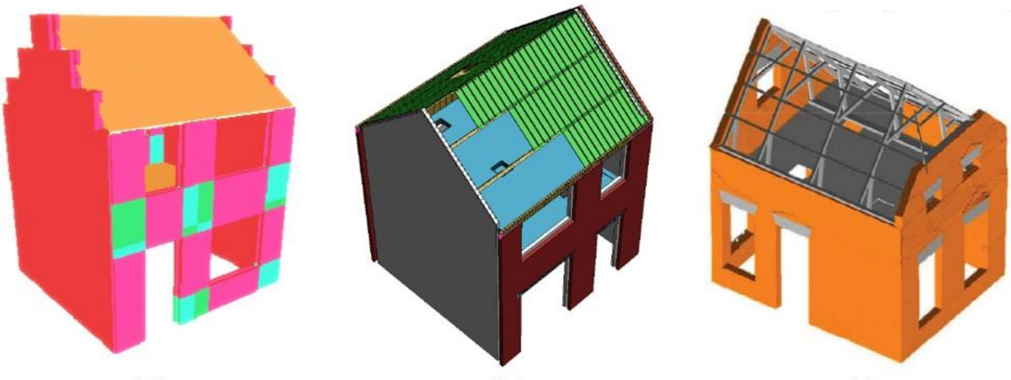


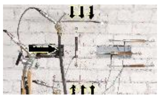
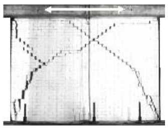
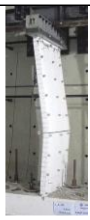
Fig. 1 - Numerical models of URM buildings using: (a) equivalent-frame macroelements (TREMURI; [9]); (b) finite elements (LS-DYNA; [10]); (c) discrete elements (Extreme Loading Software; [11])

Table 1 reports an up-to-date brief summary of the complete experimental campaign started in 2014. In order to allow interested researchers to study or model the tests conducted, all data recorded and the videos of the majority of the tests can be requested online at www.eucentre.it/nam-project.

3. Material characterisation tests on existing buildings

The main objective of material testing within this project was to provide a set of masonry properties to be used as input for numerical models, employed as a reference for the development of fragility curves and also utilized as input for the design of full-scale tests on replicated buildings.

Table 1 - Summary of the experimental campaign and its relation to risk model development efforts

Type	Tested specimens		Number of tests	Main outcome
In-situ, on building stock	*In-situ* and extracted wallettes and triplets		16+ buildings, 500+ tests	Mechanical properties catalogue of the building stock
Quasi-**static**	Wallettes, triplets, mortar, bricks		500+	Detailed mechanical characterisation of each full-scale test, input for numerical modelling
	Piers in -plane		10	Behaviour of piers loaded in plane, identification of limit states, retrofit effectiveness
	Highly loaded piers, in- and out-of-plane		2	Displacement capacity
	Full-scale assemblages		4	Cyclic behaviour of C-shaped structures
Dynamic shake table	Walls out-of-plane		14	Out-of-plane dynamic and collapse behaviour of walls
	Full-scale assemblage		1	Dynamic and collapse behaviour of timber roof
	Full-scale buildings		9	Dynamic and collapse behaviour of structures, define limit states and debris area, retrofit effectiveness

Since the information on the mechanical characteristics of the masonry in the Groningen area was very limited, 16 buildings, comprising residential structures and schools, dating from the early 1920's to 2005, were selected for material testing. The tested walls included both clay and calcium silicate brick masonry of various qualities and conditions; samples were carefully extracted to be taken to the laboratory, where the destructive campaign comprising of compressive, flexural, shear and bond wrench tests was performed by TU Delft and Eindhoven University of Technology (TU/e) laboratories [12], leading to an extensive collation of mechanical characteristics of the tested masonry [13] and the development of a preliminary masonry catalogue for the region [14].

Each of the aforementioned building was also subjected to *in-situ* testing, performed by P&P Consulting Engineers under the supervision of EUCENTRE. While laboratory tests are in general more accurate and complete, an *in-situ* campaign is typically cheaper, faster and less disruptive. Testing *in-situ* adds the unknowns of a not completely controlled environment, but eliminates the non-negligible effects of sample cutting and transportation, and allows the testing of very poor-quality masonry that cannot be brought into a laboratory. The *in-situ* campaign was organized into semi-destructive tests (single/double flat jack and shove tests), and non-destructive tests (rebound hammer test, penetrometric test on mortar and sonic test).

This material characterisation endeavour allowed also to directly compare the *in-situ* and lab tests, highlighting some inconsistencies, in particular in the ASTM C1531 [15] interpretation of the shove test (Fig. 2); complementary work by Andreotti *et al.* (*e.g.* [16]) allowed the proposal of a new procedure to the ASTM committee [17].

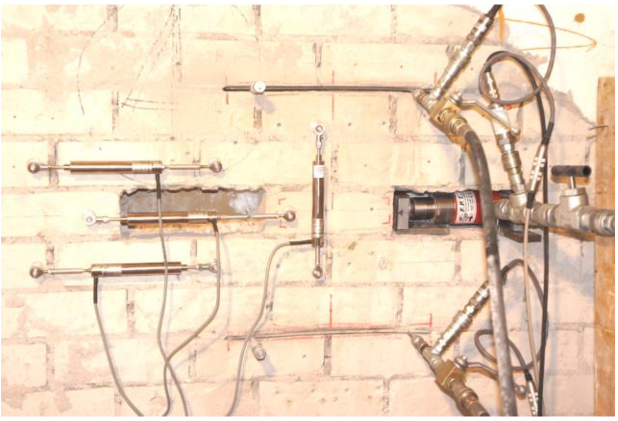


Fig. 2 – A shove test performed on calcium silicate masonry in a building of Groningen province

4. Quasi-static tests

Quasi-static tests allow an accurate investigation of several relevant aspects of structural response: a precise observation and monitoring of the damage propagation, direct measurement of the forces, direct evaluation of hysteretic energy dissipation, identification of damage levels and also calibration of reliable numerical models in term of force-displacement response. However, it is important to keep in consideration the fact that masonry exhibits a rate-dependent behaviour: propagation of cracking at constant load or at constant imposed displacement is often observed, hence quasi-static tests tend to show more extensive damage and lower strength than dynamic tests [18].

4.1 Complementary material characterisation tests

Complementary tests performed in the framework of full-scale tests on components or buildings are essential in order to fully characterize the masonry composing the primary specimen. One major scope of full-scale tests, at least in a project like the current one, is to calibrate numerical models to perform further analyses. Reducing the uncertainties in terms of boundary conditions, input, mechanical and geometrical characterisations is essential in order to obtain a reliable calibration of numerical models. For this reason, extensive mechanical characterisation campaigns (Fig. 3) were conducted in parallel with all the full-scale tests performed. In order to give an idea of the order of magnitude of the number of tests performed in the last 4 years, EUCENTRE, in collaboration with experimental laboratory of the Civil Engineering and Architecture Department (DICAr) of the University of Pavia, completed more than 100 compression test on masonry wallettes, a similar amount of triplet tests, plus hundreds of tests on mortars, bricks and small specimens.

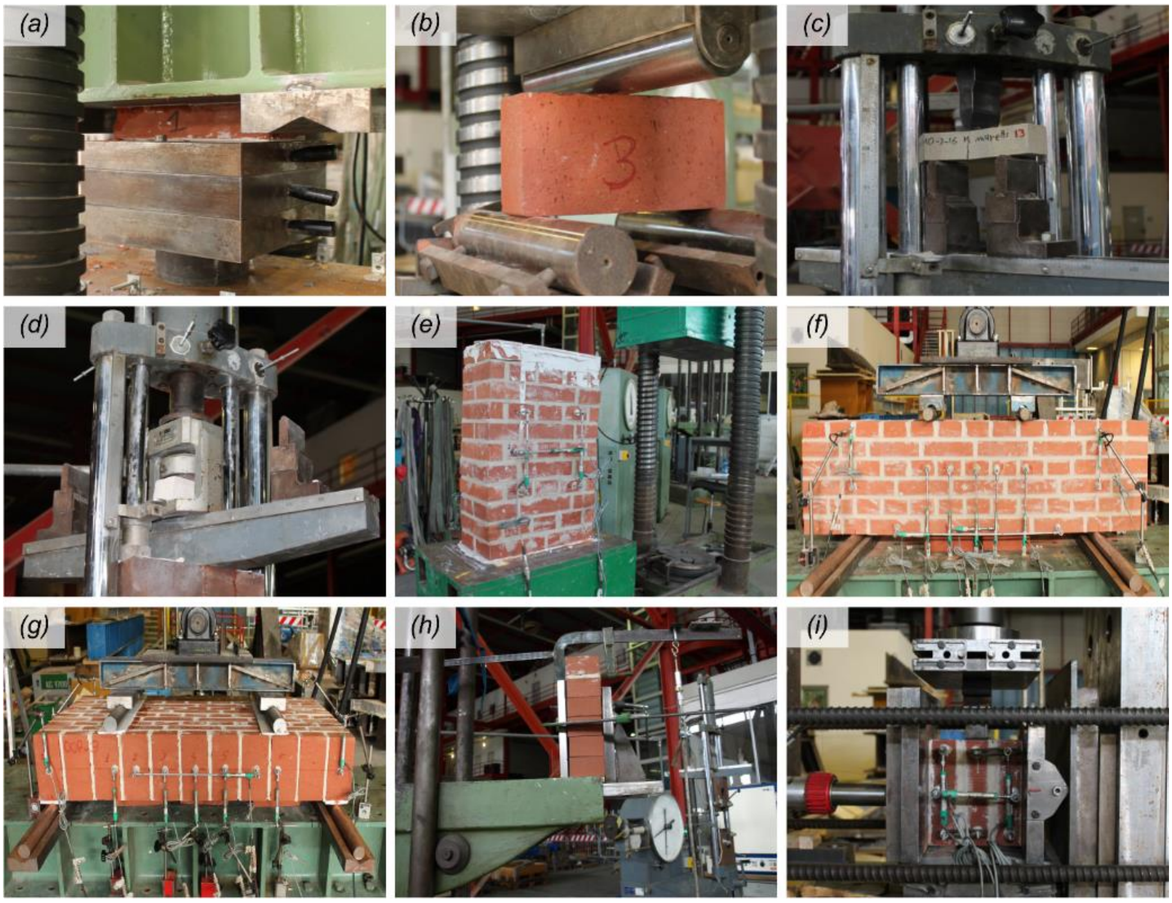


Fig. 3 - Mechanical characterisation tests: (a) compression test on a clay brick; (b) three-points bending test on a clay brick; (c) three-points bending test on a mortar specimen; (d) compression test on a mortar specimen; (e) compression test on a masonry wallette; (f) four-points in-plane bending test; (g) four-points out-of-plane bending test; (h) bond wrench test; (i) shear test on a triplet [19]

4.2 Quasi-static tests on full-scale components and structural assemblies

This part of the campaign focused on assessing both the in-plane, out-of-plane and flanged-wall behaviour of Dutch masonry typologies by applying quasi-static cyclic loading in displacement control. Tested specimens involved a total of 10 in-plane and more than 20 out-of-plane tests carried out on calcium silicate and clay masonry piers (with different aspect ratios, boundary and loading conditions). Two tests were performed on piers with high vertical compression to investigate the in-plane and out-of-plane displacement capacity these components located at the ground floor of multi-storey buildings [20]. Four tests on U-shaped walls were also performed to study the load transfer and the cyclic behaviour of these typical assemblages.

For what concerns the cyclic tests performed at EUCENTRE, Fig. 4 reports the testing setup and, as an example, the identification of the local damage limits on the envelope curve of one of the tested calcium silicate slender wall [21], whilst Fig. 5 shows a scheme of the test setup for the U-shaped flanged walls and two pictures of the damage at the end of one of the tests.

5. Dynamic tests

In the dynamic shaking table tests on full-scale specimens carried out in this endeavour, the prescribed input motion was in one or in multiple directions (including the vertical one). In the selection of the acceleration and displacement time-histories, the first aspect to consider is the capability of the shake table to apply the

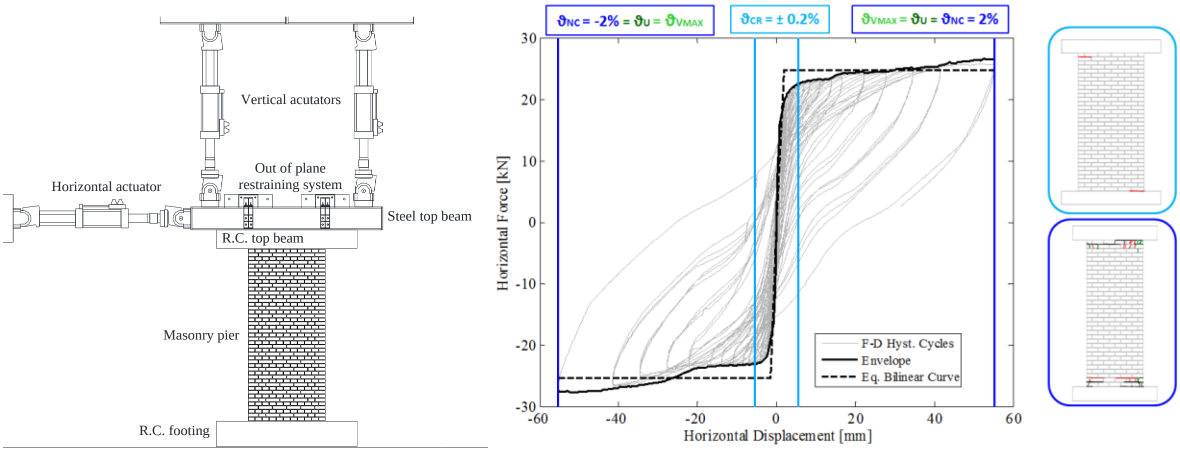


Fig. 4 - Scheme of the test setup for the in-place cyclic quasi-static tests; identification of the damage states on the base shear vs horizontal displacement curve for one of the slender calcium silicate pier [21]

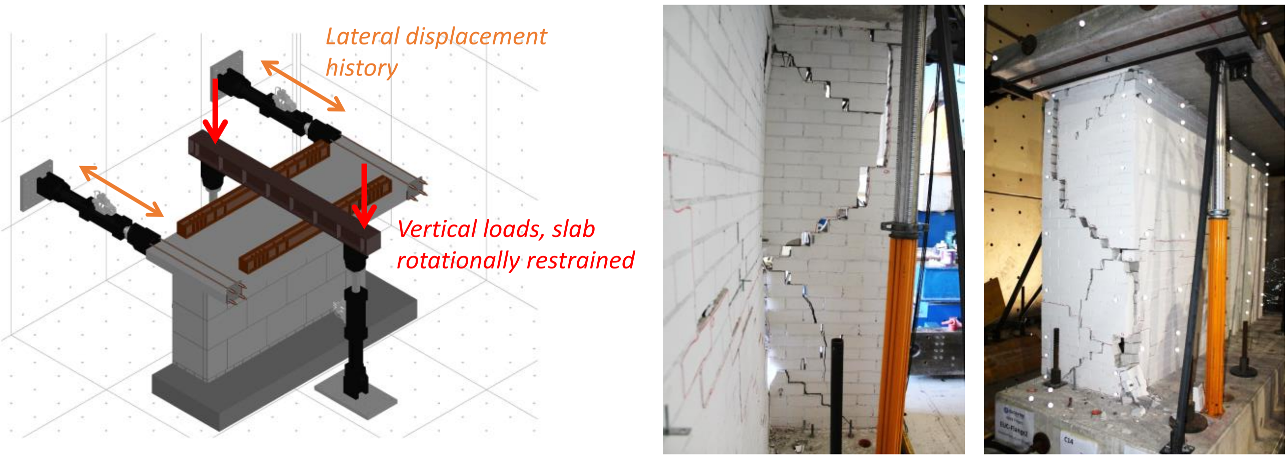


Fig. 5 - Scheme of the test setup for the flanged walls quasi-static tests; pictures of damages at the end of test

selected record with only minor distortion, in particular in the frequency range of interest (*i.e.* around the fundamental periods of the structure). Secondly, it is generally better to select a signal easy to reproduce via numerical modelling, thus characterized by a smooth acceleration spectrum to facilitate the interpretation of its effect on the structure. In particular, in case of study of the vulnerability of structures subjected to induced seismicity, it is also very important to assign a series of motions with characteristics reflecting the seismicity of the area. This is due to the fact that the dynamic behaviour of a structure going in nonlinear range is not only influenced by the elastic spectrum of the motion but also by factors such as the significant duration, the peak velocity, and the Housner intensity [22].

The amount of information that is possible to obtain from this type of experiment is plentiful. Damage pattern evolution is of primary importance, fundamental period elongation and the collapse mechanism. Furthermore, a full-scale dynamic test is a unique opportunity to associate damage states with engineering demand parameters such as the interstorey drift or even ground motion parameters. Other important outputs of these tests are hysteretic plots of the entire structure or a part of it, such as the roof subsystem. These plots, together with deformed shapes, give the opportunity to study the dynamic behaviour of the specimen in terms of dissipated energy, displacement demand, displacement capacity, strength capacity, and in general provide a reference for detailed numerical modelling and calibrations.

5.1 Out-of-plane dynamic tests on full-scale components and structural assemblies

Activation of local out-of-plane local mechanisms has been identified as a major cause of structural collapse in past and recent seismic events. Cavity walls, which are a commonly used structural system throughout the Groningen region as well as Central and Northern Europe, China, New Zealand and Australia, are found to be particularly vulnerable. In such structural systems, the inner leaf has a load-bearing function, with the outer veneer serving aesthetic and insulation functions, hence usually lightly loaded. Despite their high reported vulnerability, very less experimental data (especially dynamic tests) can be found on cavity walls in the literature (*e.g.* [23]); in fact, none can be found for a two-way-bending configuration. Consequently, 14 full-scale unreinforced masonry walls were dynamically tested [24], [25], [26].

An experimental setup was specially designed for this purpose, allowing the full-scale specimens to be tested with different input signals imposing out-of-plane one-way and two-way bending right up to collapse of the specimens. The input motions were also selected to be representative of the floor motions of a typical terrace house of the Groningen region subjected to induced seismicity. Fig. 6 summarises the configurations of the specimens tested on the EUCENTRE shaking table between 2015 and 2018. Pictures of collapses of the one-way and two-way bending specimens are reported in Figure 7.

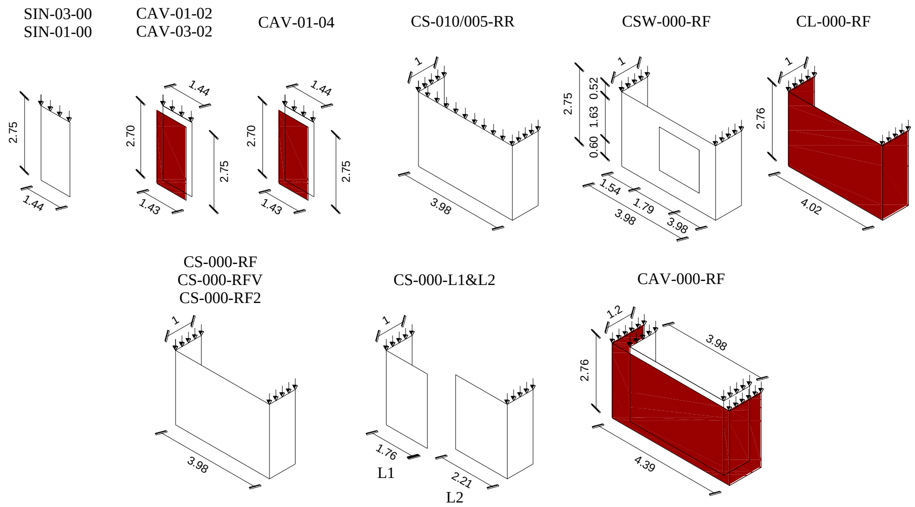


Fig. 6 - Summary scheme of specimens tested out-of-plane on shake table

Fig. 7 - Picture of collapses of the one-way- and two-way bending specimens subjected to out-of-plane shaking table tests

5.2 Dynamic full-scale tests on structures

In the past five years, ten full-scale unidirectional, bidirectional and tridirectional shake-table tests on different URM building typologies were conducted on: four cavity-wall terraced houses, one substructure, one roof, two pre-1940s clay brick detached houses and three identical models in clay brick masonry tested with one, two and three directional input respectively. Also in these cases, the incremental input motions were compatible with induced seismicity scenarios for the lower intensities, and with natural seismicity for higher intensities. An overview of the tested specimens, with a brief description of the main characteristics, the type of input and the references for detailed description and outcomes of each test are provided in Table 2. Fig. 8 depicts the pictures of full-scale building specimens tested on shake tables of EUCENTRE and LNEC.

Some of the experimental tests presented also the chance to investigate the performance of building finishes (*e.g.* the plaster layer) and non-structural building components such as common furniture, chimneys and parapets. For example, Fig. 9 illustrates the different equipment installed in the LNEC-B1 prototype; bookshelf anchored to the wall, bookshelf not anchored to the wall, ground lamp, table with flowerpot and table lamp, table with notebook, paintings, and ceiling light. LNEC-B3 (Fig. 9) and EUC-B8.1, 8.2, 8.3 tested the seismic behaviour of URM chimneys at the roof level.

Table 2 - Summary of full-scale building specimens tested on shake tables of EUCENTRE and LNEC

Name	Date	Lab	Input	Type	Mass	Reference
EUC-B1	09/2015	EUCENTRE ShakeLab	1D	Terraced house unit, cavity walls	56 t	[27]
EUC-B2	04/2016	EUCENTRE ShakeLab	1D	Clay URM building, flex. diaphragms	33 t	[19]
LNEC-B1	05/2017	LNEC-3D shaking table	2D (H, V)	Terr. house unit substructure, cavity walls, collapsed	32 t	[28]
LNEC-B2	05/2017	LNEC-3D shaking table	1D	Terraced house timber roof, gables, collapsed	6.5 t	[29]
LNEC-B3	03/2018	LNEC-3D shaking table	1D	Clay URM building, flex. diaphragms, chimneys	30 t	[30]
EUC-B6	06/2018	EUCENTRE ShakeLab	1D	Vulnerable terraced house unit, cavity walls	47 t	[31]
EUC-B7	12/2018	EUCENTRE ShakeLab	1D	Retrofitted version of EUC-B6	49 t	
EUC-B8.1	11/2019	EUCENTRE ShakeLab	1D	Three identical clay URM structures, flexible diaphragm, parapets, chimneys, unrestraint gable	14 t	[32]
EUC-B8.2	12/2019	EUCENTRE 6DLab	2D (H, V)		14 t	
EUC-B8.3	01/2020	EUCENTRE 6DLab	3D		14 t	

6. Data sharing

Proper justice to the volume of data arising from this very extensive experimental campaign (each full-scale building was monitored with at least 120 instruments plus 3D the optical acquisition system) cannot be done by a single research group. Considering the many possible important developments in the field of URM structures that can arise from this data, the authors felt the need to make such data openly available to the scientific community. For this reason, all the reports, the majority of the videos and all the data recorded by

EUCENTRE and LNEC during the tests are available for interested researchers and stakeholders (they can be requested online at www.eucentre.it/nam-project). Each paper or report explains in detail how the data were collected, processed and synthesized and how to use it. In some cases, specific open access data papers were also published; Kallioras *et al*.[33], Tomassetti *et al*. [34].

Fig. 8 - Pictures of full-scale building specimens tested on shake tables of EUCENTRE and LNEC

Fig. 9 – Pictures of LNEC-B1 and -B3 specimens, damage to nonstructural components

7. Conclusions

This brief summary paper describes the methodology adopted to support the assessment of the seismic vulnerability of unreinforced masonry buildings in the Groningen province in the Netherlands by means of a comprehensive testing programme performed by EUCENTRE.

In-situ tests on different masonry typologies common in the building stock of the region provided useful information to characterize the mechanical properties and their variability, useful for the development of the exposure model and for the design of laboratory tests.

Quasi-static cyclic tests on structural members and assemblies allowed an accurate investigation of several aspects related to their seismic response. They also constituted a valuable basis for the development of specific capacity models, strength criteria and limit state thresholds.

Out-of-plane static and dynamic tests were also performed on single and cavity wall systems in one-way and two-way bending conditions. These pioneering tests represented an important benchmark for the analysis of the response of local mechanisms in existing URM buildings.

Nine full-scale shaking table tests on buildings were performed in the EUCENTRE and LNEC laboratories. Such tests, never performed on similar structures subjected to induced seismicity records, resulted to be fundamental for assessing the modelling capabilities on complete building systems and directly allowed the study of their complex dynamic behaviour, specific energy dissipation characteristics, especially in the highly nonlinear range, and characteristic collapse modes. The shaking table tests on buildings also allowed for a direct experimental comparison between the seismic vulnerabilities of the two most common building typologies; in particular, the solid-wall detached houses showed lower vulnerability. The near-collapse conditions were attained for values of peak ground acceleration ranging from 0.6g to 0.7g for detached houses and from 0.3g to 0.4g for terraced houses. A novel timber retrofit technique was also tested, demonstrating its seismic strengthening capability.

The experimental information collected during the tests constituted a basis for the development and calibration of numerical models and analytical tools used for predicting the behaviour of buildings representative of the most common building types in the region, *i.e.* URM terraced buildings, typically with cavity walls and different diaphragm solutions depending on the construction period, and pre-1940 detached houses, with solid brick walls and timber diaphragms. These analyses were then used to feed vulnerability models and derive the fragility curves used in the risk analysis process.

Reports, videos and data recorded by EUCENTRE and LNEC during all tests are available for interested researchers at following webpage: www.eucentre.it/nam-project.

8. Acknowledgments

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